Report of Visiting Scientist mission NWP_VS16_07

Document NWPSAF-MO-VS-056

Version 1.0

12-12-16

Atmospheric clear-sky Radiative Transfer model intercomparison at mm/submm wavelengths

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 29 June 2011, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.

Change record			
Version	Date	Author / changed by	Remarks
0.1	26/10/16	Juan R. Pardo	Draft version
0.2	10/11/16	Juan R. Pardo	Incorporated comments from R. Saunders, P. Rayer, J. Eyre
0.3	12/12/16	Juan R. Pardo	Final revisions included
1.0	12/12/16	Juan R. Pardo	Final version

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ABSTRACT

The purpose of this report is to show the results of an intercomparison of Radiative Transfer Models in the millimetre/submillimetre domain. On one hand, transmittance models used in the Met Office (hereafter MO) for generating coefficients for the operational fast model RTTOV. On the other hand, models currently used for atmospheric opacity and phase calculations at the Atacama Large Millimiter Array (ALMA). Since the latter instrument operates from one of the highest and driest facilities in the world, the RT model is required to be state-of-the-art at freqeuncies close to 1 THz or even beyond. This is particularly interesting for RTTOV as new applications in the submillimetre wavelength domain are expected in the near future.

Introduction

Dr. Juan R. Pardo visited the UK Met. Office on Sept. 25-30, 2016 to perform, with Peter Rayer, a model intercomparison in the 1-1000 GHz range.The reason of this is the interest in using the RTTOV approach at higher frequencies than today's applications, i.e. well into the submillimetre domain. The intercomparison was made between, on one hand, Pardo's ATM model[1] and, on the other hand, the AMSUTRAN transmittance model that underpins the use of microwave sensors by the operational RTTOV fast model, and incorporates the MPM transmittance models[2–4].

Profile name	Profile label	label h_{ground} (km)	P_{ground} (mb)	T_{ground} (K)	Water Vapour column (mm)
Profile 1	PR1	0.0	986.1	315.2	26.34
Profile 2	PR2	4.1	620.0	272.6	0.1627
Profile 3	PR3	4.1	620.0	272.6	0.2469
Profile 4	PR4	0.0	1014.0	234.0	0.0723

Table 1. Some key parameters of the atmospheric profiles used as inputs for the RT models intercompared in this report. Labels in column 2 are used through this report to identify the profiles.

Several reference atmospheric profiles have been used in the intercomparison, shown in Figure 1 and Table 1 . One of the most relevant physical parameters to take into account in the discussions of this report is the total water vapour column in each atmospheric profile, listed in table 1 along with other relevant parameters.

It was agreed to compare the total transmittance across the atmosphere (zenith view or air mass equal to 1.0) separated by source (dry component, water lines, water non-resonant, etc...) instead of the total opacity, because transmittances are commonly used in RTTOV and also because the scale of the plots can remain always the same (0 to 1 transmittance corresponds to opacity = ∞ to 0).

A set of figures was produced as a results of the calculations. Those figures are the basis of this report and are shown and discussed in the next section.

Results and discussion

Profile 1, a very humid case

The first reference profile for which we run RT calculations corresponds to a hot (sea level ground temperature exceeding 30 Celsius) and very humid (integrated water vapour $>$ 25 mm, with relative humidity on the saturation level at several heights). In those conditions, the atmosphere is expected to be totally opaque beyond 300 GHz and, therefore, we did not perform any calculation beyond that frequency.

The results obtained for this atmosphere can be seen in Figures 2 and 3. The main conclusions about these figures are the following:

- The dry opacity component (oxygen lines, dry continuum, trace gases lines - blue and green solid lines) are reasonably similar with the exception of a noticeably larger opacity in the MO calculations in the atmospheric window between the 60 GHz O_2 band and the 118.75 GHz O_2 line. The difference can be due to the formulation of the O_2 lines in the ATM model, quite different to the models used by the MO in RTTOV, and probably not sufficiently tested (ATM has been tested mainly above 300 GHz). Therefore, the compromise is to look in detail to this issue and, to achieve this task, we are currently working with FTS measurements from Dome C in Antarctica in the frequency range 50-450 GHz, thus covering concerned frequency range.

- The water lines (red and black solid lines) look very similar with the exception of small differences in the line contour, the total intensity of the 22 GHz H_2O line and the presence of lines of H_2O isotopologues and vibrationally excited species in ATM. However, these differences are very small for an RTTOV application.

- Water vapour self and foreign continuum are also different but that difference is partially compensated by the difference in the dry continuum (in the opposite direction) so that we cannot really tell which one is best without further investigation with specially designed experiments and the review of recent works[5].

