CSIC

ALMA SIMULATIONS
Workshop:
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ATMOSPHERIC EFFECTS OF RELEVANCE FOR ALMA

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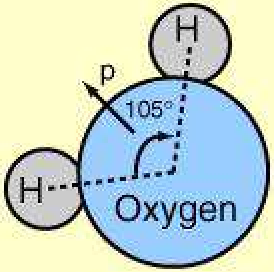
1. **Atmospheric mm/submm refractivity**
   a. **Imaginary Part (absorption spectrum)**
   b. **Real Part (Phase delay terms)**
   c. **Scattering by hydrometeors**
2. **The atmospheric problem for ALMA**
3. **ATM: Atmospheric RT model for ALMA**

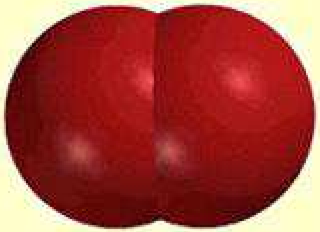
1. Atmospheric mm/submm Refractivity

1.0 + Gas-phase contribution + Hydrometeors contribution

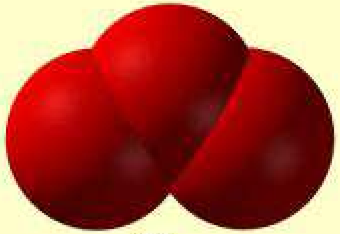
Lines



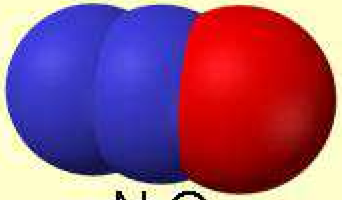
H_2O



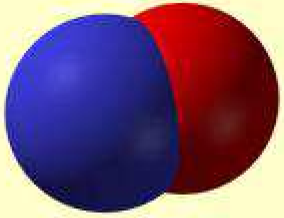
O_2



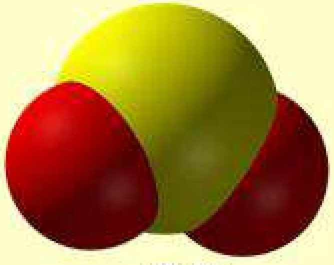
O_3



N_2O



NO



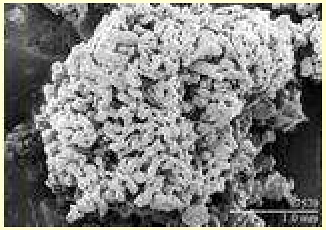
SO_2

snow

Liquid water

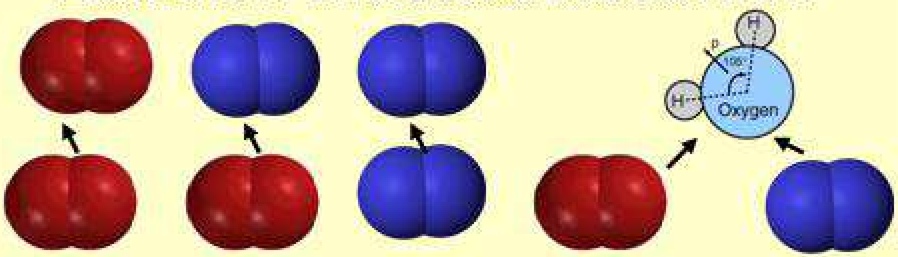
Hale

aerosols



Wet snow

Collision-induced absorption



1. Atmospheric mm/submm Refractivity

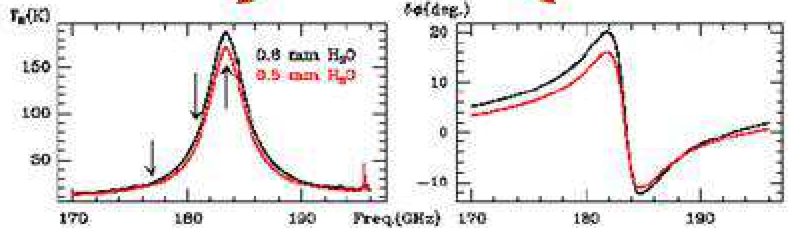
1.0 + Gas-phase contribution + Hydrometeros contribution

Impact approximation
$\tau_{\text{collision}} << 1 / \nu$
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

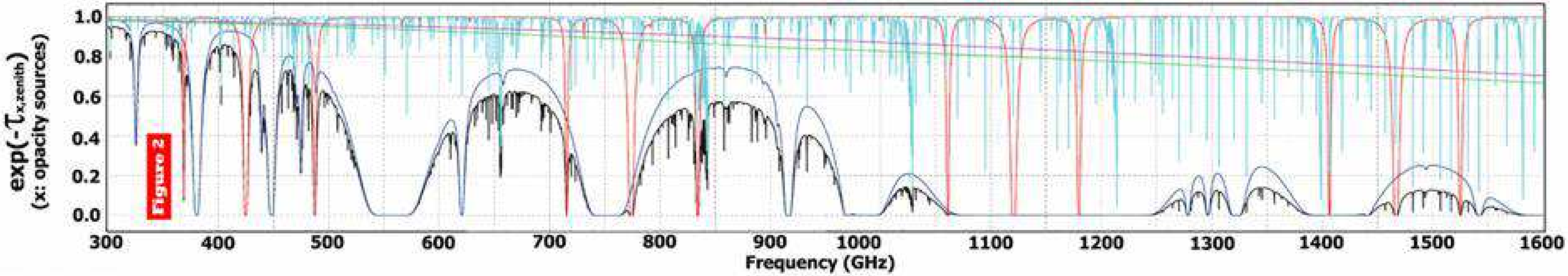
$$\mu \frac{d\mathbf{I}(z,\mu)}{dz} = \kappa(z,\mu)\mathbf{I}(z,\mu) - 2\pi \int_{-1}^{1} \mathbf{S}(z,\mu,\mu')\mathbf{I}(z,\mu')d\mu' - \epsilon(z,\mu)B[T(z)]$$

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

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

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

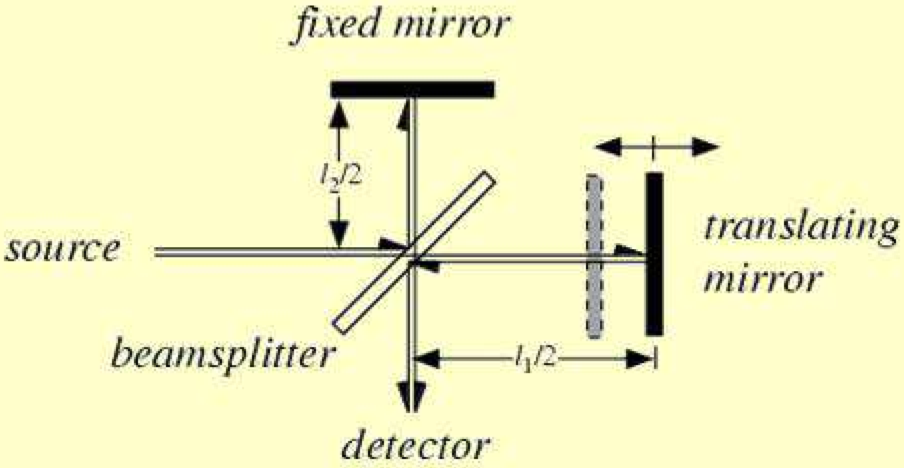
Chajnantor zenith transmission for 0.5 mm H2O / Water lines / Oxygen lines / ozone lines / H_2O-foreign / N_2-N_2 + N_2-O_2 + O_2-O_2



