Radio-astronomy

Interferometry - introduction

Action Fédératrice ALMA/NOEMA
Observatoire de Paris

P. Salomé

Credits: F. Gueth, J. Pety, R. Neri, R. Moreno …

References

Books

- « Interferometry and Synthesis in Radio Astronomy » Thompson, Moran, Swensson
- « Radio Astronomy » J.D. Kraus
- « Tools of Radio Astronomy » K. Rohlfs & T.L. Wilson

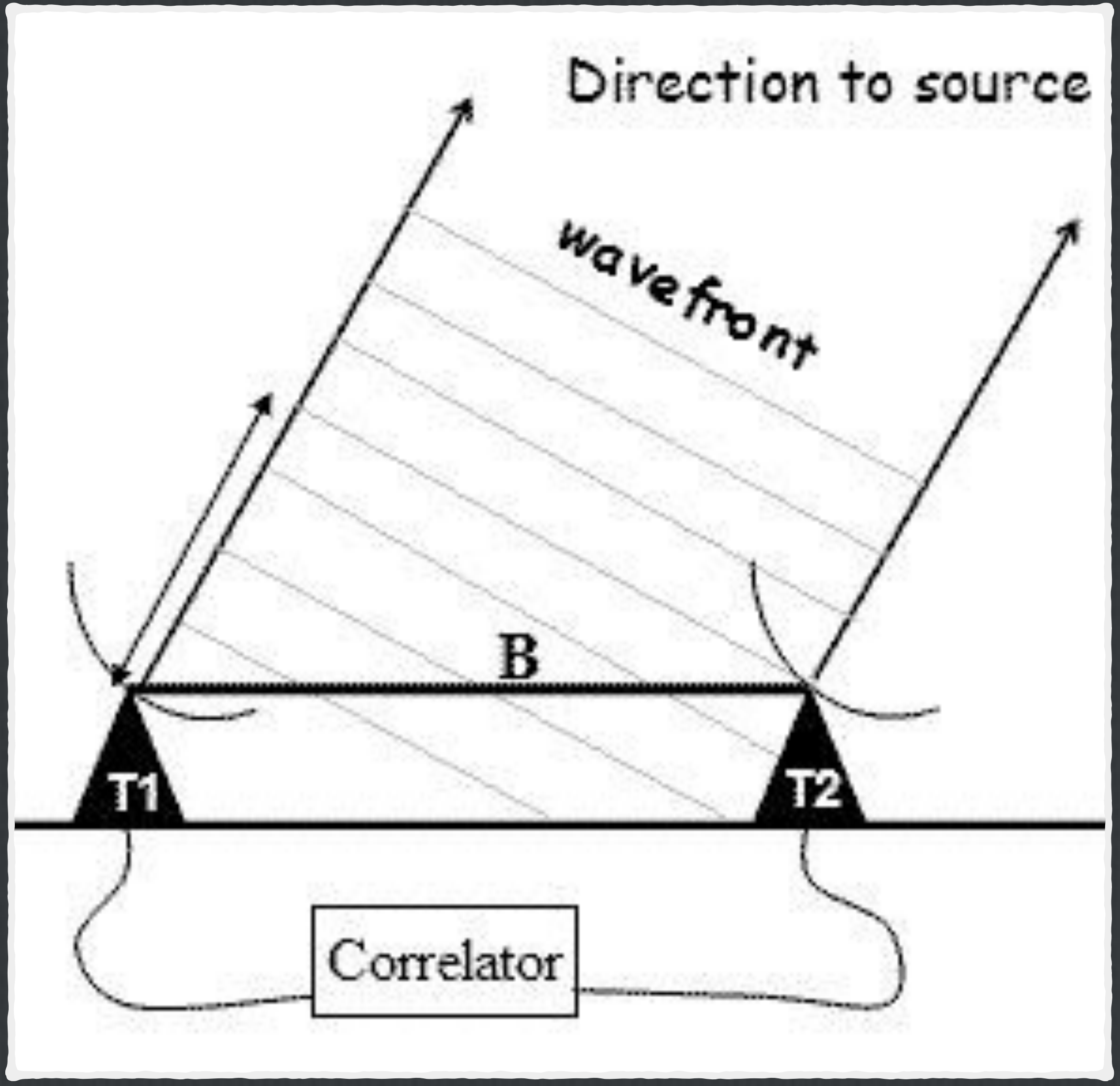
Proceedings and Talks

- NRAO and IRAM radio-interferometry summer schools (in particular by F. Gueth and J. Pety)
  - http://www.aoc.nrao.edu/events/synthesis/2012/lectures.shtml
  - http://www.iram-institute.org/EN/content-page-182-7-67-182-0-0.html

Credits

- Lectures : F. Gueth + J. Pety + R. Neri + R. Moreno + …

Outline



- Interferometry principles
- Imaging & Calibration
- Tutorials
    - Sensitivity
    - Imaging simulation
    - Proposal preparation

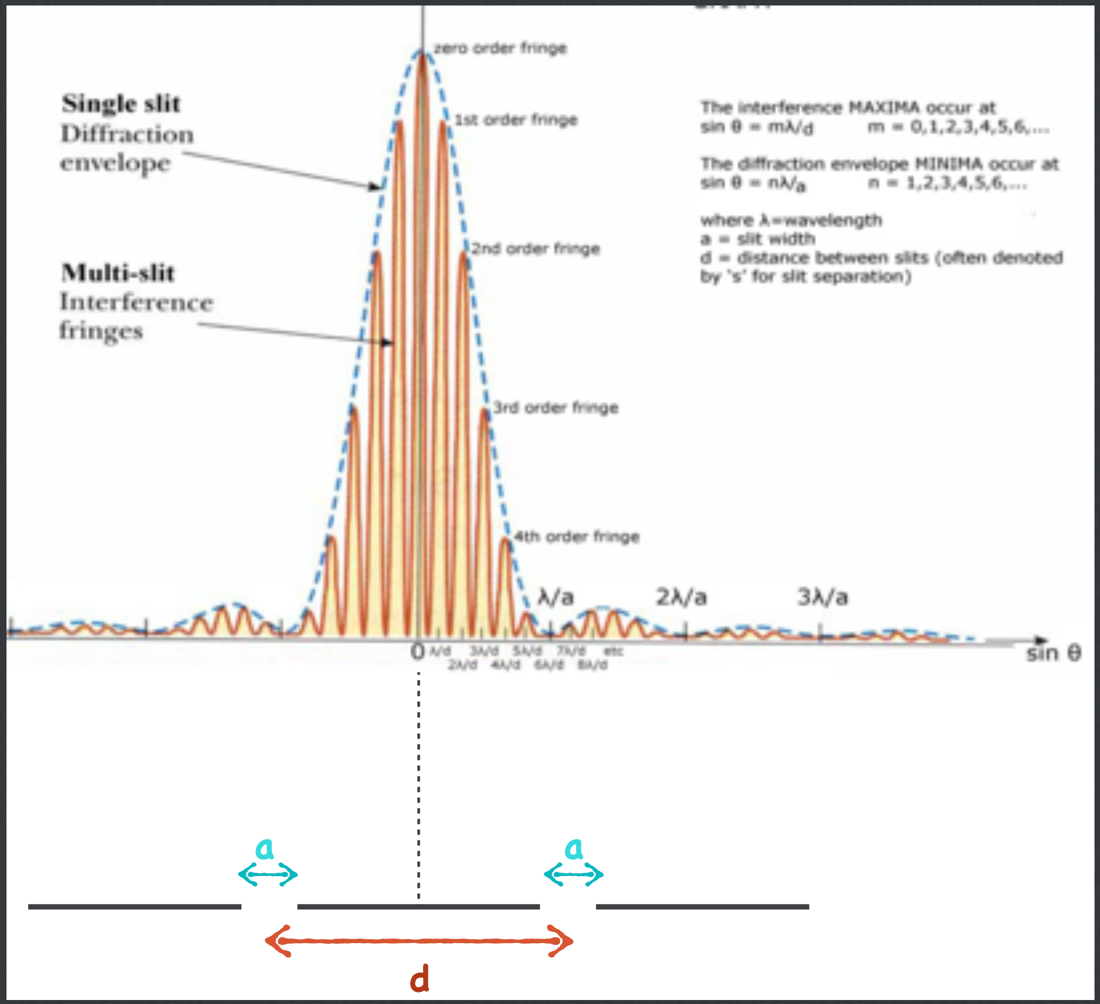
Principles

Principles

The Young's holes experiment

Diffraction pattern (related to the size of each hole) —> the **primary beam** (defined by a the antenna diameter) : $\theta_{prim} \sim 1.2\ \lambda/a$

Interferometric pattern (related to the distance between the holes) —> the **synthesized beam** (define by the distance b between 2 antennas, also called the baseline)
$\theta_{synth} \sim 1.2\ \lambda/d$



Principles

- LMT/GMT 50m telescope
- IRAM-30m telescope
- Single dish > 50 m needs :
  - High surface quality (efficiency): $\lambda/20$~$50\mu m$
  - Excellent pointing accuracy (wind / structure deformation): HPBW/10

Increase the spatial resolution from λ/D to λ/B

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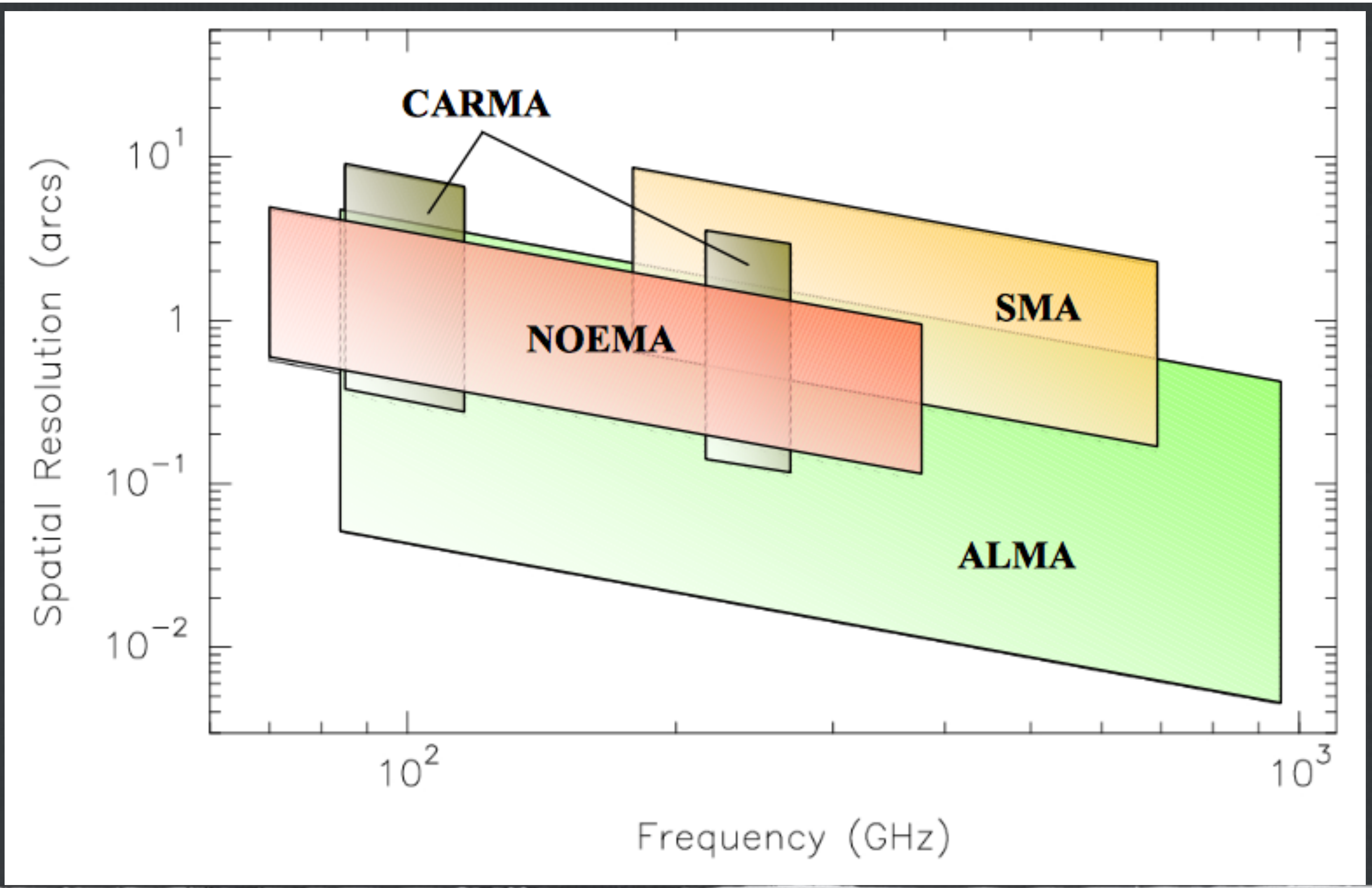
Increase the spatial resolution from λ/D to λ/B

	Altitude (m)	N_{ANT}	Diameter (m)	Coll.Area (m^2)
IRAM PDBI	2550	6	15	1060
CARMA	2200	15	6/10	772
SMA+CSO+JCMT	4080	10	6/10/15	481
NMA	1340	6	10	471
IRAM NOEMA	2550	12	15	2120
ALMA	5060	50	12	5652



