Introduction to radio/mm astronomy and interferometry

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Outline of talk

- Motivation
- Atmospheric windows
- Basic quantities
- Antenna fundamentals
- Basics of radio/mm interferometry
- ALMA
- software OT, CASA
- proposal submission

(Personal) Motivation

- ALMA
- Molecular gas – material for star formation in galaxies
- Radio/mm astronomy in the Czech rep.
  - 10m radio antenna in Ondřejov for solar research
  - Effelsberg 100m telescope – MW observation
  - IRAM 30m, PdB interferometer
  - ESO APEX antenna
  - ALMA interferometer



Literature and lectures

- books:
  - Tools of radio astronomy (Rohlfs & Wilson)
  - Synthesis imaging in radio astronomy (NRAO)
- on-line courses:
  - IRAM summer schools
  - NRAO Synthesis Imaging Workshops
  - …

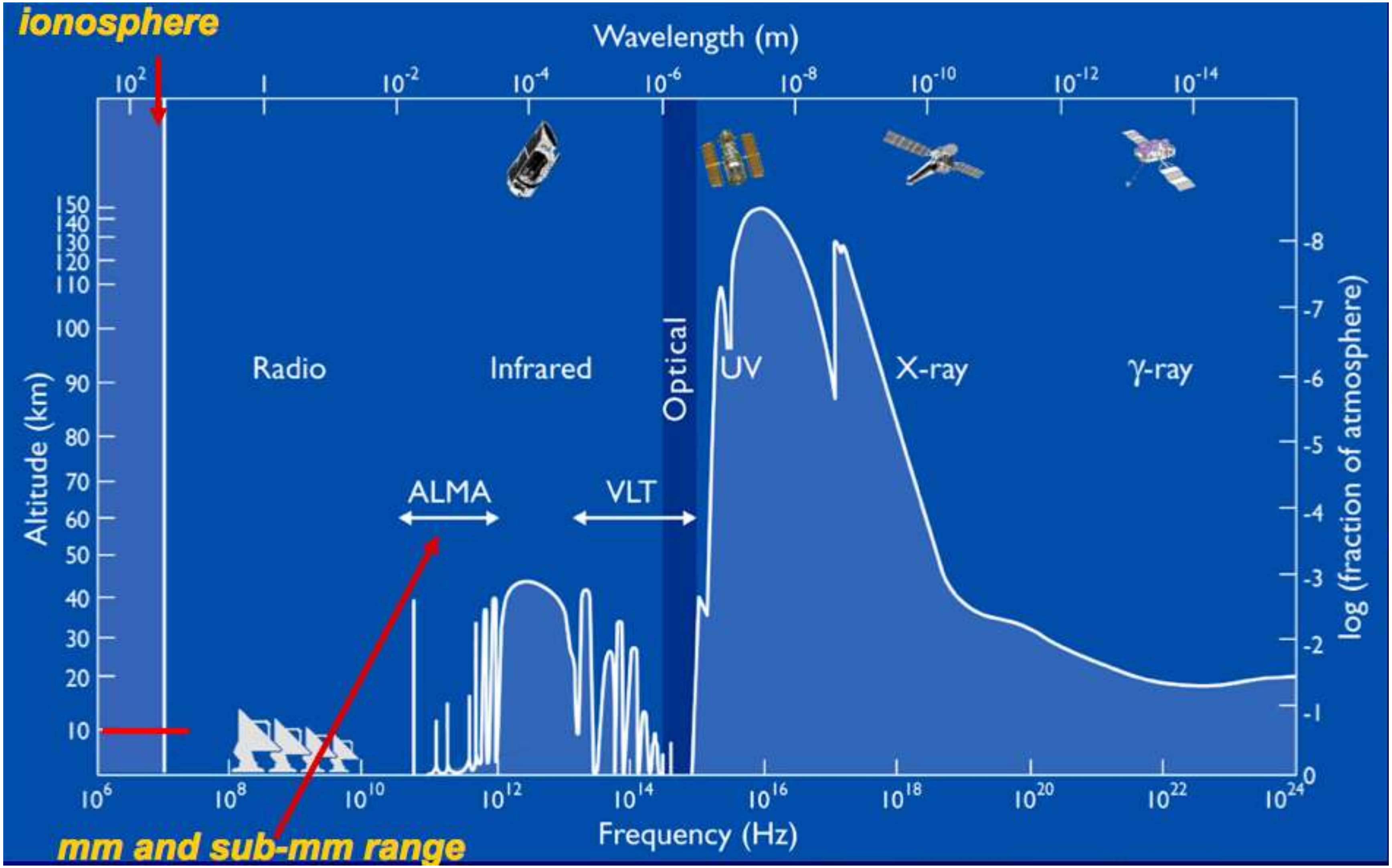
LECTURE 1

Radio/mm universe

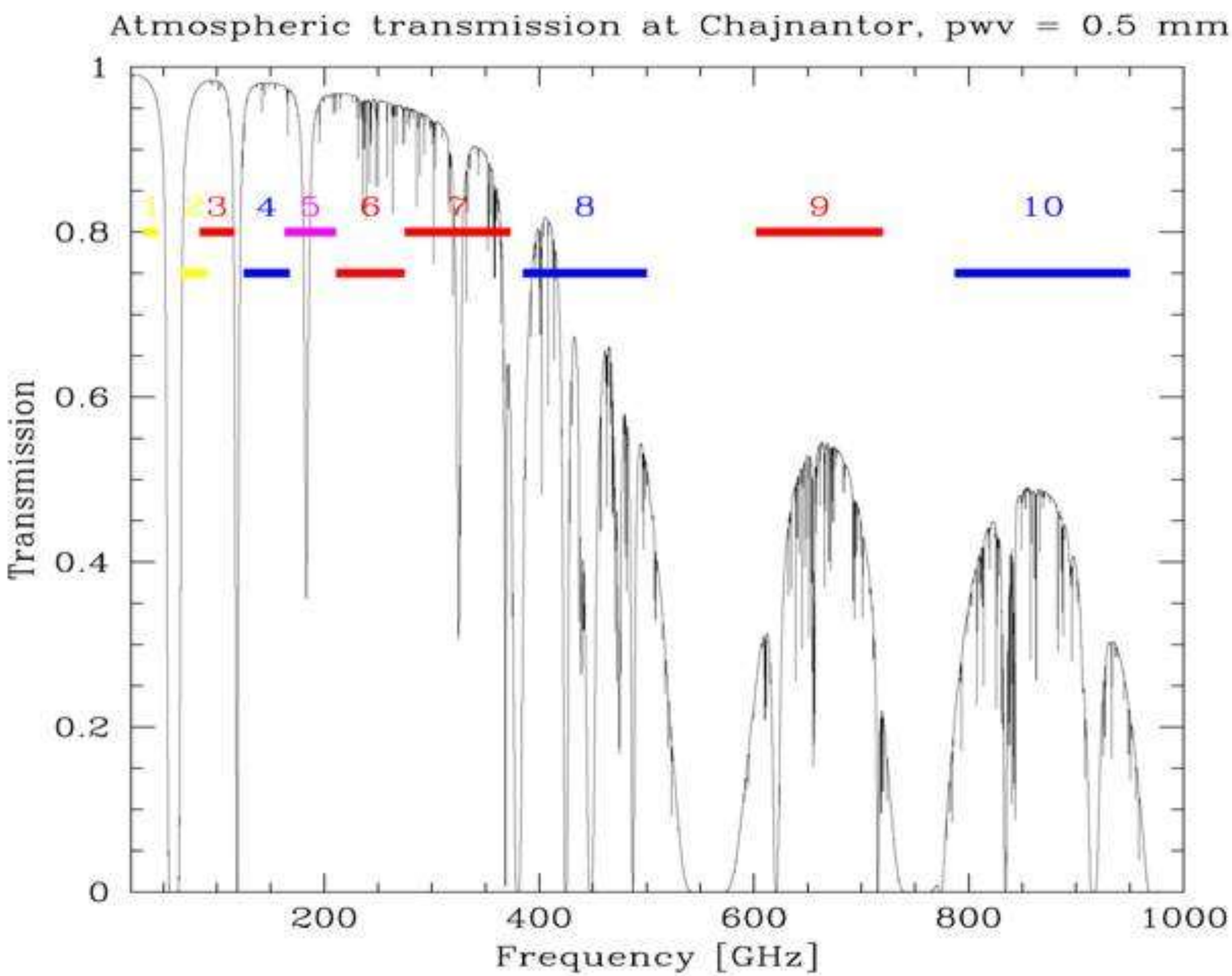
- Advantages of Radio:
  - radio waves reach the ground
  - objects or phenomena that are difficult or impossible to detect in other wavelengths
  - can use radio emission for quantatitive physical diagnostics of object parameters
- Radio/mm wavelengths are produced in a large number of ways
  - HI
  - Free-free emission
  - Molecular spectral lines
  - Synchrotron emission
  - Inverse Compton scattering
- emission properties provide quantitative physical information about conditions in the source
- spectral information, since different emission mechanisms have different characteristic spectral properties
- radio range is very broad (6 or 7 orders of magnitude)
- a complete picture of the physical nature of astronomical sources

- atmosphere remains transparent to long-wavelength radio waves, but the ionosphere reflects the radiation.

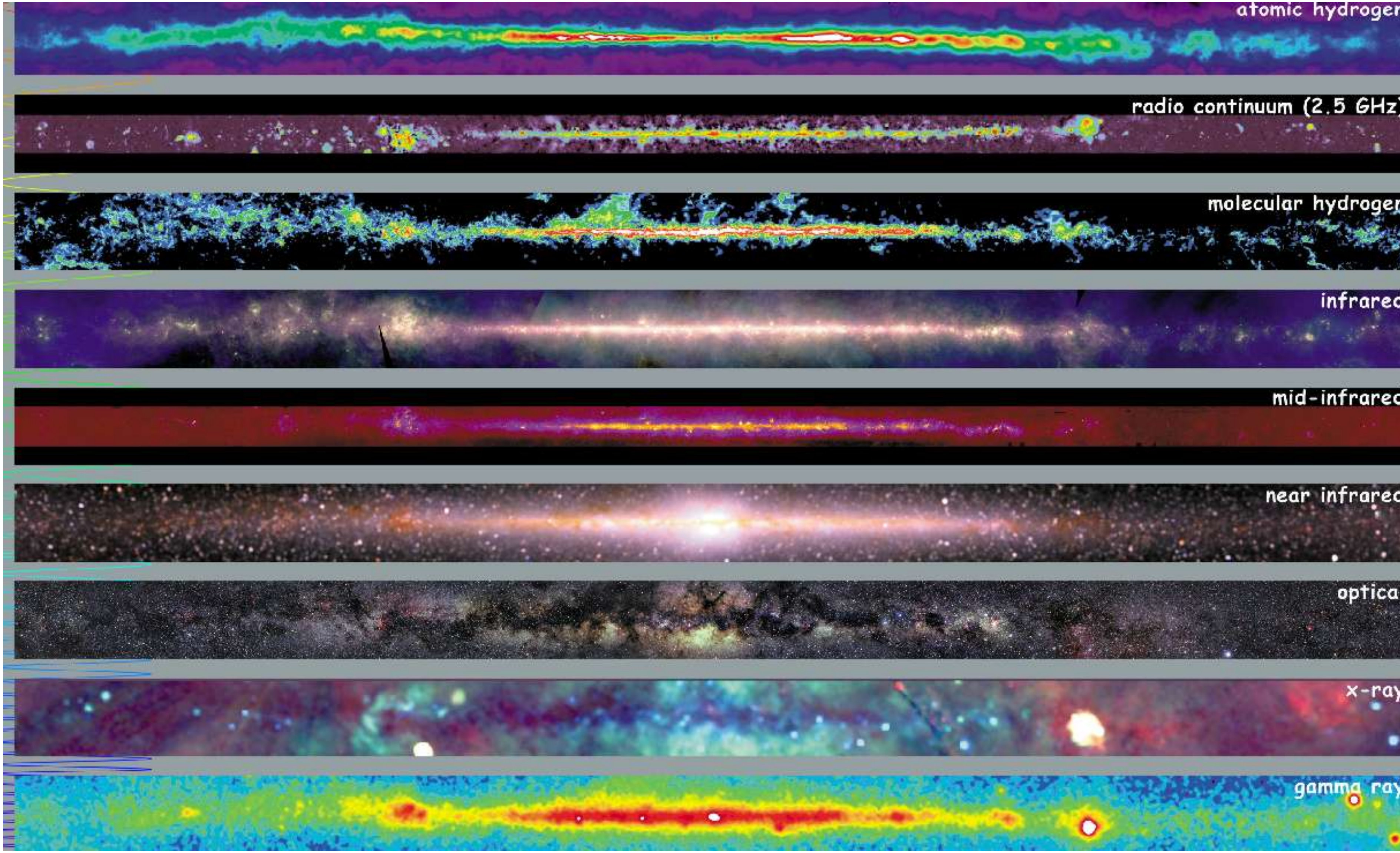
Opacity of the atmosphere



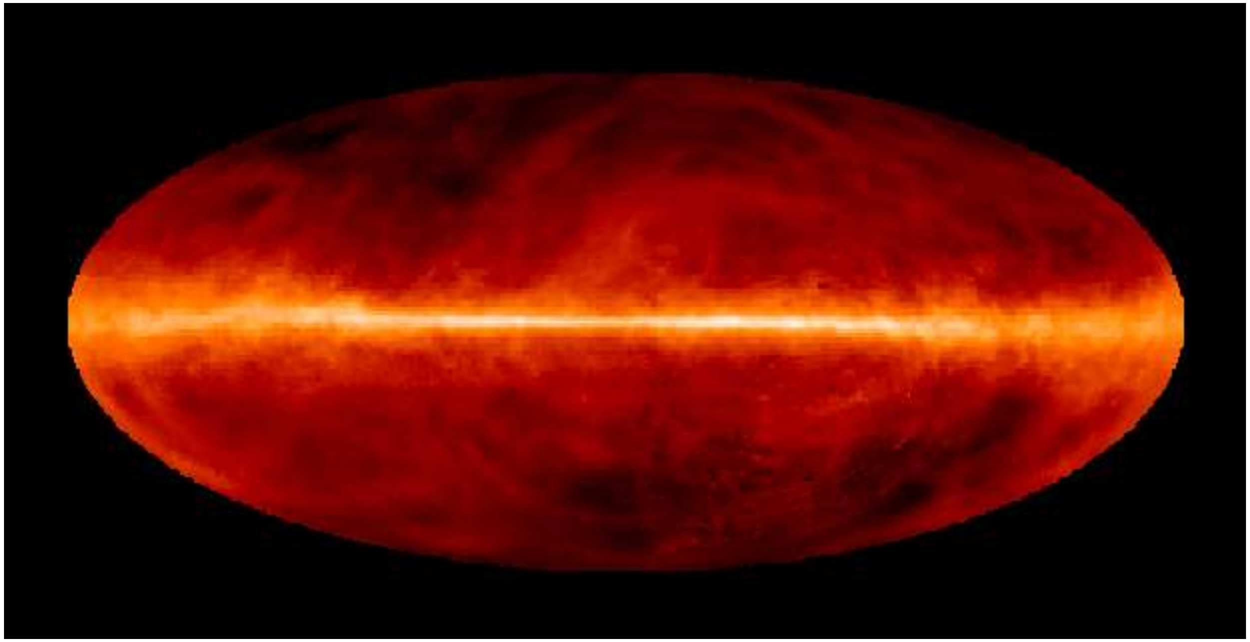
Atmospheric transmission on ALMA site

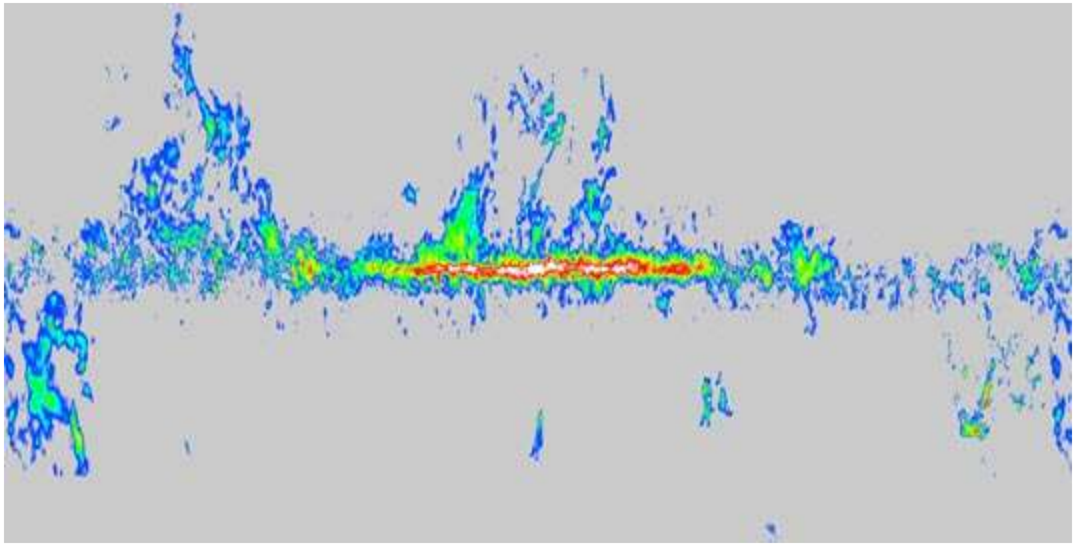


MW

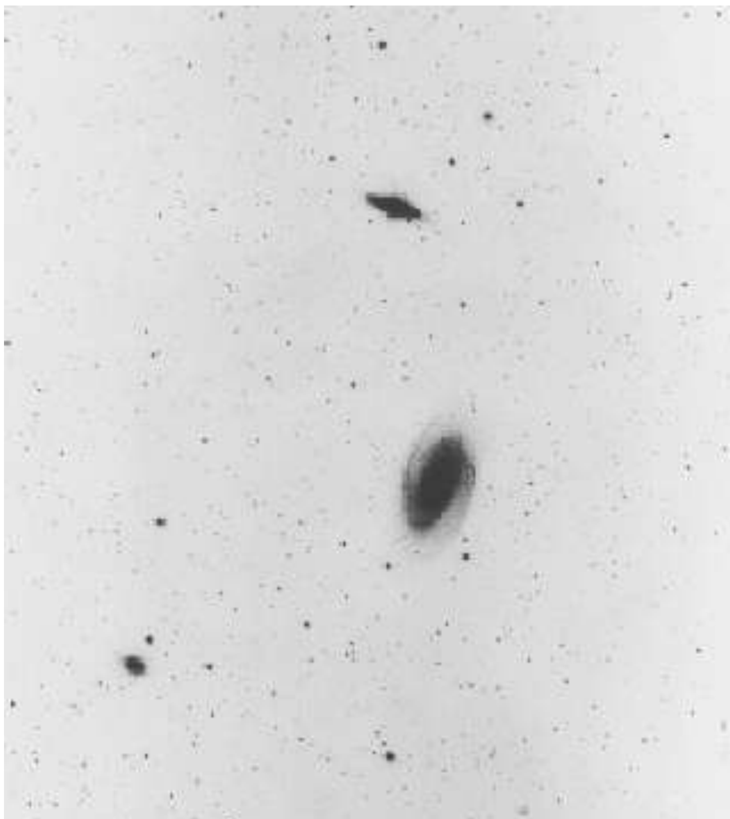


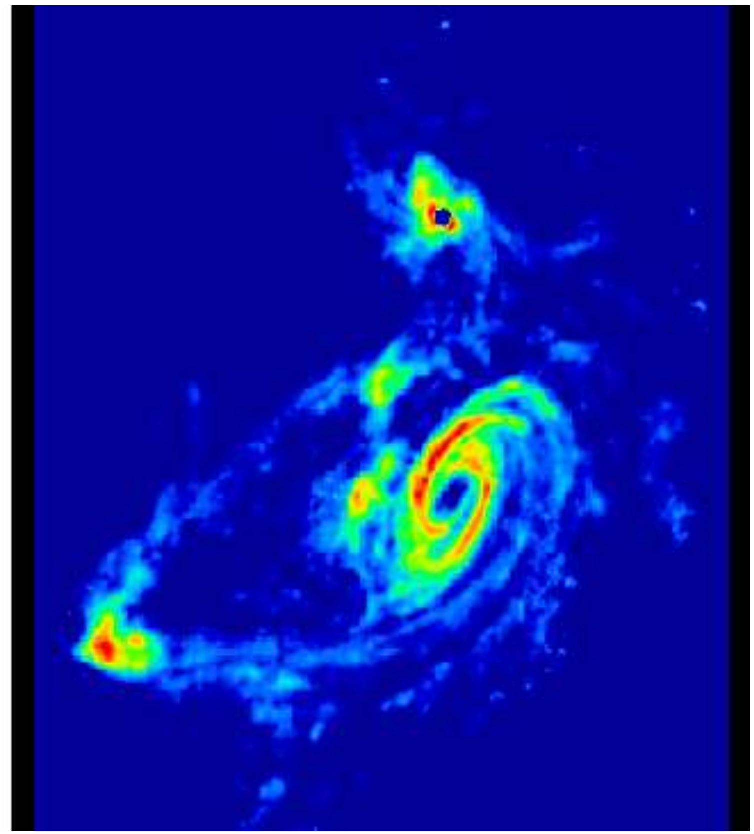
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray



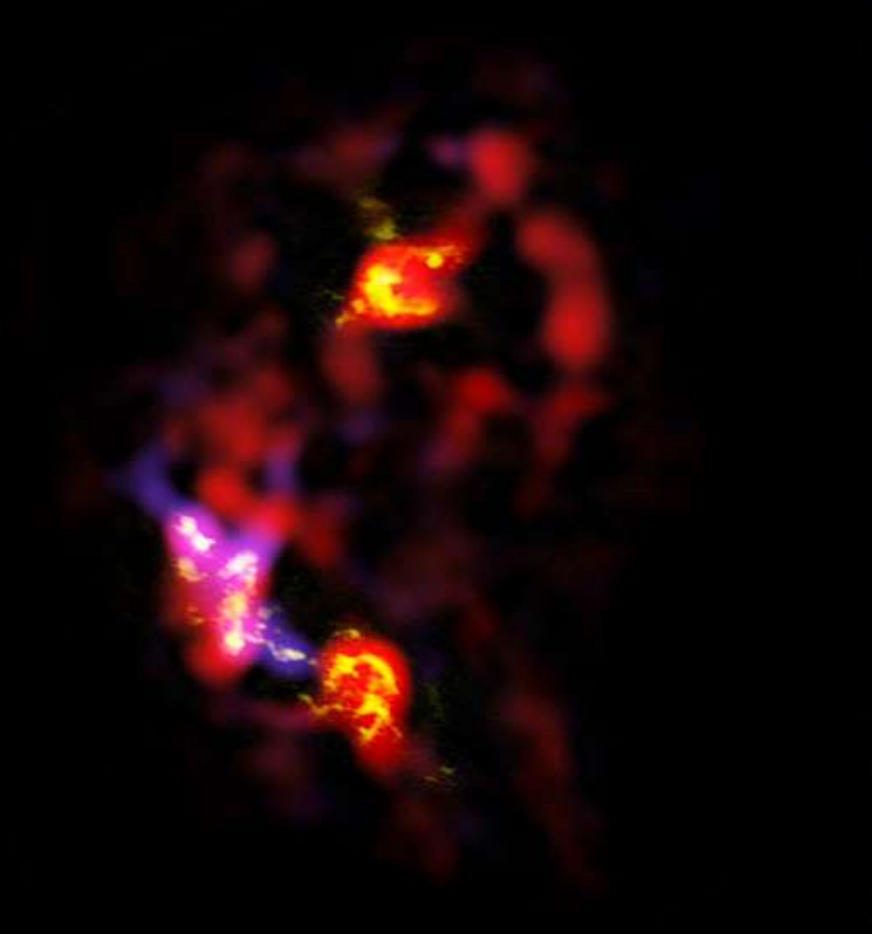


- Tidal interaction in M81 group





The Antennae – ALMA SV



Why interferometers?

