IRAM Memo 2009-5

Comparison of ATM versions: Impact on the calibration of IRAM instruments

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Dec, 4th 2009
Version 1.0

Abstract

Since its first introduction into GILDAS in 1985, the ATM modelling program completely changed. With the advent of large bandwidth receivers and submillimeter receivers, it is time to upgrade the version of ATM used in GILDAS to calibrate IRAM instruments. This memo tries to assess the impact of changing the atmospheric model on the calibration of IRAM instruments.

After a short description 1) of the single-dish calibration, 2) of ATM 2009 and 3) the GILDAS interface to ATM 1985 and ATM 2009, an in-depth comparison of the results obtained with ATM 1985 and ATM 2009 is described. From this study, we expect slight variations of the calibration results when swapping from ATM 1985 to ATM 2009.

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1 Rayleigh-Jeans or not Rayleigh-Jeans?

Let $J(\nu, T)$ be the power radiated by a black-body at frequency ν and temperature T. It is always possible to define in a conventional way a Rayleigh-Jeans temperature T^{RJ} such as

$$k_{\mathrm{bolt}}\, T^{\mathrm{RJ}} = J(\nu, T). \tag{1}$$

It happens that T^{RJ} has a direct physical meaning, *i.e.* $T^{\mathrm{RJ}} = T$, when $h\nu << k_{\mathrm{bolt}}\, T$. However, T^{RJ} can always be defined (even when $h\nu >> k_{\mathrm{bolt}}\, T$: T^{RJ} just loses its physical meaning. The advantage of doing this is that all the equations of calibrations are considerably simpler to write and to implement in source code using the conventional Rayleigh-Jeans temperature than the black-body formula. The only constraint is to remember to transform physical temperature (in particular hot and cold load temperature) in conventional Rayleigh-Jeans temperature for all the input parameters. This is what is done in GILDAS/TELCAL, in ATM and thus in this memo.

2 Single-dish calibration in a nutshell

The output of the (telescope + front-end + back-end) system is a signal proportional to the sum of the atmospheric emission and the astronomical signal attenuated by the atmospheric absorption. Various ON-OFF schemes are used to subtract the atmospheric emission, leaving us with signal proportional to the source brightness. The purpose of the calibration is to disentangle the different effects to be able to convert the signal counts into antenna temperatures.

2.1 Description of the received signal

A perfectly linear (front-end + back-end) system delivers a signal (C) in counts which is defined as

$$C = c_{\mathrm{dark}} + g\,(T_{\mathrm{ant}}^{\mathrm{tot}} + T_{\mathrm{rec}}), \tag{2}$$

where

- c_{dark} is the signal delivered when the (front-end + back-end) system is blind;
- g is the (front-end + back-end) system gain;
- T_{rec} the noise added by the receiver and the optics, usually called receiver temperature;
- $T_{\mathrm{ant}}^{\mathrm{tot}}$ the signal seen by the receiver, usually called antenna temperature.

As heterodyne receivers mix input signal from two different frequencies, $T_{\mathrm{ant}}^{\mathrm{tot}}$ can be written as

$$T_{\mathrm{ant}}^{\mathrm{tot}} = \frac{T_{\mathrm{ant}}^{\mathrm{sig}} + G_{\mathrm{im}}\, T_{\mathrm{ant}}^{\mathrm{ima}}}{1 + G_{\mathrm{im}}}, \tag{3}$$

where

- $T_{\mathrm{ant}}^{\mathrm{sig}}$ and $T_{\mathrm{ant}}^{\mathrm{ima}}$ are respectively the signal in the signal and image bands;
- and G_{im} is the ratio of the receiver gain in the signal (g_{sig}) and image g_{ima} bands (at least 0.1 for (sub-)millimeter receivers at IRAM).

T_{ant} is a combination of losses T_{loss} and of the sum of the atmospheric emission (T_{atm}) and astronomical emission (T_{astro}) attenuated by the atmospheric absorption

$$T_{\mathrm{ant}} = F_{\mathrm{eff}}\ [T_{\mathrm{atm}} \exp(-a\tau) + T_{\mathrm{astro}}] + (1 - F_{\mathrm{eff}})\, T_{\mathrm{loss}} \tag{4}$$

where

- F_{eff} is the forward efficiency, describing the forward coupling to of the receiver to the signal;

- τ is the atmopsheric zenith opacity at the observed frequency;
- a is the airmass, which relate the zenith opacity to the opacity at the elevation of the observation:

$$a = 1/\sin(\text{elevation}); \tag{5}$$

The losses come from the imperfect coupling of the receiver to the sky. It is here important to note that $T_{\rm loss}$ comes from two sources: 1) the (sub-)millimeter emission inside the cabin, picked up by the receiver optic and proportional to the cabin temperature $T_{\rm cab}$ and 2) the (sub-)millimeter emission of the ground, picked up by the antenna and proportional to the outside ambient temperature $T_{\rm amb}$. Thus

$$T_{\rm loss} = \alpha T_{\rm cab} + (1-\alpha) T_{\rm amb}, \tag{6}$$

with α being a largely unknown coupling factor.

It is usually supposed that $F_{\rm eff}$ and $T_{\rm loss}$ are identical for both bands of an heterodyne receiver. This maybe should be revisited with the large IF of today receivers.

2.2 Description of the calibration scheme

In order to disentangle the different effects, three steps are needed

1. Once in a while, skydips are measured to determine the telescope forward efficiency ($F_{\rm eff}$) as a function of frequency;
2. Every 10 to 15 minutes, observations of 1) two references at very different temperatures (the hot and cold load) and 2) the atmosphere in a direction devoid of signal are used to deduce the opacity of the atmosphere and the calibration factor. In modern system, the hot load is a foam at roughly the room temperature and the cold load is the cryostat window of the receiver which is roughly at liquid nitrogen temperature;
3. The telescope is regularly switched on and off source to subtract the atmospheric contribution to the signal seen by the receiver.

2.2.1 Skydips and determination of the forward efficiency

In a skydip, the atmospheric emission, as seen by the receiver ($T_{\rm sky}$), is measured at equally spaced airmass (a). $T_{\rm sky}$ is a combination of the atmospheric emission $T_{\rm emi}^{\rm tot}$ and of losses $T_{\rm loss}$

$$T_{\rm sky} = F_{\rm eff} T_{\rm emi}^{\rm tot} + (1-F_{\rm eff}) T_{\rm loss}. \tag{7}$$

And the atmospheric emission is the sum of the atmospheric emission in both receiver bands

$$T_{\rm emi}^{\rm tot} = \frac{T_{\rm emi}^{\rm sig} + G_{\rm im}\, T_{\rm emi}^{\rm ima}}{1+G_{\rm im}}, \tag{8}$$

each contribution computed from an equivalent atmospheric temperature $T_{\rm atm}$ and opacity τ

$$T_{\rm emi}^{\rm sig} = T_{\rm atm}^{\rm sig}\ \{1-\exp(-a\tau_{\rm sig})\} \quad \text{and} \quad T_{\rm emi}^{\rm ima} = T_{\rm atm}^{\rm ima}\ \{1-\exp(-a\tau_{\rm ima})\}. \tag{9}$$

The zenith opacity can be written as a combination of a dry and wet components

$$\tau = \tau_{\rm dry} + \tau_{\rm wet}, \tag{10}$$

where $\tau_{\rm dry}$ is the opacity due to the permanent components of the atmosphere (mainly oxygen) and $\tau_{\rm wet}$ is proportional to the varying amount of water vapor amount ($\mathrm{w}_{\mathrm{H_2O}}$) in the atmosphere: $\tau_{\rm wet} = \alpha_{\mathrm{H_2O}}\, \mathrm{w}_{\mathrm{H_2O}}$

Assuming that $F_{\rm eff}$ and $T_{\rm loss}$ are independent of the elevation and that $\tau_{\rm dry}$ and $\alpha_{\mathrm{H_2O}}$ are correctly modeled by an atmospheric model, we obtain that $T_{\rm sky}$ is a function of $F_{\rm eff}$, $T_{\rm loss}$, $G_{\rm im}$, $\mathrm{w}_{\mathrm{H_2O}}$ and the airmass (a). If $G_{\rm im}$ and $T_{\rm loss}$ are assumed to be measured by other means, then $F_{\rm eff}$ and $\mathrm{w}_{\mathrm{H_2O}}$ can be fitted through the measured couples ($T_{\rm sky}$,a).

