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Atmospheric Measurement Techniques Discussions
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Interactive comment on "A Fourier transform spectroradiometer for ground-based remote sensing of the atmospheric downwelling long-wave radiance" *by* Giovanni Bianchini et al.

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First of all I would like to thank the reviewer for the thoughtful and in-depth review, which had provided good tools for improving this work.

I'll answer, as much as possible, to each of the single questions posed:

Generally speaking, more references are needed in this paper. Furthermore, the majority of the references (28 out of 34) were by the authors of this paper; are there no other papers written by outsiders that are relevant to this study?

Yes, definitely, I must say that the choice of the references has been biased by the attempt of providing information about the specific instrument described in the paper without repeating what was already published, while the use of references to show other relevant works in the field has been quite overlooked. The introductory section has been reorganized in order to add references to previous works that are relevant to the paper topic.

Page1, Line 40: This is true only in clear sky horizontally homogeneous scenes. This approach will generally not work when there are clouds overhead

True, it will be clarified that this consideration, so as other to which a similar remark could apply, are referred to clear sky conditions, since the considerations and problems related to the study of clouds are out of the scope of this work.

Page 3, line 10: "that result critical in the delicate process" is very awkward. Please rephrase

Rephrased in the revision.

Page 3, line 75: Is the spectral calibration procedure similar to that in Knuteson et al. JTECH 2004? What is the spectral region used for this calibration?

The procedure has some similarities, but is not the same: in order to provide a robust algorithm that can operate in all the possible measurement conditions, it has been chosen to use the hot blackbody acquisitions for frequency calibration. This will not to perform an independent frequency calibration of each spectrum, but has the advantage of using the much more reproducible absorption spectrum due to CO_2 on the about 1.5 m optical path inside of the instrument. The calibration operates in two phases, first a rough peak finding algorithm detects the Q band center, then the whole P band in the 635-665 cm^{-1} spectral region is fitted using the simplified $0.9 \cdot \text{sinc} + 0.1 \cdot \text{sinc}^2$ lineshape (see attached Figure 1).

This two-step process is required due to the fact that the diode laser could in principle have a frequency shift larger than the spacing of the CO_2 lines and this could induce a systematic error due to a "skip" of one or more lines. The description of the algorithm, and all the information and figures here provided will be added to the revised paper.

Page 3, line 85: What are the details of this scene mirror? Is it gold plated? What polarization properties?

The folding mirror is bare gold on an aluminum substrate, and has been characterized through laboratory measurement in order to provide the small correction needed for the calibration (correction that is applied using the monitored mirror temperature).

The effect of polarization is estimated as negligible, taking into account the fact that the instrument is not operating in polarization mode and the zenith scene, in clear sky condition (the operating conditions taken as a reference in this paper) is not polarized.

Page 3, line 85: What are the properties of these blackbodies? Emissivity spectra, operating temperatures, etc. How stable are they? What is the shape, arrangement of the thermistors, gradients, etc?

Detailed information on the blackbody sources is available in [Palchetti et al., Infrared Physics Technology 51 (2008)], but in order to improve text readability the main details on the blackbody performances will be added to the text. Specifically, the emissivity is better than 0.999 and the operational temperatures are between 10 and 80 °C. Stability is about same order of the temperature reading uncertainty (0.3 K), while gradients are within 0.5 K.

It should be noted that the calibration procedure compensates for linear temperature drifts of the blackbody temperature (specifically, of the reference blackbody source placed on the second input, which is providing a common reference to all the acquisitions).

Page 5, line 68: How high? What is the IWV amount? What does a LBL radiative transfer model suggest the radiance should be for this condition? Is the small bias shown in the figure due to the small amount of atmospheric emission (which could be *confirmed by a RT model), or is it a real instrument artifact?*

The plot was obtained exploiting the full RHUBC-II dataset, acquired from the Cerro Toco site at about 5500 m a.s.l. in the Atacama region. The dataset nevertheless included some acquisitions characterized by 1 mm or more in terms of PWV. This in fact hasn't been a good choice, since the atmospheric residual emission is the main cause of the small offset observed: an improved version of the figure (Figure 3 here attached) has been made using only measurement selected to have a PWV < 0.6 mm, which would give an offset negligible with respect to the instrument estimated accuracy.

*Page 6, line 4 and elsewhere in that paragraph: Should be mW / (m**2 sr cm**-1).*

Corrected in the revision.

Page 6, line 58: What is this chain? Does it use the Revercomb technique to calibrate in complex radiance? How is non-unity emissivity of the BBs handled?

The level 1 data analysis is described in detail in [Bianchini et al., ACP 8 (2008)], it makes use of the complex calibration [Revercomb et al., Appl. Opt. 27 (1988)], while for the blackbody sources a specific mathematical model has been developed [Palchetti et al., J. Infr. Phys. Tech. 51 (2008)], it will be made an effort to add as much information as possible from the above mentioned references in order to make the paper more readable.

Page 7, line 4: what is "assimilable"? Perhaps you mean "similar" ?

Corrected in the revision in order to avoid the confusion with the most used meaning of "assimilation" in this field...

Figure 8 and in the text: Is the imaginary component of the calibrated spectra zero with some noise? Would be good to see that, esp since fig 8 shows some unbalanced spectra with significant phase signals. What is a typical noise spectrum for a standard radiance measurement?