- single radio elements have limited spatial resolution (the diffraction limit of the telescope)
  - for a circular aperture of diameter *D* the difraction limit is

$$\theta \cong 1.22\lambda / D$$

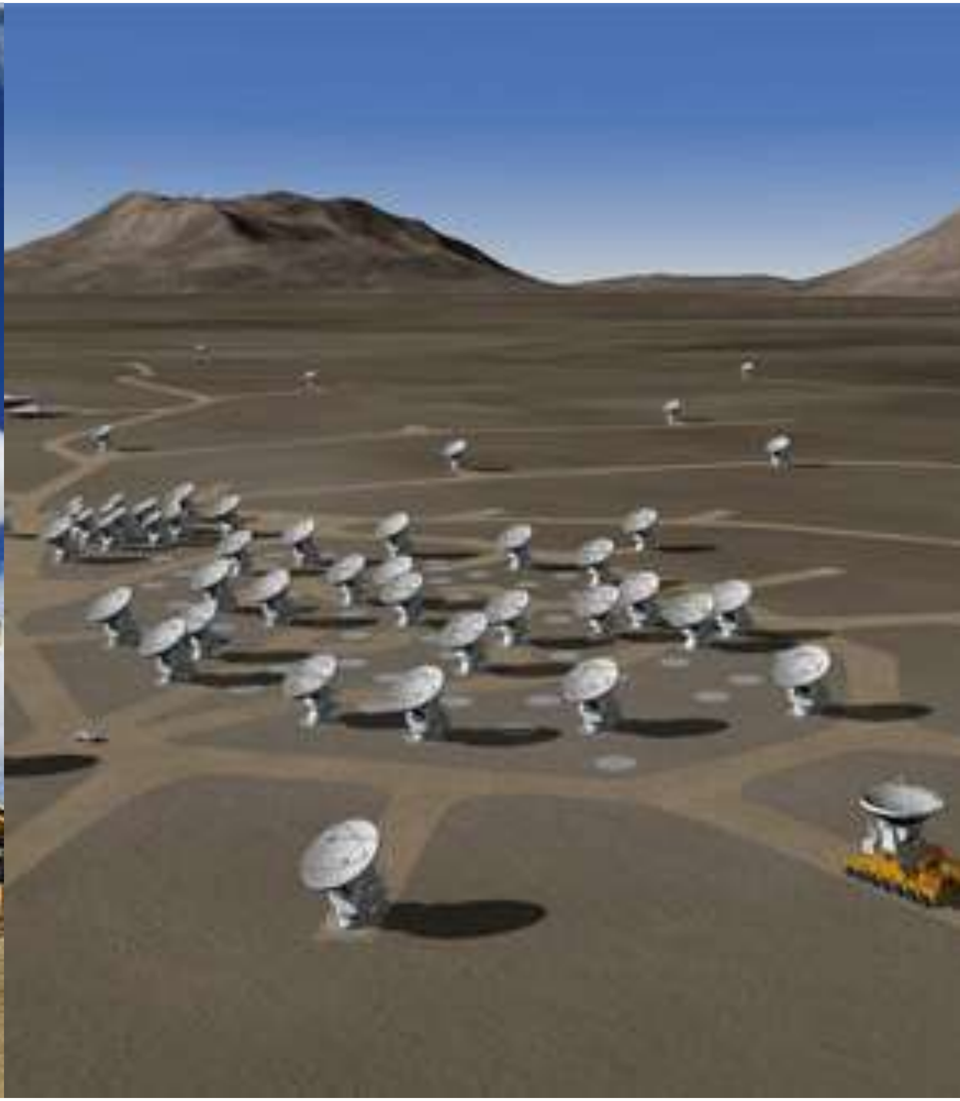
  - at a frequency of 5 GHz, even the Arecibo dish has an angular resolution of only about 50 arcseconds.
- limited spatial resolution of single element telescopes
- thus, sophisticated techniques to combine single elements into multiple-element arrays, which work together to form a "single telescope"
- in such arrays, the spatial resolution is determined by the maximum separation between elements, the ***baseline length, b***
- with an interferometer, the diffraction limit is

$$\theta \sim \lambda / b$$

- An interferometer reconstructs an image of the sky from measurements of specific spatial frequencies, i.e. measurements of the Fourier transform of the sky brightness (in the *uv*-plane).

eVLA

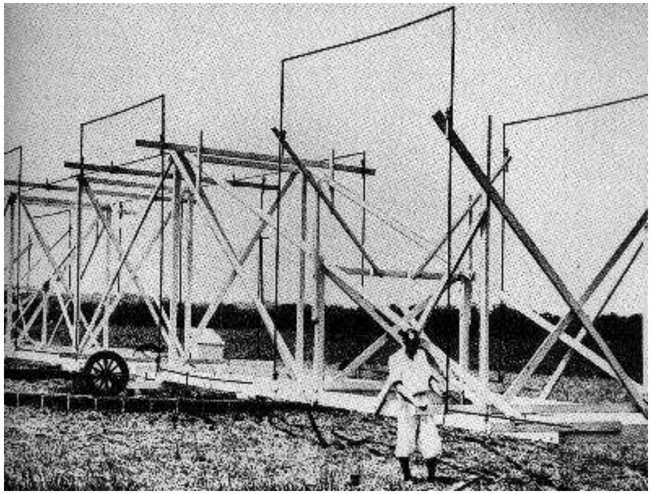
ALMA



ALMA

- Atacama Large Millimeter/sub-millimeter Array
- At an elevation 5000m at a latitude -23deg (Chile)
- 66 reconfigurable high-precision antennas:
  - fifty 12m diameter antennas+ ATCA (twelve 7m)
- Imaging in all atmospheric windows from 3.5mm to 300μm (84-950GHz)
- Maximum baselines from 150m to 16km
- Angular resolution as small as 0.005'' at 950GHz (0.04'' at 115GHz)
- Velocity resolution as fine as 0.008km/s
- Ability to split the array into several sub-arrays

A bit of history



- 1932 – K. Jansky discovered natural radio emission from our Galaxy
- Planck function

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

  – in the low-frequency (i.e., low energy photons) limit,

$$\frac{h\nu}{kT} << 1$$

  – e.g., at 100GHz, *T=hv/k=4.8K*

  – using Taylor-series approximation:

$$\exp\left(\frac{h\nu}{kT}\right) - 1 \approx 1 + \frac{h\nu}{kT} + \ldots - 1 \approx \frac{h\nu}{kT}$$

Black body

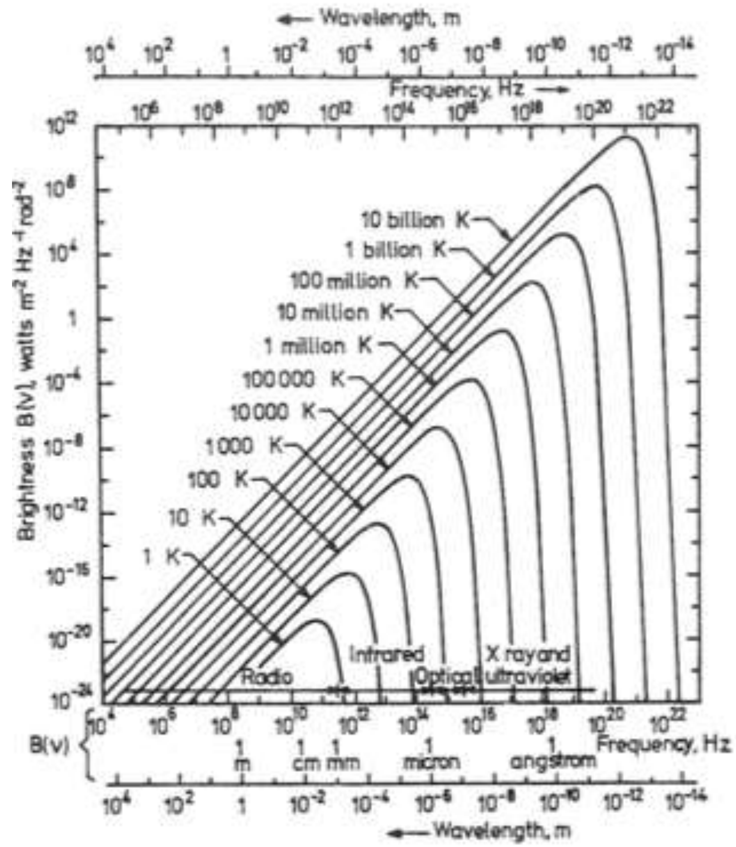
Rayleigh-Jeans approximation

$$B_\nu(T) \approx \frac{2h\nu^3}{c^2}\frac{kT}{h\nu} = \frac{2kT\nu^2}{c^2} = \frac{2kT}{\lambda^2}$$

peak of black body (Wien displacement)

$$\left(\frac{\lambda}{\mathrm{mm}}\right)\left(\frac{T}{\mathrm{K}}\right) = 2.8978$$

$$\left(\frac{\nu_{\mathrm{max}}}{\mathrm{GHz}}\right) = 58.789\left(\frac{T}{\mathrm{K}}\right)$$



T= 3K, λ=1mm

T=10K, λ=0.3mm

- we learn about a source by measuring the strength of its radiation as a function of direction on the sky (mapping) and frequency (spectroscopy)
- + other quantities such as time, polarization, etc.
- we need a clear description of the strength of radiation and how it varies with distance between the source and the observer

Brightness vs. flux density

- empty space + ray-optics approx.
- brightness (independent of distance) vs. apparent flux (function of distance)
  - Energy that flows through an area *dσ* in time dt in freq. range *(ν, ν+dν)* within solid angle *dΩ*:

$$dE_\nu = I_\nu \cos\theta d\sigma d\Omega dt d\nu$$

    where θ is projection angle,

    I_ν is specific intensity (spectral brightness)

  - since power = energy/unit t
  - **spectral brightness [$Wm^{-2}Hz^{-1}sr^{-1}$]**
  - I_ν is constant along any ray in empty space
  - i.e., it is the same at source and at detector
  - Total intensity also conserved

$$I_\nu \equiv \frac{dP}{\cos\theta d\sigma d\nu d\Omega}$$

$$I = \int_0^\infty I_\nu d\nu$$

Brightness vs. flux density

- discrete source with solid angle $d\Omega$
- spectral power received by detector of unit projected area
  = **flux density [$Wm^{-2}Hz^{-1}$]**

$$\frac{dP}{d\sigma d\nu} = I_\nu \cos\theta d\Omega$$

- integrating over the solid angle,
  (compact source Ω<<1rad, $\cos\theta \approx 1$)

$$S_\nu = \int_{\text{source}} I_\nu(\theta,\varphi) d\Omega$$

$$S_\nu \propto d^{-2}$$

- Flux density is function of distance
- Unresolved source – flux density may be measured but not spectral brightness
- Extended source – sp. brightness at any position on the source can be measured, but flux density must be calculated by integrating observed brightness over source solid angle
- Thus, flux density normally used to describe only (relatively) compact sources

$$1\,\text{Jansky} = 1\,\text{Jy} \equiv 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$$

luminosity

- **spectral luminosity [WHz^{-1}]**

  = total power per unit bandwidth radiated by source at freq. ν:

  $$L_\nu = 4\pi d^2 S_\nu$$

  - intrinsic property of the source
  - does not depend on the distance
- bolometric luminosity

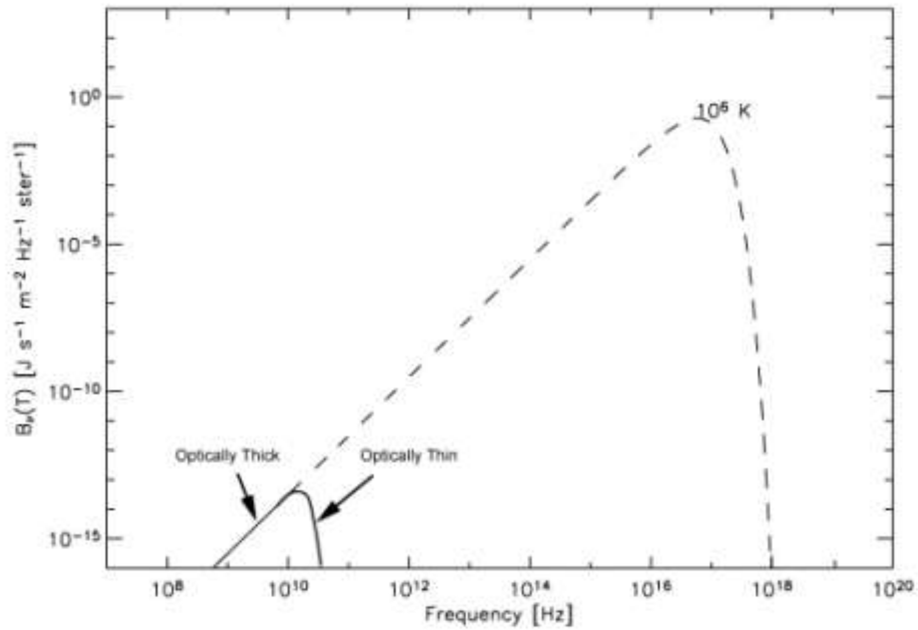
  $$L_{\mathrm{bol}} = \int_0^\infty L_\nu \, d\nu$$

summary

- monochromatic intensity [$\mathrm{Wm^{-2}Hz^{-1}sr^{-1}}$]
  - integrate over all frequencies intensity [$\mathrm{Wm^{-2}sr^{-1}}$]: $I = \int I_\nu d\nu$
  - integrate over angular area flux [$\mathrm{Wm^{-2}}$]: $S = \int I d\Omega$
  - flux density [$\mathrm{Wm^{-2}Hz^{-1}}$]: $S_\nu \equiv \int_{\text{source}} I_\nu(\theta, \varphi) d\Omega$
  - flux density (over some band *Δν*) fundamental quantity measured by radio telescopes:

$$1\,\text{Jansky} = 1\,\text{Jy} \equiv 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$$

Brightness temperature



- Black body is by definition optically thick
- But many radio-emitting plasmas are optically thick at low frequencies but optically thin at high frequencies
- R-J limit:

$$T = \frac{B_\nu(T)\, c^2}{2k\nu^2}$$

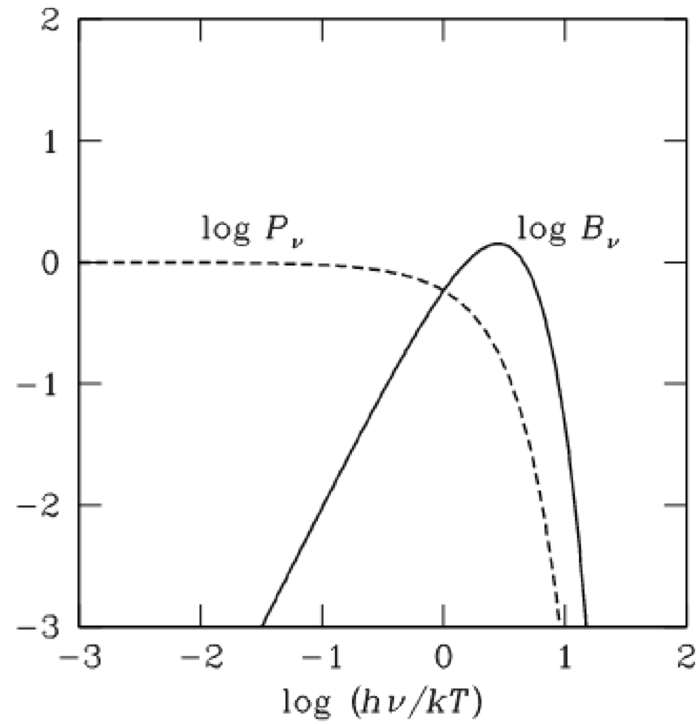
- Flux density observed by a telescope:

$$S = \int \frac{2kT_b\nu^2}{c^2} d\Omega = \frac{2k\nu^2}{c^2} \int T_b d\Omega$$

- When optically thin, intensity is less than Planck function
- Equivalent (effective) temperature

Power generated by a resistor

- Warm resistor = "black body" of electric circuits
  - at temperature T>0K it generates electrical noise
  - amount of power generated depends only on T
  - noise generated is indistinguishable from noise coming from an antenna observing a blackbody radiator
  - power received by antenna can be described in terms of resistor temperature required to generate the same power thermally
  - **warm resistors are in radio astronomy used as standards for calibrating receiver gains**
  - gain of a radio receiver is calibrated by connecting it alternately to hot and cold loads with known temperatures



Electrical power per unit bandwidth generated by a resistor:

$$P_\nu = kT$$ in the limit hν<<kT

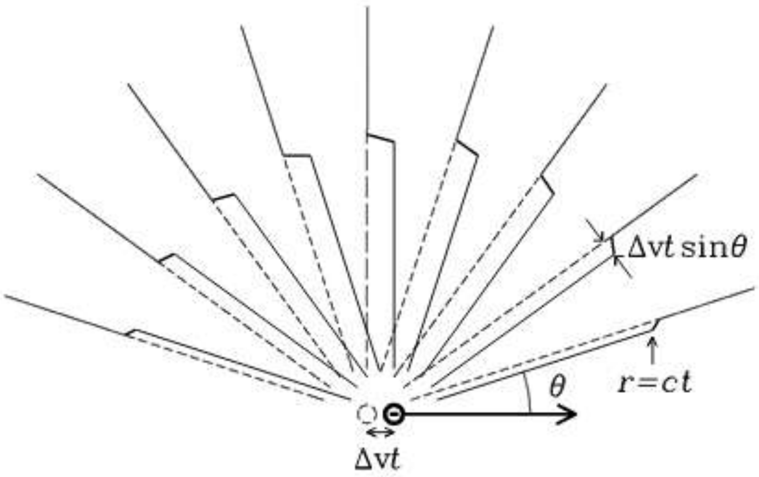
Nyquist formula (electrical equivalent of Rayleigh-Jeans law for radiation)

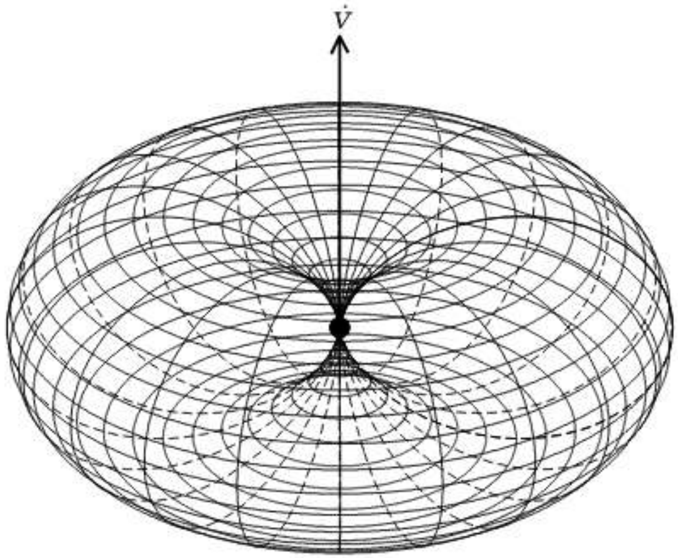
Larmor formula

- Radiation from an accelerated charge
- Total power emitted:

$$P = \frac{2}{3}\frac{q^2\dot{\upsilon}^2}{c^3}$$

  - any charged particle radiates when accelerated
  - total power prop. to square of acceleration
  - non-relativistic formula