1a. Atmospheric absorption: 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)

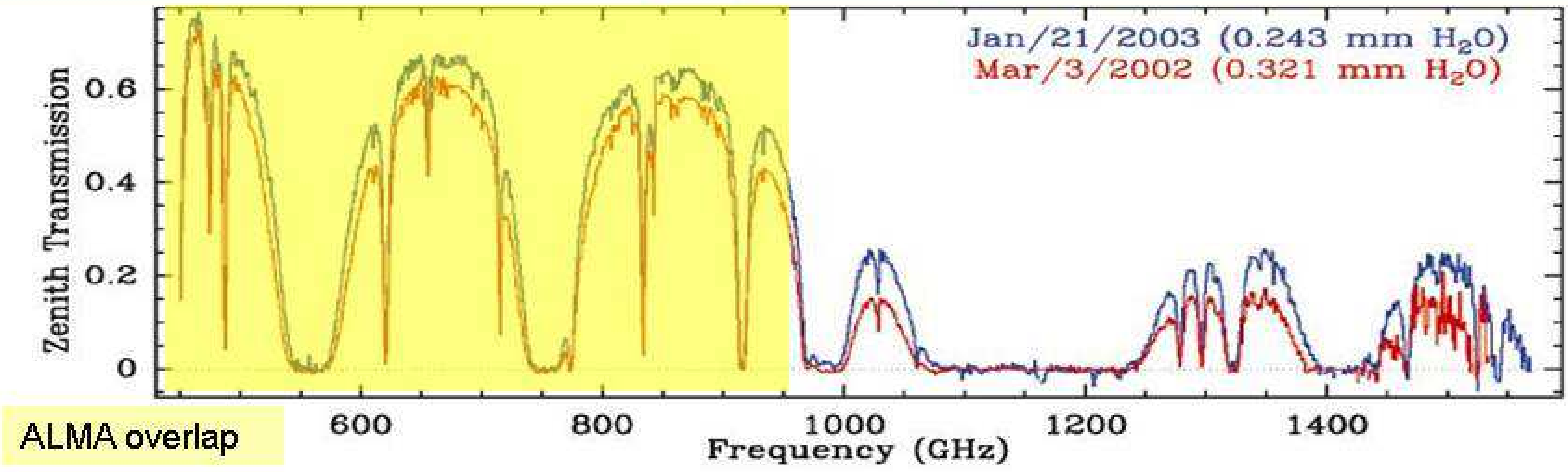


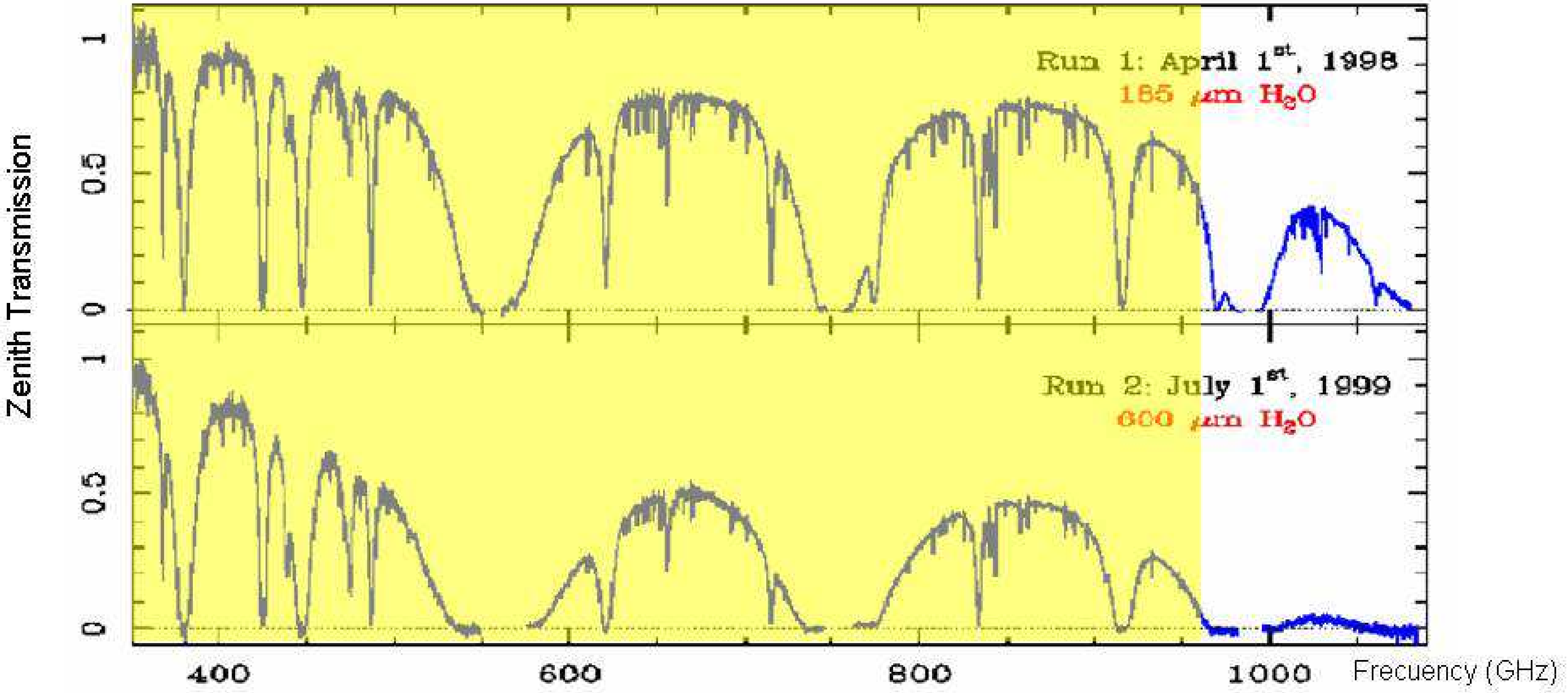
Schematics of FTS experiment

Characteristics of CSO-FTS

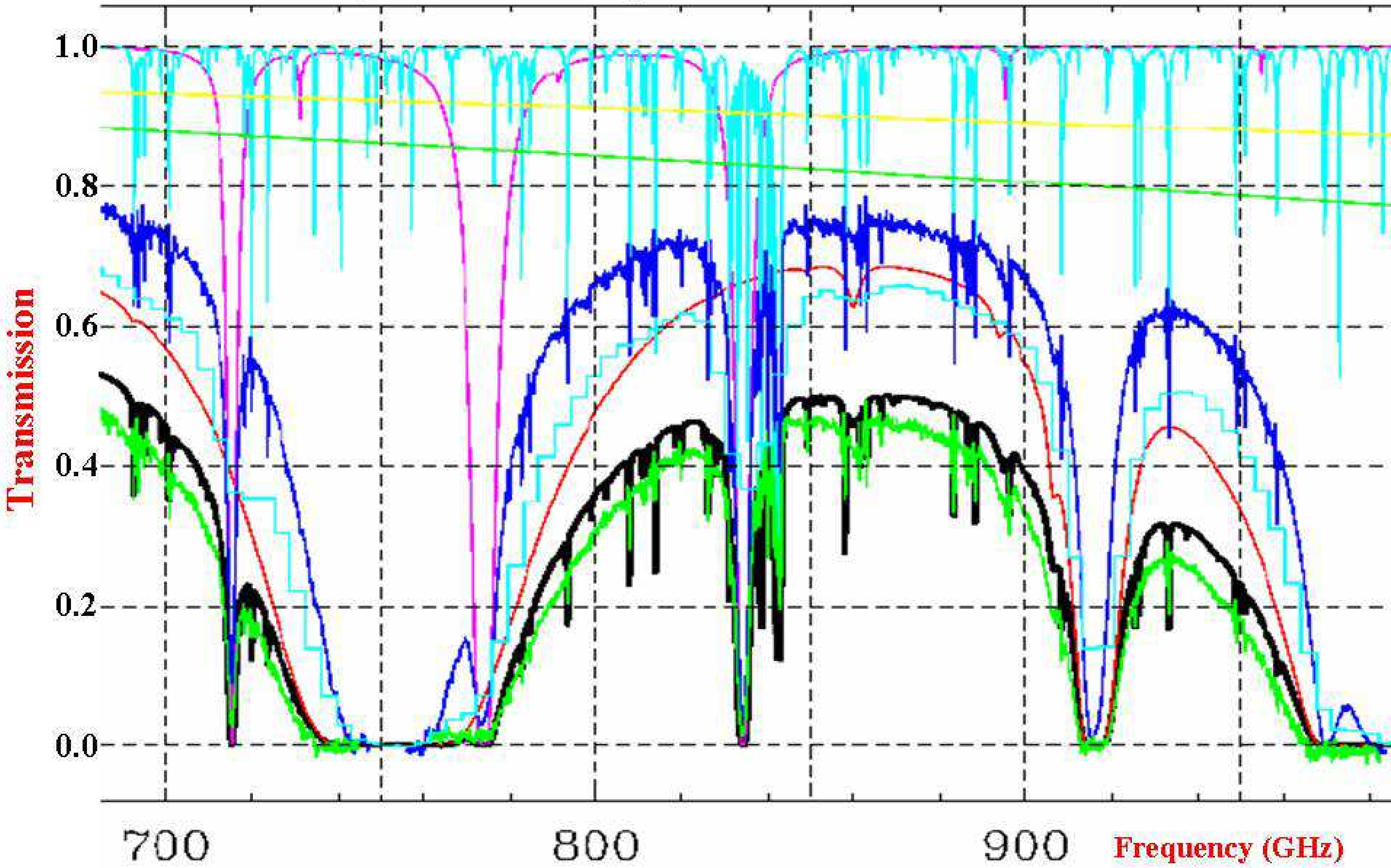
- Mounted on Cassegrain focus of telescope for dedicated obs. runs.
- Detector: ^{3}He cooled Bolometer
- Moving arm: 50 cm ~ 200 MHz resolution
- Filters: 7 different (165 to 1600 GHz)

CSO-FTS: Some of the best data sets, subsequently used to study the collision-induced non-resonant absorption

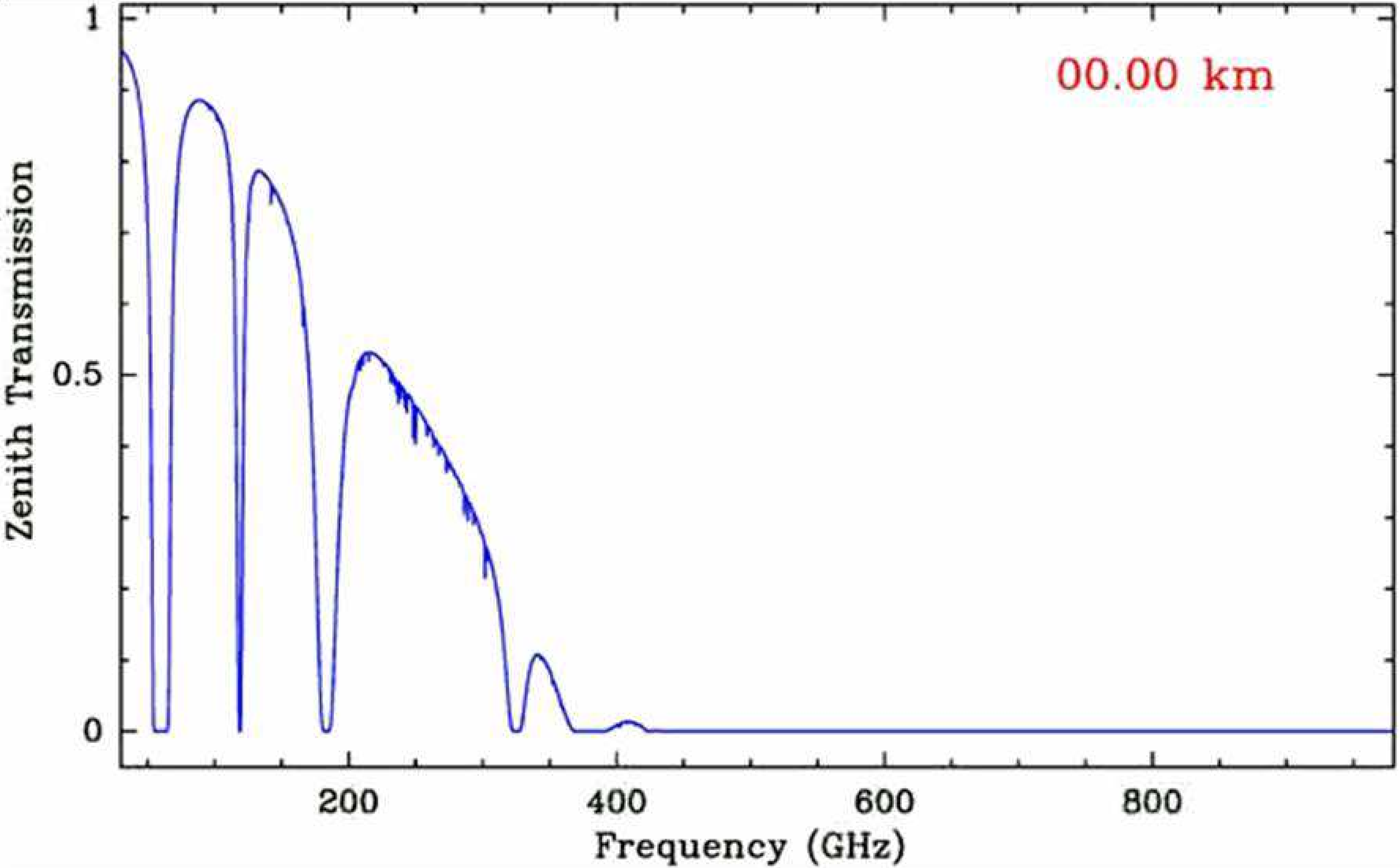




Example 2: Atmospheric transmission at high frequencies in dry Mauna Kea conditions



Model (0.5 mm H2O) **CSO data 3/98** **CSO data 7/99** **Atacama data 6/98**


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

1. Atmospheric mm/submm Refractivity

1.0 + Gas-phase contribution + Hydrometeros contribution

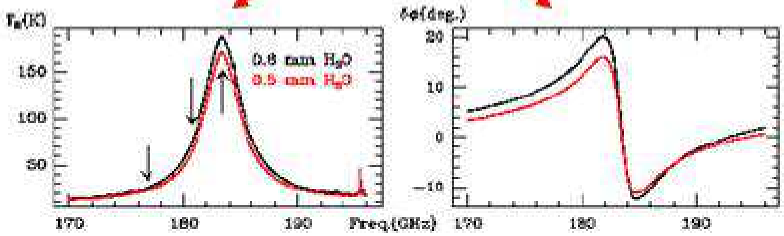
Impact approximation
$\tau_{\text{collision}} << 1 / \nu$
Van-Vleck-Weisskopf line profile

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

$$\left. + \frac{1 + i\delta}{\nu_{u\leftrightarrow l} + \nu + \Delta\nu}\right] \qquad (1)$$