Profiles 2 and 3, real transmittance measurements available

The main interest of the intercomparison is to see how the different models work beyond ∼300 GHz, i.e. the submillimetre domain. Of special interest is the behaviour of the models near 1000 GHz, the upper limit of several reference models used in the past 25 years by RTTOV[2–4]. For this task it is of great help to have accurate transmittance measurements[6,7] that can be compared with the models. These measurements were achieved from a high and dry mountain site (Mauna Kea, Hawaii) with a Fourier Transform Spectrometer, providing a frequency resolution as fine as 200 MHz across the frequency range 200-1600 GHz.

The results obtained for this profile can be seen in Figures 4, 5, 6 and 7. The main conclusions about these figures are the following:

- $^{16}O_2$ lines look very similar in all models. However, ATM includes $^{17}O^{16}O$, $^{18}O^{16}O$ and v=1 $^{16}O_2$, some of them clearly seen in the data.

- H_2O lines are very different in ATM and MO models. The former includes all water lines up to 10 THz plus non-resonant collision-induced absorption whereas the latter only includes lines up to 1 THz + a fitted continuum term to deal with the excess of H_2O absorption that has been adjusted to fit laboratory measurements below 300 GHz[2,3]. H_2O foreign and self continuum differ also between ATM and MO models for the same reason.

- ATM foreign and self H_2O continuum has been established from fitting the remaining H_2O opacity, once all H_2O lines have been up to 10 THz have been considered in the calculations. The resulting term compares well with theoretical calculations[8]. Obviously, the result is a quite perfect fit of the data. MO model results in an excess of opacity mainly due to a wrong description of the continuum H_2O opacity beyond 300 GHz.

- ATM also includes an empirically derived N_2-N_2, O_2-O_2 and N_2-O_2 non-resonant collision-induced opacity term that is good agreement with theoretical works[9,10].

- ATM includes trace gases lines (O_3 and others) whereas for the current models used for RTTOV, there are no trace gases, and no O_3 lines are included beyond 300 GHz.

- Transmittances in the 1.35 and 1.5 THz windows are well fitted by ATM, although this requires rather high values of the dry and wet continua terms. This item will require, of course, further investigation in the future.

Profile 4, the driest case

Finally, we decided to take from the data base proposed by the MO (the same from which we took Profile 1) an extreme case, the driest atmosphere, in order to explore as far as possible in frequency the differences between models.

The results obtained for this profile can be seen in Figures 8 and 9. The main conclusions about these figures are the following:

- The need of taking into account O_3 and and other trace gases appears very clear.

- H_2O lines and continua terms differ clearly between models as a consequence of the number of included lines and the formalism used to describe them.
- The dry continuum increases dramatically beyond 1 THz as a result of including all layers down to sea level. However the validity of these calculations cannot be established now because we do not have data corresponding to a situation similar to this one.

Conclusions

This report shows the results of a quick radiative transfer model intercomparison performed during only 4 working days at the central Headquarters of the Met Office on Sept. 26-29, 2016. Despite the short amount of time for this work, we can conclude that current RT models used at the MO for RTTOV applications are quite consistent with ATM at frequencies below 300 GHz. However, in the submillimetre range (300-1000 GHz) differences appear due to:

- Lack of O_3 and other trace gases in MO models.
- No H_2O lines beyond 1000 GHz in H.J. Liebe's models (included in MO's).
- Failure of the dry and wet continuum terms of H.J. Liebe's models beyond 300 GHz.
- Lines from isotopic and vibrationally excited species of H_2O and O_2 missing in MO models.

The work started with this report is intended to be the beginning a collaboration aimed at improving RTTOV in the submillimetre range for future applications.

Acknowledgements
J.R. Pardo thanks the interest of the MO in this model intercomparison work and thanks the support of this institution and of EUMETSAT to achieve it. His Research is also supported by ERC under grant ERC-2013-Syg-610256- NANOCOSMOS, Spanish MINECO under grants AYA2012-32032 and the CONSOLIDER-Ingenio program "ASTROMOL" CSD 2009-00038.