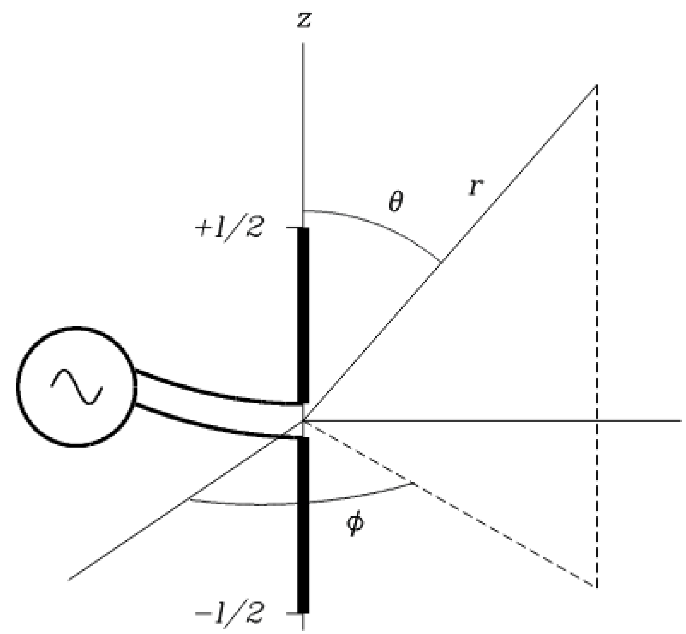
Antenna fundamentals

- antenna = device for converting EM radiation in space into electrical currents in conductors (or vice-versa)
- passive radio telescopes = receiving antennas
- usually, it is easier to calculate the properties of transmitting antennas
- fortunately, most characteristics are unchanged when the antenna is used for receiving (*reciprocity theorem*)

steerable parabolic reflector
first focal room
secondary reflector
+ radio wave
receiver
parabolic reflector
second focal room
support structure
upper laboratory
www.visualdictionaryonline.com
rotating track
counterweight
elevator
laboratory
circular track

Short dipole antenna

- the simplest antenna
- length <<λ
- current in the bottom conductor is 180º out of phase with the top one
- Radiation from a dipole depends on frequency



$$I = I_0 \cos(\omega t) = I_0 \exp(-i\omega t)$$

- using Larmor formula, the radiated el. field from a “wire” is prop. to integral of the current along the antenna:

$$E = \frac{-i\omega \sin\theta}{rc^2} \int_{-l/2}^{l/2} I dz$$

Short dipole antenna

- current along the antenna must drop to zero at the ends
- linear decline approx.

$$I(z) = I_0 e^{-i\omega t}\left[1 - \frac{|z|}{l/2}\right]$$

then

$$E = \frac{-i\pi \sin\theta}{c} \frac{I_0 l}{\lambda} \frac{e^{-i\omega t}}{r}$$

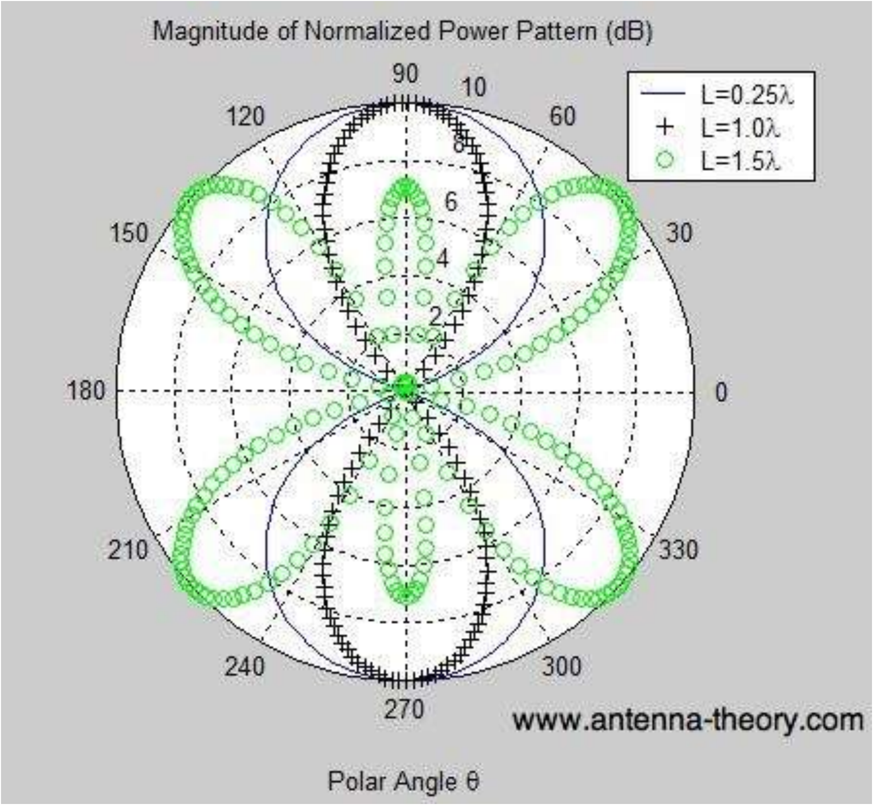
- angular distribution of radiated power (power pattern) is the same doughnut-shaped as in the case of Larmor radiation:

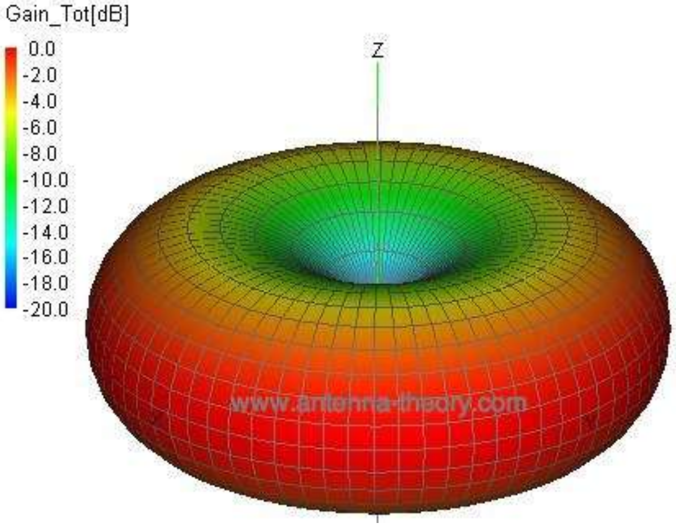
$$P \propto \sin^2\theta$$

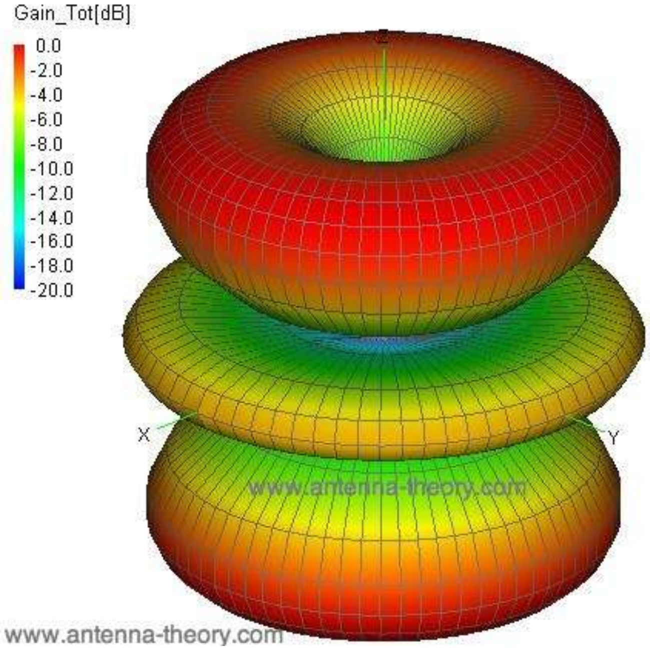
- such an antenna will radiate different amounts of power in different directions
- time-averaged total power emitted: $\langle P \rangle = \frac{\pi^2}{3c}\left(\frac{I_0 l}{\lambda}\right)^2$
- in a more general case the shape of the power pattern will depend on both spherical coordinates

Dipole antenna

- Radiation patterns



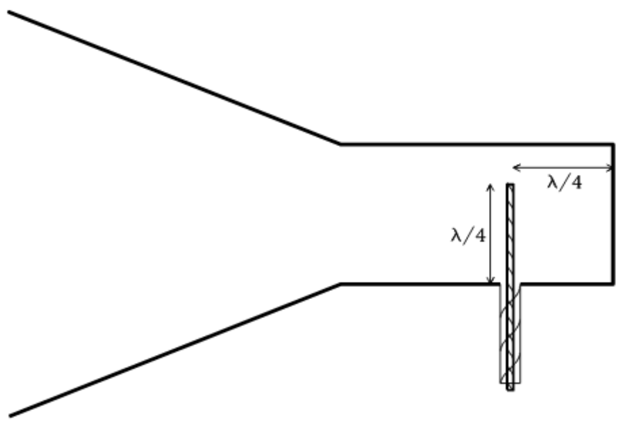


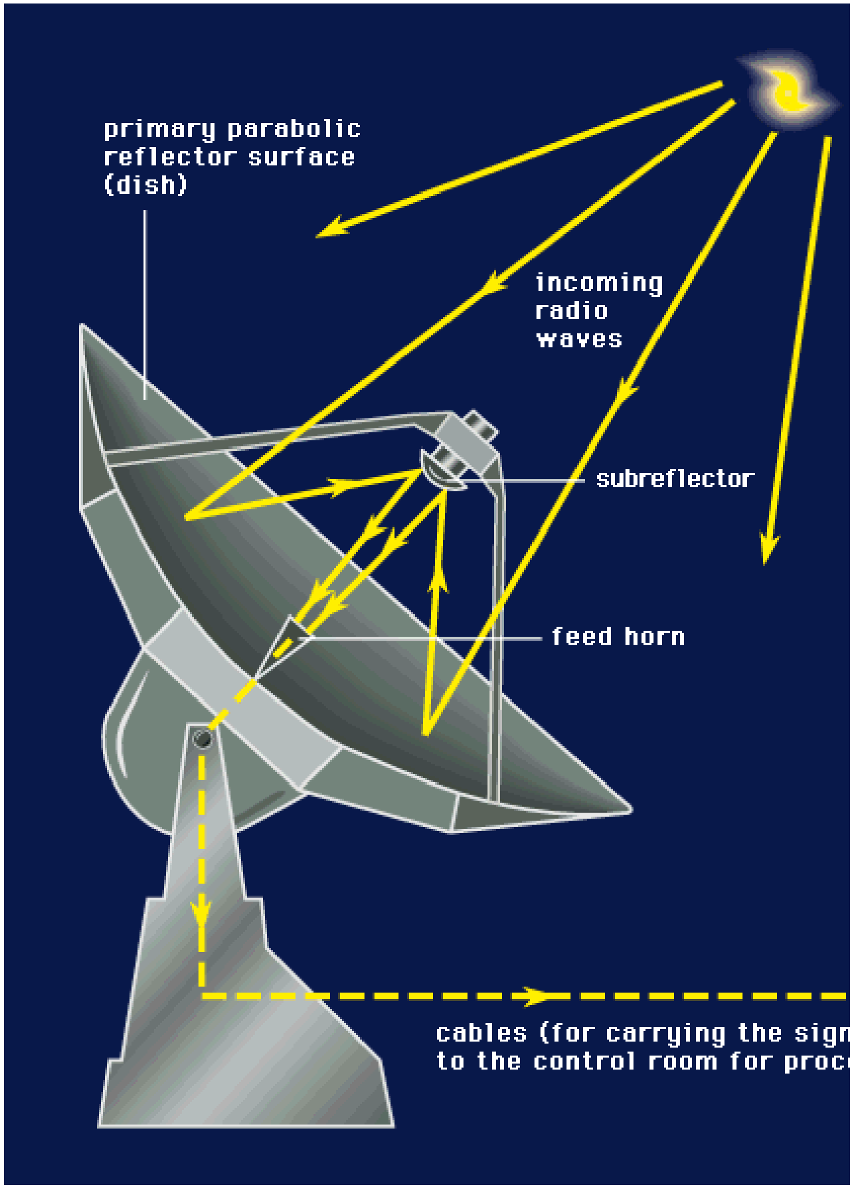


- Antennas in most radio telescopes are half-wave dipoles ($l \approx \lambda/2$, or their relatives)
- large parabolic reflector serves only to focus plane waves onto the *feed antenna* – the “feed” feeds transmitter power to the main reflector; or vice-versa in receiving antennas, it collects radiation from the reflector
- half-wave dipoles used as feeds at low frequencies (<1GHz, λ>0.3m)

Artist's impression of SKA low frequency aperture arrays

- At shorter wavelengths, almost all radio telescope feeds are quarter-wave ground-plane verticals inside *waveguide horns*
- The $\lambda/4$ vertical collects most of the (vertically polarized) radiation and converts it into an electric current that travels down the coaxial cable to receiver





Radiation resistance

- Radiation resistance is caused by the radiation reaction of the conduction electrons in the antenna
- While the energy lost by ohmic resistance is converted to heat, the energy lost by radiation resistance is converted to electromagnetic radiation
- radiation resistance of an antenna is a good indicator of the strength of the electromagnetic field being received by a receiving antenna (or radiated by a transmitting antenna), since its value is directly proportional to the *power* of the field.
- Ohm's law for time-varying currents: $\langle P \rangle = \langle I^2 \rangle R$
- Radiation resistance of antenna: $R \equiv \frac{2\langle P \rangle}{I_0^2}$
- Radiation resistance of free space: $R_0 = \frac{4\pi}{c} = 120\pi\,\Omega \approx 377\,\Omega$

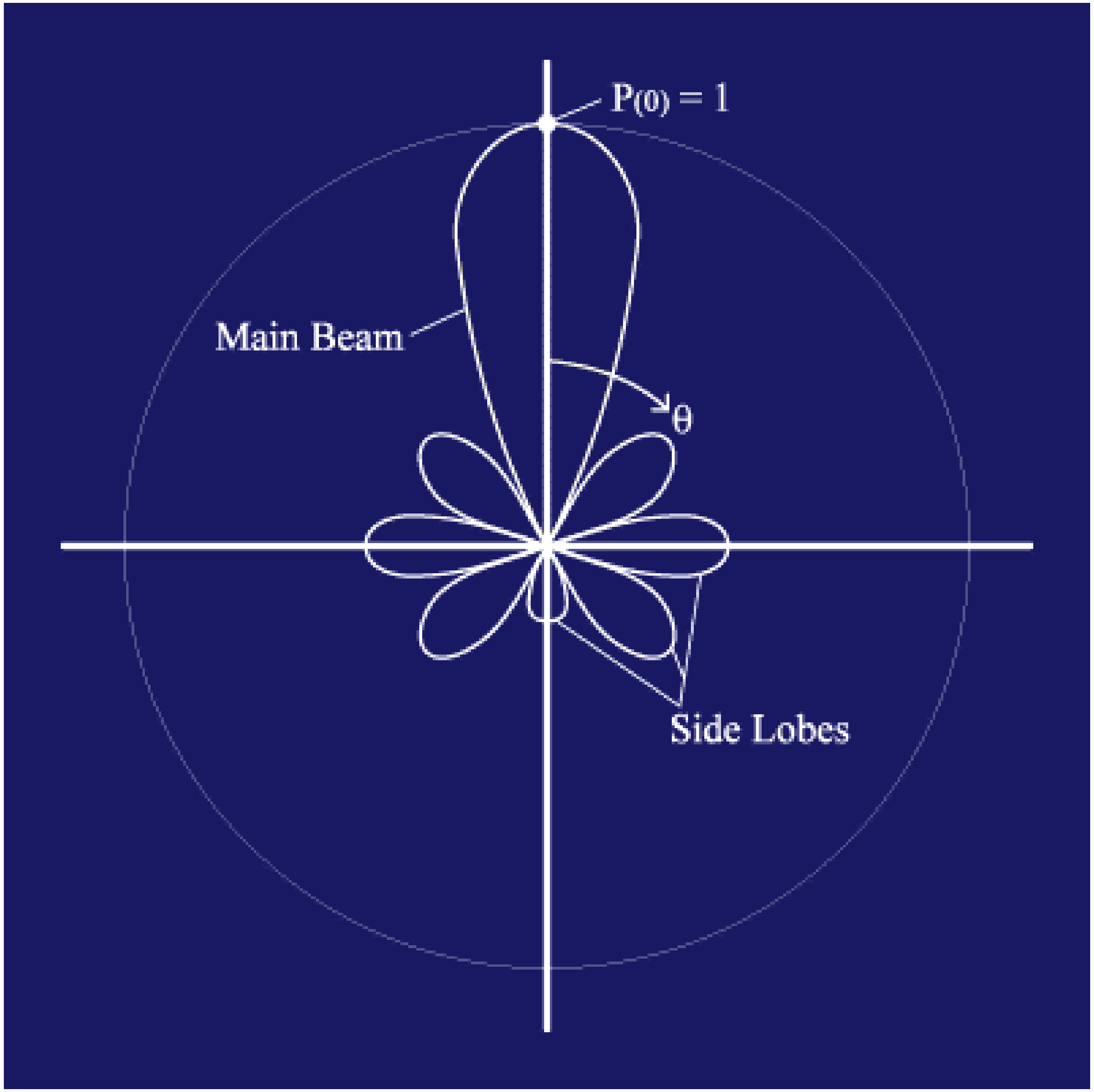
Antenna power gain

- Power gain (directive gain) $G(\vartheta,\varphi)$ of a transmitting antenna is defined as the power transmitted per unit solid angle in direction (ϑ,φ) divided by the power transmitted per unit solid angle from an isotropic antenna
- If the total power W_v is fed into a lossless isotropic antenna, this would transmit P power units per solid angle. Then the total radiated power: $W_v=4\pi P$
- In a realistic (but still lossless) antenna, a power $P(\vartheta,\varphi)$ per unit solid angle is radiated in the direction (ϑ,φ) .
- If we define directive gain $G(\vartheta,\varphi)$ as factor by which $P(\vartheta,\varphi)$ exceeds P, then

$$G(\vartheta,\varphi) = \frac{4\pi P(\vartheta,\varphi)}{\iint P(\vartheta,\varphi)d\Omega}$$

- In general, peak gain of an antenna must beam most of its power into a solid angle $\Delta\Omega$ such that $\Delta\Omega \approx \frac{4\pi}{G_{\max}}$
- Expressed logarithmically in units of dB: $G(\mathrm{dB}) \equiv 10\log_{10} G$

Power pattern



Effective area

- Receiving counterpart of transmitting power gain is *effective area* of antenna
- **Effective aperture** of the antenna = an amount of power that is extracted by the antenna from a plane wave with the power density |<S>|:

$$A_e = P / \left| \langle S \rangle \right|$$

- Effective aperture is very much like a cross-section. Comparing it to the geometric aperture A_g, we can define an **aperture efficiency** η_A by

$$A_e = \eta_A A_g$$

- Usually the peak value of the effective aperture is used – this is the direction of main beam:

$$D = G_{\max} = \frac{4\pi A_e}{\lambda^2}$$

- thus a *highly directive antenna has a small* Ω_A

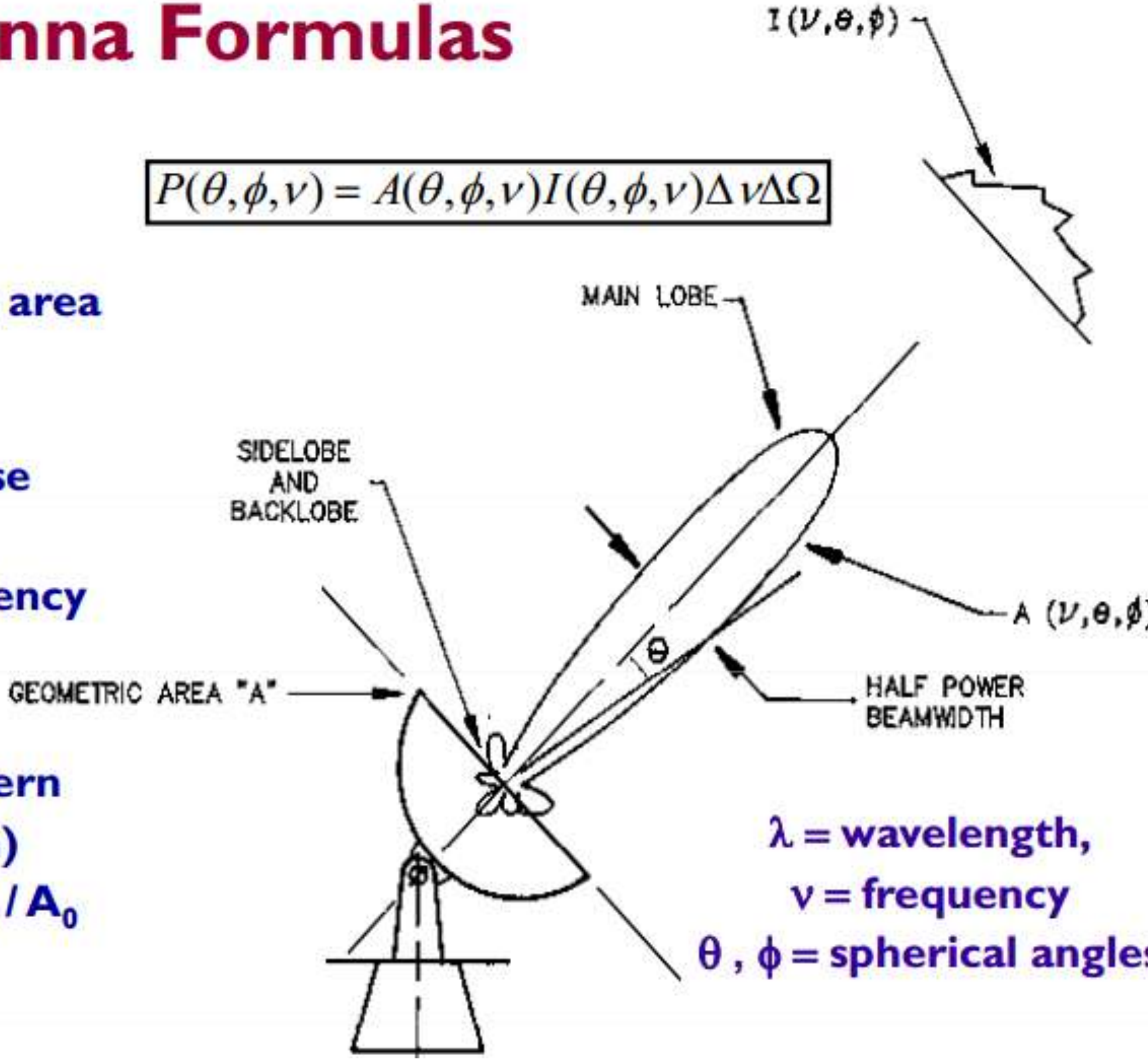
Basic Antenna Formulas

$$P(\theta,\phi,\nu) = A(\theta,\phi,\nu) I(\theta,\phi,\nu) \Delta\nu \Delta\Omega$$

Effective collecting area
$A(\nu,\theta,\phi)$ m^2

On-axis response
$A_0 = \eta A$
η = aperture efficiency

Normalized pattern (primary beam)
$\mathcal{A}(\nu,\theta,\phi) = A(\nu,\theta,\phi) / A_0$



λ = wavelength,
ν = frequency
θ , ϕ = spherical angles

Reciprocity theorem

- Power pattern of an antenna is the same for transmitting and receiving: $G(\theta,\varphi) \propto A_e(\theta,\varphi)$
- For any antenna $$A_e(\theta,\varphi) = \frac{\lambda^2 G(\theta,\varphi)}{4\pi}$$
- This lets us compute the receiving power pattern from the transmitting power pattern and vice versa.

