Lecture:

CALIBRATION OF MM AND SUBMM OBSERVATIONS: ATMOSPHERIC EFFECTS

INAOE

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Gobierno de España
Ministerio de Economía y Competitividad

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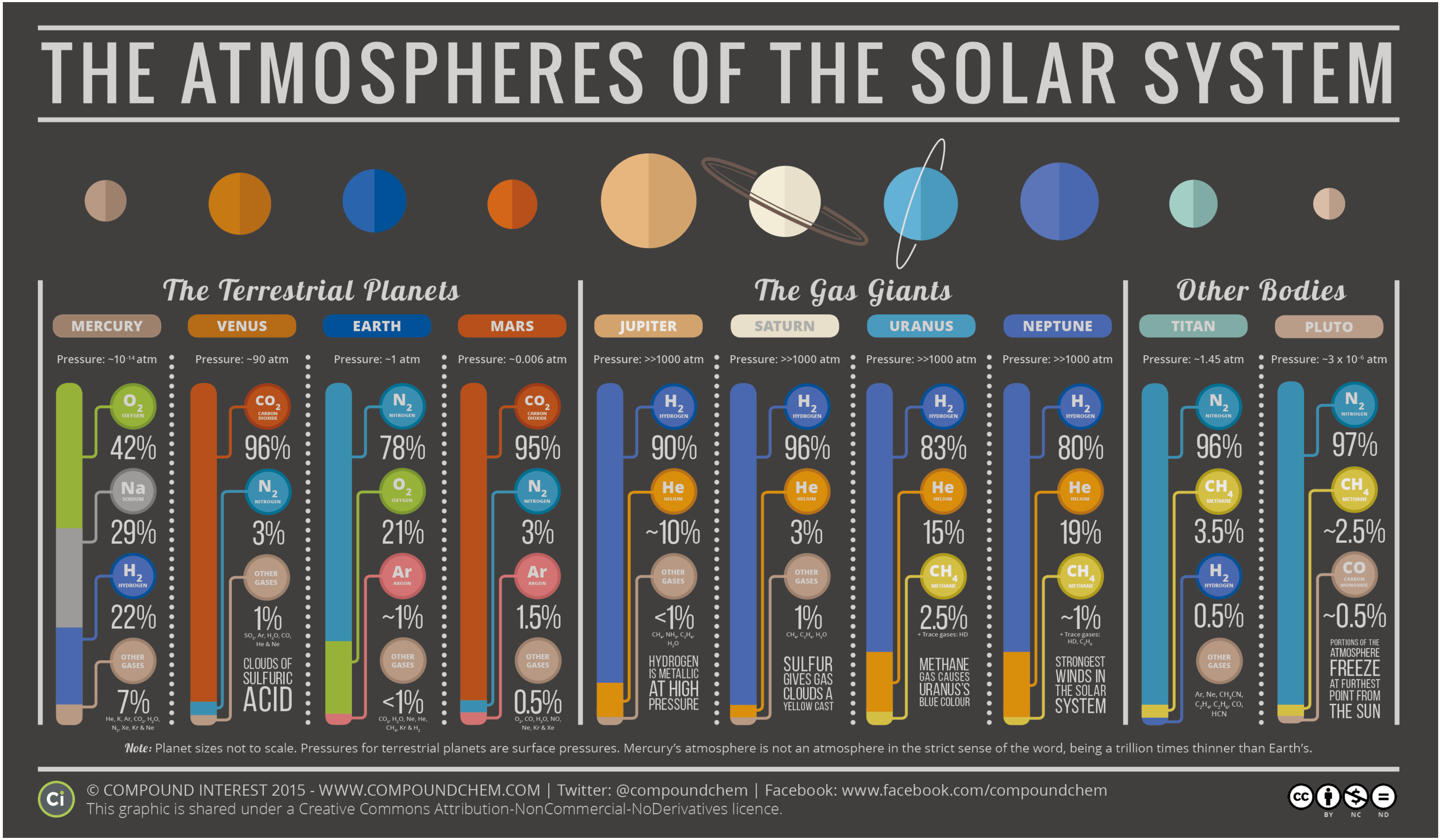
OUTLINE:

- *The Earth's atmosphere: absorption and scattering of EM radiation*
- *The millimeter wavelength range*
- *Curves of atmospheric transmission*
- *Observational strategies*
- *Calibration (atmospheric): single-dish observations*
- *ATM: atmospheric transmission model*
- *Radiometers*
- *Calibration (atmospheric): interferometry*

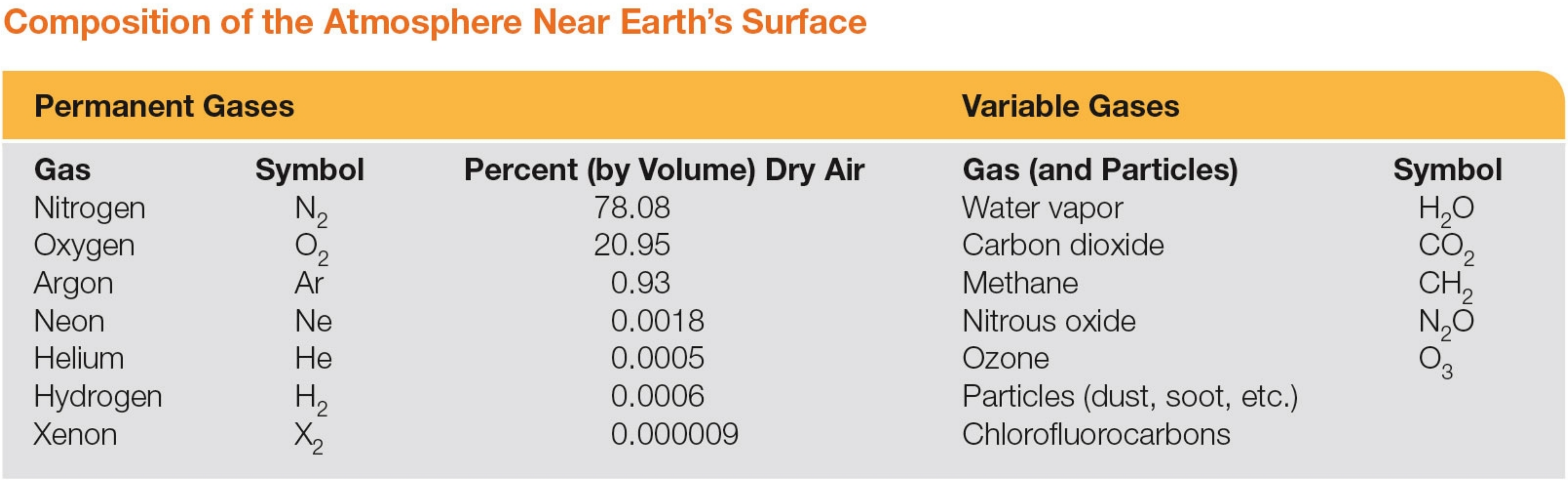
Earth's atmosphere: Solar system

- Solar system atmospheres:



Note: Planet sizes not to scale. Pressures for terrestrial planets are surface pressures. Mercury's atmosphere is not an atmosphere in the strict sense of the word, being a trillion times thinner than Earth's.

Earth's atmosphere: composition



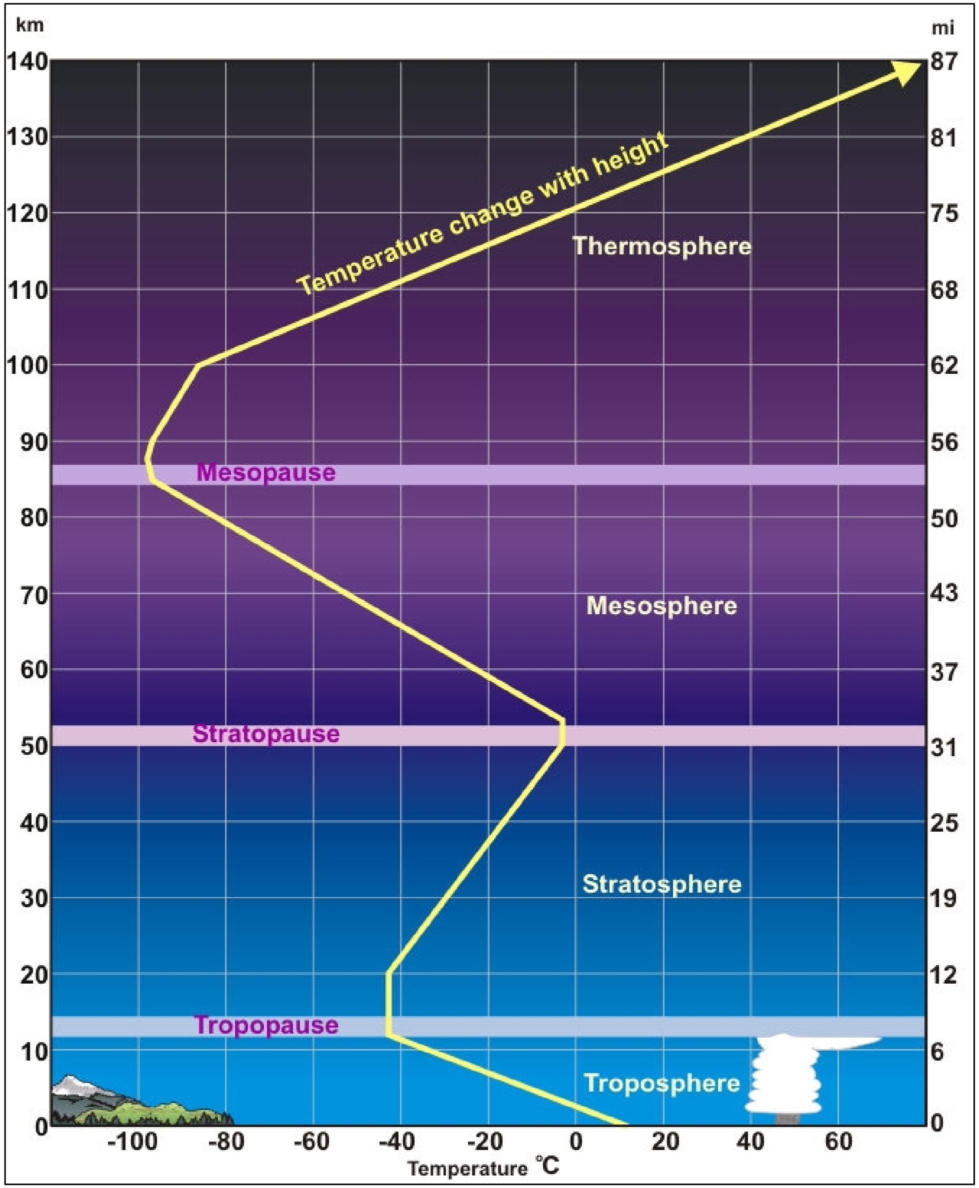
Composition of the Atmosphere Near Earth's Surface

Permanent Gases			Variable Gases	
Gas	**Symbol**	**Percent (by Volume) Dry Air**	**Gas (and Particles)**	**Symbol**
Nitrogen	N_2	78.08	Water vapor	H_2O
Oxygen	O_2	20.95	Carbon dioxide	CO_2
Argon	Ar	0.93	Methane	CH_2
Neon	Ne	0.0018	Nitrous oxide	N_2O
Helium	He	0.0005	Ozone	O_3
Hydrogen	H_2	0.0006	Particles (dust, soot, etc.)	
Xenon	X_2	0.000009	Chlorofluorocarbons	

- Water vapor content will determine the feasibility of observations in the mm and submm range

Earth's atmosphere: structure

- Layers of the atmosphere:

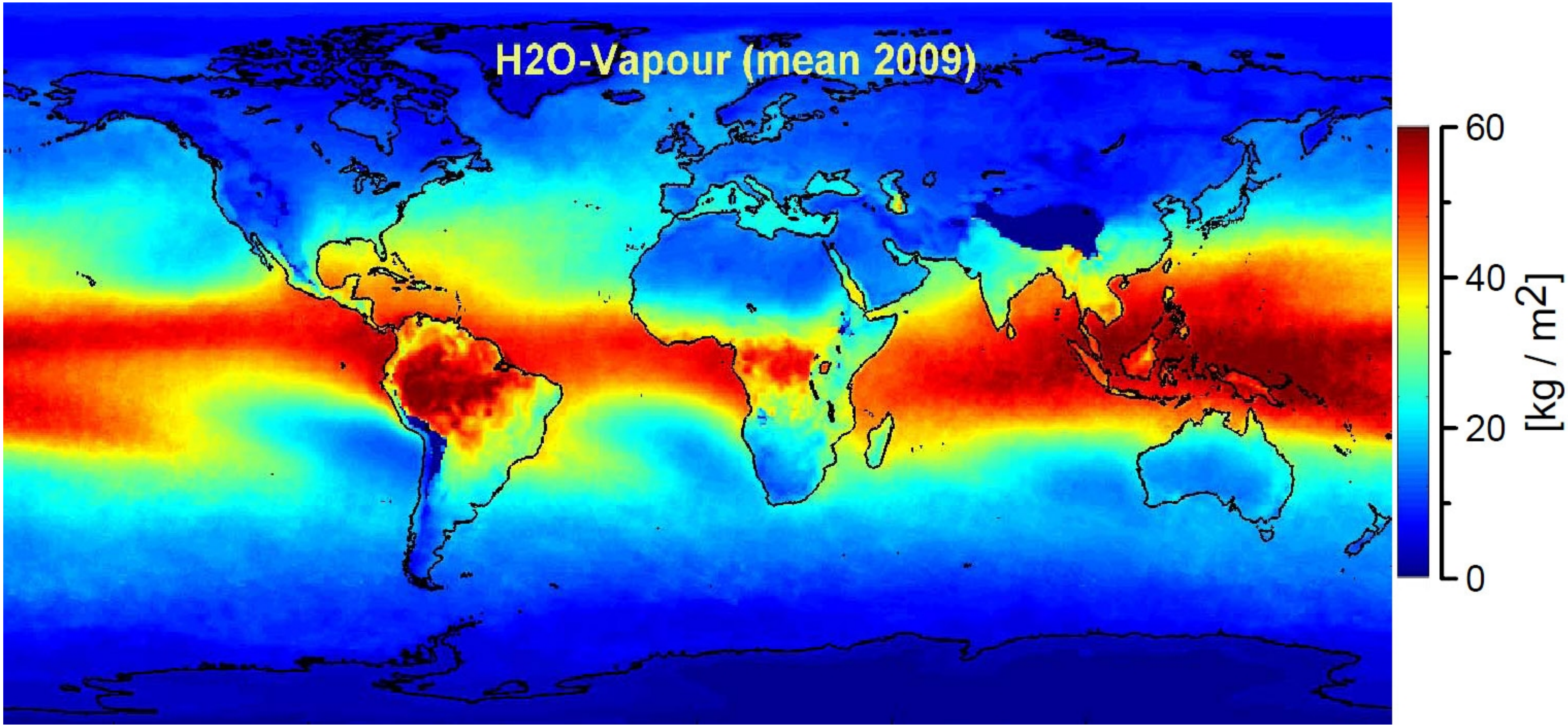


- 70-80% of the total mass of the atmosphere is contained in the troposphere

- Troposphere contains almost all atmospheric water vapor

Earth's atmosphere: water vapor

- *Water vapor:*



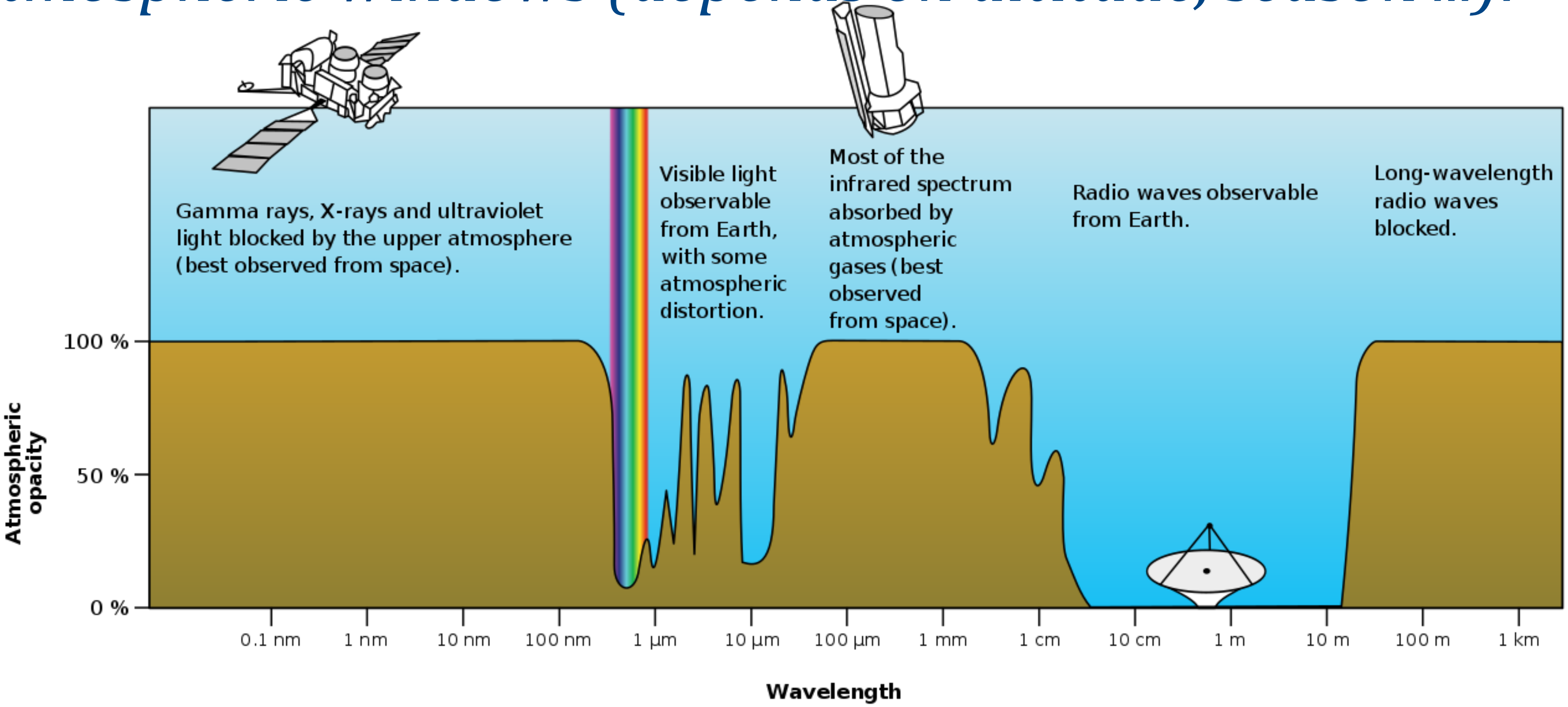
Water vapor content is variable (~1-5% by volume)

Earth's atmosphere: physical processes

- The atmosphere absorbs and transmits different wavelengths of EM radiation

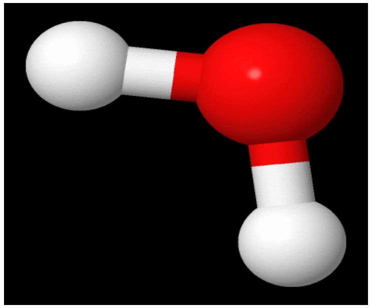
- The main physical processes involved are absorption and scattering

- Atmospheric windows (depends on altitude, season ...):

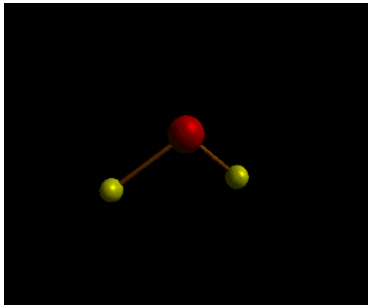


Earth's atmosphere: absorption process

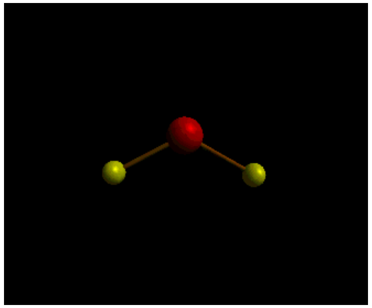
- *Molecules in the atmosphere absorb photons at certain wavelengths (electronic, rotational, vibrational, and ro-vibrational transitions + ionisation + dissociation)*



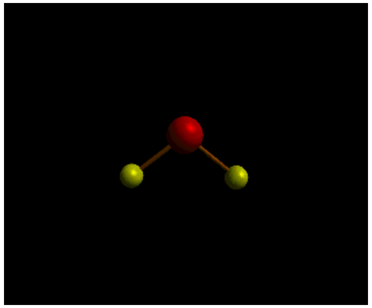
Rotation



Antisymmetric stretching



Bending



Symmetric stretching

And also overtones, combinations of modes …

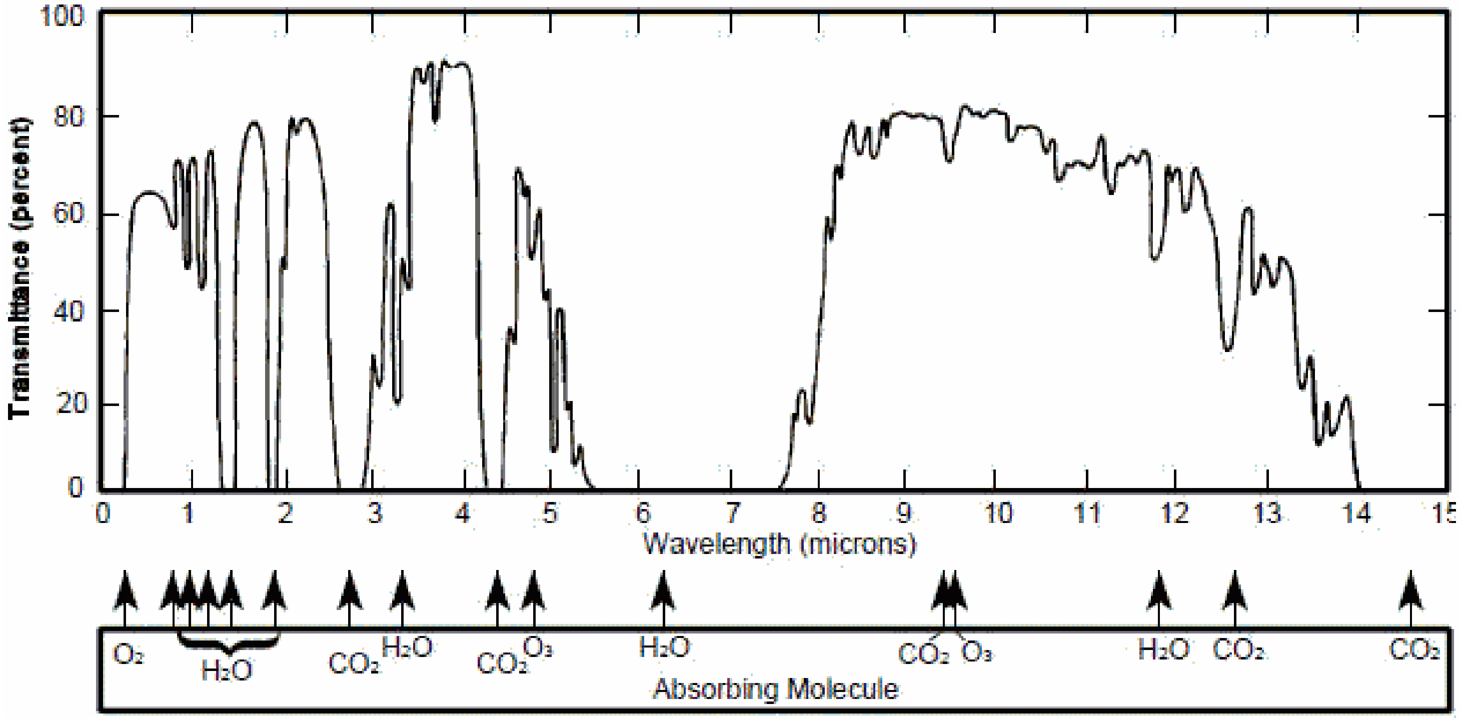
Rotation+vibration

<u>Most important absorbers:</u>
Water vapor: low abundance but it has electric dipolar transitions
Oxygen: high abundance but it has magnetic dipolar transitions