A figure (Figure 4 here below) will be added, showing a typical calibrated radiance spectrum (obtained by the real part of the result of the calibration procedure), and the corresponding discarded imaginary part, which contains only the noise, confirming the reliability of the complex calibration procedure.

Page 7, line 28: Are these instrumental parameters (line shape, spectral calibration) not stable with time ? If that is true, why is this so?

An analysis of the long-term stability of the instrument calibration will be added, in which it is shown that, in absence of spurious effects, the laser stability allows for a < 30 ppm frequency calibration accuracy over a period of 2 years (dominated by a drift due to laser aging). The instrumental line shape is instead affected by misalignment that can occur in case of large thermal excursions of the instrument (Figure 5 here attached).

This analysis involves a 2-year long period in which no maintenance has been performed on the instrument. The observed effect around the middle of the considered period arises from operations performed on other instrumentation inside of the shelter where REFIR-PAD is installed, operations that caused some level of disturbance due to temperature fluctuations and vibrations.

Page 7, line 32: How were these number of layers determined; e.g., why a 4pt temperature profile? Turner and Löhnert JAMC 2014 using mid-infrared portion of the spectrum suggest that there is 6 pieces of information on temperature (and similar for water vapor when the IWV is small), so I would have assumed that the REFIR-PAD observations would have had at least this number of pieces, unless the noise level is much larger than the AERI used in the T/L paper (which is why the noise spectrum needs to be shown).

The number and altitudes of the fitted levels have been determined by an analysis of Jacobians and a subsequent tuning to avoid oscillations in absence of a-priori constraints, as described in [Bianchini et al., JGR 116 (2011)]. Please note that the noise level on REFIR-PAD spectra is actually higher than that on AERI spectra, this is mainly due to the use of uncooled pyroelectric detectors instead of cooled MCT/InSb.

Page 7, line 33: "tipical" is misspelled.

Corrected in revision.

Page 7, line 34: Is the entire spectral range of the REFIR-PAD observations used in the retrieval?

Only a subset of the REFIR-PAD spectra between 350 and 850 cm^{-1} is used for the temperature and water vapor profile retrieval. This in general provides consistent results in a wide range of atmospheric conditions. A different subset, between 920 and 1070 $^{-1}$ is used for the ozone column retrievals. This will be clarified in the revised text.

Fig 11: The spectral structure of the radiance observations in the 15 m band suggest that there is an inversion in the purple spectrum, and that the lapse rate is markedly different for the dark green vs. light green profiles. But these characteristics don't show up in these retrieved profiles shown in Fig 11 (or at least are not obvious to my eye). Is this due to the low number of vertical layers?

As can be seen in the attached plots (Figures 6-9 here below), showing the fitted spectra in the ν_2 band region, the fitting residuals are well inside of the measurement error, apart for one case in which I noticed that a laser mode jump happened, distorting the averaged spectrum (Figure 6 in this document, corresponding to the light green spectrum in the paper). In this case I removed the spectra showing mode jumps from the average, and as a consequence now the chi-square is better (Figure 7 here, light green spectrum after correction). Anyway, there isn't a relevant change in the resulting temperature profiles, and no significant inversion is present.

Most of the effect seen on the ν_2 band can be attributed to the CO_2 present inside and nearby the instrument enclosure but outside of the calibration path so it doesn't cancel out. This doesn't give significant effects on the retrieval, since the overall contribution to the chi square is negligible. In Figure 8 here below (corresponding to the purple spectrum in the paper) the instrument was slightly cooler than the environment, being placed in cool shade on a warm spring day, while in Figure 9 here below (corresponding to the dark green spectrum in the paper) it's the opposite since the instrument was operating outside in February. Please note that I made these plots for example purposes, In my opinion these shouldn't be included in the revised text, unless it is deemed absolutely necessary.

Page 8, line 6: How were these accuracies determined? Are they just the uncertainties from the propagation through the retrieval, or comparison against other obs? If you are going to talk about the retrievals in this paper, then more information needs to be provided so that the reader does not have to search through all of the references to get this information. Please include a discussion on the basic retrieval framework, what assumptions are made, the forward model used, any prior data used to constrain the solution, etc.

Accuracy on the total PWV has been estimated through the error on water vapor column fitting, and validated with a microwave radiometer [Fiorucci et al., JGR 113 (2008)], [Bianchini et al., JGR 116 (2011)]. I understand the fact that repeating some information that is in the cited references could greatly improve readability, but I have been advised (by the other reviewer) not to introduce information that is redundant with other published papers. An effort will be made anyway to add the required information in the revised text.

The retrieval was performed by using the MINUIT routine which is part of the CERNlibs. The subroutine MIGRAD, based on the Davidon-Fletcher-Powell (DFP) algorithm, was used to minimize the chi square cost function given by:

$$\chi^2 = (y - F(X))^T S_y^{-1} (y - F(x)) \tag{1}$$

where y and x are the vector of the measurements and the state of the atmosphere

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respectively, F is the forward model (LBLRTM version 12.2 in our case) and S_y is the diagonal VCM for the measurements. The DFP algorithm, on which the MINUIT MIGRAD routine is based, is a quasi-Newton method which does not require the calculation of the jacobians at each iteration but uses an approximated form. This algorithm updates the inverse hessian matrix calculating the derivatives just at the first step and then using the iterative formula shown above. The same fitting approach which was applied in a previous works [Bianchini et al., JGR 116 (2011)], was used in this paper. No a-priori information was assumed as regularly done in a Bayesian approach, such as optimal estimation, and the initial guess is represented by a local monthly climatology, obtained averaging over a set of radiosoundings daily performed at Dome-C. Since no a-priori information was used to constrain the solution and no regularization was introduced, to avoid the oscillation effects due to the ill-conditioning of the problem this approach requires to limit the number of retrieved parameters, hence the number of fitted levels both for water vapor and temperature profiles is equal to the number of degrees of freedom (DOF). The DOF were derived from a preliminary study performed through singular values decomposition of the Hessian matrix which includes Jacobian and the measurements noise.