Main beam

- Beam solid angle Ω_A [sr] of an antenna

$$\Omega_A = \iint_{4\pi} P_n(\vartheta,\varphi)\,d\Omega = \int_0^{2\pi}\int_0^{\pi} P_n(\vartheta,\varphi)\sin\vartheta\,d\vartheta\,d\varphi$$

- For real antennas the (normalized) power pattern has considerably larger values for a certain range of both ϑ and φ.
- Main beam solid angle: $\Omega_{\mathrm{MB}} = \iint_{\substack{\text{main}\\\text{lobe}}} P_n(\vartheta,\varphi)\,d\Omega$

Main beam efficiency

- Quality of an antenna as a direction measuring device depends on how well the power pattern is concentrated in the main beam
- If a large fraction of the received power comes from the side lobes it would be rather difficult to tell where the radiation source is situated
- Therefore we define main beam efficiency (or simply beam efficiency)

$$\eta_B = \frac{\Omega_{\mathrm{MB}}}{\Omega_{\mathrm{A}}}$$

- η_B indicates how much of the power pattern is concentrated in the main beam

Antenna temperature

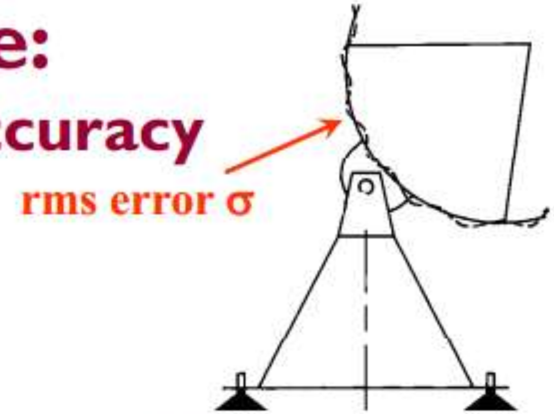
- a convenient practical unit for the power output (per unit frequency) from an antenna is the **antenna temperature**
- it has nothing to do with the *physical* temperature of the antenna
- it is the *temperature of a resistor* whose thermally generated power per unit frequency equals that produced by the antenna

$$T_A = \frac{P_\nu}{k}$$

  - T_A=1K corresponds to a conveniently small power of 1.38×10^{-38} W Hz^{-1}
  - It can be calibrated by a direct comparison with hot and cold loads connected to the receiver input
  - Units of receiver noise are also K – comparison makes easy to decide if a signal will be detectable

Antenna Performance:

Aperture Efficiency & Surface Accuracy



On axis response: $A_0 = \eta A$

Efficiency: $\eta = \eta_{sf} \cdot \eta_{bl} \cdot \eta_s \cdot \eta_t \cdot \eta_{misc}$

Where..

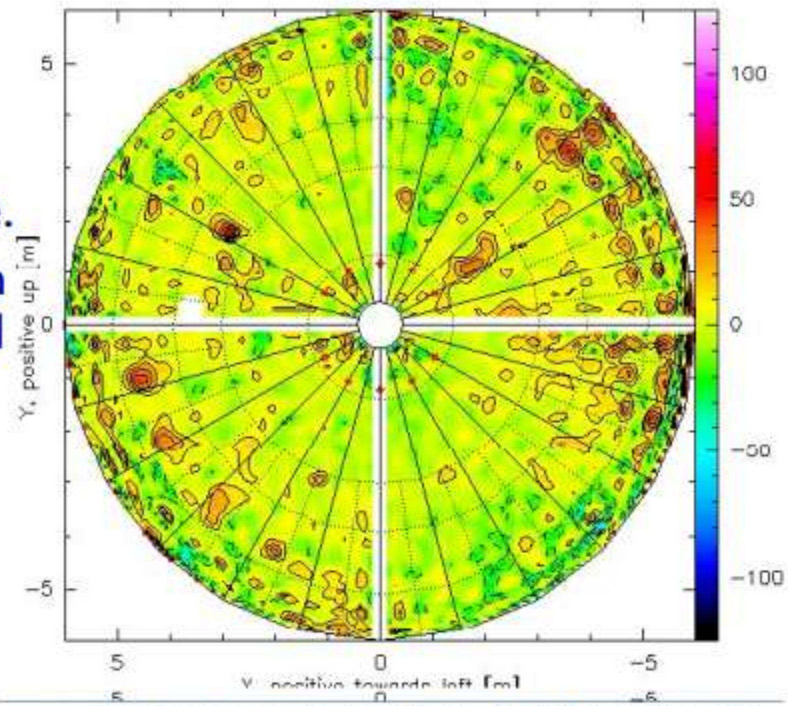
η_{sf} = Reflector surface efficiency, due to imperfections in reflector surface.

η_{bl} = Blockage efficiency caused by the subreflector and its support structure.

η_s = Feed spillover efficiency, the fraction of power radiated by feed intercepted by subreflector.

η_t = Feed illumination efficiency (outer parts of reflector illuminated at lower level than inner part.

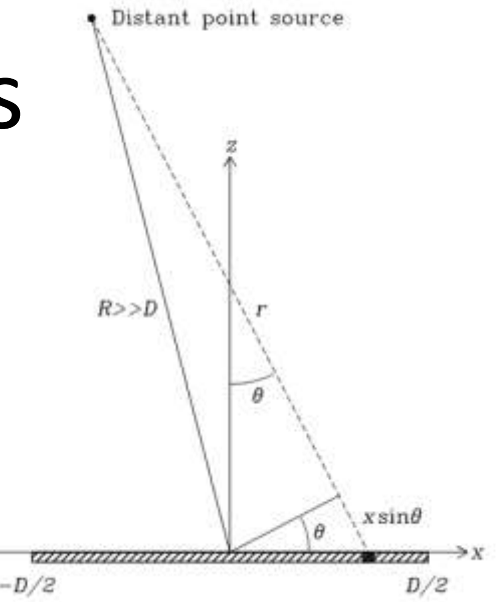
η_{misc}= Reflector diffraction, feed position phase errors, feed match and loss



Surface accuracy of an ALMA antenna measured with holography = 10um rms

LECTURE 2

Patterns of aperture antennas



- Beam pattern of a 1D aperture?
  - treating as transmitting antenna
  - feed illuminates the aperture with a sine wave with electric field strength *g(x)* that varies across the aperture. This induces currents that will vary with position and time
  - Diffraction theory
    - Huygens principle: $$df = g(x)\frac{\exp(-i2\pi r/\lambda)}{r}dx$$
    - + Fraunhofer approx.: $$r \approx R + x\sin\theta$$
- In the far-field, the electric field pattern of an antenna is the Fourier transform of the el. field illuminating the aperture:

$$f(l) = \int_{aperture} g(u)e^{-i2\pi lu}du$$

$$E_{far-field}(l,m) \propto \mathscr{F}[E_A(x,y)]$$

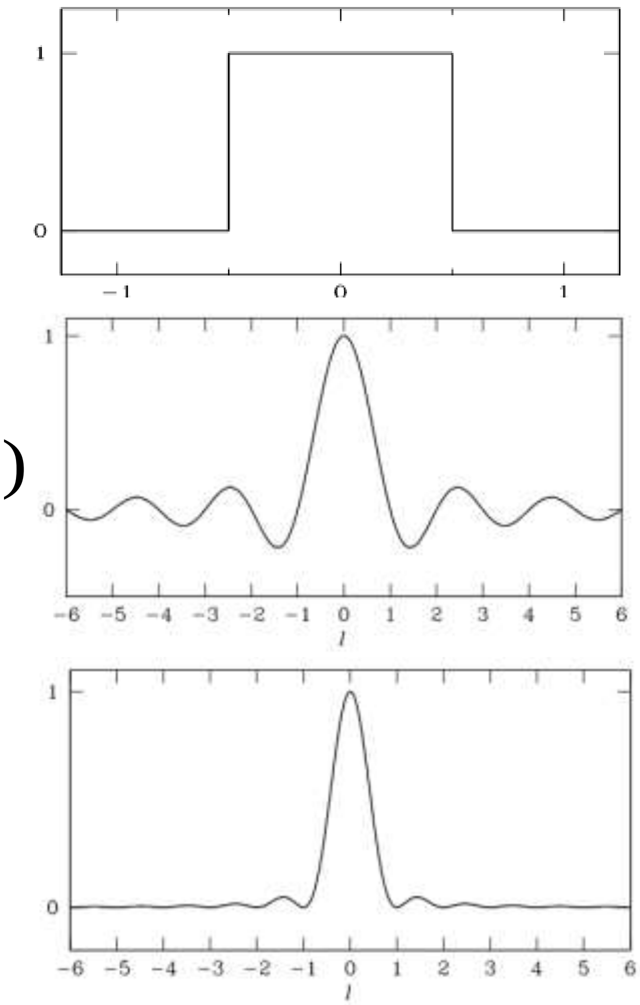
1D uniformly illuminated aperture

- for $g(u) = const.,$
  $-D/2\lambda < u < D/2\lambda$
- far-field el. field pattern

$$f(l) \propto \int_{-D/2\lambda}^{D/2\lambda} e^{-i2\pi l u} du = \mathrm{sinc}(lD/\lambda)$$

- Power radiated per unit area

$$P(l) \propto \mathrm{sinc}^2\left(\frac{lD}{\lambda}\right)$$



Uniformly illuminated apertures

- Distribution of electric field on the dish:

  $E_A(x, y)$

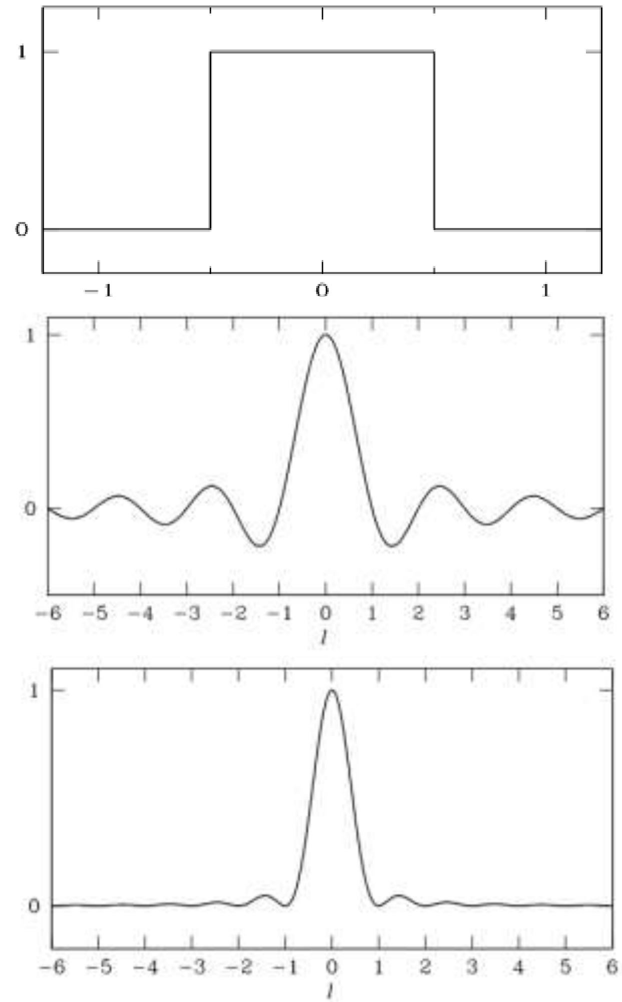
- Far-field radiated by the dish:

  $$E_{f-f}(l,m) \propto \mathscr{F}[E_A(x,y)]$$

- Power emitted is a function of direction:

  $$P(l,m) \propto \left|E_{f-f}(l,m)\right|^2$$

- Main beam FWHM: $\theta_{\mathrm{HPBW}} \propto \dfrac{\lambda}{D}$

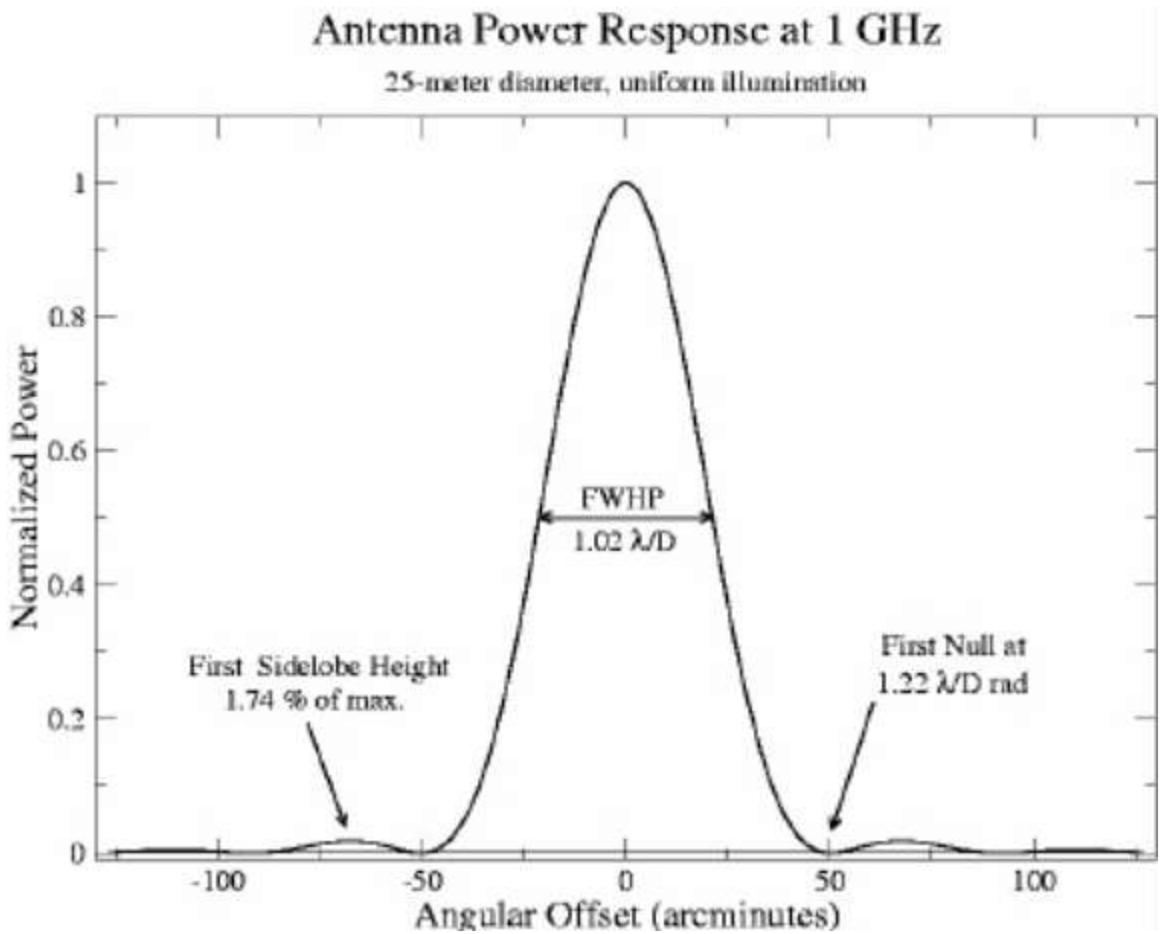


- Main beam FWHM:

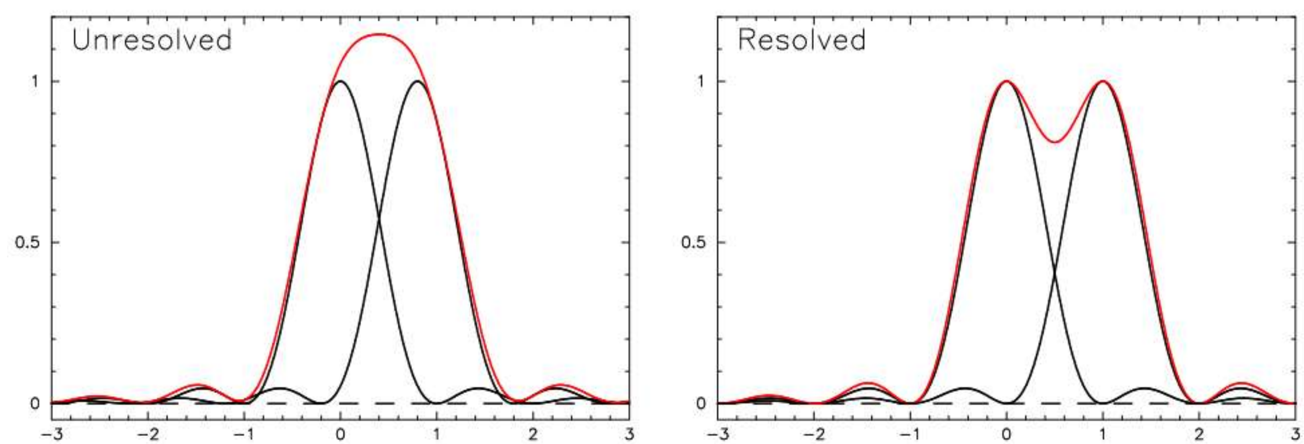
$$\theta_{\text{HPBW}} \propto \frac{\lambda}{D}$$

- 2D aperture (single dish):

$$\theta_{\text{HPBW}} \approx 1.22\frac{\lambda}{D}$$



- Reciprocity theorem:
  - transmitting power pattern = receiving power pattern
  - power pattern represents point-source response: scanning the telescope beam in angle θ across a point source will cause the antenna temperature to vary as $\mathrm{sinc}^2\theta$, and the HPBW will equal the transmitting one
- receiving HPBW sometimes called the resolving power of telescope
  - two equal point sources separated by the HPBW can just be resolved



2D aperture antennas

- Electric field pattern of an aperture is the Fourier transform of the aperture field illumination
- Fourier transform relationship between the complex voltage distribution of the field in the aperture and the complex far-field voltage radiation pattern of the antenna

$$f(l) = \int_{aperture} g(u) e^{-i2\pi lu} du$$

$$f(l,m) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} g(u,v) e^{-i2\pi(lu+mv)} du dv$$

  - where m is the *y*-axis analog to *l*, and *v=y/λ*

Fourier transform

- Given two spatial coordinates *x, y*, we consider corresponding ***spatial frequencies*** *u, v*, [in wavelengths], defined as $u = x/\lambda$, $v = y/\lambda$
- Then $F(l,m)$ is the fourier transform of $f(u,v)$:

$$F(l,m) = \iint f(u,v)\, e^{2\pi i(ul+vm)} du dv$$

where

f(u,v) is complex voltage distribution in the aperture

F(l,m) is complex far-field voltage radiation pattern, with *l,m* … angular distances on the sky

- inverse: $$f(u,v) = \iint F(l,m)\, e^{-2\pi i(ul+vm)} dl dm$$

2D uniformly illuminated apertures

- rectangular aperture:

$$f(l,m) \propto \mathrm{sinc}\left(\frac{lD_x}{\lambda}\right)\mathrm{sinc}\left(\frac{mD_y}{\lambda}\right)$$

$$P_n(l,m) \propto \mathrm{sinc}^2\left(\frac{lD_x}{\lambda}\right)\mathrm{sinc}^2\left(\frac{mD_y}{\lambda}\right)$$

$$G \approx \frac{4\pi D_x D_y}{\lambda^2}\mathrm{sinc}^2\left(\frac{\theta_x D_x}{\lambda}\right)\mathrm{sinc}^2\left(\frac{\theta_y D_y}{\lambda}\right)$$