1a. Imaginary Part (absorption)

1b. Real Part (phase delay)



1c. Scattering. Polarization must be included

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

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

K: 2x2 extinction matrix ε: emission vector

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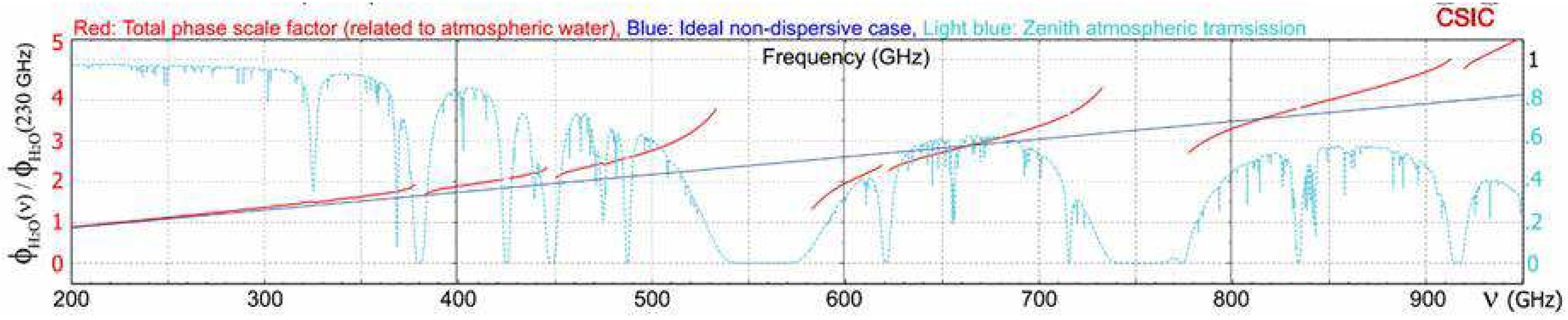
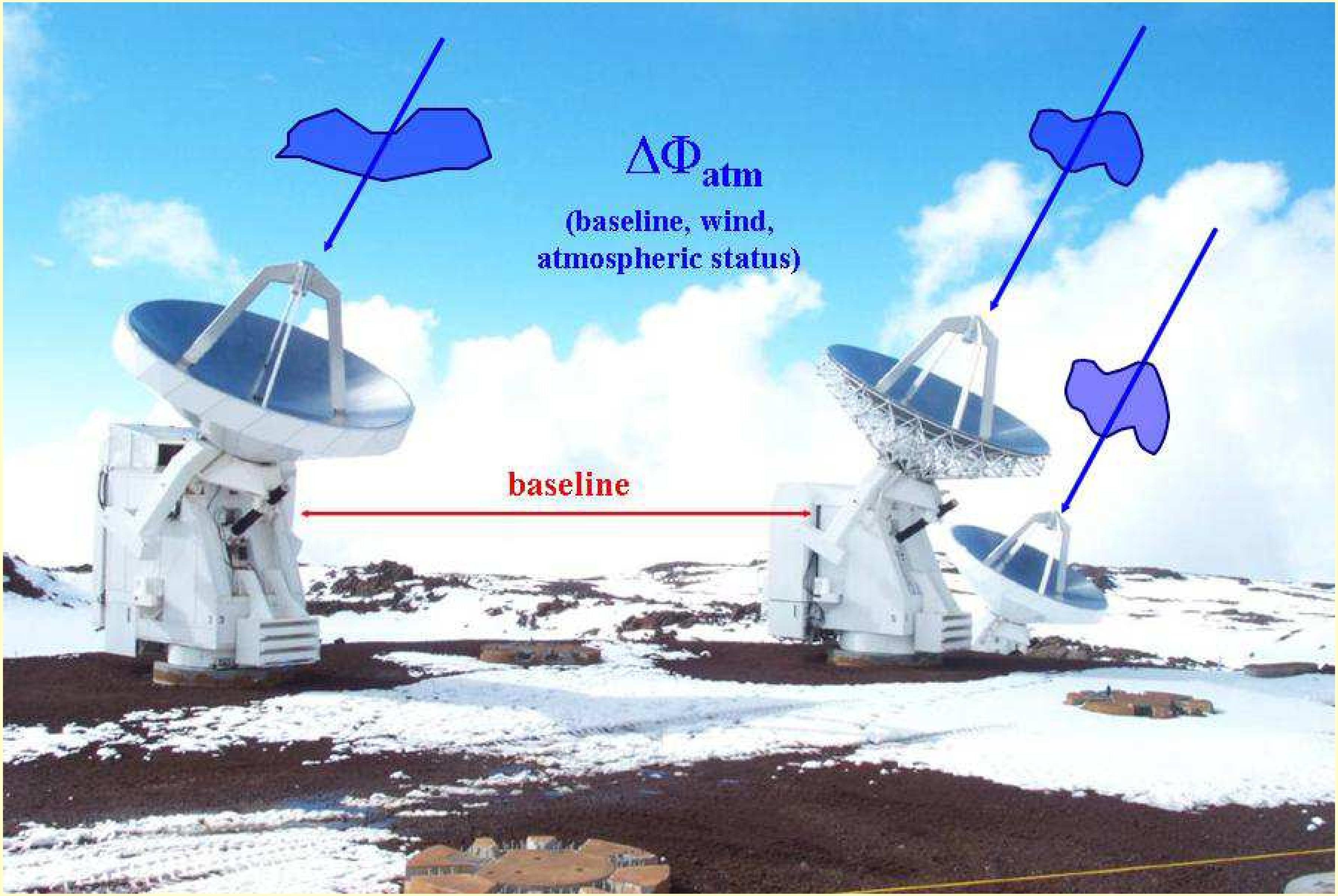