Page 8, line 29: I don't think that an interferometer like REFIR-PAD can be considered a "relatively simple tool". Even compared with other spectroradiometers this instrument is pretty advanced. Now, perhaps is operating characteristics make it easy to deploy and it can run autonomously, and that is what the authors are referring to here. If so, then there is little information in this paper about the long-term calibration stability and responsivity of the instrument, other than the oblique reference that some instrument parameters need to be retrieved (see above)

I agree that the choice of the term "simple" is at least misleading, if not plainly wrong, the sentence will have to be rephrased in order to stress the simplicity of operation and the ruggedness that allow for minimal need for interventions and maintenance. As stated before, long-term stability of instrument parameters will be described in the revised text, so will be the hardware that allow for remote operation and management.

Page 8, line 34: this instrument cannot "resolve all relevant atmospheric processes". For example, 10-minute resolution is not able to resolve the rapid changes in cloud optical properties as they advect over the sky port of this instrument.

Yes, as stated before, and as will be explicitly described in the revised text, this has to be intended as in clear sky conditions.

Page 8, line 43: The o3, ch4, and n2o retrievals were demonstrated here, and references to papers that show this are few / none.

More details on the procedure to retrieve N_2O and O_3 will be added: in the first case it is an extra parameter that rescales the vertical N_2O profile in the T/WV fitting process, making use of the 589 cm^{-1} spectral band. In the case of O_3 a separate fitting process is used, operating in the 920-1070 cm^{-1} spectral region with a total of three fitted levels. In Figure 10 here attached are shown some results obtained in the September 2017 – April 2018 period, in case of ozone the available OMI data are also shown for comparison.

While a noticeable offset in ozone data is present and needs to be investigated further, the temporal variability is in good agreement with the satellite data, and the vertical variability observed in the retrieved 3-points profile shows a noticeable variation in the vertical ozone structure in coincidence with the rapid variations in the columnar amounts (Figure 11 here below). This can be explained with the fact that Dome C is on the edge of the polar vortex region.

Page 8, line 47: As indicated above, you haven't spoken about the long-term operations at all, and certainly not the ability to remotely control the instrument (this is the first mention of it). What are the "relevant settings" ?

A section of the revised text will describe the infrastructure allowing for remote control and management (remote shell connection, transfer of selected and preprocessed

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data through low-bandwidth connection, auxiliary instrumentation and subsystems as thermal stabilizers)

Page 8, line 55: "aknowledge" is misspelled.

Corrected in the revised text.

Interactive comment on Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2018-233, 2018.

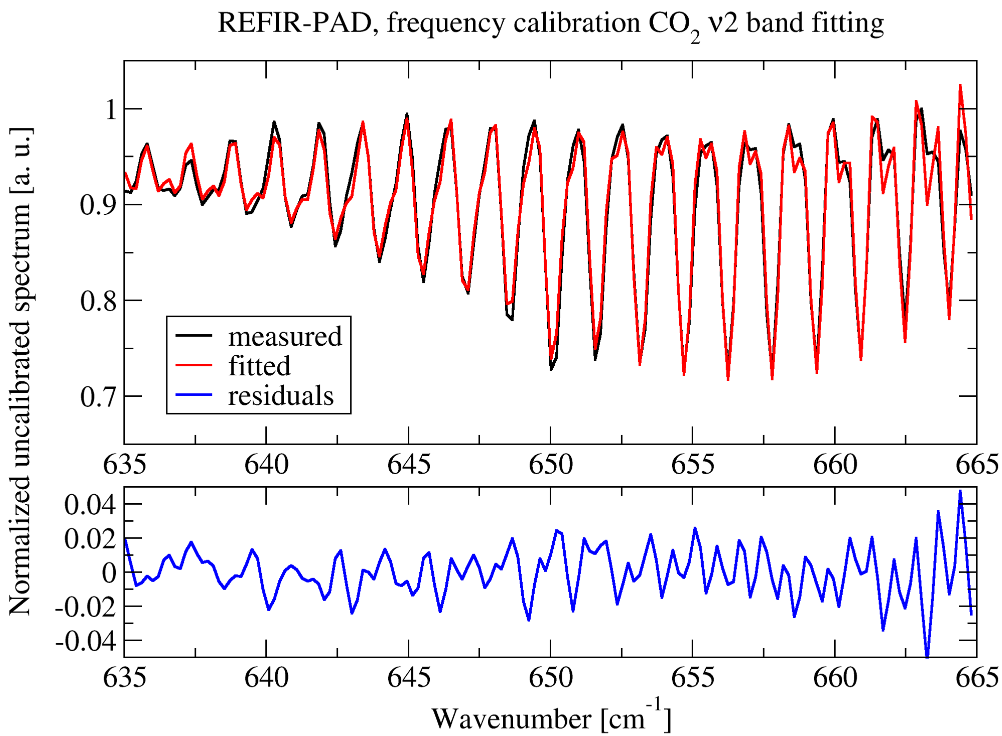

Fig. 1.

