Interferometry @ mm

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Italian Node of ALMA Regional Center

Slides & contributions from
Arturo Mignano

http://www.alma.inaf.it/index.php/Courses

Ideas and slides borrowed from

IRAM interferometry school

http://www.iram-institute.org/EN/content-page-248-7-67-248-0-0.html

NRAO interferometry school

https://science.nrao.edu/science/meetings/2016/15th-synthesis-imaging-workshop

LOFAR school

http://www.astron.nl/lofarschool2014/

European Radio interferometry (ERIS) school

https://www.eso.org/sci/meetings/2015/eris2015.html

Synthesis Imaging in Radio Astronomy: II – The “White Book”

Virtual Radio Interferometer
http://www.narrabri.atnf.csiro.au/astronomy/vri.html

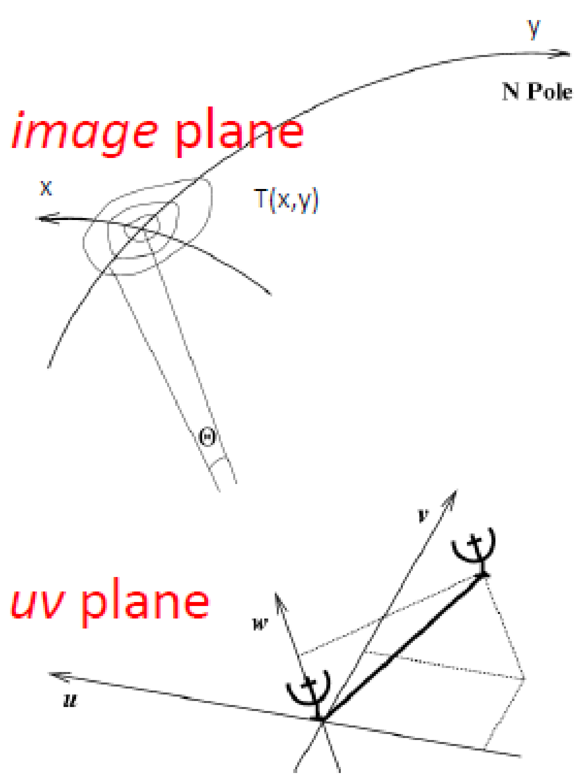
https://casaguides.nrao.edu/index.php?title=M100_Band3

Interferometry basics

Indeed the CORRELATOR performs a more complicated operation (i.e. the true cross-correlation) to deliver VISIBILITIES:

$$V^{ij}(\tau_g) = \langle V^i V^j \rangle = lim_{T \to \infty} \int_{-T/2}^{T/2} V^i(t)\, V^{j*}(t+\tau_g)\, dt$$

In the (2-D) uv-plane each visibility samples the FT of the (2-D) B(θ,ϕ)



(van Cittert-Zernike theorem)

Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dx dy$$

$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$

Image space/domain

Interferometry basics

In the next two weeks we are going to deal with

visibilities and **uv plane**

To get familiar with them you can play with

- a java applet online:

http://www.narrabri.atnf.csiro.au/astronomy/vri.html

- or a python script written by Ivan Marti-Vidal (nordic ARC node) APSYNSIM

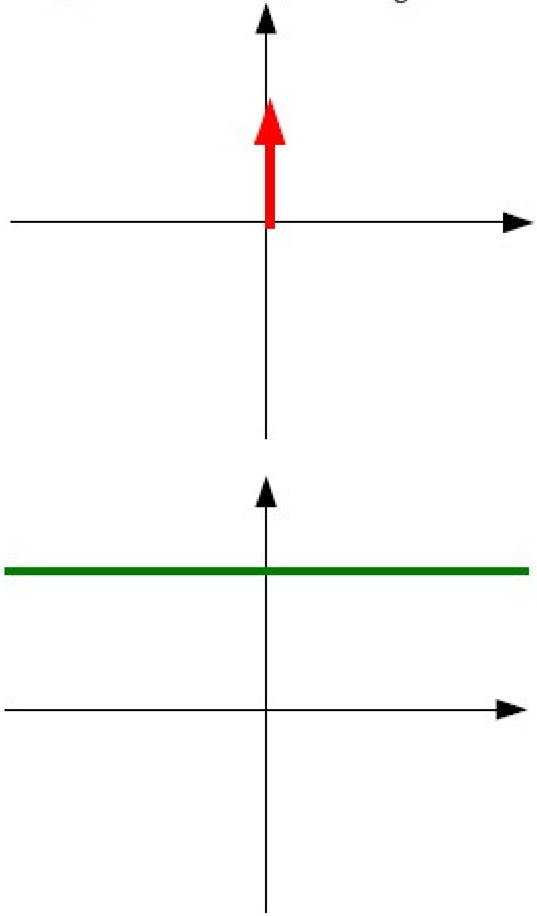
https://launchpad.net/apsynsim

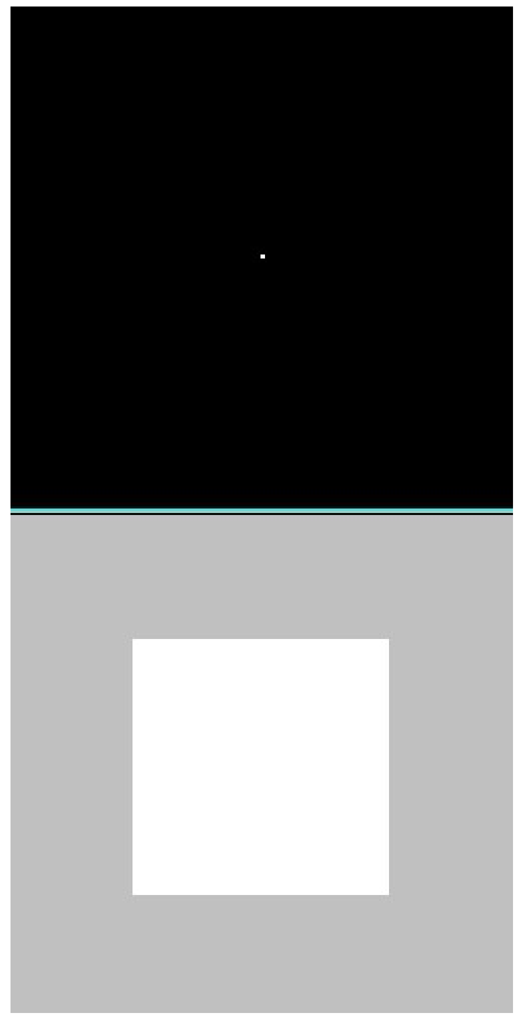
Interferometry basics

1 D

2 D

1. *The pulse:* $\delta(x - x_o)$



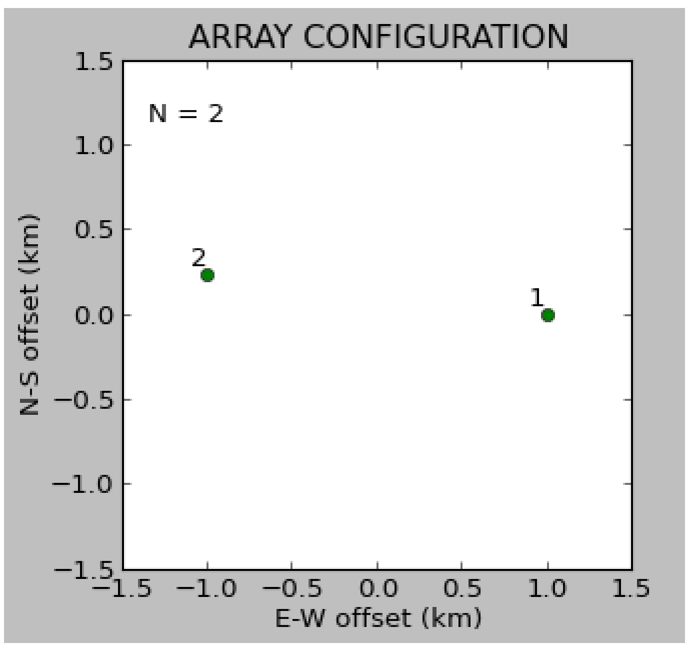


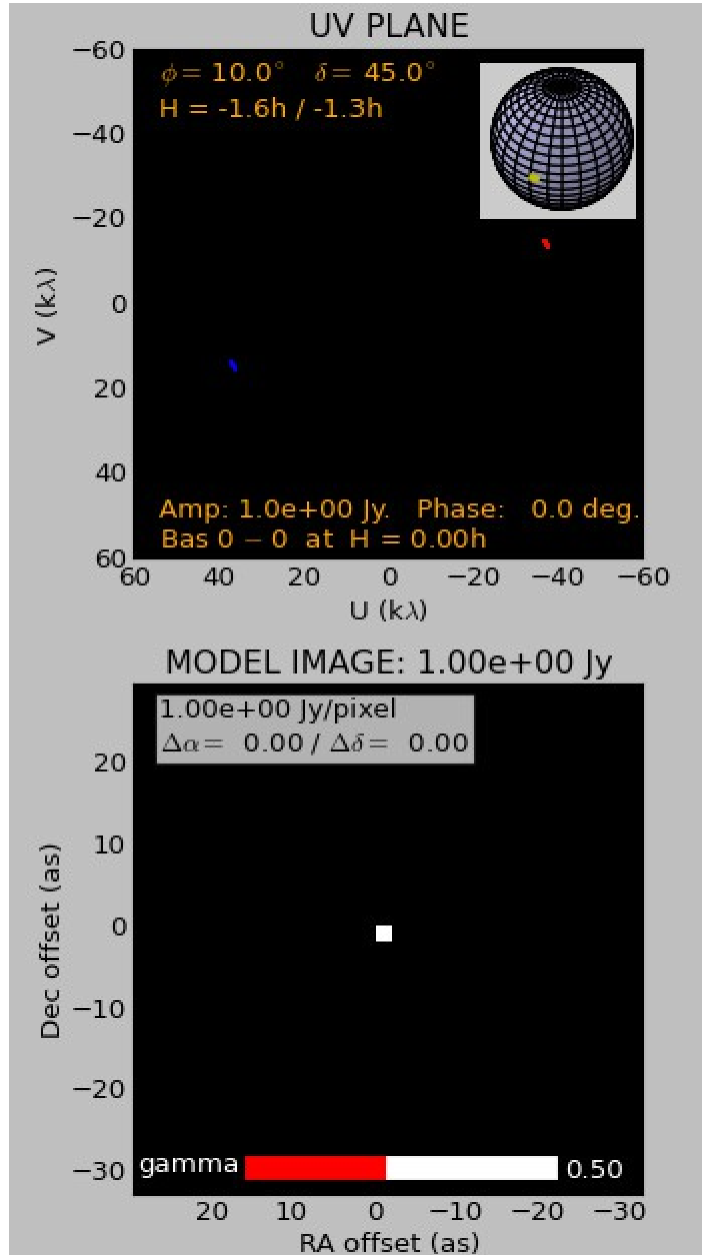
Point source in the sky

Ideal uv plane

Interferometry basics

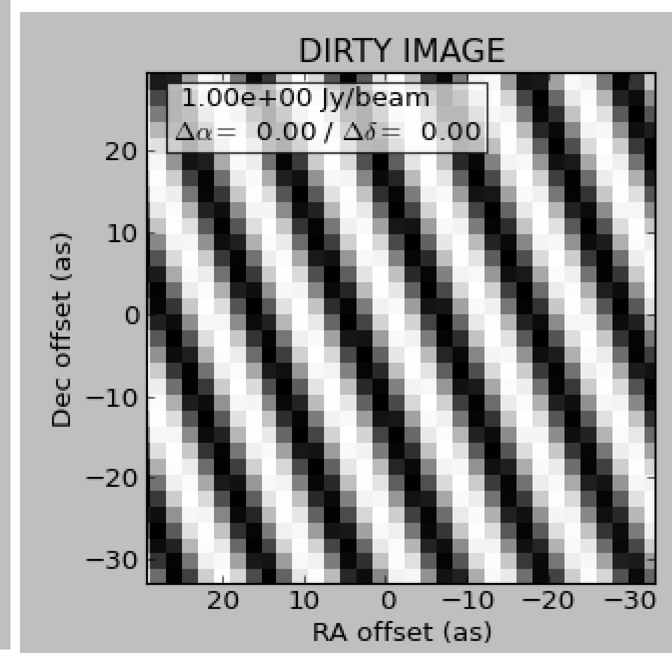
Snapshot observation with two antennas 1 baseline