$$(EDT/MDT)_{strength} \sim [100\text{-}1000]$$

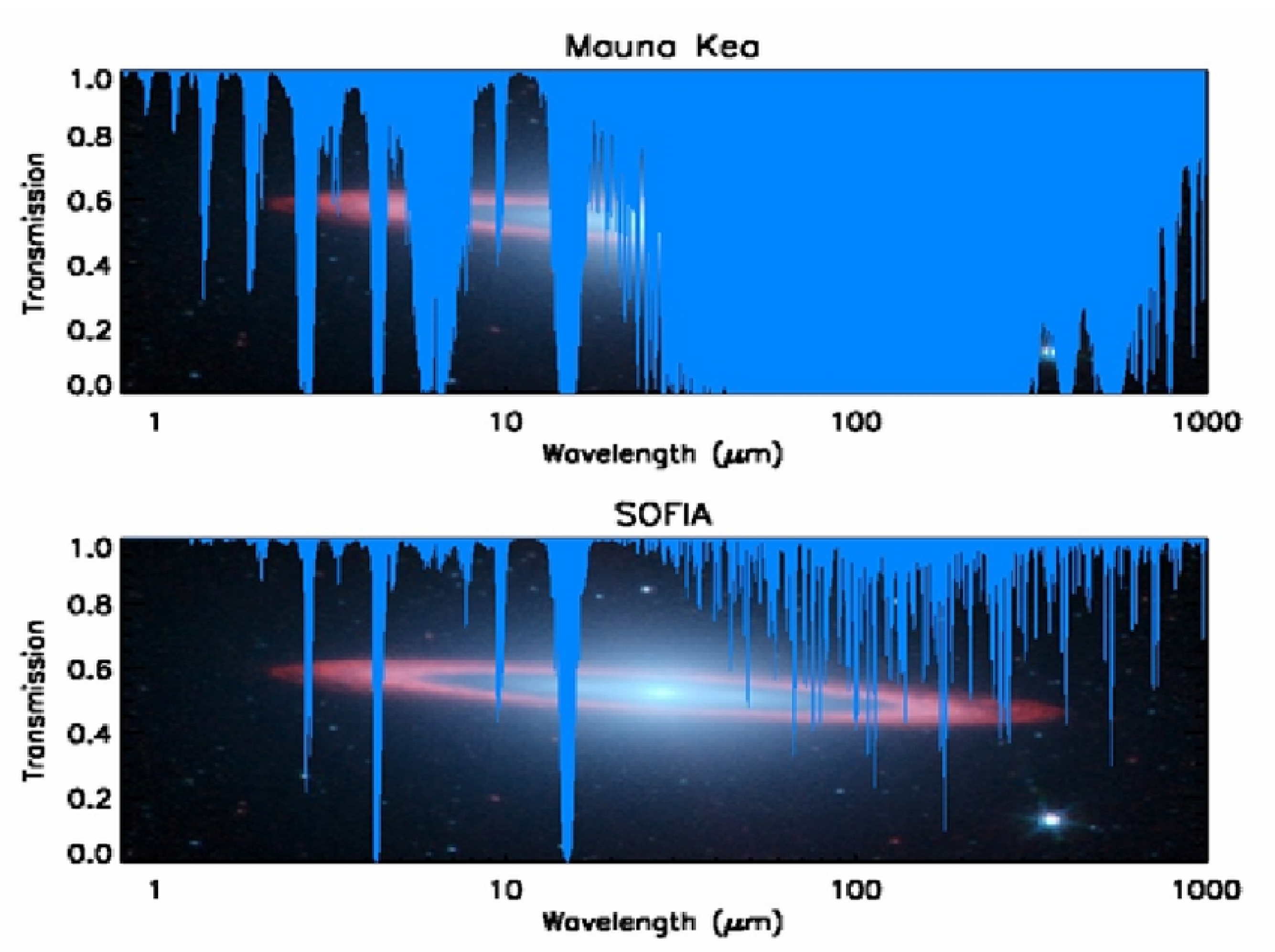
Earth's atmosphere: absorption visible and IR

- *Absorption in the visible and IR is caused by gases in the atmosphere, mainly: Water vapor(H_2O), carbon dioxide (CO_2), and ozone (O_3)*



Earth's atmosphere: infrared altitude transmission

- *Increasing altitude improves transmission*



Aprox. 4500 m.

Aprox. 13000 m.

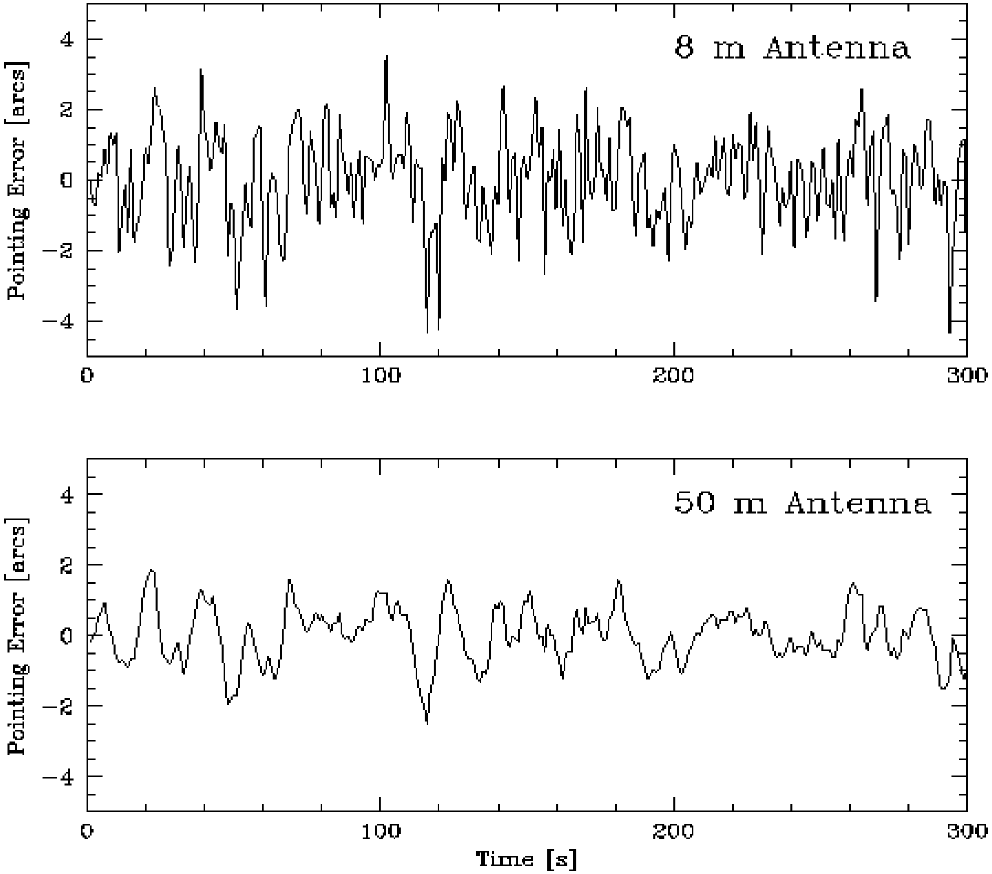
Earth's atmosphere: scattering

- *Relevant types of scattering: Rayleigh and Mie*
- *Rayleigh scattering:* $x=2\pi r/\lambda<<1$ *(e.g. VIS molecules)*
  - · *Wavelength dependency:* λ^{-4}
- *Mie scattering:* $x\sim1$ *(e.g. VIS dust, water droplets, hydrometeors)*
  - · *Not so wavelength dependent*

Earth's atmosphere: anomalous refraction or “radio-seeing”

- Atmospheric turbulence causes pointing errors (~1'') and results are worst with poor weather conditions

- This is particularly worse for interferometric observations (different columns of water vapor for each antenna): phase errors



CORRECTION WITH RADIOMETERS FOR INTERFEROMETERS

Earth's atmosphere: long wavelengths

- *Ionosphere: UV radiation from the Sun photodissociates molecules (Lyman-α, NO, O_2, ...) producing ions and free electrons that interact with EM waves*
- *Transmission cut-off (plasma frequency):*

$$\boxed{\frac{\nu_p}{kHz} = 8.97\sqrt{\frac{N_e}{cm^{-3}}}}$$

- *Electron density varies between 1.5×10^6 cm^{-3} (daytime) down to 2.5×10^5 cm^{-3} (at night)*
- *Observatories in radio-quiet locations (human interference)*

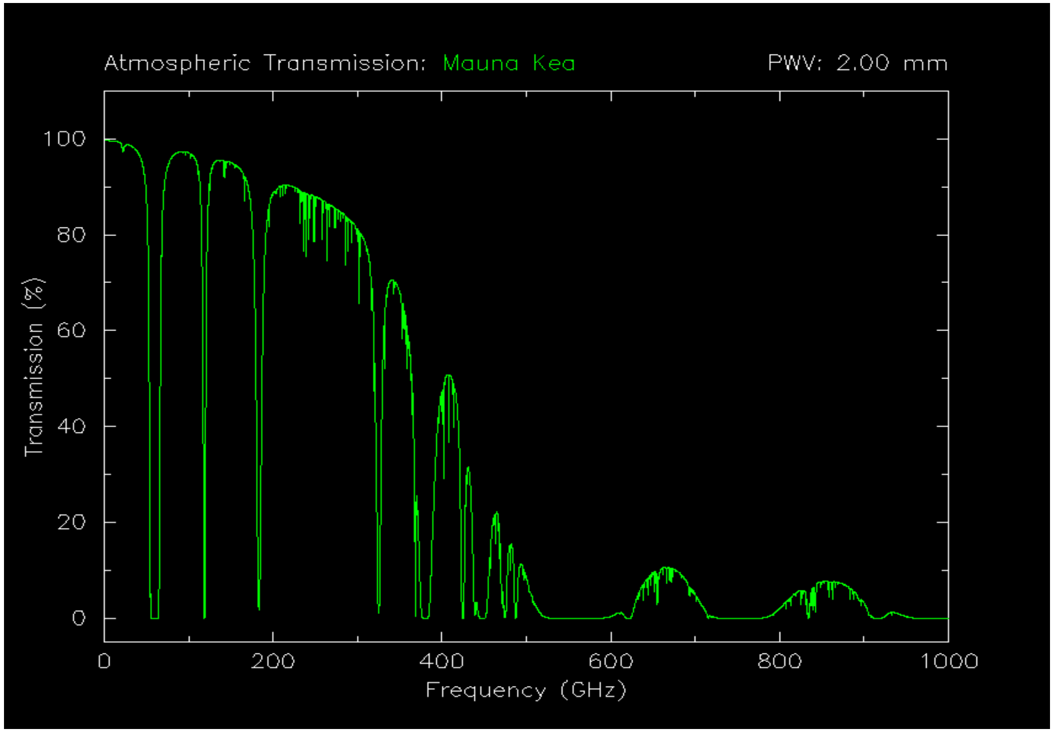
The mm and submm wavelength range

- *Atmospheric opacity mainly due to:*

  · *Water vapor(H_2O) bands: 1.63, 0.92mm ...*

  · *Oxygen (O_2) bands: 2.52, 5mm ...*

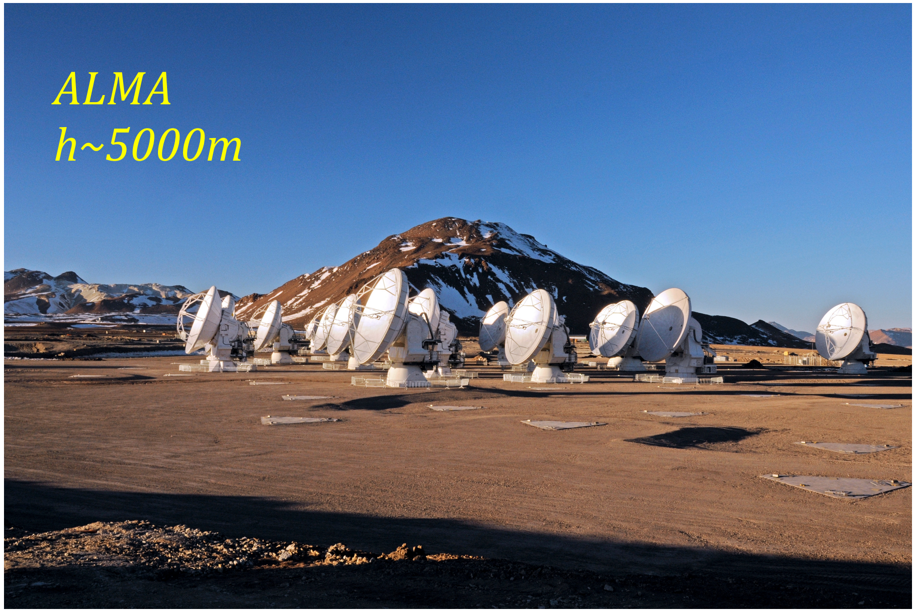
  . *And other molecules like N_2 or CO_2 for ν>300GHz*