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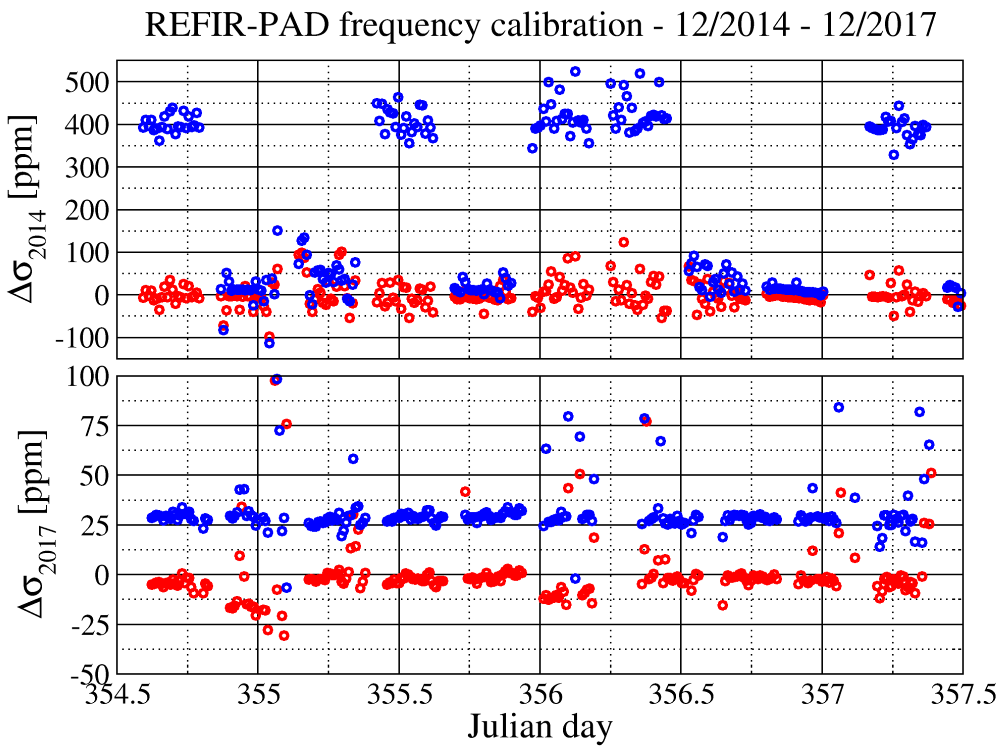

Fig. 2.

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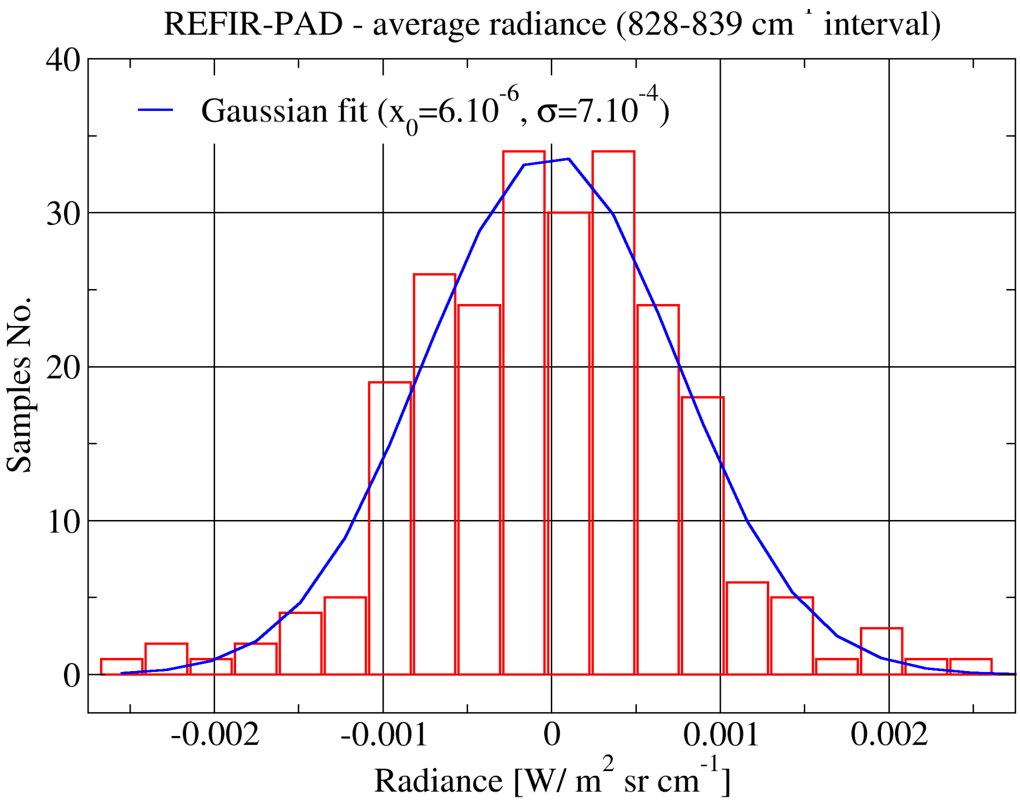

Fig. 3.