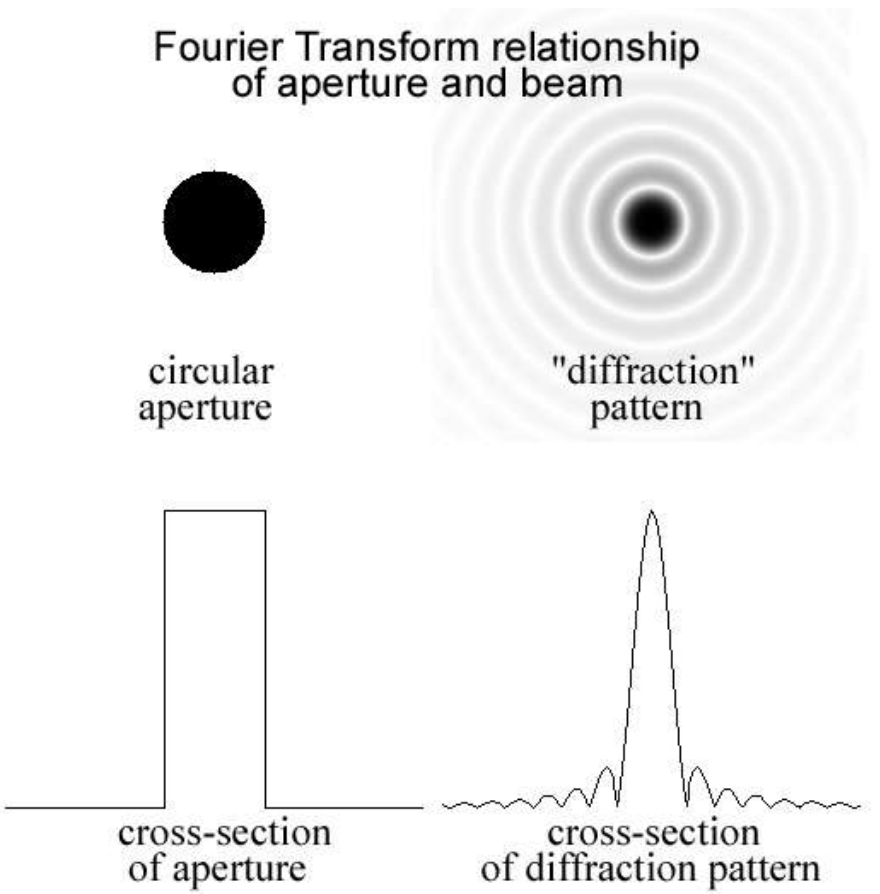
- Peak power gain is prop. to geometric area
- circular aperture: power pattern = Airy pattern
- Gaussian pattern

Patterns of aperture antennas

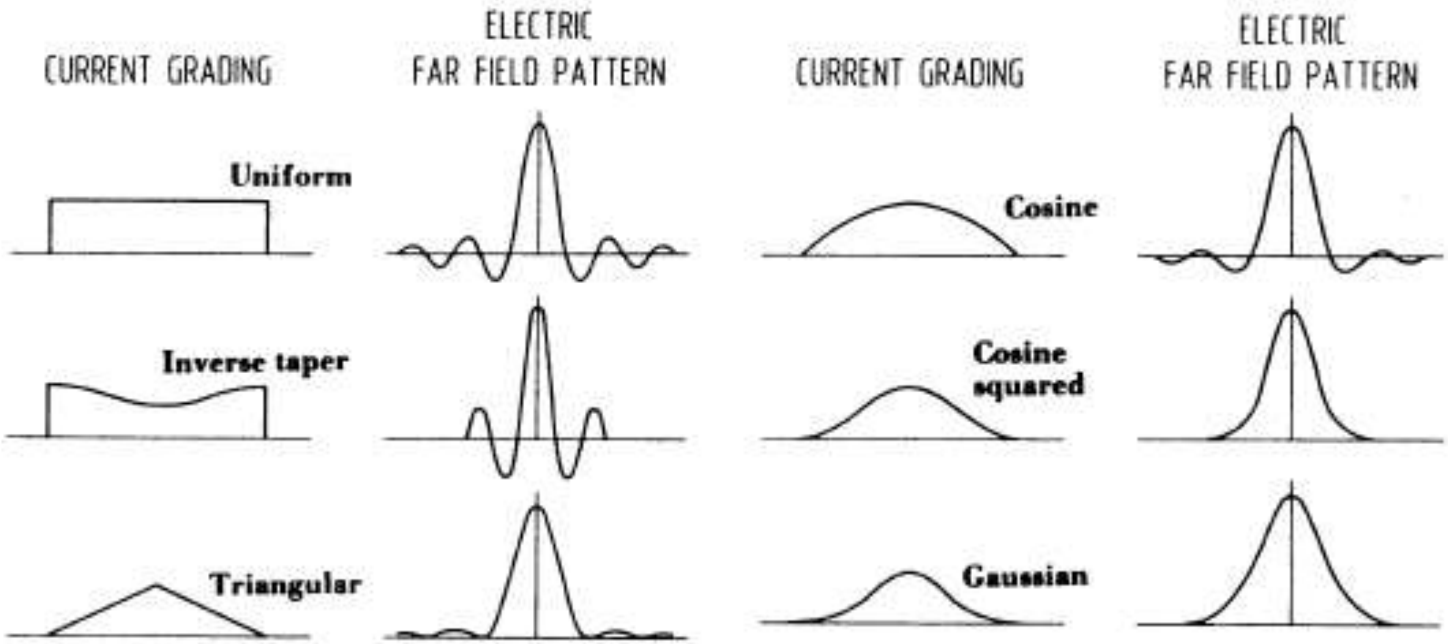
- Diffraction theory (Huygen's principle + Fraunhofer approx.) =>

$$E_{far-field}(l,m) \propto \mathscr{F}[E_A(x,y)]$$

- sharp cut of the antenna domain)oscillations (side-lobes)
- apodization or taper: decrease the level of the sidelobes,
- to the cost of increasing *ΔΩ*



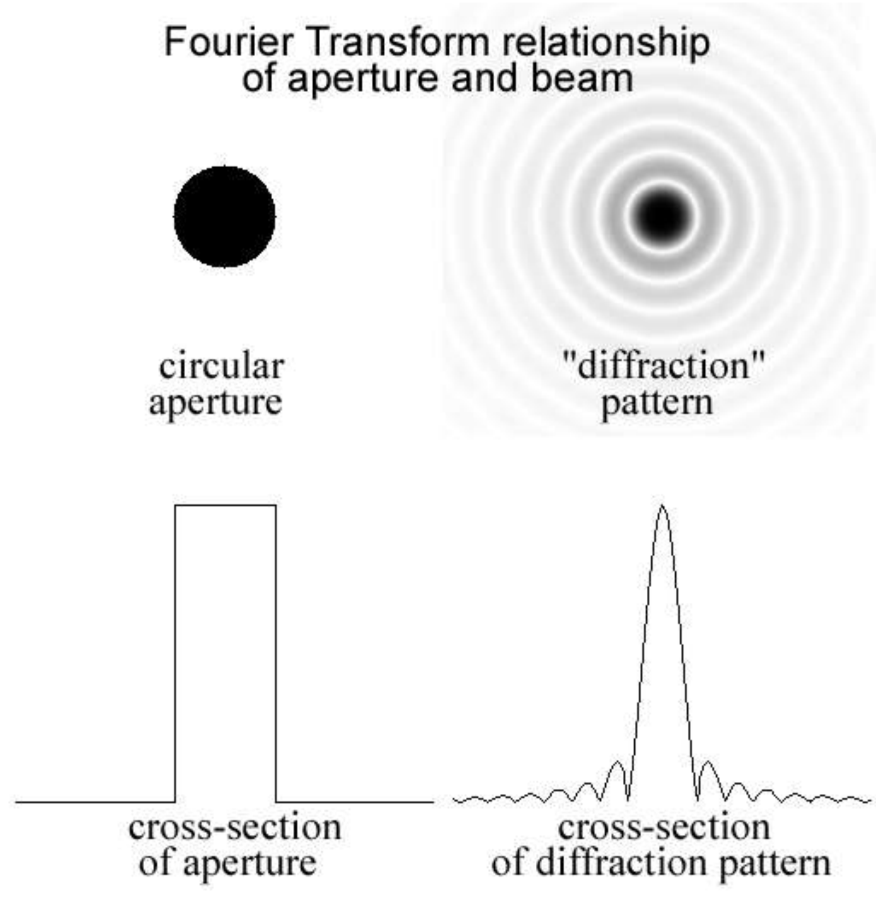
- Current gradings which give rise to lower side lobes and larger FWHP beamwidths.
- Gaussian – FT of a Gaussian is another Gaussian



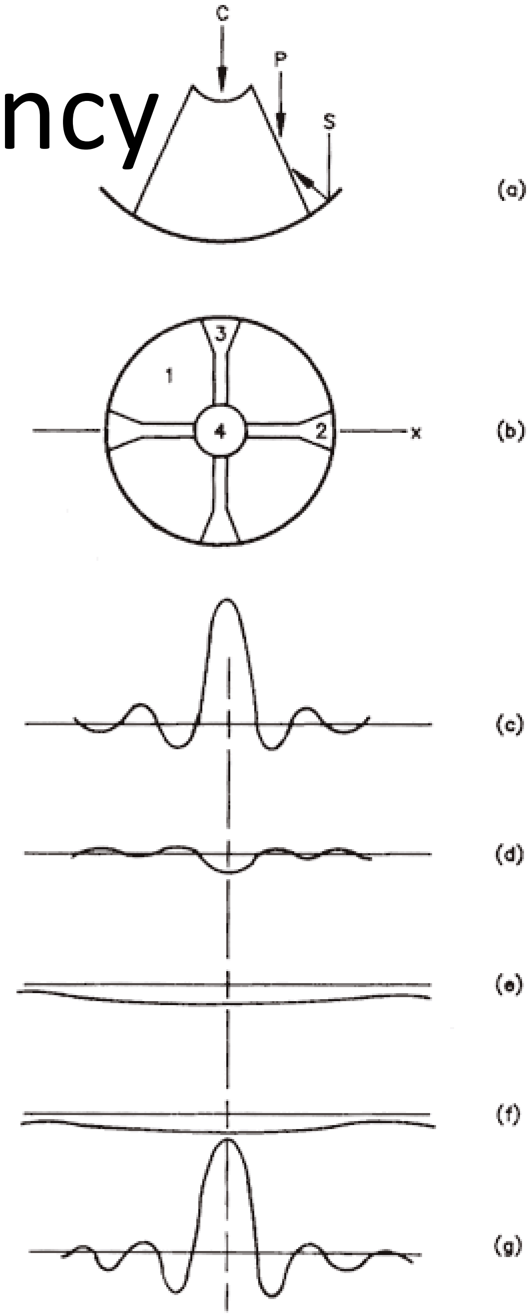
- Antenna effective area *A(ν,ϑ,φ)*
- collected power [W]:

$$P = \iint A_\nu(\theta,\varphi) I_\nu(\theta,\varphi)\, d\Omega\, d\nu$$

- Associated with collecting area (effective area) is beam pattern (also called the primary beam)
- Primary beam = Fourier transform of aperture



Aperture efficiency



- aperture efficiency $A_o = \eta A$ is made up of several factors:

  $\eta = \eta_{sf}\, \eta_{bl}\, \eta_s\, \eta_t\, \eta_{misc}$

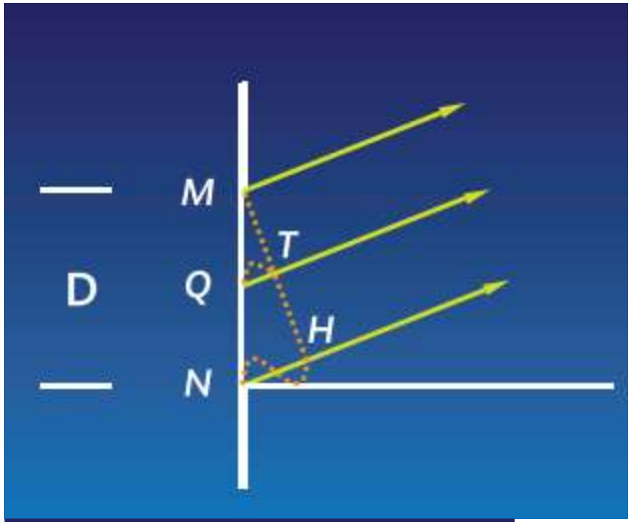
  – where

    η_{sf} is reflector surface efficiency
    η_{bl} is reflector blockage efficiency
    η_s is feed spillover efficiency
    η_t is illumination efficiency
    η_{misc} is losses due to reflector diffraction, feed position errors, feed mismatch, and others

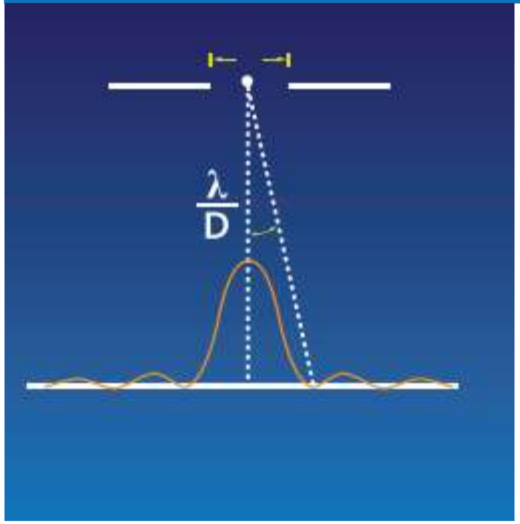
Basics of radio interferometry

Interferometers

- Angular resolution $\theta \approx \lambda/D$
  - *HST: 0.04'' at 45GHz (λ=6.7mm) requires 1.4km aperture*
  - *IRAM 30m 23'' at 100GHz*
  - *12m ALMA antenna 50'' at 100GHz*

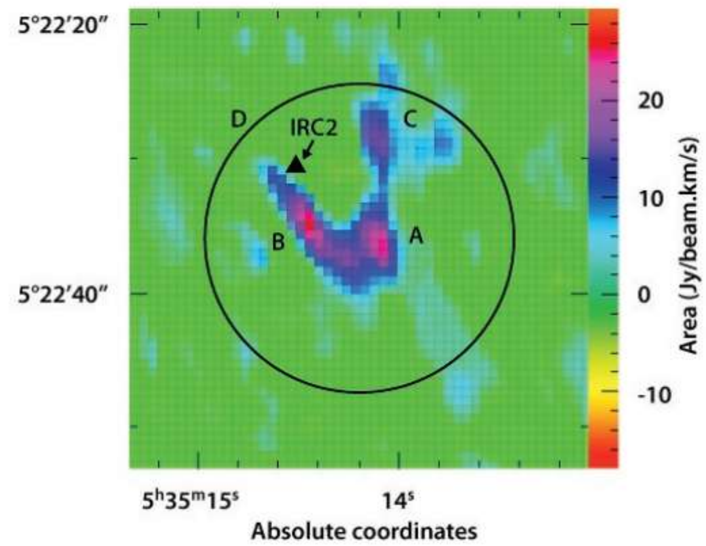


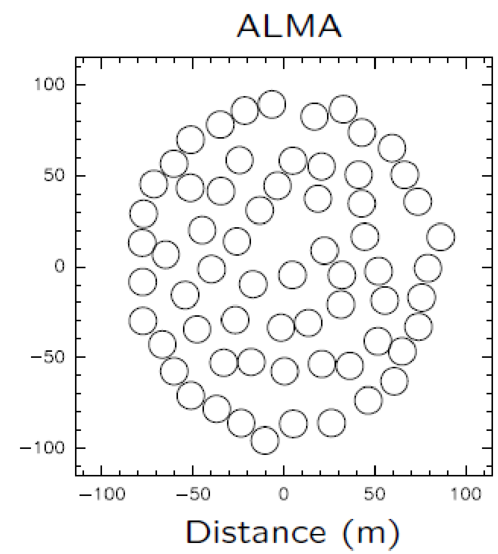
- Single dish size limits (largest steerable antenna *D≈100m*)
- Tracking accuracy problem for large antennas
- Gravitational deformations, solar heating, torques, best radio telescopes pointing accuracy ~1''
- Surface accuracy needs to be high
- all this is technically difficult/impossible

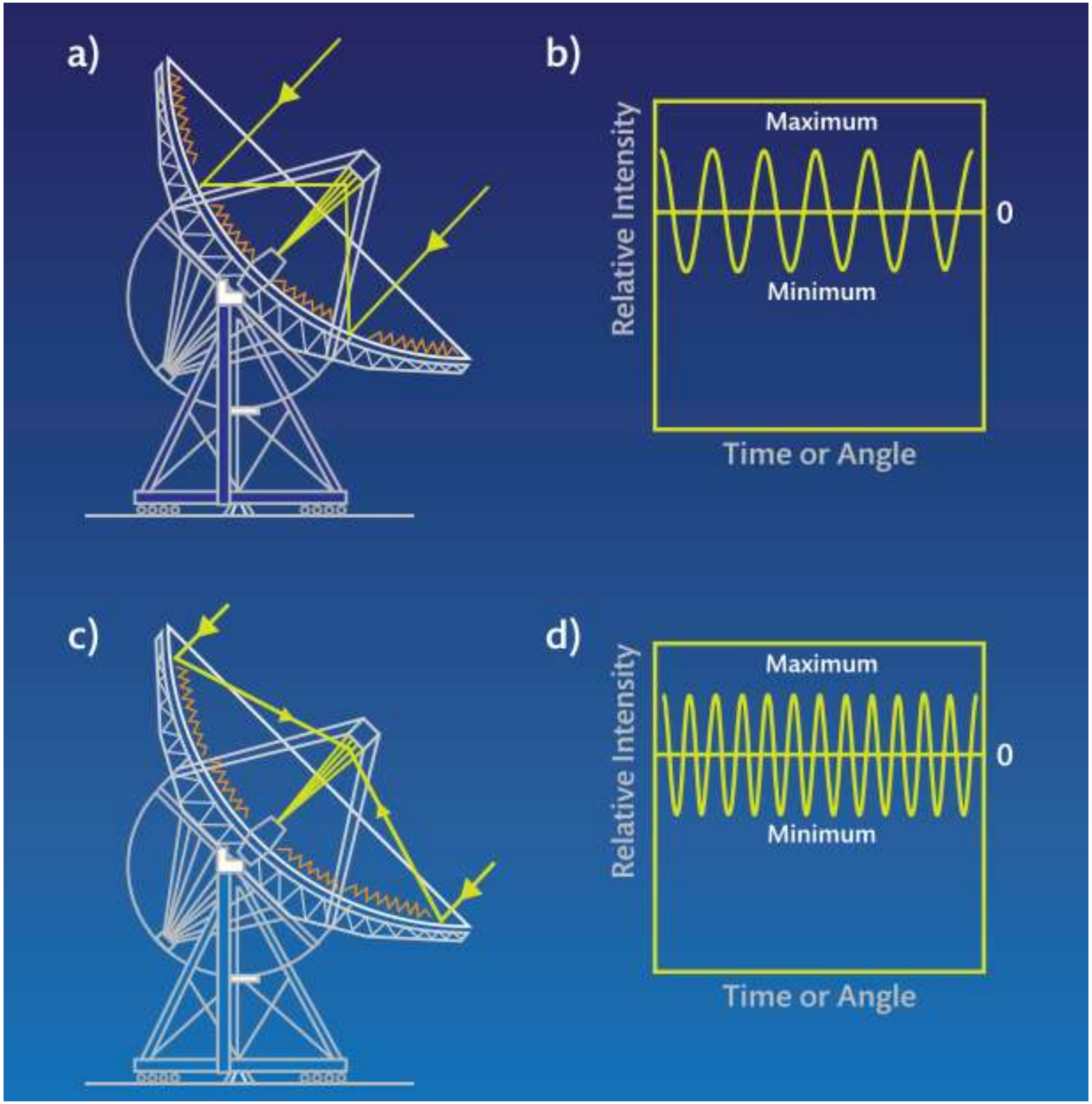


Interferometers

- Aperture synthesis
  synthesizing the equivalent aperture through combinations of elements – replacing a single large telescope by a collection of small telescope “filling" the large one
- resolution becomes θ $\sim\lambda/D$ with D being the array size
  - IRAM PdB 3.3’’x1.7’’ at 1km maximum distance between antennas
  - ALMA resolution even exceeds the resolution of HST (0.004’’ at 0.3mm wavelength and 16km max. extent)
- This method was developed in the 1950s in England and Australia
- use Earth rotation to fill in (u,v) plane with time (Sir Martin Ryle 1974 Physics Nobel Prize)







fringe spacing

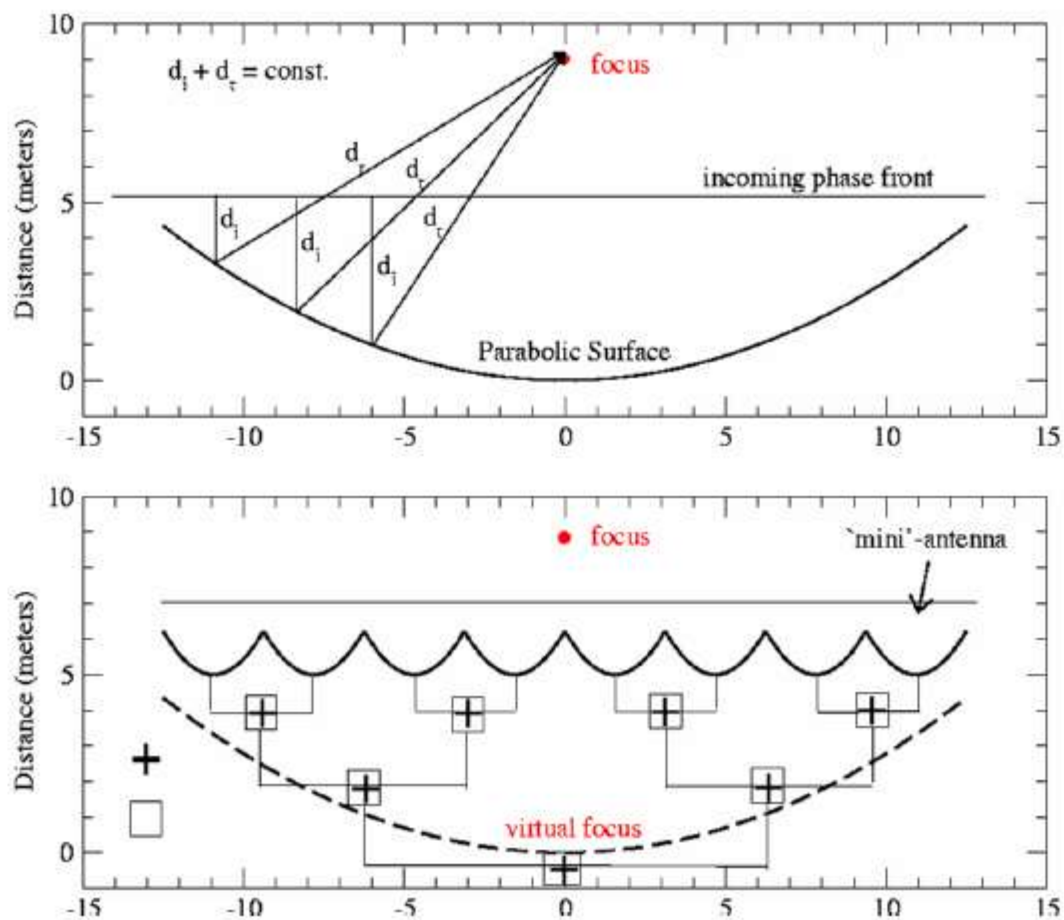
$$\theta = \sin^{-1} \lambda / D$$

Interferometers

- baseline … line segment between two antennas (b_{ij} = baseline length between antenna *i* and *j* projected in the direction of the source)
- configuration … antennas layout (compact vs. extended configuration)
- D … configuration size (e.g. 150 m).
- Primary beam resolution of one antenna (e.g. 27’’ @ 1mm)
- Synthesized beam resolution of the array (e.g. 2’’ @ 1mm)
- PSF = diffraction pattern = beam pattern
- Correlator = special computer that combines outputs of antennas.
  - In the ALMA 12-m array, the correlator can combine the outputs of 1225 antenna pairs