2.2.2 Load calibration and determination of the zenith opacity

The hot and cold load as well as the atmosphere in a region devoid of signal are measured in turn. From Eq. 2, it is easy to show that

$$\frac{T_{\rm hot} - T_{\rm sky}^{\rm tot}}{C_{\rm hot} - C_{\rm sky}^{tot}} = \frac{T_{\rm hot} - T_{\rm cold}}{C_{\rm hot} - C_{\rm cold}}, \tag{11}$$

where

- $T_{\rm hot}$ and $T_{\rm cold}$ are the Rayleigh-Jeans temperature of the loads;
- $C_{\rm hot}$ and $C_{\rm cold}$ are the associated measured counts.

From this equation, we deduce $T_{\rm sky}^{\rm tot}$. Using an atmospheric model and Eqs. 7–9, the total opacity of the atmosphere at signal and image frequencies are then fitted.

2.2.3 Data calibration

The telescope is regularly switched on and off source. It can be shown (see *e.g.* Kramer, 1997) that the brightness temperature of the source can be related to the measured counts (on and off-source) by

$$T_{\rm a}^{\star} = T_{\rm cal}\,\frac{C_{\rm on} - C_{\rm off}}{C_{\rm hot} - C_{\rm off}}, \tag{12}$$

where $T_{\rm cal}$, the calibration factor, is given by

$$\begin{aligned} T_{\rm cal} &= (1+G_{\rm im})\,\left[T_{\rm emi}^{\rm sig} - T_{\rm bg}\right] && (13)\\ &+ (1+G_{\rm im})\,\left[T_{\rm loss} - T_{\rm emi}^{\rm sig}\right]\,\exp(a\tau_{\rm sig}) && (14)\\ &+ G_{\rm im}\,\left[T_{\rm emi}^{\rm sig} - T_{\rm bg}\right]\,\left[\exp\left\{a(\tau_{\rm sig} - \tau_{\rm ima})\right\} - 1\right] && (15)\\ &+ \frac{1+G_{\rm im}}{F_{\rm eff}}\,\left[T_{\rm hot} - T_{\rm loss}\right]\,\exp(a\tau_{\rm sig}). && (16) \end{aligned}$$

If the cosmic background power ($T_{\rm bg}$) is negligeable compared to the atmospheric emission ($T_{\rm emi}^{\rm sig}$), then the last equation reduces to

$$T_{\rm cal} = (T_{\rm hot} - T_{\rm sky})\frac{1+G_{\rm im}}{F_{\rm eff}\,\exp\left(-a\tau_{\rm sig}\right)}. \tag{17}$$

From the previous steps, all the parameters are known to compute $T_{\rm cal}$ and thus $T_{\rm a}^{\star}$.

3 Description of ATM 2009

A thorough description of the physics underlying recent version of ATM can be found in Pardo et al. (2001a, 2001b, 2005). A brief summary is given here.

3.1 Atmospheric profile

The atmospheric profile is computed from a combination of input parameters and physical laws. The shape of the atmosphere density and pressure are defined by the physical laws (hydrostatic equilibrium + mixture of ideal gas). The shape of the temperature profile is defined by the following two parameters.

Troposperic lapse rate, which is used to fix the temperature gradient up to the tropopause. Its recommanded value is -5.6 K/km.

Atmospheric type, which is used to reproduce the shape of the temperature profile above the tropopause. For Pico Veleta and Plateau de Bure, it should be the well defined mid-latitude averaged profiles for summer and winter. Continuity of the temperature atmospheric profile is enforced at the tropopause.

The atmospheric model is computed assuming a plane-parallel geometry defined by the following three parameters.

Atmospheric upper boundary, which is the maximum altitude of the modeled atmosphere, typically 48 km.

Primary pressure step, which is the pressure step used to define the height of the first atmospheric layer, typically 10 mb.

Pressure step factor, which is the multiplicative factor used to define the next pressure step from the current one, typically 1.2.

The atmospheric profile of the minor components is defined by the following two parameters.

Water vapor scale height, which is used to define the exponential distribution of water, typically 2 km (could be between 1.5 and 3 km).

Atmospheric type, which is also used to define the profile repartition of the other minor components (*e.g.* ozone) of the atmosphere.

For our applications (calibrating radio-astronomy data), most of these parameters should have a minor impact (still to be checked). The 3 remaining parameters, *i.e.* the ground temperature and pressure at the telescope as well as the amount of precipitable water vapor at zenith, are used to hook the atmospheric profile defined above to the current conditions at the telescope site. These three parameters thus have a major impact on the modeled results.

3.2 (Sub-)mm radiative transfer

3.2.1 Line

Under clear weather, the atmospheric absorption/emission at (sub)-millimeter wavelengths is dominated by the rotational and fine structure line of molecules in their ground electronic and low vibrational states. Three molecules plays a major role

H_2O is the most abundant polar molecule present in the atmosphere. Its electric dipole moment is 1.88 Debye. ATM 2009 also takes into account the water isotopomers.

O_2 Being an homonuclear molecule, O_2 has a zero-valued electric dipole moment. However, it has a triplet electronic ground state, with two electrons paired with parallel spins, implying a weak magnetic dipole moment. The weakness of this dipole moment is compensated by the large O_2 abundance, implying O_2 line intensities similar to H_2O ones.

O_3 is an asymmetric top molecule, such as H_2O. Despite the small ozone abundance, its lines have significant peak opacities, especially in the submillimeter domain. This is dues to linewidths much narrower than water. This can be explained by two facts: 1) the ozone dipole moment is 0.53 Debye, about 3 times less than water and 2) ozone is mostly concentrated between 11 and 40 km of altitude, implying linewidths 20 times narrower than sea level lindwidths.

3.2.2 Continuum

The continuum in ATM 2009 is divided into two components

The dry component, which comes from collision induced absorption due to transient eletric dipole moments generated in binary interactions of symmetric molecules with eletric quadrupole moments such as N_2 and O_2, and the relaxation of the O_2 absorption.

The wet component, which is indeed a pseudo-continuum. It is a modeling of the long-range linewidth of the water lines, whose true shape is not known accurately enough beyond a few times the halfwidth from the line centers.

Both components have been modeled from 200 GHz to 1.1 THz using FTS measurements at CSO on Mauna Kea.

3.3 GILDAS interface

The GILDAS interface to ATM 1985 and ATM 2009 was thought to enable an easy swap from one version to the other. We first describe this interface at the programmer level (*i.e.* FORTRAN interface) and then at the user level (*i.e.* ASTRO interface).

3.3.1 FORTRAN interface

The different subroutines, which interface both version of ATM, are extensively described in Appendix A. In short, the programmer first calls

```
call atm_setup('1985',error)
```

or

```
call atm_setup('2009',error)
```

to select the version of ATM to be used from this point on. If this call is missing, GILDAS assumes that it must use ATM 1985 (default behavior). ATM 2009 enables the fine tuning of the atmospheric profile. This is implemented in the GILDAS interface by the call of two subroutines

```
call atm_atmosp_get(ctype_out,humidity_out,wvsh_out,tlr_out,top_out,  &
    p_step_out,p_step_factor_out,error)
```

which gets the default values and

```
call atm_atmosp_set(ctype_in,humidity_in,wvsh_in,tlr_in,top_in,  &
    p_step_in,p_step_factor_in,error)
```

which sets the wanted values. `ctype_in` and `ctype_out` are the atmospheric types, which can be set to `tropical, midlatsummer, midlatwinter, subarcticsummer, subarcticwinter`.