HL Tau

A planet-forming disc around a young star

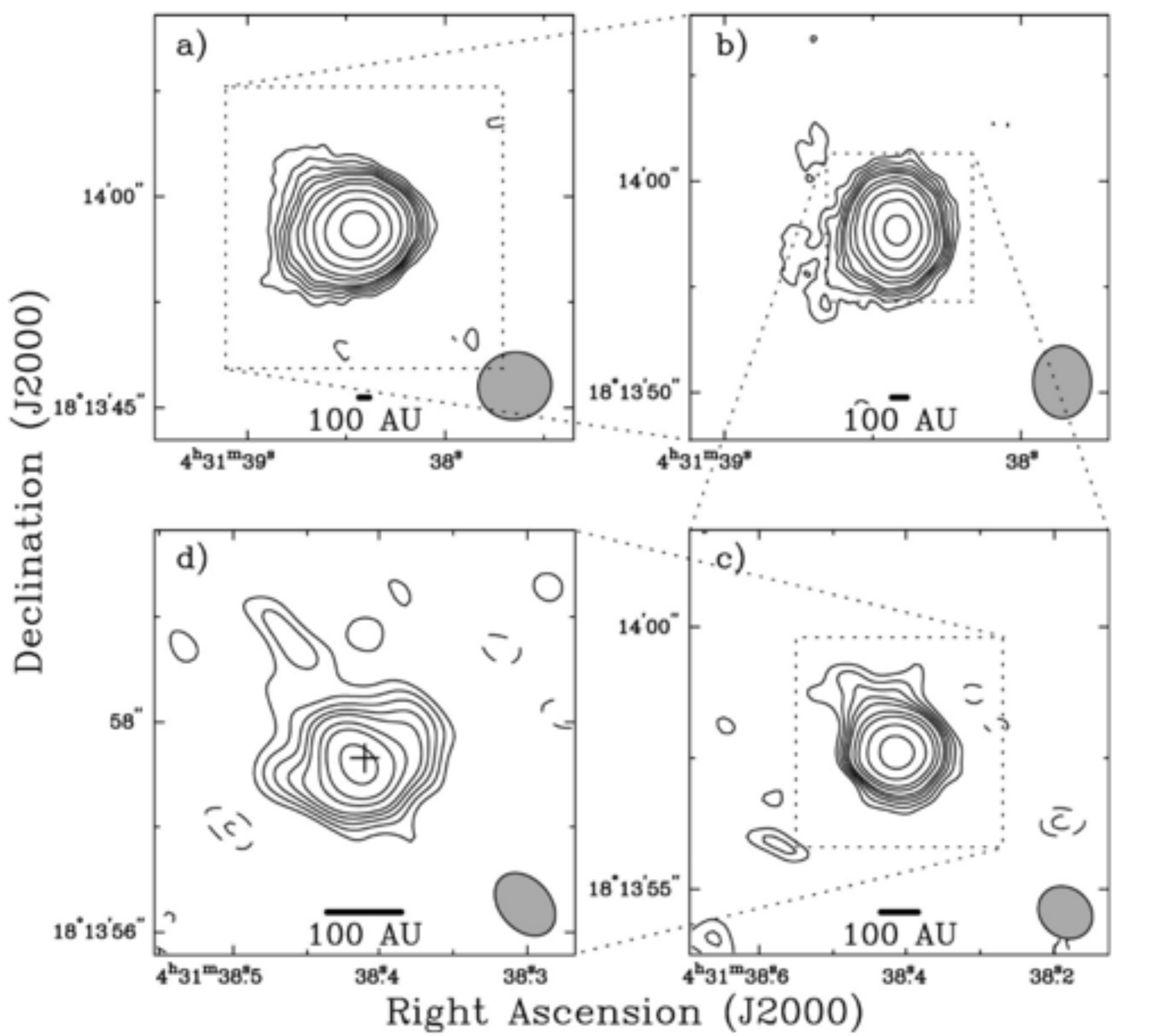


FIG. 4.—HL Tauri maps of the $\lambda = 2.7$ mm continuum emission. All panels are contoured in steps of $(-4, -3, -2, 2, 3, 4, 5, 6, 8, 10, 14.14, 20, 28.28)$ times an rms noise of 2.9 mJy beam^{-1}. (*a*) $\sigma = 1.7$ mJy beam^{-1}; beam is $5''.31 \times 4''.79$ P.A. $= -81°$. (*b*) $\sigma = 1.7$ mJy beam^{-1}; beam is $3''.43 \times 2''.79$ P.A. $= 1°$. (*c*) $\sigma = 2.4$ mJy beam^{-1}; beam is $1''.11 \times 0''.94$ P.A. $= 53°$. (*d*) $\sigma = 2.9$ mJy beam^{-1}; beam is $0''.68 \times 0''.48$ P.A. $= 43°$. The cross in panel (*d*) is the $\lambda = 3.6$ cm peak from Rodríguez et al. 1994.

Looney et al (2000)

BIMA observations

HL Tau

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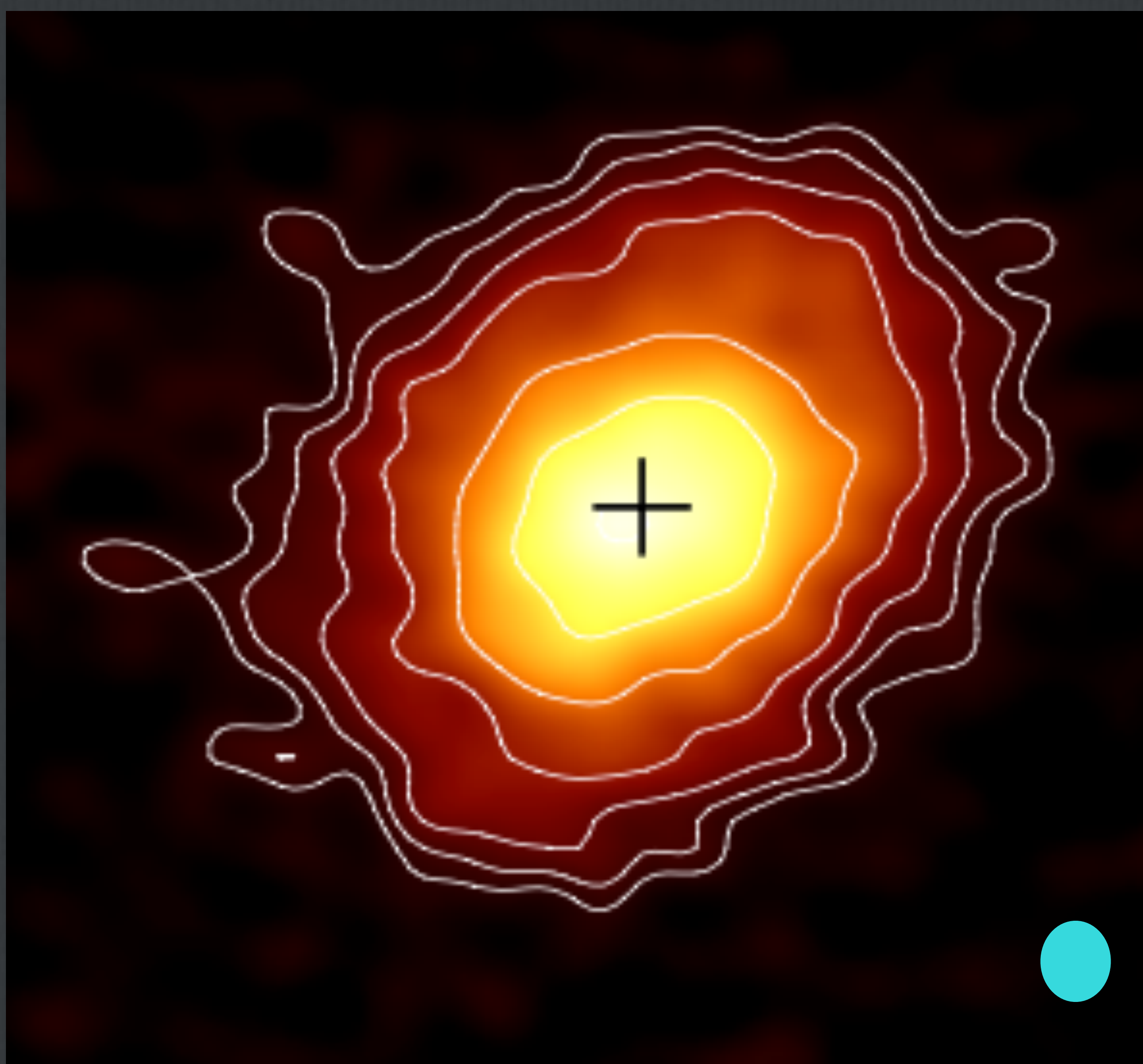

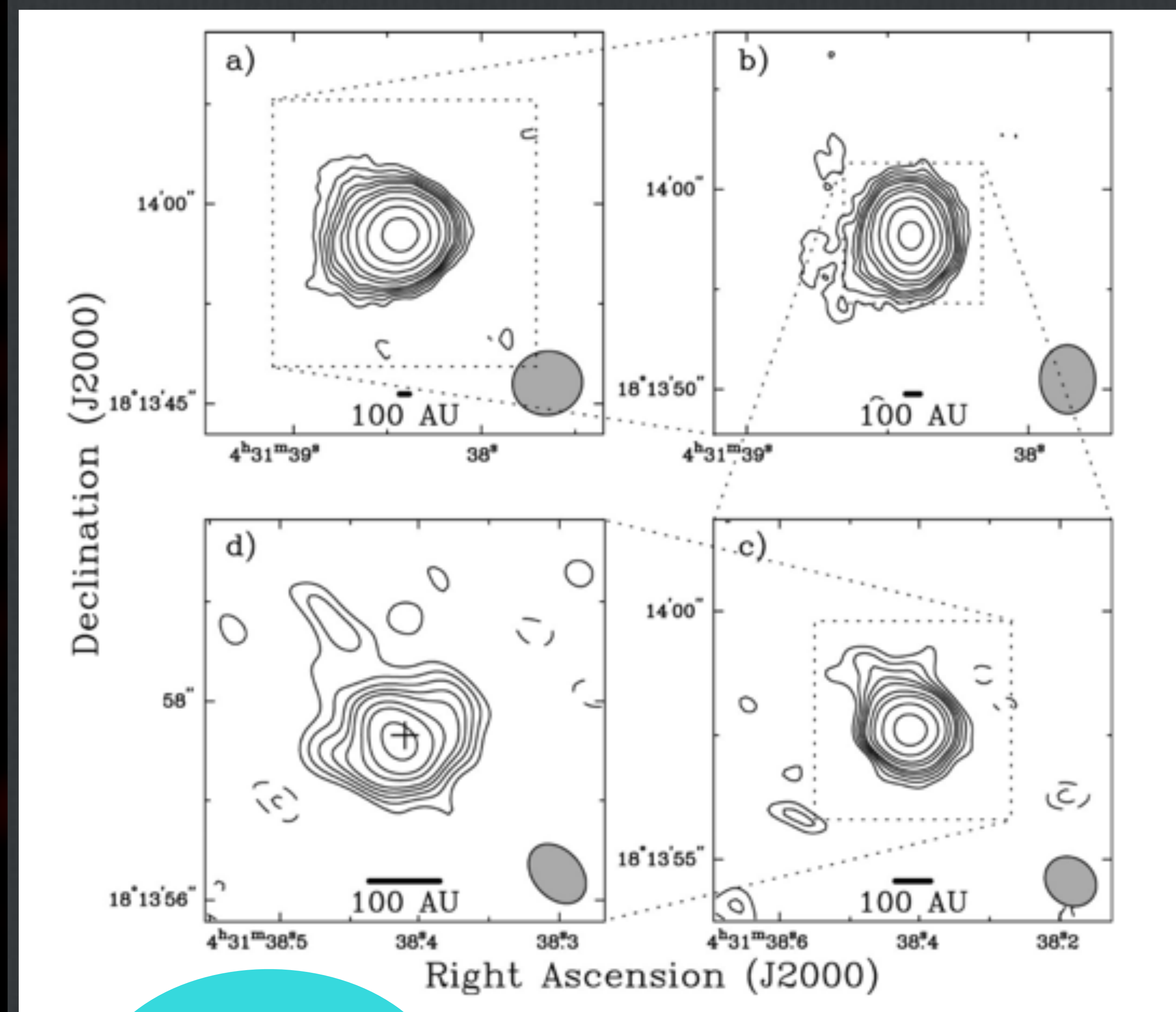

CARMA 2011: A,B,C configuration @ 230 GHz
—> 130 milli-arcsec. Kwon et al (2011)

HL Tau

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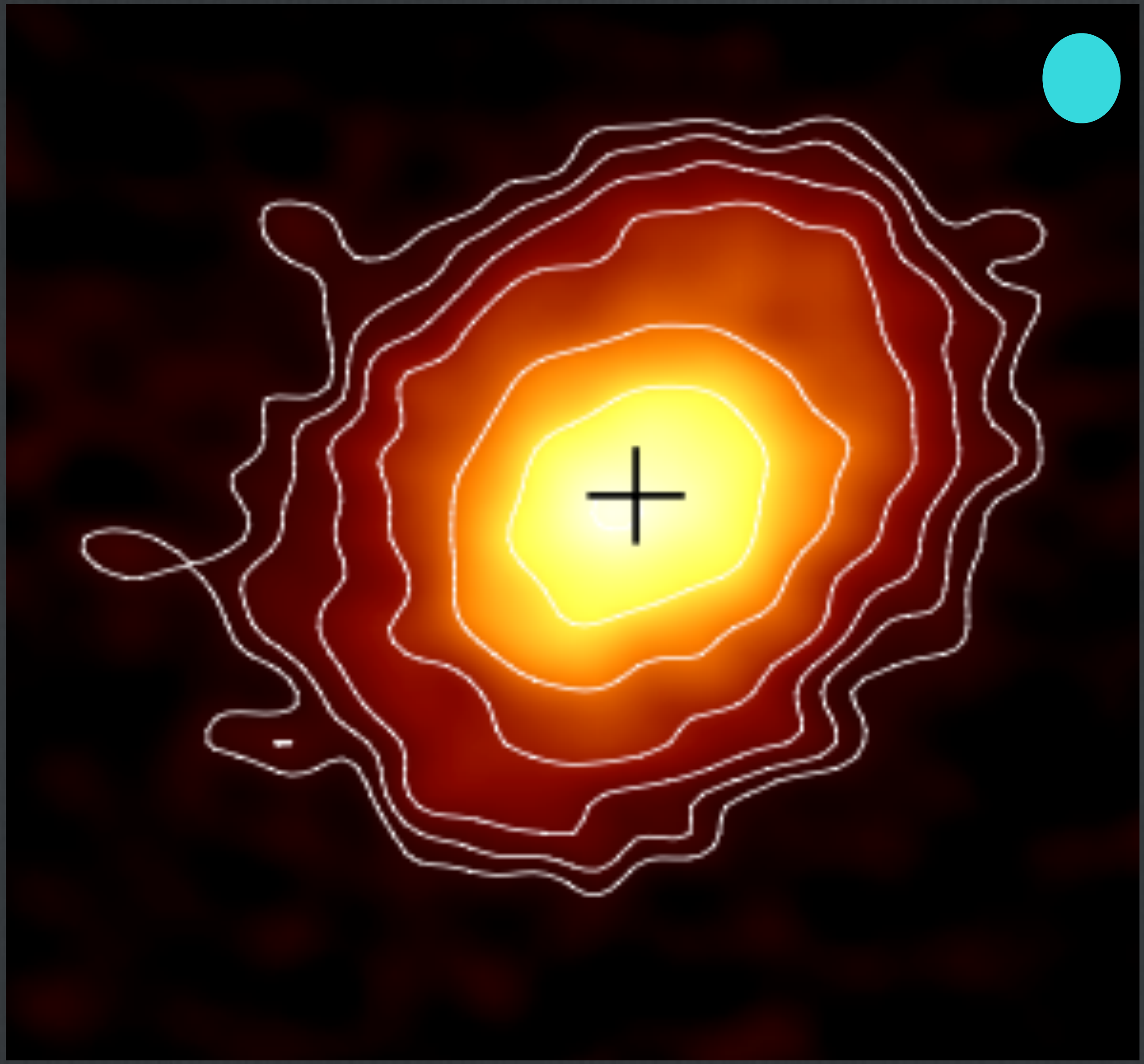