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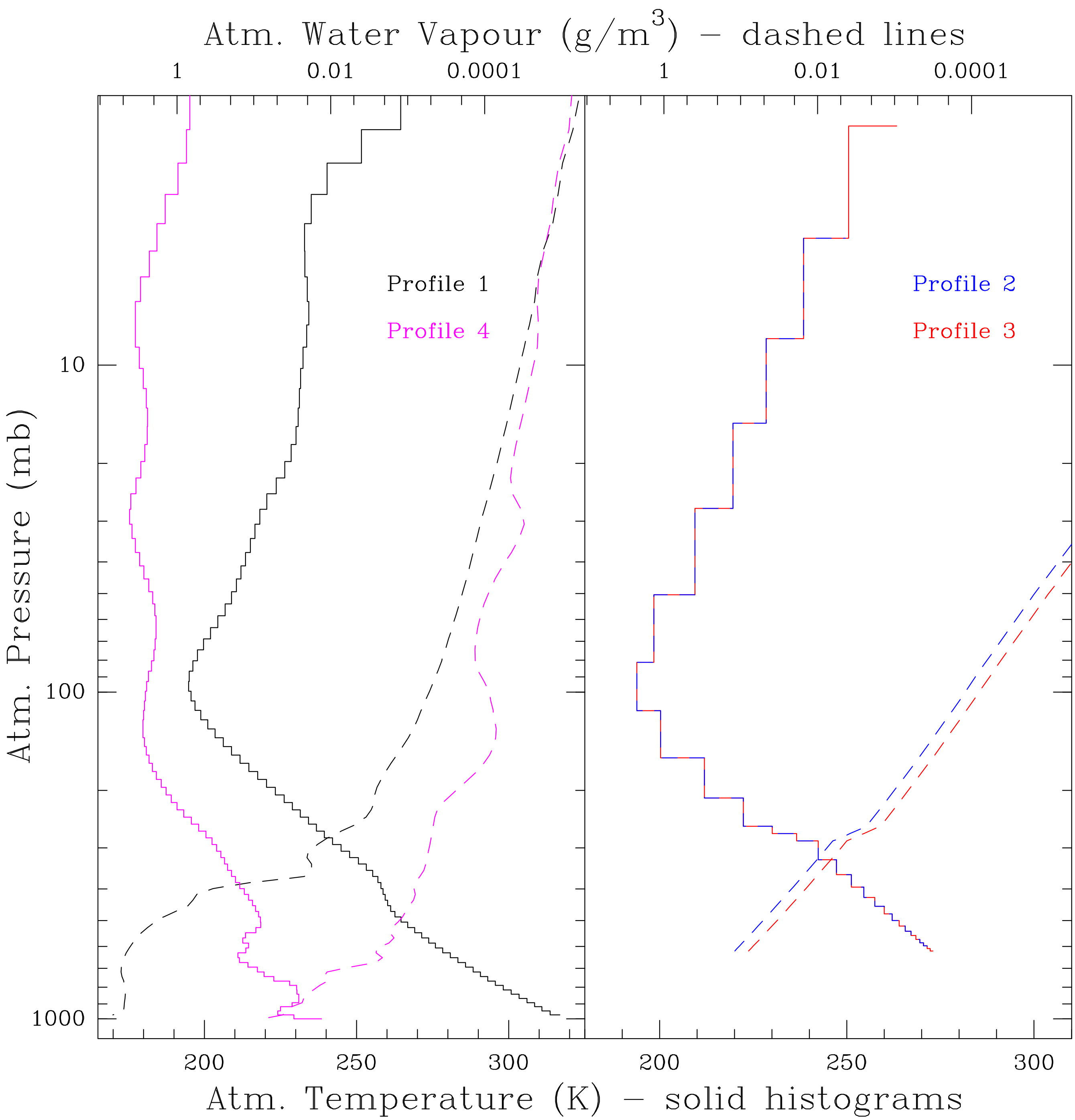

Figure 1. Atmospheric profiles used for the RT model intercomparison.