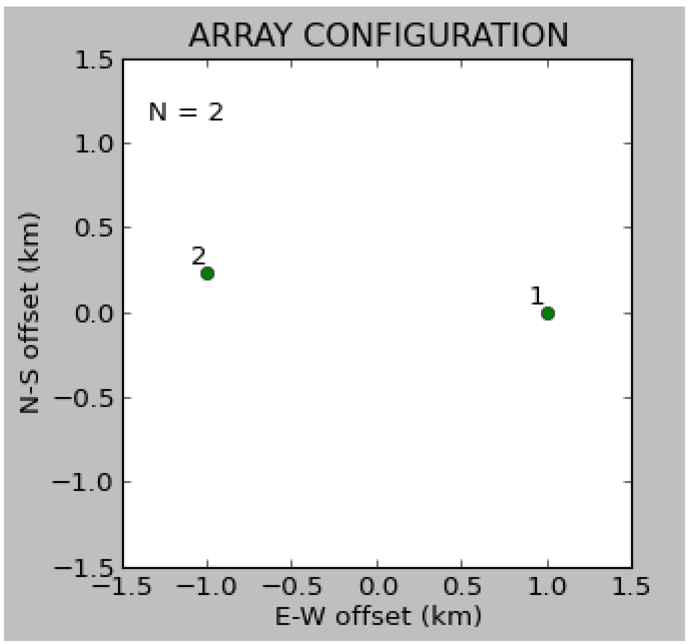
← uv-coverage

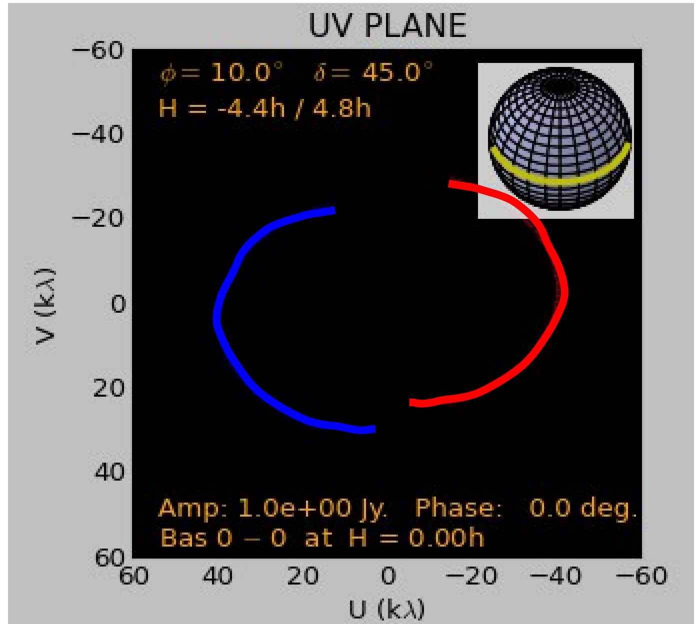
Resulting image



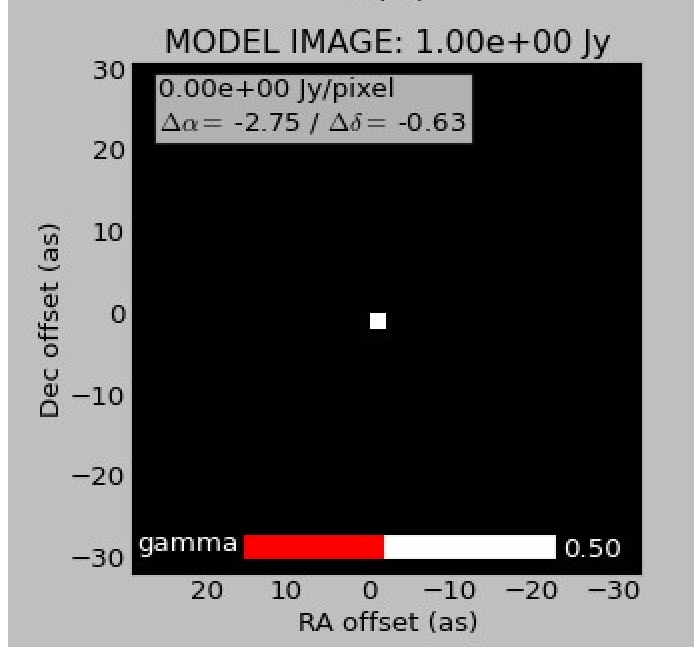
Interferometry basics

8 hrs observation
with two antennas
1 baseline (~2 km)

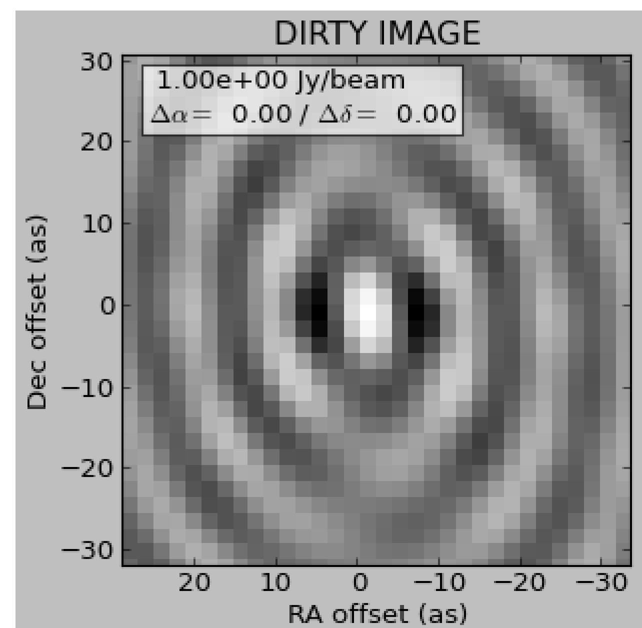




← uv-coverage

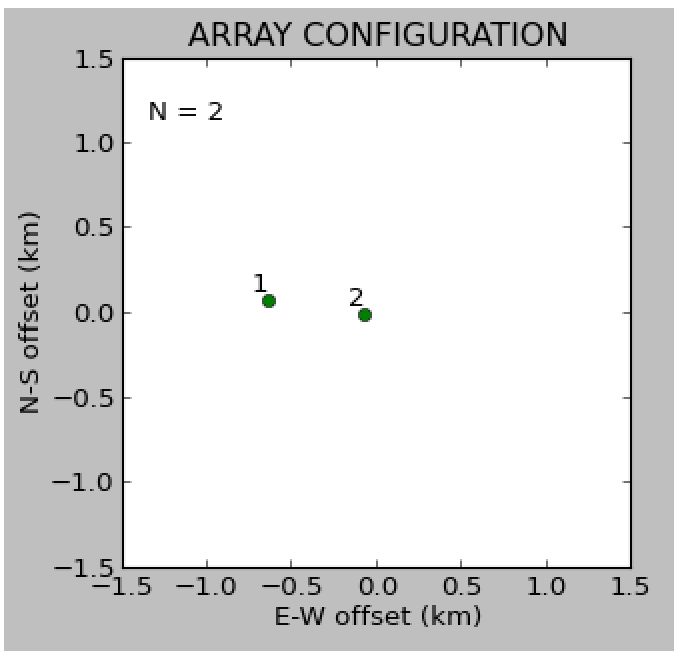


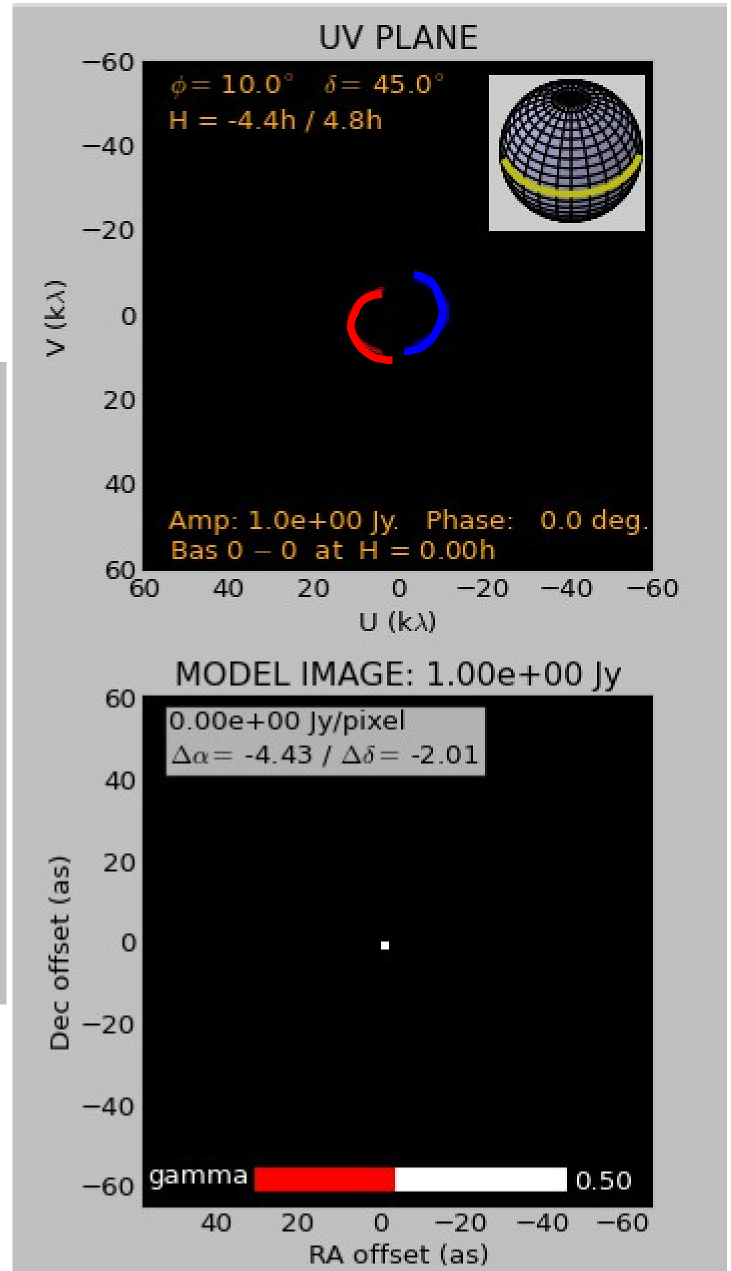
Resulting image



Interferometry basics

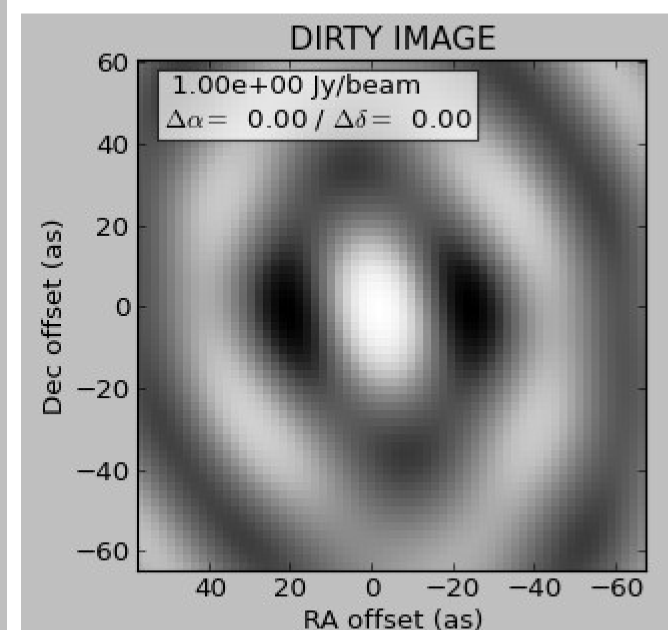
8 hrs observation
with two antennas
1 baseline (~800 m)