The calls to the other ATM routines are unchanged compared to the historical behavior, *i.e.*

```
call atm_atmosp(t0,p0,h0)
```

defines the atmosphere profiles,

```
call atm_transm(water,airmass,freq,temi,tatm,tauox,tauw,taut,ier)
```

returns the atmospheric temperatures and opacities and

```
call atm_path(water,airmass,freq,path,ier)
```

returns the integrated optical length of current atmosphere. Note that the support for the `atm_path` is not yet available with ATM 2009.

3.3.2 ASTRO interface

The `SET ATM 1985|2009|OLD|NEW` command switches the ATM version and the `ATM` command computes the atmospheric parameters. In ATM 1985, the atmosphere properties other than temperature, pressure and humidity, are fixed while they can be changed for ATM 2009 through the following SIC variables with their default values, their units and their definitions

```
ATM%PROFILE%TYPE      MIDLATSUMMER        Atmospheric type
ATM%PROFILE%HUMIDITY         1.000 [%]    Ground relative humidity (indicative)
ATM%PROFILE%WVSH             2.000 [km]   Water vapor scale height
ATM%PROFILE%TLR             -5.600 [K/km] Tropospheric lapse rate
ATM%PROFILE%TOP             48.000 [km]   Upper atm. boundary for calculations
ATM%PROFILE%DP              10.000 [hPa]  Primary pressure step
ATM%PROFILE%DP_FACTOR        1.200 []     Pressure step ratio between two consecutive layers
```

The other input parameters of the ATM command are the following SIC variables

```
TEMPERATURE      Outside temperature
ZERO_PRESSURE    Pressure at sea level.
AIRMASS          Number of air masses
WATER            Precipitable water vapor
FORWARD_EFF      Forward efficiency
GAIN_IMAGE       Receiver gain ratio
TREC             Receiver temperature
FREQ_SIG         Signal frequency (in GHz)
FREQ_IMA         Image frequency (in GHz)
```

These variables can be assigned using the LET command. The remaining input variable

```
ALTITUDE         Site altitude
```

is modified by the OBSERVATORY command. The output of the ATM command consists in the following variables

```
TRUE_PRESSURE    Local pressure, derived from the site altitude and
                 the sea level pressure by the scale height of 5.5 km
TSYS             The system temperature in the signal sideband
TAU_H2O          The water vapor opacity
TAU_O2           The dry atmosphere opacity (mostly due to Oxygen,
                 but minor constituents like Ozone may also play a role)
TAU_TOT          The total opacity: H2O + O2 (+ minor components for new ATM versions)
EMIS_SIG         The atmospheric emission (Kelvin) in the signal side band
EMIS_IMA         The atmospheric emission (Kelvin) in the image sideband
PATH_SIG         The atmospheric excess optical path length (mm)
                 in the signal sideband
PATH_IMA         The atmospheric excess optical path length (mm)
                 in the image sideband
```

These variables can then be used to produce plots of atmospheric transparency, system temperatures, etc...

4 Comparison of ATM 1985 and ATM 2009

4.1 Comparison of the implementation

There are at least 2 main differences between the implementations of ATM 1985 and ATM 2009.

- ATM 1985 gives sensible (*i.e.* continuous) results even for negative amount of water vapor while ATM 2009 displays a discontinuity for an amount of water vapor equal to zero and then constant values for negative amount of water vapor (See Fig. 1). The ATM 2009 behavior comes from the fact that the atmospheric profile is first computed for an indicative humidity value and then scaled to the ture amount of water vapor. The current version of ATM 2009 just default to non continuous values for zero or negative amount of water vapor.
- For T_{emi}, ATM 1985 gives just the emission of the atmosphere while ATM 2008 gives the sum of the atmosphere plus the cosmic microwave background emissions. The impact on the calibration has to do with the comparison of Eqs. 16 and 17. A numeric comparison should be done.

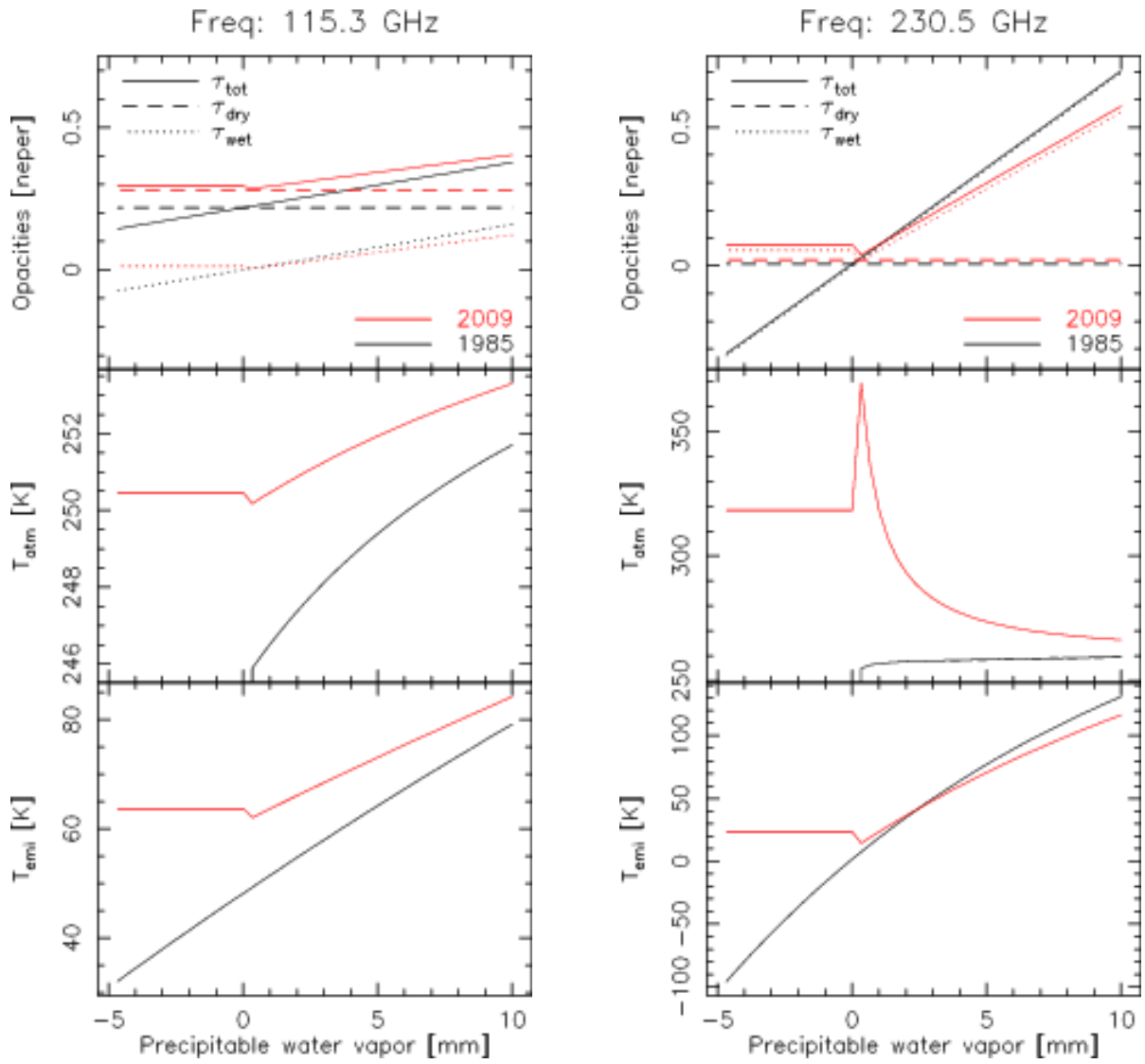


Figure 1: Opacities, $T_{\rm atm}$ and $T_{\rm emi}$ as a function of precipitable water vapor for two different frequencies: 115.3 GHz (left) and 230.5 GHz (right). ATM 2009 results are shown in red while ATM 1985 are shown in black.