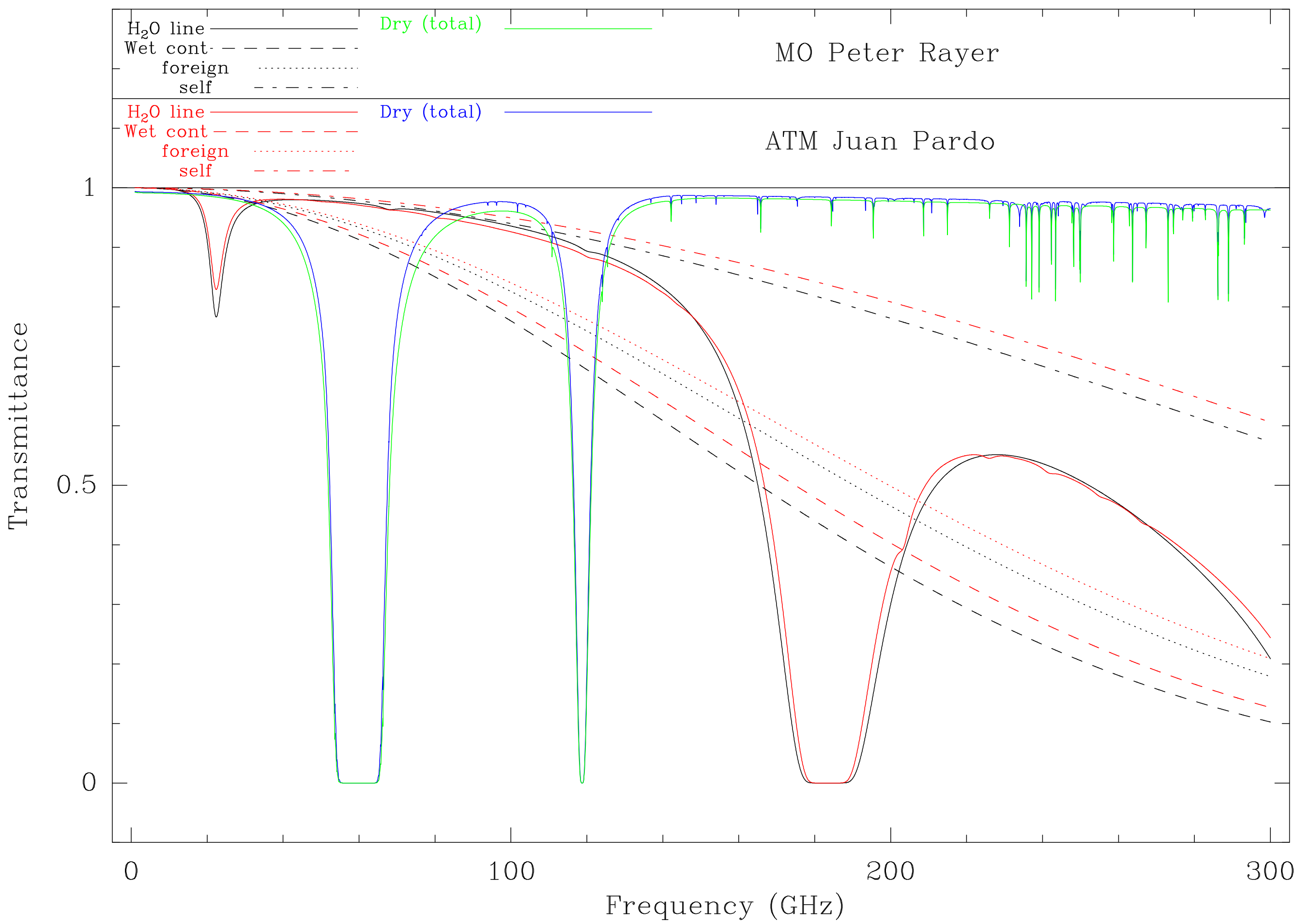

Figure 2. Transmittances, separated by source, calculated by the different RT models for atmospheric profile PR1 of Table 1

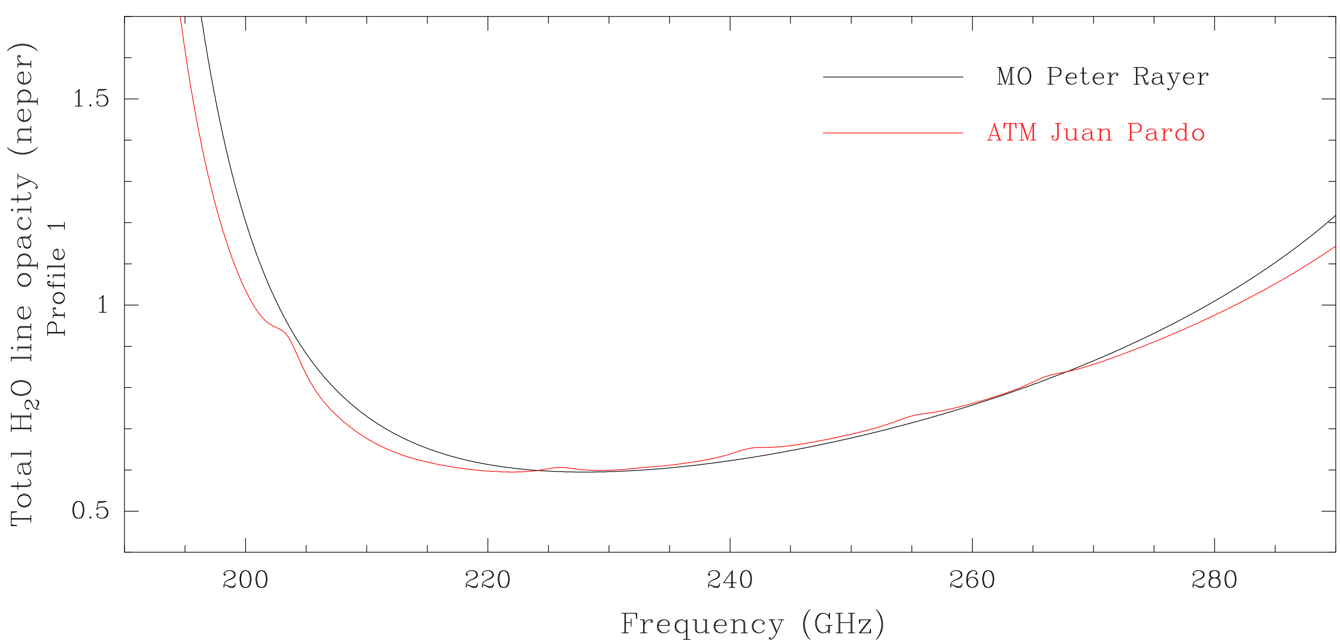

Figure 3. Zoom on the H_2O line transmittance from the previous figure. Although the agreement is acceptable, there are differences due to line shape and H_2O isotopologues and vibrationally excited species, all of them only present in the ATM model[1].