2. The atmospheric problem for ALMA



The ALMA Site

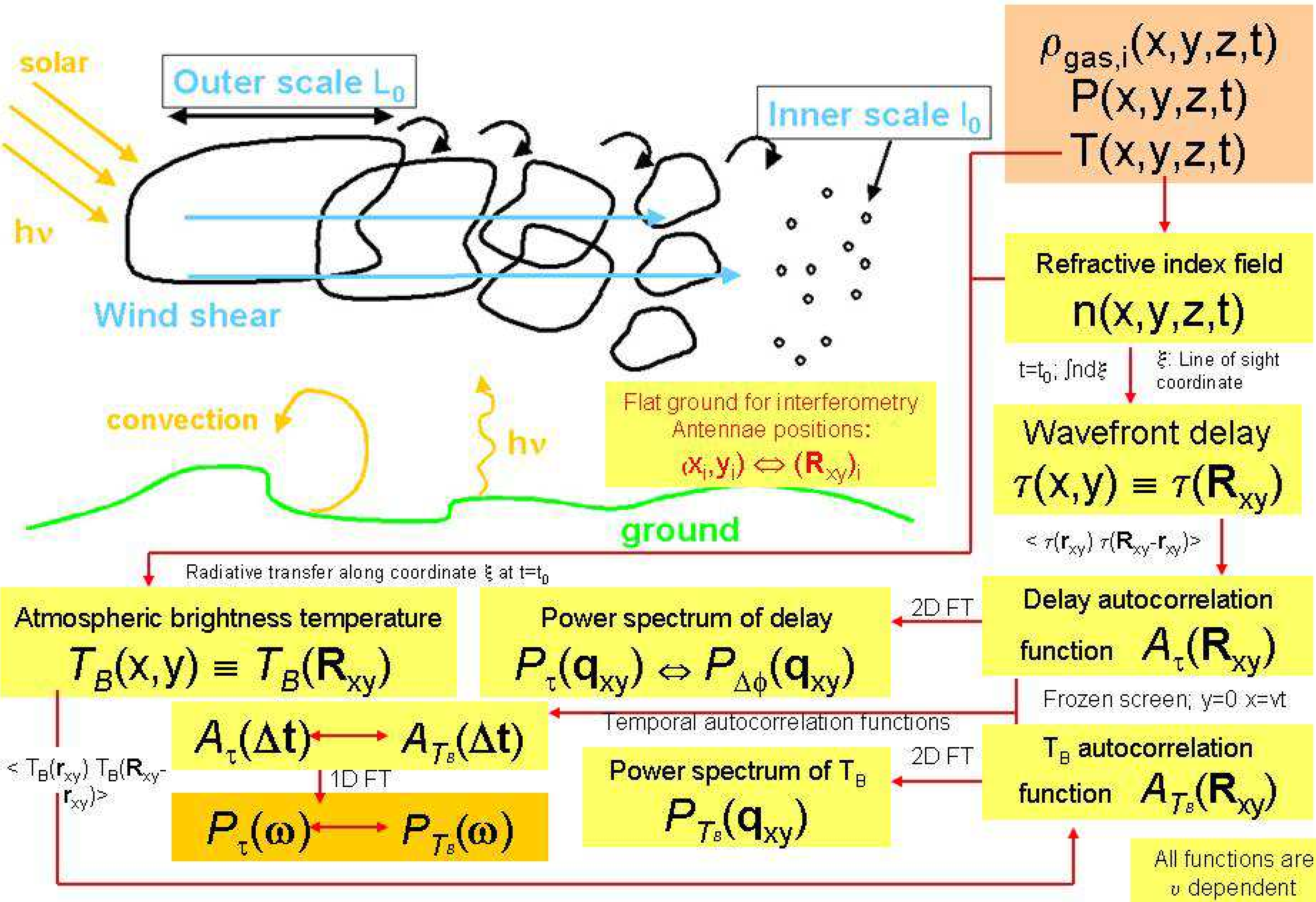
	10m	20m	30m	40m	50m
10	7.2	10.7	13.6	16.1	18.3
20	10.2	15.4	19.6	23.3	26.6
30	13.6	20.7	26.5	31.6	36.1
40	17.9	27.4	35.1	41.9	48.0
50	23.7	36.4	46.7	55.7	64.0
60	31.7	48.7	62.5	74.6	85.6
70	43.7	66.7	85.3	101.6	117.0
80	63.6	95.4	120.9	143.0	162.9
90	108.6	154.2	190.6	221.3	248.2

Pathlength error (microns) estimates due to tropospheric PWV fluctuations. Estimated extrapolating the SSF measured on site with the STI data at 300m and 11GHz. Computed at 60 degrees ELV.

In red, conditions that cause 10% decorrelation at 950 GHz (2% at 345GHz)

In blue, conditions that cause 10% decorrelation at 345 GHz

Atmospheric water vapor fluctuations



Flat ground for interferometry
Antennae positions:
$(x_i,y_i) \Leftrightarrow (\mathbf{R}_{xy})_i$

$\rho_{gas,i}(x,y,z,t)$
$P(x,y,z,t)$
$T(x,y,z,t)$

Refractive index field
$n(x,y,z,t)$

$t=t_0$; $\int n d\xi$
ξ: Line of sight coordinate

Wavefront delay
$\tau(x,y) \equiv \tau(\mathbf{R}_{xy})$

$< \tau(\mathbf{r}_{xy})\, \tau(\mathbf{R}_{xy}-\mathbf{r}_{xy}) >$

Delay autocorrelation function $A_\tau(\mathbf{R}_{xy})$

2D FT

Power spectrum of delay
$P_\tau(\mathbf{q}_{xy}) \Leftrightarrow P_{\Delta\phi}(\mathbf{q}_{xy})$

Frozen screen; y=0 x=vt

Temporal autocorrelation functions

$A_\tau(\Delta t) \leftrightarrow A_{T_B}(\Delta t)$

1D FT

$P_\tau(\omega) \leftrightarrow P_{T_B}(\omega)$

Radiative transfer along coordinate ξ at $t=t_0$

Atmospheric brightness temperature
$T_B(x,y) \equiv T_B(\mathbf{R}_{xy})$

$< T_B(\mathbf{r}_{xy})\, T_B(\mathbf{R}_{xy}-\mathbf{r}_{xy}) >$

T_B autocorrelation function $A_{T_B}(\mathbf{R}_{xy})$

2D FT

Power spectrum of T_B
$P_{T_B}(\mathbf{q}_{xy})$

All functions are ν dependent

Example of atmospheric water vapor field: Kolmogorov Screen

With one antenna we can measure $\Delta T_B(t)$, from which we obtain: $<\Delta T_B(t')\ \Delta T_B(t-t')>$