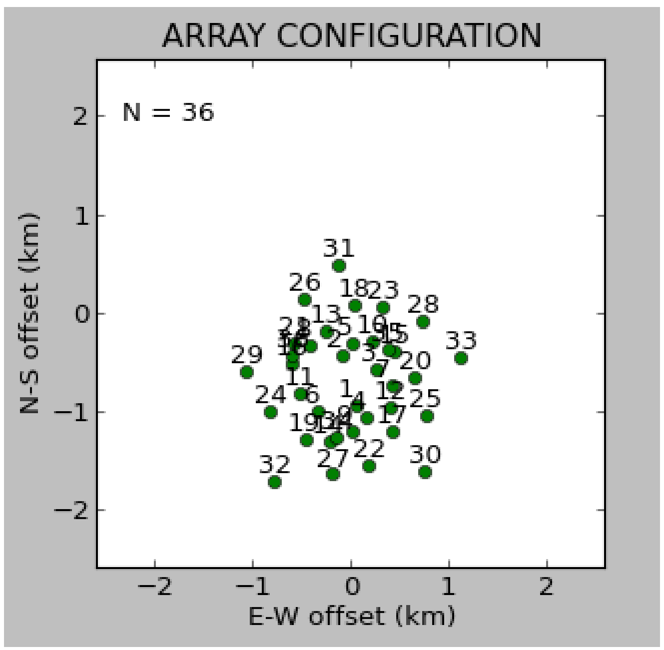
← uv-coverage

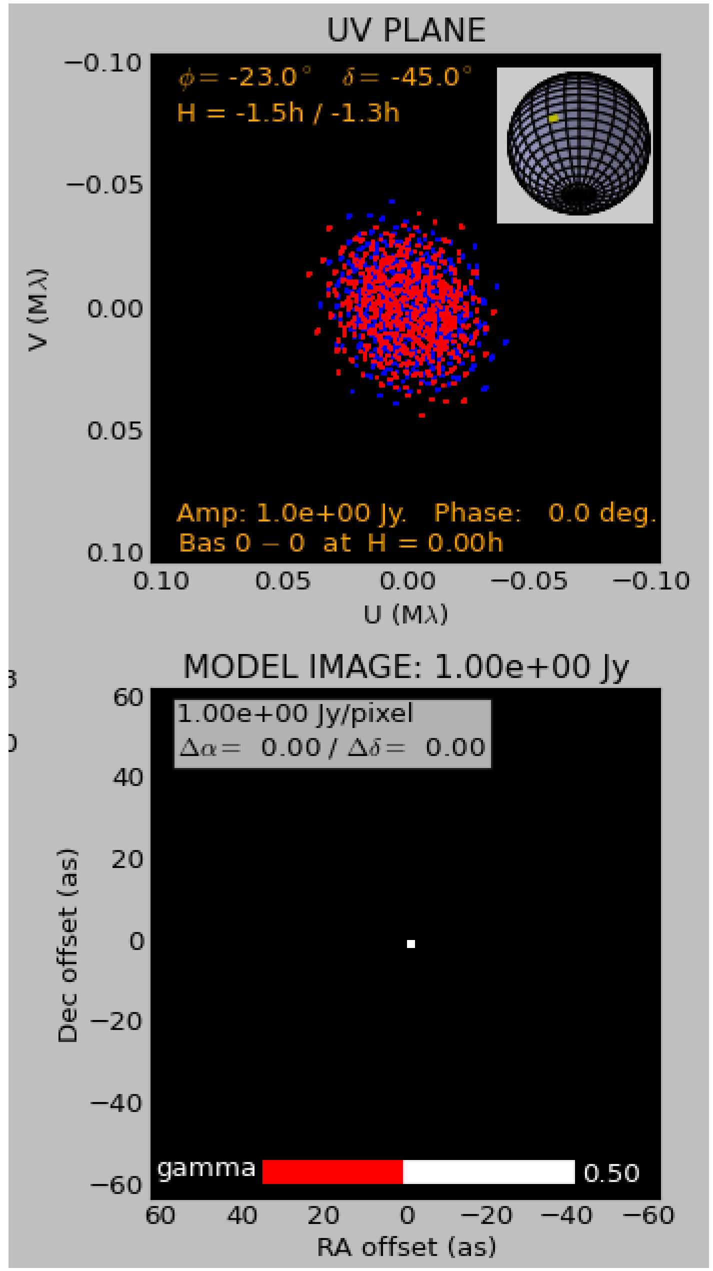
Resulting image



Interferometry basics

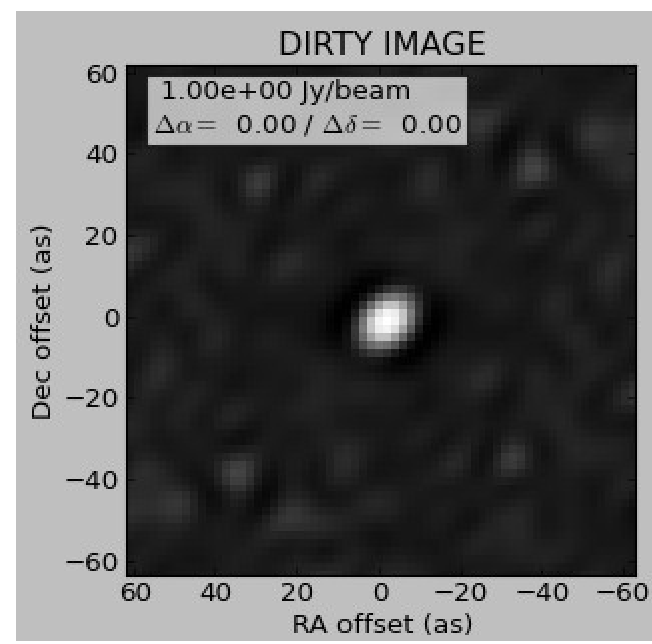
Snapshot observation with 36 antennas 1260 baselines





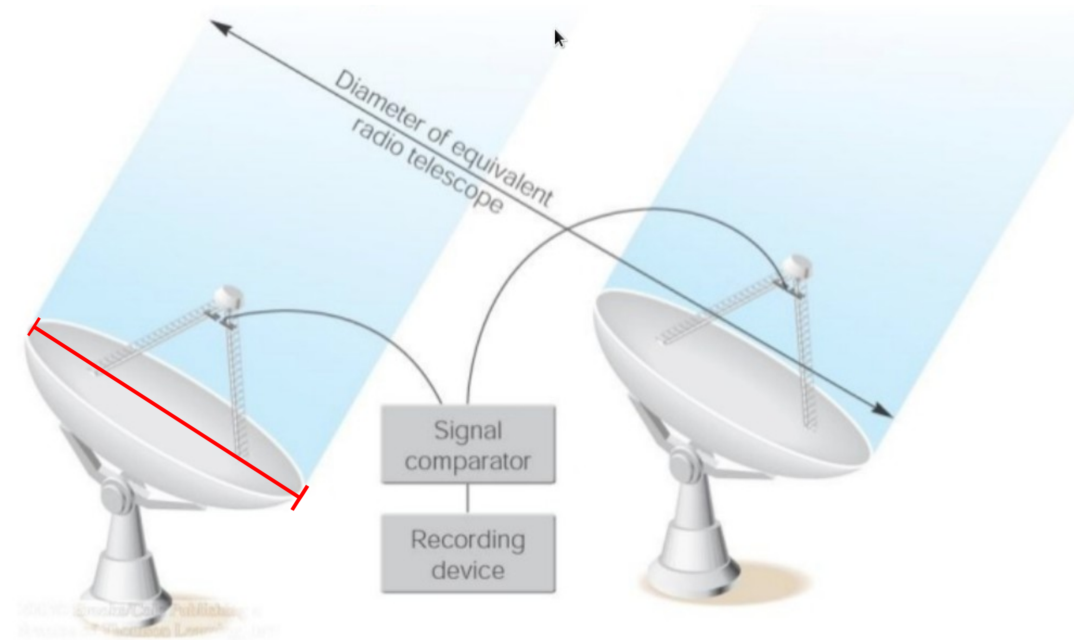
← uv-coverage

Resulting image



Interferometry basics

Field of View $FOV \propto \frac{\lambda}{D}$

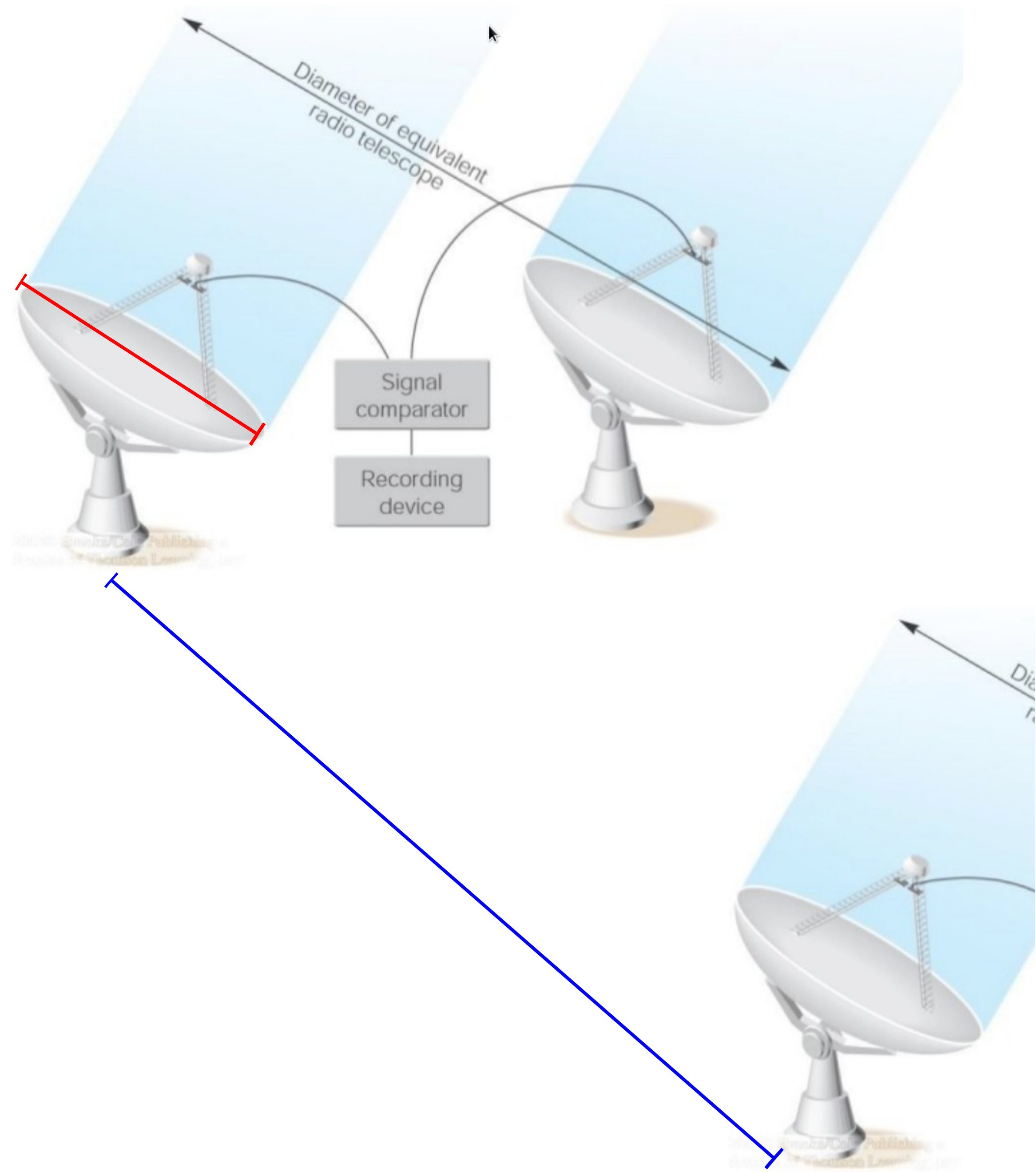


Interferometry basics

Field of View $FOV \propto \frac{\lambda}{D}$

Resolution

$$\theta_{res} \approx \frac{\lambda}{B_{max}}$$



Interferometry basics

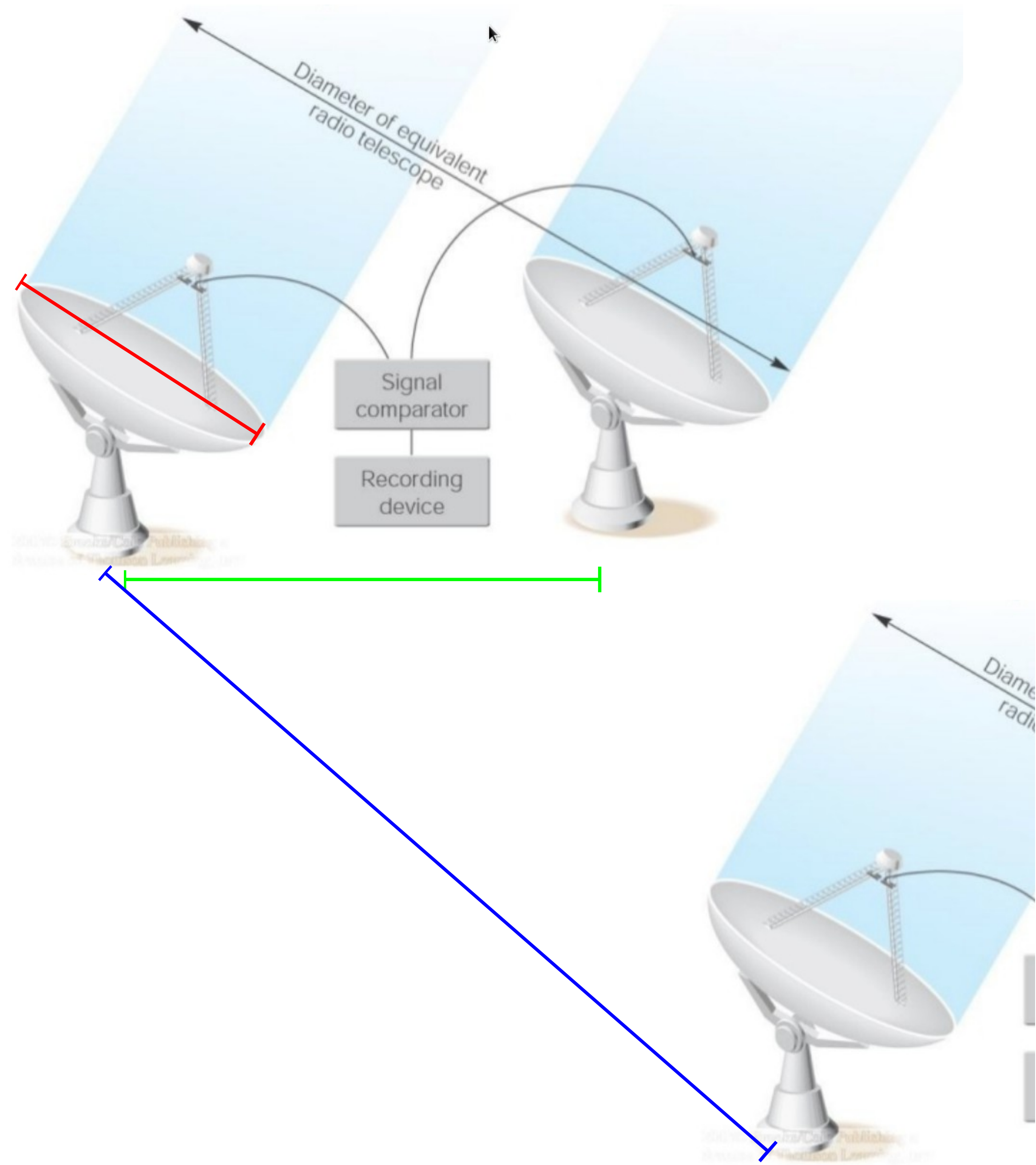
Field of View $FOV \propto \frac{\lambda}{D}$