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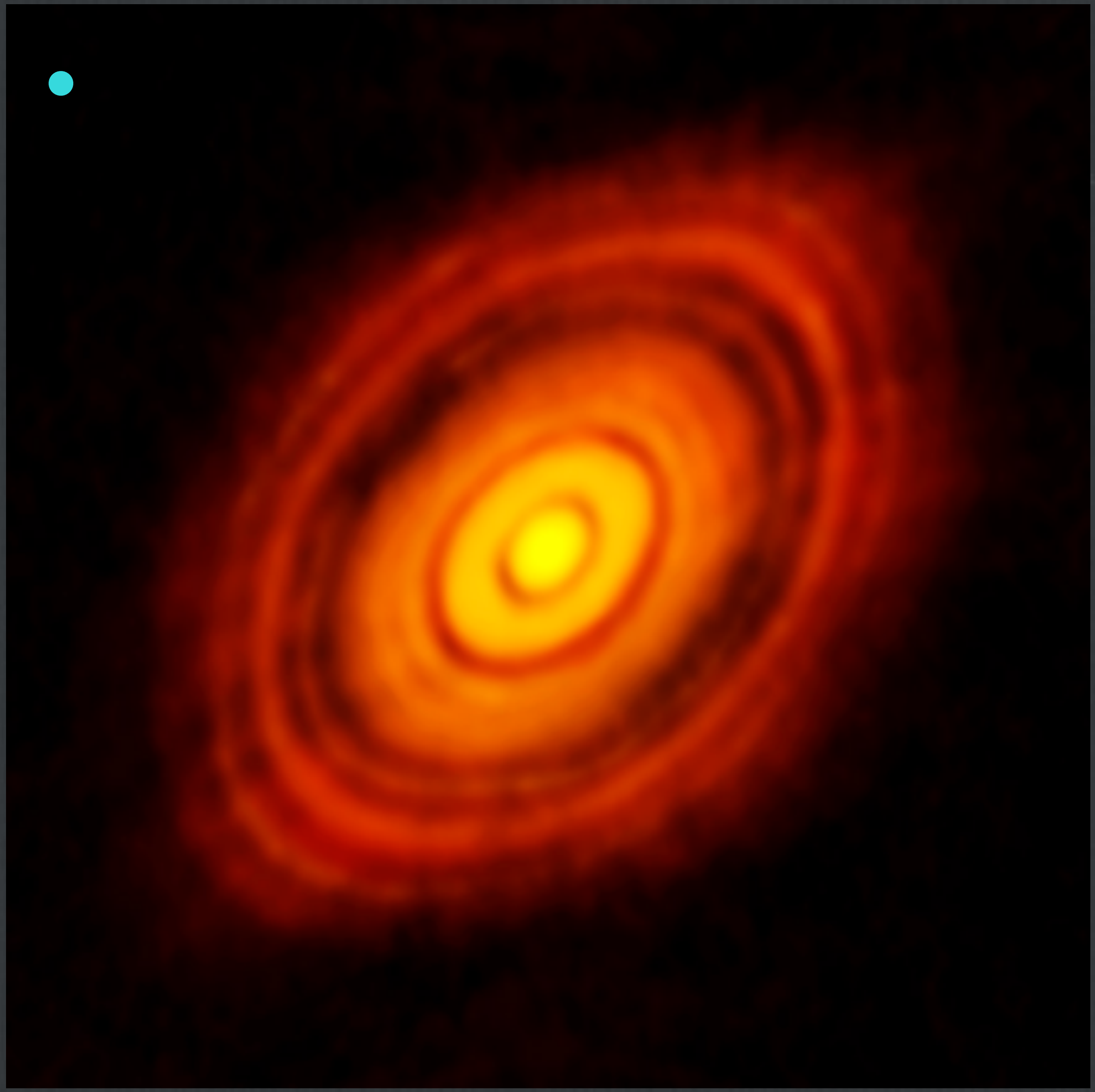
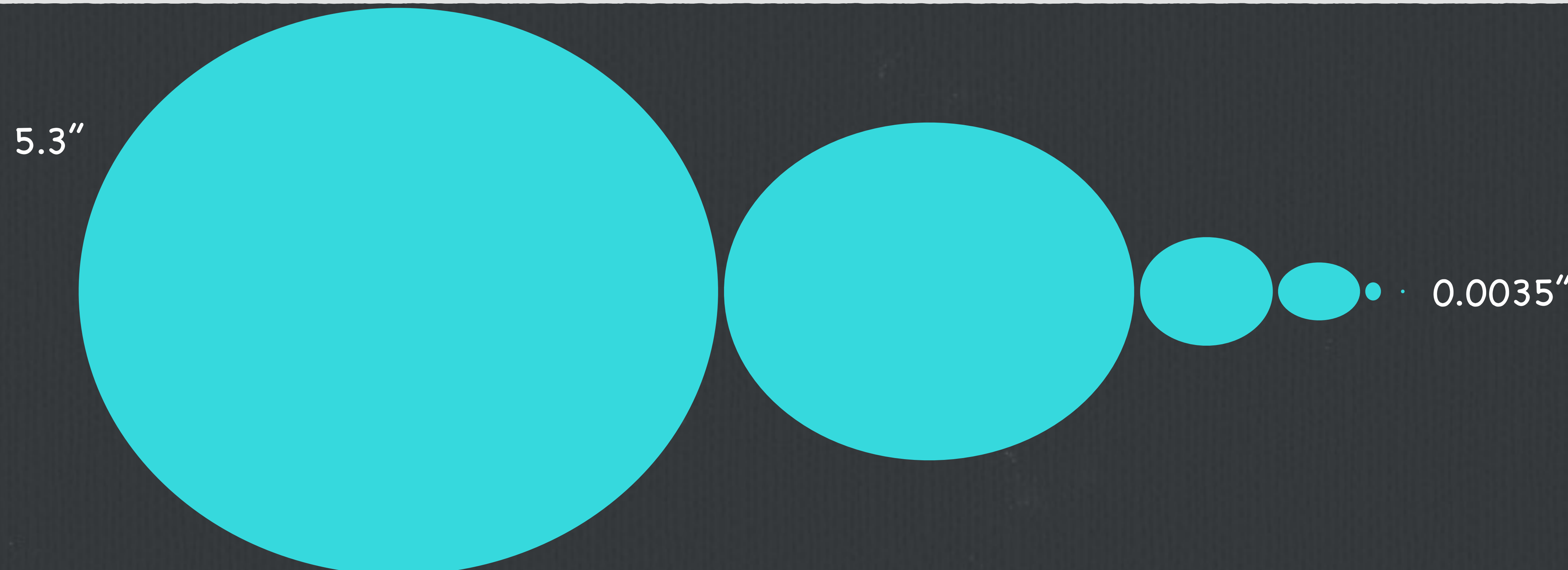
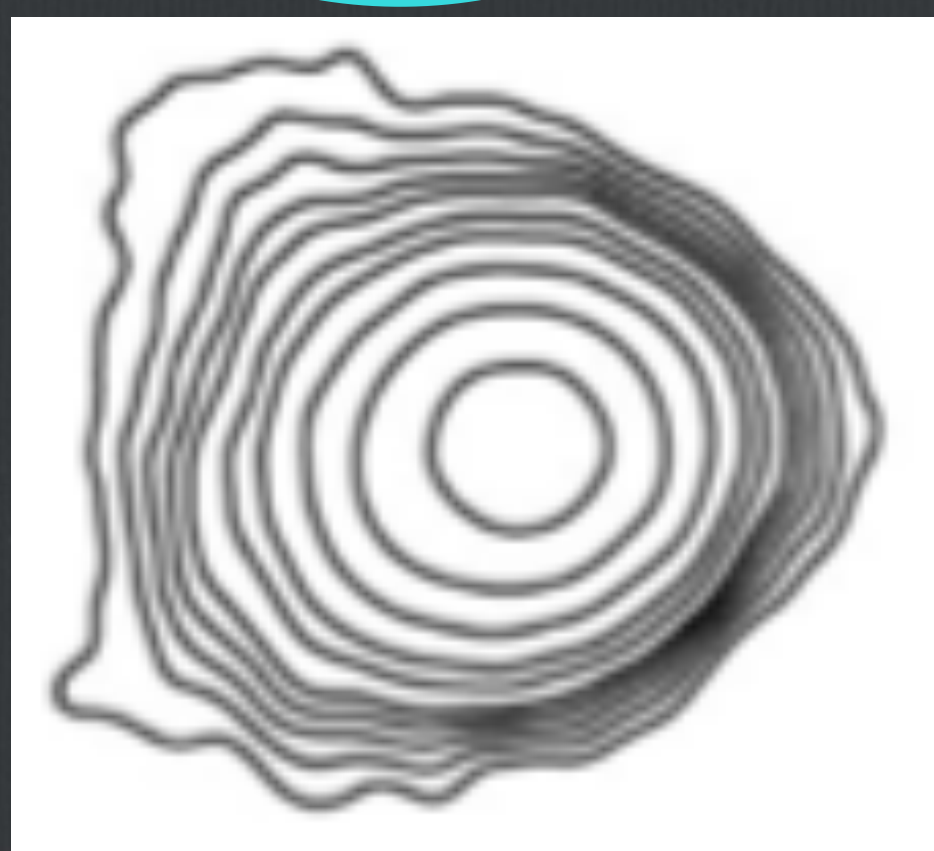


ALMA 2014: 15 km-baseline @ 233 GHz 4.5 hours —>35 milli-arcsec

HL Tau





HL Tau

Good imaging capability needs :

- if necessary : spatial resolution (and good weather)
- uv-coverage (sampling of the equivalent larger telescope area by the collection of smaller apertures)
- sensitivity

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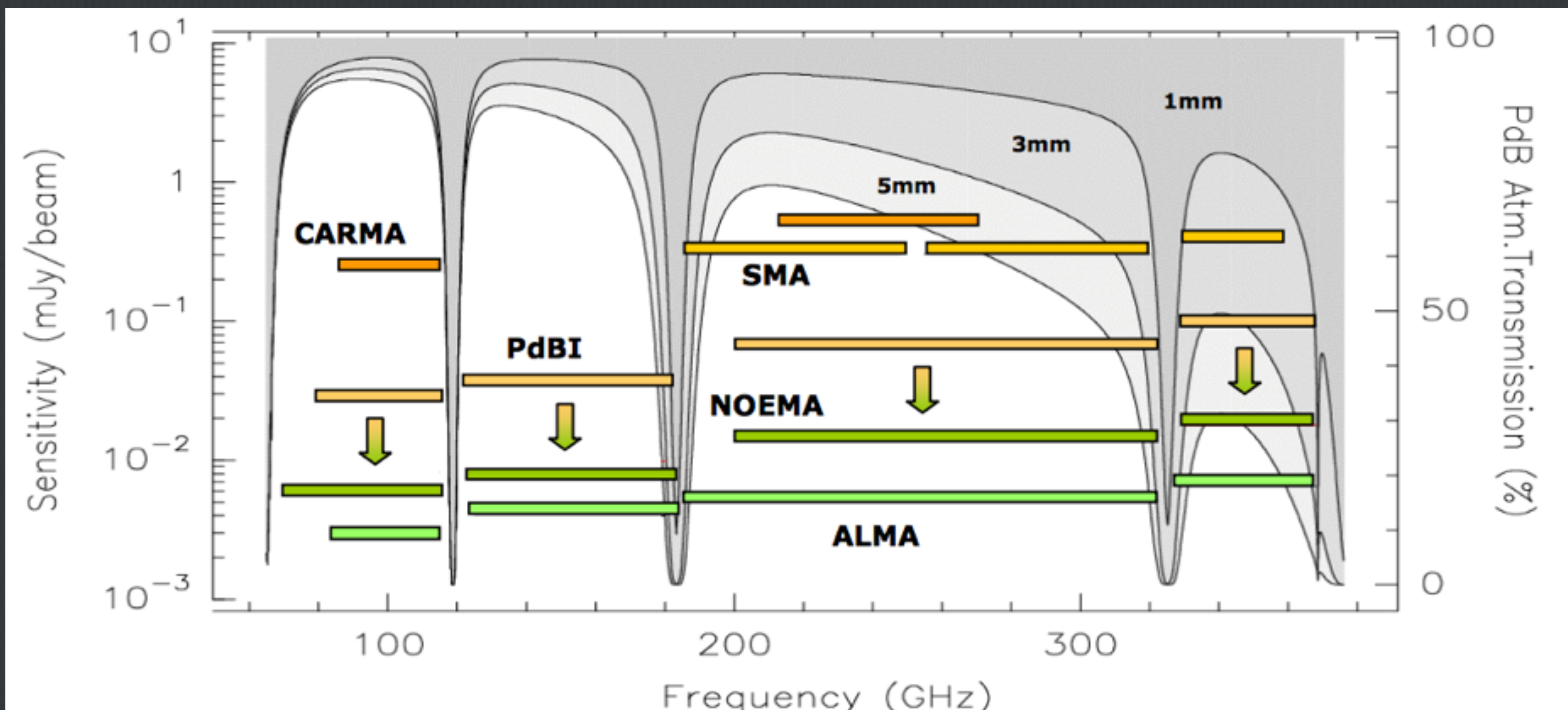
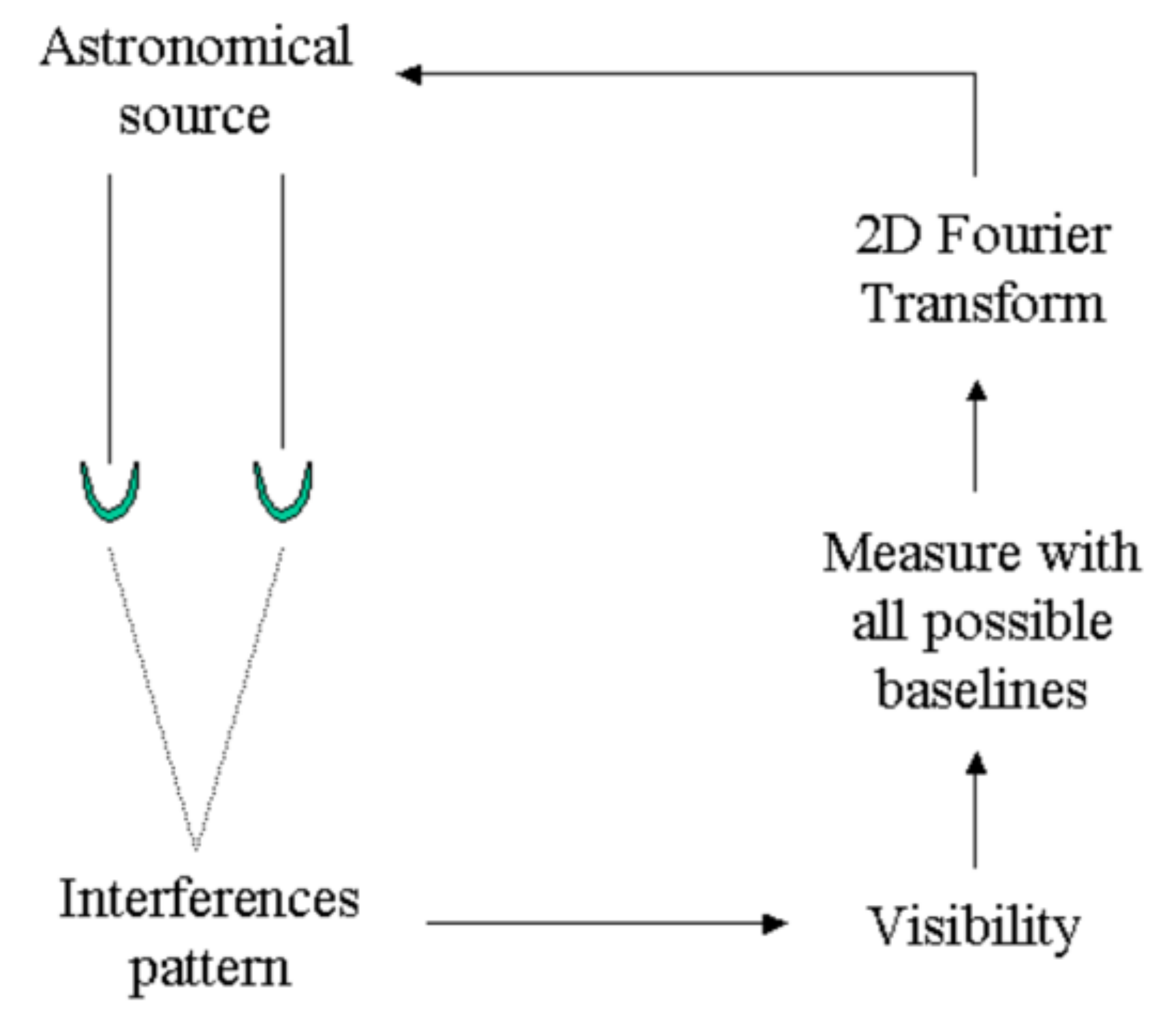