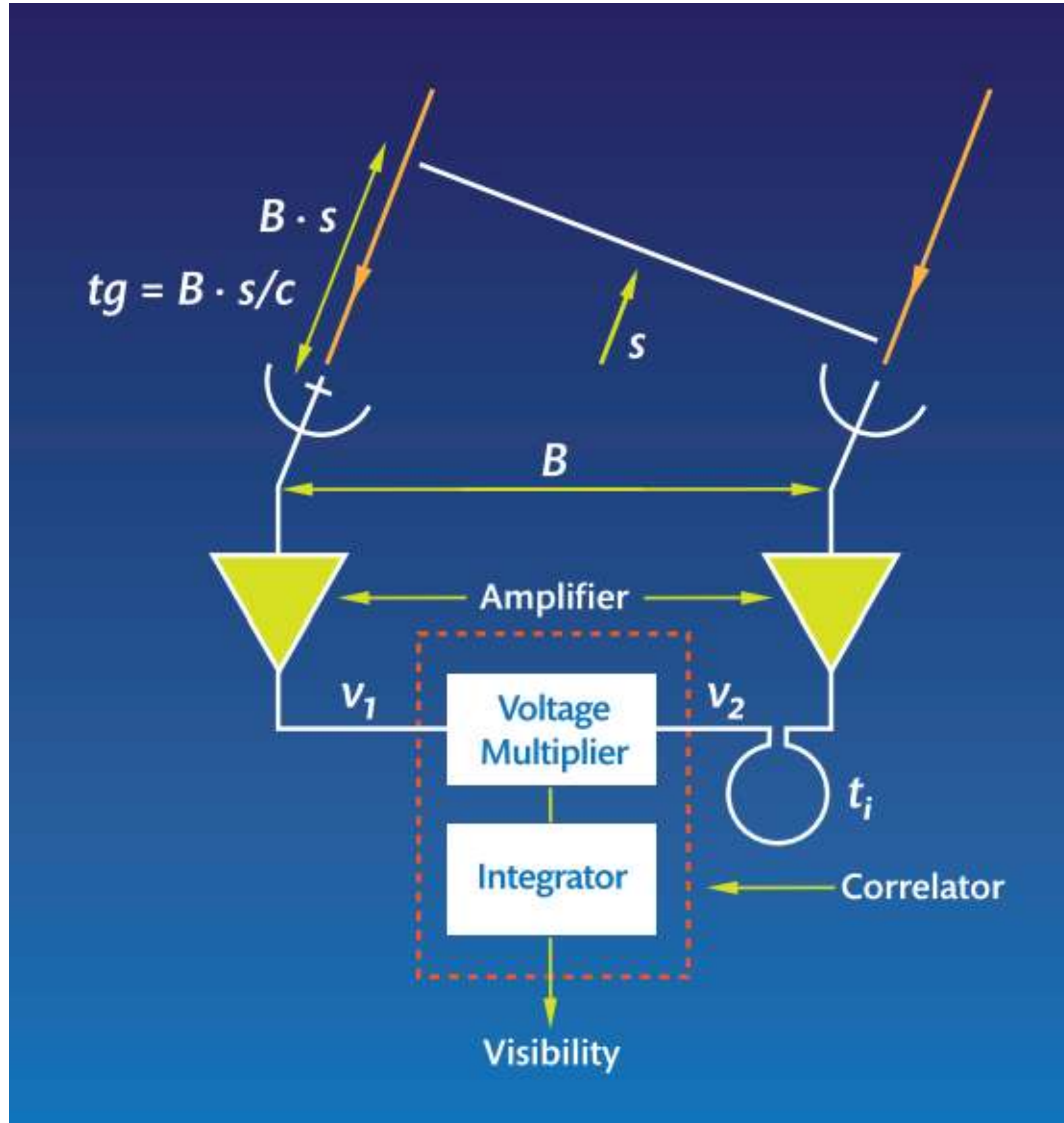
Basic concept

- We don't need a single parabolic structure
- We can consider a series of small antennas, whose individual signals are summed in a network.
- This is the basic concept of interferometry.
- Aperture Synthesis is an extension of this concept.



Two-element interferometer

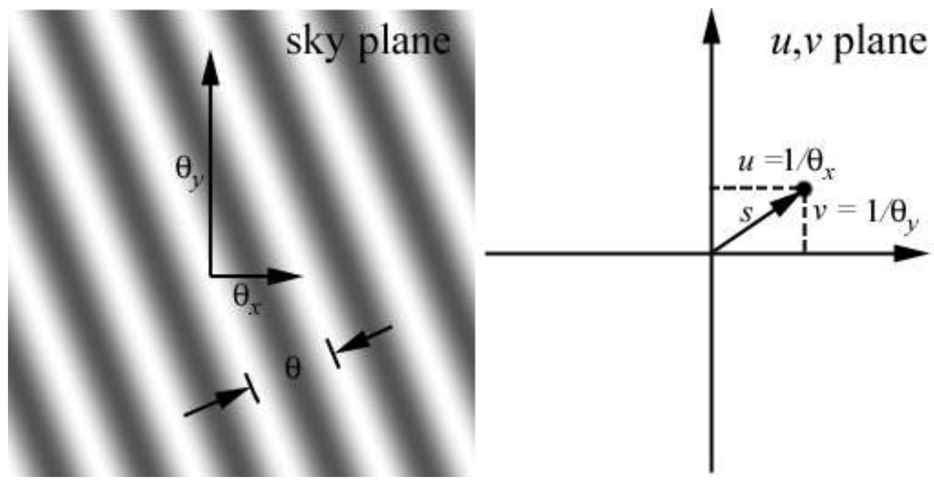
- Even the largest interferometers with N>>2 elements can be treated as N(N-1)/2 independent interferometer pairs
- antennas
  - size <<B
  - they track a source as it moves across the sky
  - by varying B, for some sources the response changes
- this allows to determine position and size of the source
- Multi-antenna arrays allow to obtain images



response of pairs of antennas

- response of pairs of antennas (interferometer baselines):
- pair of antennas measures one point in the u,v plane, and the Fourier Transform of this point gives interference fringes on the sky

$$\theta = \sin^{-1} \lambda / B$$



- Spatial frequencies = baseline lengths projected onto a plane perpendicular to the source mean direction
- Earth rotation - Possibility to measure different Fourier components without moving antennas

Ideal interferometer

- Fixed in space – no rotation or motion
- Quasi-monochromatic (i.e., responds only to radiation in a very narrow band)
- Single frequency throughout – no frequency conversions
- Single polarization
- No propagation distortions (no ionosphere, atmosphere …)
- Idealized electronics (perfectly linear, perfectly uniform in frequency and direction, perfectly identical for both elements, no added noise, …)
- electric field properties (amplitude, phase) of the incoming wave are stationary over timescales of interest (seconds), and we can write the field at this position as

$$E_\nu(t) = E\cos(2\pi\nu t + \phi)$$

- The purpose of a sensor (a.k.a. 'antenna') and its electronics is to convert this E-field to a voltage, Vn(t), which can be conveyed to a remote location. This voltage must be a faithful replica of the originating electric field, preserving its amplitude E and phase f

Two-element ideal interferometer

- plane waves from a distant point source travel an extra distance to reach antenna 1

$$\vec{b} \cdot \hat{s} = b \cos\theta$$

- output of antenna 1 is delayed by geometric delay
- $$\tau_g = \vec{b} \cdot \hat{s} / c$$
- output voltages:

$$V_1 = E\cos[\omega(t - \tau_g)]$$

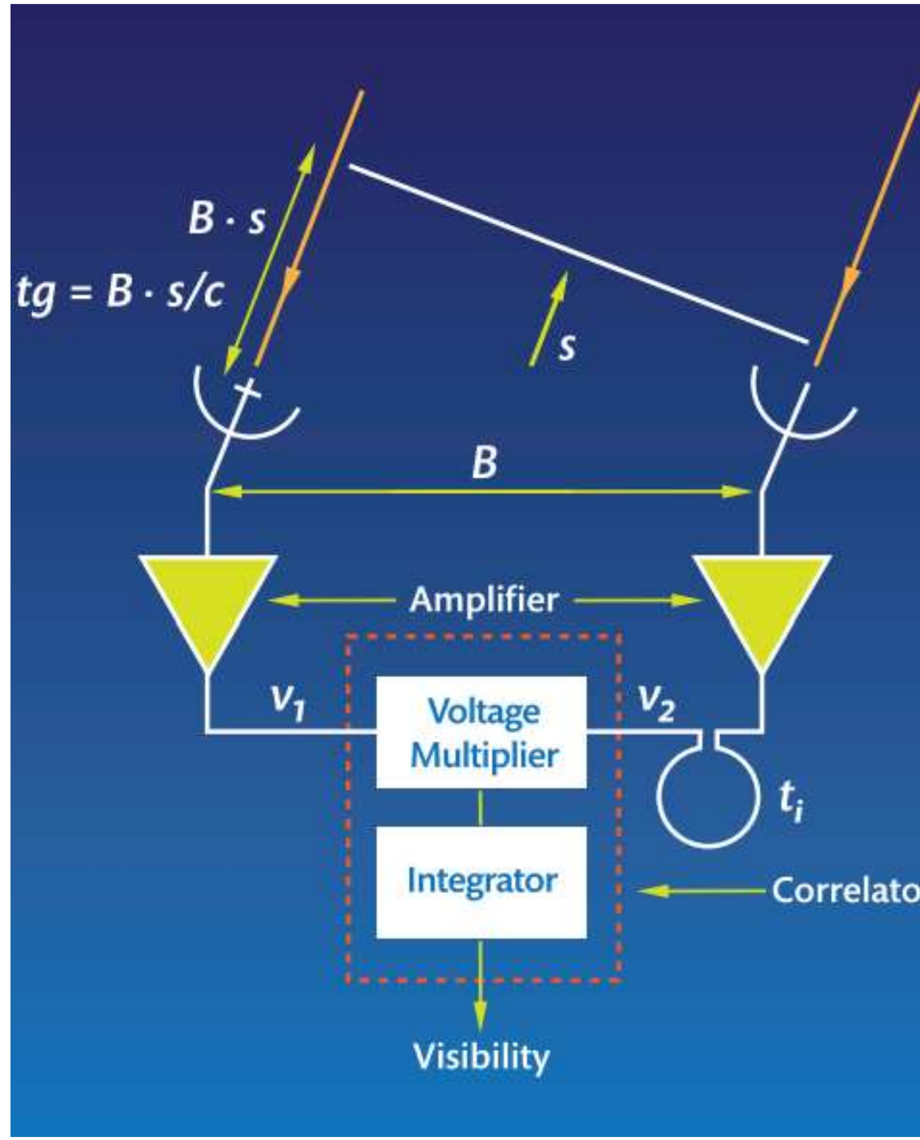
$$V_2 = E\cos(\omega t)$$

- correlator first multiplies:

$$V_1 V_2 = \frac{E^2}{2}[\cos(2\omega t - \omega\tau_g) + \cos(\omega\tau_g)]$$

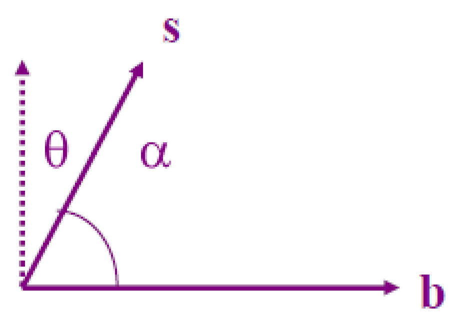
and then time-averages:

$$R = \langle V_1 V_2 \rangle = \frac{E^2}{2}\cos(\omega\tau_g)$$



Two-element ideal interferometer

$$R = \langle V_1 V_2 \rangle = \frac{E^2}{2}\cos(\omega\tau_g)$$



- In 1D:

$$\frac{b \cdot s}{\lambda} = u\cos\alpha = u\sin\theta = ul$$

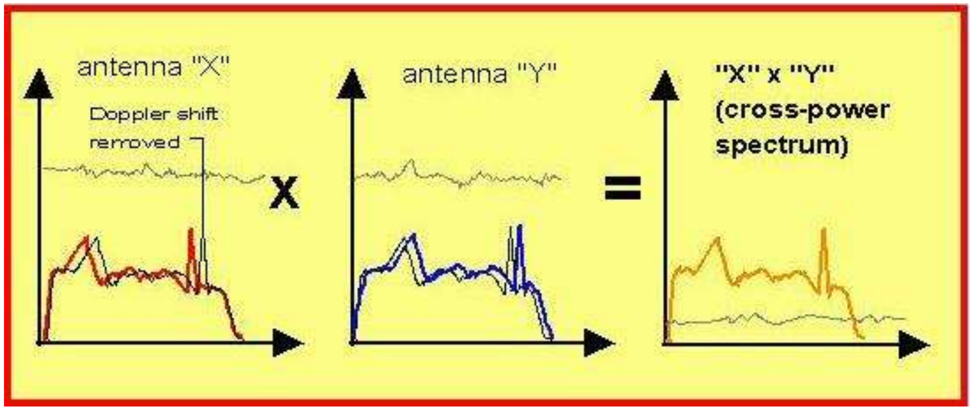
- *u = b/λ* is the <u>baseline length in wavelengths</u>, and θ is the angle w.r.t. the plane erpendicular to the baseline

$$l = \cos\alpha = \sin\theta$$

- Thus

$$R = \frac{E^2}{2}\cos(\omega\tau_g) = \frac{E^2}{2}\cos(2\pi\frac{\vec{b}\cdot\hat{s}}{\lambda}) = \frac{E^2}{2}\cos(2\pi ul)$$

Cross-correlation



- Correlation reduces noise!

  (most of noise is uncorrelated)

Two-element ideal interferometer

- The averaged product is dependent on the received power ($E^2/2$) and geometric delay (τ_g), and hence on the baseline orientation and source direction (in the interferometer frame):

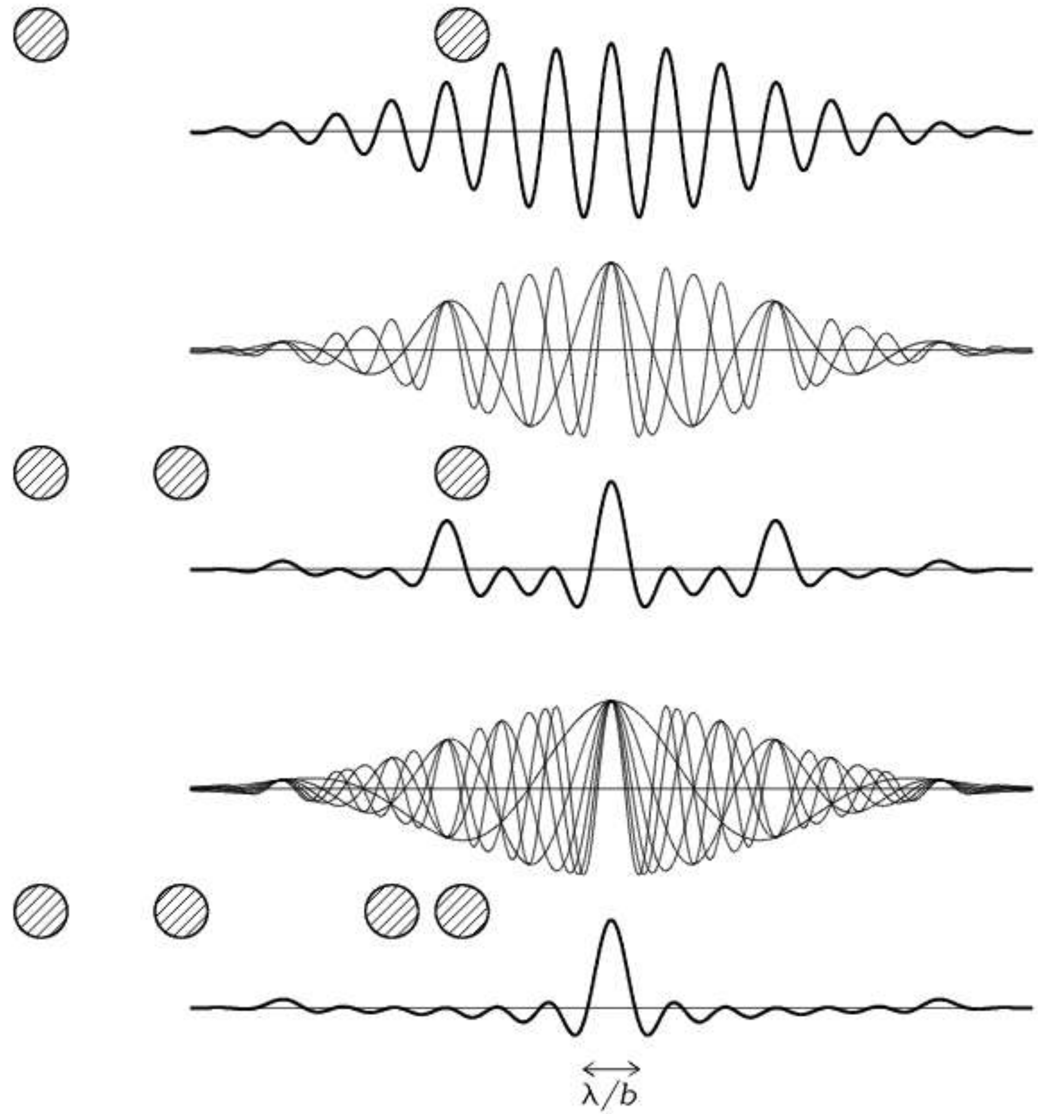
$$R = \langle V_1 V_2 \rangle = \frac{E^2}{2}\cos(\omega\tau_g)$$

