CSIC

ARENA Workshop

"Site testing at Dome C"

Torvergata, Roma (11-13/Jun/07)

A review of the Atmospheric Transmission at Microwaves (ATM) model

Juan R. Pardo[1]

Col.: J. Cernicharo[1], E. Serabyn[2], C. Prigent[3], F. Viallefond[3], M. Wiedner[4], R. Hills[5], J. Richer[5]
(1) Consejo superior de Investigaciones Científicas (Spain), (2) California Institute of Technology (USA), (3) LERMA-Observatoire de Paris, (4) Köln University (Germany), (5) Cavendish Laboratory (UK),

Atmospheric mm/submm refraction index

Physical basis b. Experimental basis c. Up-to-date model

The atmospheric problem for ground-based obs.

Sofware implementations

1. Atmospheric Refraction Index: The whole story

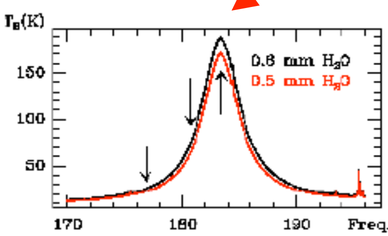
1.0 + Gas-phase contribution + Hydrometeros contribution

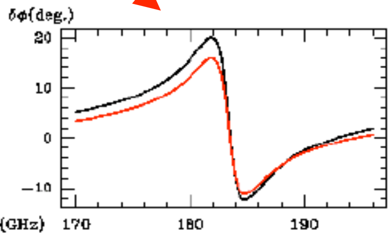
Impact approximation
$\tau_{collision} << 1 / \nu$
Van-Vleck-Weisskopf line profile

$$\mathcal{F}(\nu, \nu_{u\leftrightarrow l}) = \frac{\nu}{\pi \nu_{u\leftrightarrow l}}\left[\frac{1 - i\delta}{\nu_{u\leftrightarrow l} - \nu - i\Delta\nu} + \frac{1 + i\delta}{\nu_{u\leftrightarrow l} + \nu + \Delta\nu}\right] \quad (1)$$

1a. Imaginary Part (absorption)

1b. Real Part (phase delay)





1c. Scattering. Polarization must be included

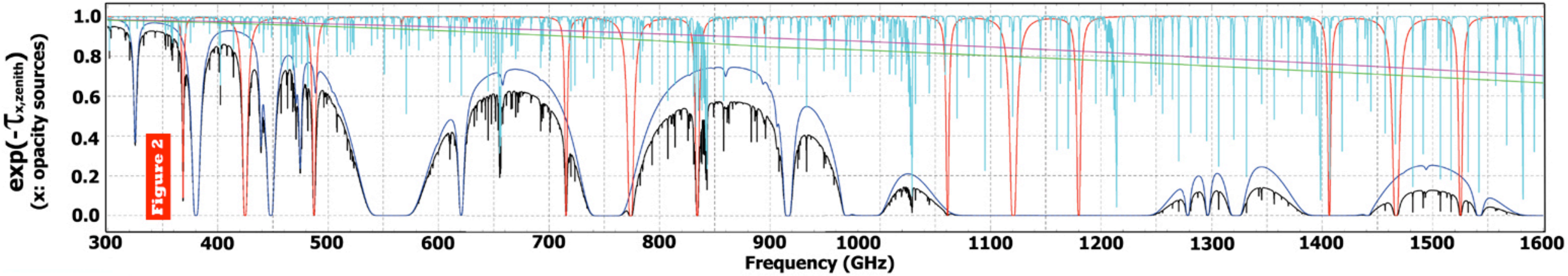
$$\mu \frac{d\mathbf{I}(z,\mu)}{dz} = \kappa(z,\mu)\mathbf{I}(z,\mu) - $$
$$-2\pi \int_{-1}^{1} \mathbf{S}(z,\mu,\mu')\mathbf{I}(z,\mu')d\mu' - \epsilon(z,\mu)B[T(z)]$$

$\mathbf{I} = \begin{pmatrix} I \\ Q \end{pmatrix}$ **« Intensity vector »**

***K:* 2x2 extinction matrix *ε:* emission vector**

***S:* 2x2 scattering matrix** ***K*=2π∫*S*+ ε**

Chajnantor zenith transmission for 0.5 mm H2O / Water lines / Oxygen lines / ozone lines / H_2O-foreign / N_2-N_2 + N_2-O_2 + O_2-O_2



1. Atmospheric Refraction Index: The whole story

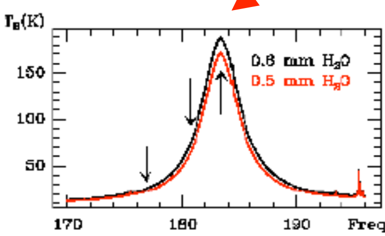
1.0 + Gas-phase contribution + Hydrometeros contribution

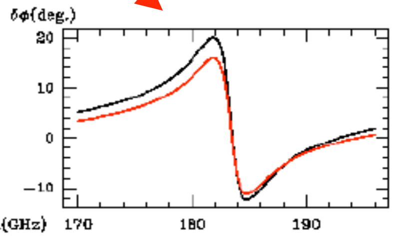
Impact approximation
$\tau_{collision} << 1/\nu$
Van-Vleck-Weisskopf line profile

$$\mathcal{F}(\nu, \nu_{u\leftrightarrow l}) = \frac{\nu}{\pi \nu_{u\leftrightarrow l}}\left[\frac{1 - i\delta}{\nu_{u\leftrightarrow l} - \nu - i\Delta\nu} + \right.$$
$$\left. + \frac{1 + i\delta}{\nu_{u\leftrightarrow l} + \nu + \Delta\nu}\right] \quad (1)$$

1a. Imaginary Part (absorption)

1b. Real Part (phase delay)





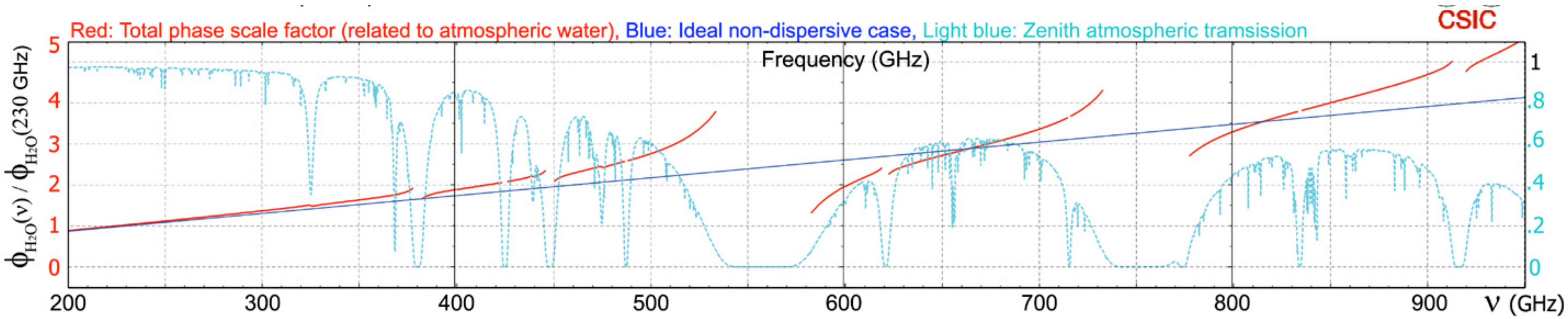
1c. Scattering. Polarization must be included

$$\mu \frac{d\mathbf{I}(z,\mu)}{dz} = \kappa(z,\mu)\mathbf{I}(z,\mu) -$$
$$-2\pi \int_{-1}^{1} \mathbf{S}(z,\mu,\mu')\mathbf{I}(z,\mu')d\mu' - \epsilon(z,\mu)B[T(z)]$$

$$\mathbf{I} = \begin{pmatrix} I \\ Q \end{pmatrix}$$ **« Intensity vector »**

K: **2x2 extinction matrix** ***ε:*** **emission vector**

S: **2x2 scattering matrix** ***K=2π∫S+ ε***



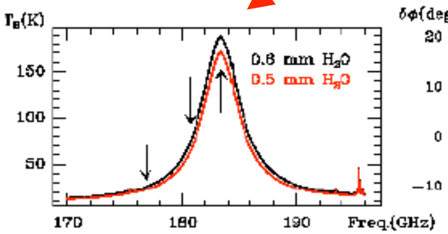
1. Atmospheric Refraction Index: The whole story

1.0 + Gas-phase contribution + Hydrometeros contribution

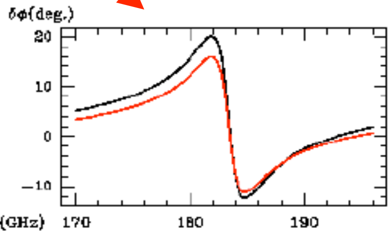
Impact approximation
$\tau_{collision} << 1/\nu$
Van-Vleck-Weisskopf line profile

$$\mathcal{F}(\nu,\nu_{u\leftrightarrow l}) = \frac{\nu}{\pi\nu_{u\leftrightarrow l}}\left[\frac{1-i\delta}{\nu_{u\leftrightarrow l}-\nu-i\Delta\nu} + \frac{1+i\delta}{\nu_{u\leftrightarrow l}+\nu+\Delta\nu}\right] \qquad (1)$$

1a. Imaginary Part (absorption)



1b. Real Part (phase delay)



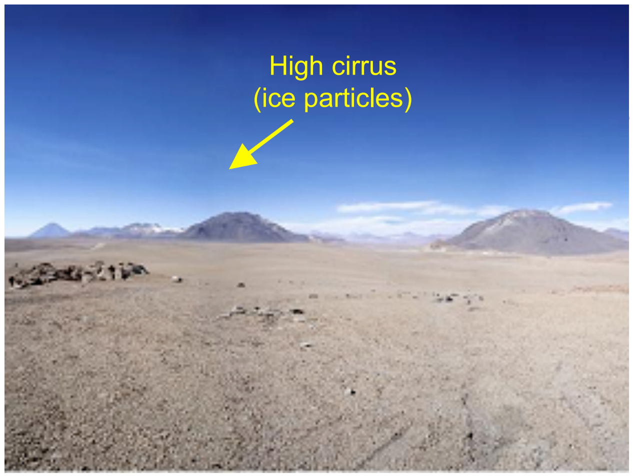
1c. Scattering. Polarization must be included

$$\mu\frac{d\mathbf{I}(z,\mu)}{dz} = \kappa(z,\mu)\mathbf{I}(z,\mu) - 2\pi\int_{-1}^{1}\mathbf{S}(z,\mu,\mu')\mathbf{I}(z,\mu')d\mu' - \epsilon(z,\mu)B[T(z)]$$

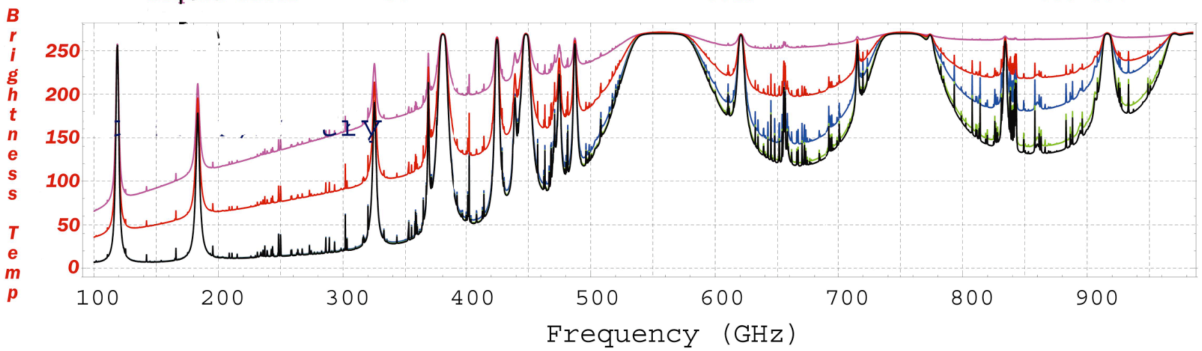
$\mathbf{I} = \begin{pmatrix} I \\ Q \end{pmatrix}$ **« Intensity vector »**

K: **2x2 extinction matrix** ***ε:*** **emission vector**

S: **2x2 scattering matrix** ***$K = 2\pi\int S + \varepsilon$***



Cloud type	Part. radius (microns)	Equiv. Water Path (mm)	Cloud Position (km)
Clear Atm.	----	----	----
Ice	30	0.07	6.0-6.7
Ice	50	0.15	6.0-6.7
Liquid Water	30	0.07	6.0-6.7
Liquid Water	50	0.15	6.0-6.7