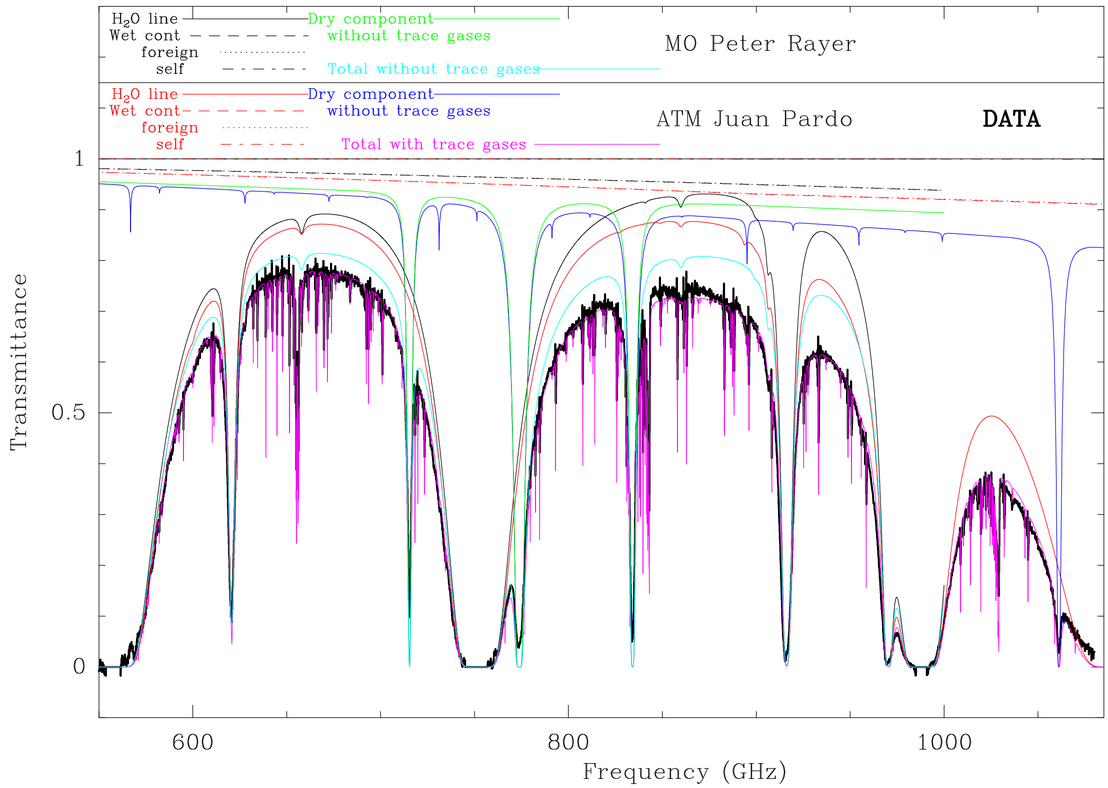

Figure 4. Transmittances, separated by source, calculated by the different RT models for atmospheric profile PR2 of Table 1. A Real transmittance measurement from Pardo et al.[6] is shown as a dark histogram.