4.2 Comparison at constant amount of water vapor

Figures in Appendix B displays an exhaustive comparison of the influence on the calibration of the different modeling by ATM 1985 and ATM 2009. The columns of these figures display $1-\exp(-a\tau)$, $T_{\rm emi}$, $T_{\rm sky}$ and $T_{\rm cal}$ as a function of the frequency. There are two figures per frequency band of the EMIR generation of receivers at Pico Veleta: one at medium elevation (*i.e.* 45 deg) and one at low elevation (*e.g.* 20 deg) were the differences between models will be maximum. For each band, realistic values of $F_{\rm eff}$, $G_{\rm im}$, $T_{\rm rec}$ and $T_{\rm hot}$ values were used. The top rows displays the results for ATM 1985, the middle rows displays the results for ATM 2009 and the bottom rows displays the relative difference, *i.e.* (ATM 1985 - ATM 2009)/ATM 2009 in percentage. The computations (and in particular the relative differences) are done for one value of water vapor at a time in the range between 0.1 and 8 mm.

The first fact arising from the comparison, is that both models have clearly different behaviors as a function of frequency: ATM 1985 have a much simpler dependency on the frequency than ATM 2009. This comes mainly from the inclusion of water isotopologue lines (*e.g.* the large line at about 105 Ghz) and ozone lines (the many narrow lines) in ATM 2009 but also from a finer modeling of water lines by ATM 2009.

Another general trend is that the differences between models for $1-\exp(-a\tau)$, $T_{\rm emi}$ and $T_{\rm sky}$ decreases when the amount of water vapor increases. This points toward a good consistency of the treatment of water vapor in both models but a very different treatment of the dry continuum emission/absorption of the atmosphere. However, this result is inversed on $T_{\rm cal}$, *i.e.* the differences on $T_{\rm cal}$ increases when the amount of water vapor increases. This surprising result probably comes from the fact that $T_{\rm emi} \propto T_{\rm atm}\,[1-\exp(-a\tau)]$ while $T_{\rm cal} \propto \exp(a\tau)$. In other words, while $T_{\rm emi}$ can have close values in both model, this may require very different values of τ. Also, the differences between model results are much more pronounced on $1-\exp(-a\tau)$ and $T_{\rm emi}$ than on $T_{\rm sky}$ and $T_{\rm cal}$. The reason of the decrease of the differences between $T_{\rm emi}$ and $T_{\rm sky}$ comes from the fact that the loss term added in $T_{\rm sky}$ is independent of the ATM model while it represents a significant fraction of the $T_{\rm sky}$ value. We guess that the large differences in modeling between ATM versions have finally a relatively small impact on $T_{\rm cal}$ comes from the fact that $T_{\rm sky}$ and $\exp(-a\tau)$ consistently cancel the modeling impact of ATM. Hence at 45 deg of elevation, the relative difference in $T_{\rm cal}$ is almost always smaller than 5%, while at 20 deg of elevation, this relative difference is of the order of 10%.

4.3 Comparison of the full calibration scheme

As described in sections 2.2.2, the actual calibration of data is a two-steps process. In the first step, $T_{\rm sky}$ is simply deduced from Eq. 11 and the ATM model is then just used to associate to this $T_{\rm sky}$ value, a value of the total opacity of the atmosphere at signal and image frequencies. In the second step, the $T_{\rm cal}$ value is computed with Eq. 17 and then used on the data.

Hence, in Eq. 17, the value of the term $(T_{\rm hot}-T_{\rm sky})$ is independent of the ATM model and/or of the coupling factors, while the value of the term $[1+G_{\rm im}]\,/\,[F_{\rm eff}\,\exp(-a\tau)]$ is directly dependent of the ATM modeling and/or of the coupling factors. Two different situations arise: 1) the measured coupling parameters are at best known only to a given accuracy and at worst biased and 2) the model is inaccurate. To model both situations, we will assume that $\tau_{\rm true}$, $G_{\rm im}^{\rm true}$, $F_{\rm eff}^{\rm true}$ and $T_{\rm cal}^{\rm true}$ are the actual values of those different parameters while $\tau_{\rm mod}$, $G_{\rm im}^{\rm meas}$, $F_{\rm eff}^{\rm meas}$, and $T_{\rm cal}^{\rm meas}$ are the modeled or measured values. It is easy to show that the relative error on $T_{\rm cal}$ is

$$\frac{T_{\rm cal}^{\rm meas}-T_{\rm cal}^{\rm true}}{T_{\rm cal}^{\rm true}} = \frac{F_{\rm eff}^{\rm true}(1+G_{\rm im}^{\rm meas})}{F_{\rm eff}^{\rm meas}(1+G_{\rm im}^{\rm true})}\exp\left[a(\tau_{\rm mod}-\tau_{\rm true})\right]-1 \qquad (18)$$

Thus the accuracy of $T_{\rm cal}$ directly depends on the accuracy of the coupling factors and on the modeled opacity. It must be noted that 1) this equation assumes that the load and data calibration are made at the same airmass (*i.e.* elevation) 2) $G_{\rm im}$ is close to zero for the EMIR receivers, implying that the $F_{\rm eff}$ is one of the key parameter to get high calibration accuracy and 3) it is better to underestimate the opacity than to overestimate it.

Fig. 1 compares the values of opacities, $T_{\rm atm}$ and $T_{\rm emi}$ as a function of precipitable for both version of ATM. The comparison is made at two different frequencies, which have a very different opacity behavior:

115.3 GHz The opacity is dominated by the dry continuum due to the transparency of water at this frequency and to the presence of a close oxygen line. It is known that at 3mm under submillimeter weather conditions, the measured sky emission is lower than the modeled one with ATM 1985. This facts comes from the uncertainty on the knowledge of the $F_{\rm eff}$, an incorrect modeling of the dry continuum with ATM 1985, or a combination of both. Anyway, this is why ATM 1985 authorizes negative amount of water vapor. ATM 2009 makes the situation even worse because the total opacity and thus emission are larger with ATM 2009 than with ATM 1985. This comes mainly from the dry continuum opacity being larger with ATM 2009 than with ATM 1985... On the other hand, the same amount of atmospheric emission is reached with significantly less water vapor in ATM 2009.

230.5 GHz The opacity is dominated by its wet component, the dry continuum being almost negligeable. This is the reason why $T_{\rm atm}$ sharply increases when the amount of water vapor goes to zero with ATM 2009. It is unclear why such an effect is not seen with ATM 1985. Here also, the total opacity and thus emission are larger with ATM 2009 than with ATM 1985, and the wet opacity increases slowlier with ATM 2009 than with ATM 1985. But the effects are much less pronounced at 230.5 than at 115.3 GHz. The consequence is that the amount of precipitable vapor (and thus of opacity) needed to reproduce the emission of the sky is similar in both ATM versions.

5 Recommendations

ATM 2009 largely improves the modelling of the atmosphere emission and absorption compared to ATM 1985 (*e.g.* introduction of minor atmospheric components, better (pseudo)-continuum modelling). However, the ATM 2009 version used in GILDAS shows a problem of continuum for a zero amount of water vapor. In addition, a negative amount of water is forbidden by ATM 2009, while this possibility can be useful when systematic biases dominate the measure (*e.g.* 3mm observations during sub-millimeter conditions). J.R. Pardo is interested by 30m skydip results to constrain the dry and wet continuum opacities under 200 GHz in ATM 2009.

From the implementation viewpoint, ATM 2009 version is robust. It can be run routinely without risk of crashing. The GILDAS interface to ATM 1985 and ATM 2009 was thought to enable an easy swap from one version to the other. When swapping from ATM 1985 to ATM 2009, variations of the calibration results are expected. In particular, the accuracy of $T_{\rm cal}$ is given by Eq. 18. It directly depends on the accuracy of the coupling factors and on the modeled opacity. It is better to underestimate the opacity than to overestimate it.