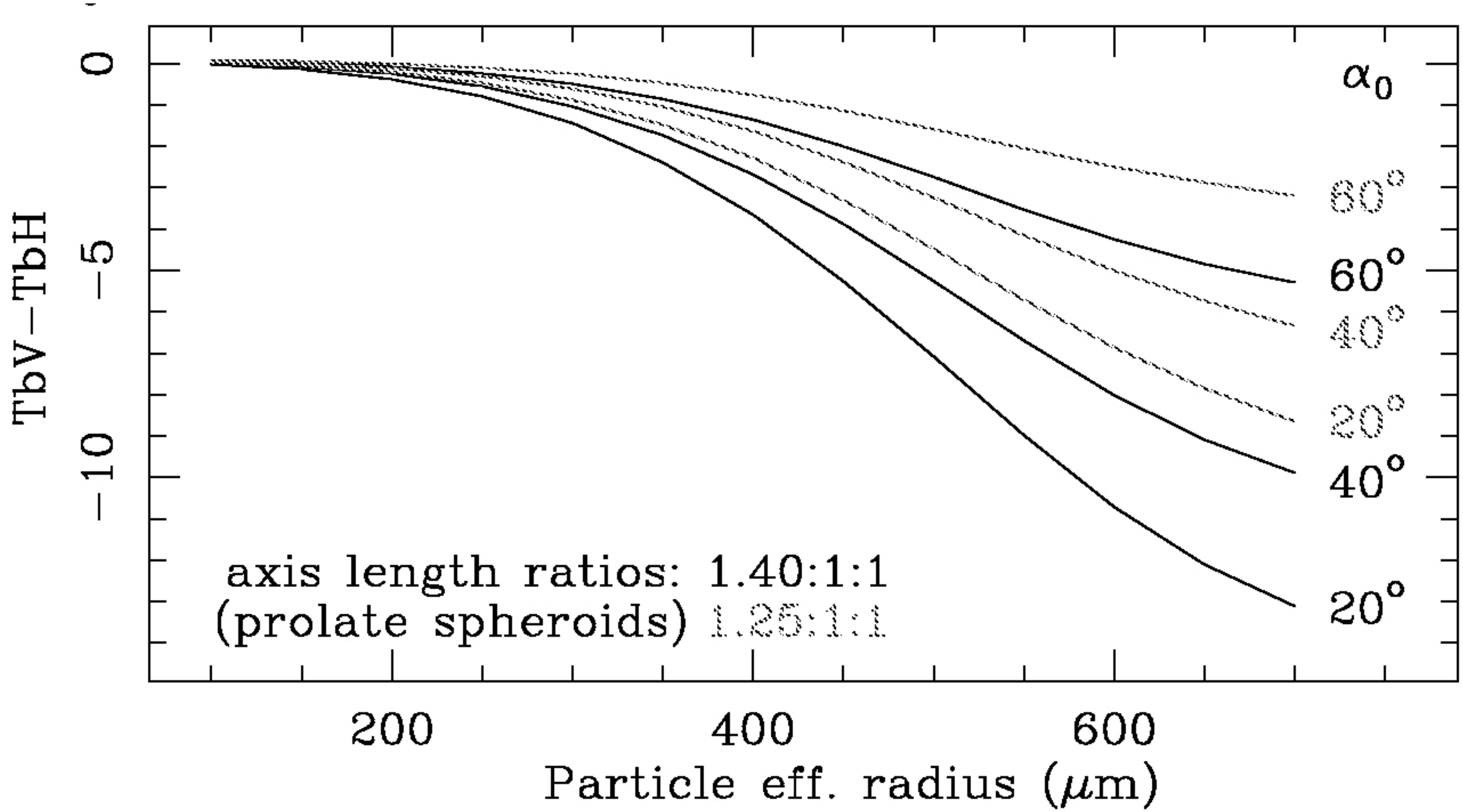
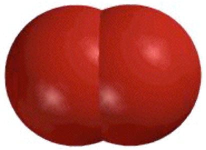
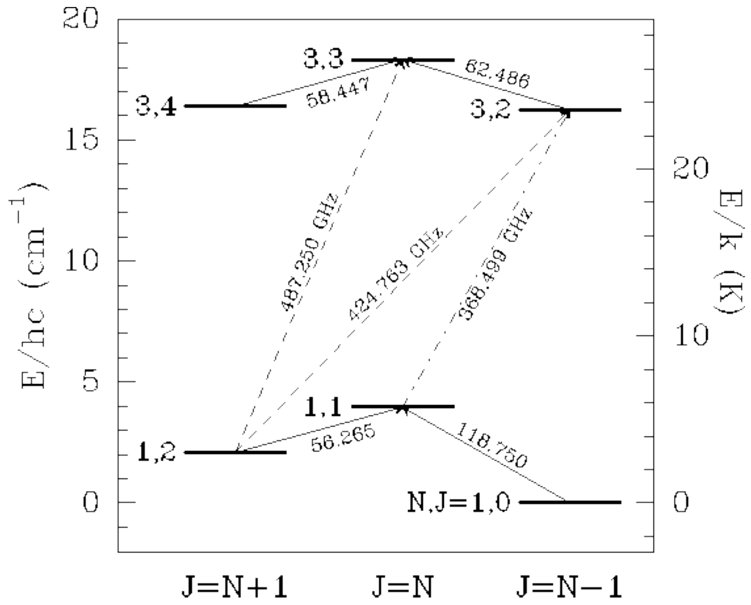
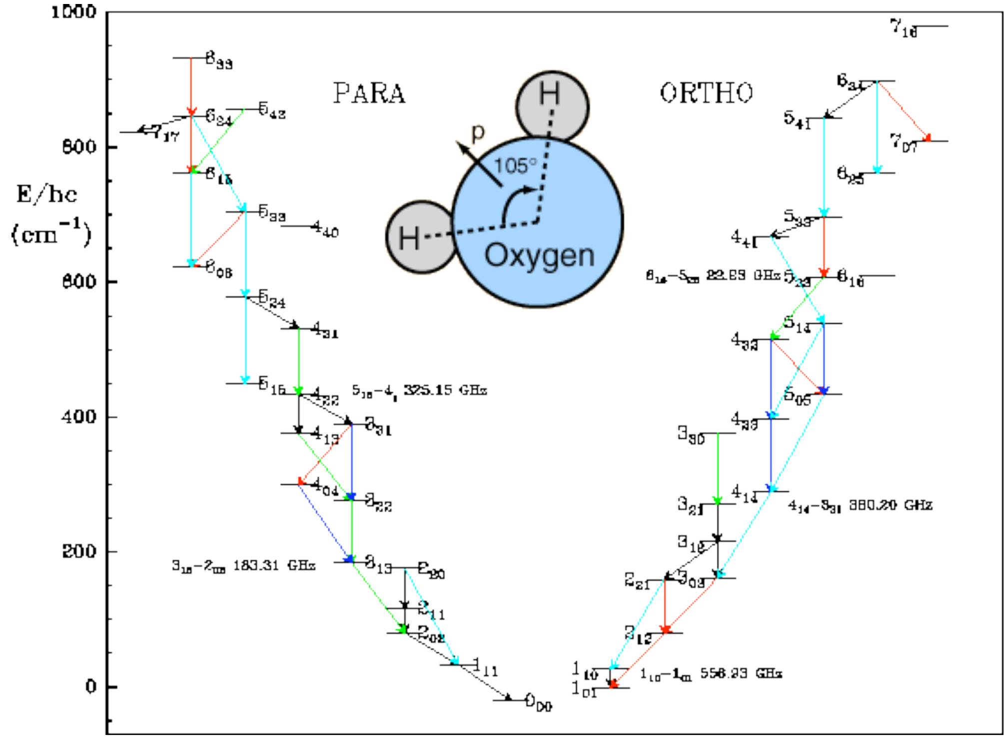


Figure 2. Sensitivity of the 85 GHz polarization difference to the orientation of the non-spherical ice particles as a function of particle size. The orientation of the particles is random within α_0 from the vertical axis.

1a. Physical basis: mm/submm atmospheric absorption





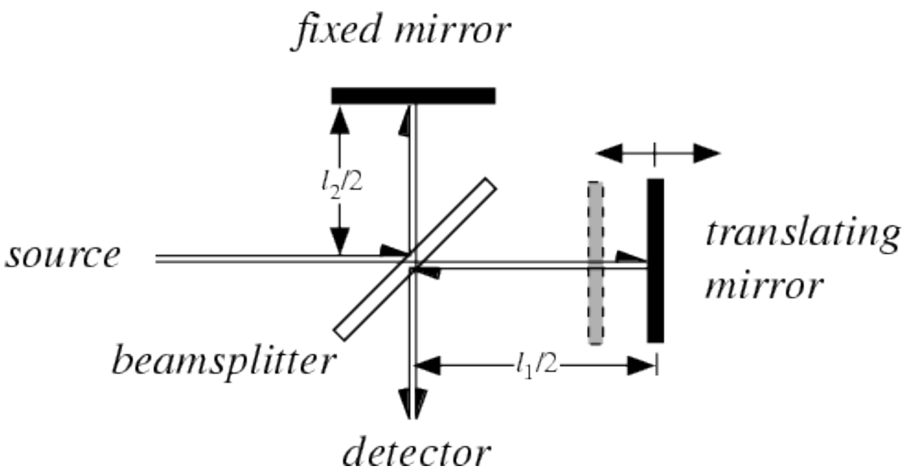


- "Line" spectrum: rotational transitions of H_2O, O_2, O_3, N_2O, CO, and other trace gases.
- "Hydrometeor" contribution: absorption & scattering by liquid, ice and other particles.
- Collision-induced absorption by N_2-N_2, O_2-O_2 and N_2-O_2, H_2O-N_2, H_2O-O_2 mechanisms

1b. Experimental basis: Direct measurements with FTS experiments at Mauna Kea, Chajnantor & Sout Pole

- **Accurately measure the shape of the terrestrial longwave spectrum.**
- **Solve the « excess of continuum » problem.**
- **Input to build an state-of-the-art absorption models:**

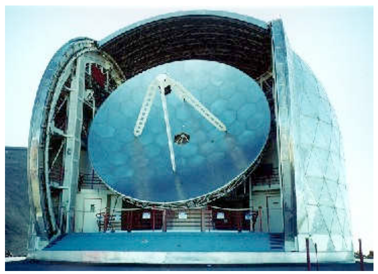
ARTS (Bremen University) **AM** (CfA, Harvard) **ATM** (CalTech, CSIC)

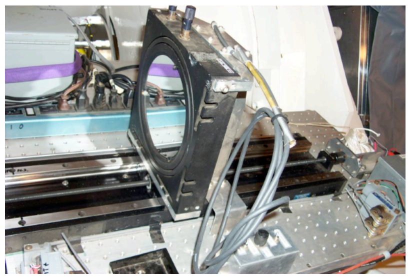


Schematics of FTS experiment

Characteristics of CSO-FTS

- Mounted on Cassegrain focus of telescope for dedicated obs. runs.
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)

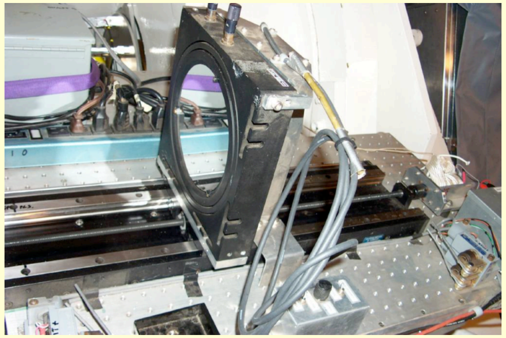




Mauna Kea (4200 m, -5 ºC), Hawai'i
Hapuna Beach (0 m, 25 ºC, Hawai'i)

The CSO-FTS experiment. Set-up.

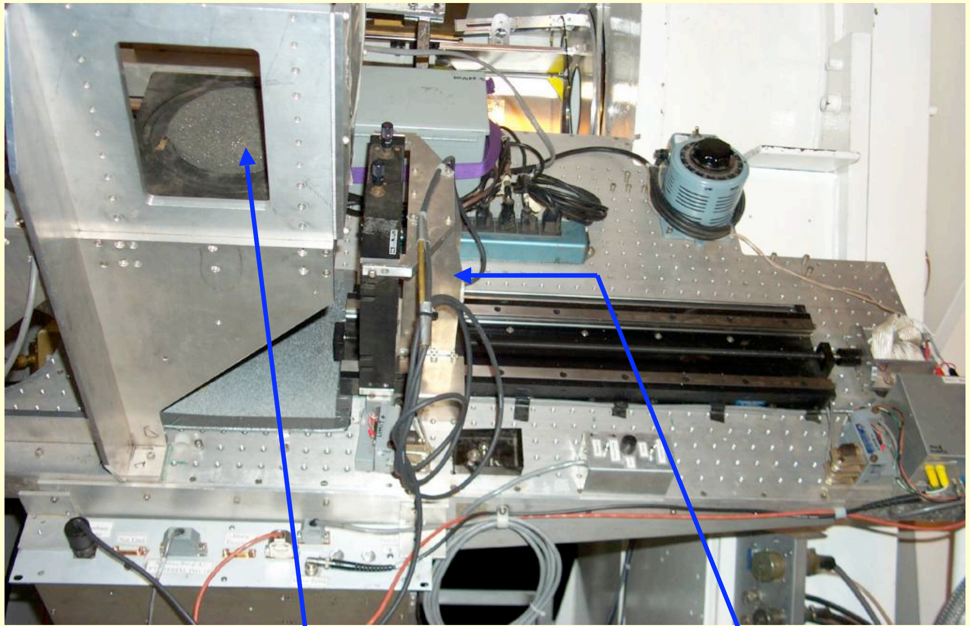
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm → ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)



- **CO: Double Fabry-Pérot with maximum transmission at CO frequencies.**
- **550 GHz (low pass): to explore low frequencies.**
- **650 GHz: To explore the 450 μm window.**
- **850 GHz: To explore the 350 μm window.**
- **750 GHz: To simultaneously explore both.**
- **1.1 THz (low pass): To explore 300-1100 GHz.**
- **1.6 THz (low pass): To explore 300-1600 GHz.**

Caltech Submillimeter Observatory - Fourier Transform Spectrometer (CSO-FTS)

Last mirror and bolometer (cooled to liq. ^3He)



Fixed mirror (can rotate for holography)

Moving mirroir

CSO-FTS approach to solve the « excess of continuum » problem

Use well calibrated measurements acquired during very dry conditions

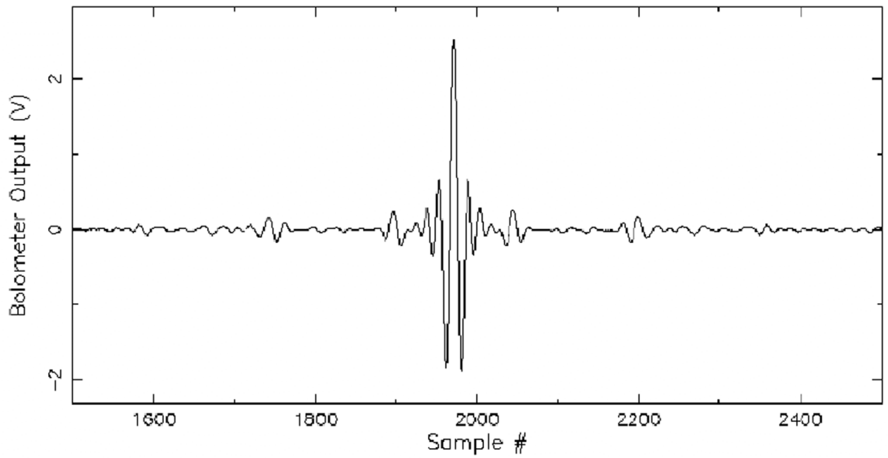
- $T_0 \sim 270 \pm 3$ K
- $P \sim 620 \pm 1.5$ mb at Mauna Kea summit.