Resolution

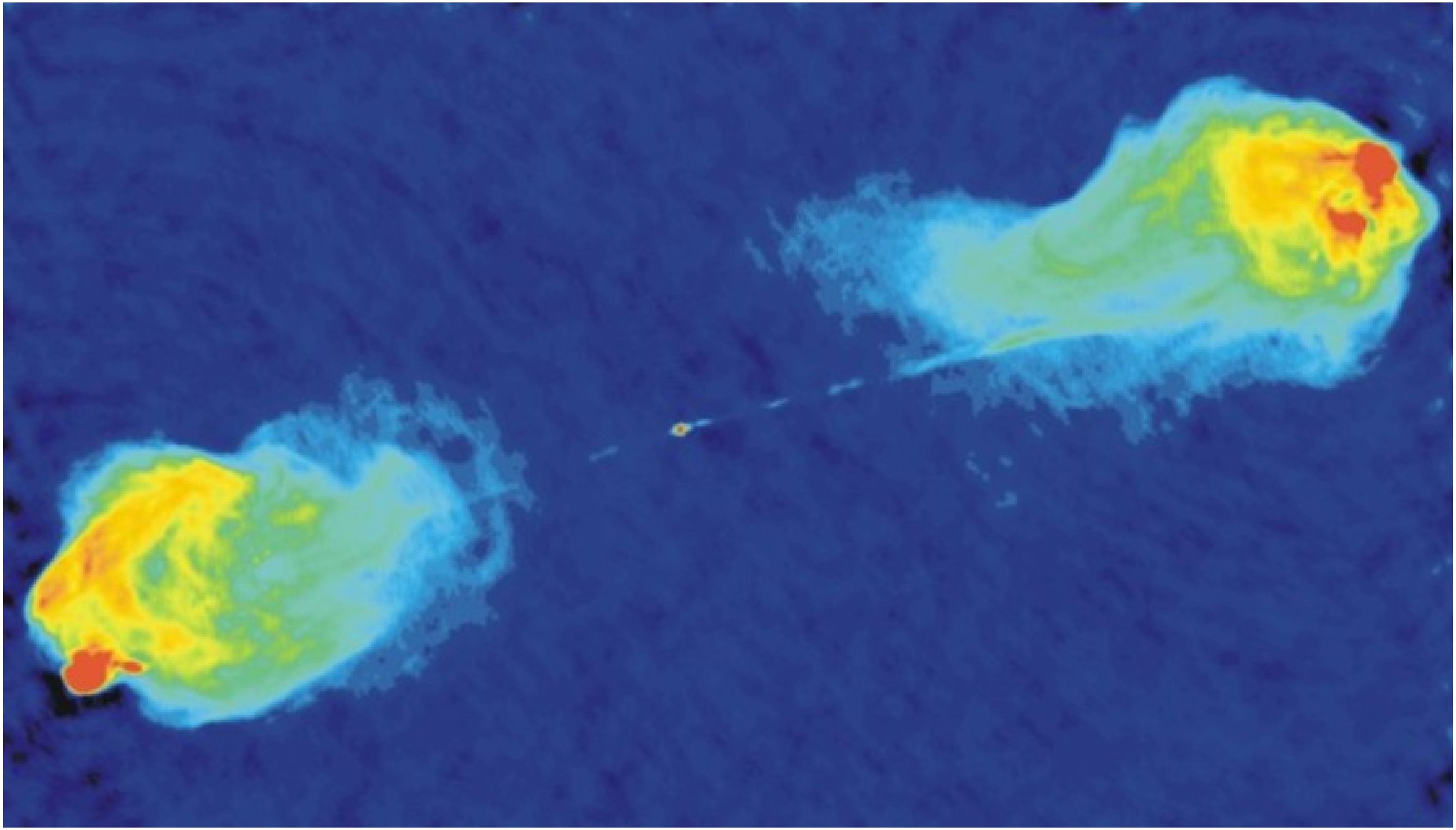
$$\theta_{res} \approx \frac{\lambda}{B_{max}}$$

Largest recoverable scale

$$\theta_{MRS} \approx \frac{\lambda}{B_{min}}$$



How to get this image of Cygnus A?



Credit: Image courtesy of NRAO/AUI; R. Perley, C. Carilli & J. Dreher

Peculiarities @ mm

With increasing frequency:

- **No external human interferences in the data**

- **No ionospheric effect**

- Tropospheric effects: absorption and delay of signal
  - → stronger weather dependency
  - → T_{sys} dominated by atmosphere noise

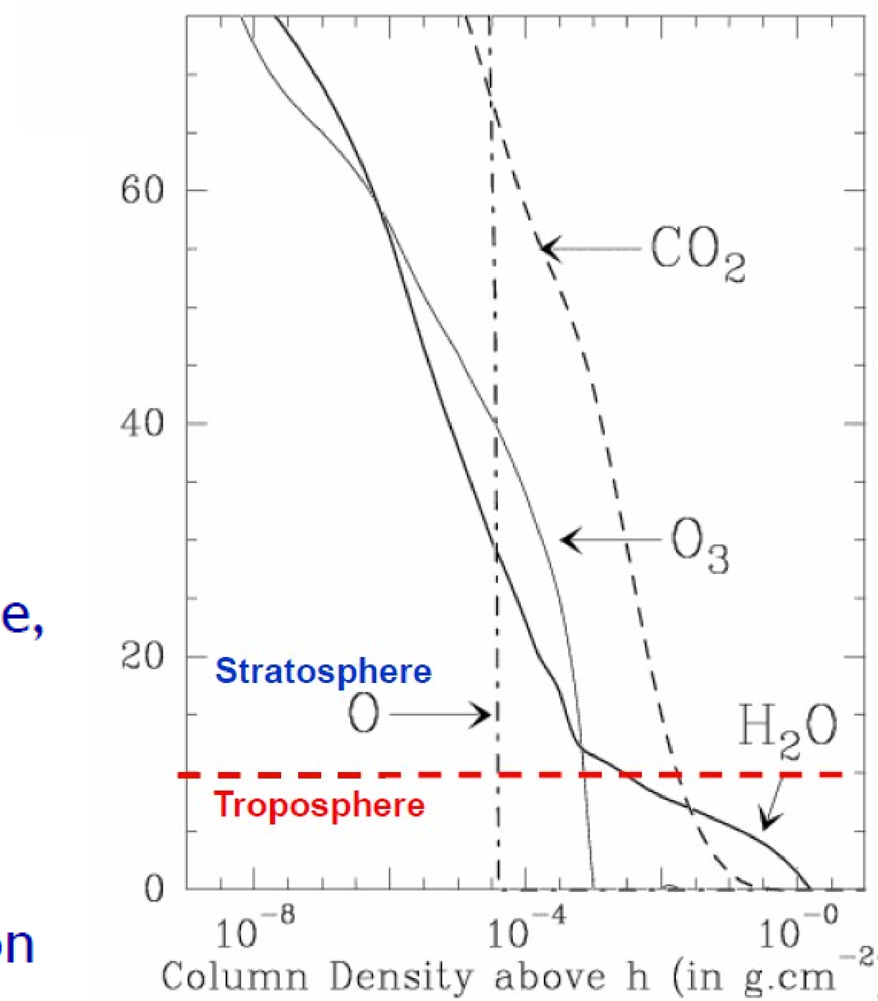
- Time variability of quasar increases
  - → which flux calibrators?

Peculiarities @ mm

The role of troposphere

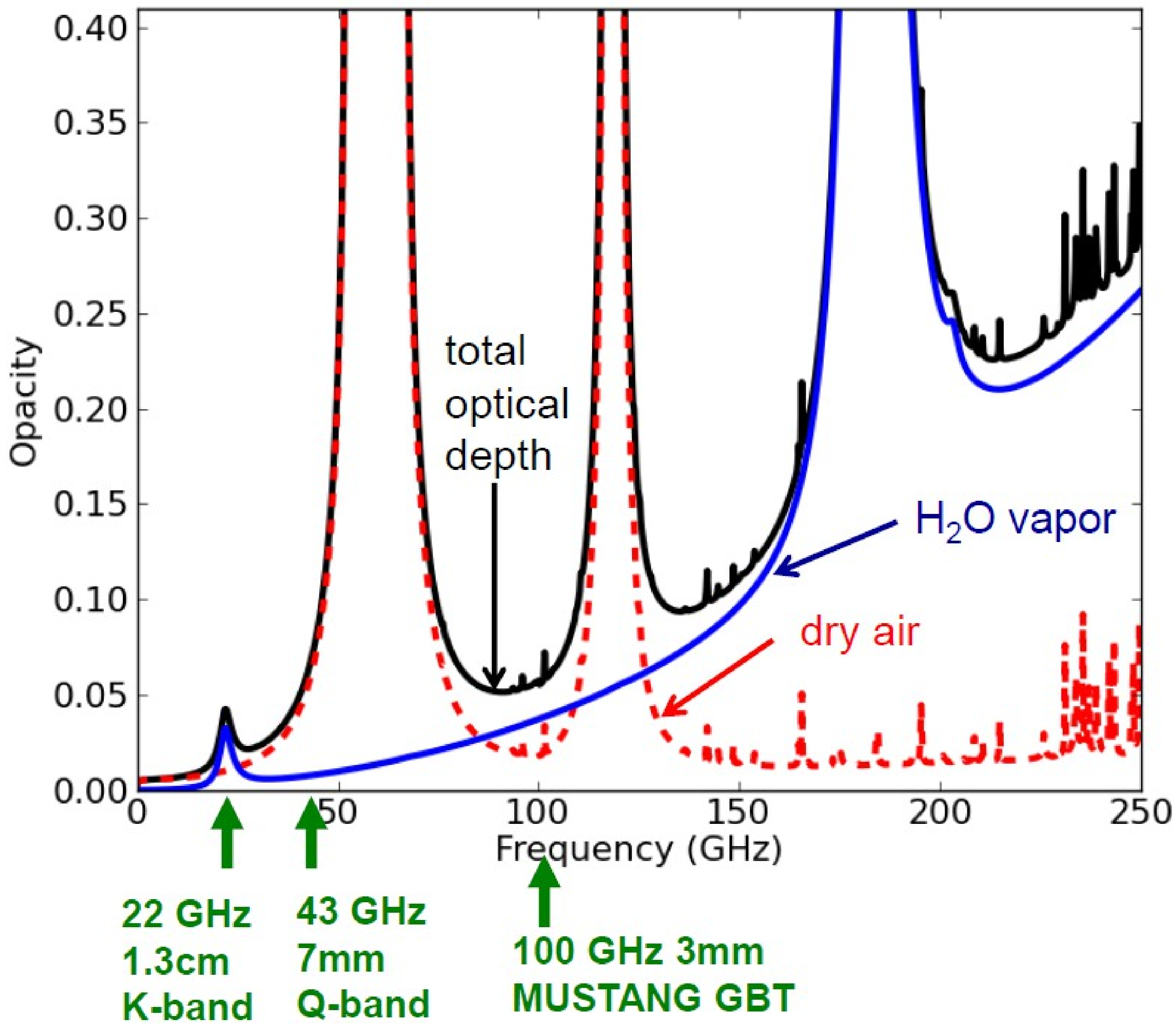
- H_2O (mostly vapor)
- "Hydrosols" (water droplets in clouds and fog)
- "Dry" constituents: O_2, O_3, CO_2, Ne, He, Ar, Kr, CH_4, N_2, H_2
- clouds & convection = time variation