$$\downarrow$$

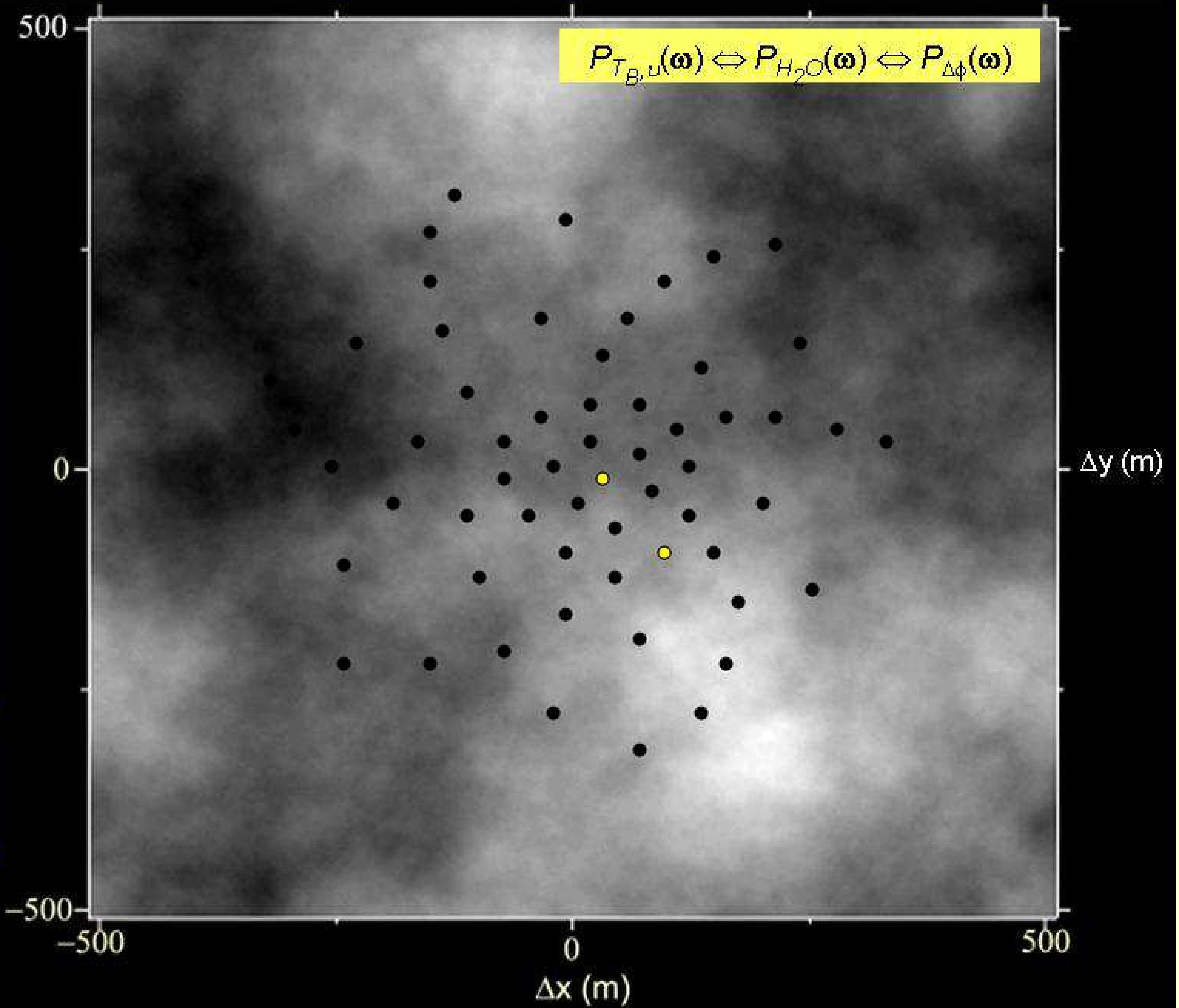
$$P_{T_B,\upsilon}(\omega)$$

Chose υ very sensitive to H_2O so that we track

$$P_{H_2O}(\omega)$$

With two antennas:

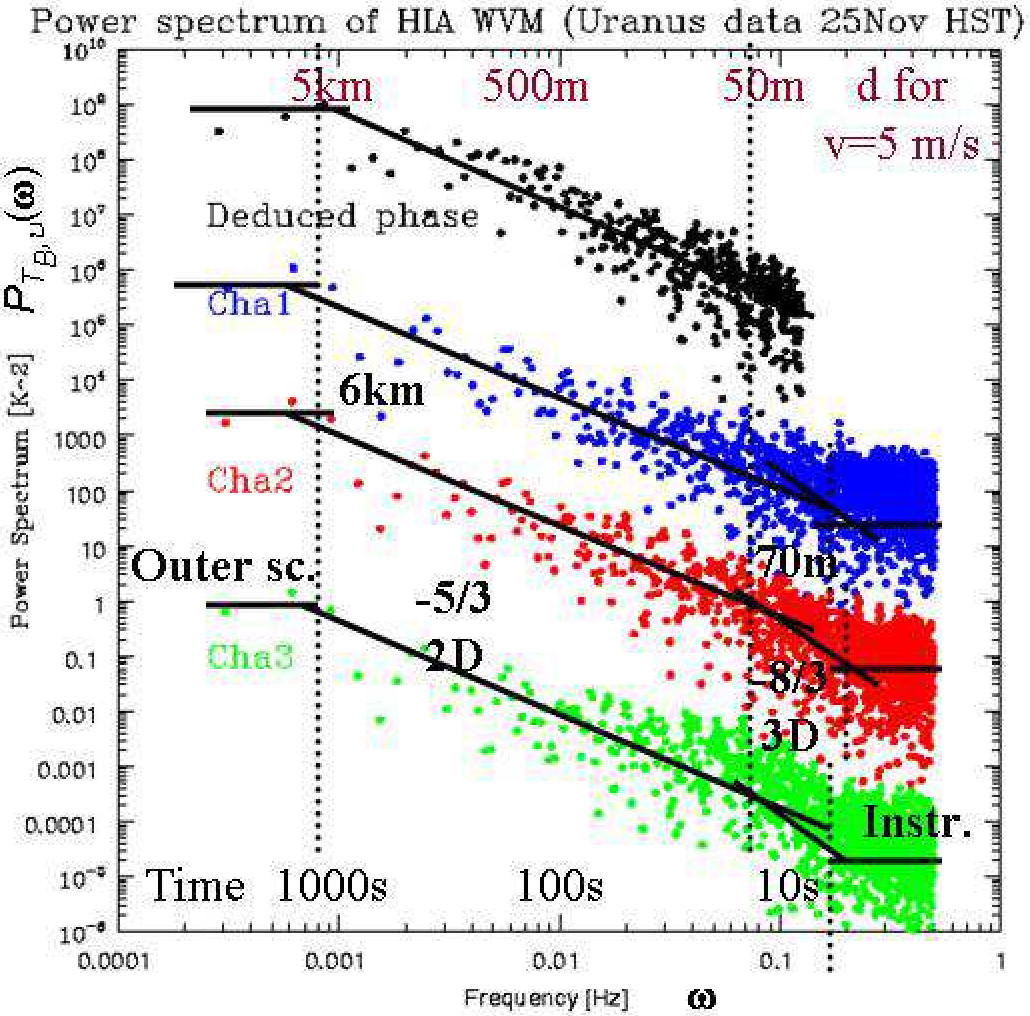
$P_{\Delta\phi}(\omega)$ at υ_{astro}

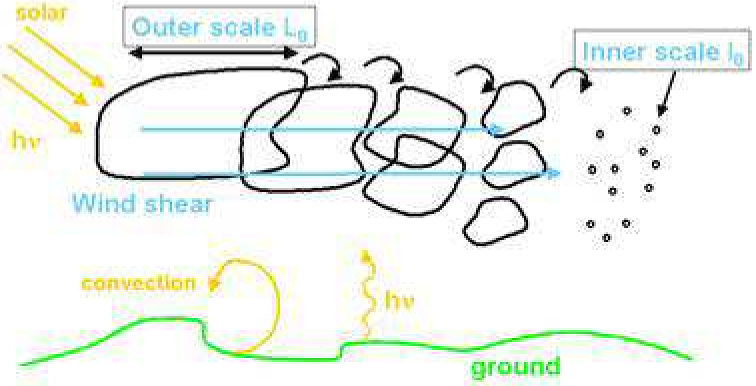


$$P_{T_B,\upsilon}(\omega) \Leftrightarrow P_{H_2O}(\omega) \Leftrightarrow P_{\Delta\phi}(\omega)$$

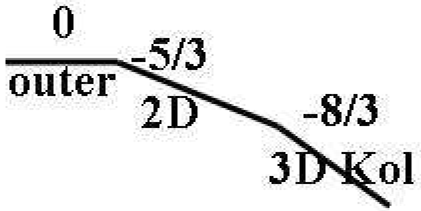
Temporal Power Spectra: $P_X(\omega)$

The slope infoms on the scale of phenomena





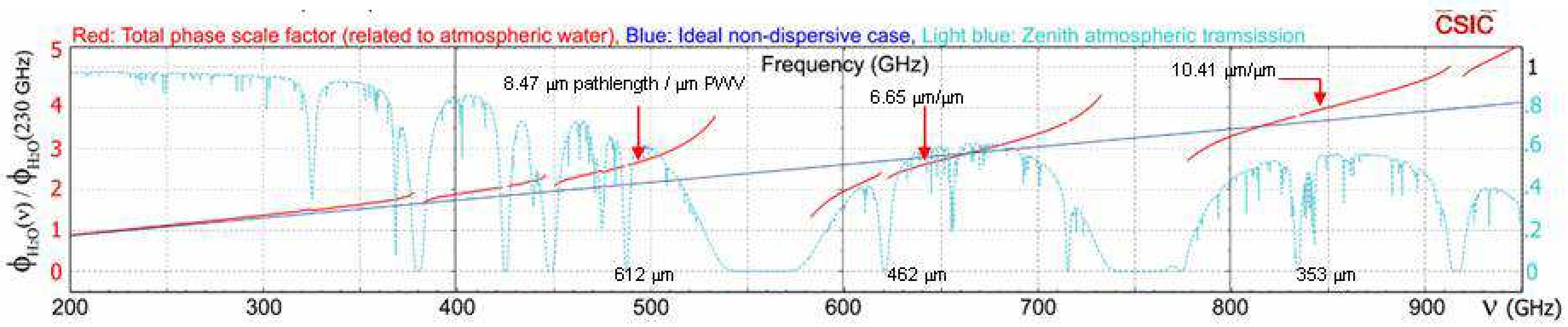
$P_{T_B,\upsilon}(\omega)$ measured on
Nov/25/2001 at Mauna Kea
υ_1 = 183.31±7.8 GHz
υ_2 = 183.31±3.0 GHz
υ_3 = 183.31±1.3 GHz