Principles : V_ν <—> $I_\nu(\sigma)$

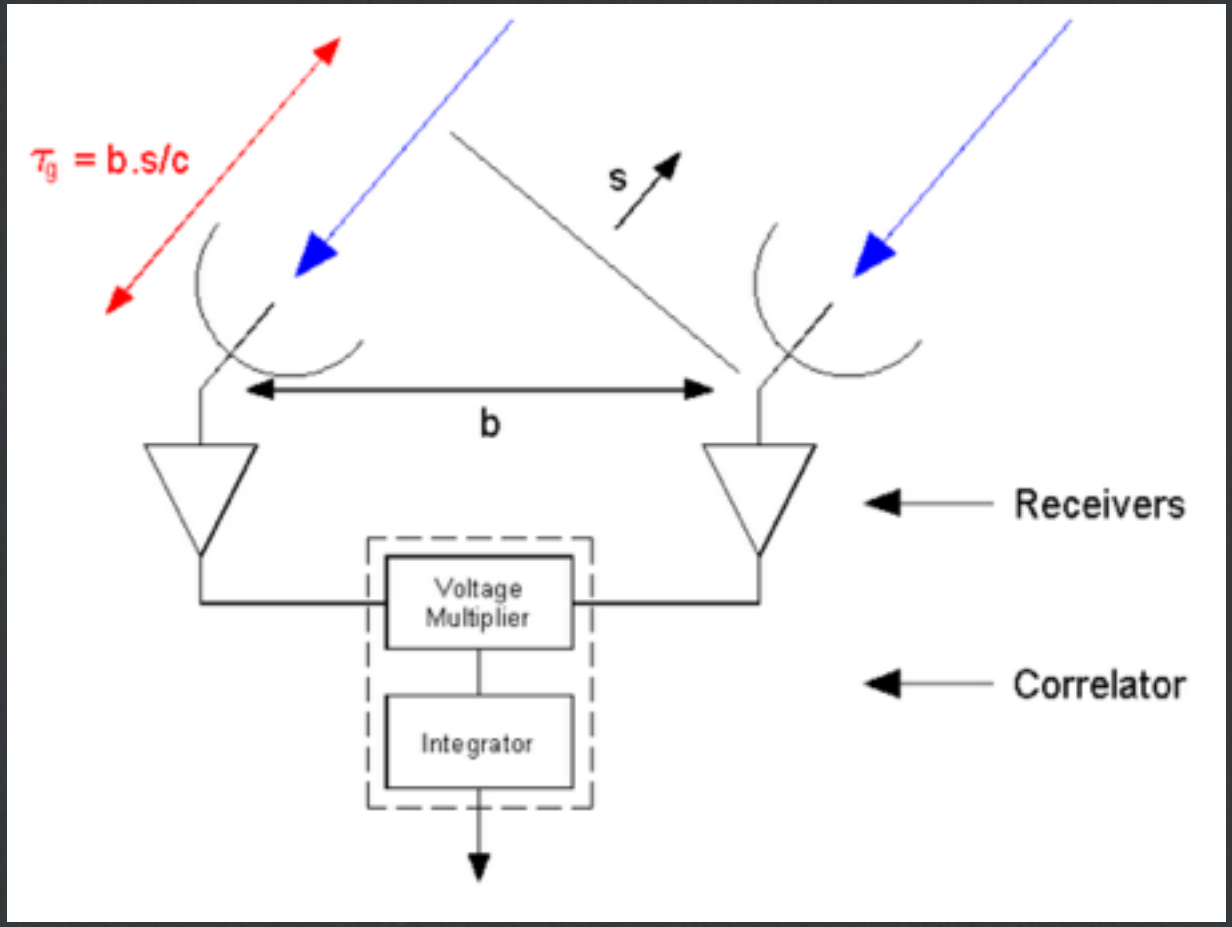
The van Cittert-Zernike theorem

The **Visibility** (the measured spatial coherence fonction) is the Fourier transform of the **source surface brightness spatial distribution**

$$V_\nu = TF\,[A(\sigma)\ I_\nu(\sigma)]$$



Principles : a point source



The heterodyne receivers measure the incoming electric field :

$$E \cos(2\pi\nu t)$$

The correlator is a multiplier followed by a time integrator. It measures :

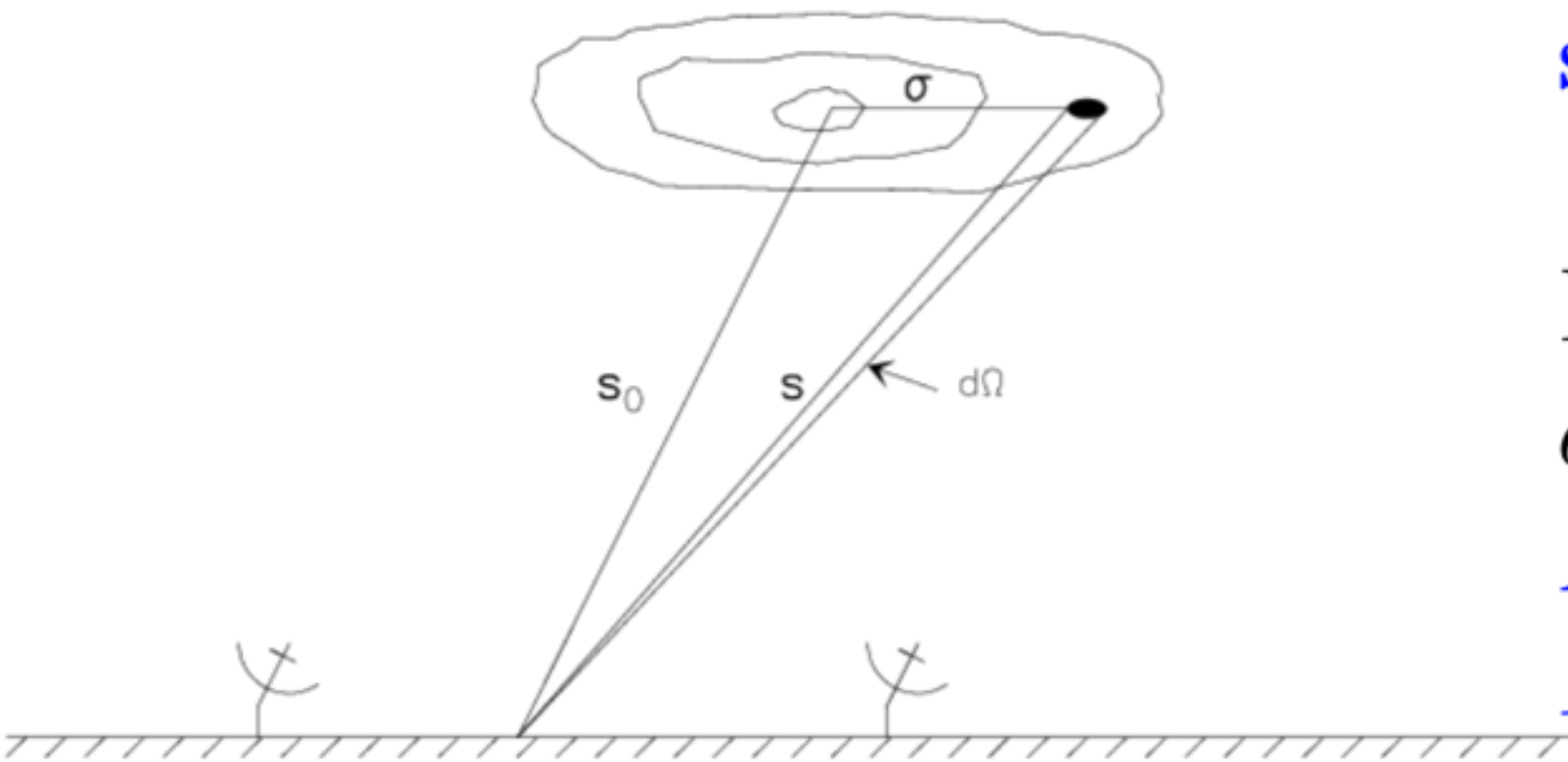
$$r(t) = \langle E_1 \cos(2\pi\nu(t-\tau_g)).E_2 \cos(2\pi\nu t) \rangle$$

$$= E_1 E_2 \cos(2\pi\nu\tau_g)$$

with τ_g the time delay that corresponds to the geometrical delay for a coherent signal to reach each antenna :

$$\tau_g = (b.s)/c$$

Principles : an extended source



$\mathbf{s} = \mathbf{s_o} + \sigma$

Power received from $d\Omega$: $A(\mathbf{s})I(\mathbf{s})d\Omega$

$A(s)$ = beam

$I(s)$ = source

Correlator output: $r = E_1 E_2 \cos(2\pi\nu\tau_g)$

$$r = A(\mathbf{s})I(\mathbf{s})d\Omega\cos(2\pi\nu\tau_g(\mathbf{s}))$$

Principles : an extended source

$$R = \int_{Sky} A(\mathbf{s}) I(\mathbf{s}) \cos(2\pi\nu \mathbf{b.s}/c)\, d\Omega$$

Measured correlator output

$$= \cos\left(2\pi\nu\frac{\mathbf{b.s}_o}{c}\right) \int_{Sky} A(\sigma) I(\sigma) \cos(2\pi\nu \mathbf{b}.\sigma/c) d\Omega$$

$$- \sin\left(2\pi\nu\frac{\mathbf{b.s}_o}{c}\right) \int_{Sky} A(\sigma) I(\sigma) \sin(2\pi\nu \mathbf{b}.\sigma/c) d\Omega$$

$$= \cos\left(2\pi\nu\frac{\mathbf{b.s}_o}{c}\right) |V| \cos\varphi_{\mathrm{V}} - \sin\left(2\pi\nu\frac{\mathbf{b.s}_o}{c}\right) |V| \sin\varphi_{\mathrm{V}}$$

$$= |V| \cos(2\pi\nu\tau_g - \varphi_{\mathrm{V}})$$

need to correct from the delay

We want something that resembles a TF

$$V = |V| e^{i\varphi_{\mathrm{V}}} = \int_{Sky} A(\sigma) I(\sigma) e^{-2i\pi\nu \mathbf{b}.\sigma/c} d\Omega$$

Delay correction

- The geometrical delay varies slowly with the earth rotation at a rate of ($\upsilon . d\tau_g/dt \approx \Omega_{terre} . b . \upsilon / c \sim 10$ Hz @ b=300m and 100 GHz)
- Because the source is not monochromatic, the delay attenuates the fringes visibility

$$R = \frac{1}{\Delta\nu} \int_{\nu_0-\Delta\nu/2}^{\nu_0+\Delta\nu/2} |V| \cos(2\pi\nu\tau_g - \varphi_V)\, d\nu$$
$$= |V| \cos(2\pi\nu_0\tau_g - \varphi_V)\, \frac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$$