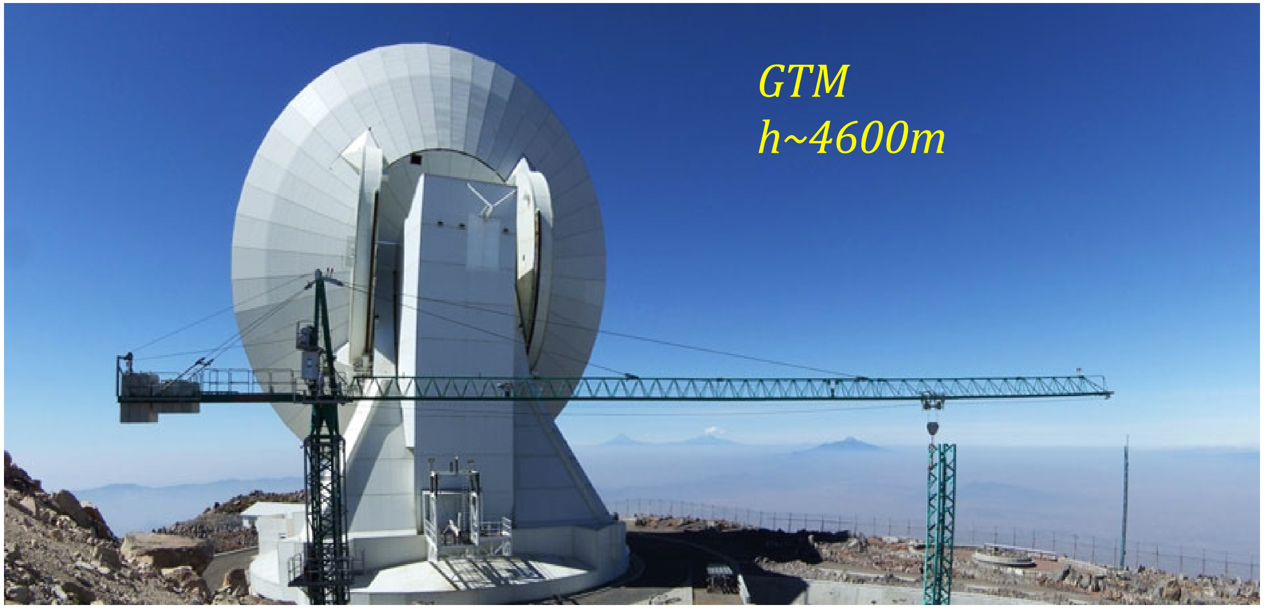


The mm and submm wavelength range: altitude

- *Observatories at high altitude and dry atmospheric conditions*

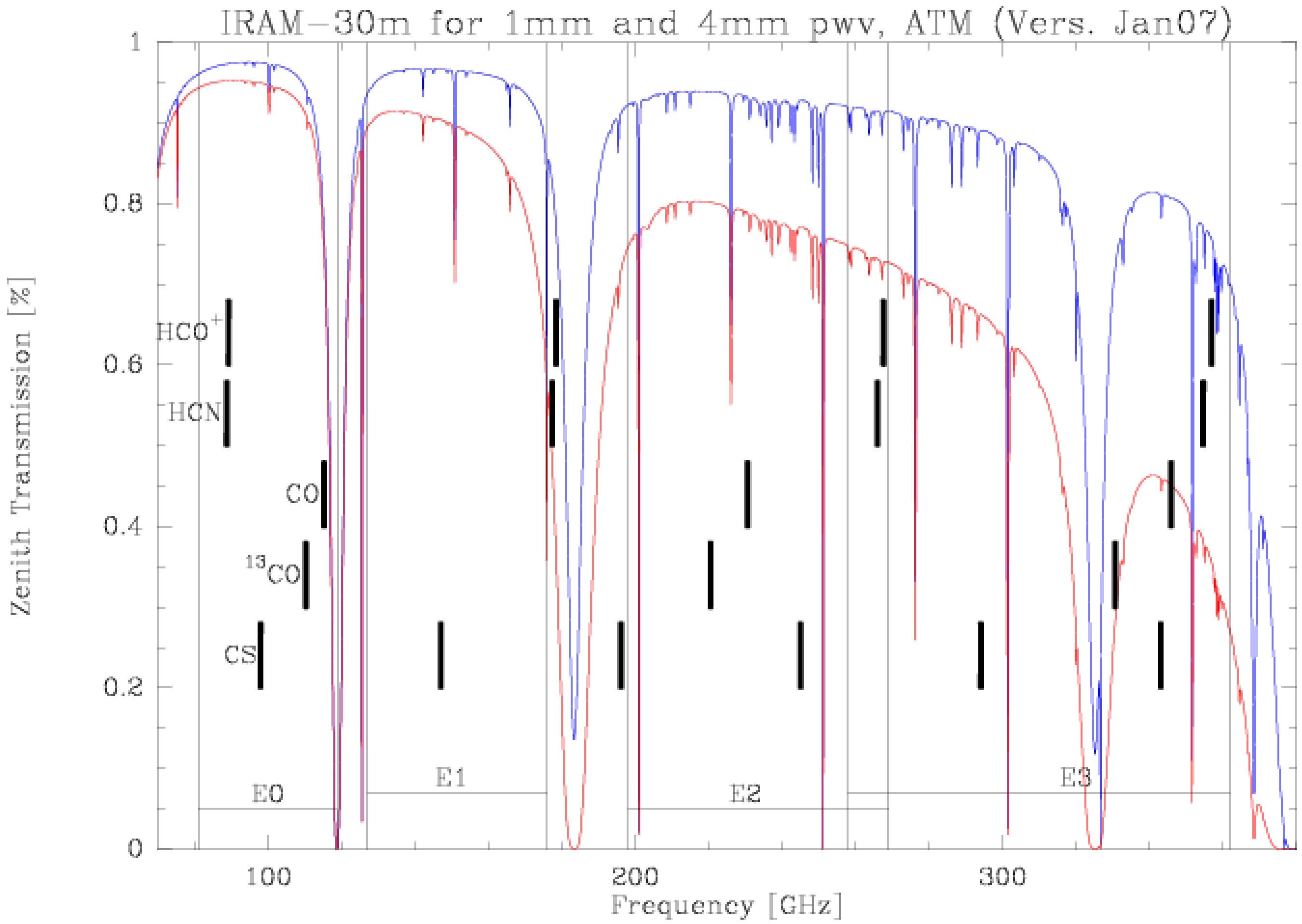

IRAM-30m
h~2850m


ALMA
h~5000m


GTM
h~4600m

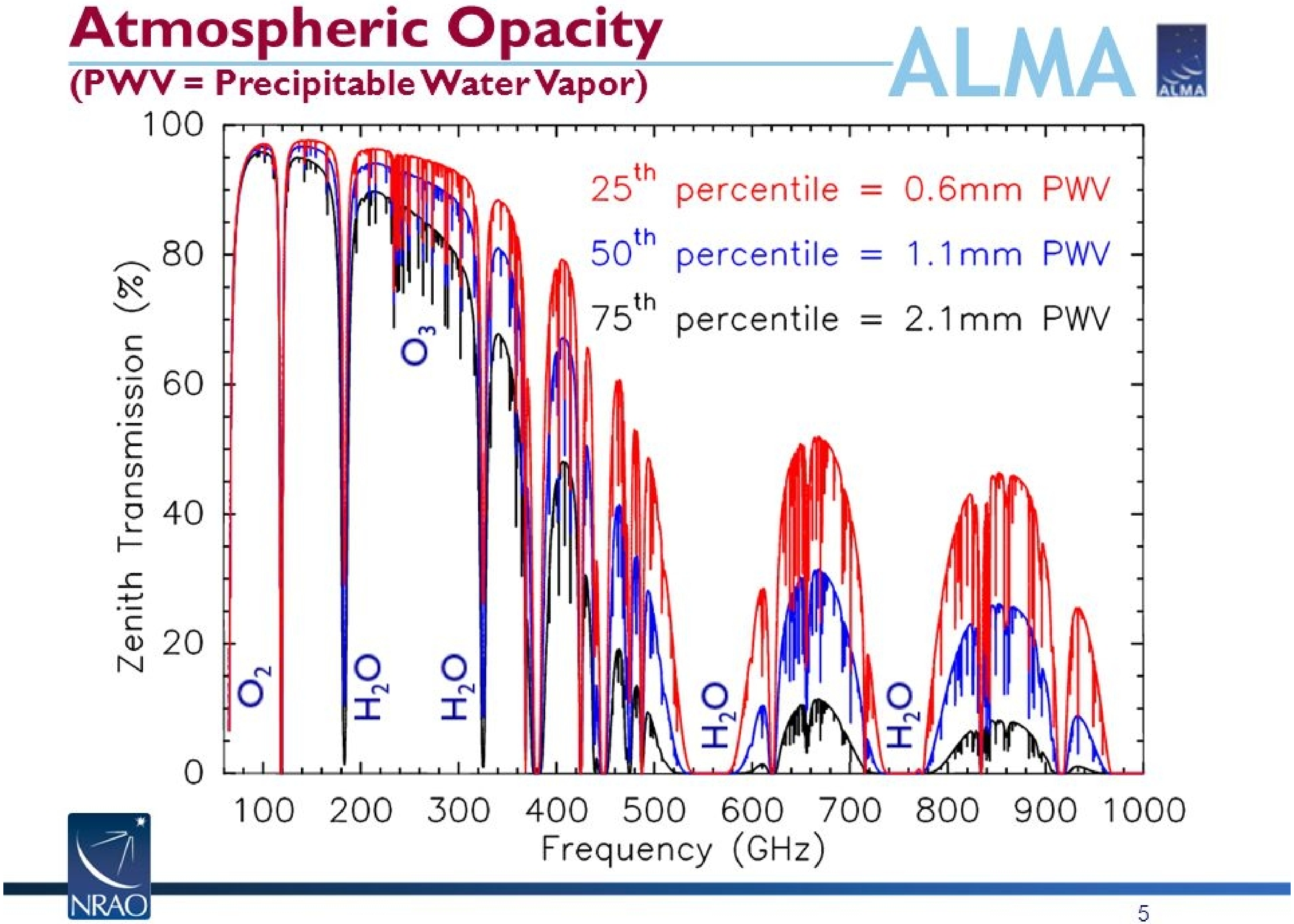
Curves of atmospheric transmission

- *IRAM-30m (h~2850m):*



Curves of atmospheric transmission

- *ALMA (h~5000m):*



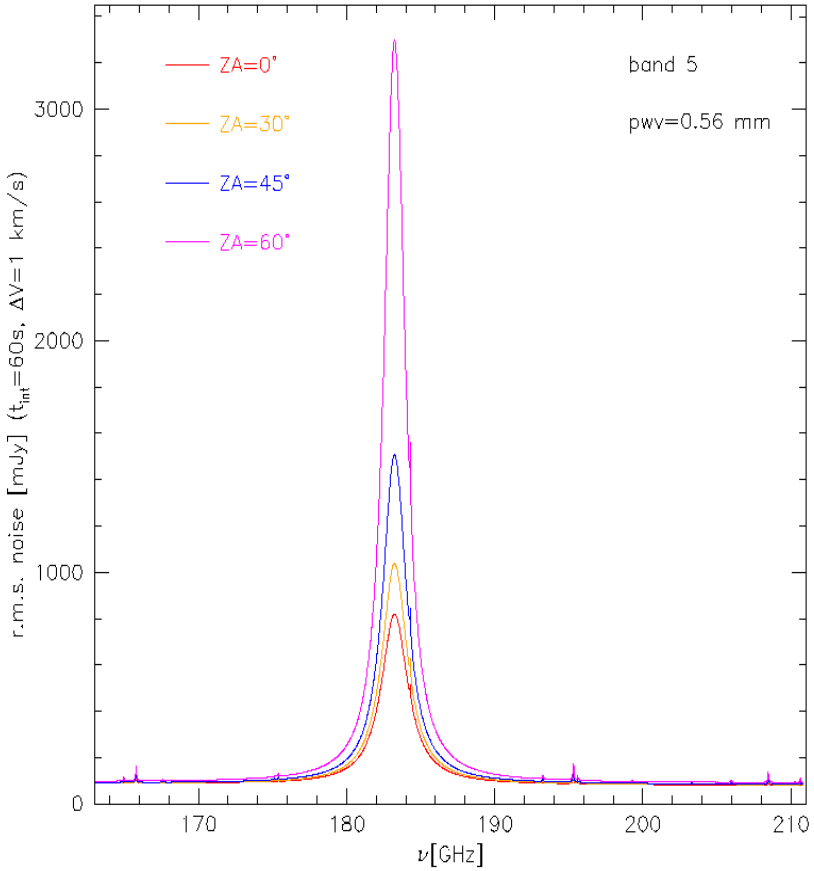
Atmospheric Opacity

(PWV = Precipitable Water Vapor)