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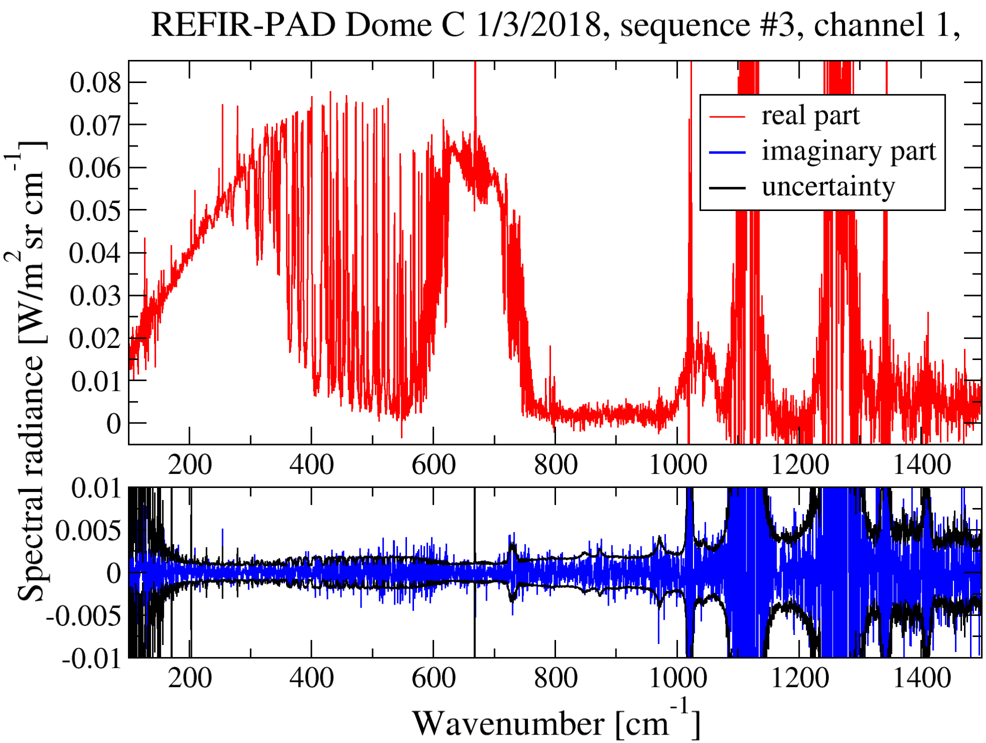

Fig. 4.

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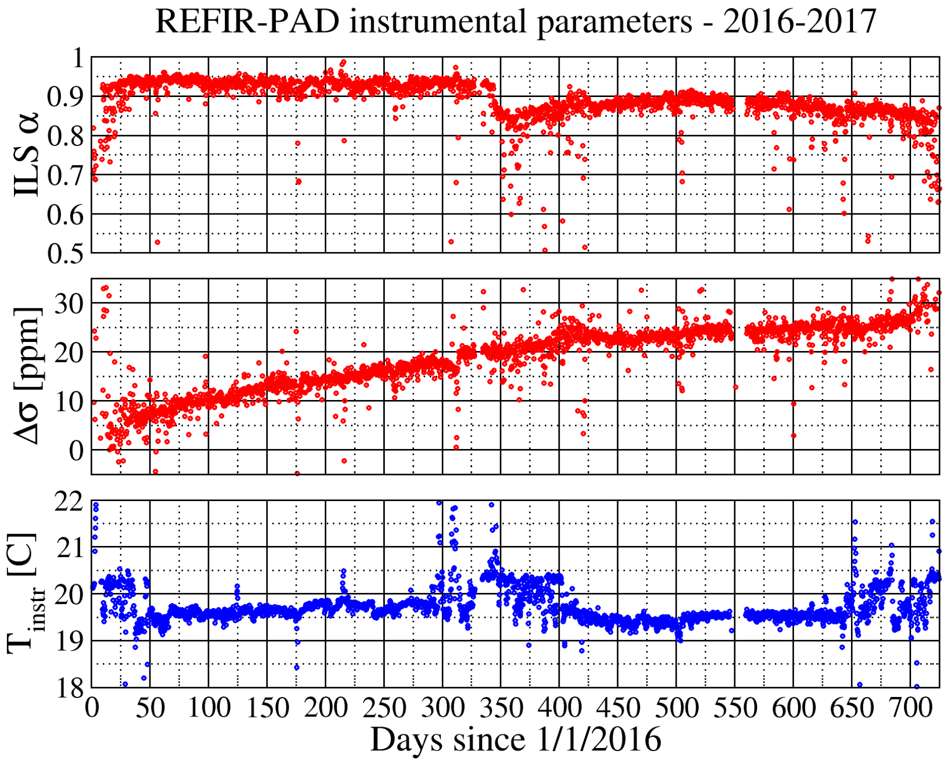
REFIR-PAD instrumental parameters - 2016-2017
ILS α
1
0.9
0.8
0.7
0.6
0.5
Δσ [ppm]
30
20
10
0
T instr [C]
22
21
20
19
18
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Days since 1/1/2016

Fig. 5.