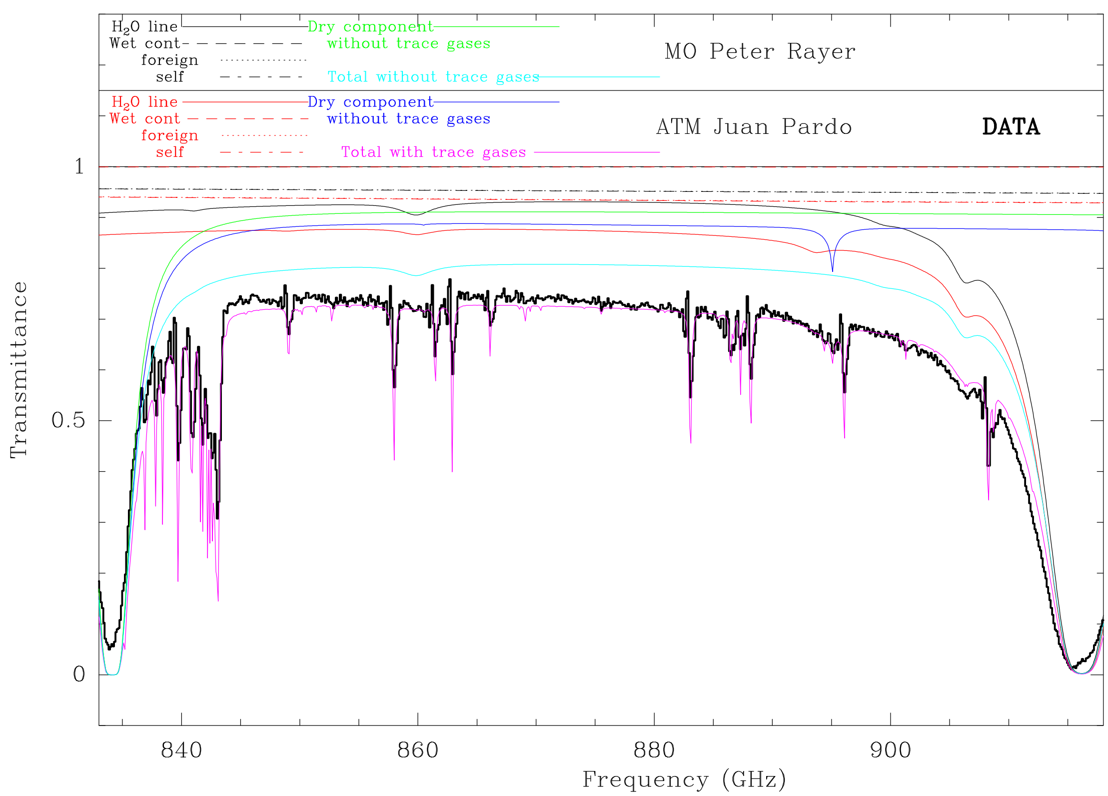

Figure 5. Zoom on the previous figure, showing the effect of trace atmospheric gases (mainly O_3). The difference in the transmittance near the centre of O_3 lines is a numerical effect due to the resolution of the calculations.

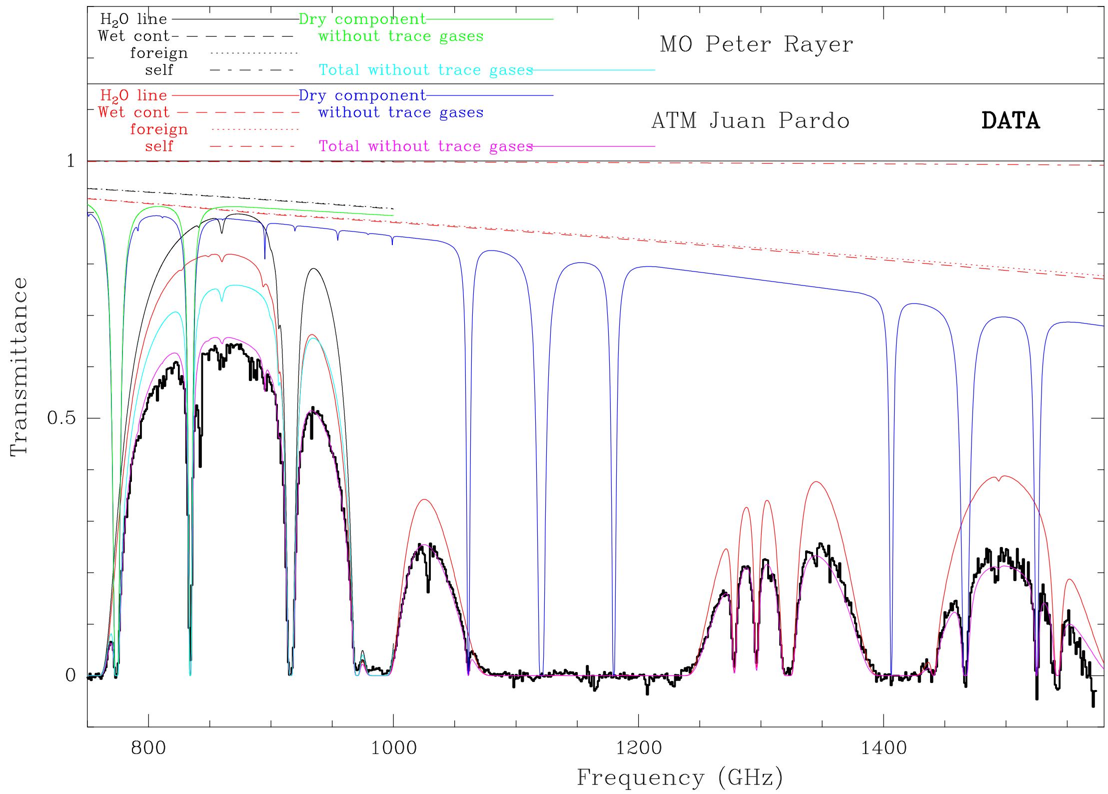

Figure 6. Transmittances, separated by source, calculated by the different RT models for atmospheric profile PR3 of Table 1. A Real transmittance measurement from Pardo et al.[6] is shown as a dark histogram.