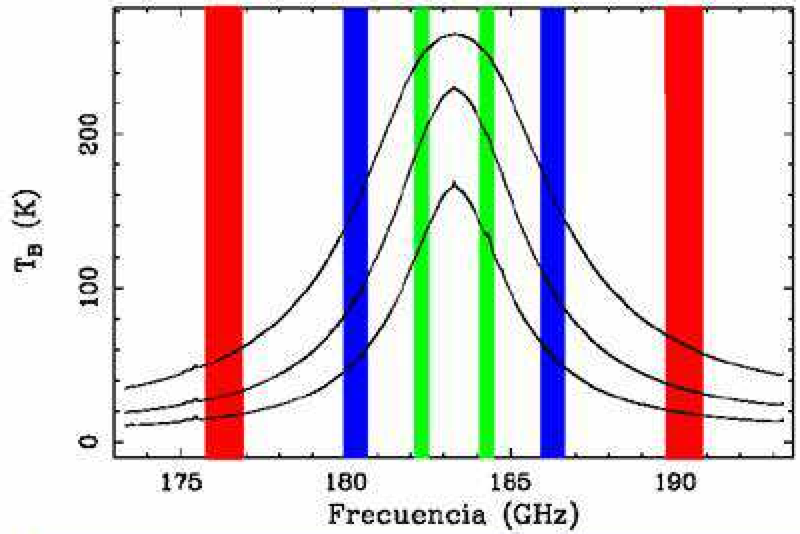


$P_{\Delta\phi}(\omega)$ measured on
Nov/25/2001 at Mauna Kea
at υ_{astro} = 230.5 GHz
Target source: Uranus
Base line: 48 m

$P_{T_B,\upsilon}(\omega) \Leftrightarrow P_{H_2O}(\omega) \Leftrightarrow P_{\Delta\phi}(\omega)$ OK / 70 m - 6 km : 2D Kolmogorov screen

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

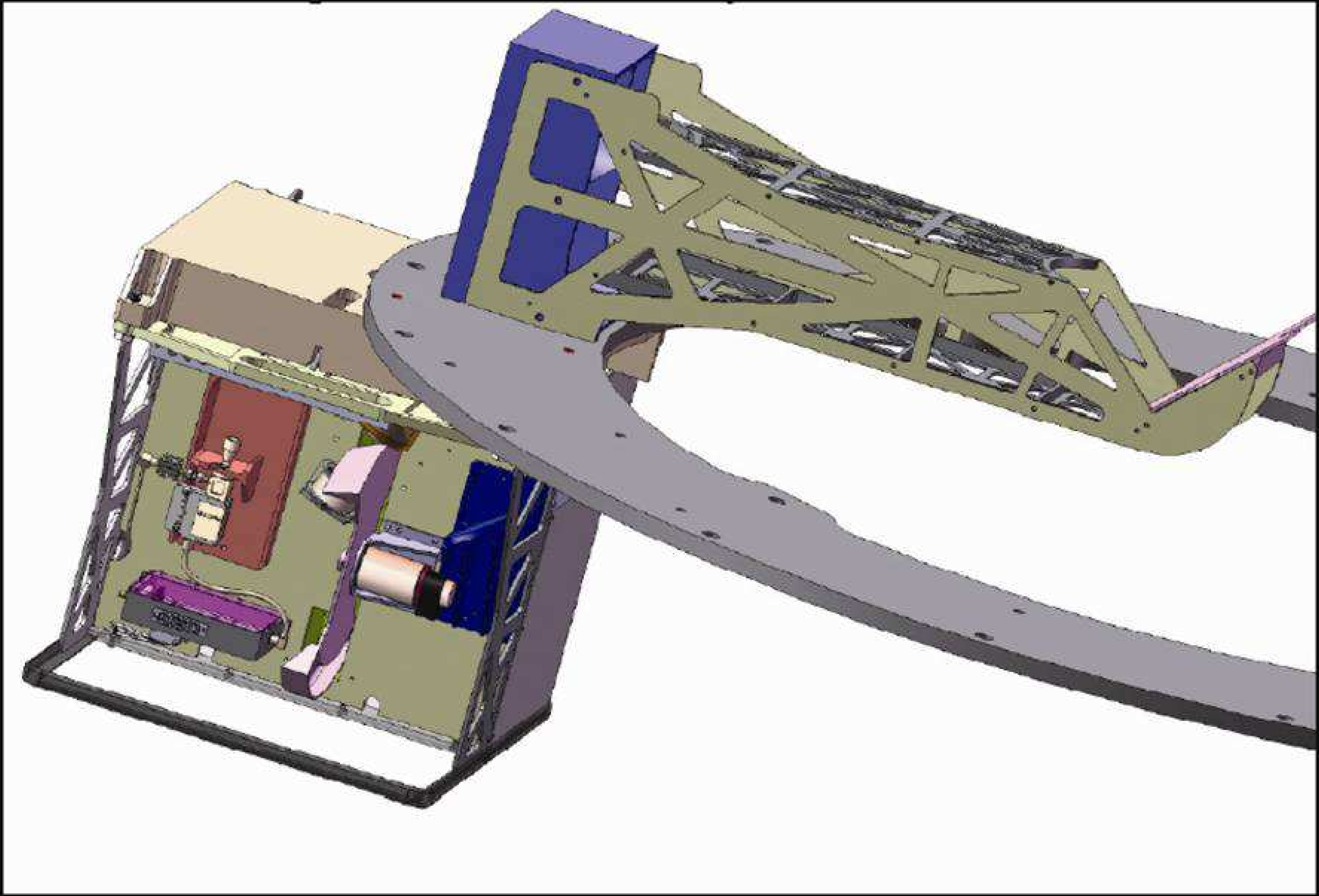
Assuming 0.4 K noise in 1 s in all three channels of the Water Vapor Radiometer

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.