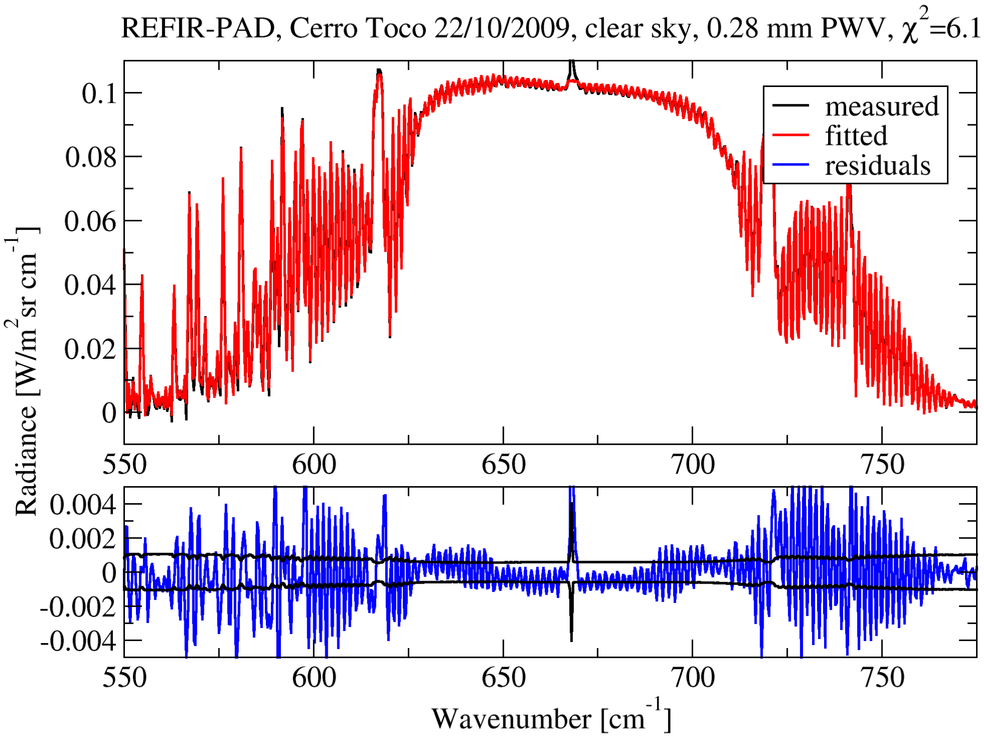
REFIR-PAD, Cerro Toco 22/10/2009, clear sky, 0.28 mm PWV, χ^2=6.1
measured
fitted
residuals
Radiance [W/m^{2}sr cm^{-1}]
0.1
0.08
0.06
0.04
0.02
0
550
600
650
700
750
0.004
0.002
0
-0.002
-0.004
Wavenumber [cm^{-1}]

Fig. 6.

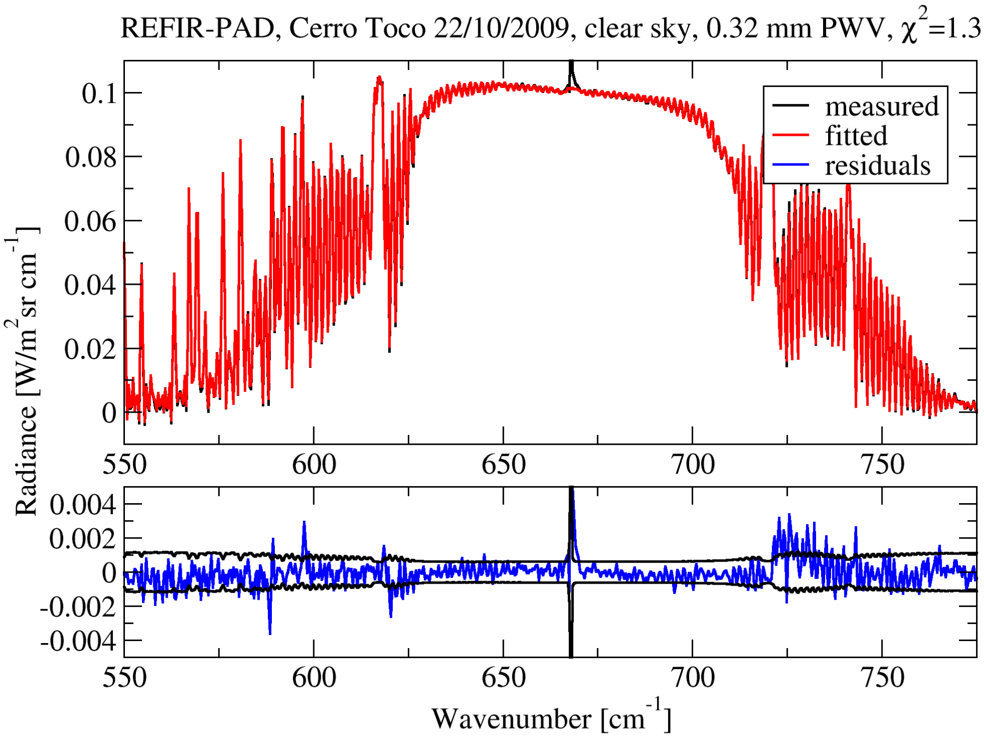
REFIR-PAD, Cerro Toco 22/10/2009, clear sky, 0.32 mm PWV, χ^2=1.3
measured
fitted
residuals
0.1
0.08
0.06
0.04
0.02
0
0.004
0.002
0
-0.002
-0.004
550
600
650
700
750
Radiance [W/m^{2}sr cm^{-1}]
Wavenumber [cm^{-1}]

Fig. 7.