As a consequence: The"dry" atmospheric absorption is basically the same (within 1-3 %) in the different situations. The remaining opacity is proportional to the PWV

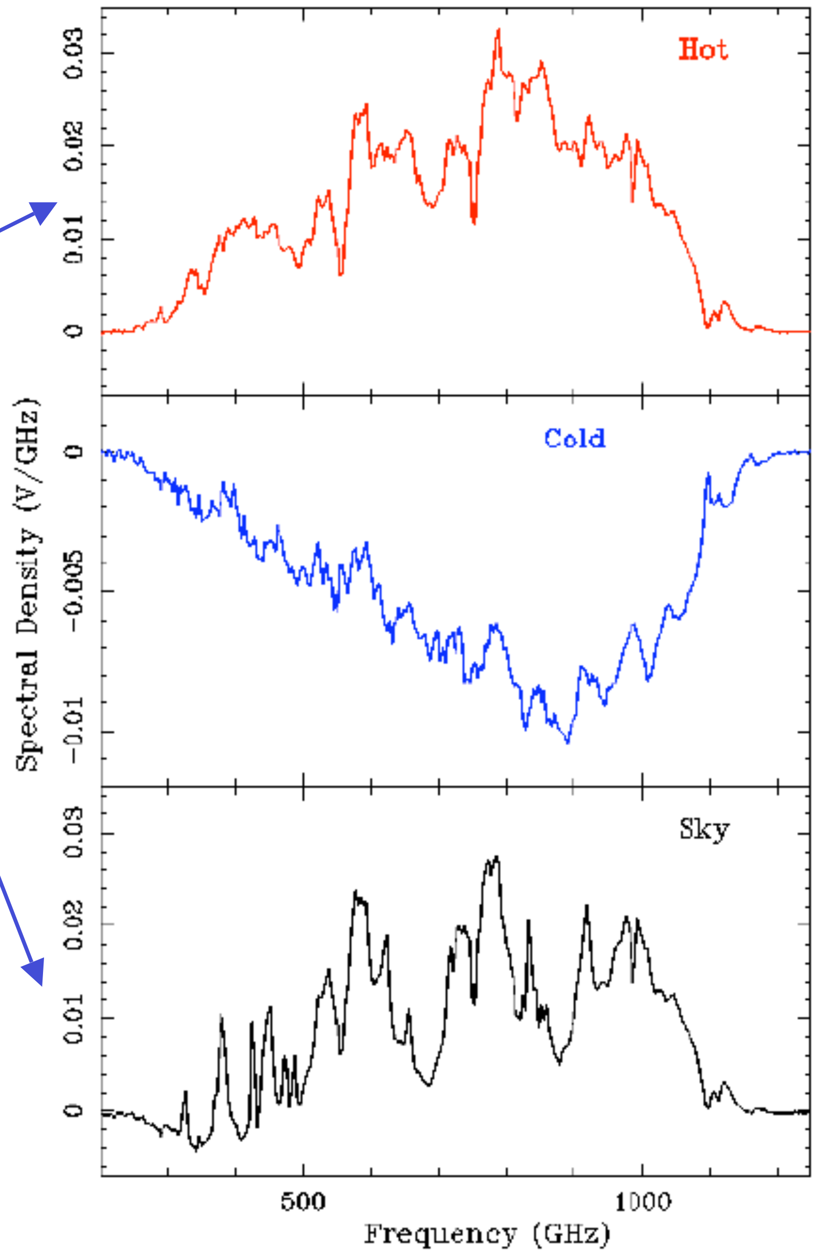
The water vapor column can be determined very precisely from the near wings of water lines, virtually independently of the continuum terms.

CSO-FTS. Calibration of atmospheric measurements

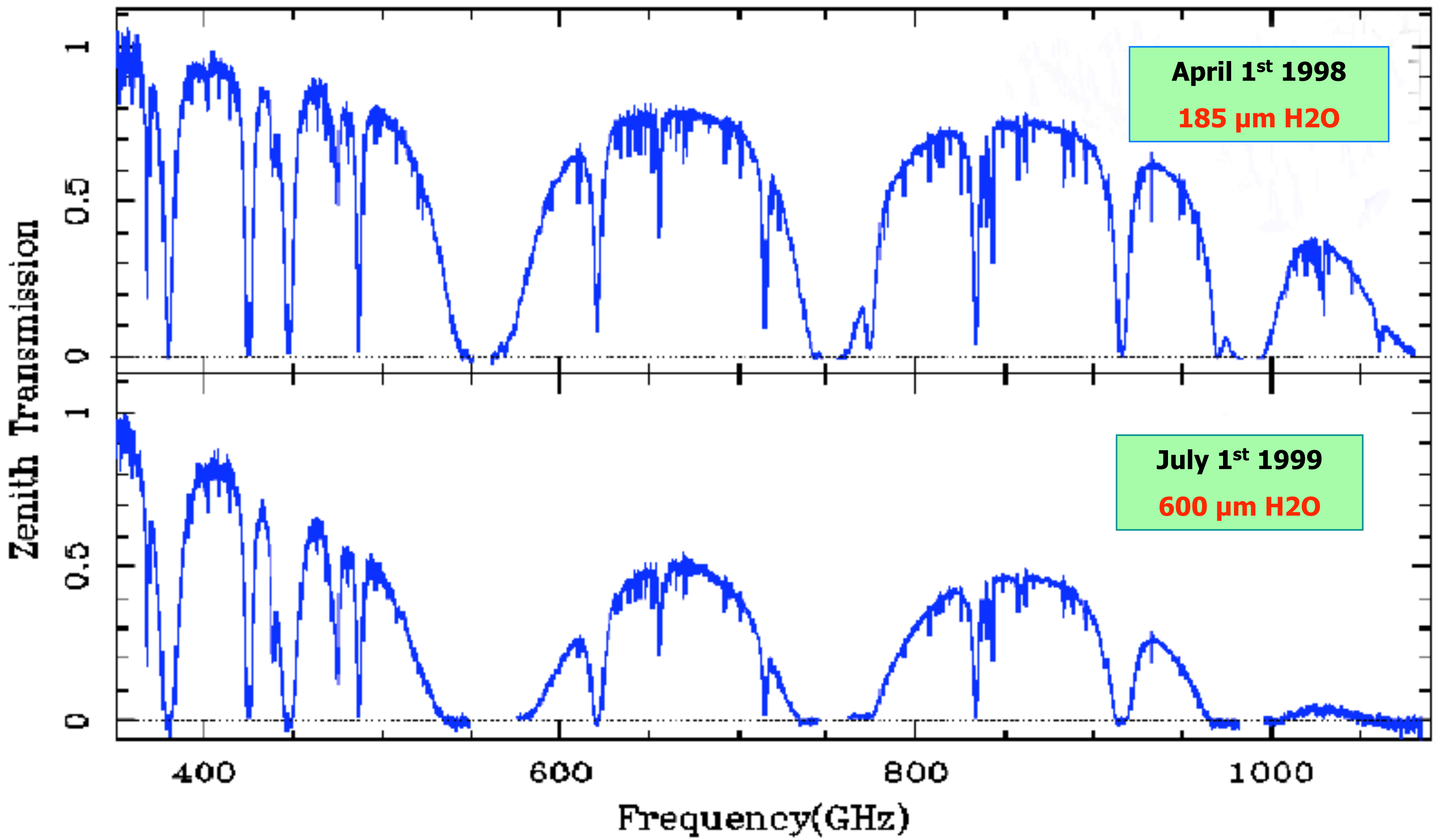
An accurate calibration of the spectra is key to the atmospheric goals of the experiment



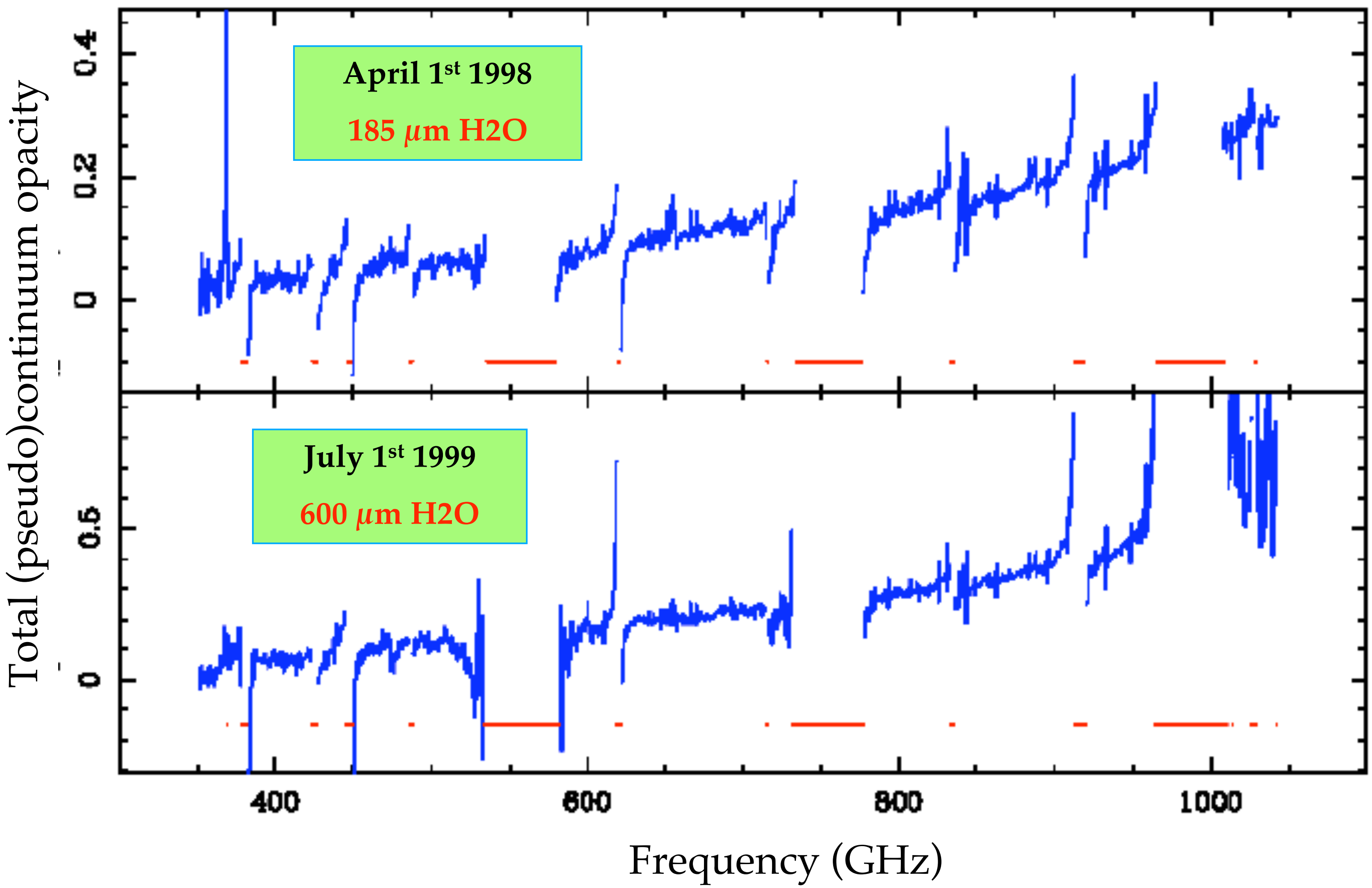
Raw data of CSO- FTS experiment (full resolution two-sided scan takes about 5 minutes to complete)