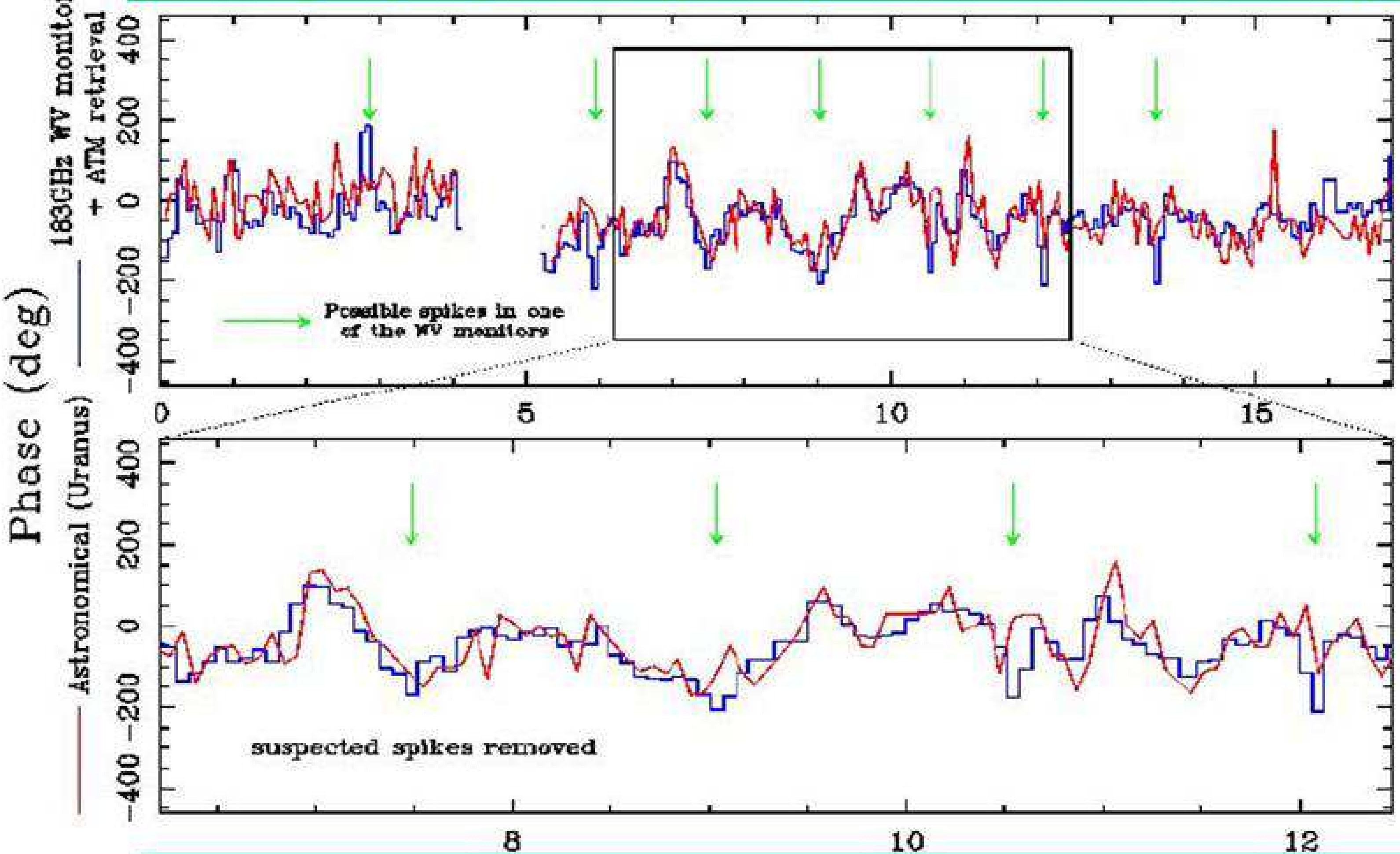
CURRENT PROTOTYPES ALREADY MEET THESE REQUIREMENTS

183 GHz WVR Design – in review



Phase fluctuations: Correction using 183 GHz water vapor radiometers

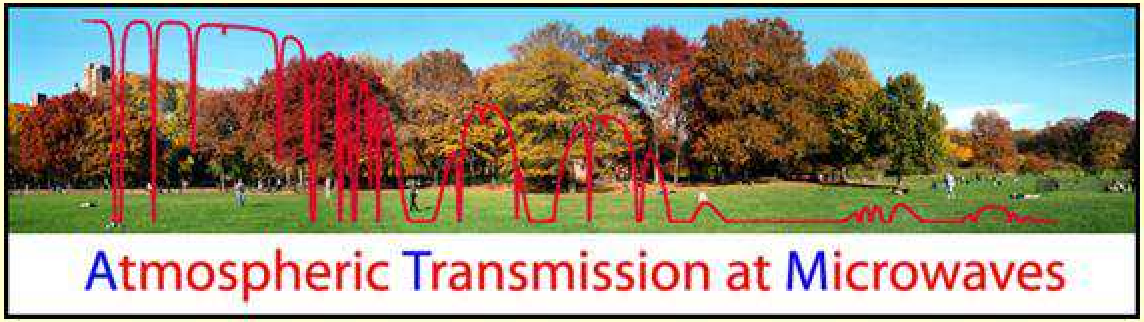
Observing Frequency: 230.5 GHz, PWV to phase conversion factor: 1.944 deg/μm



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

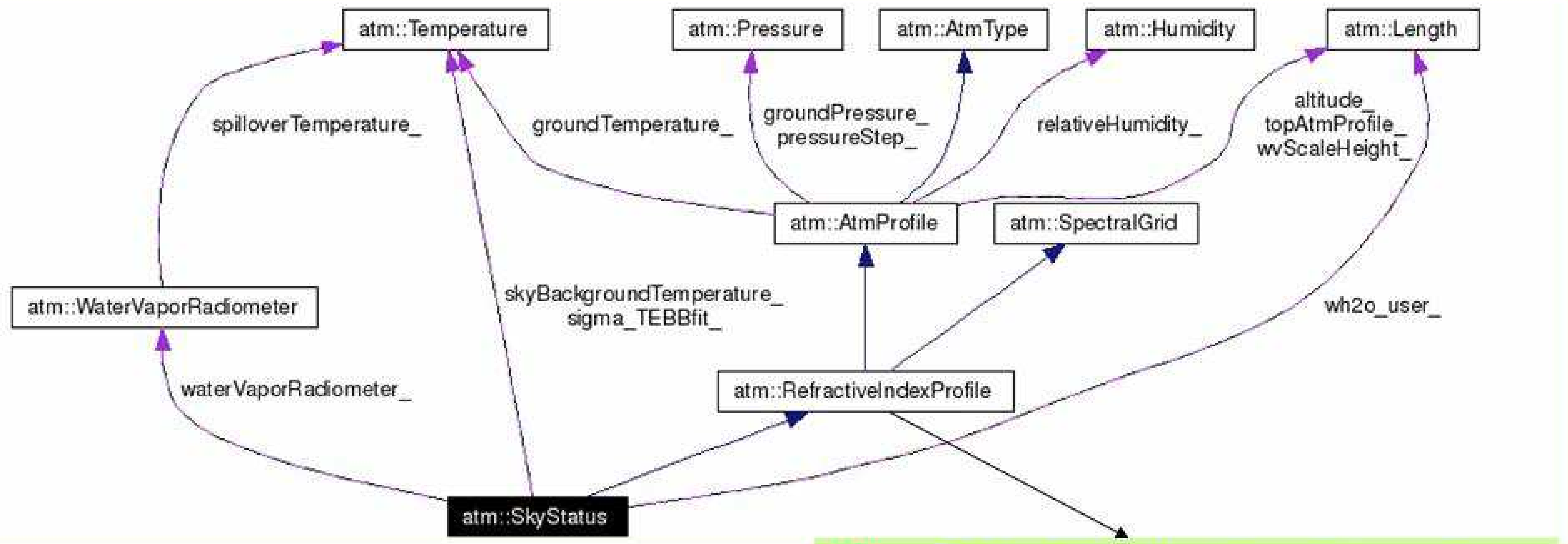
3. ATM: Atmospheric software for ALMA

- Starting point: Fortran code developed during 20 years.
- Contract with ESO to develop ATM for alma.
  - Fortran library created to encapsulate "fundamental" physics of the problem now fully translated into a C++ class.
  - C++ interface developed specifically for ALMA needs.
  - Updated via CVS (located in the TelCal subsystem)
  - Doxygen documented.
  - Test examples provided using real FTS and WVR data.
  - Work done within the TelCal working group.



ALMA-ATM C++ structure:

Collaboration diagram between the most important classes



Class RefractiveIndex Core of the software

Class AtmProfile: Profiles of physical conditions & chemical abundances

Class RefractiveIndexProfile: 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