6 Acknowledgement

The authors thank J.R. Pardo, D. Broguière, S. Guilloteau and C. Kramer for useful discussions.

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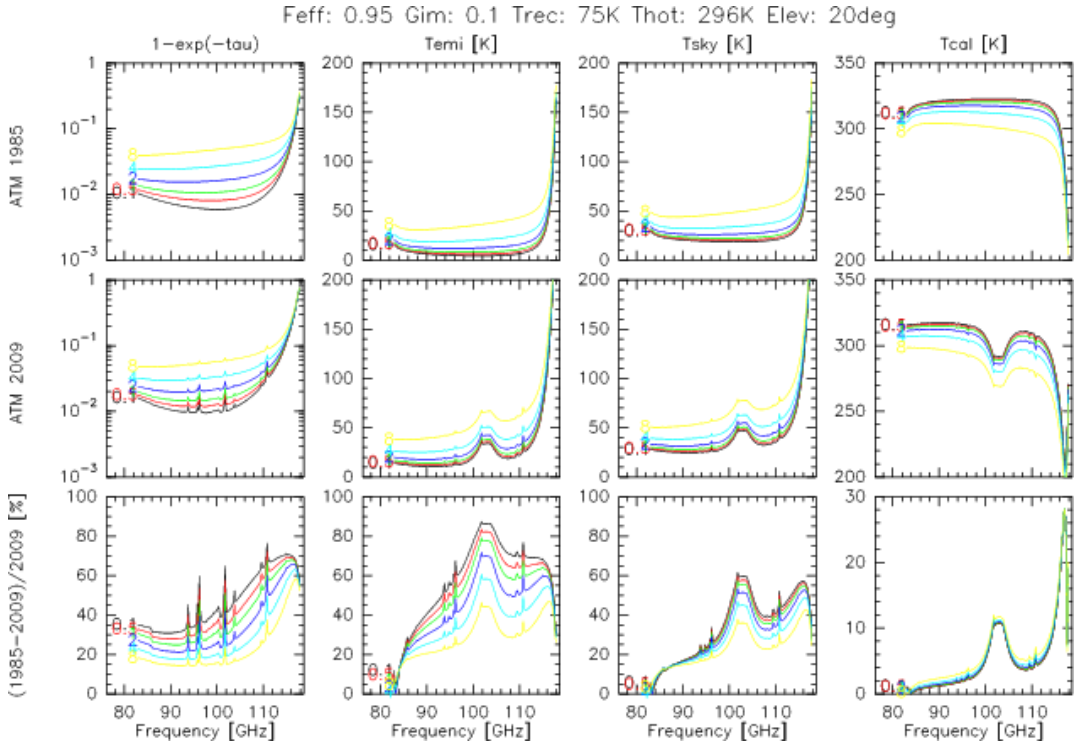
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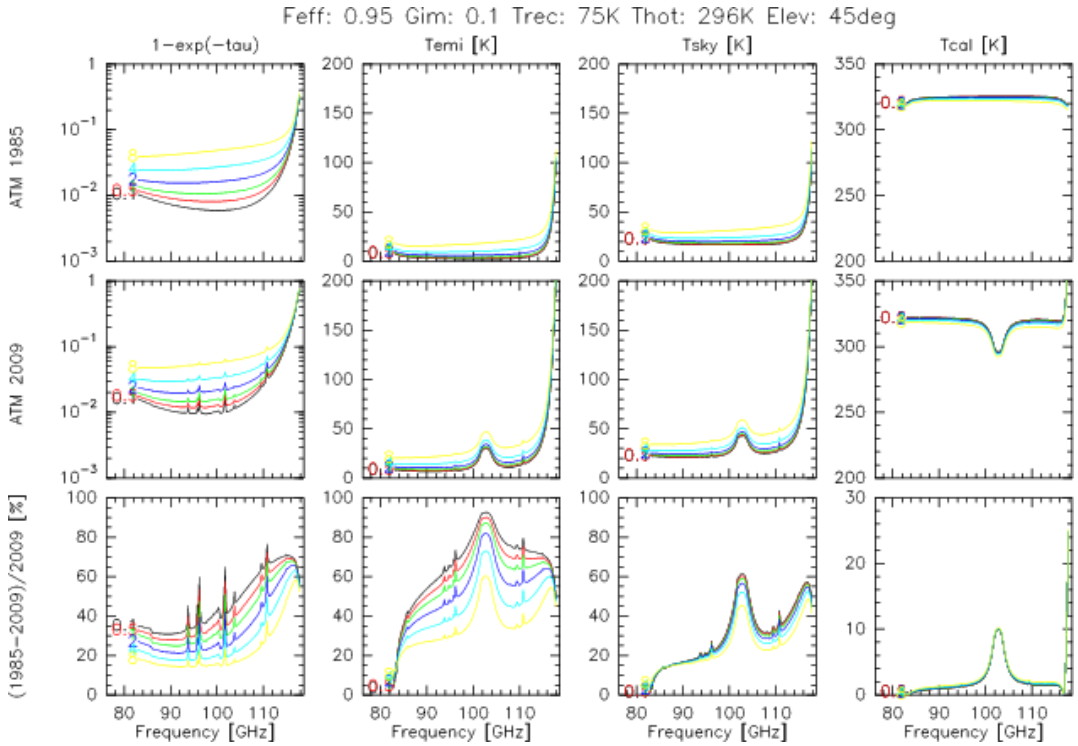
A GILDAS fortran interfaces to ATM