Column density as function of altitude



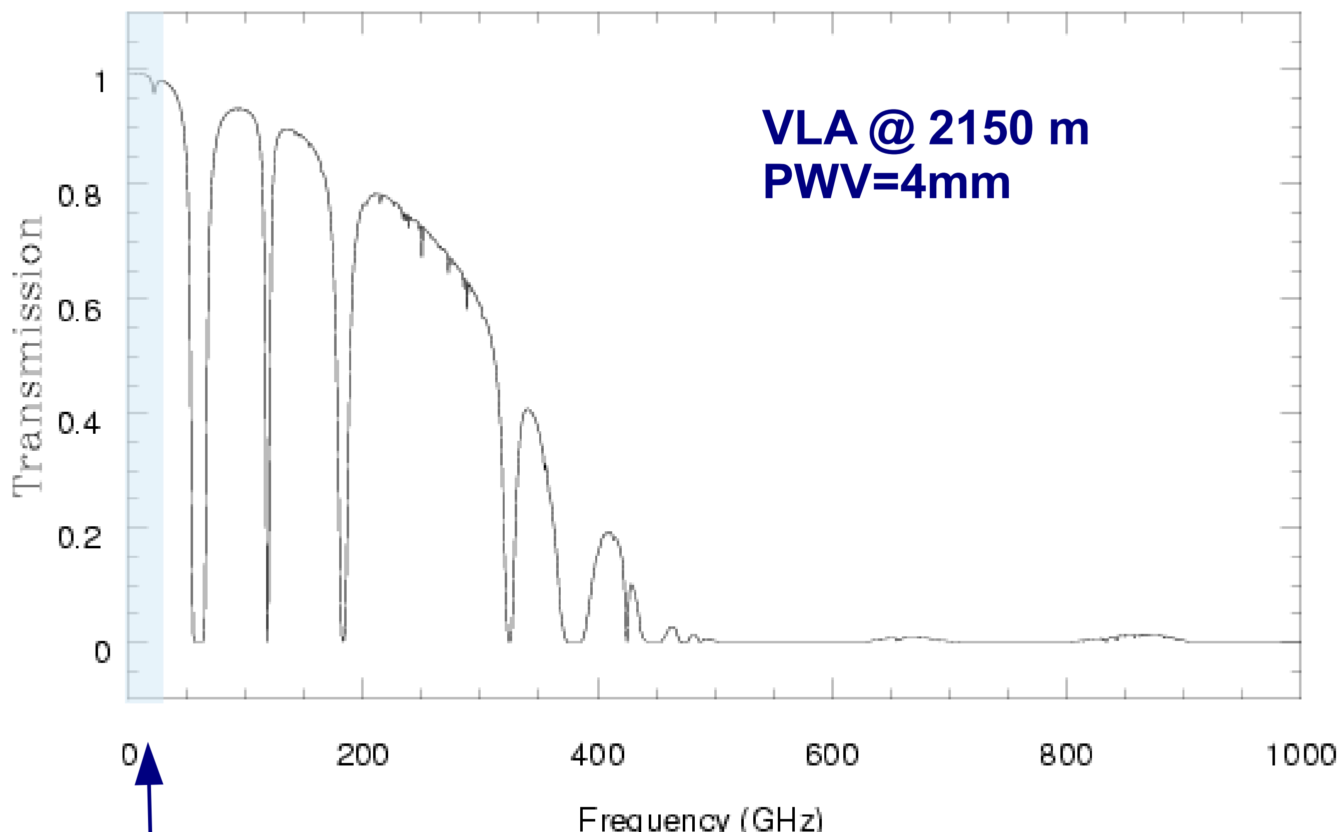
Peculiarities @ mm

Optical depth as function of frequency



Peculiarities @ mm

Tropospheric opacity depends on altitude

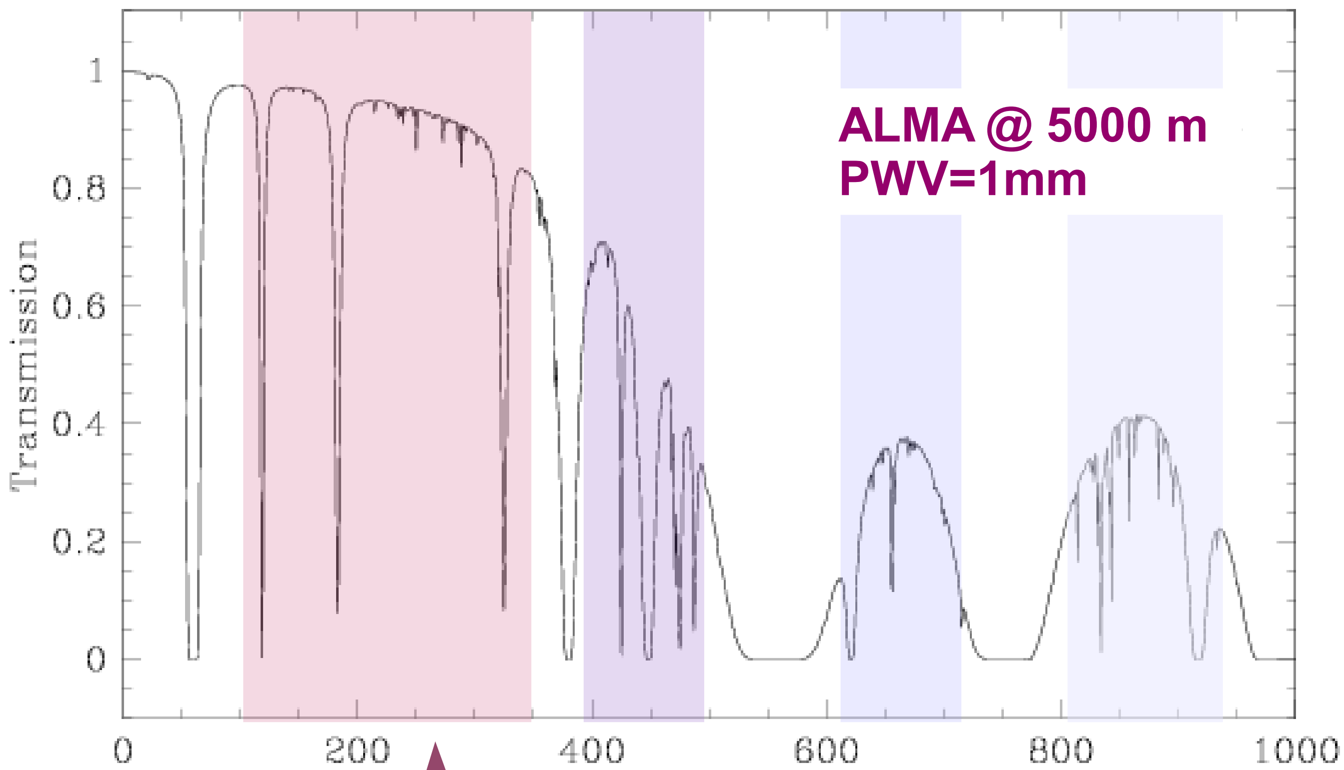


VLA bands

Atmospheric transmission not a problem @ $\lambda >$ cm

Peculiarities @ mm

Tropospheric opacity depends on altitude

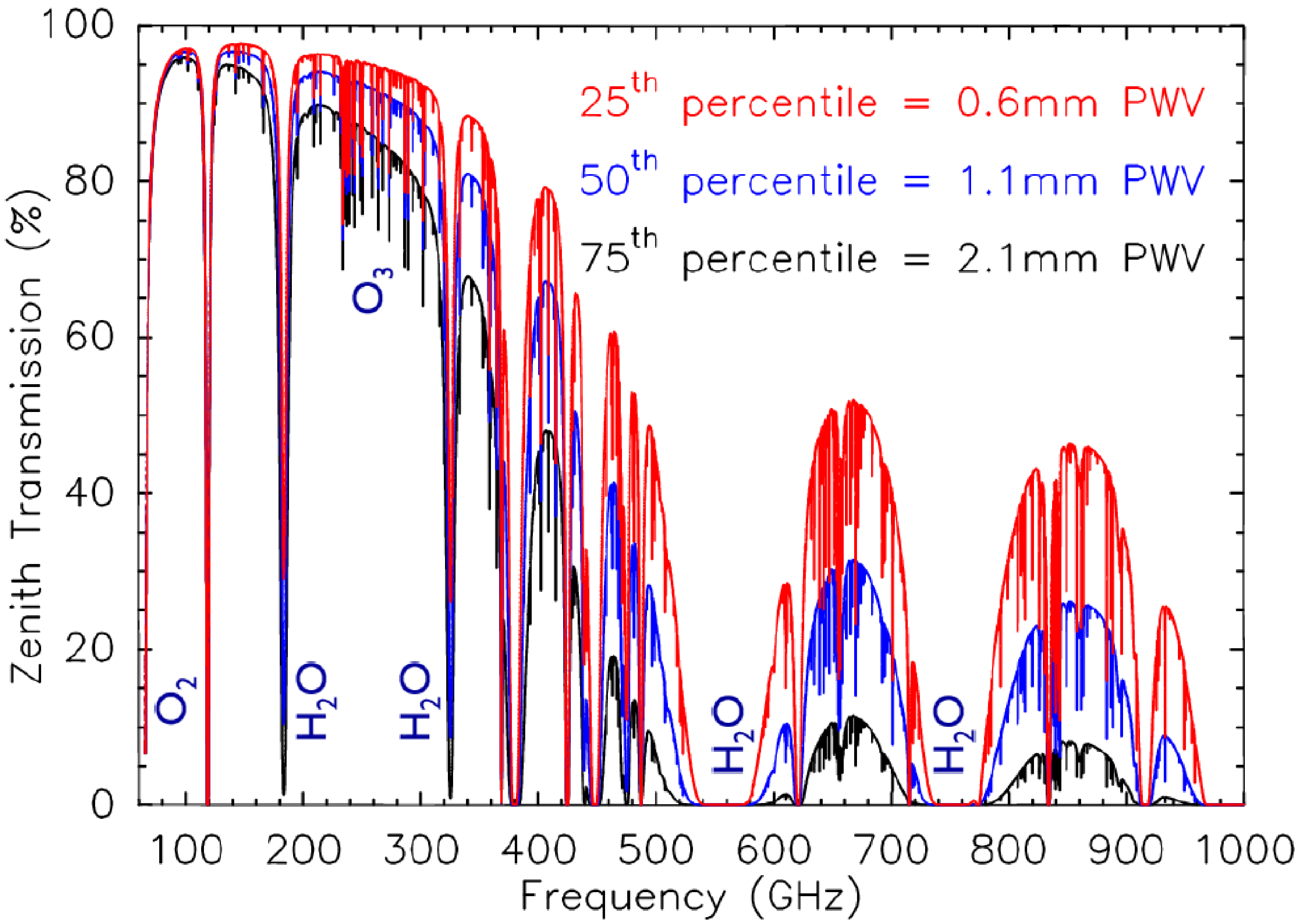


Difference due to the scale height of water vapor

ALMA bands

Peculiarities @ mm

PWV= Precipitable Water Vapour



Peculiarities @ mm

System noise temperature

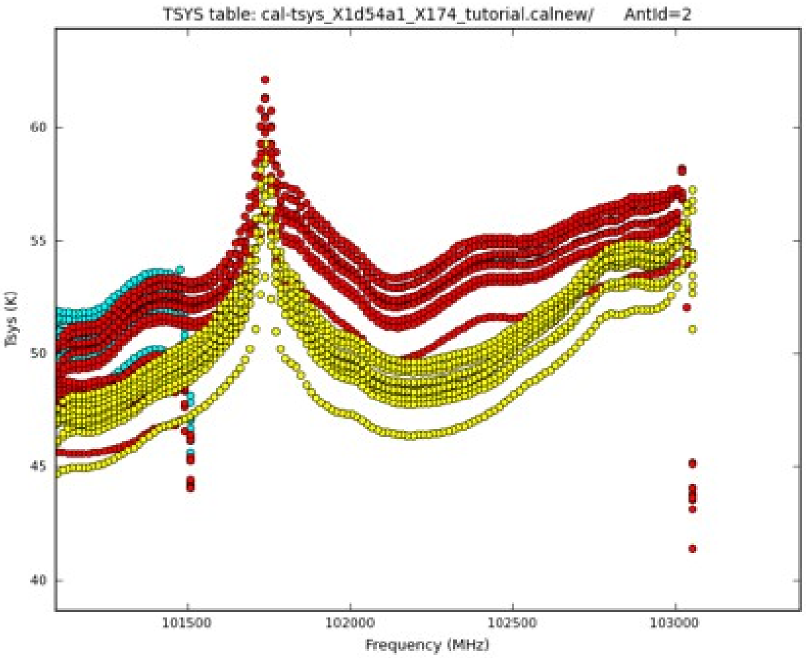
$$T_{sys} \sim T_{atm}\,(e^{\tau} - 1) + T_{rx}\,e^{\tau}$$

At lower frequencies T_{rx} is dominant

ALMA front end are equipped with an Amplitude Calibration Device (ACD)

$\rightarrow$ T_{sys} and T_{rx}

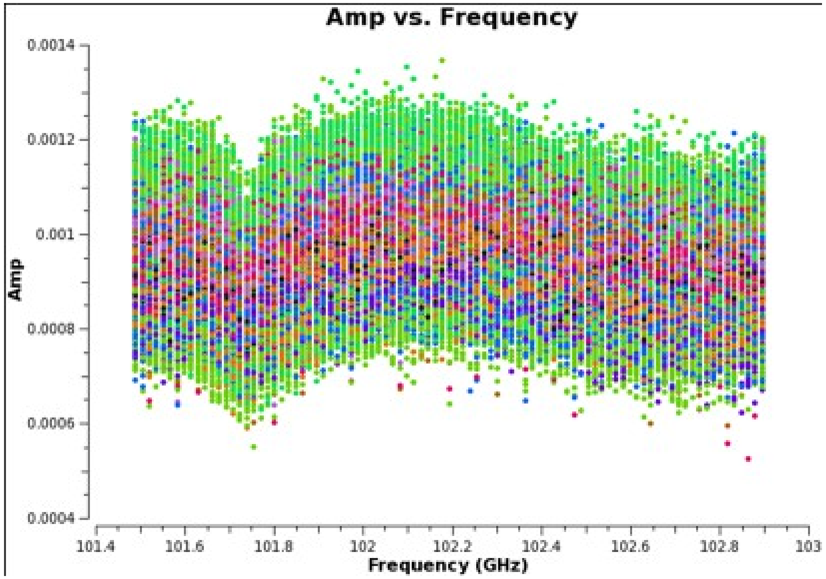
Peculiarities @ mm



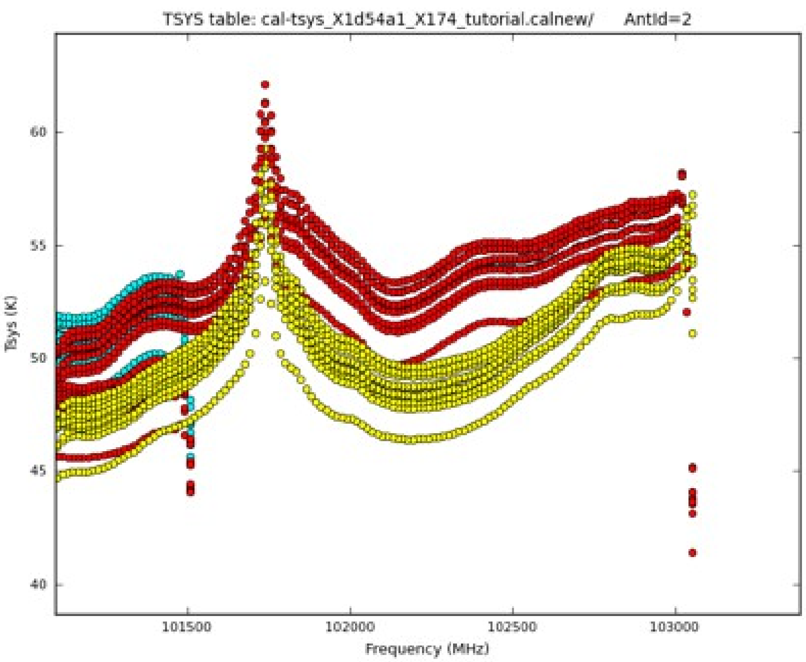
Tsys calibration

Spectral Tsys
band 3 (~100 GHz)