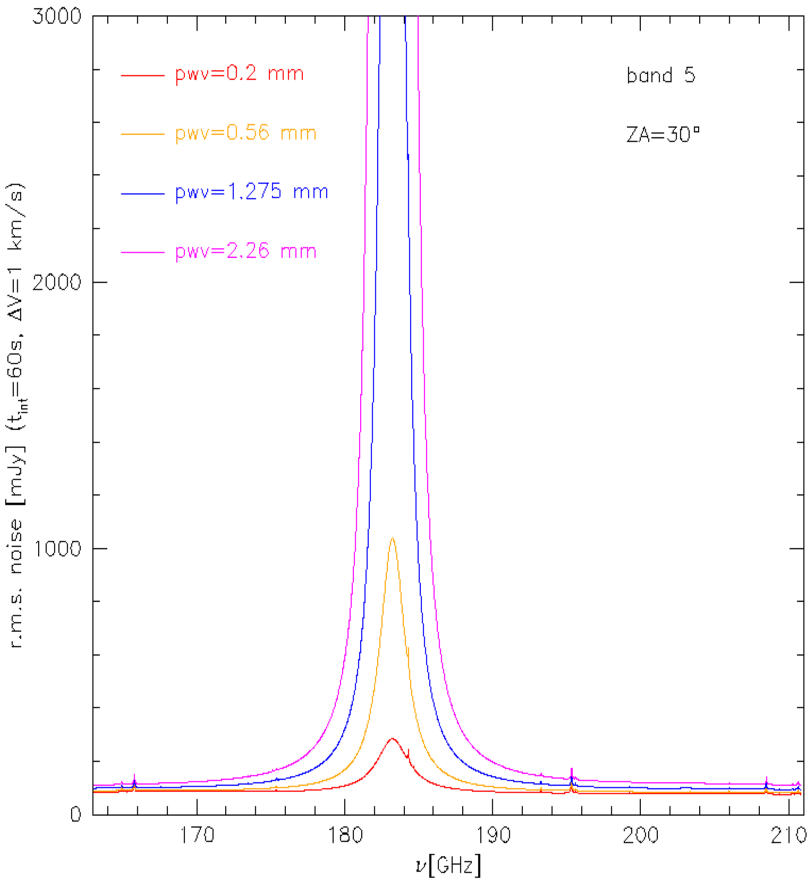
5

Curves of atmospheric transmission: zenith + pwv variation

- *ALMA (h~5000m):*



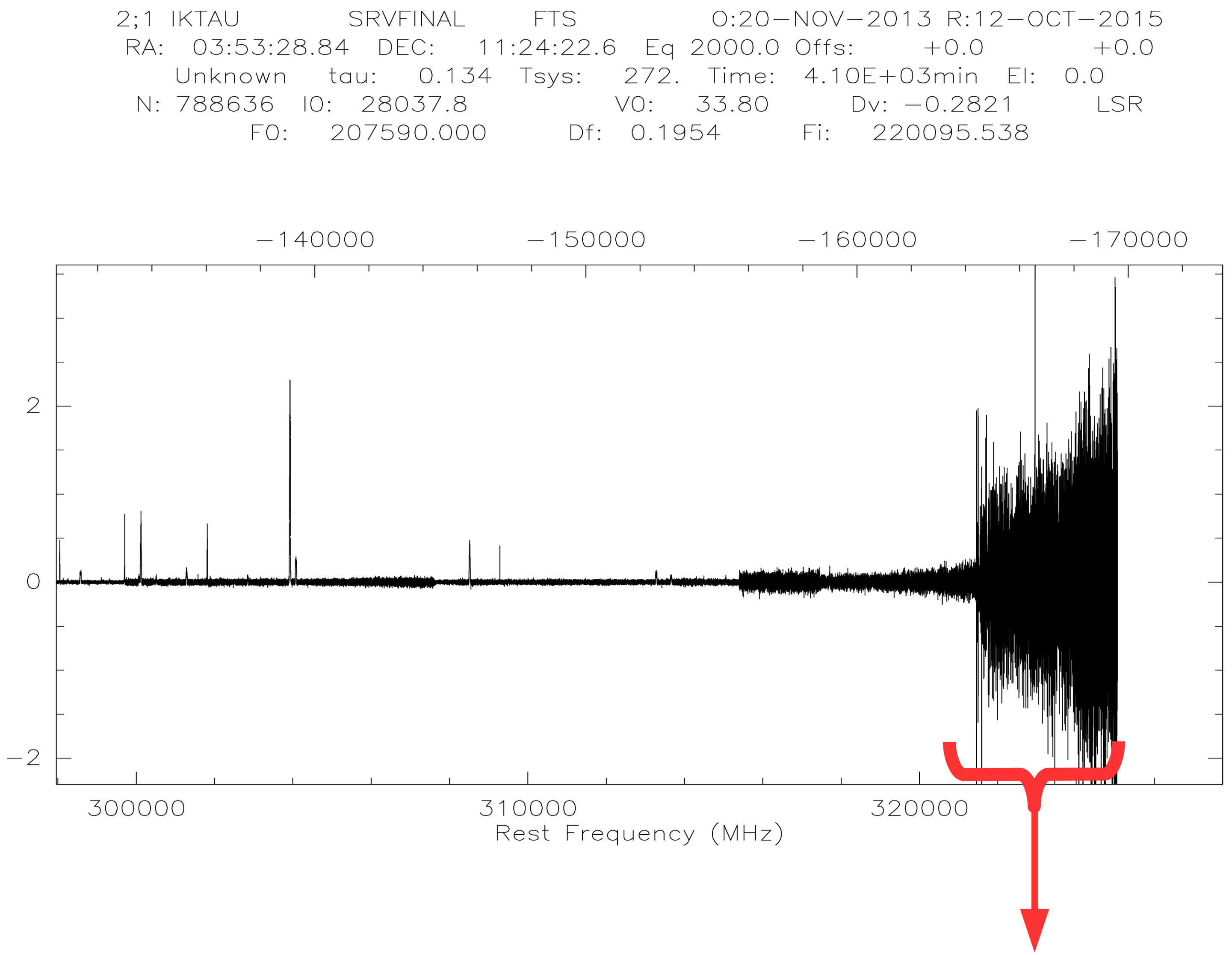
Increase ZA = Increase air mass



Increase pwv

Observational strategies: water vapor

The effect of water vapor in our observations:



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2;1  IKTAU          SRVFINAL      FTS           O:20-NOV-2013  R:12-OCT-2015
 RA:   03:53:28.84   DEC:    11:24:22.6   Eq  2000.0  Offs:      +0.0          +0.0
      Unknown      tau:     0.134   Tsys:    272.   Time:   4.10E+03min   El:   0.0
  N:  788636   I0:   28037.8              V0:    33.80       Dv:  -0.2821        LSR
             F0:    207590.000        Df:   0.1954        Fi:    220095.538
```

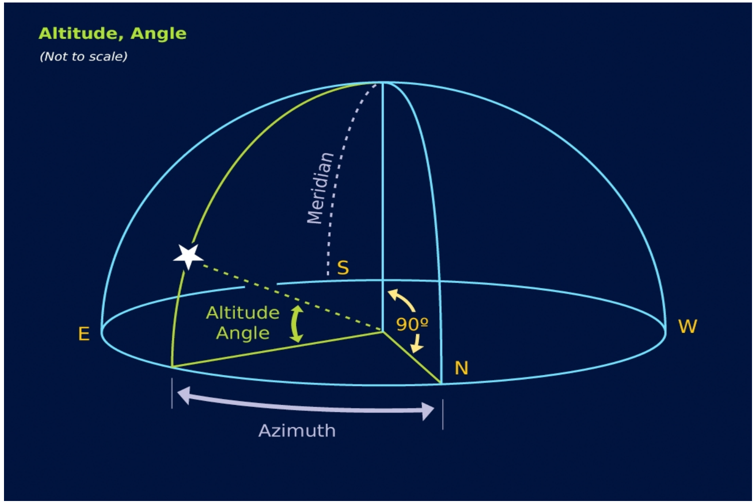
H_2O (325.1 GHz)

Observational strategies

Winter or summer?

Daytime or night?

Altitude (astronomical)?



Altitude (geographical)?

Pause to summarise

- The atmosphere causes absorption of incoming astronomical radiation

- High contents of water vapor in the atmosphere are bad for mm and submm observations

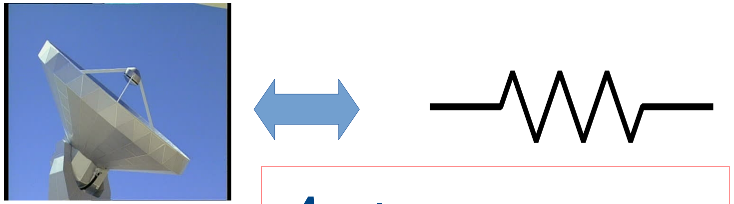
- High altitude and dry conditions improve the detection of astronomical signals

What else can we do?

Calibration – single-dish: basics

- *Review of concepts that we will use:*

Nyquist theorem: $$P = \Delta\nu k T$$



Antenna temperature

Planck's law: $$B_\nu(T) = \frac{h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

Radiation temperature: $$J(T) = \frac{c^2}{2k\nu^2} I = \frac{h\nu}{k}\frac{1}{e^{h\nu/kT}-1}$$

Radiative transfer: $$I_\nu(s) = I_\nu(0)\,\mathrm{e}^{-\tau_\nu(0)} + \int_0^{\tau_\nu(0)} B_\nu(T(\tau))\,\mathrm{e}^{-\tau}\,\mathrm{d}\tau$$

Optical depth: $$\tau_\nu(s) = \int_{s_0}^{s} \kappa_\nu(s)\,\mathrm{d}s$$

Calibration – single-dish: signal from empty sky

- **Goal:** *obtain the net astronomical signal*

- *What are we really measuring? (Empty sky):*

$$T_{\mathrm{A}}(z) = T_{\mathrm{rx}} + T_{\mathrm{atm}}\,\eta_{\mathrm{l}}\left(1 - \mathrm{e}^{-\tau_0 X(z)}\right) + T_{\mathrm{amb}}\left(1 - \eta_{\mathrm{l}}\right)$$

$T_A(z)$: *Antenna temperature at an elevation z*
T_{rx}: *receiver temperature*
T_{atm}: *effective temperature of the atmosphere*
η_L: *feed/forward efficiency (~0.9)*
τ_o: *zenith optical depth*
$X(z)$: *air mass at zenith distance z*
T_{amb}: *ambient temperature*

Calibration – single-dish: chopper wheel method (T_{rx})

- **Goal:** *obtain a Kelvin per Volt conversion factor*

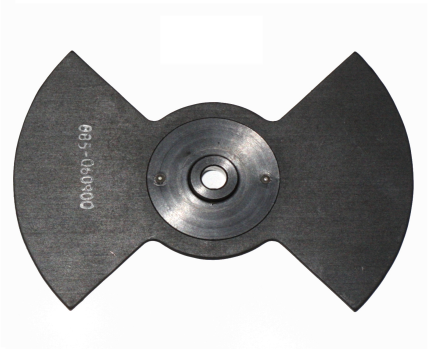
$$\boxed{P_{out} \propto V_{out} = g\left(T_{input} + T_{rx}\right)} \Longleftrightarrow \boxed{y = mx + b}$$

P_{out}, V_{out}: power detector

g: gain factor (slope)

T_{input}: calibrated loads → *T_{cold}: ~77K (He, N_2)*

→ *T_{hot}: room temp.*



T_{rx}: receiver temperature →

$$\boxed{T_{rx} = \frac{T_{hot} - YT_{cold}}{Y - 1}} \qquad \boxed{Y = \frac{V_{rx} + V_{hot}}{V_{rx} + V_{cold}}}$$

$$\boxed{g[V/K] = \frac{\left(V_{rx} + V_{hot}\right) - \left(V_{rx} + V_{cold}\right)}{T_{hot} + T_{cold}}}$$

Calibration – single-dish: skydip

η_L: forward efficiency (aka F_{eff}~0.9) is measured with a skydip

1) Obtain different pairs of (T_A, z) measures:

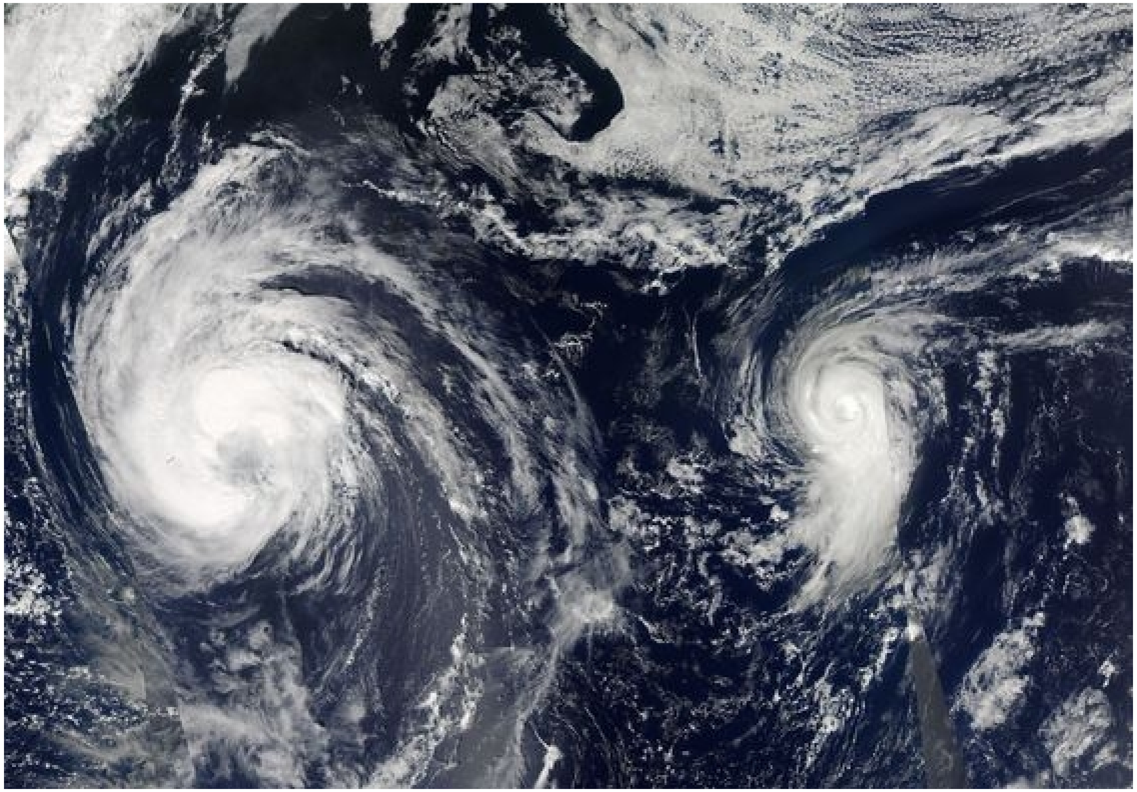
Observe at different zenith distances with almost equal weather conditions (same noise from other sources)

2) Least squares fitting of: $T_\mathrm{A}(z) = T_\mathrm{rx} + T_\mathrm{atm}\,\eta_\mathrm{l}\left(1 - \mathrm{e}^{-\tau_0 X(z)}\right) + T_\mathrm{amb}\left(1 - \eta_\mathrm{l}\right)$

This is usually done by the observatory staff

Calibration – single-dish: atmospheric effects

The atmosphere is a complex system, how do we simplify it?



SIMPLE MODEL:

Static, 1-D plane parallel, LTE, ideal gas

Calibration – single-dish: simple model of the atmosphere

Equation of state: $\boxed{P=\frac{\rho}{M}RT}$

Scale height: $\boxed{H=\frac{RT}{\mu g}\approx 7998\,m.}$