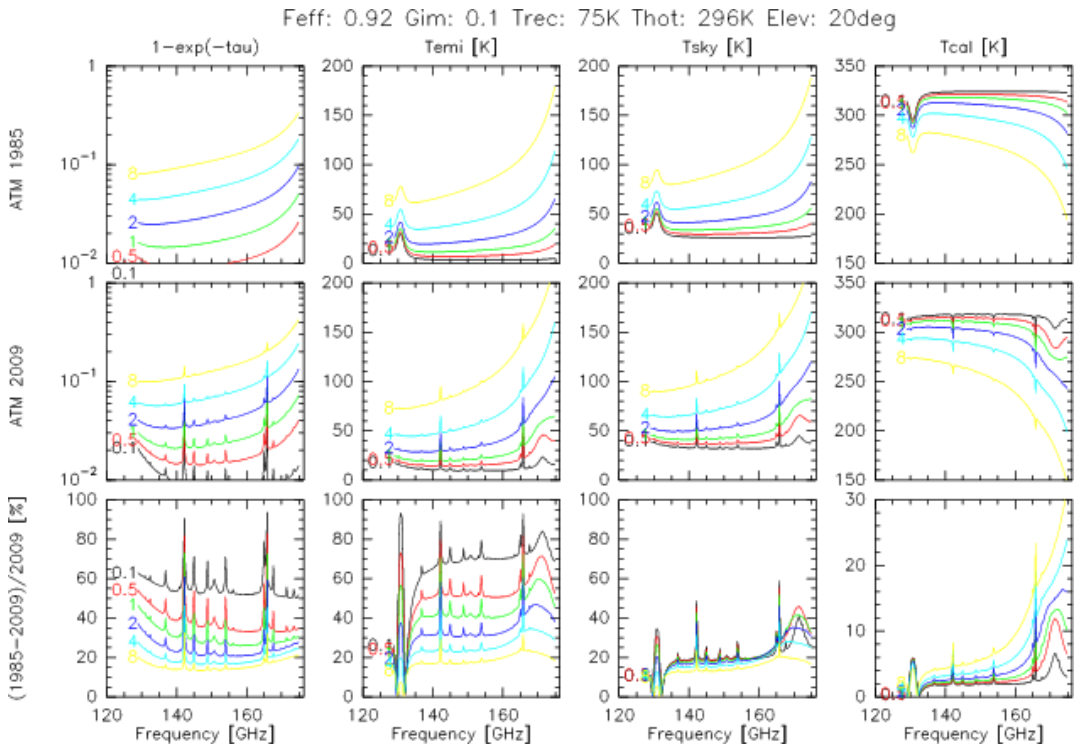
```
interface
  subroutine atm_setup(inversion,error)
     use atm_version
     !---------------------------------------------------------------------
     ! @ public
     ! Set the ATM version to be used. Supported versions are 1985,
     ! and 2009. 'OLD' (resp. 'NEW') is an alias for 1985 (resp. 2009).
     !---------------------------------------------------------------------
     character(len=*), intent(in)    :: inversion  ! User input version
     logical,          intent(inout) :: error      ! Error flag
  end subroutine atm_setup
  !
  subroutine atm_atmosp_get(ctype_out,humidity_out,wvsh_out,tlr_out,top_out,  &
    p_step_out,p_step_factor_out,error)
    use atm_version
    !---------------------------------------------------------------------
    ! @ public
    ! Public entry point to:
    !  1) get the C++ global variables into the Fortran-SIC ones,
    !  2) return these latter ones.
    ! Warning: these variables make sense only with ATM 2009. Return ATM
    ! 2009 values even if it is not currently used (not an error).
    !---------------------------------------------------------------------
    character(len=*), intent(out)    :: ctype_out          ! Atmospheric type (as a string)
    real(4),          intent(out)    :: humidity_out       ! [%]    Ground Relative Humidity (indicatio
    real(4),          intent(out)    :: wvsh_out           ! [km]   Water vapor scale height
    real(4),          intent(out)    :: tlr_out            ! [K/km] Tropospheric lapse rate
    real(4),          intent(out)    :: top_out            ! [km]   Upper atm. boundary for calculation
    real(4),          intent(out)    :: p_step_out         ! [mb]   Primary pressure step
    real(4),          intent(out)    :: p_step_factor_out  ! []     Pressure step ratio between two con
    logical,          intent(inout)  :: error              ! Logical error flag
  end subroutine atm_atmosp_get
  !
  subroutine atm_atmosp_set(ctype_in,humidity_in,wvsh_in,tlr_in,top_in,  &
    p_step_in,p_step_factor_in,error)
    use atm_version
    !---------------------------------------------------------------------
    ! @ public
    ! Public entry point to:
    !  1) set the Fortran-SIC global variables values,
    !  2) set the C++ global variables from these values.
    ! Warning: these variables make sense only with ATM 2009. Nothing
    ! will be done if ATM 2009 is not the version in use (not an error).
    ! NB: 'ctype_in' is not case-sensitive, and can be shorten as long
    ! as it is not ambiguous.
    !---------------------------------------------------------------------
    character(len=*), intent(in)    :: ctype_in          ! Atmospheric type (as a string)
    real(4),          intent(in)    :: humidity_in       ! [%]    Ground Relative Humidity (indication)
    real(4),          intent(in)    :: wvsh_in           ! [km]   Water vapor scale height
    real(4),          intent(in)    :: tlr_in            ! [K/km] Tropospheric lapse rate
    real(4),          intent(in)    :: top_in            ! [km]   Upper atm. boundary for calculations
    real(4),          intent(in)    :: p_step_in         ! [mb]   Primary pressure step
```

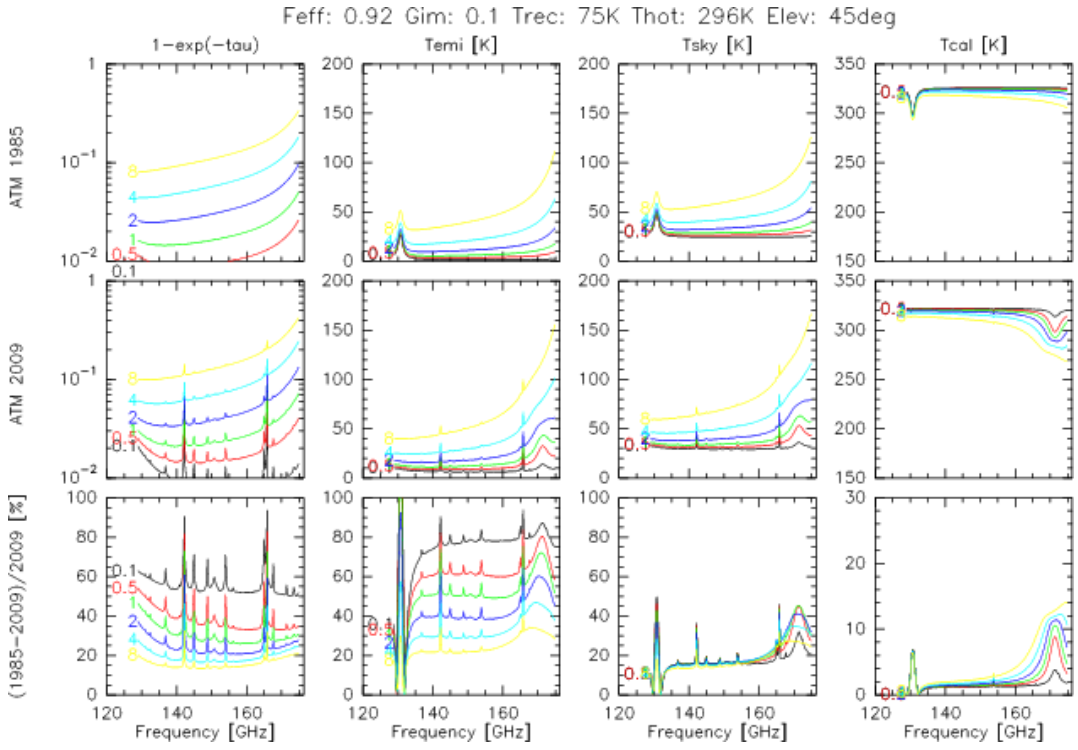
```
    real(4),          intent(in)    :: p_step_factor_in  ! []     Pressure step ratio between two conse
    logical,          intent(inout) :: error             ! Logical error flag
  end subroutine atm_atmosp_set
  !
  subroutine atm_atmosp(t0,p0,h0)
    use atm_version
    !-----------------------------------------------------------------------
    ! @ public
    ! Setup the atmospheric structure
    !-----------------------------------------------------------------------
    real(4), intent(in) :: t0  ! Ground temperature [K]
    real(4), intent(in) :: p0  ! Ground pressure [hPa]
    real(4), intent(in) :: h0  ! Altitude of the site [km]
  end subroutine atm_atmosp
  !
  subroutine atm_transm(water,airmass,freq,temi,tatm,tauox,tauw,taut,ier)
    use atm_version
    !-----------------------------------------------------------------------
    ! @ public
    ! Return the atmospheric temperatures and opacities given the amount
    ! of water and the frequency, for current atmosphere previously set
    ! with 'atm_atmosp()'
    !-----------------------------------------------------------------------
    real(4),    intent(in)  :: water    ! Precipitable water vapor [mm]
    real(4),    intent(in)  :: airmass  ! Number of air masses []
    real(4),    intent(in)  :: freq     ! Frequency [GHz]
    real(4),    intent(out) :: temi     ! Atmospheric emission [K]
    real(4),    intent(out) :: tatm     ! Mean temperature [K]
    real(4),    intent(out) :: tauox    ! Opacity (dry component) [neper]
    real(4),    intent(out) :: tauw     ! Opacity (wet component) [neper]
    real(4),    intent(out) :: taut     ! Total opacity [neper]
    integer(4), intent(out) :: ier      ! Error status
  end subroutine atm_transm
  !
  subroutine atm_path(water,airmass,freq,path,ier)
    use atm_version
    !-----------------------------------------------------------------------
    ! @ public
    ! Integrated optical length of current atmosphere
    !-----------------------------------------------------------------------
    real(4),    intent(in)  :: water    ! Precipitable water vapor [mm]
    real(4),    intent(in)  :: airmass  ! Number of air masses []
    real(4),    intent(in)  :: freq     ! Frequency [GHz]
    real(4),    intent(out) :: path     ! Optical length [cm]
    integer(4), intent(out) :: ier      ! Error status
  end subroutine atm_path
  !
end interface
```