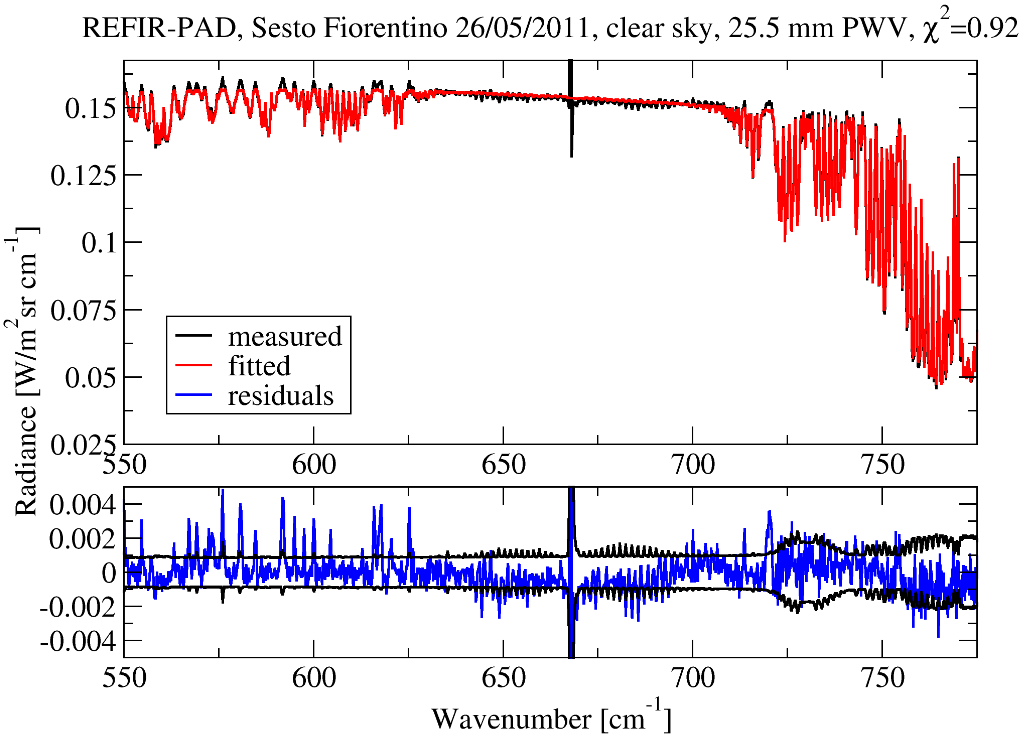
REFIR-PAD, Sesto Fiorentino 26/05/2011, clear sky, 25.5 mm PWV, χ2=0.92
0.15
0.125
0.1
0.075
0.05
0.025
550
600
650
700
750
measured
fitted
residuals
Radiance [W/m2 sr cm-1]
0.004
0.002
0
-0.002
-0.004
550
600
650
700
750
Wavenumber [cm-1]

Fig. 8.

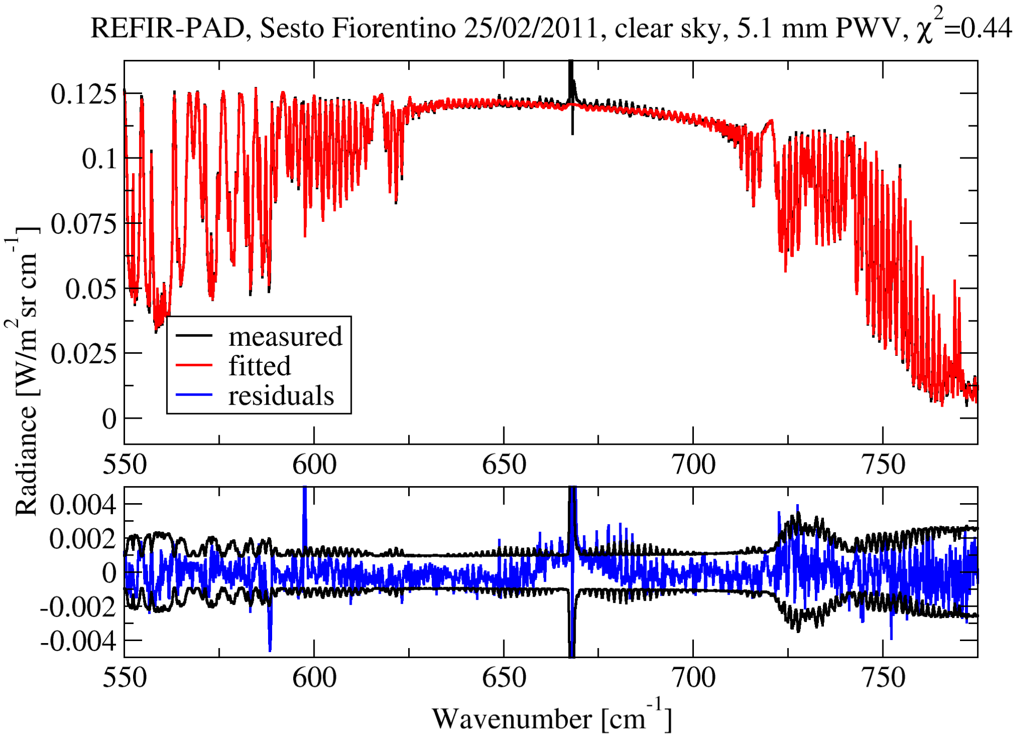

Fig. 9.