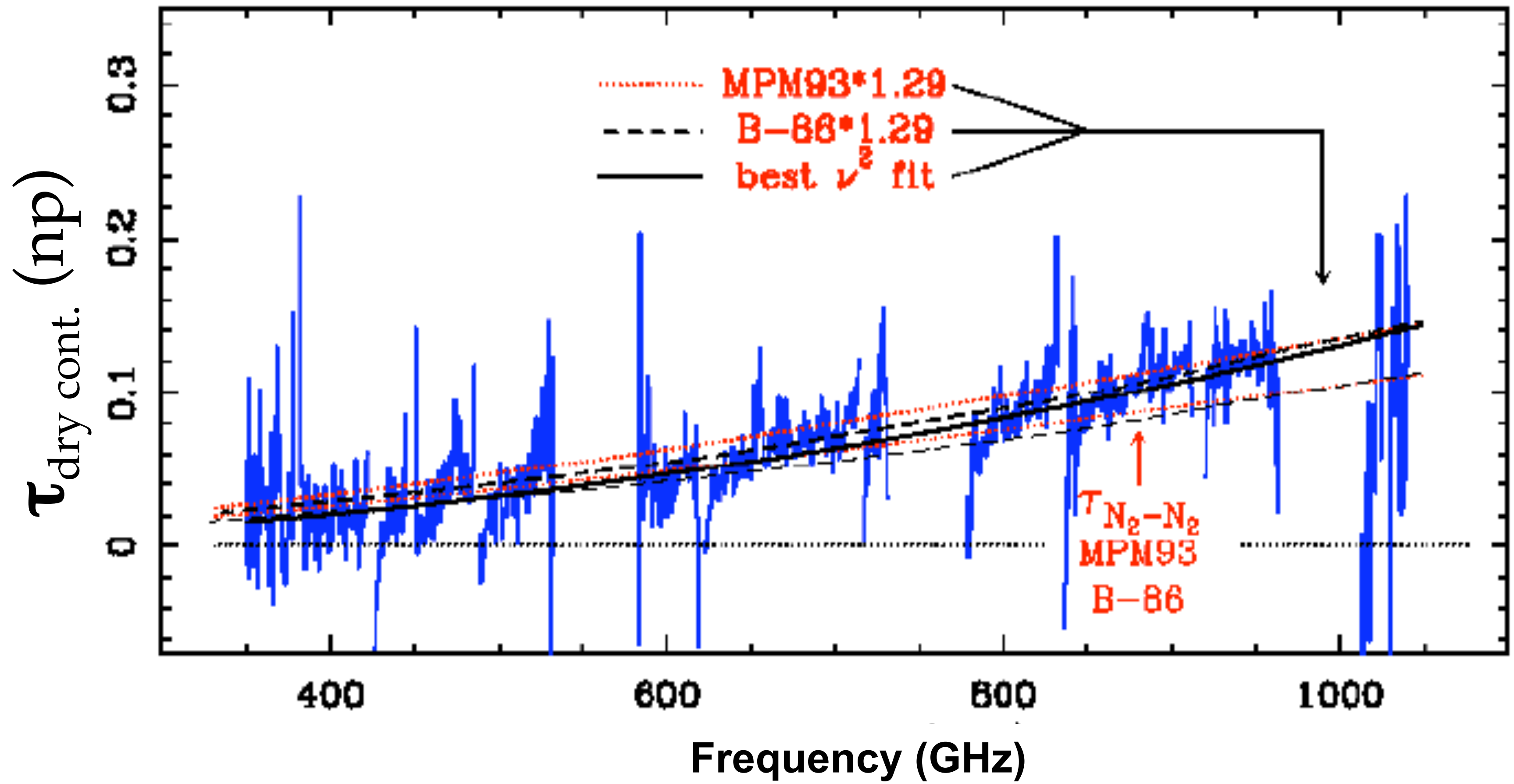
Relevant results for continuum-like atmospheric absorption below 1 THz



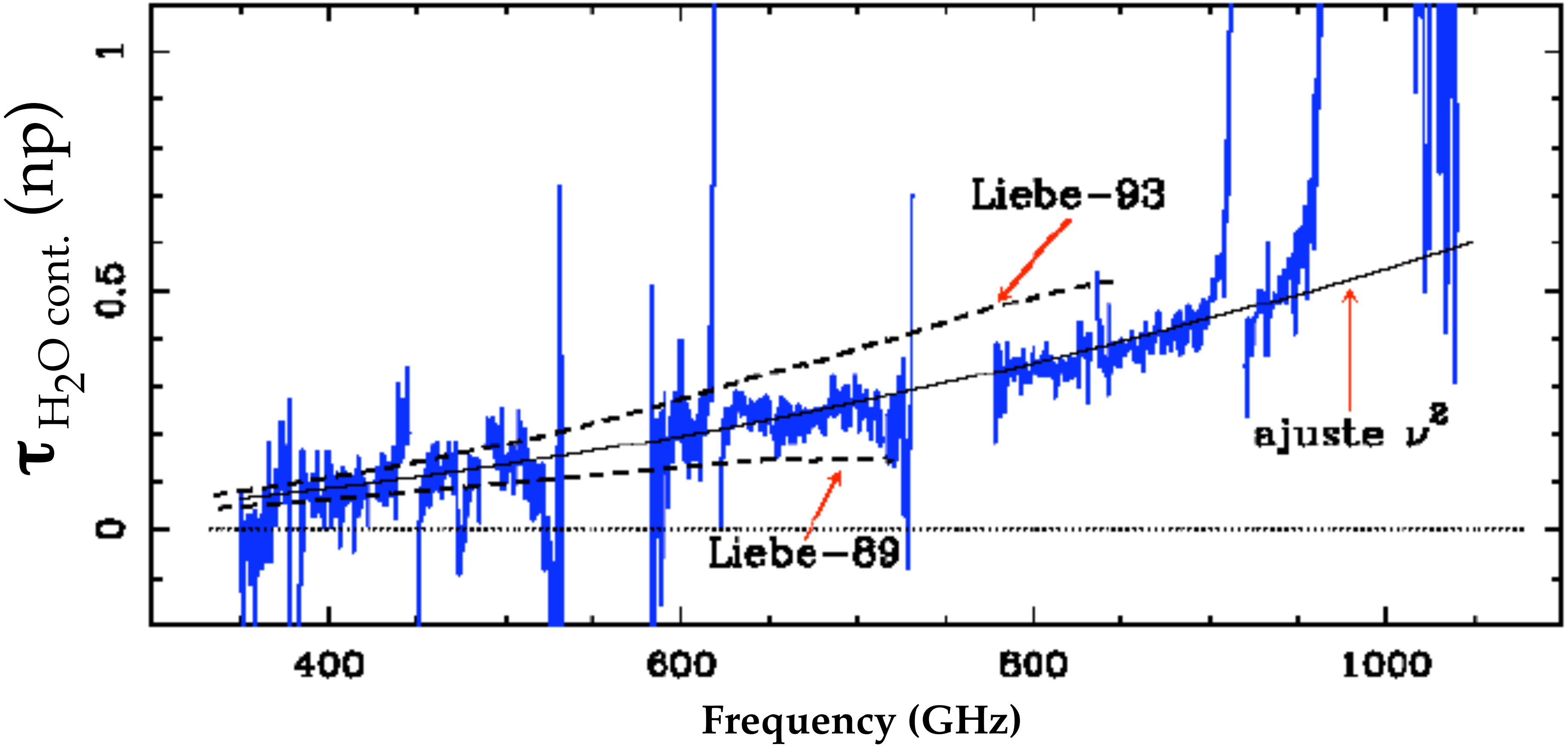
Continuum-like terms measured with the FTS



Dry continuum: O_2 and N_2 collision induced absorption



H_2O continuum-like



"Submillimeter atmospheric transmission measurements on Mauna Kea during extremely dry El Niño conditions: Implications for broadband opacity"

J. R. Pardo, E. Serabyn and J. Cernicharo, **JQSRT, 68/4, 419-433 (2001).**

CSO-FTS approach to solve the « excess of continuum » problem

Use well calibrated measurements acquired during very dry conditions

- $T_0 \sim 270 \pm 3$ K
- $P \sim 620 \pm 1.5$ mb at Mauna Kea summit.

As a consequence: **The "dry" atmospheric absorption is basically the same (within 1-3 %) in the different situations. The remaining opacity is proportional to the PWV**

The water vapor column can be determined very precisely from the near wings of water lines, virtually independently of the continuum terms.

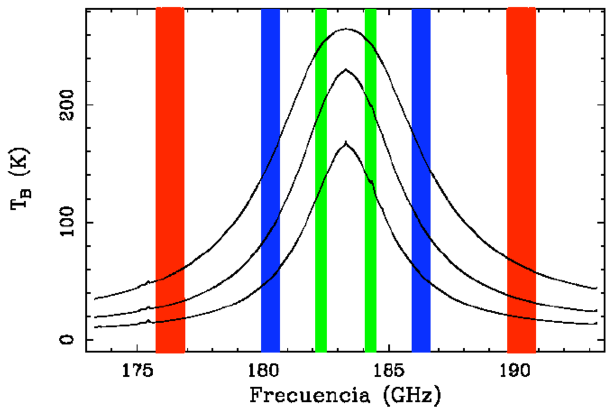
Same approach remains valid for $\nu > 1$THz

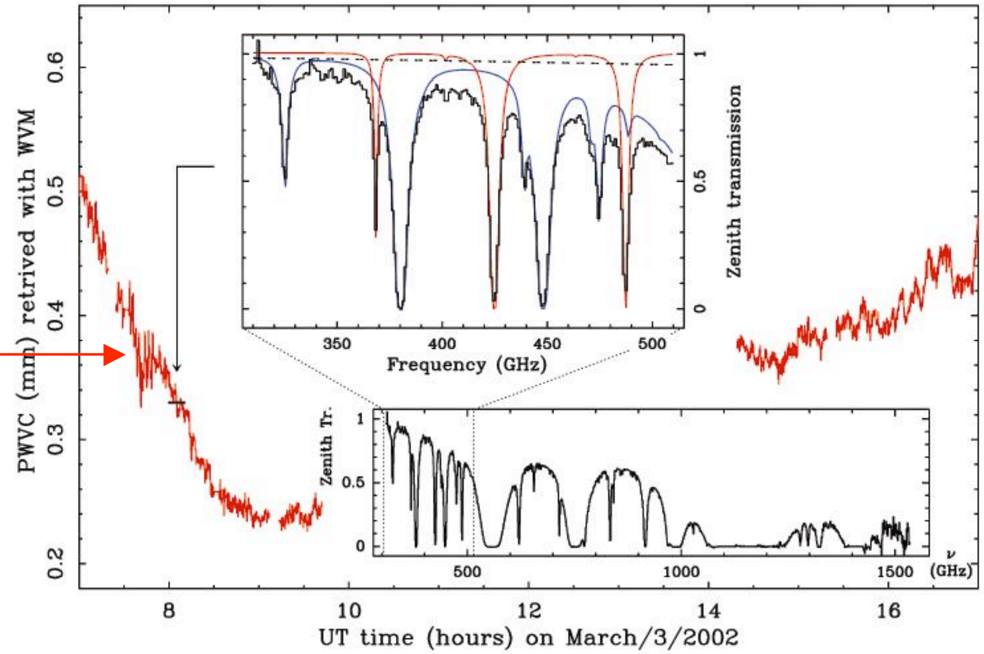
Complementary measurements

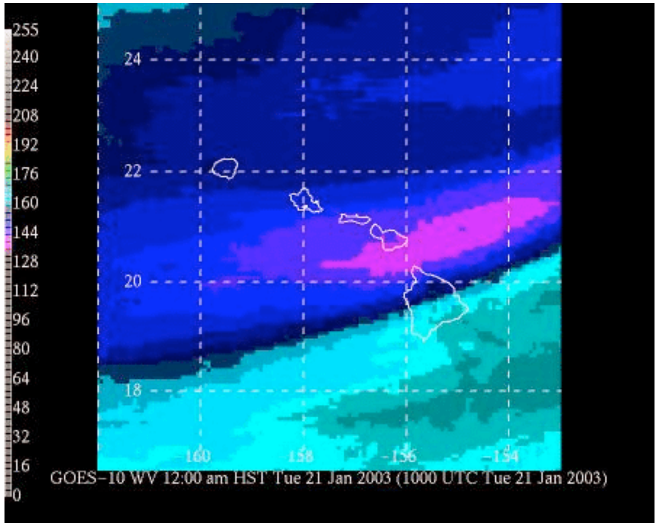
WVM data + FTS data below 500 GHZ + GOES-10 data + Tau_meter data + weather station data: PWV can be determined independently of uncertainties in continuum-like terms and cross-checked

183 GHz WV Monitor - Martina Wiedner

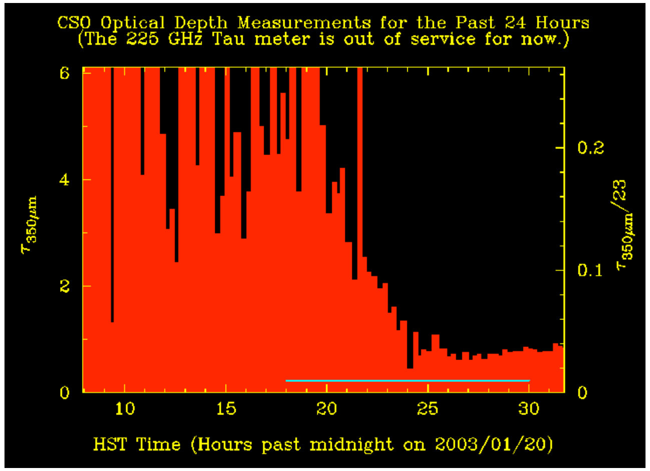
- 3 channels, uncooled T_{sys}=2000-2500K, mounted on telescope, calibration on 300 K and 370 K at 1Hz