Before



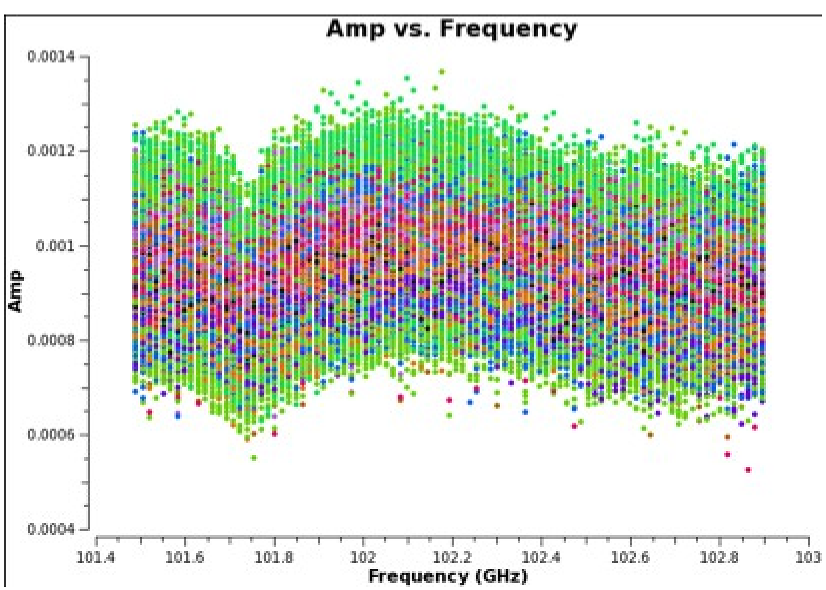
Peculiarities @ mm



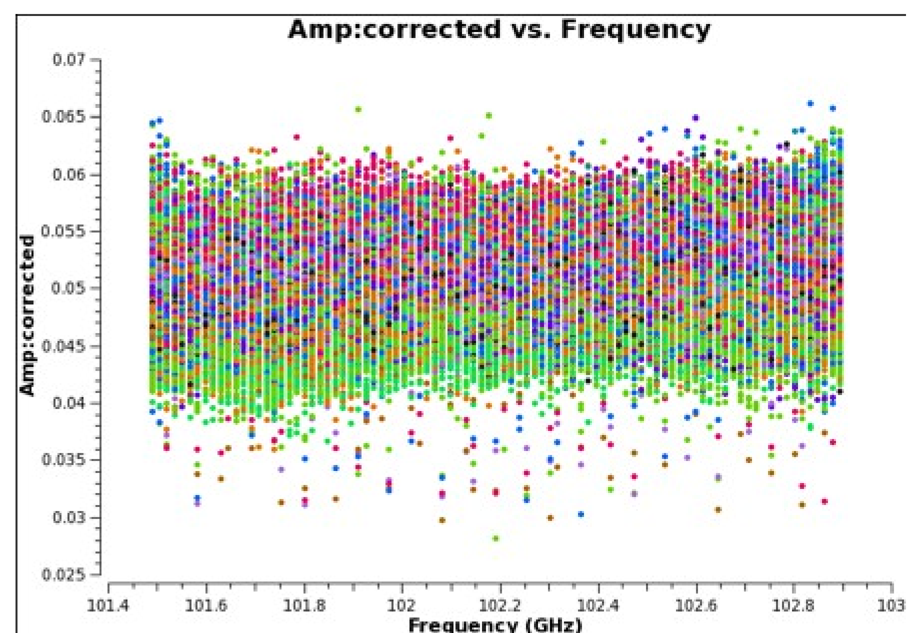
Tsys calibration

Spectral Tsys
band 3 (~100 GHz)

Before



After



Peculiarities @ mm

Mean effect of atmosphere on Phase

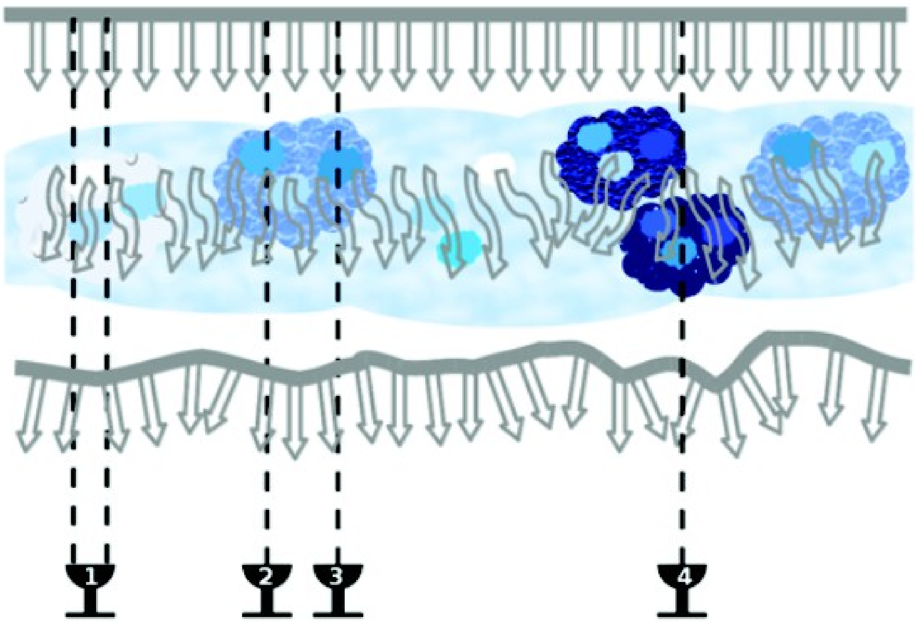
Variations in precipitable water vapor (PWV) cause phase fluctuations, worse at higher frequencies, resulting in:

- Phase shift due to refractive index n $\neq 1$
- Low coherence (loss of sensitivity)

Patches of air with different pwv
(and hence index of refraction)
affect the incoming wave front differently.

Antenna 1, 2, 3 see slightly different disturbances

Sky above antenna 4 varies independently



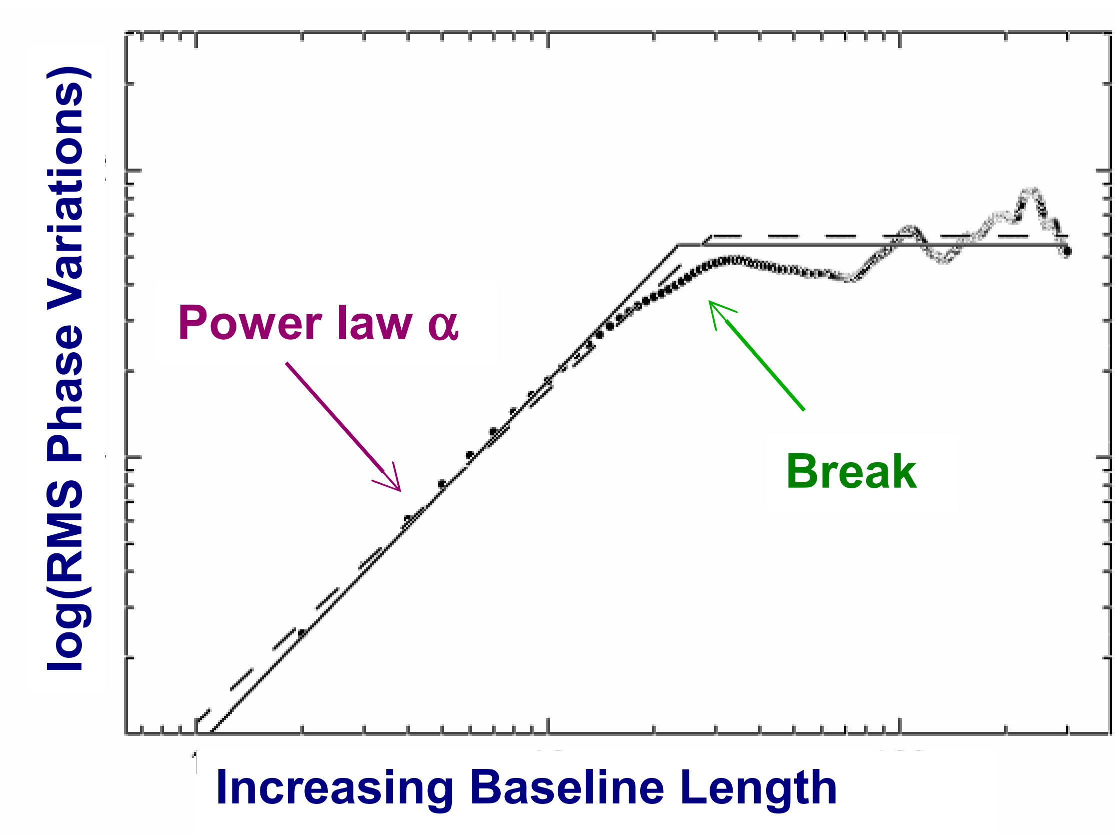
The phase change experienced by an e.m. wave can be related to pwv

$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$

Hogg, Guiraud, & Decker, 1981

Peculiarities @ mm

Atmospheric phase fluctuations



Kolmogorov turbulence theory

Phase noise

$$\varphi_{rms} = \frac{K\, b^{\alpha}}{\lambda}$$

b=baseline length (km)
α = 1/3 to 5/6 (thin or thick atmosphere)
λ = wavelength (mm)
K constant (~100 for ALMA)

The break is typically @ baseline lenghts few hundred meters to few km (scale of the turbulent layers)

Break and maximum are weather and wavelength dependent

Peculiarities @ mm

Atmospheric phase fluctuations → decorrelation

We loose integrated flux because visibility vectors partly cancel out

$$\langle V \rangle = V_o \langle e^{i\varphi} \rangle = V_o e^{-(\varphi_{rms}^2)/2}$$

φ_{rms} = 1 radian → <V> = 0.60 V_0

In summary
Fluctuations in the line-of-sight pwv of an antenna
cause phase variations of the order of ~30 deg / sec at 90 GHz,
and scales linearly with frequency....

$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$

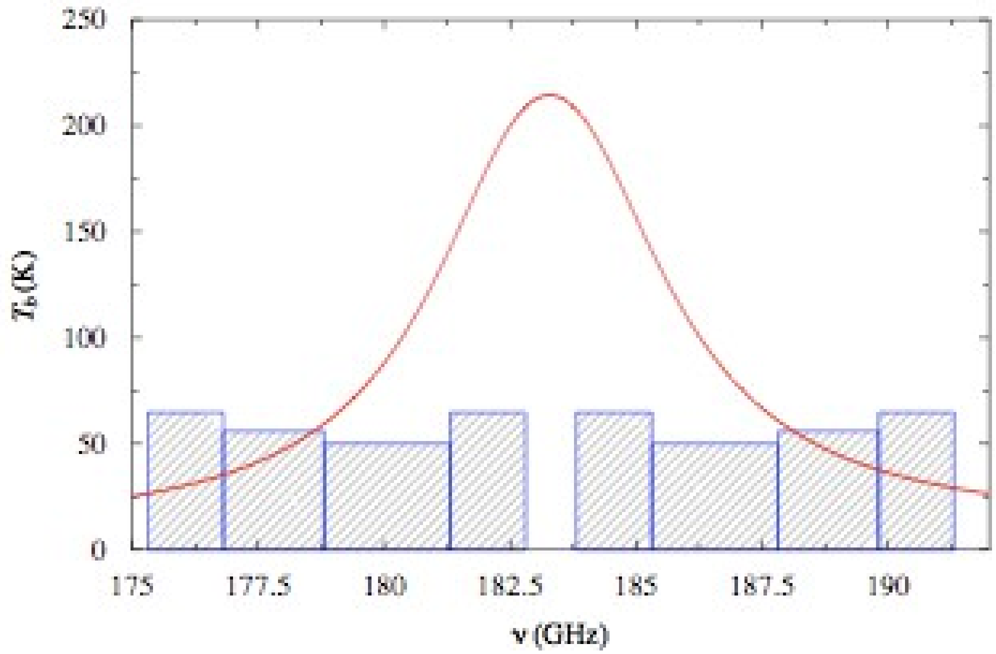
and the phase noise is worse at longer baselines...

$$\varphi_{rms} = \frac{K\, b^{\alpha}}{\lambda}$$

Peculiarities @ mm

WVR correction

Each ALMA 12 m antenna has a water **vapour radiometer**



Four “channels” flanking the peak of the 183 GHz water line

Data taken every second

Peculiarities @ mm

WVR correction

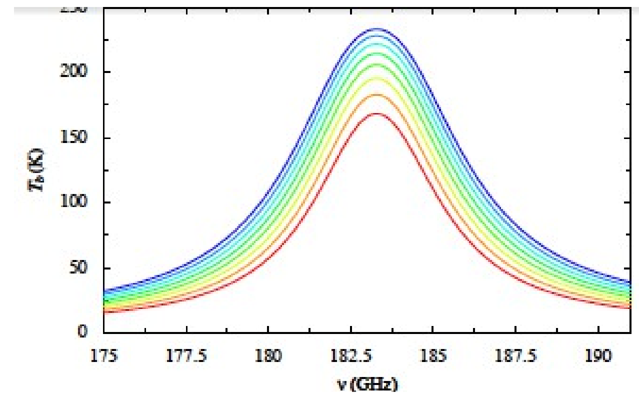
Each ALMA 12 m antenna has a water **vapour radiometer**

Four “channels” flanking the peak of the 183 GHz water line

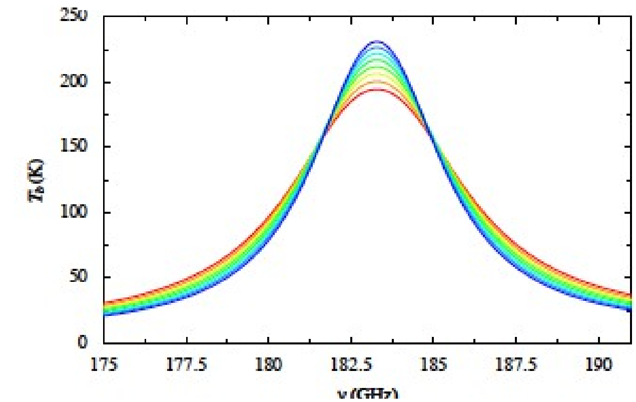
Data taken every second

Convert 183 GHZ brightness to PWV (wvrgcal):
model PWV, temperature and pressure
compare to the observed “spectrum”
compute the correction:

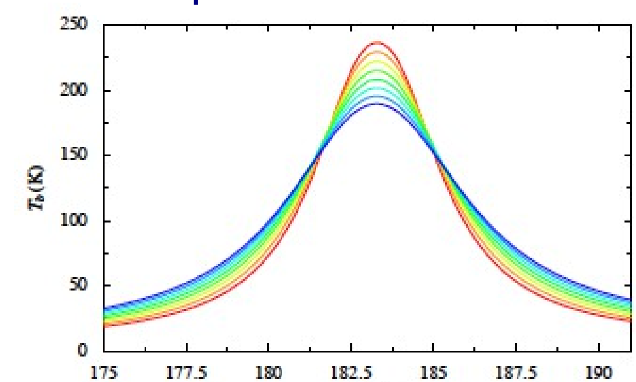
$$\varphi_e \approx \frac{12.6\pi}{\lambda} \cdot pwv$$