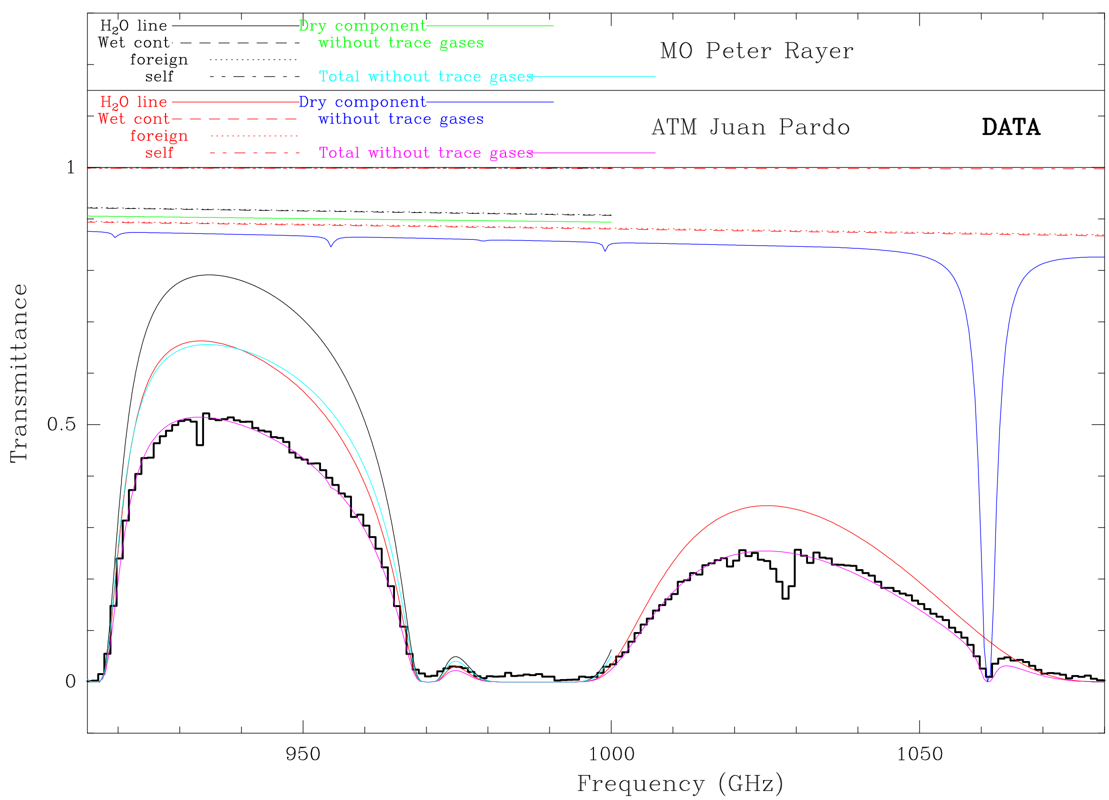

Figure 7. Zoom on the previous figure, showing the 1 THz limit of MO models.