GOES-10 Water vapor

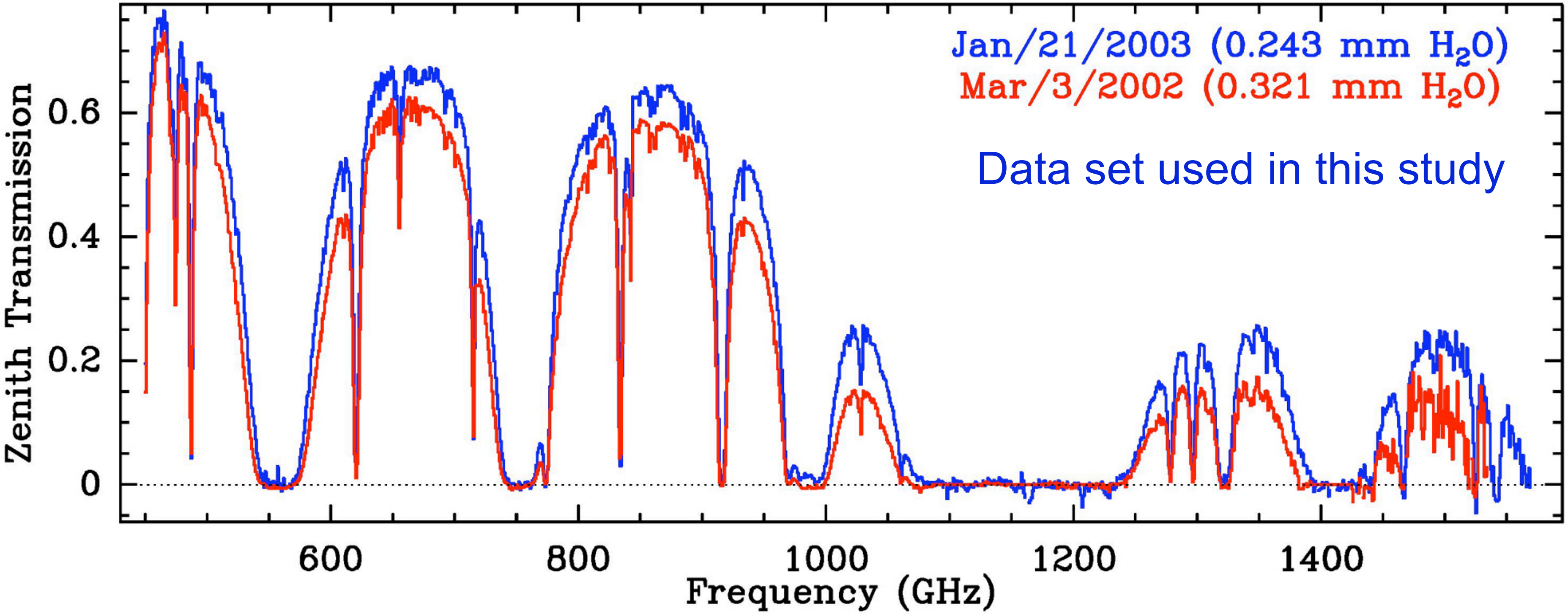


350 μm opacity meter

OTHER:

Hand-held thermo-hygrometer

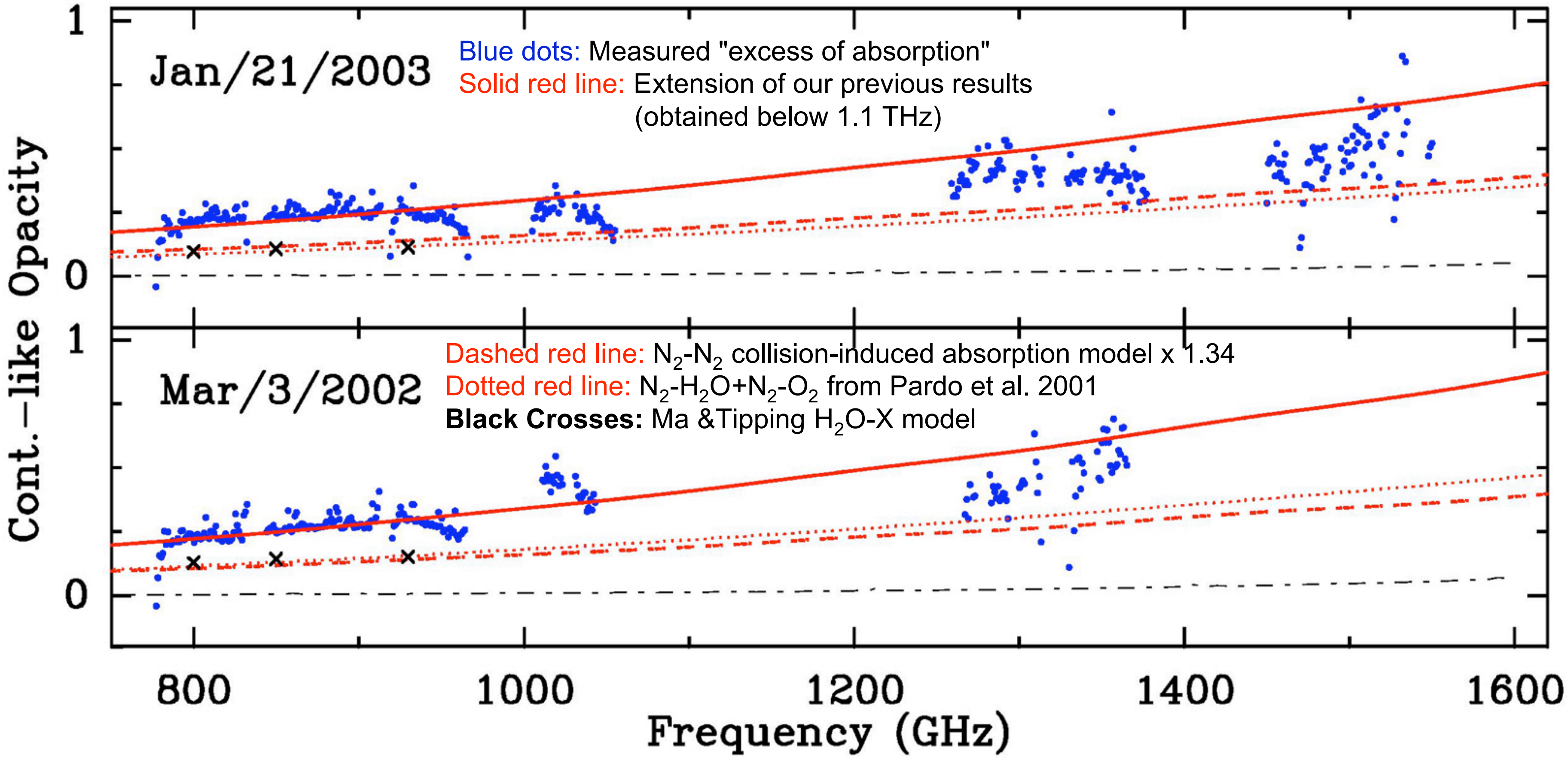
Telescope's weather station



WVM data + FTS data below 500 GHZ:
Allow a Water Vapor Column determination independent of uncertainties in continuum-like terms

GOES-10 data + Tau_meter data + weather station data
Used as extra information to check consistency

Line opacity can be removed considering calculated and/or laboratory line parameters. The remaining absorption is the "excess of opacity"



¿What is the nature of this opacity term?

- Errors in far wings of lines above 2 THz can be ruled out
- Earlier (Pardo et al 2001) collision-induced absorption explanation confirmed below 1.1 THz
- Extension of those results above 1.1 THz results on overestimation
- IF N_2-N_2x1.34 collision induced absorption model (Boissoles et al. 2003) is assumed correct THEN the H_2O-O_2+H_2O-N_2 collision induced absorption calculations (Ma & Tipping 2002) provide very good results below 1 THz and it appears that above that frequency we may start seeing the flattening of this term.

GENERAL CONCLUSIONS

- **An accurate determination of WVC from FTS or WVM data can be done only if the continuum opacity is well know or unimportant (below 0.5 GHz is best).**

- **Below 0.9 GHz the continuum-like opacity has been measured and successfully separated into wet and dry parts in Pardo et al. 2001.**

- **Recent data presented here (both FTS and WVM) have allowed to separate the total continuum from the lines in the range 1.0-1.6 THz.**

Serabyn, Weisstein, Lis & Pardo, Appl. Optics, 37:2185, 1998

Matsushita, Matsuo, Pardo, & Radford, PASJ, 51:603, 1999.

Pardo, Serabyn & Cernicharo, JQSRT, 68:419, 2001

Pardo, Cernicharo & Serabyn, IEEE TAP, 49:1683, 2001

Pardo, Wiedner, Serabyn, Wilson, Cunningham, Hills & Cernicharo, Ap. J. Suppl., 153:363, 2004

Pardo, Serabyn, Wiedner & Cernicharo, JQSRT, 96:537, 2005

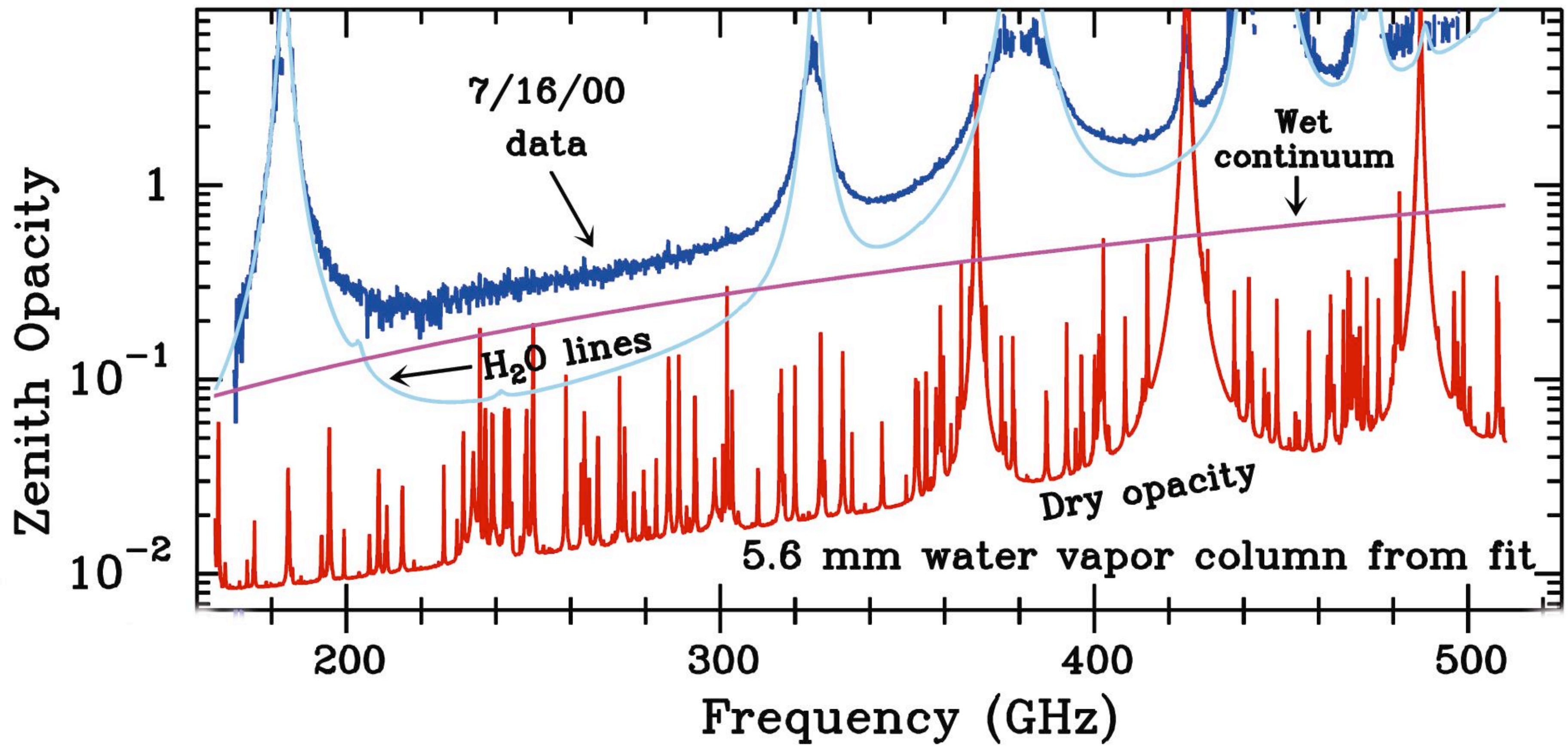
THE DERIVED 1.0-1.6 THz CONTINUUM…

- Not yet totally separated into wet and dry components.
- Line wings from resonances between 2 and 10 THz can be ruled out as a significant contribution to the continuum-like opacity.
- Previously derived continuum terms below 900 GHz extrapolated to higher frequencies provide some overestimation at frequencies beyond 1.1 THz.
- The dry continuum appears to be well understood as N_2-N_2 collision induced absorption scaled by a factor in the range 1.29 to 1.34 (last factor found theoretically by Boissoles et al. 2003).
- A flattening in the ν^x wet continuum ($x<2$) may be present according to a fit of our data (Theoretical work by Ma & Tipping, 2002 provides good results below 1 THz, but needs to be extended beyond that frequency [some approach problems appear]).
- A good enough model is currently available for the frequency range of the future Atacama Large millimeter Array, that is currently been integrated in the calibration software