It depends on the antenna positions, the source direction and the time

So the delay can be corrected

Delay correction

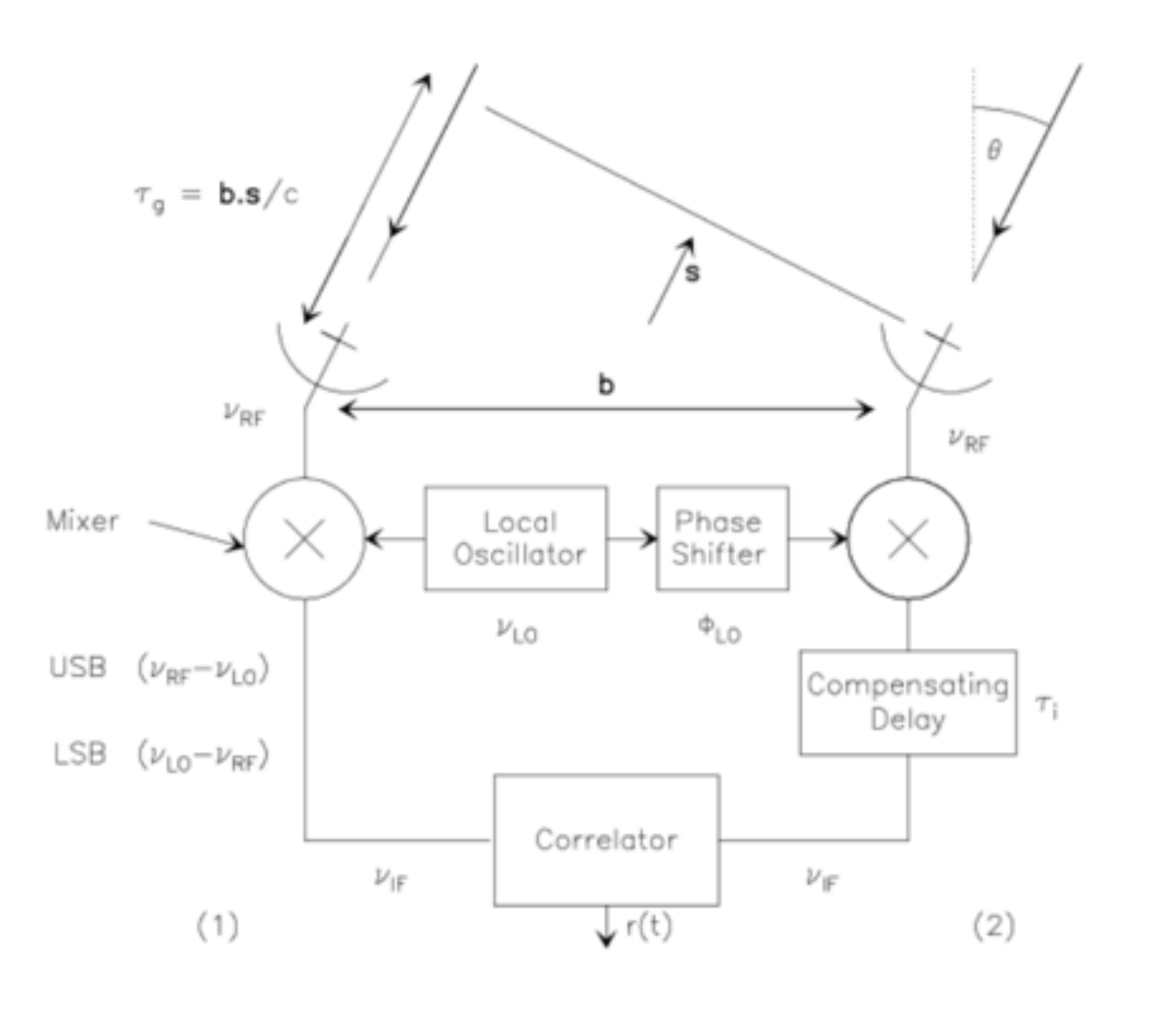
A compensating delay is introduced in one of the branch of the interferometer, on the IF signal

- After fringe stopping, the correlator measures

$$R = |V| \cos(-\varphi_V)$$

- A second correlator is necessary, with a signal phase shifted by pi/2

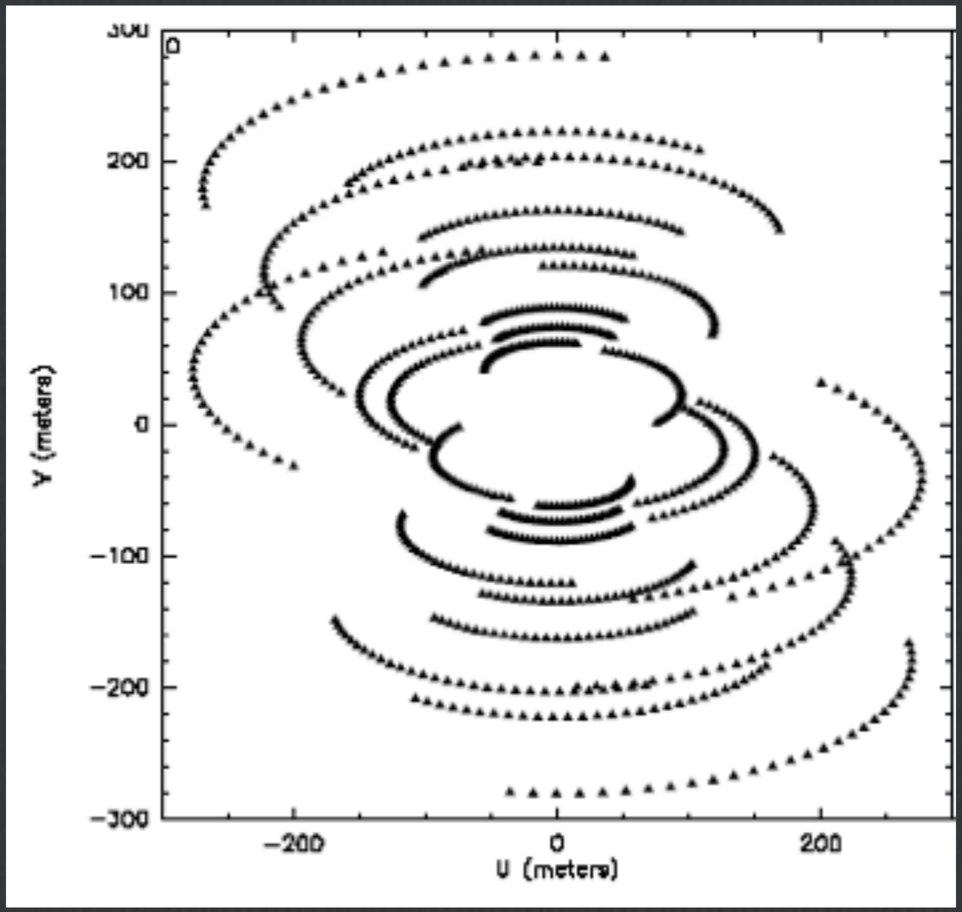
$$R_i = |V| \sin(-\varphi_V)$$



...it measures the complex visibility (amplitude and phase) for each baseline

uv-plane

- The interferometer measures the complex visibility for each baseline
- (u, v) is the 2-antenna vector (baseline) projected on the plane perpendicular to the sourced direction : the uv-plane
- (u, v) are also called spatial frequencies
- Earth rotation (super-synthesis)



Spatial frequencies

$$V(u,v) = \int_{Sky} A(\ell,m) I(\ell,m) e^{-2i\pi\nu(u\ell+vm)} d\Omega$$

Weights

For small field of view, V is the 2D FT of the sky brighthness distribution multiplied by A(l,m) the primary beam

Measurements = uv plane sampling x visibilities

Imaging

The measurements by the interferometer are

$$V(u,v) = \int\int A(x,y)\, I_{source}(x,y)\, e^{-2i\pi(ux+vy)}\, dxdy = FT\{B_{primary}.I_{source}\}$$

To determine the source brightness distribution, one must compute the inverse Fourier transform FT^{-1}

$$I_{meas}\,(x,y) = \int\int S(u,v)\, V(u,v)\, e^{\,2i\pi(ux+vy)}\, dudv = FT{-}1\, \{S.V\}$$

but because of the limited sampling function (uv-coverage), the measurements are discrete (need to be gridded for computation)

- $S(u,v)=1$ at (u, v) points where visibilities are measured and $S(u,v)=0$ elsewhere
- One defines the dirty beam as B_{dirty} = 2D FT–1 {S} : the FT of the uv plane coverage i.e. the PSF of the observations

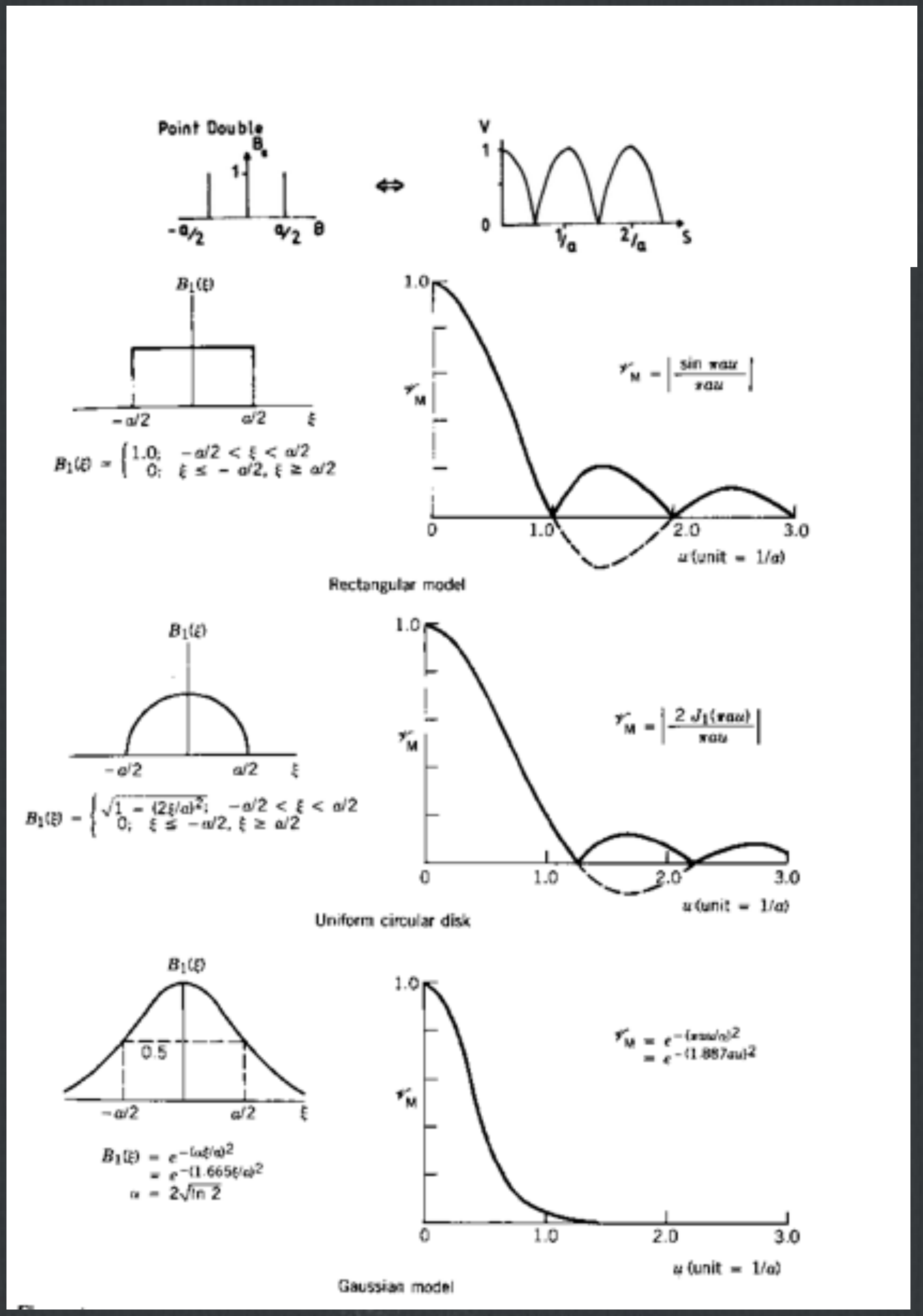
$$I_{meas} = FT{-}1\, \{S.V\} = FT{-}1\, \{S\} * FT{-}1\{V\} = FT{-}1\, \{S\} * FT{-}1\{FT\{B_{primary}.I_{source}\}\}$$

$$\Leftrightarrow$$

$$I_{meas} = B_{dirty} * (\, B_{primary}\, .I_{source}\,)$$

measure I_{meas} and B_{dirty} –> do a deconvolution (a clean) –> divide by $B_{primary}$ –> get I_{source}