- Output amplitude $E^2/2$ is proportional to the point-source flux density multiplied by $(A_1 A_2)^{1/2}$, where A_1 and A_2 are effective collecting areas of the two antennas
- Uncorrelated noise from receivers and atmosphere does not appear in the correlation output!
- the sinusoids in the correlator output are called fringes
- fringe phase: $\phi = \omega\tau_g = \frac{\omega}{c} b\cos\theta$
- fringe phase is a sensitive measure of source position (if the projected baseline is many wavelengths long). It depends on time measurement

$$\frac{d\phi}{d\theta} = 2\pi\left(\frac{b\sin\theta}{\lambda}\right)$$

Instantaneous point-source response

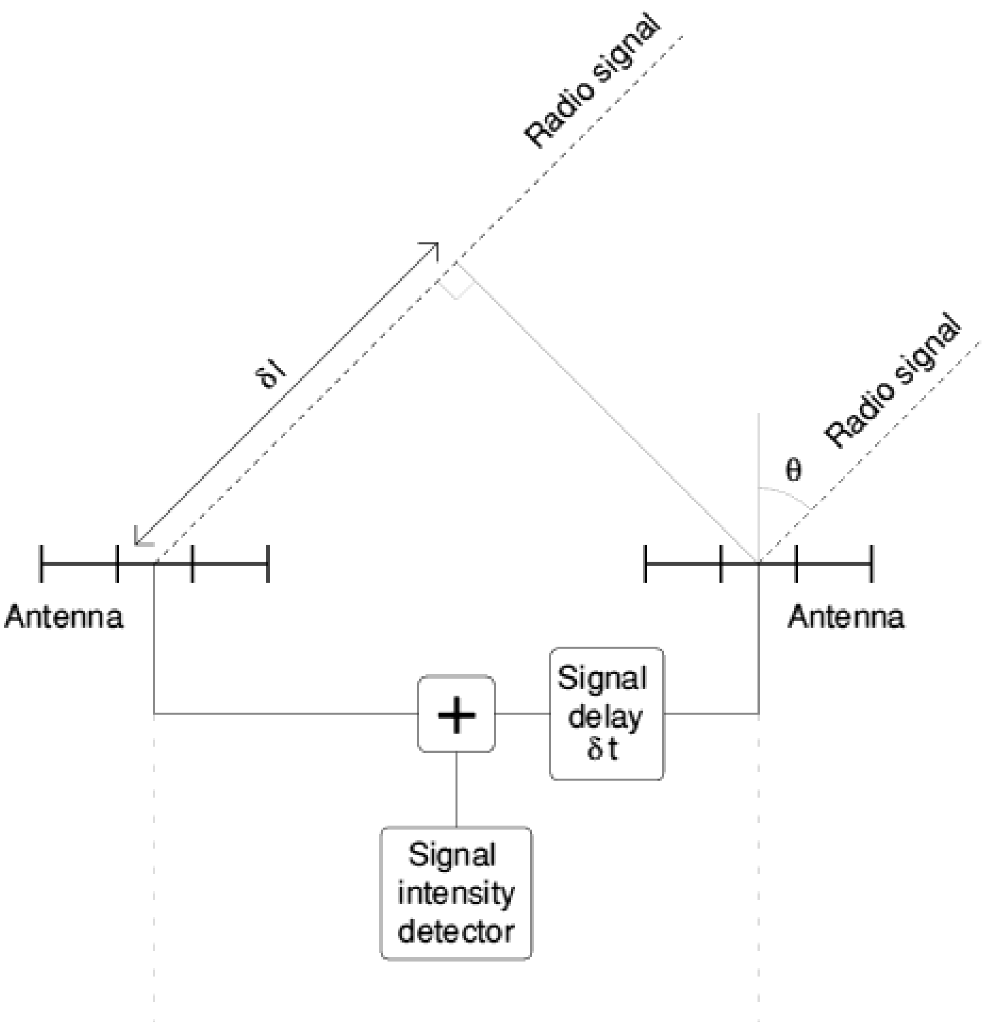
- Response of a two-element interferometer with directive antennas is a sinusoid multiplied by the product of the voltage patterns of individual antennas
- This product is the power pattern, i.e. the primary beam
- it is usually a Gaussian much wider than a fringe period
- Fourier transform of a product of two functions is the convolution of their Fourier transforms
- Thus, an interferometer with directive antennas responds to a finite range of angular frequencies centered on $b\sin\theta/\lambda$



- Real sensors impose their own patterns, which modulate the amplitude, and phase, of the output – large sensors (antennas) have very high directivity
- Interferometer with N antennas contains

  N(N-1)/2 pairs of antennas
- Instantaneous *synthesized beam* (i.e., point-source response obtained by averaging the outputs of all pairs) rapidly approaches a Gaussian as *N* increases

Signal delays



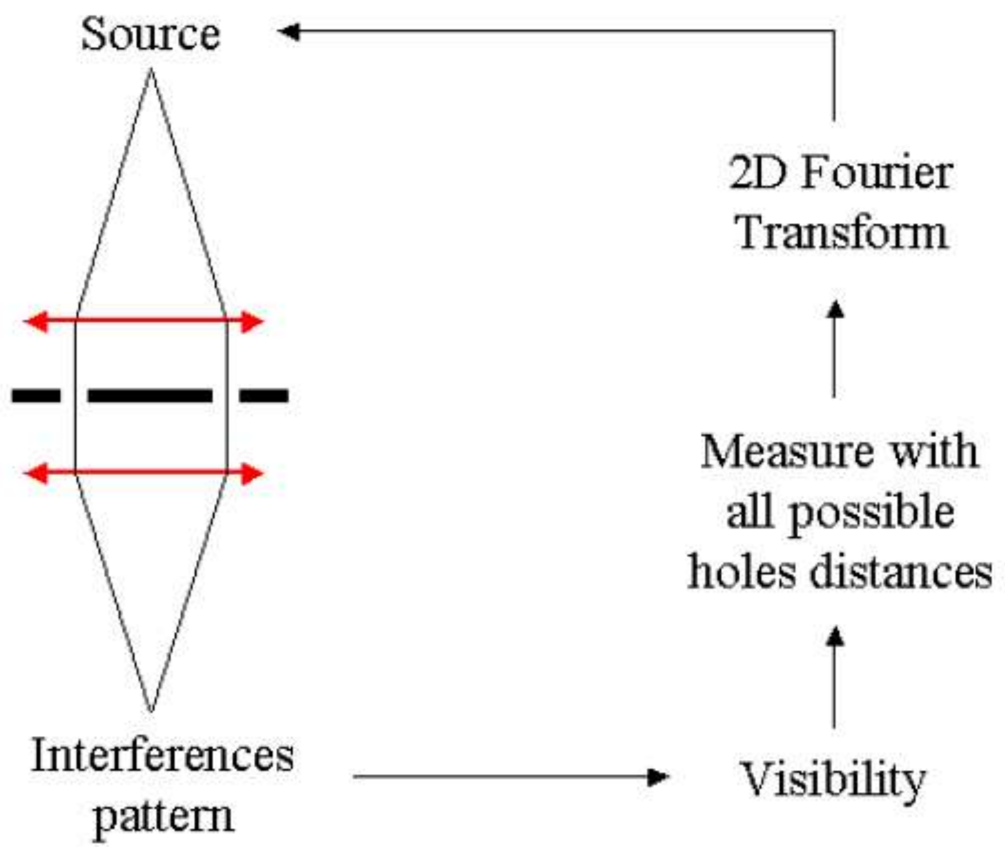
- Problem: signal arrives at different antennae at different times – would yield no correlation
- Solution: add a signal delay by sending signal from one antenna through one of "delay lines"
- Set of cables of various specific lengths, giving specific time delays
- Maximum cable length comparable to maximum baseline in interferometer, delay times in 10-1000's nanosec

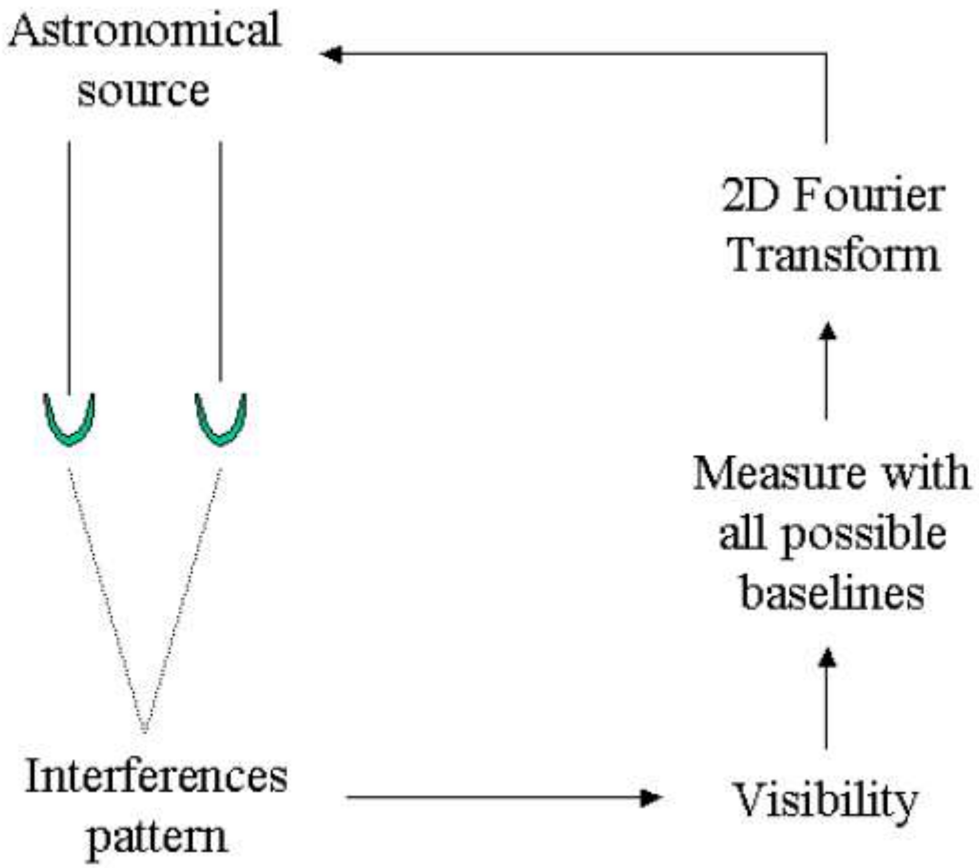
Van Cittert-Zernike theorem

- states that under certain conditions the Fourier transform of the mutual coherence function of a distant, incoherent source is equal to its complex visibility
- this implies that the wavefront from an incoherent source will appear mostly coherent at large distances
- because they are observed at distances large enough to satisfy the van Cittert–Zernike theorem, these objects exhibit a non-zero degree of coherence at different points in the imaging plane. By measuring the degree of coherence at different points in the imaging plane (the so-called "visibility function") of an astronomical object, a radio astronomer can thereby reconstruct the source's brightness distribution and make a two-dimensional map of the source's appearance.
- Implementing the van Cittert–Zernike theorem:
  - Build a device that measures the spatial autocorrelation of the incoming signal
  - Do it for all possible scales
  - Take the FT and get an image of the brightness distribution

- Implementing the van Cittert–Zernike theorem:
  - Build a device that measures the spatial autocorrelation of the incoming signal
    - 2-elements interferometer
  - Do it for all possible scales
    - N antennas
  - Take the FT and get an image of the brightness distribution
    - software
- If all of the (u,v) plane can be filled with data, one can, after some mathematics, obtain almost the same detail as that measured with a filled aperture of the same size
- τ_g is known from the antenna position, source direction, time => could be corrected
- Problems
  - the source is not a point source
  - the signal is not monochromatic

- Young’s holes




Astronomical source
2D Fourier Transform
Measure with all possible baselines
Interferences pattern
Visibility

Extended source

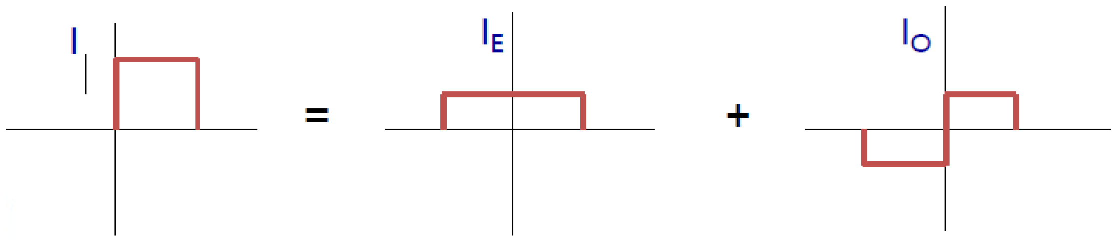
- Spatially incoherent extended source
- Response of interferometer is obtained by treating the extended source as the sum of independent point sources

$$R_c = \int I_\nu(\hat{s}) \cos(2\pi\nu\vec{b}\cdot\hat{s}/c)d\Omega = \int I_\nu(\hat{s}) \cos(2\pi\vec{b}\cdot\hat{s}/\lambda)d\Omega$$

- This expression links what we want – the source brightness on the sky – to something we can measure – the interferometer response

  => Can we recover the source brightness from observations of R?

- Any real function can be expressed as the sum of two real functions which have specific symmetries: even + odd part



- cosine = even function => sensitive only to the even part of an arbitrary source brightness distribution (which can be written as the sum of even and odd parts)
- Supposedly the source of emission has a component with odd symmetry
- The integration of the cosine response, Rc, over the source brightness is sensitive to only the even part of the brightness since the integral of an odd function with an even function (cos x) is zero.
- To detect the odd part, we need a <u>sine correlator</u> whose output is odd $(V^2/2)\sin\omega\tau$.
- The second correlator follows a 90deg phase delay inserted into the output of one antenna:

$$R_s = \int I_\nu(\hat{s}) \sin(2\pi \vec{b} \cdot \hat{s} / \lambda) d\Omega$$

Extended source

- Then, complex correlator is a combination of cosine and sine correlators
- We define complex visibility: $$V \equiv R_c - iR_s = Ae^{-i\phi}$$

  where visibility amplitude and phase:

$$A = (R_c^2 + R_s^2)^{1/2} \qquad \phi = \tan^{-1}(R_s / R_c)$$

- Response to an extended source of a 2-element interferometer with a complex correlator is the complex visibility:

$$V_\nu = \int I_\nu(\hat{s}) \exp(-i2\pi \vec{b} \cdot \hat{s} / \lambda) d\Omega$$

- this is a 2D Fourier transform, giving us a well established way to recover *I(s)* from *V(b)*

$$V(u,v) = \int I(l,m) \exp[-i2\pi(ul + vm)] dl dm$$

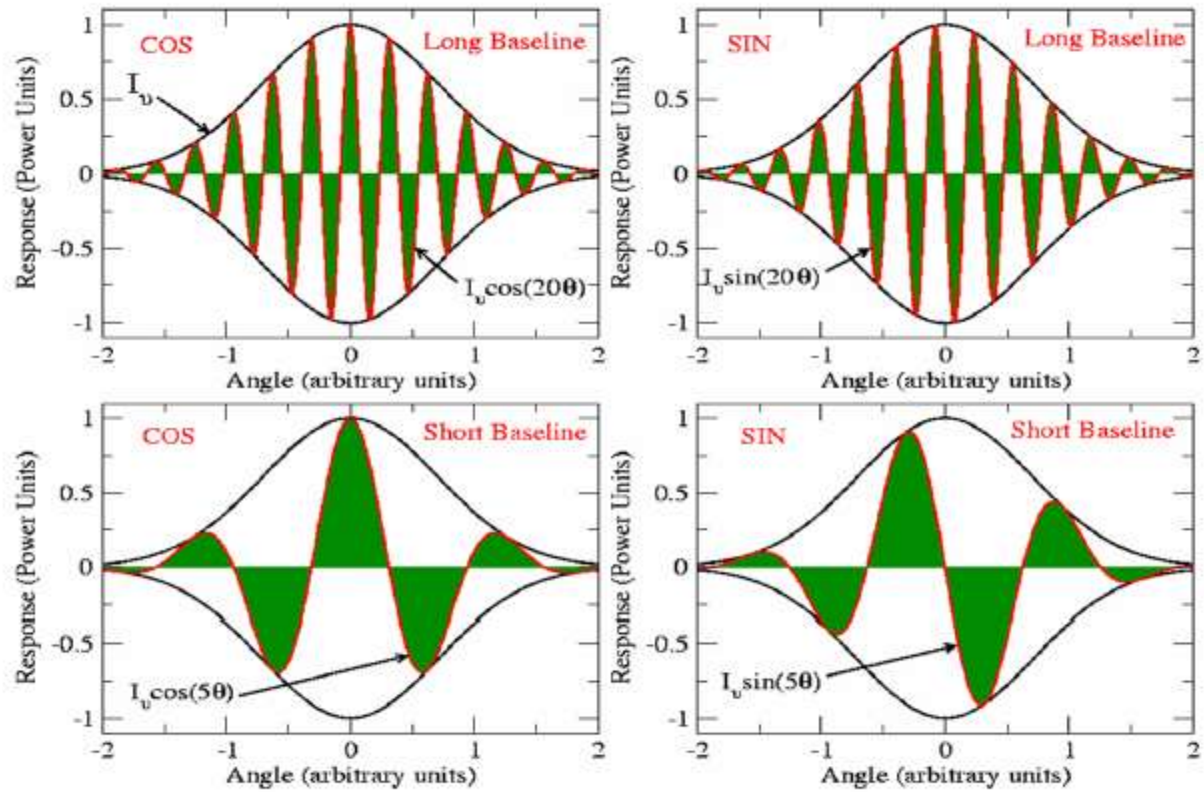
Picturing the Visibility

- The source brightness is Gaussian, shown in black.
- The interferometer 'fringes' are in red.
- The visibility is the integral of the product – the net dark green area.

R_C R_S

Long Baseline

Short Baseline



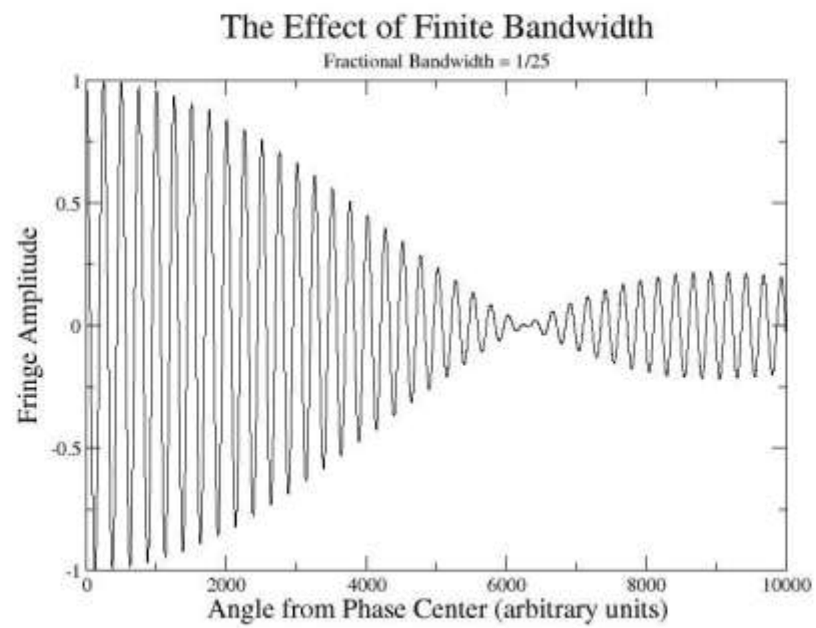
NRAO

Visibility

- As the baseline gets longer, the visibility amplitude will in general decline.
- When the visibility is close to zero, the source is said to be ‘resolved out’.
- Interchanging antennas in a baseline causes the phase to be negated – the visibility of the ‘reversed baseline’ is the complex conjugate of the original.
- Visibility is a unique function of the source brightness.
- The two functions are related through a Fourier transform.
- An interferometer, at any one time, makes one measure of the visibility, at baseline coordinate (u,v).
- Sufficient knowledge of the visibility function (as derived from an interferometer) will provide us a reasonable estimate of the source brightness.

Effect of finite bandwidth and averaging times

- the **fringe attenuation function, sinc(x)**
- The fringe-attenuation function depends only on bandwidth and baseline length – not on frequency.
- In our basic scenario -- stationary source, stationary interferometer -- the effect of finite bandwidth will strongly attenuate the visibility from sources far from the meridional plane.