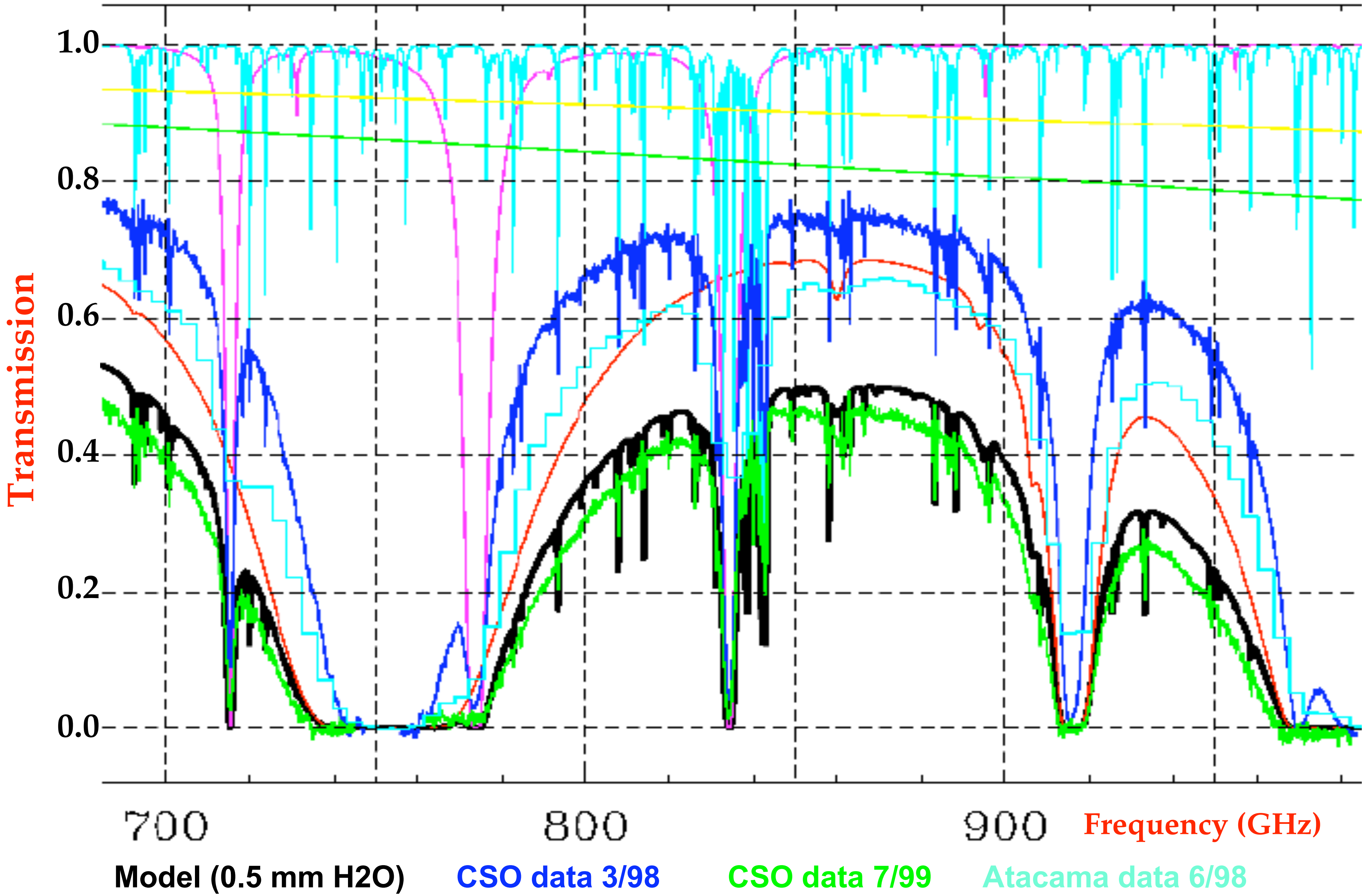
1c. Up-to-date model: ATM

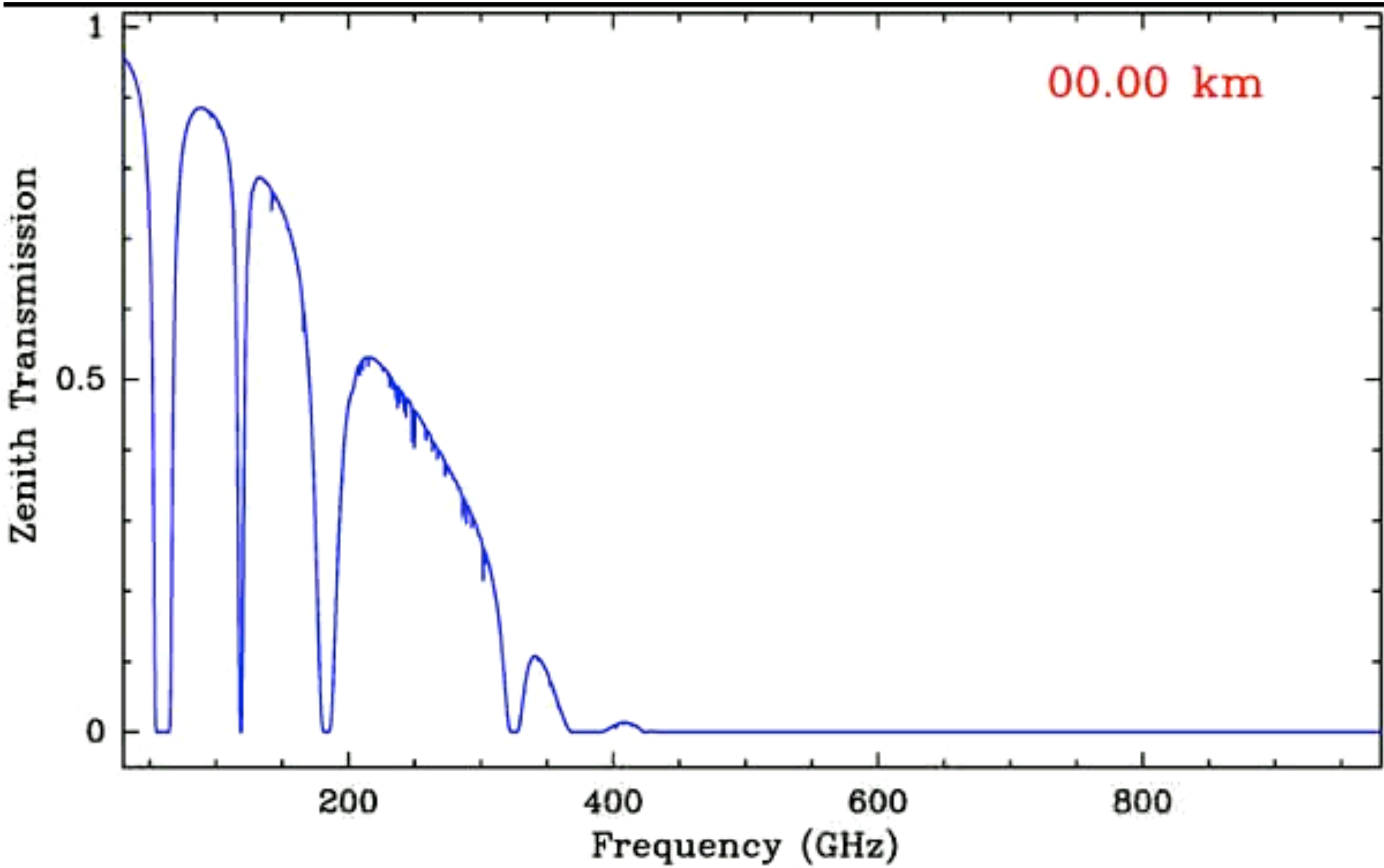
Atmospheric Transmission at Microwaves

Example 1: Opacity terms in wet atmospheric conditions at Mauna Kea



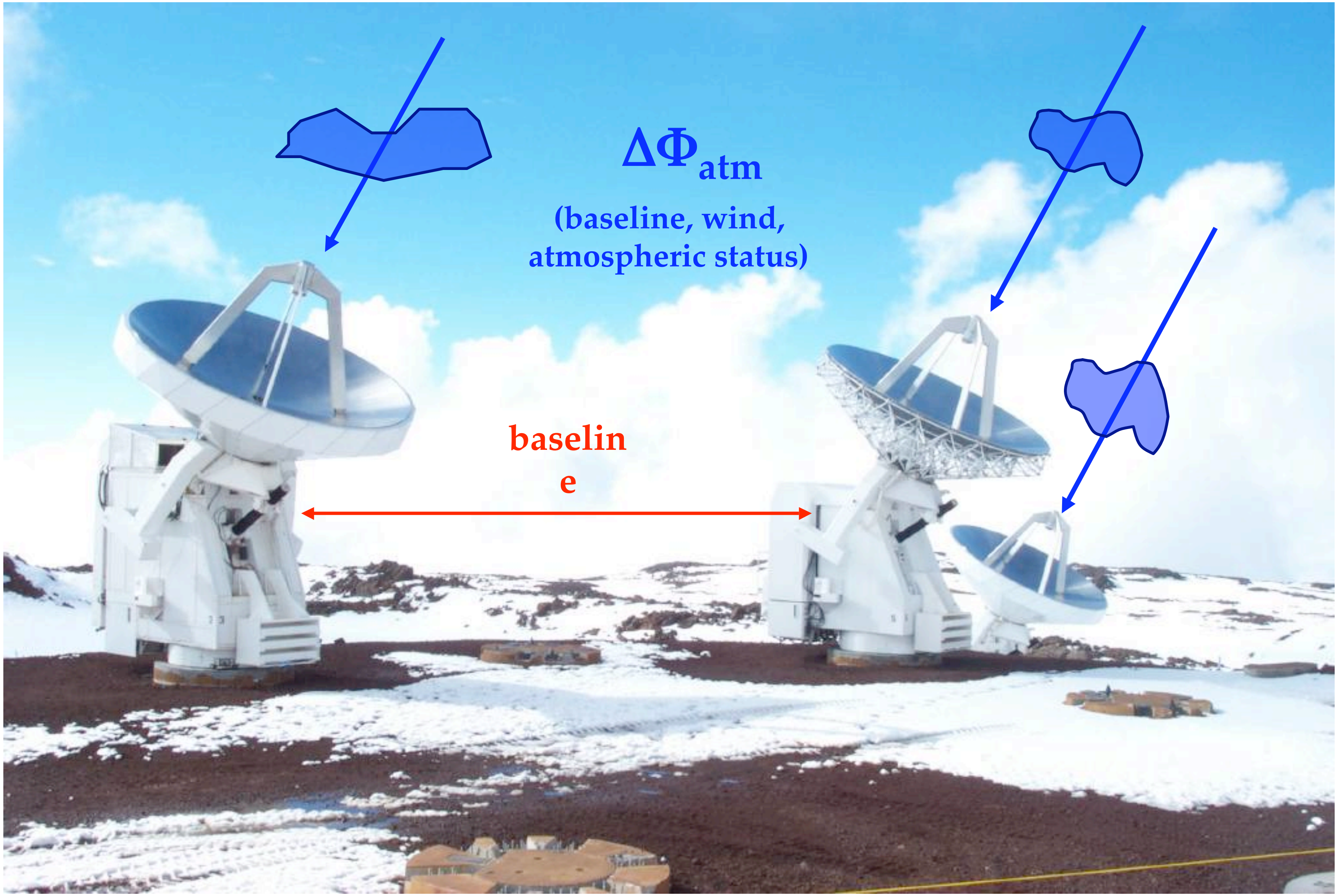
Example 2: Atmospheric transmission at high frequencies in dry Mauna Kea conditions