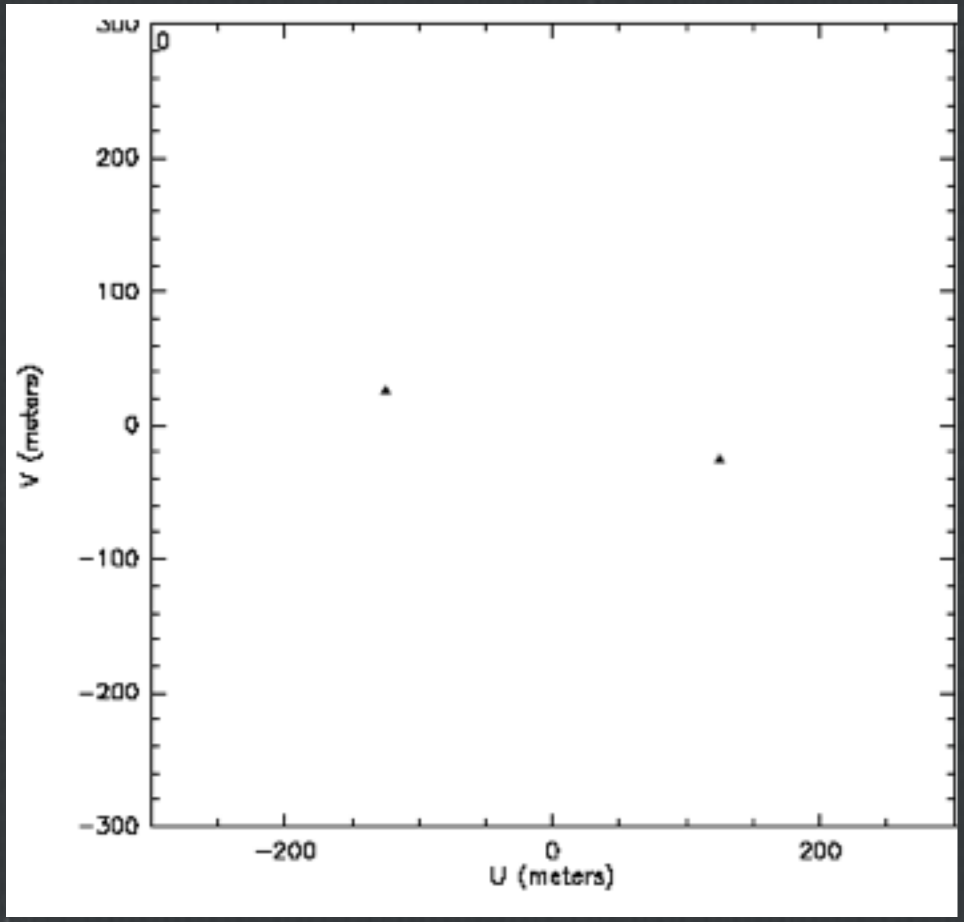
1D Fourier transform

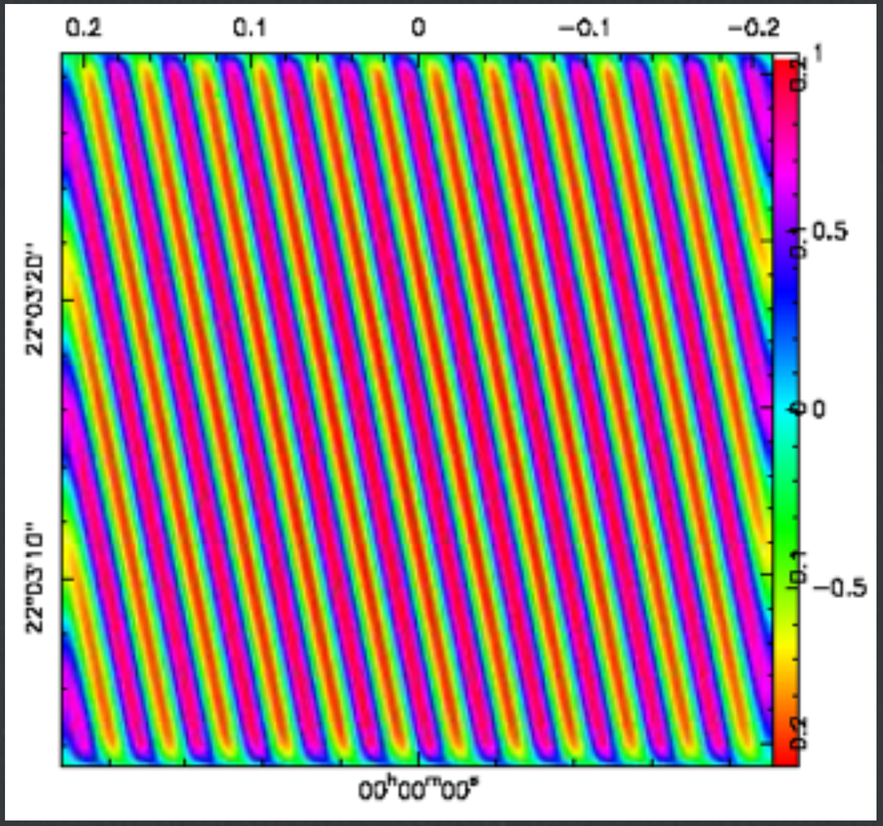


Dirty beam

Bdirty = 2D FT−1 {S}

The FT of the uv plane coverage gives the dirty beam i.e. the PSF





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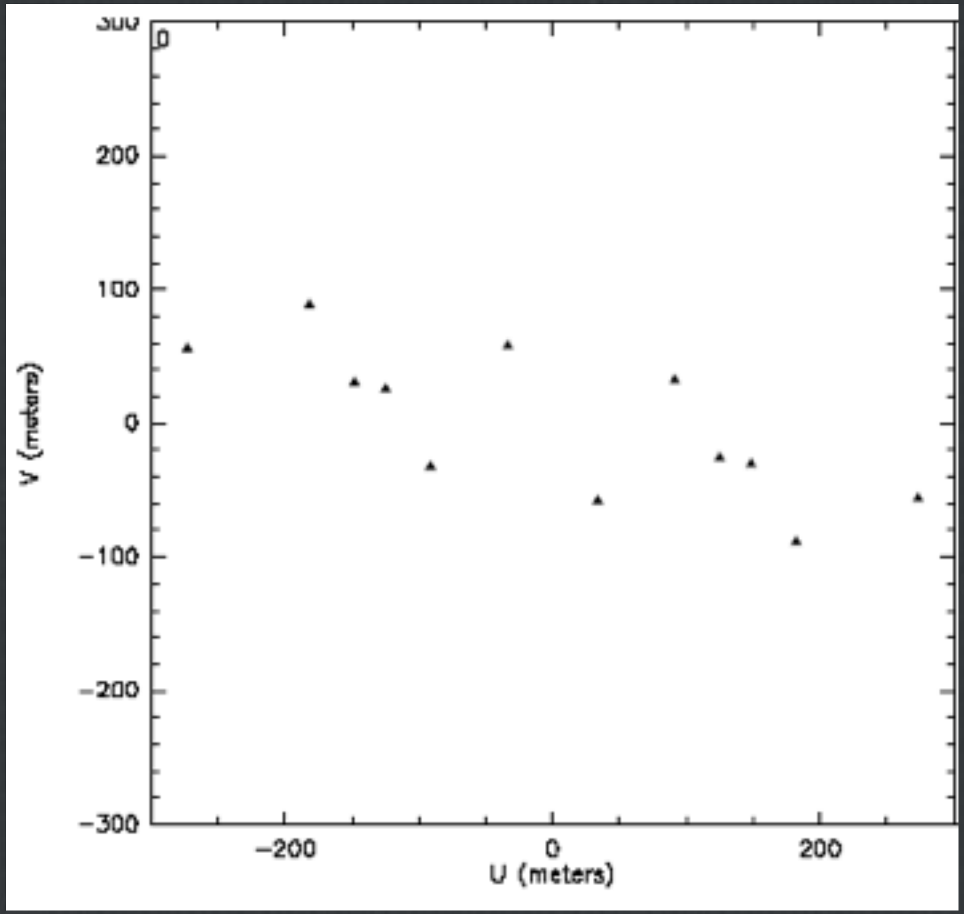

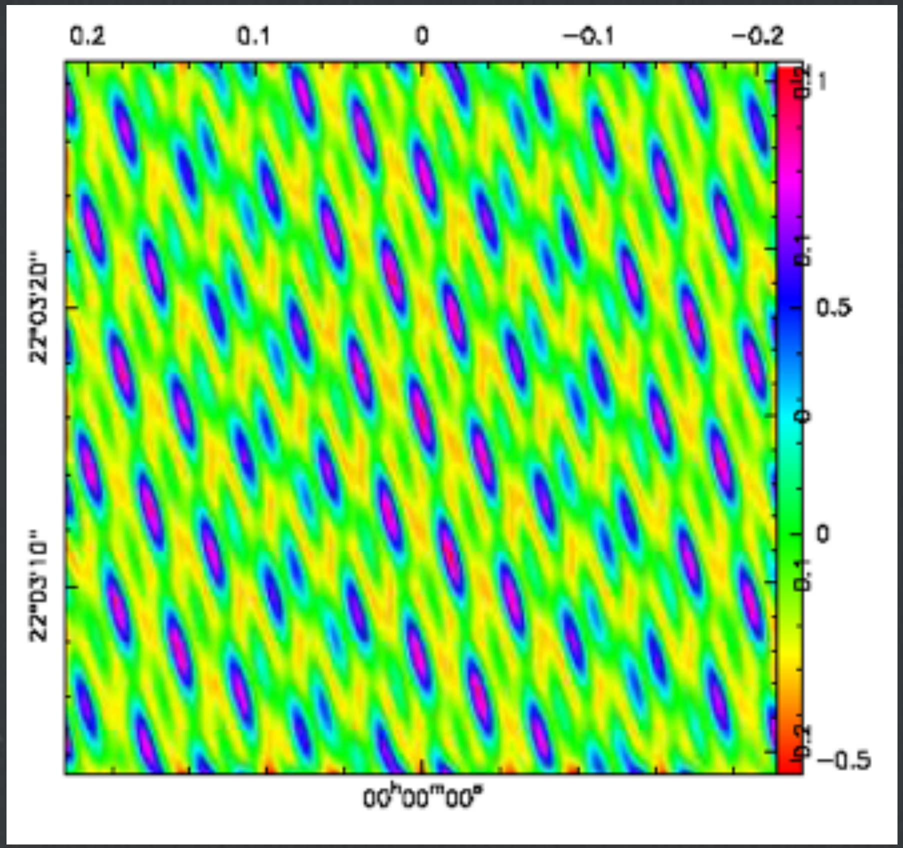

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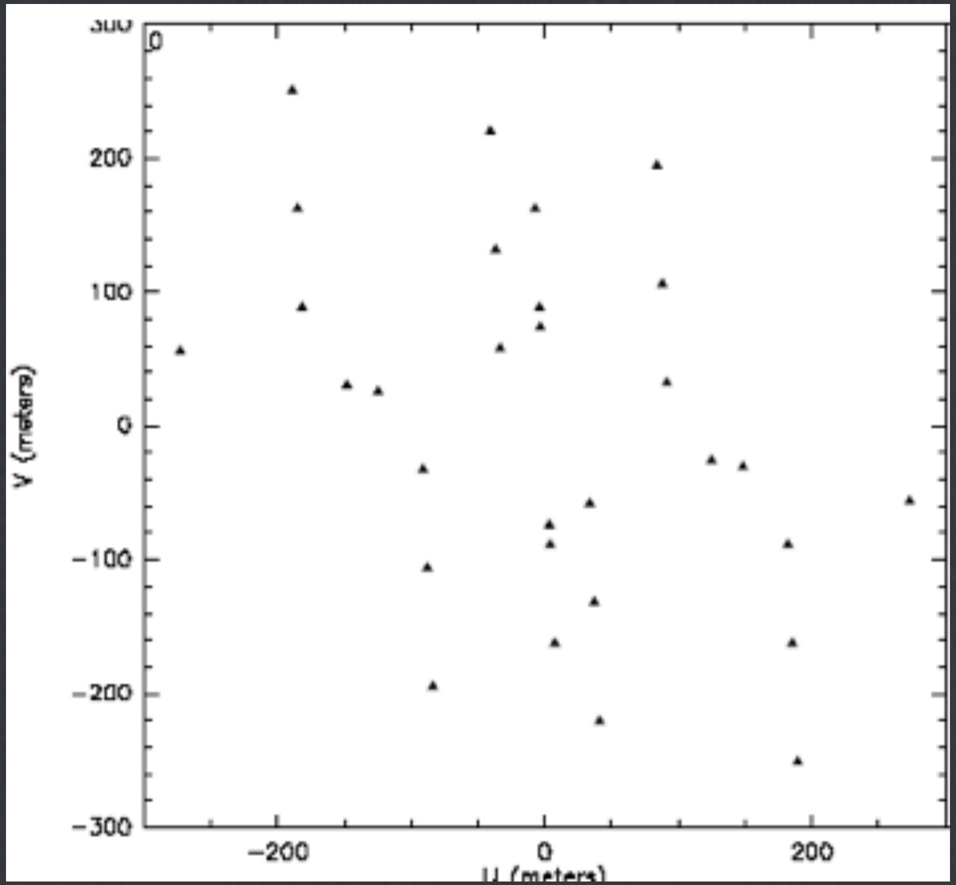

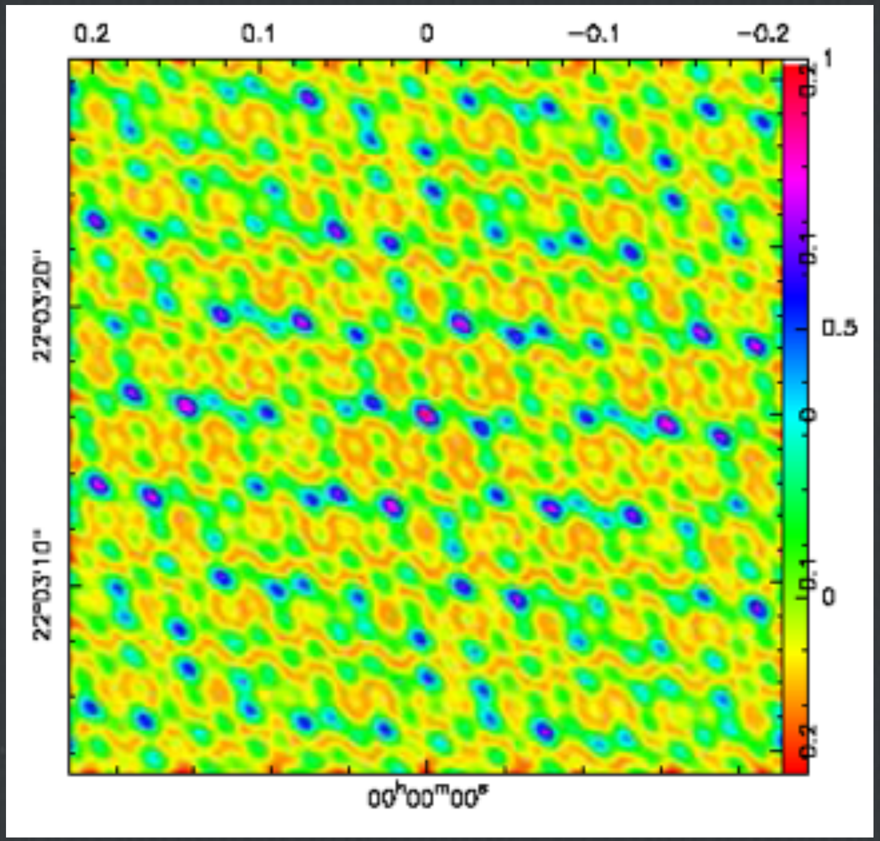

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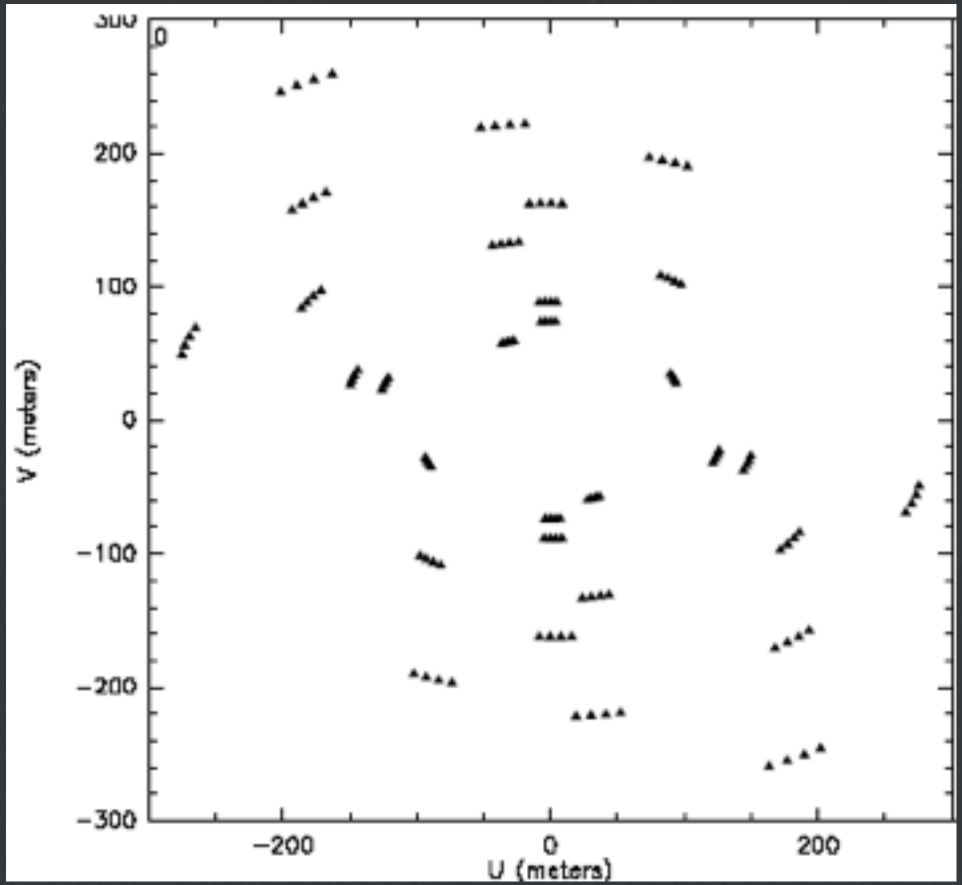