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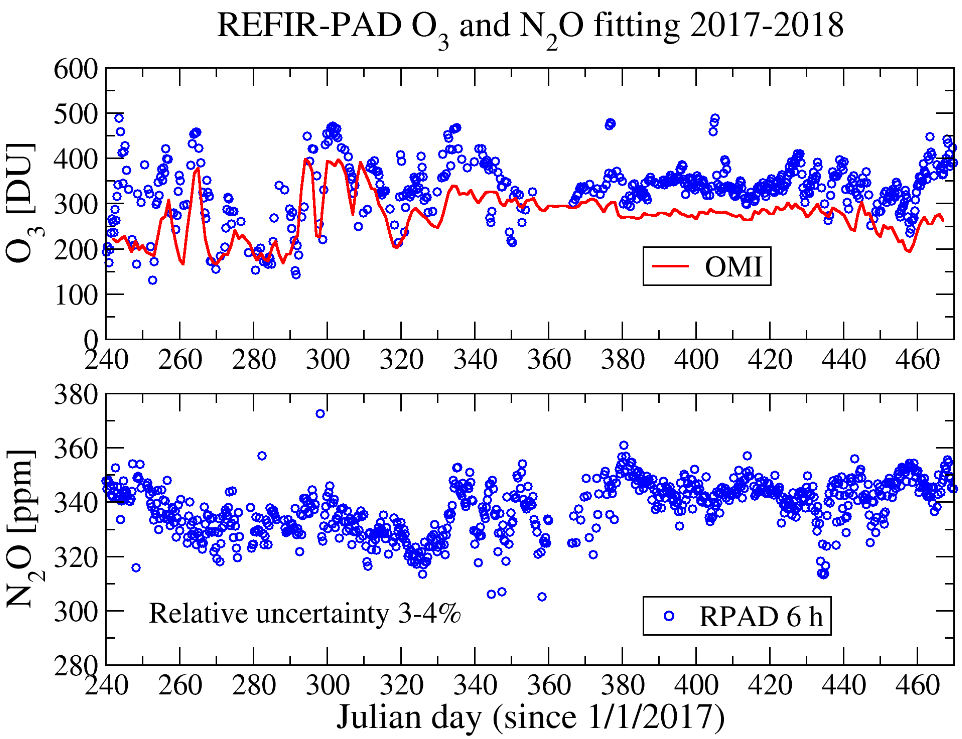
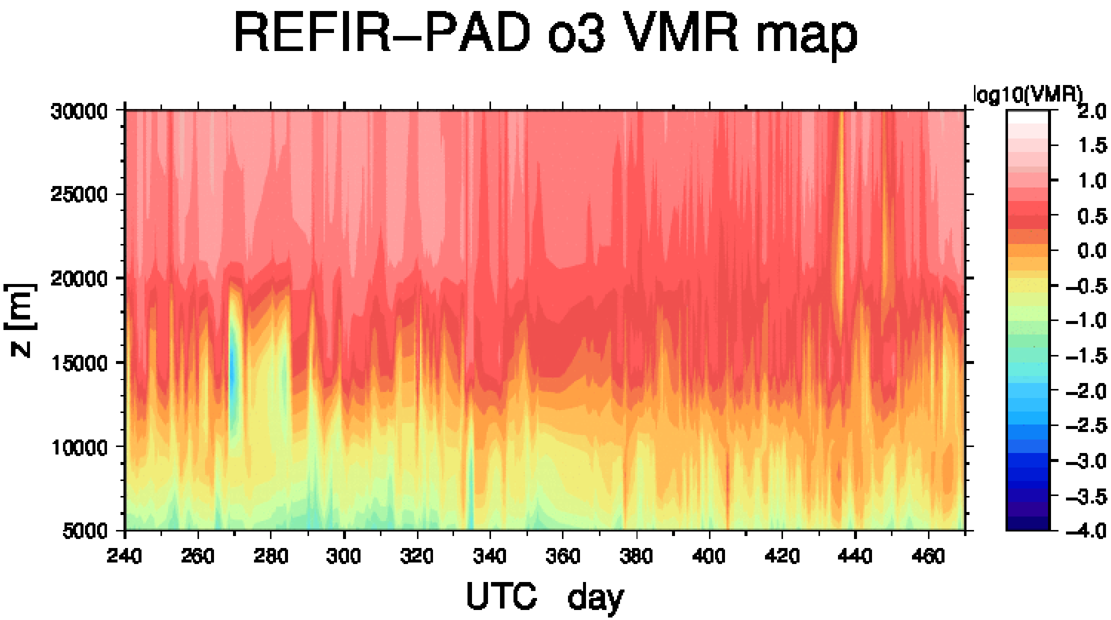

REFIR-PAD O3 and N2O fitting 2017-2018
O3 [DU]
600
500
400
300
200
100
0
OMI
240
260
280
300
320
340
360
380
400
420
440
460
N2O [ppm]
380
360
340
320
300
280
Relative uncertainty 3-4%
RPAD 6 h
Julian day (since 1/1/2017)

Fig. 10.



REFIR–PAD o3 VMR map
log10(VMR)
z [m]
30000
25000
20000
15000
10000
5000
240
260
280
300
320
340
360
380
400
420
440
460
UTC day
2.0
1.5
1.0
0.5
0.0
–0.5
–1.0
–1.5
–2.0
–2.5
–3.0
–3.5
–4.0

Fig. 11.