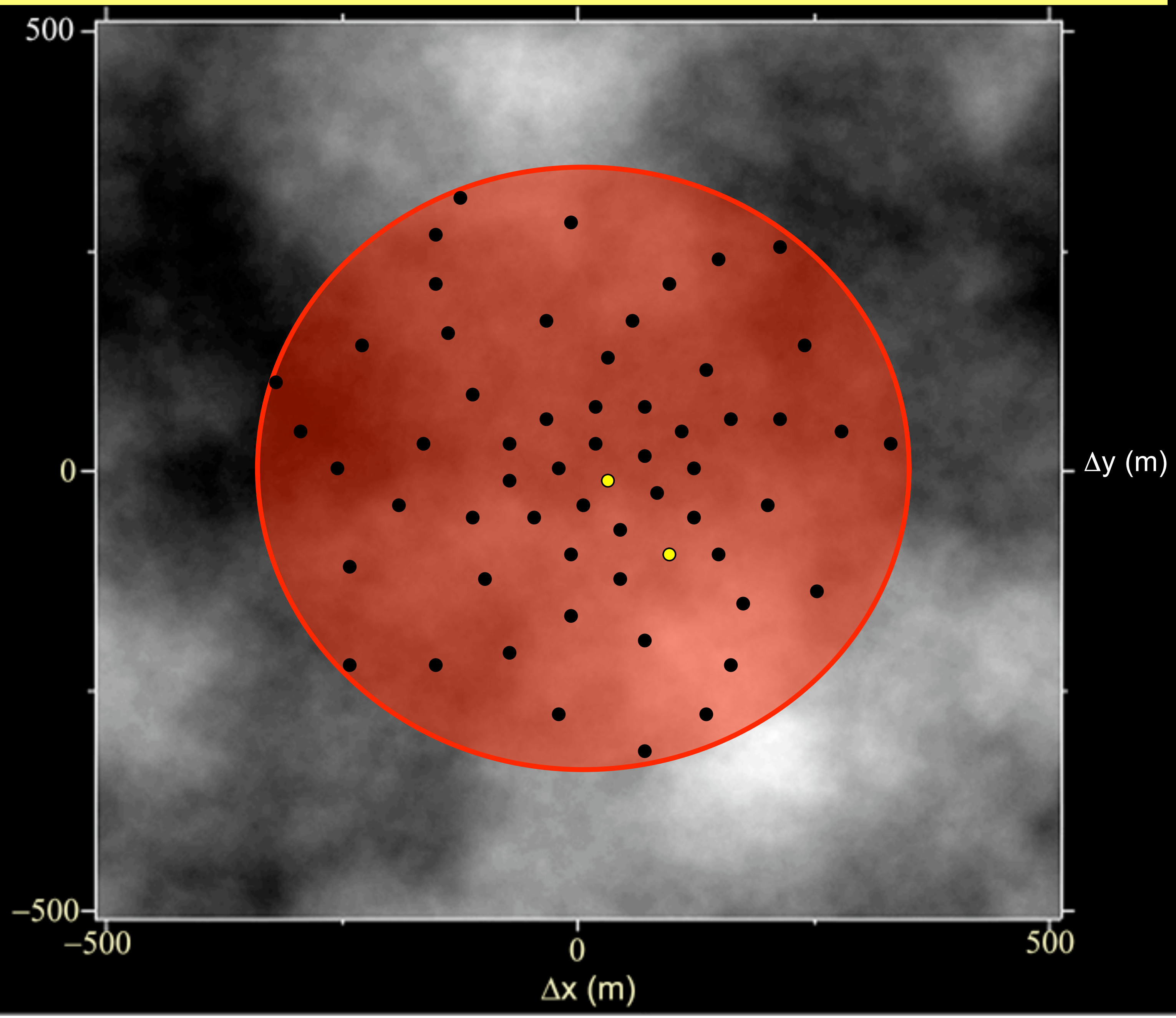


00.00 km
Zenith Transmission
Frequency (GHz)
1
0.5
0
200
400
600
800

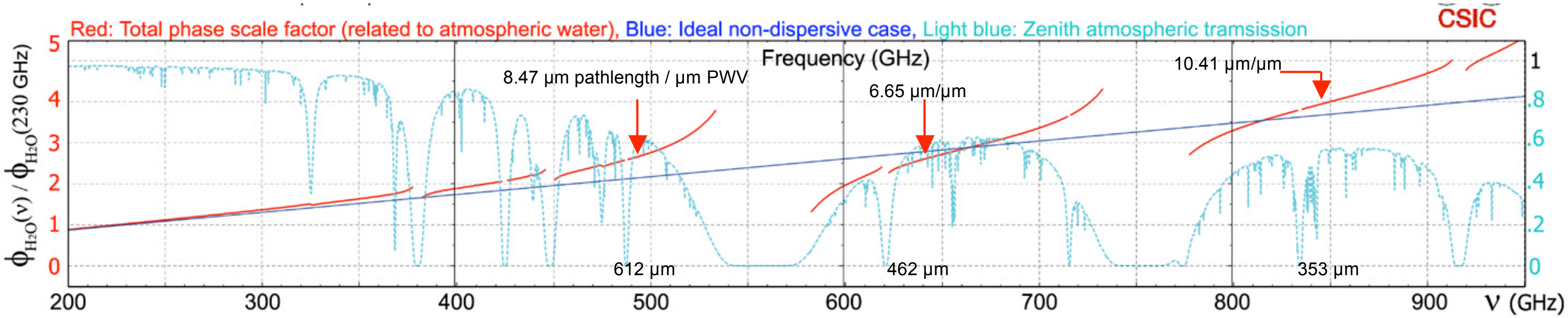
2. The atmospheric problem for ground-based obs.

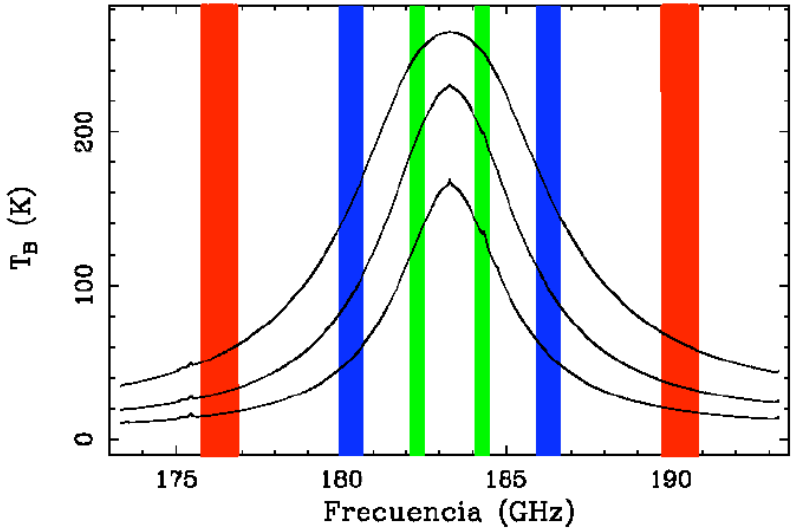


Example of atmospheric water vapor fluctuations



Phase correction can be performed using water vapor radiometry at frequencies sensitive to H_2O





Taking an average Precipitable Water Vapor amount of 0.5 mm, we have:

23 mk/µm **60 mk/µm** **173 mk/µm**

Assuming 0.4 K noise in 1 s in all three channels of the Water Vapor Radiometer

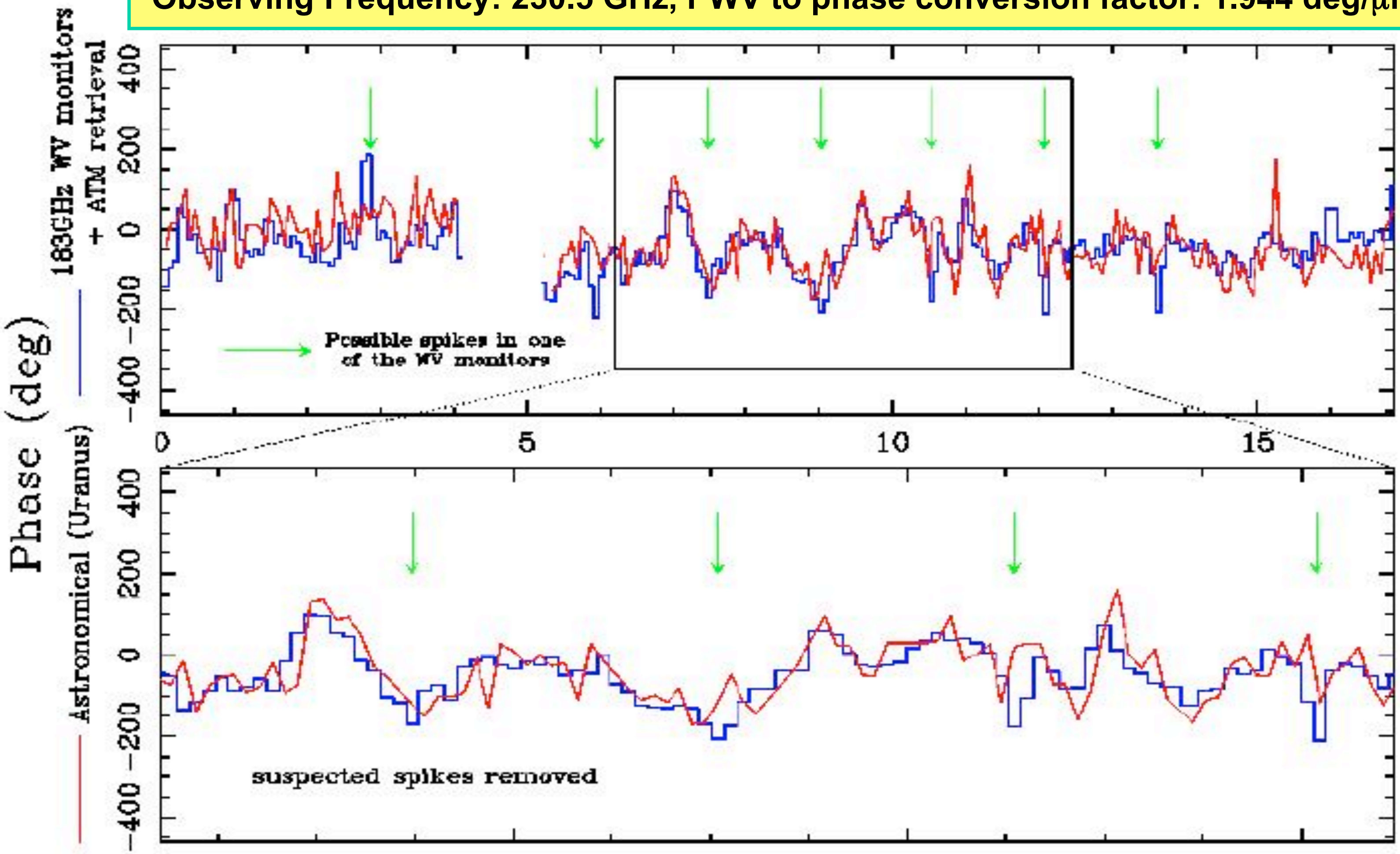
Uncertainty in determining ΔPWV: **2.3 µm**

The goal of **15 µm pathlength correction accuracy** for ALMA should be reachable with this technique in time scales of the order of 1 s.

CURRENT PROTOTYPES ALREADY MEET THESE REQUIREMENTS

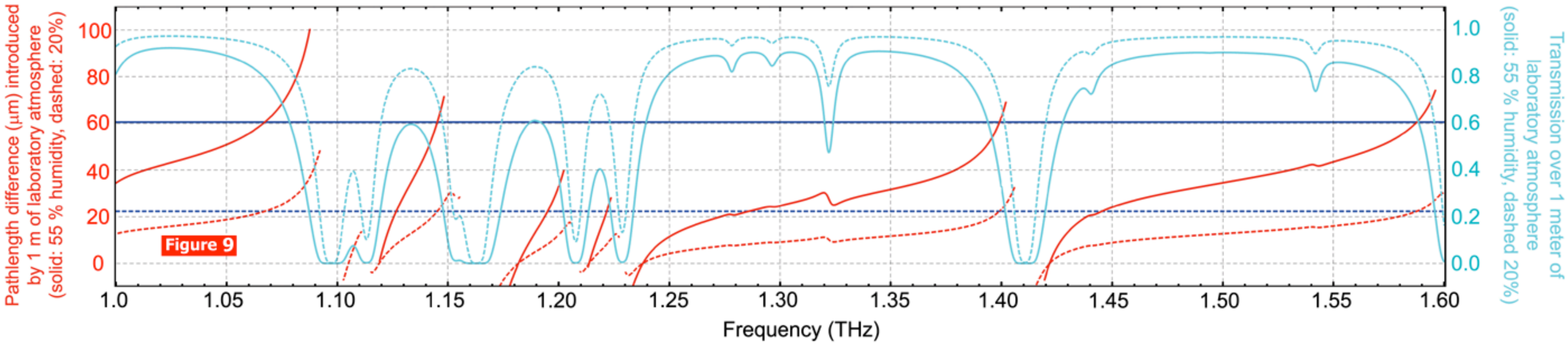
Phase fluctuations: Correction using 183 GHz water vapor radiometers

Observing Frequency: 230.5 GHz, PWV to phase conversion factor: 1.944 deg/μm



Time since the beginning of the observation (min) on Nov. 25, 2001

Atmosphere in the laboratory



Transmission over 1 meter of laboratory atmosphere (solid: 55% relative humidity, dashed: 20%)

Pathlength difference (in microns) introduced by 1 meter of laboratory atmosphere (solid: 55% rel. humidity, dashed: 20%)

ATM model is expected to be very accurate up to 3 THz, quite accurate up to 5 THz

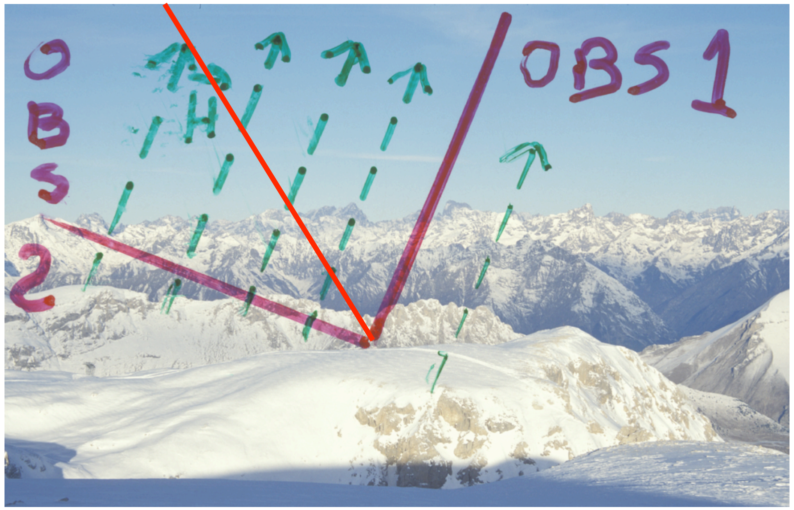
Polarization effects due to Zeeman splitting

$$\begin{bmatrix} N_0 \sin^2\phi + (N_+ + N_-)\cos^2\phi & -i(N_+ - N_-)\cos\phi \\ i(N_+ - N_-)\cos\phi & N_+ + N_- \end{bmatrix}$$

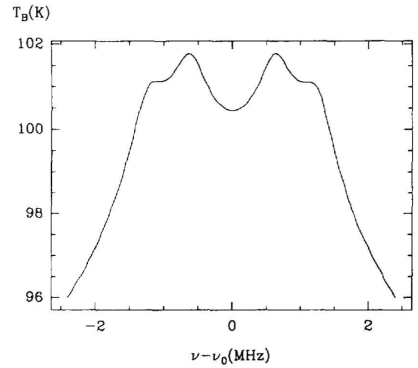
Nota: Sólo es válido en el caso que que la propagación se realice en un plano que contenga los dos polos magnéticos y nuestro lugar de observación.