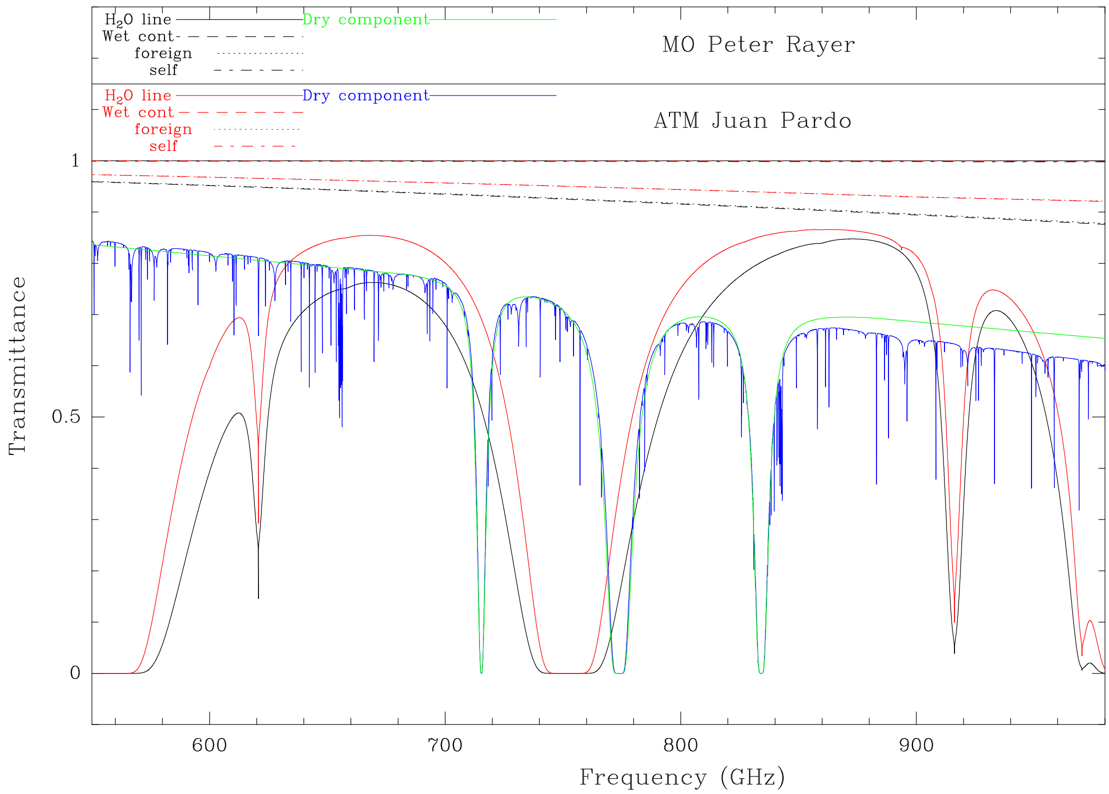

Figure 8. Transmittances, separated by source, calculated by the different RT models for atmospheric profile PR4 of Table 1, the driest case, in the range 750-980 GHz

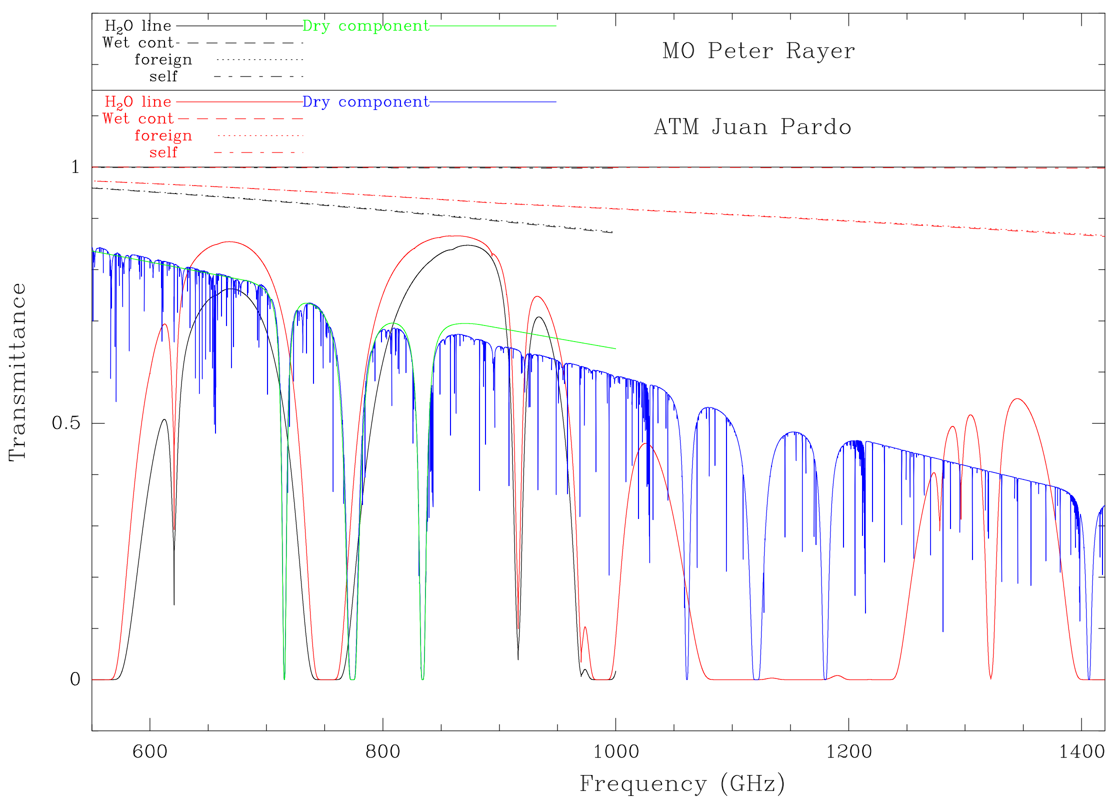

Figure 9. Previous figure extended up to 1450 GHz in the higher end.