Hydrostatic equilibrium: $\boxed{\frac{dP}{dz}=-\rho g} \longrightarrow \boxed{P(z)=P_o e^{-z/H}}$

Temperature gradient: $\boxed{\frac{dT}{dz}=-6.5\,[K/km],(z<11\,km)}$

LTE:
(z<90km.)

$$\left\{\begin{array}{l}\boxed{220<T<320\,K}\\ \\ \boxed{1020<P<0.0015\,mb}\end{array}\right\} \longrightarrow \boxed{\frac{N_u}{N_l}=\frac{g_u}{g_l}\exp(-\Delta E/kT)}$$

Boltzmann's distribution

Calibration – single-dish: Atmospheric Transmission Model

Atmospheric transmission model (Cernicharo, 1985, IRAM report):

- *Radiative transport in a plane parallel atmosphere:*

$$\boxed{I_\nu(s) = I_\nu(0)\,e^{-\tau(0,s)} + \int_0^s S_\nu(s')\,e^{-\tau(s',s)}\,\kappa_\nu(s')\,ds'}$$

$$(\kappa_\nu)_{lu} = \frac{8\pi^3 N\nu}{3hcQ}\left(e^{-E_l/kT} - e^{-E_u/kT}\right) \cdot |< u \mid \mu \mid l >|^2\, f(\nu, \nu_{l\to u})$$

- *Estimate the integrated opacity along the line of sight:*
  - *Abundance distribution of all the species:* $N_i(s)$
  - *Spectroscopic parameters: transition probabilities...*
  - *Species:* $H_2{}^{16}O$, $H_2{}^{18}O$, $H_2{}^{17}O$, *HDO*, ${}^{16}O_2$, ${}^{16}O^{18}O$, ${}^{16}O^{17}O$, ${}^{16}O_3$, ${}^{16}O^{16}O^{18}O$, ${}^{16}O^{18}O^{16}O$, ${}^{16}O^{16}O^{17}O$, ${}^{16}O^{17}O^{16}O$, N_2O, *CO*, SO_2, H_2S, NO_2
- *Integrate for all the spectrum (all frequencies)*

Calibration – single-dish: ATM line profiles

Line profile:

Natural broadening: negligible (~10^{-6} Hz)

Pressure broadening: dominates at h<50km. (~2.5 Mhz/mbar)

Van Vleck-Weisskopf profile:
Collisional broadening
Approximation: $t_{col} << 1/A_{ul}$

$$f_{\mathrm{VVW}}(\nu,\nu_{l\to u}) = \frac{\nu\Delta\nu}{\pi\nu_{l\to u}}\left(\frac{1}{(\Delta\nu)^2+(\nu-\nu_{l\to u})^2} + \frac{1}{(\Delta\nu)^2+(\nu+\nu_{l\to u})^2}\right).$$

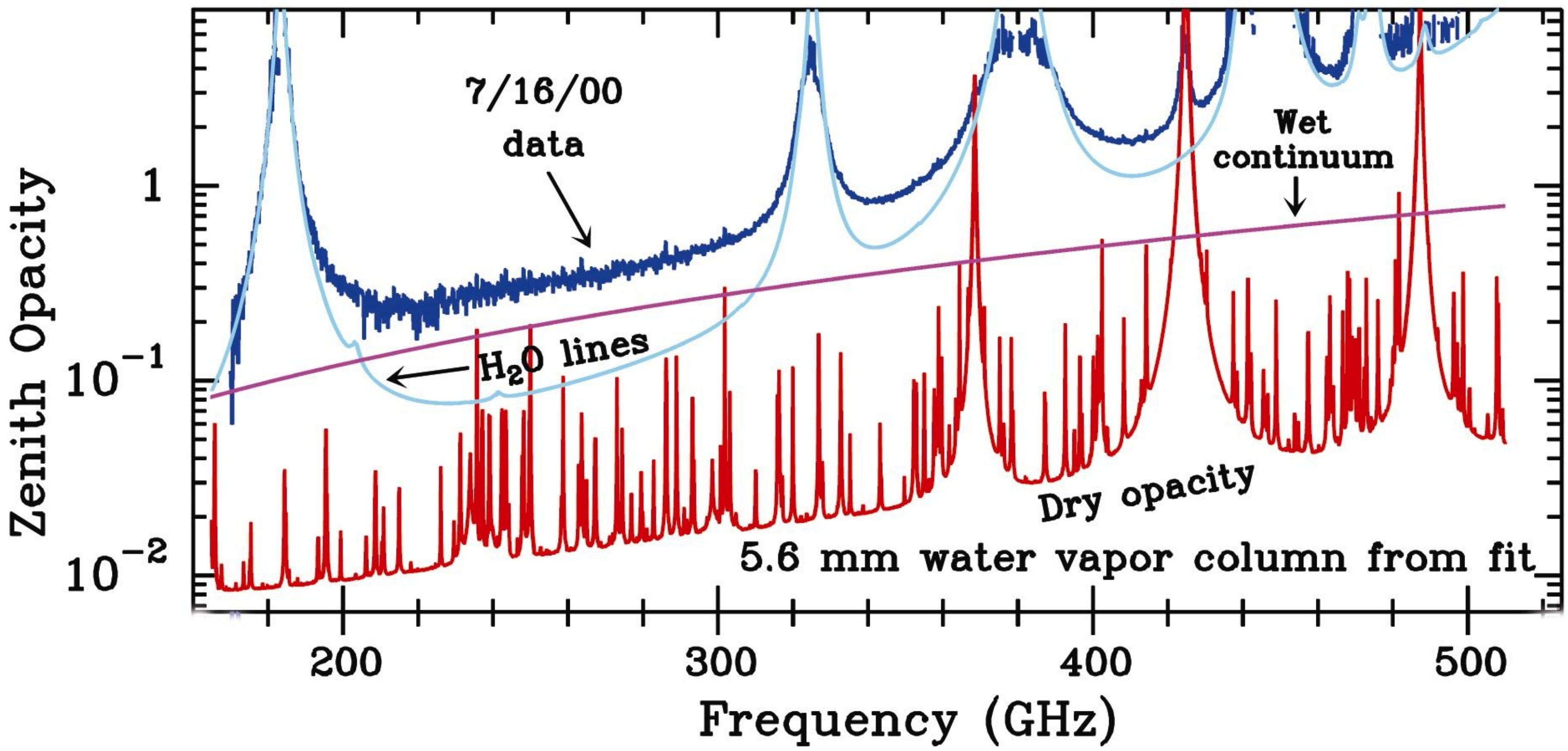
Doppler broadening: low pressure (density)

Gaussian profile:

$$f_D(\nu,\nu_{l\to u}) = \frac{1}{\Delta\nu_D}\left(\frac{\ln 2}{\pi}\right)^{\frac{1}{2}} exp\left[-\left(\frac{\nu-\nu_{l\to u}}{\Delta\nu_D}\right)^2 \ln 2\right]$$

Calibration – single-dish: ATM pseudo-continuum

Continuum-like absorption:



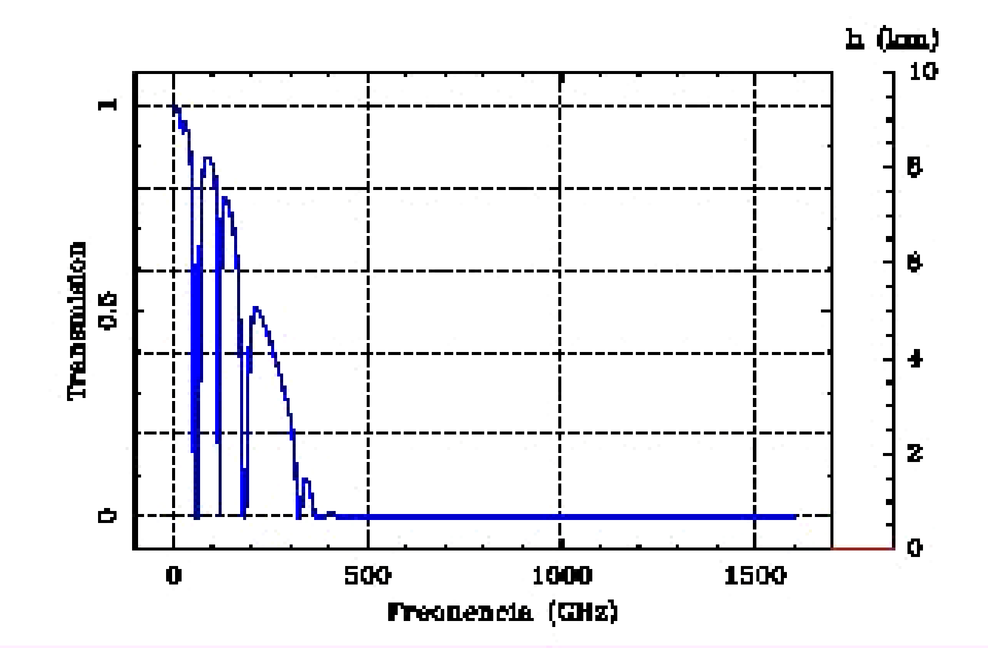
Empirical law proportional to:

1) (water vapor partial pressure)^2

2) product of water vapor and foreign-gas partial pressure

Calibration – single-dish: ATM results

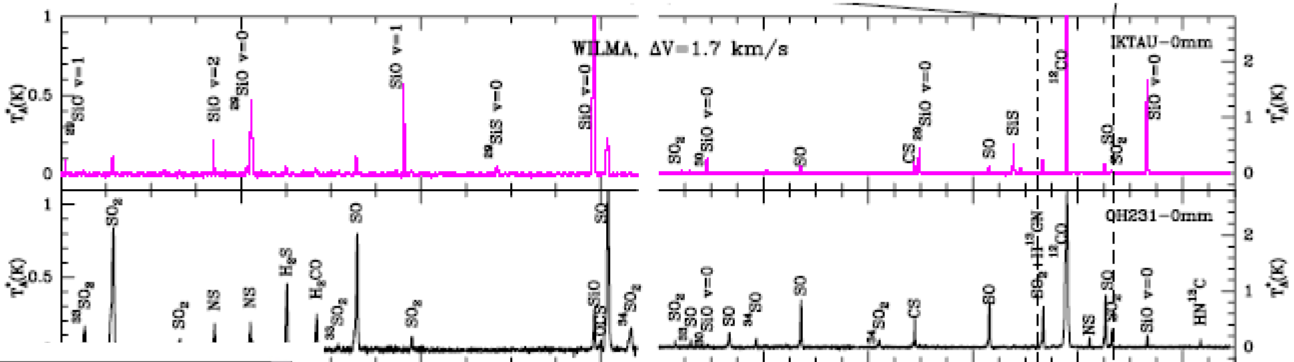
Example: Variation with alitude

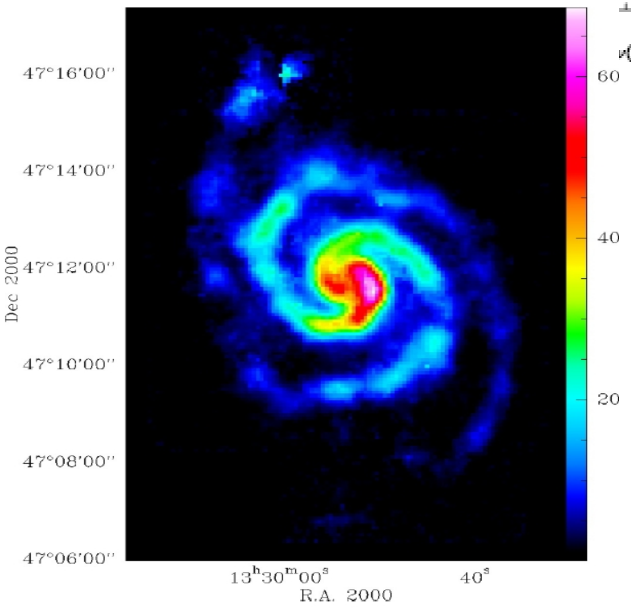


Calibration – single-dish: results

- Atmospheric calibration procedure is done automatically (chopper wheel method to obtain counts for: SKY-HOT LOAD-COLD LOAD) you only need to include this procedure in your observing run

- Result:

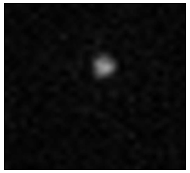




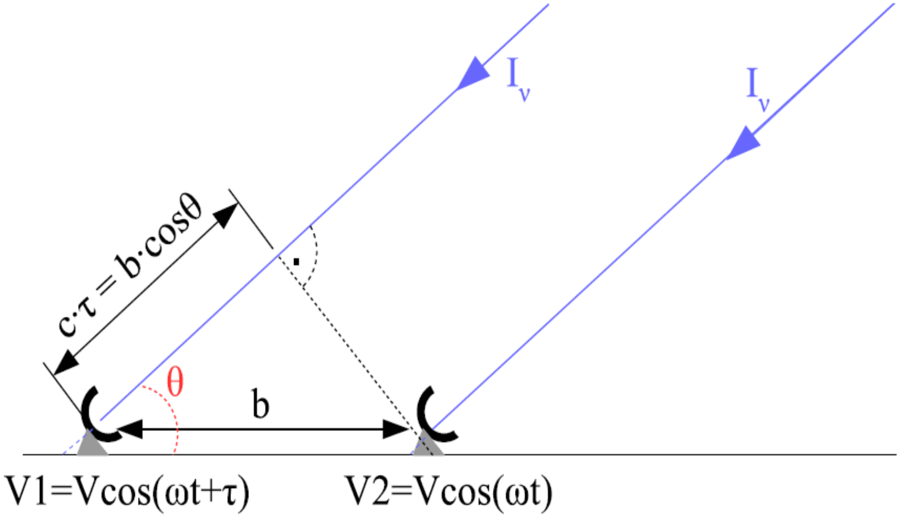
Astronomical data ready for the analysis

Calibration – interferometry: phase delay

- We have seen that fluctuating atmosphere causes anomalous refraction or “radio-seeing”



- Refractive effects cause phase delays when using long baseline interferometry: tropospheric variability of H_2O



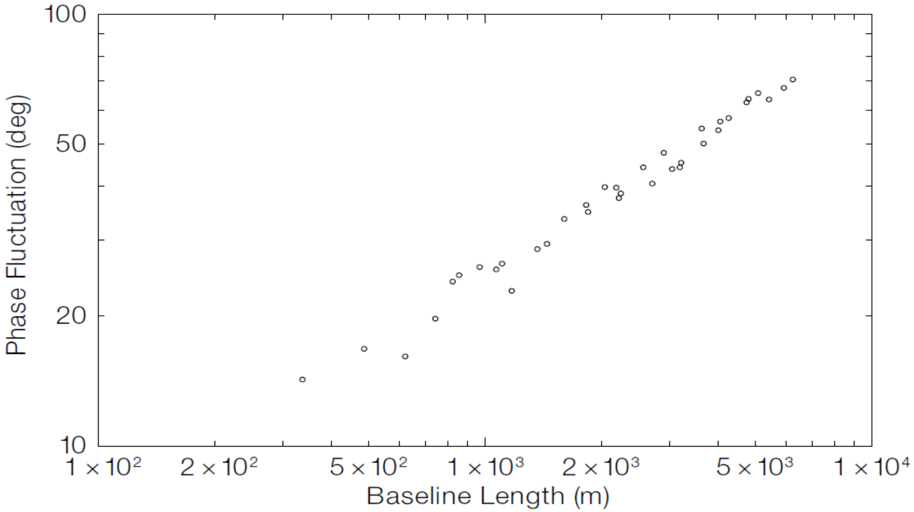
<u>Alma goal:</u> ~0.001'' angular resolution

<u>Alma baselines:</u> up to ~10 km.

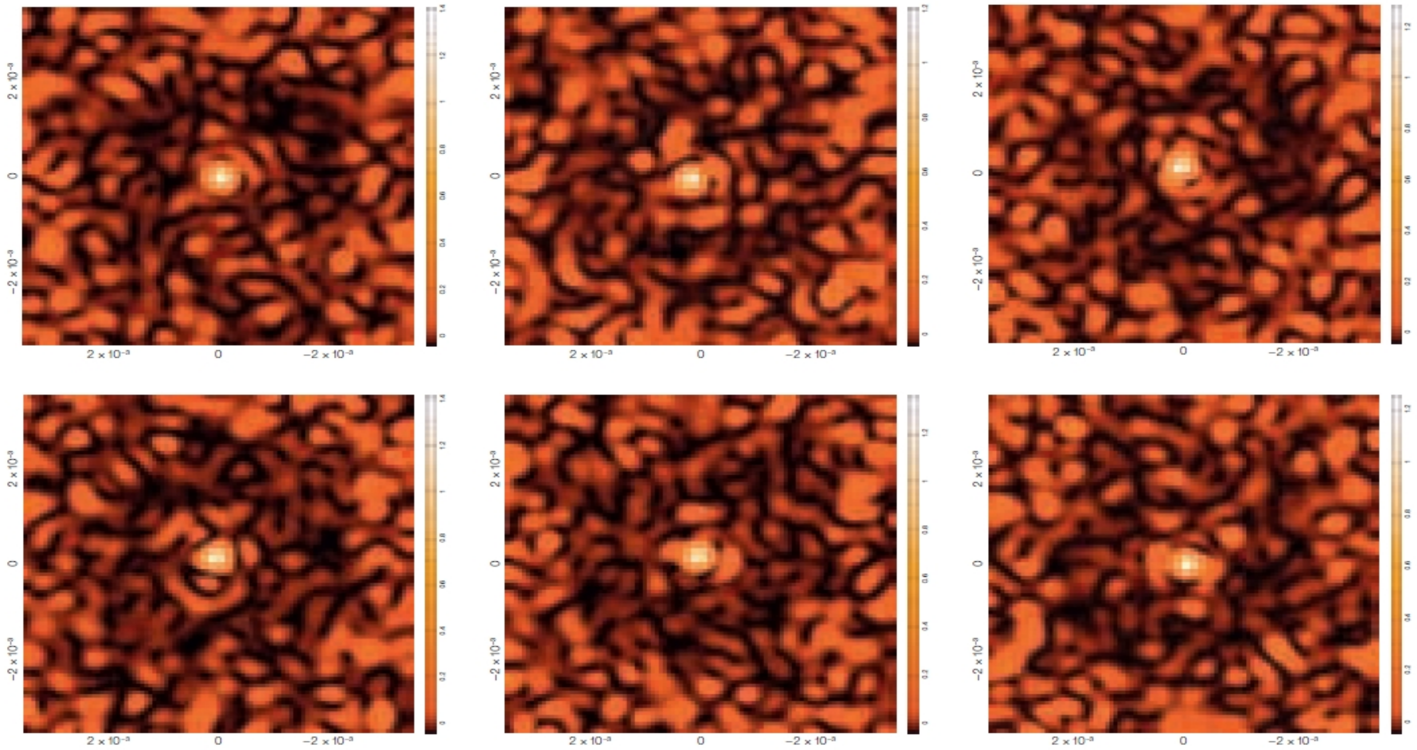
1mm of pwv is equivalent to 7mm pathlength delay

ALMA shortest wavelength is ~0.3mm (delay~20λ)

Calibration – interferometry: phase delay effects



Phase fluctuations measured with the Very Large Array at 22 GHz as a function of the baseline



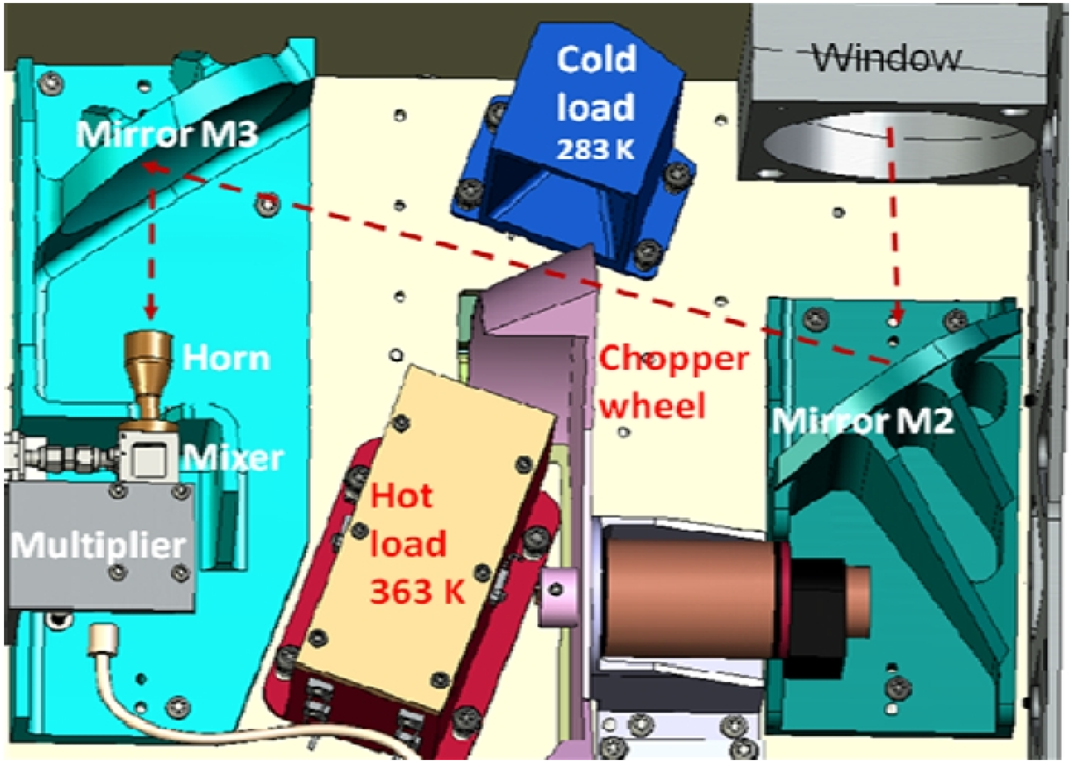
Simulated images of a 2 Jy point-source observed with ALMA with the presence of uncorrected phase fluctuations

Calibration – interferometry: radiometers

- Solution:

1) Fast switching: observe well-known source

2) Radiometers: predict pathlength variations due to H_2O vapor using radiometers+ATM and correct the delay



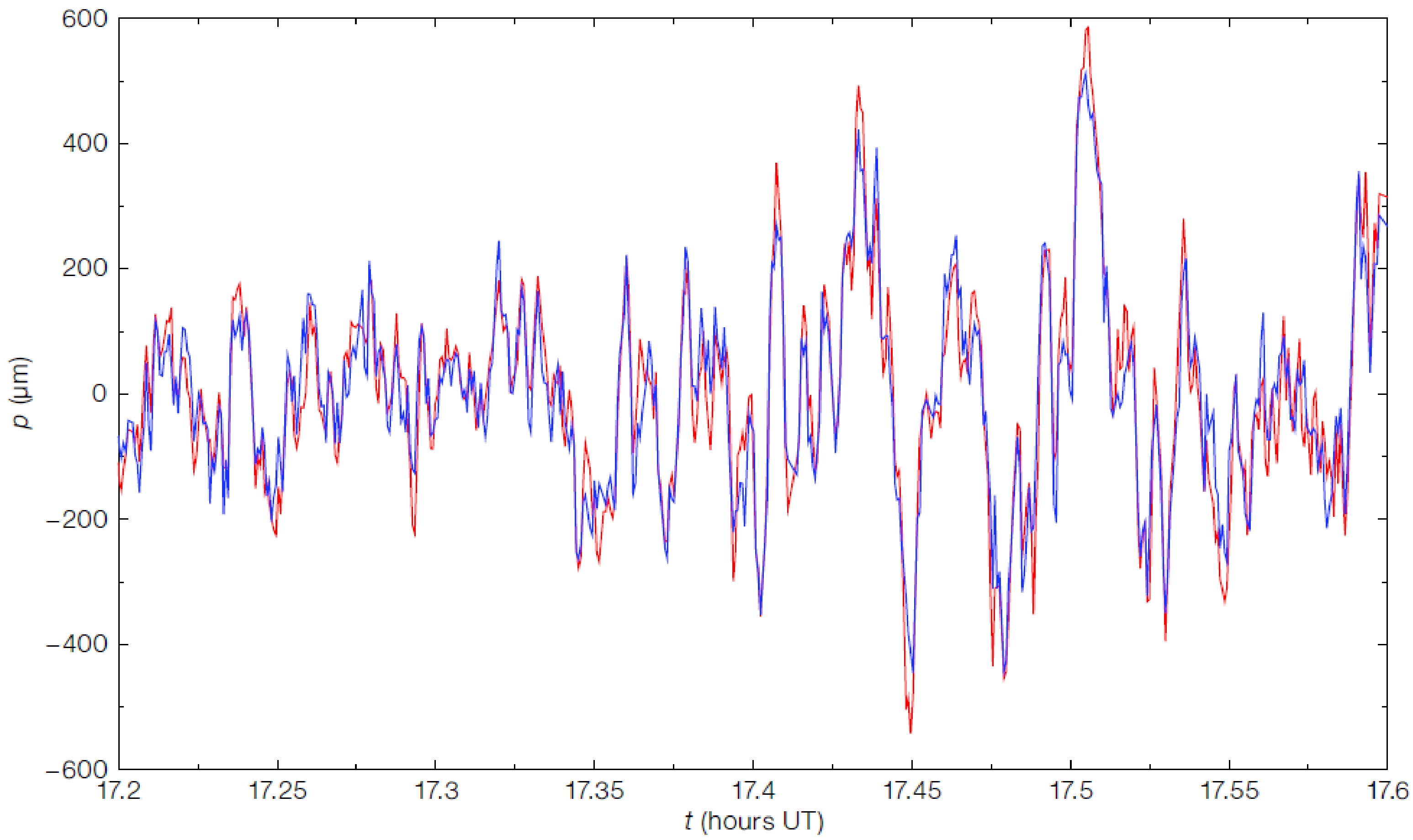
Scheme of an ALMA Radiometer operating at 183 GHz (p-H_2O 3,1,3 - 2,2,0 line)

The beam enters through the window, and goes to the horn after succesive reflections in M2 and M3.

The chopper wheel deflects the beam following the sequence:
Sky-Cold-Sky-Hot

Calibration – interferometry: radiometers

- Performance of an ALMA radiometer tested at the SMA:



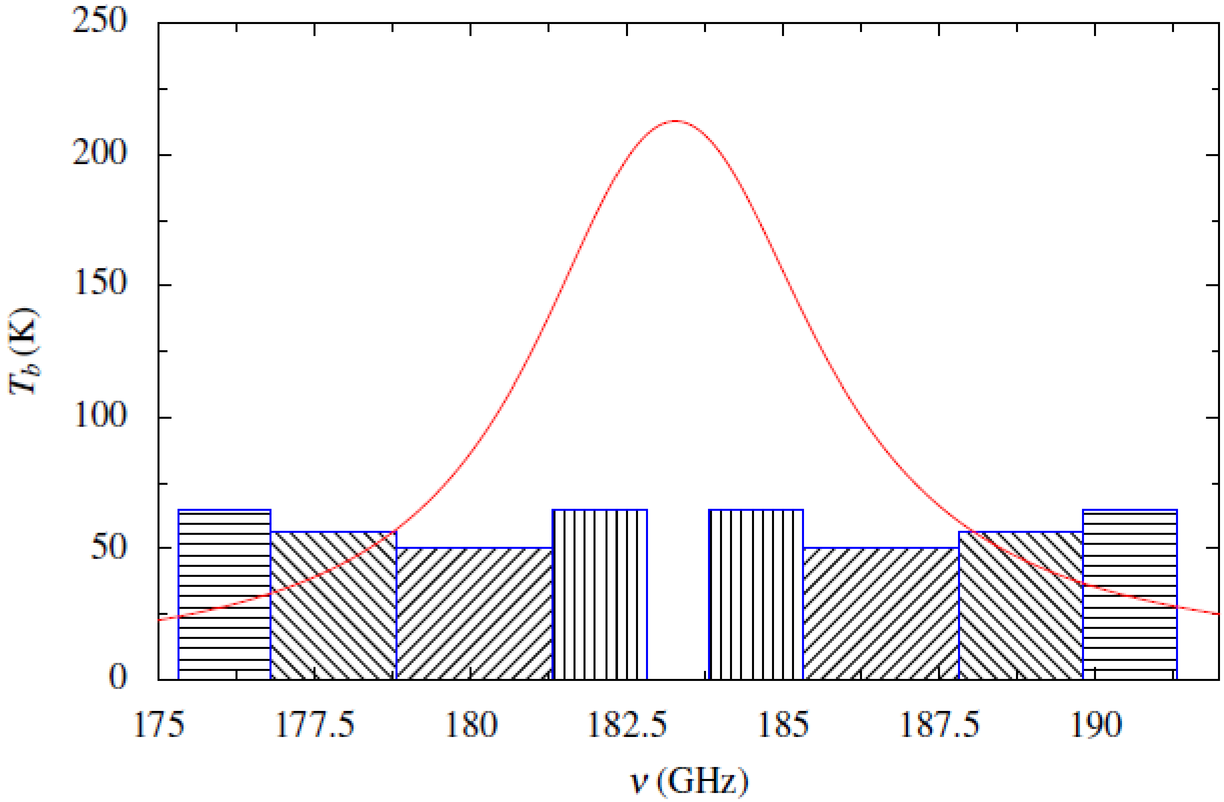
Red curve: *fluctuating atmospheric path measured by the interferometer*
Blue curve: *estimated by the radiometer*

Calibration – interferometry: ALMA radiometers

- Each 12 m antenna has its own radiometer which measures the T_b of the sky on timescales ~1 s.

- On timescales longer than 3 min.: phase calibrators

- These data are stored for phase-correction (Nikolic et al. 2013)



Red curve: *brightness temperature model of the 183 GHz line of water with 1 mm of pwv.*

The eight channels of the radiometer are shown

BASIC BIBLIOGRAPHY

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- *Ulich, B.L. & Haas, R.W. 1976, ApJ, 30, 247*
- *Check EMIR for astronomers Wiki (internal reports):*

  http://www.iram.es/IRAMES/mainWiki/EmirforAstronomers

  http://www.iram.es/IRAMES/mainWiki/CalibrationPapers
- *Play with it:*

  https://almascience.eso.org/about-alma/atmosphere-model

  https://www.mrao.cam.ac.uk/~bn204/alma/atmomodel.html

Additional slide: Calibration method equations

- *Loads are considered black bodies and their physical temperatures are equivalent to their Rayleigh-Jeans radiation temperature (hν<<kT):* $T_B = 77\ K \longrightarrow J_\nu(T_B, 345\ GHz) = 70\ K$

  This is equivalent to a 10% higher T_{rx} ➡ *acceptable approximation*

- *How to convert counts into antenna temperature (when measuring the sky):*

$$\boxed{\frac{T_{hot}-T_A^{sky}}{C_{hot}-C_{atm}}=\frac{T_{hot}-T_{cold}}{C_{hot}-C_{cold}}}$$

with

$$\boxed{T_A^{sky}=\eta_l T_{sky}+(1-\eta_l)T_{cab}}$$

$$T_{cab}=0.8T_{hot}+0.2T_{amb}$$ *(IRAM-30m)*

- T_{sky} *and* τ *are calculated by fitting the emission of both receiver sidebands with ATM (pwv)*

- *Spectral line calibration: difference of counts between the source and the blank sky (off position) is related to the difference of counts between the hot load and the blank sky:*

$$\boxed{T_A^*=T_{cal}\frac{C_{source}-C_{atm}}{C_{hot}-C_{atm}}=\frac{1+G_i}{\eta_l\exp(-\tau_{sig}A)}\left(T_{hot}-T_A^{sky}\right)}$$

A: airmass= 1/sin(elev.)
G_i*: gain ratio of the two sidebands=* G_{ima}/G_{sig}

Additional slide: Calibration method equations

- *Counts for the hot load:*

$$C_{hot} = g\left[G_{sig} J(\nu_{sig}, T_{hot}) + G_{ima} J(\nu_{sig}, T_{hot}) + T_{rx}\right]$$

- *Counts for the blank sky:*

$$C_{atm} = g\left(G_{sig}\left[\eta_l J(\nu_{sig}, T_{sky}) + (1-\eta_l) J(\nu_{sig}, T_{cab})\right] + G_{ima}\left[\eta_l J(\nu_{ima}, T_{sky}) + (1-\eta_l) J(\nu_{ima}, T_{cab})\right] T_{rx}\right)$$

- *For each sideband:*

$$J(\nu, T_{sky}) = J(\nu, T_{atm})(1-\exp(-\tau A)) + J(\nu, T_{bg})\exp(-\tau A)$$

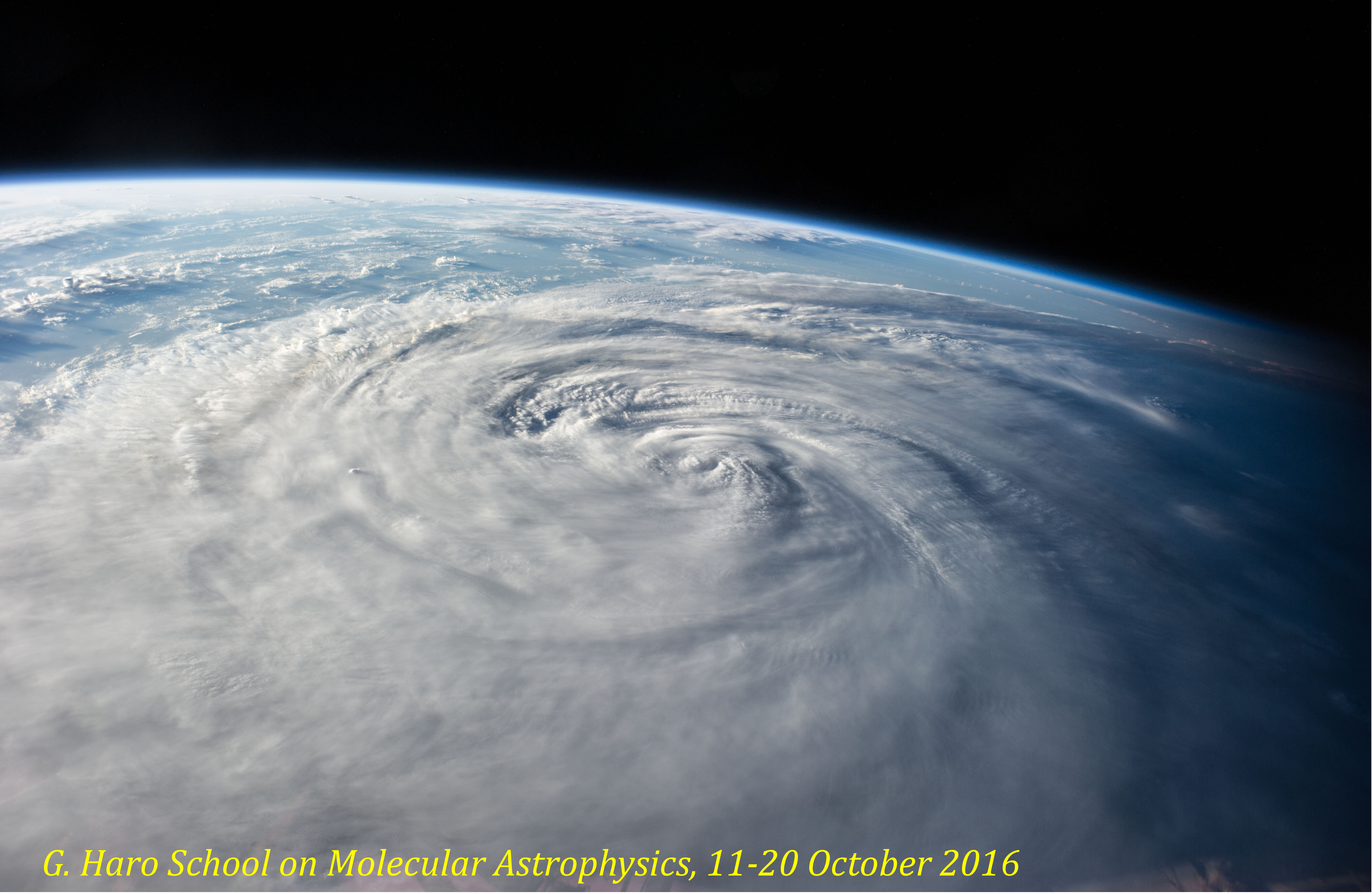
where we assumed:

$$J(\nu_{sig}, T) = J(\nu_{ima}, T) = J(T)$$

- *Difference of counts between source and blank sky:*

$$C_{source} - C_{atm} = g\, G_{sig}\, \eta_l \exp(-\tau_{sig} A)\, T_A^*$$

See "Calibration of spectral line data at the IRAM-30m radio telescope" C. Kramer, 1997 (Bilbiography: Calibration Papers).



G. Haro School on Molecular Astrophysics, 11-20 October 2016

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