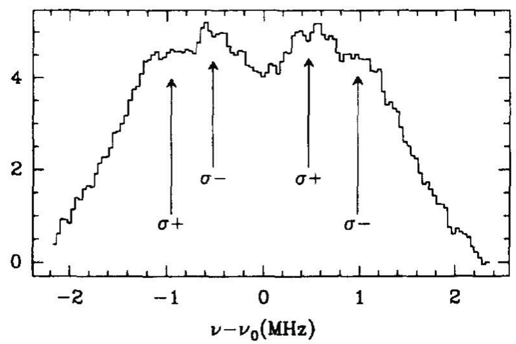
N0, N+, N-: Proporcionales a la intensidad total de la línea no perturbada, multiplicada por una fuerza relativa de línea de cada componente Zeeman y por una función de forma de línea normalizada.

Φ: Ángulo entre la dirección de propagación y el campo magnético.

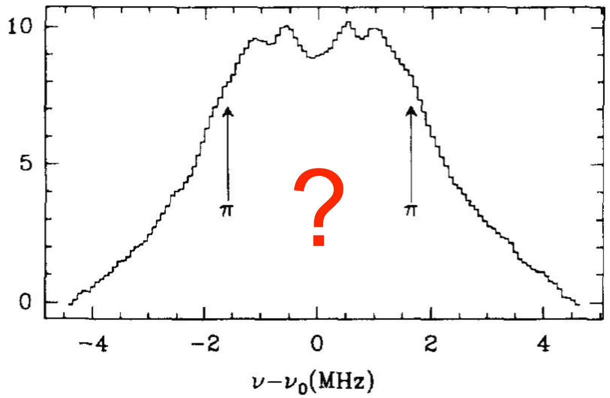


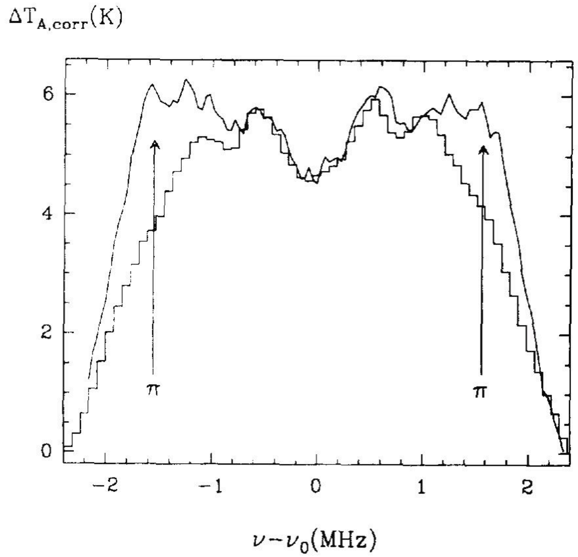
Φ=0



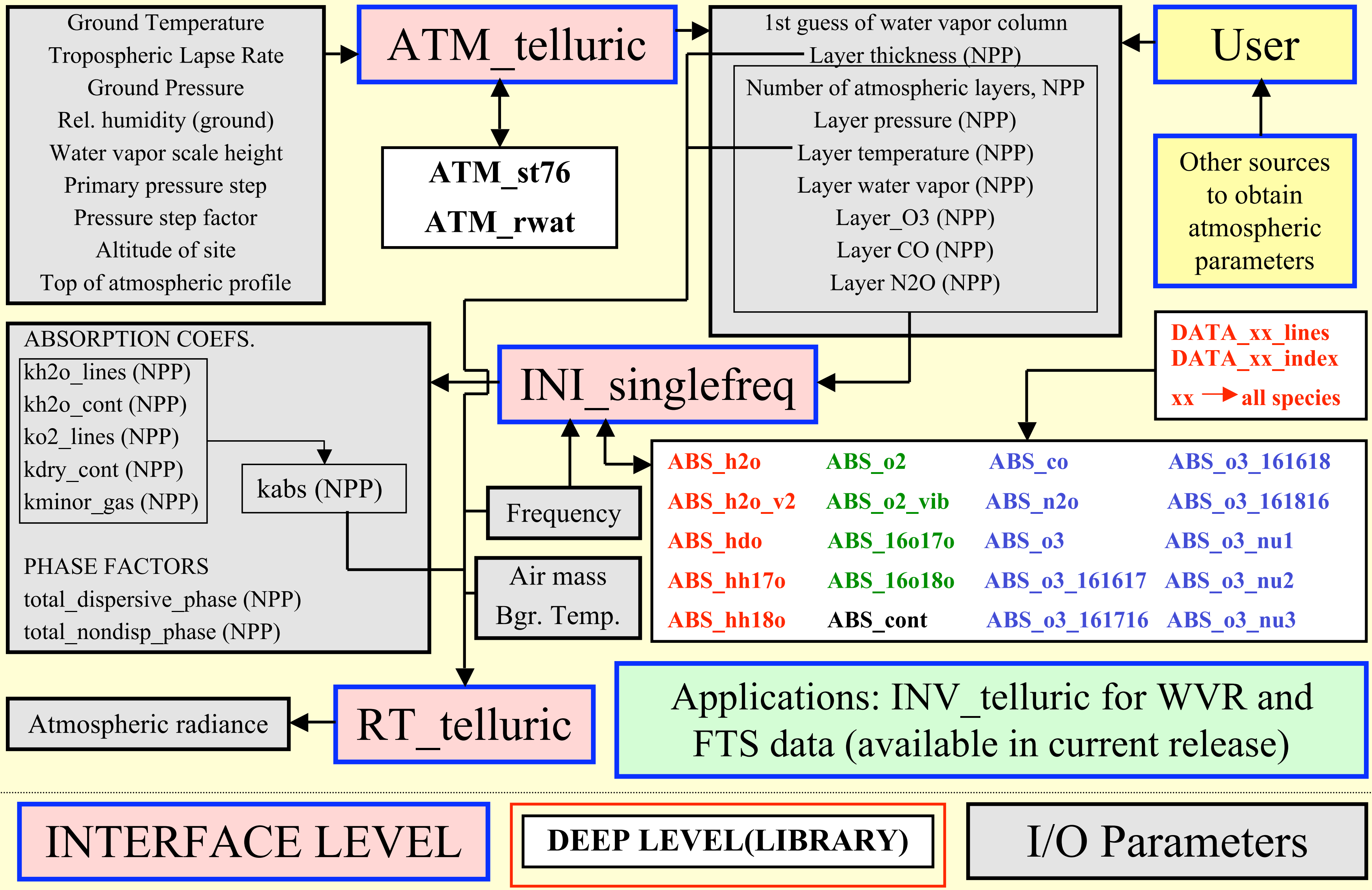


Φ=π/2



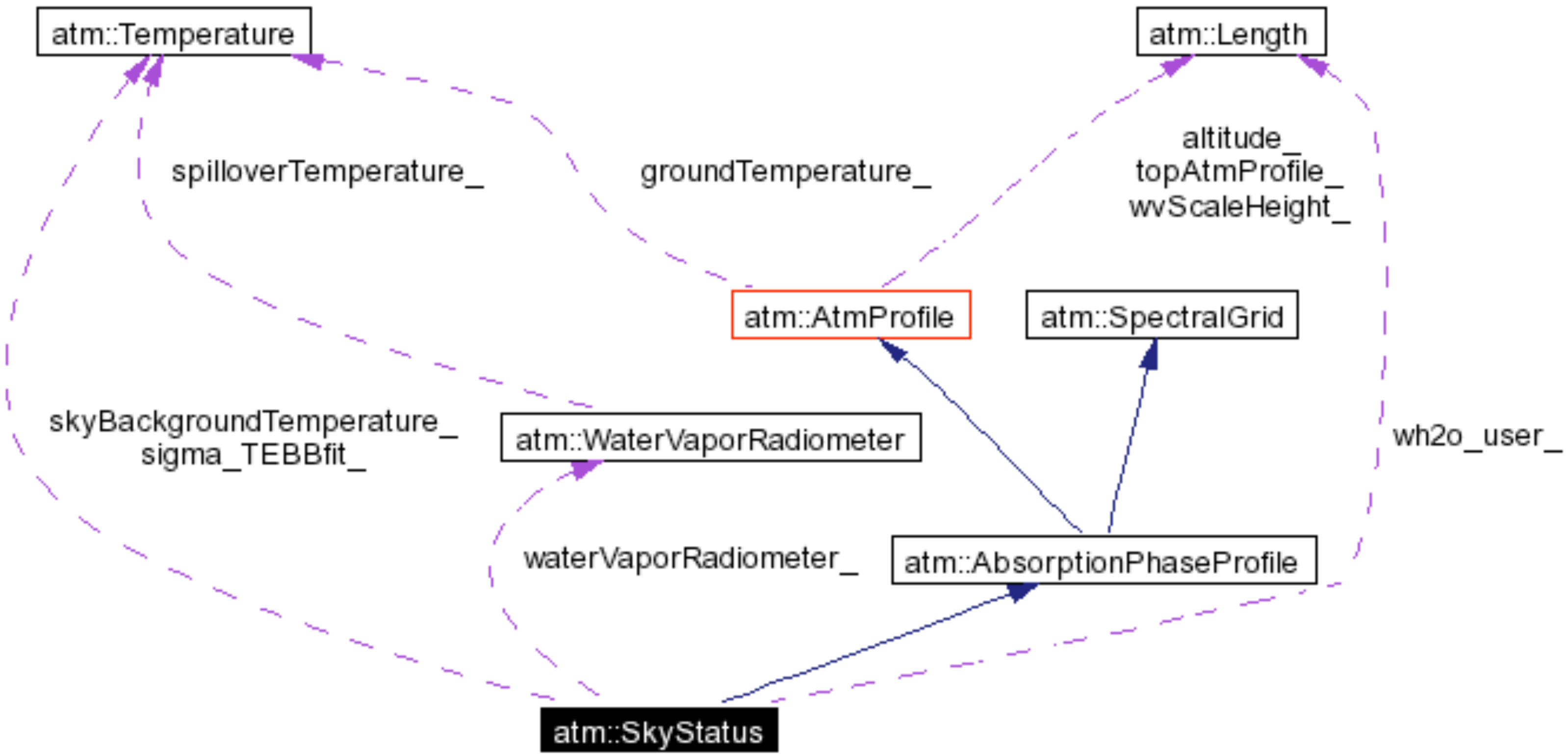


Old ATM fortran code



ALMA-ATM C++ structure:

Collaboration diagram between the most important classes



Class AtmProfile: Profiles of physical conditions & chemical abundances

Class AbsorptionPhaseProfile: Profiles of refractive index for an array of frequencies

Class WaterVaporRadiometer: WVR system in place for phase correction

Class SkyStatus: Relevant atmospheric information for antenna operations

Development of the Atmospheric Transmission at Microwaves model and related research

- 1985 IRAM Internal Report (J. Cernicharo)
- 80 's Implementation on IRAM instruments
- 1993 1st Extension of ATM: minor components
- 1995 Adaptation for remote sensing research
- 1996 Ph. D. disertation of J.R. Pardo
- 1996-7 Beginning of FTS work at the CSO
- 1998 Supra-THz windows measured
- 1999 Hydrometeors Abs. & Scattering included
- 2000 Dispersive phase included
- 2001 Publication of results on continuum terms (below 900 GHz)
- 2002 Beginning of work on array simulator and ALMA software
- 2003 ALMA-ATM library available. ATM software for APEX.
- 2004 Web page at http://damir.iem.csic.es
- 2004-2007 C++ Implementation for ALMA coplete
- Currently being used to produce transmission curves at DOME C from radiosounding data (see M. de Petris)