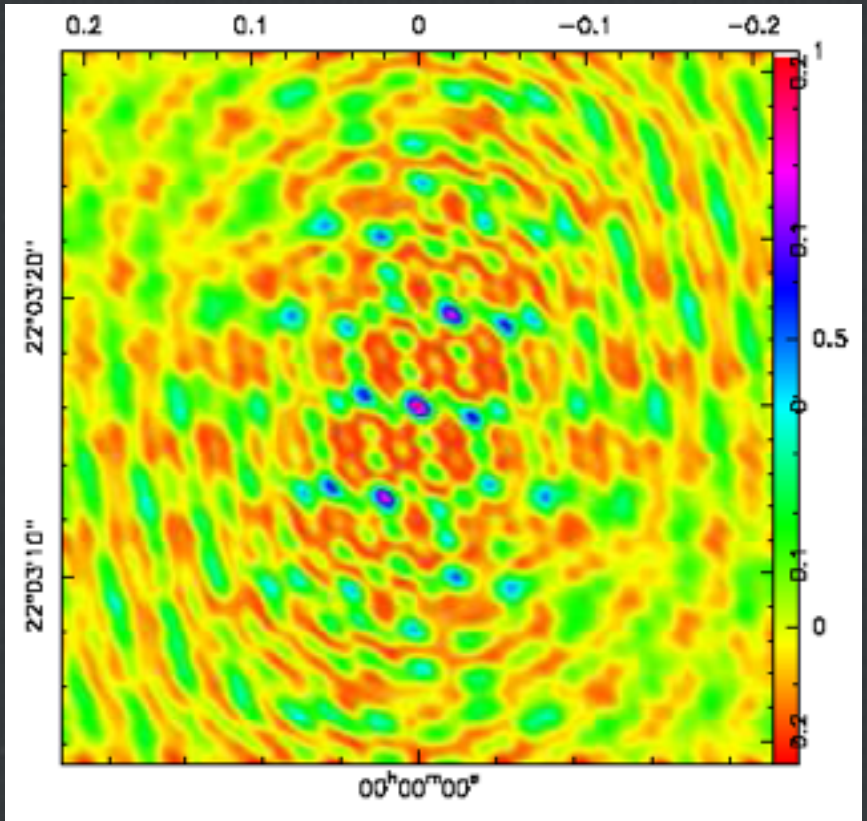

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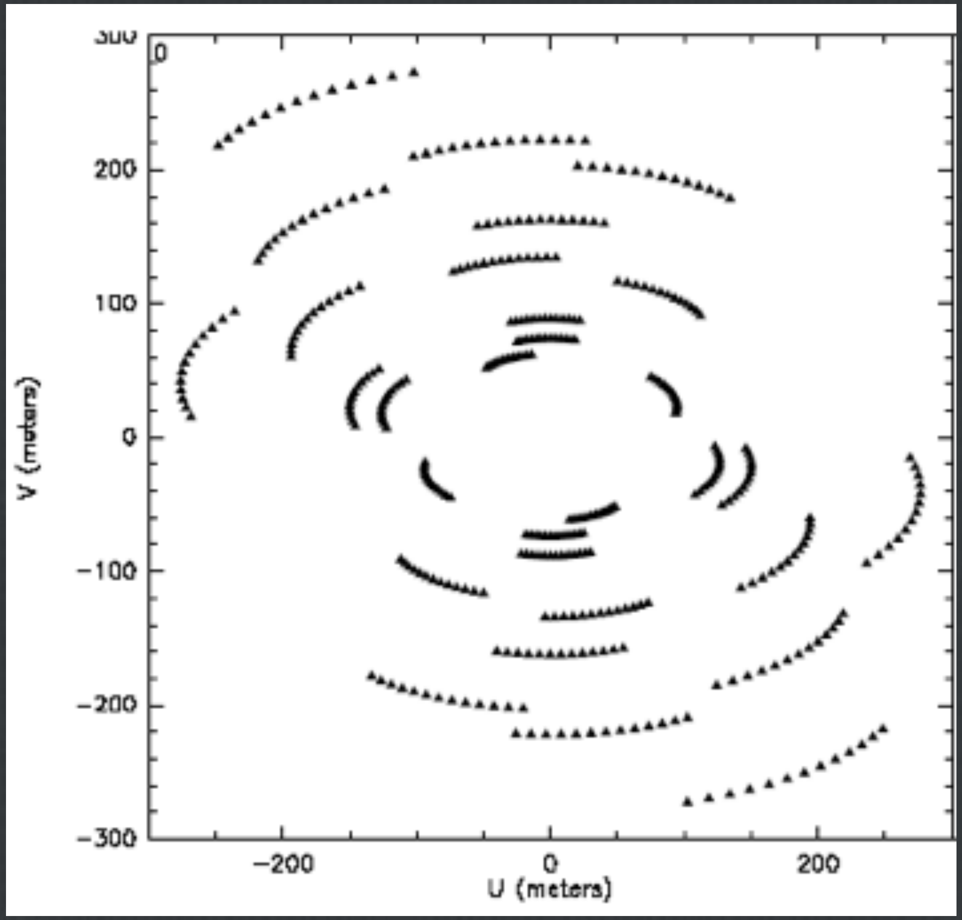

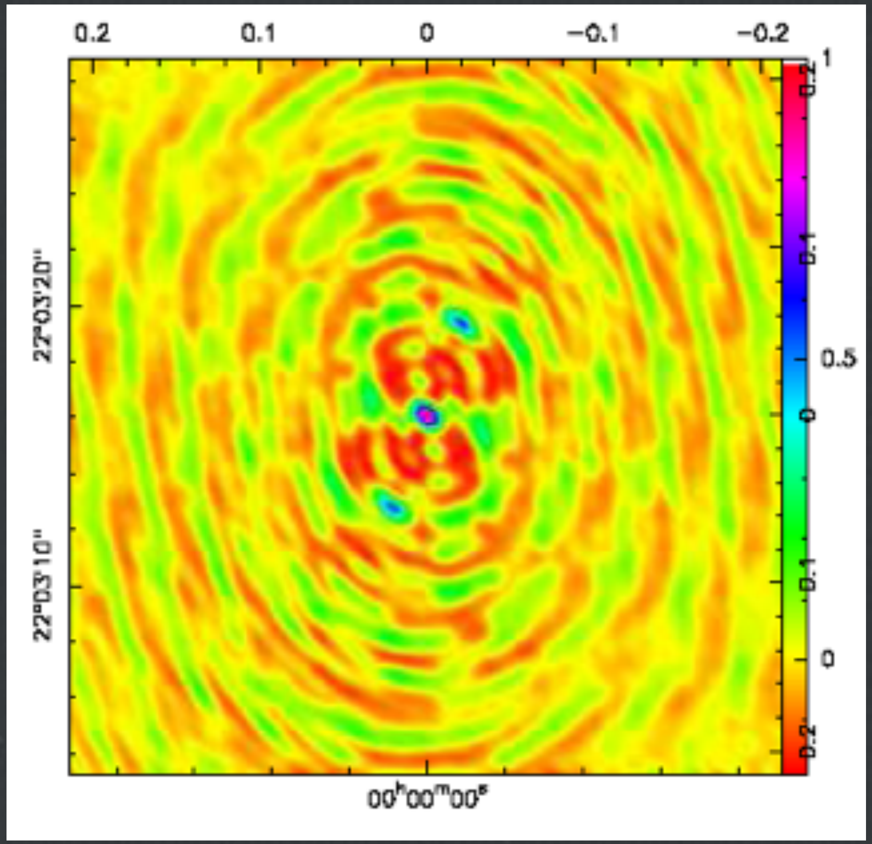

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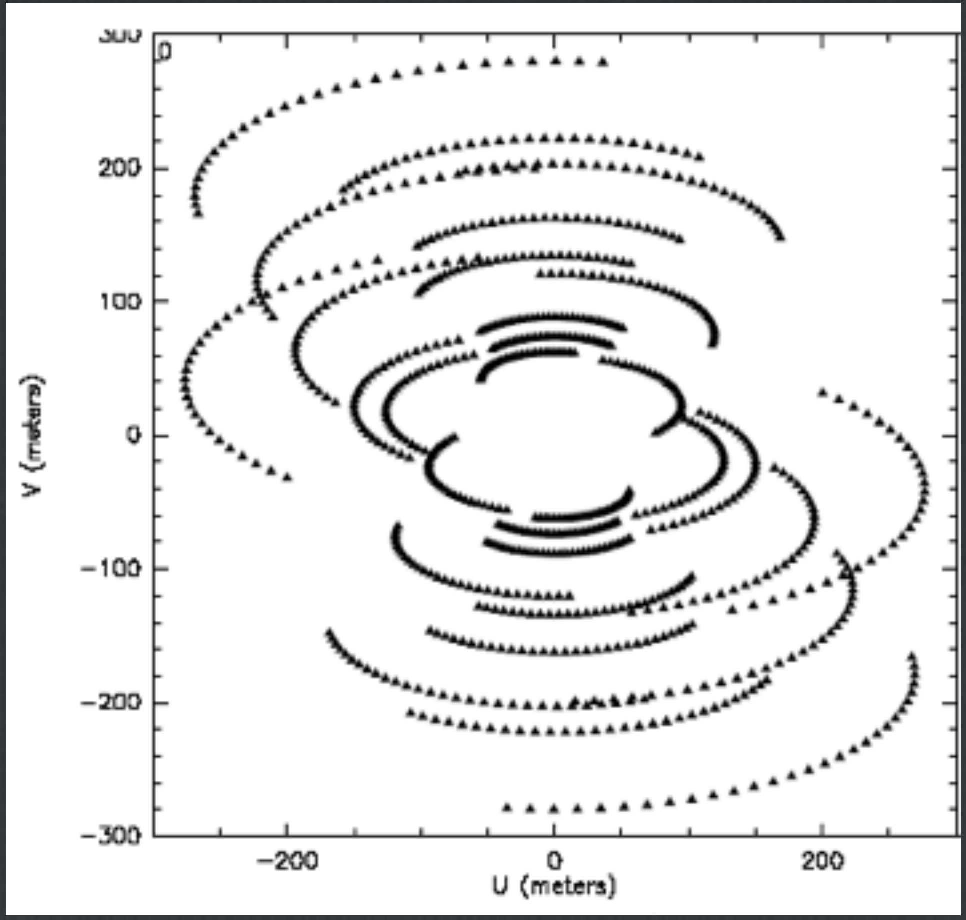
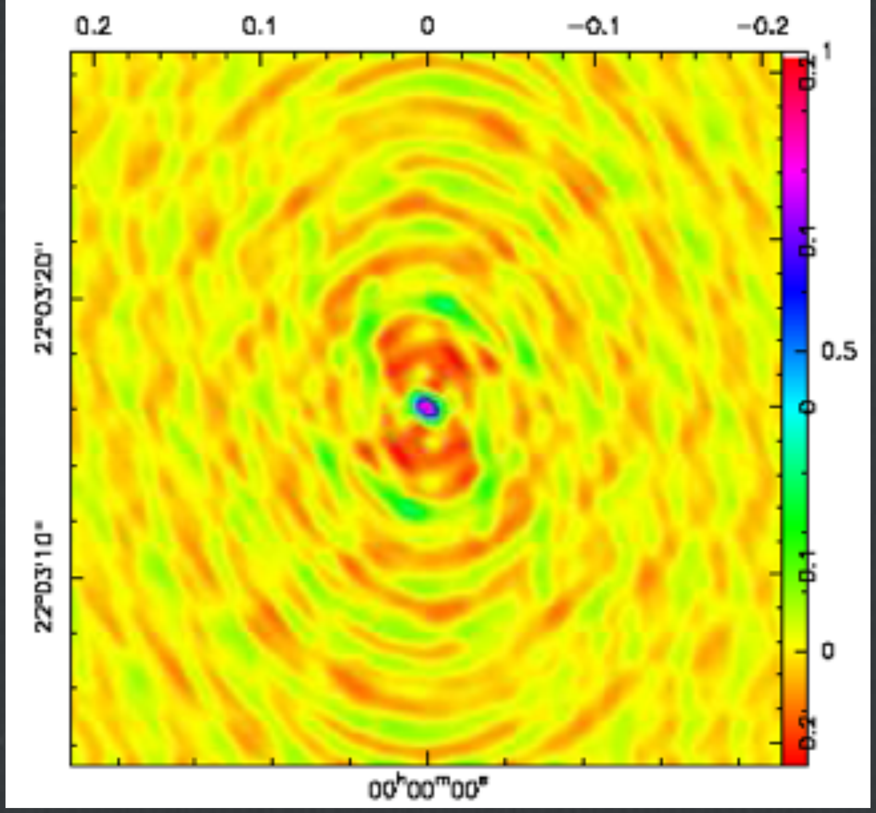
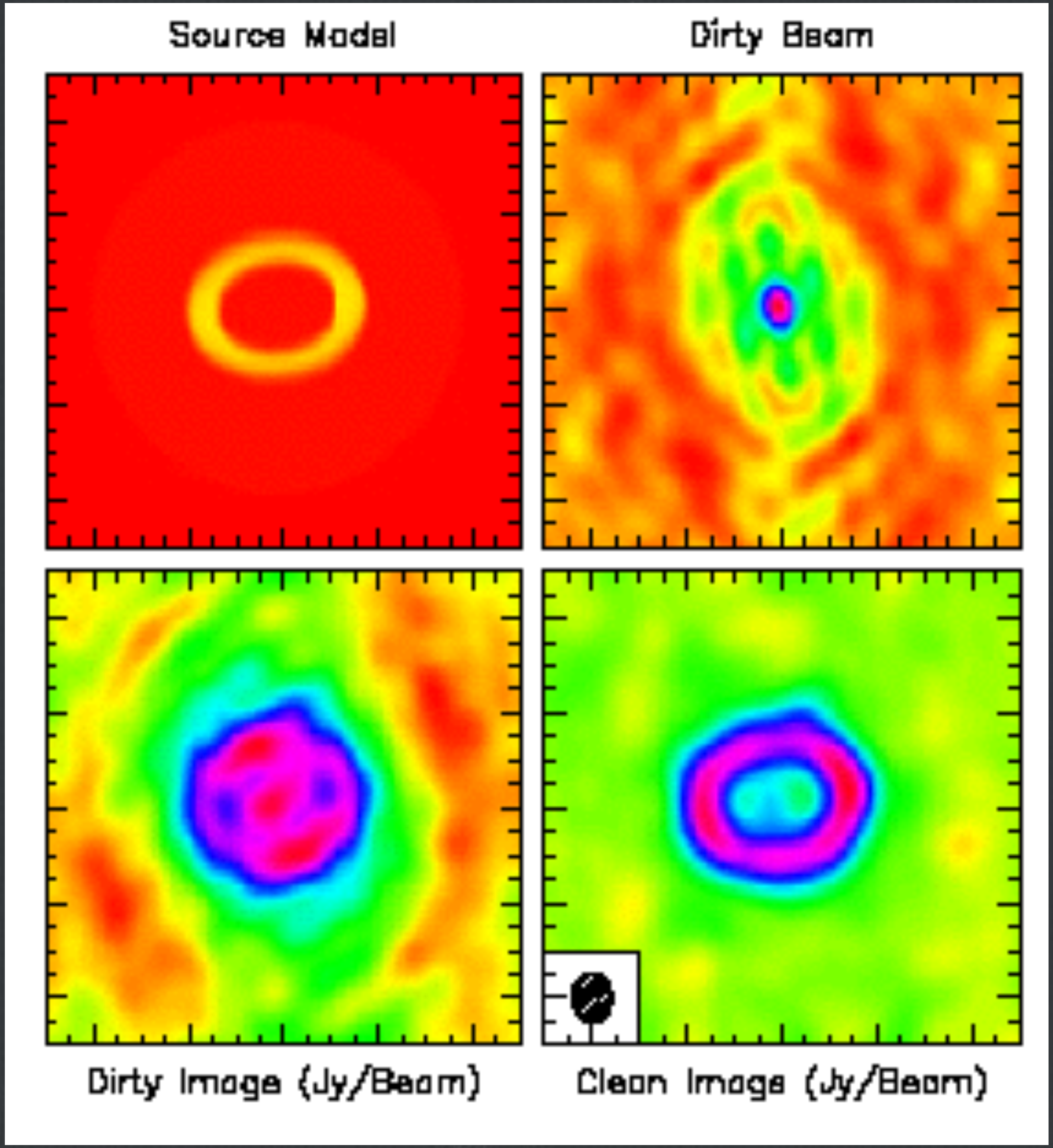