PWV from 0.6 to 1.3 mm



Temperature 230-300 K

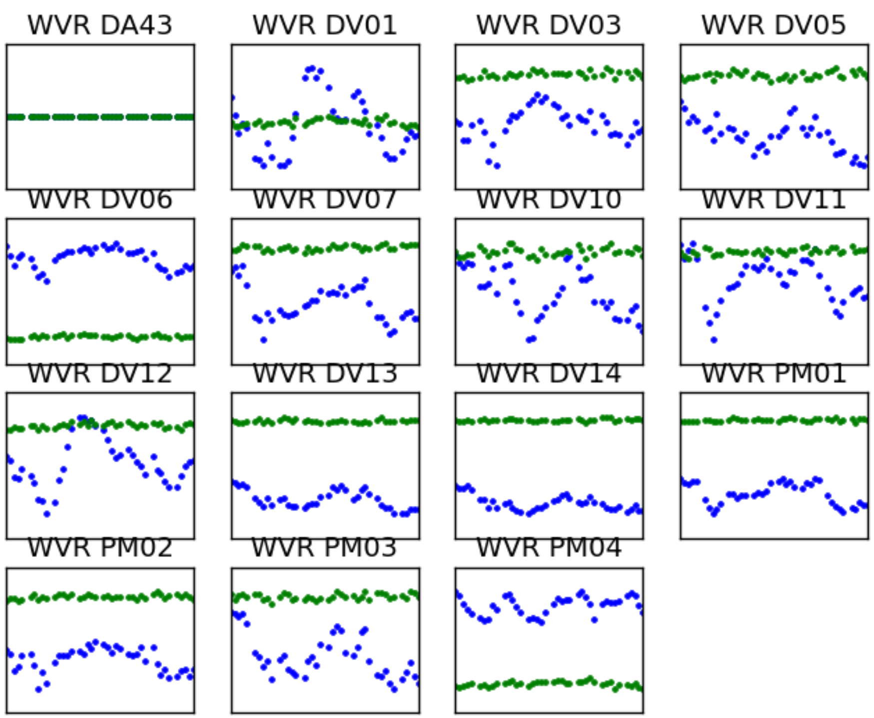


Pressure 400-750 mBar

Peculiarities @ mm

WVR correction

Band 6 (230 GHz)

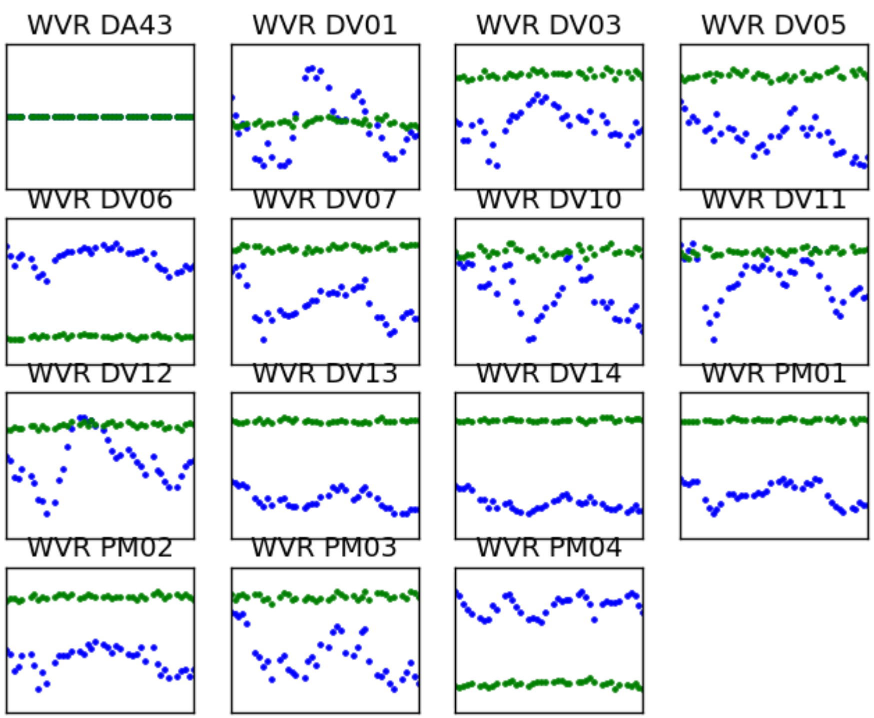


Raw phases & WVR corrected phases

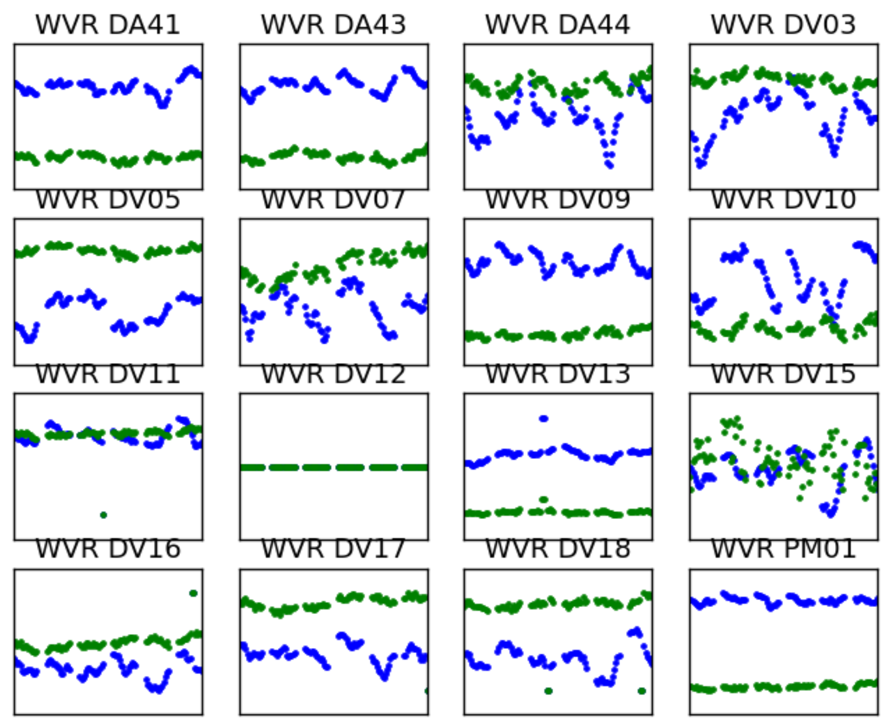
Peculiarities @ mm

WVR correction

Band 6 (230 GHz)



Band 7 (340 GHz)

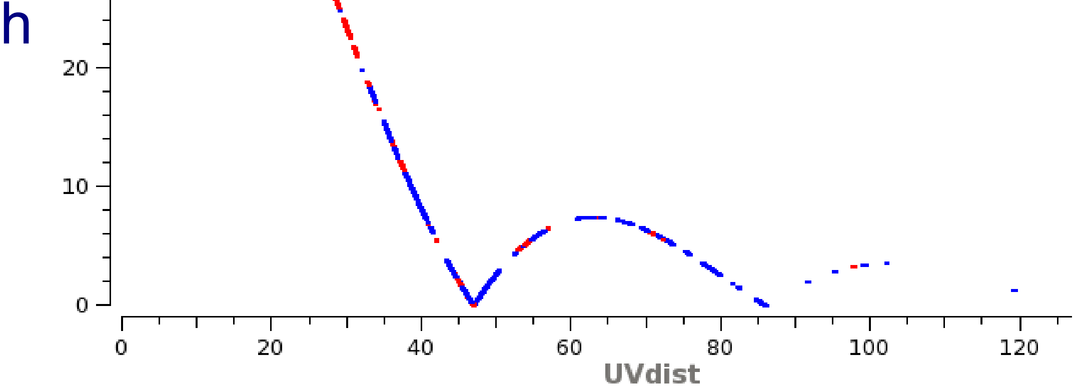


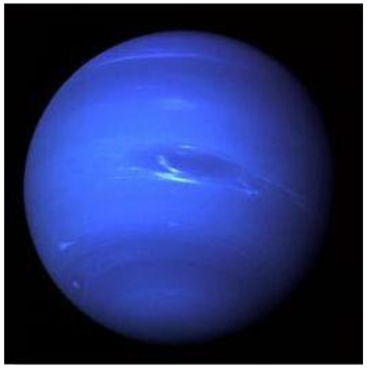
Raw phases & WVR corrected phases

Peculiarities @ mm

Flux calibrators

Neptune
690 GHz
Extended
config





- Quasars are strongly time-variable and good models do not exist at high frequencies

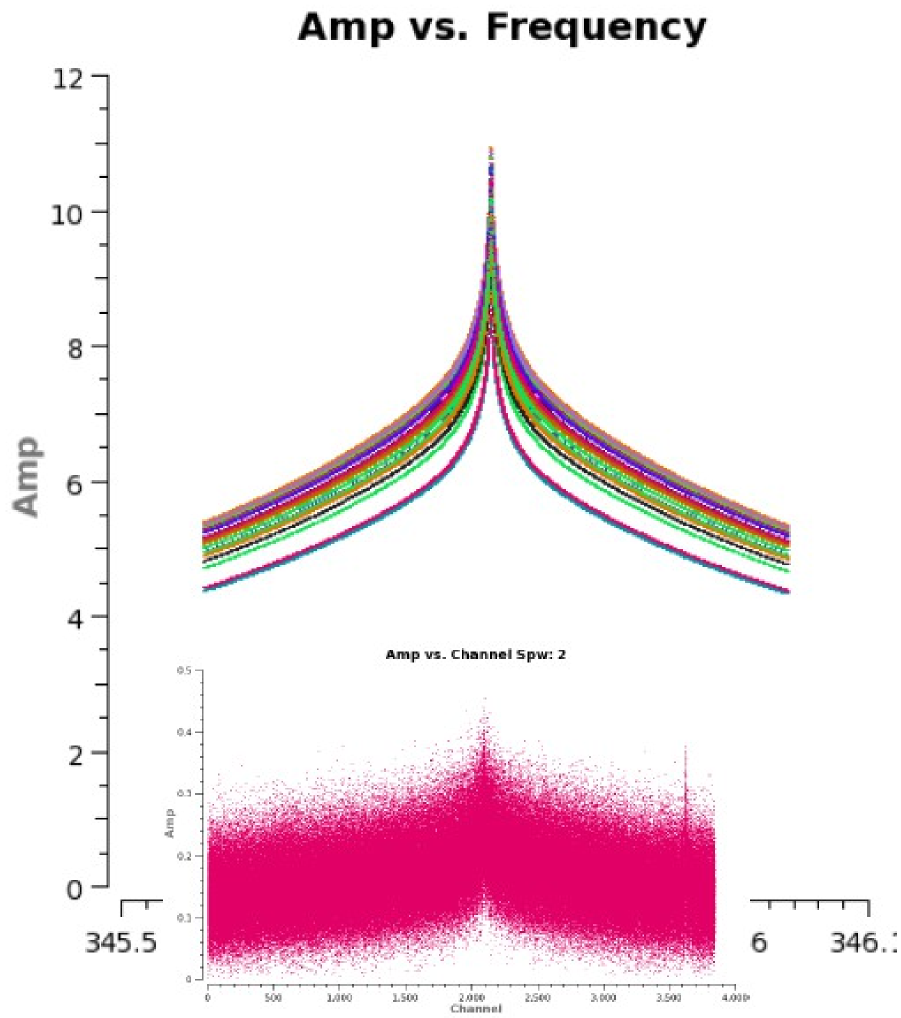
- Solar System bodies are used as primary flux calibrators (Neptune, Jovian moons, Titan, Ceres) but with many challenges:
  - **all are resolved on long baselines**
  - **brightness varies with distance from Sun and Earth**
  - **line emission present → need models**

Other possibilities: asteroids, red giant stars...
Monitoring of point-like quasars