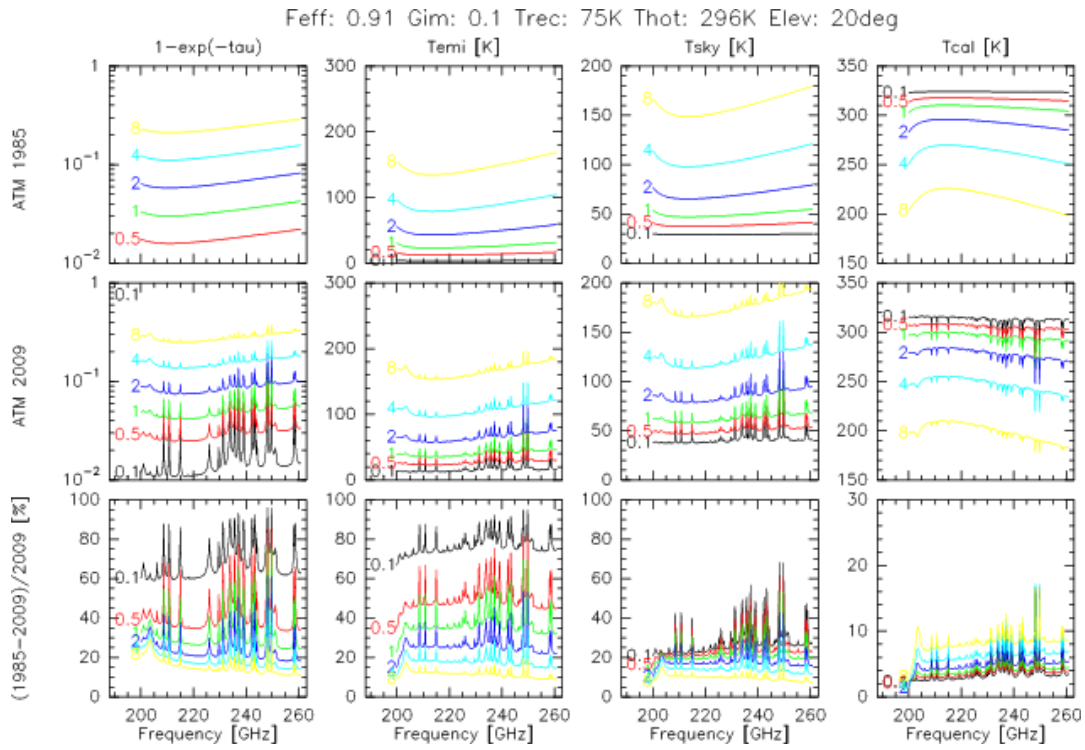
B Comparison at constant amount of water vapor as a function of the frequency

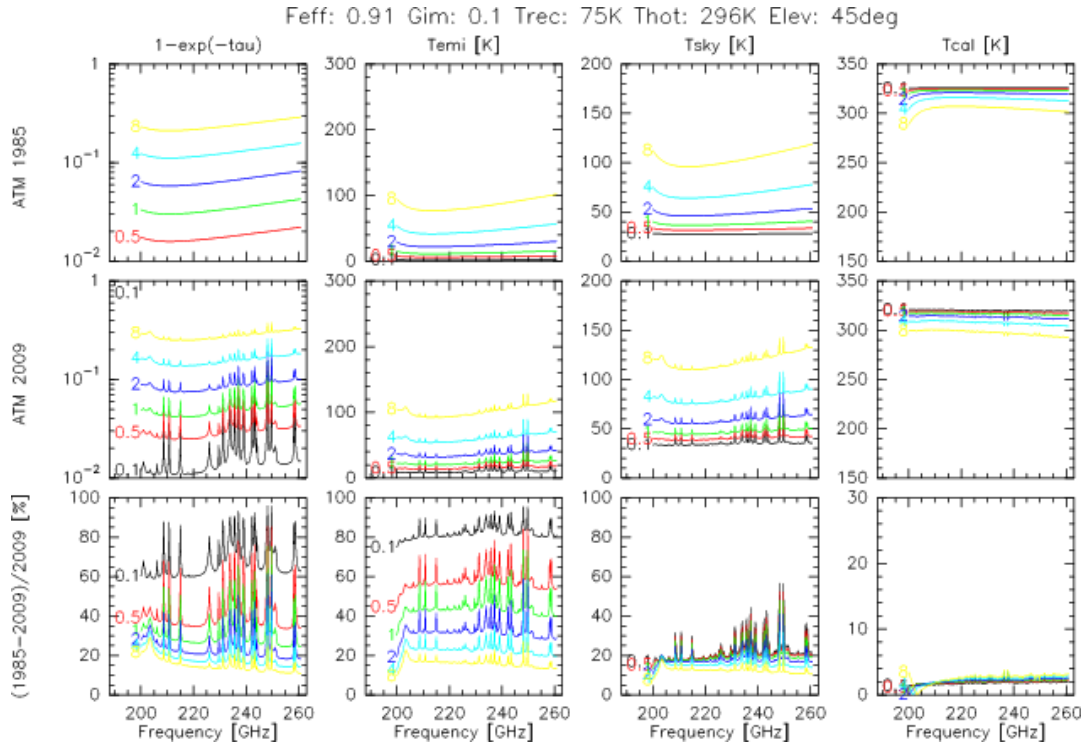




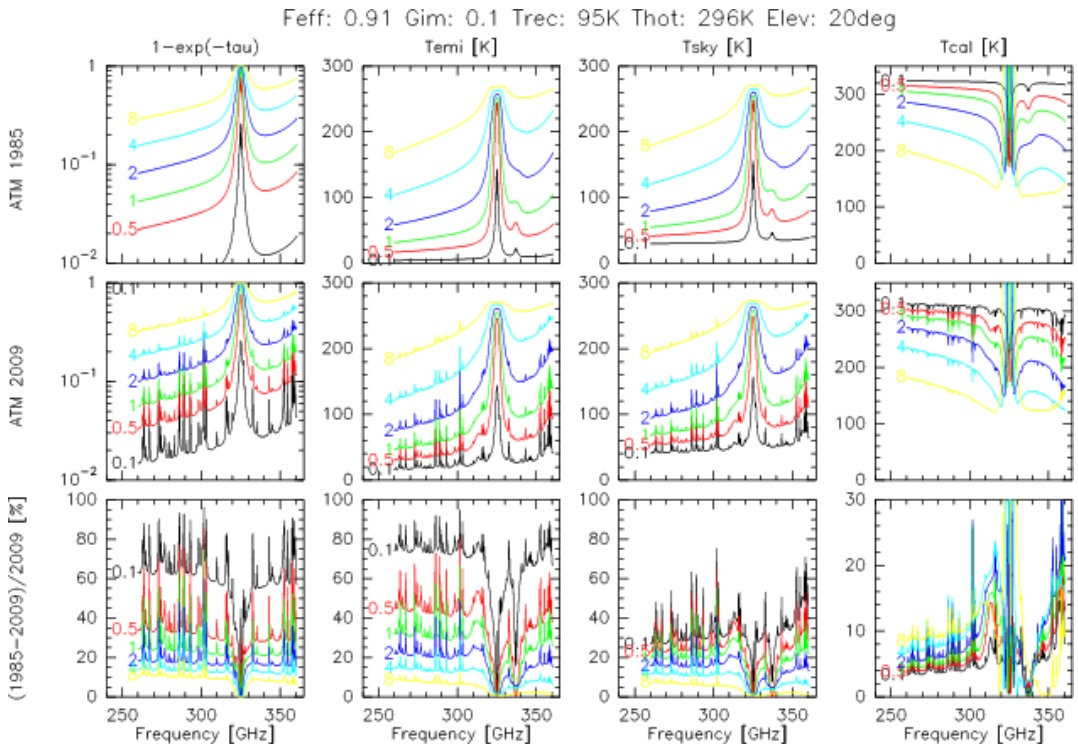

Feff: 0.92 Gim: 0.1 Trec: 75K Thot: 296K Elev: 20deg
1−exp(−tau)
Temi [K]
Tsky [K]
Tcal [K]
ATM 1985
ATM 2009
(1985−2009)/2009 [%]
Frequency [GHz]