Clean

- Look for clean components (emitting peaks in the map) in the dirty image
- Deconvolve from the dirty beam (side-lobes)
- Convolve the clean components by a clean beam (without the side-lobes) –> clean image
- Different methods exists : adapted to source distribution kind

Clean



Source Model
Dirty Beam
Dirty Image (Jy/Beam)
Clean Image (Jy/Beam)

Real life : On-line calibrations

- Pointing
- Focus
- IF filters band pass

Real-time calibrations

- Atmospheric calibration
- Antenna positions
- Delay

New values can be entered off-line if necessary

- Atmospheric phase correction

Uncorrected data are also stored

Phase decorrelation

The atmosphere turbulence, the water vapor and temperature variations induce optical length variations, that means a adding a phase noise in the visibility : $\Delta\varphi = 2\pi\, \delta l/\lambda$

$$\Delta\varphi \propto \nu \quad \text{and} \quad \Delta\varphi \propto B^{0.5}$$

The timescale of atmosphérique phase fluctuations is ~ 30s (short)

At PdB, for a 300m-baseline : δl ~ 200μm : $\Delta\varphi$ ~ 55° @ 1.3mm

that corresponds to a radio-seeing of ~ 0.3-1"

Short time scale atmospheric phase fluctuations difficult to calibrate (WVR). It leads to a loss in the signal amplitude because of signal decorrelation (phase σ). The atm decorrelation efficiency is :

$$\eta_a = e^{-0.5\sigma^2} \sim 0.63 \text{ @1.3mm (63\% only)}$$

Real life : offline-calibrations

• **Bandpass**	phase and amplitude vs freq
• **Phase**	phase vs time
• **Amplitude**	amplitude vs time
• **Flux**	absolute flux scale

Calibration principles

- Calibrate only temporal or frequency effects, no dependence on (u,v)
- True visibility: $V_{ij}(\nu,t)$ (baseline ij)
- Observed visibility:

$$Vobs_{ij}(\nu,t) = G_{ij}(\nu,t)\, V_{ij}(\nu,t) + noise$$

- G_{ij} = complex gain (amplitude & phase)
- Scalar description – no polarization

Calibration principles

- **Most of the effects are antenna-based**
  - Pointing, Focus, Antenna position, Atmosphere, Receivers noise, Receivers bandpass…
- **Gain decomposition:** $$Vobs_{ij} = G_{ij} V_{ij} = g_i g_j V_{ij}$$
- Baseline-based effect?
  - Correlator bandpass → real-time calibration
  - Time and frequency averaging → **decorrelation**

Calibration principles

- Observation of a **point source** of flux S:

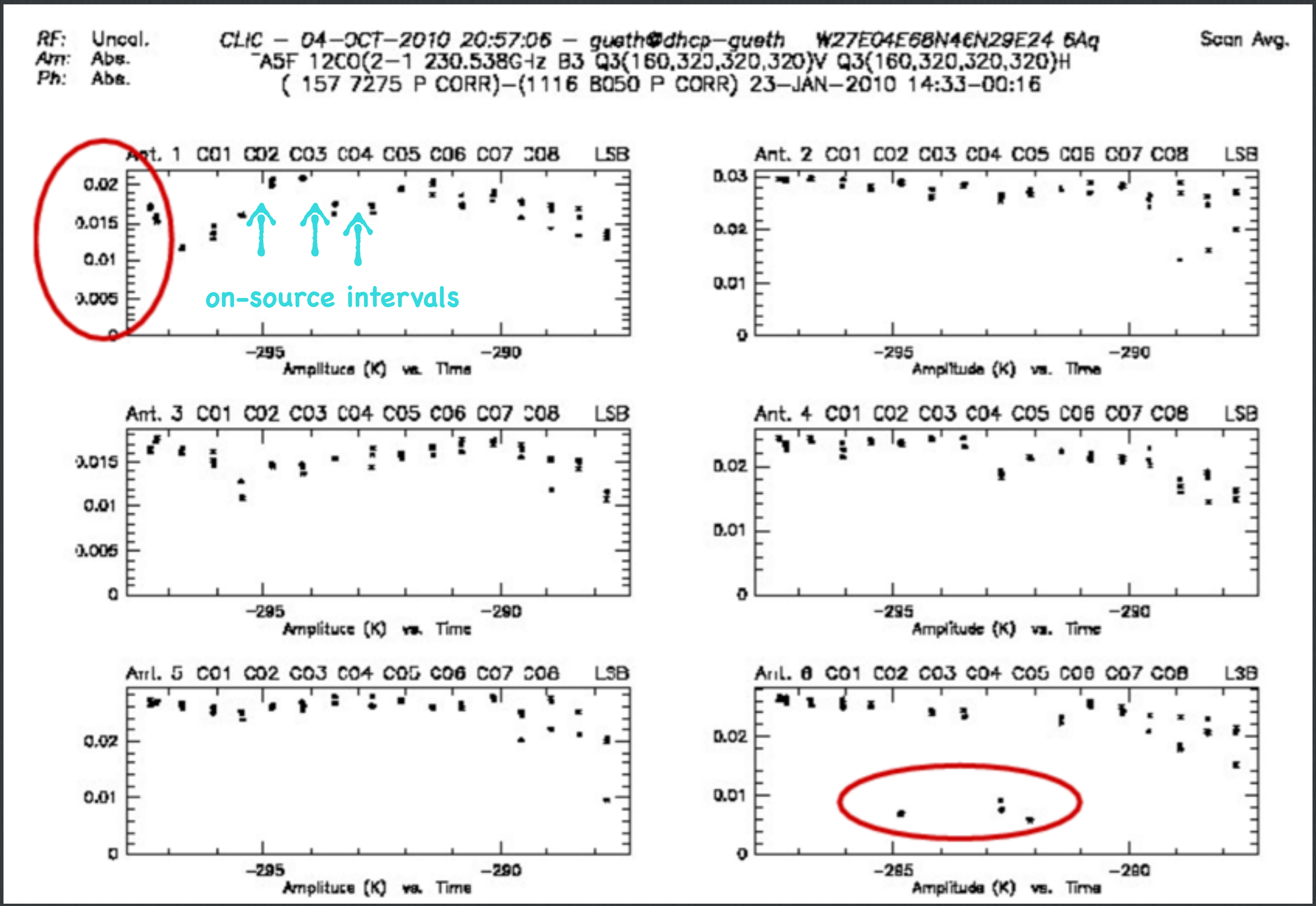
$$Vobs = G_{ij}\, V \quad V = S \quad G_{ij} = Vobs/S$$

- Antenna –based gains: $g_i g_j = Vobs/S$
- Can solve for antenna gains:

$$(g_1)^2 = Vobs_{12}\, Vobs_{31} \,/\, S\, Vobs_{32}$$

- Do it for all triangles and average

Example calibration : phase (gain)



Softwares

- GILDAS / astro : prepare observations (source LST, uv_coverage, spectral configuration, calibrators) —> ALMA/NOEMA …

- GILDAS / clic : continuum and Line Interferomter Calibration) software —> NOEMA

- GILDAS / mapping : uv-table to maps, deconvolution, analysis —> ALMA / NOEMA …

- ALMA-OT : proposal preparation

- CASA : Calibration (ALMA) + Imaging (ALMA / NOEMA)

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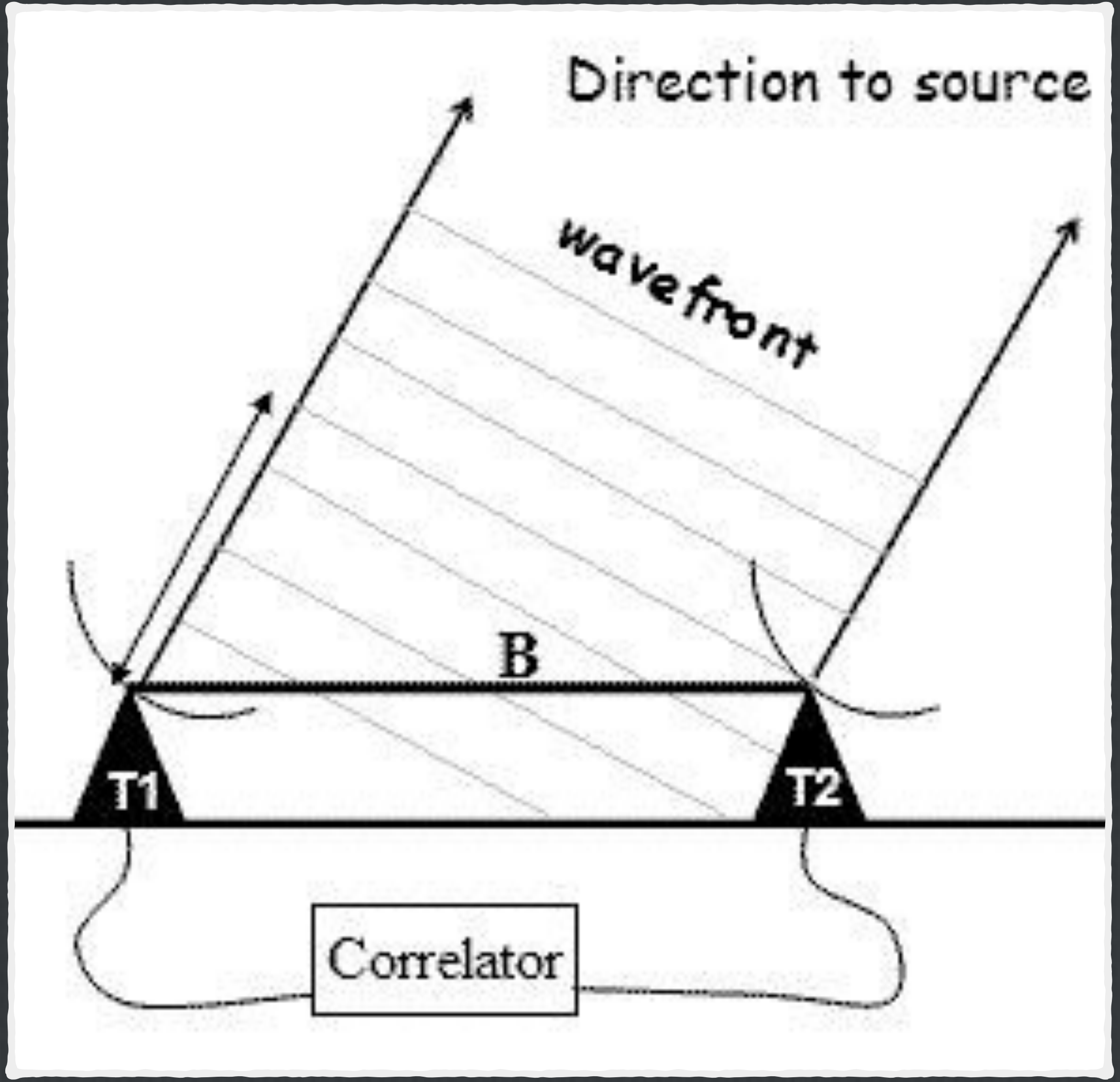

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Thank you