Peculiarities @ mm

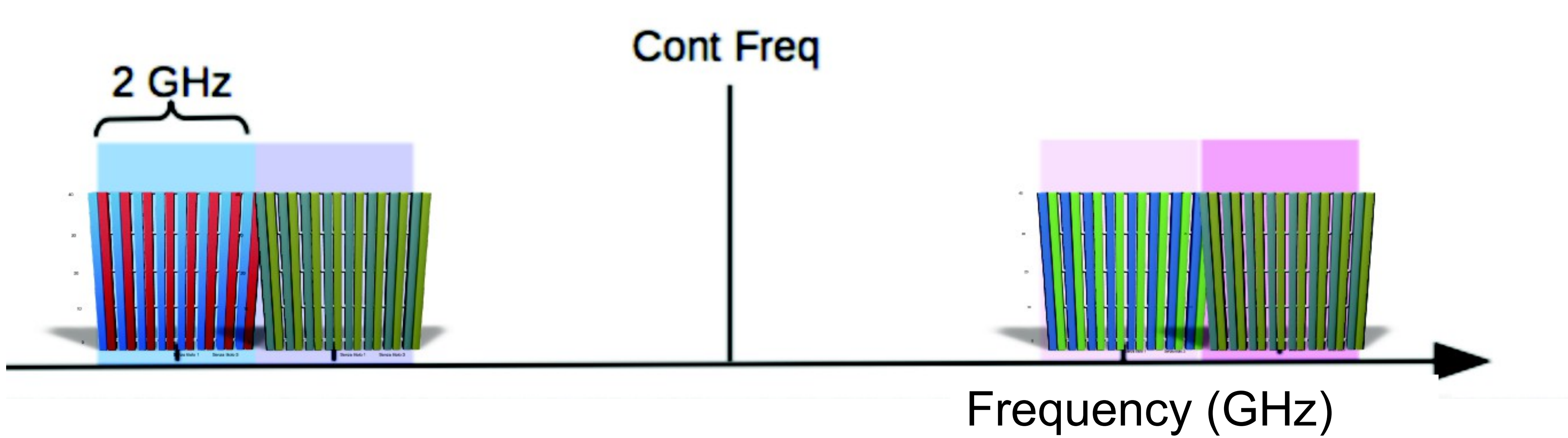
Flux calibrators

Model spetral lines: CO in Titan



Interferometric data

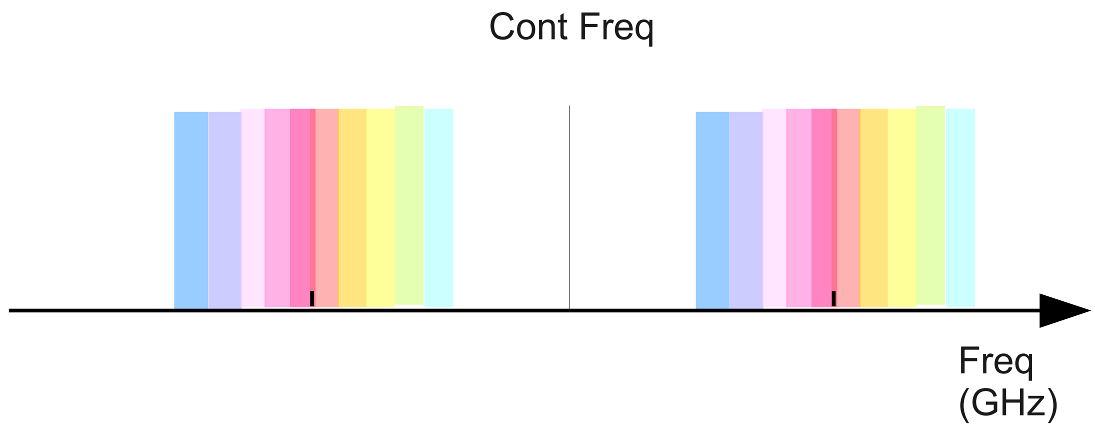
Modern interferometric observations are taken in multi-channel mode regardless if they are continuum or line observations

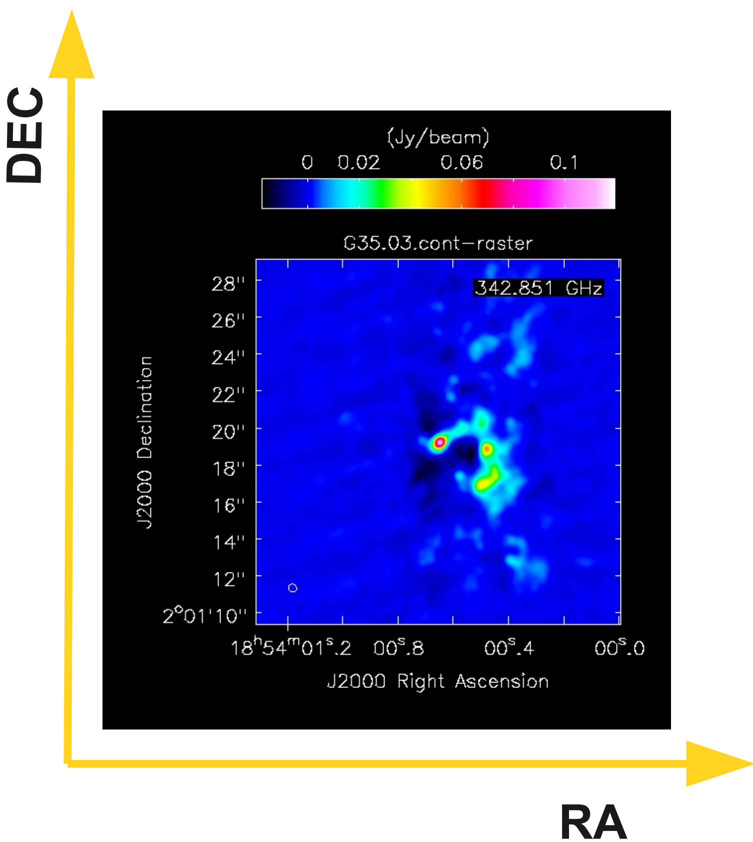


Data are actually **data cube:**
from each channel (freq, velocity) 1 uv-plane

Interferometric data

Continuum images are obtained combining all the (line-free) channels.



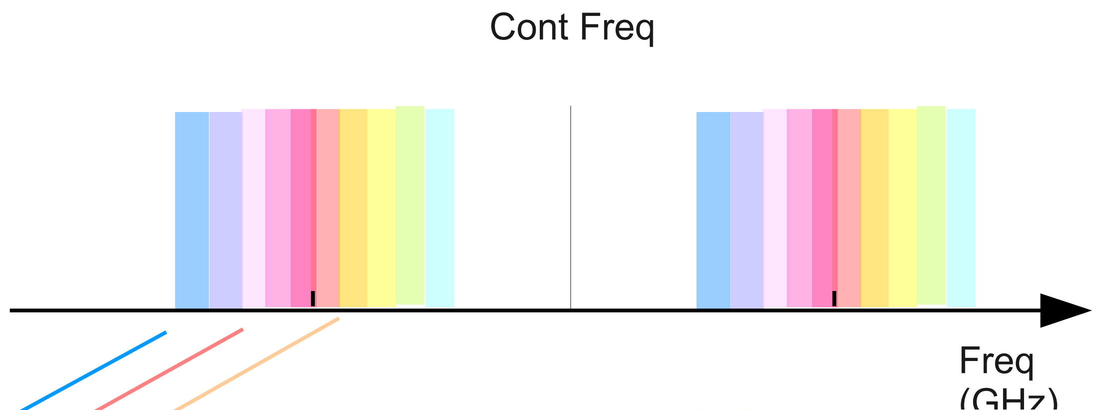


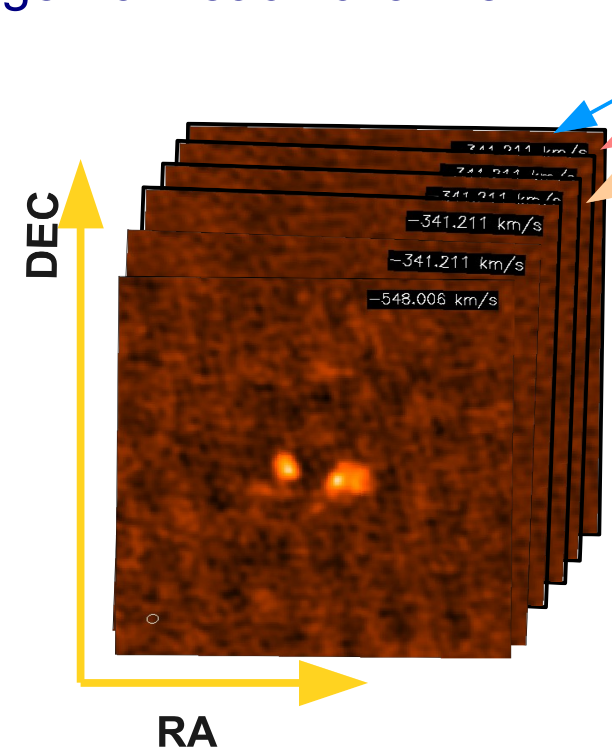
The resulting image is a 2-Dimensional image at the central frequency.

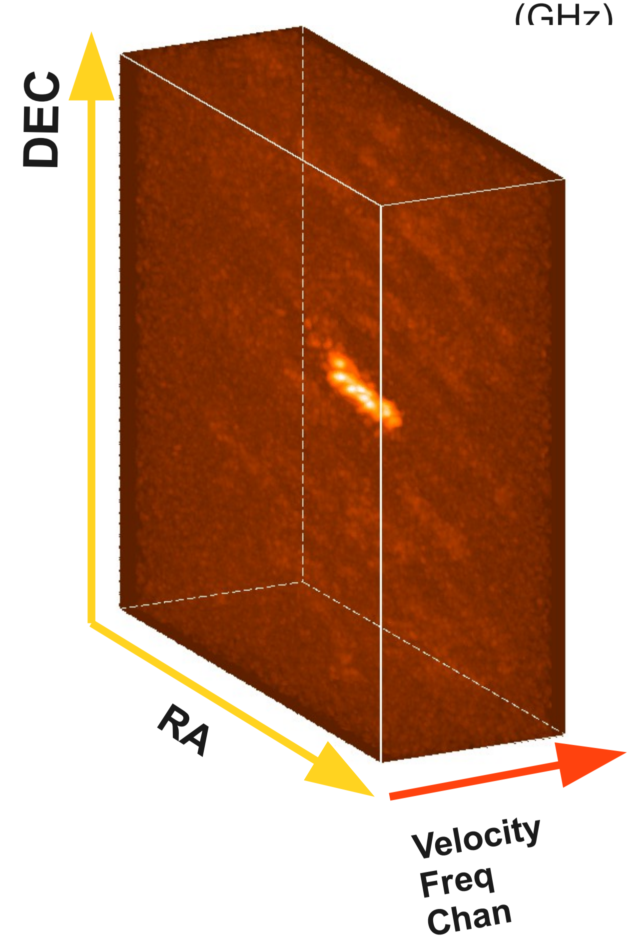
Interferometric data

Spectral line images
are 3-dimensional.

One image from each channel

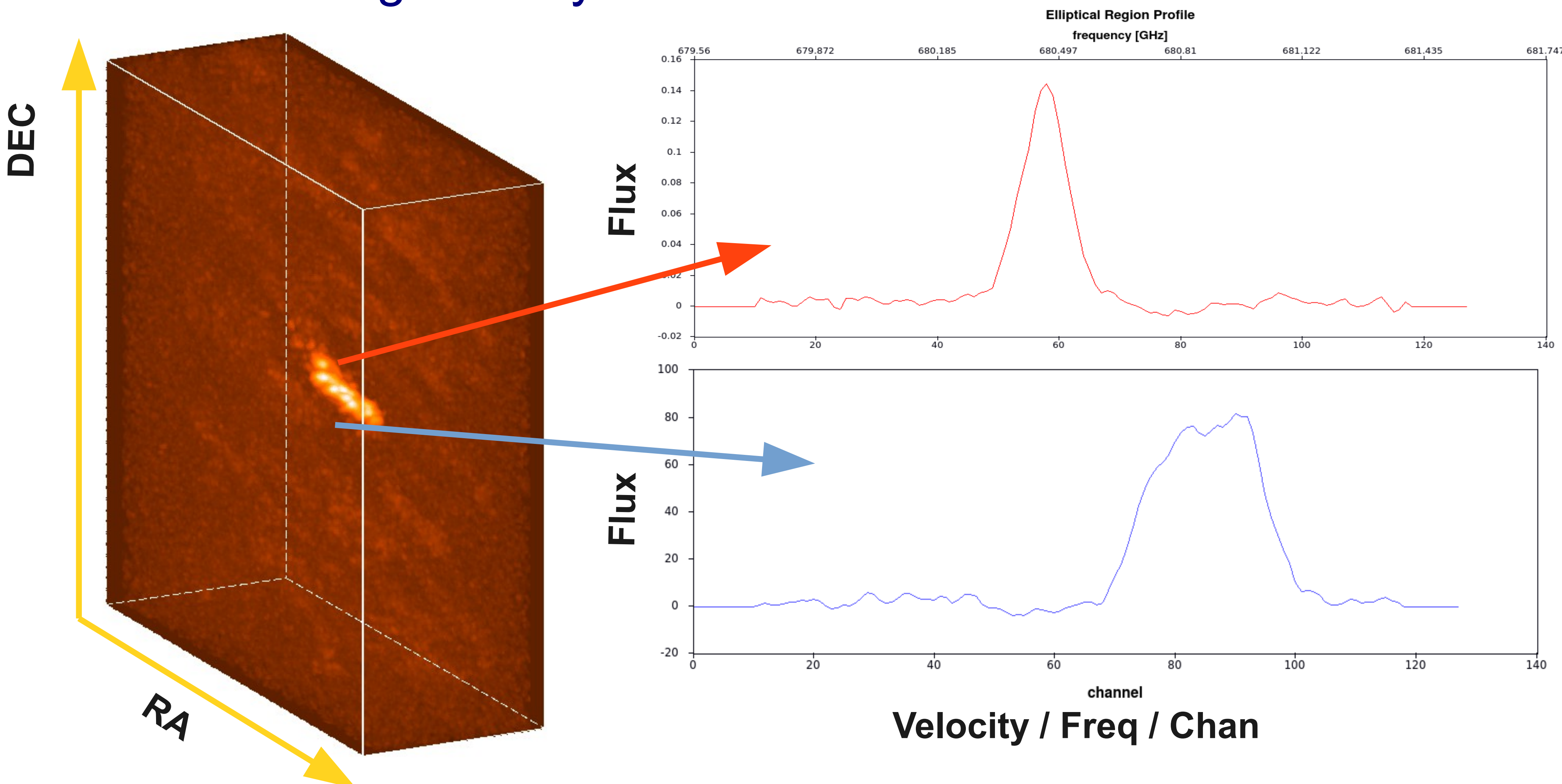






Spectral lines

1-D slice along velocity axis



From each pixel one spectrum

Laboratorio ALMA
IRA – Quarto piano (stanza in fondo al corridoio)

Lun 17, mar 18 ore 09:00 – 13:00
Mer 19 seminario UniBO
Gio 20, Ven 21 ore 09:00 – 17:00

Lun 24, mar 25, mer 26 ore 09:00 – 13:00
Gio 27, Ven 28 ore 09:00 – 17:00