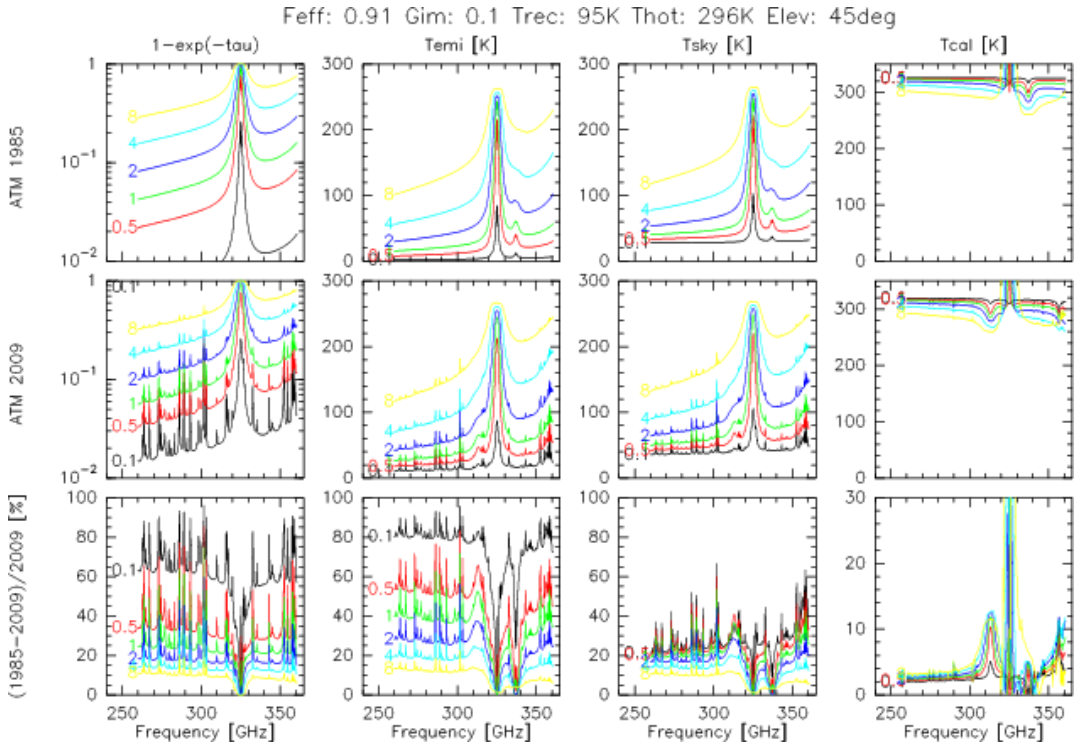

Feff: 0.92 Gim: 0.1 Trec: 75K Thot: 296K Elev: 45deg
1−exp(−tau)
Temi [K]
Tsky [K]
Tcal [K]
ATM 1985
ATM 2009
(1985−2009)/2009 [%]
Frequency [GHz]





Comparison of ATM versions for constant amount of water vapor as a function of the frequency


Feff: 0.91 Gim: 0.1 Trec: 95K Thot: 296K Elev: 20deg
1−exp(−tau)
Temi [K]
Tsky [K]
Tcal [K]
ATM 1985
ATM 2009
(1985−2009)/2009 [%]
Frequency [GHz]


Feff: 0.91 Gim: 0.1 Trec: 95K Thot: 296K Elev: 45deg
1−exp(−tau)
Temi [K]
Tsky [K]
Tcal [K]
ATM 1985
ATM 2009
(1985−2009)/2009 [%]
Frequency [GHz]

C Effect of Earth curvature

In gildas, the effect of the Earth curvature is approximated by a correction to the usual airmass definition (See Eq. 5). Fig. 2 displays the airmass as a function of the elevation for 3 different atmosphere models: 1) a plane parallel atmosphere, 2) a curved atmosphere with a scale height of 2.7 km, and 3) a curved atmosphere with a scale height of 5.5 km. It is clear that as long as the elevation is larger than 20 deg, the difference in airmass between these different atmosphere models is negligeable.

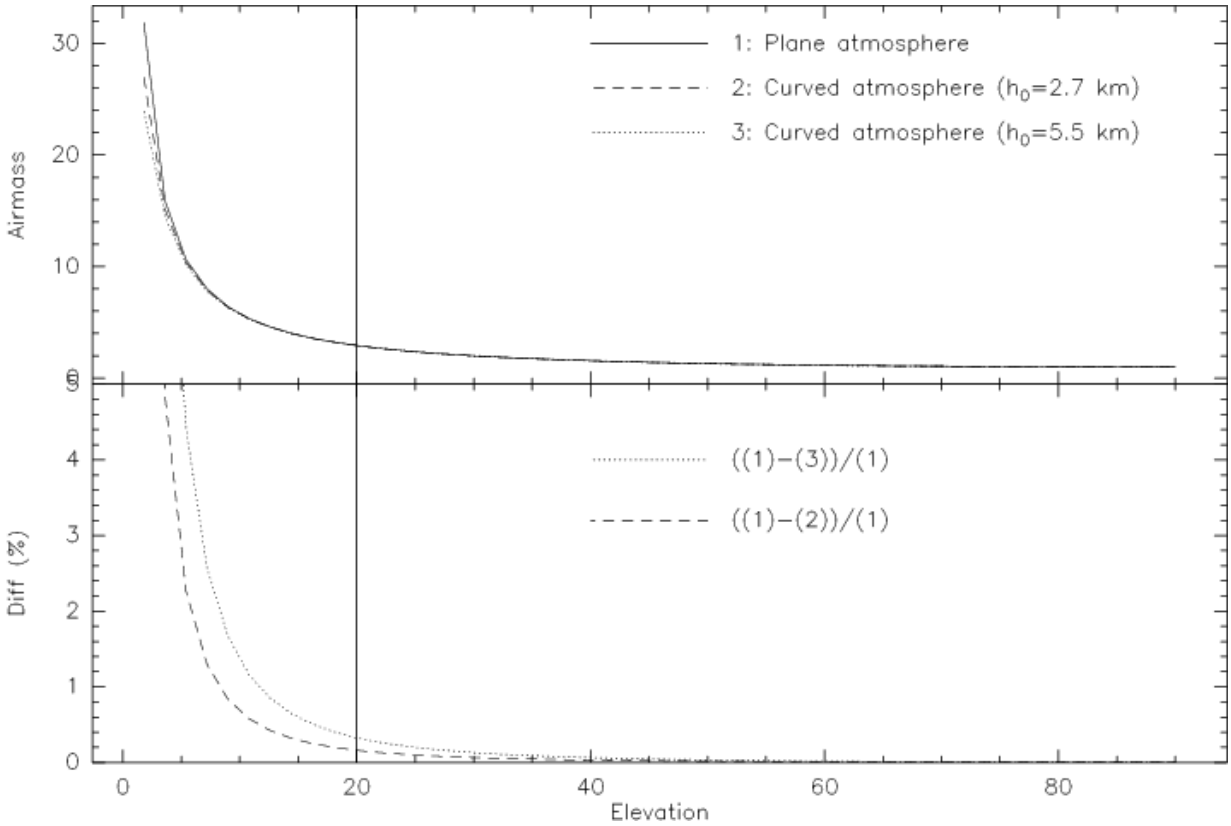


Figure 2: Top: Effect of the Earth curvature on the airmass as a function of the elevation. Bottom: Relative difference as a function of the elevation.