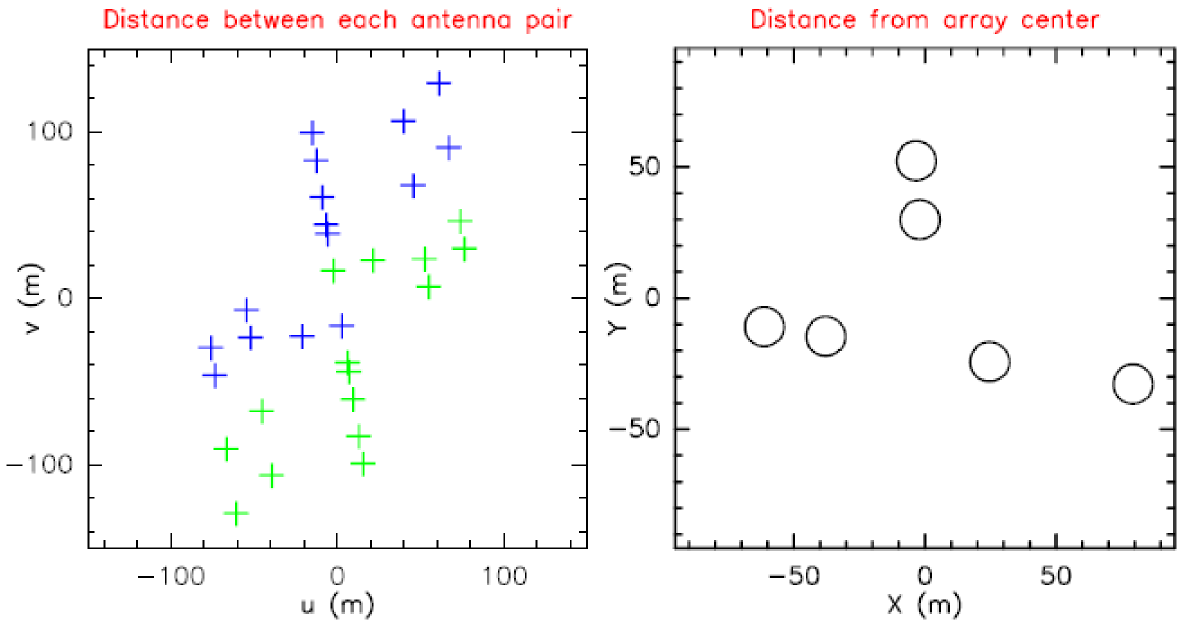
$$V = \int I_\nu(\hat{s}) \mathrm{sinc}(\Delta\nu\tau_g) \exp(-i2\pi\nu_c\tau_g) d\Omega$$

- => Shift the fringe-attenuation function to the center of the source of interest.
- By <u>adding time delay</u> (continuously adjusted)

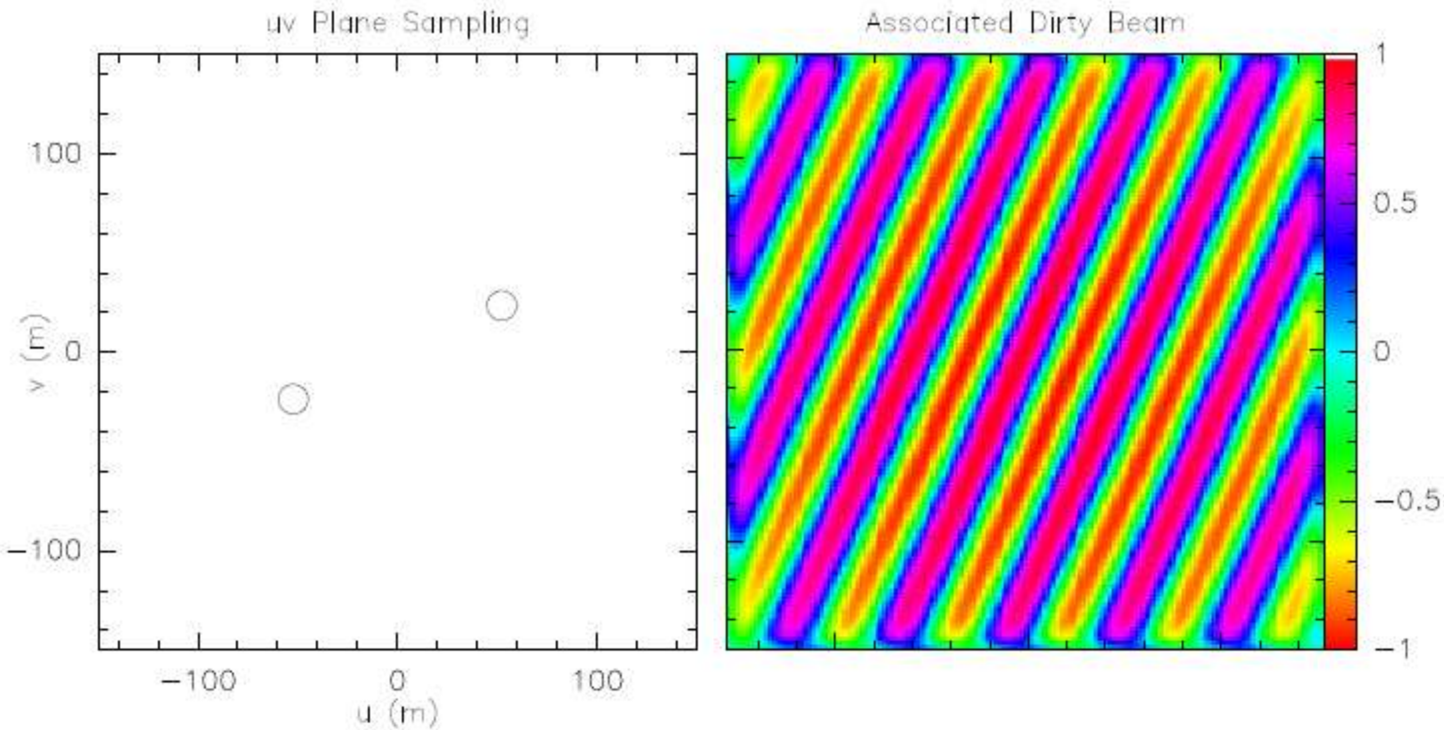
- van Cittert–Zernike theorem:

$$V_{ij}(b_{ij}) = \overset{\text{2DFT}}{\Leftrightarrow} B_{\text{primary}} I_{\text{source}}$$

- One Fourier component of the source (i.e. one visibility) is measured by baseline (or antenna pair).
  - Each baseline lenght bij = a spatial frequency.
    - Convention: Spatial frequencies are measured in meter.

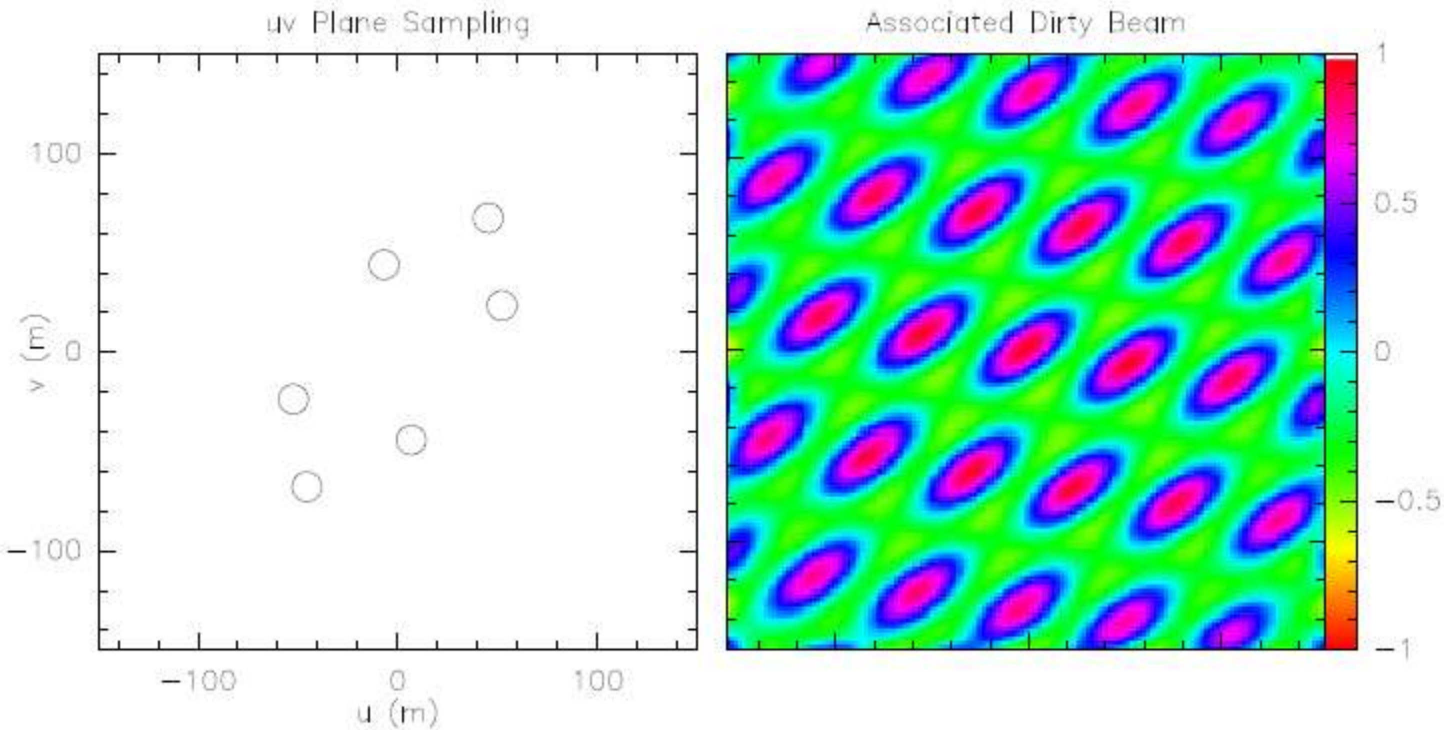


2 antennas



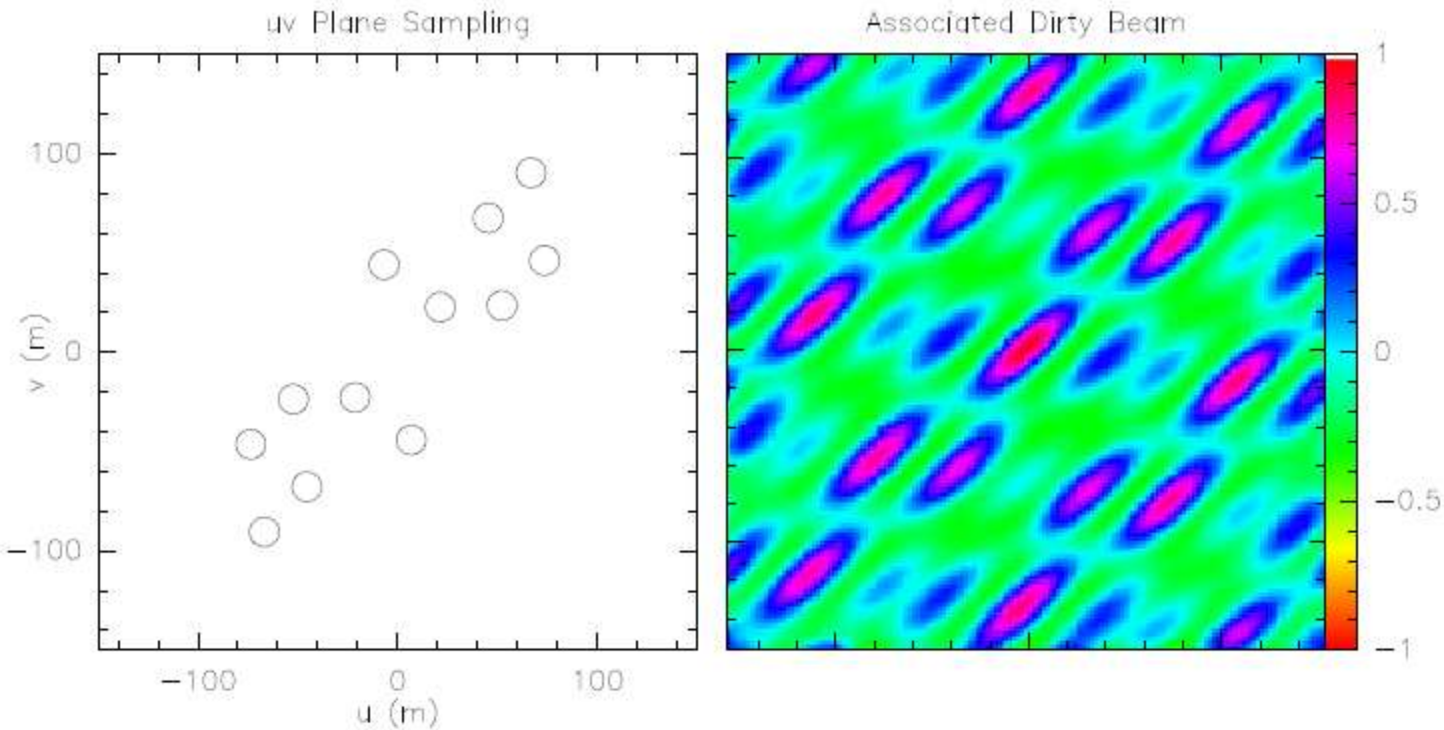
uv Plane Sampling
Associated Dirty Beam
100
0
−100
v (m)
−100
0
100
u (m)
1
0.5
0
−0.5
−1

3 antennas

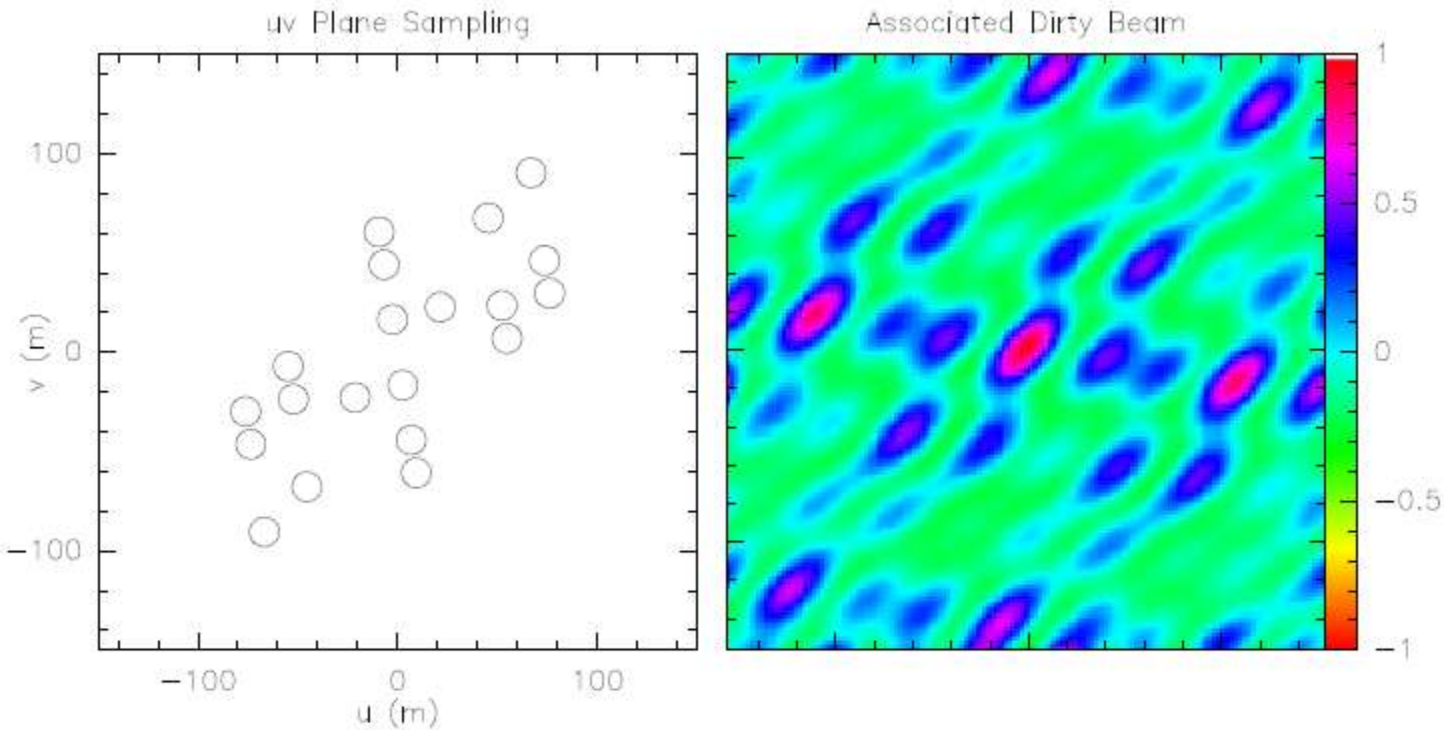


uv Plane Sampling
Associated Dirty Beam
100
0
−100
v (m)
−100
0
100
u (m)
1
0.5
0
−0.5
−1

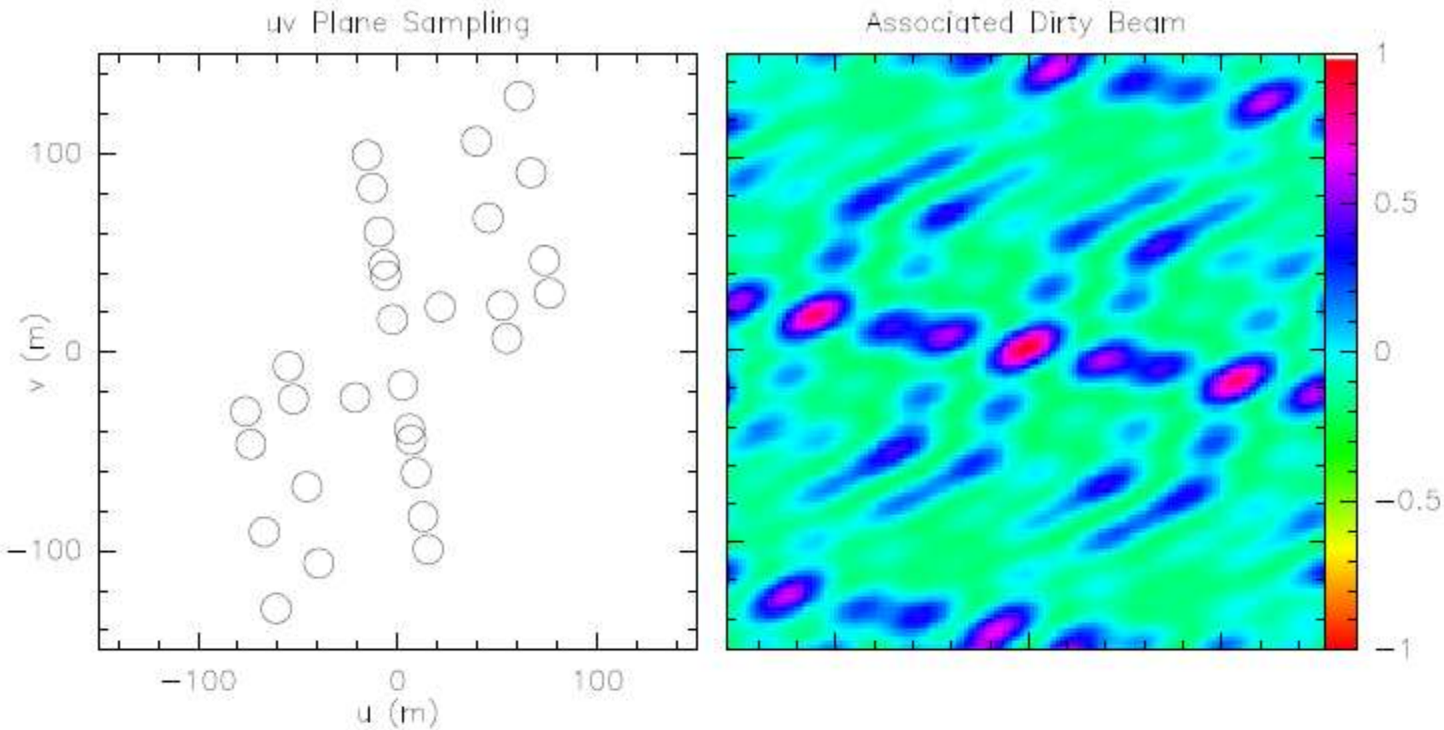
4 antennas


uv Plane Sampling
100
0
−100
v (m)
−100
0
100
u (m)
Associated Dirty Beam
1
0.5
0
−0.5
−1

5 antennas


uv Plane Sampling
Associated Dirty Beam
100
0
−100
v (m)
−100
0
100
u (m)
1
0.5
0
−0.5
−1

6 antennas

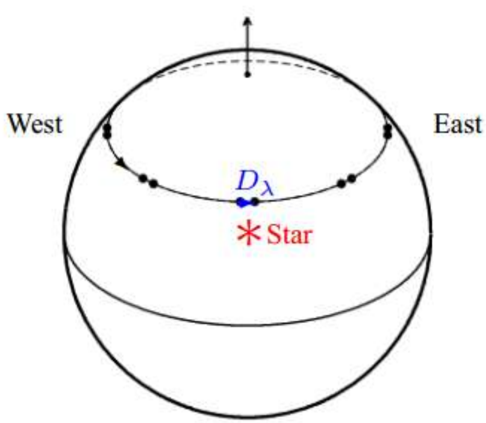

uv Plane Sampling
Associated Dirty Beam
100
0
−100
v (m)
−100
0
100
u (m)
1
0.5
0
−0.5
−1

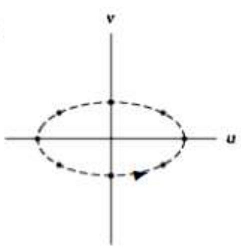
Earth-rotation aperture synthesis

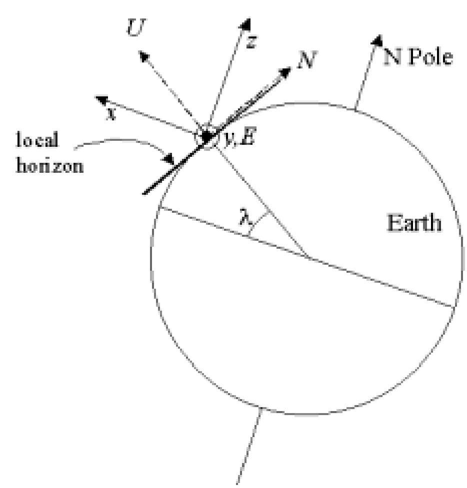
- Geometric delay varies slowly with time due to earth rotation
- Natural fringe rate

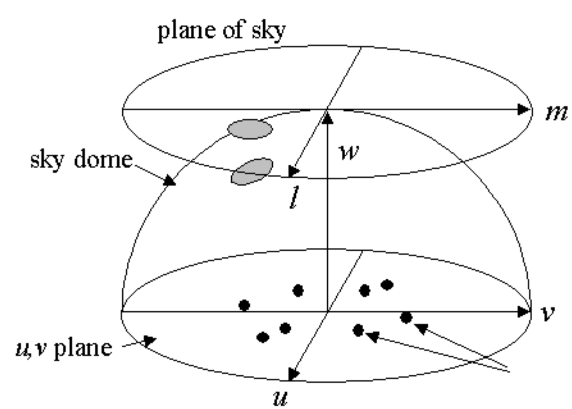
$$\tau_g = \frac{\vec{b} \cdot \hat{s}}{c} \qquad \nu \frac{d\tau_g}{dt} \cong \Omega_{\text{earth}} \frac{b\nu}{c}$$

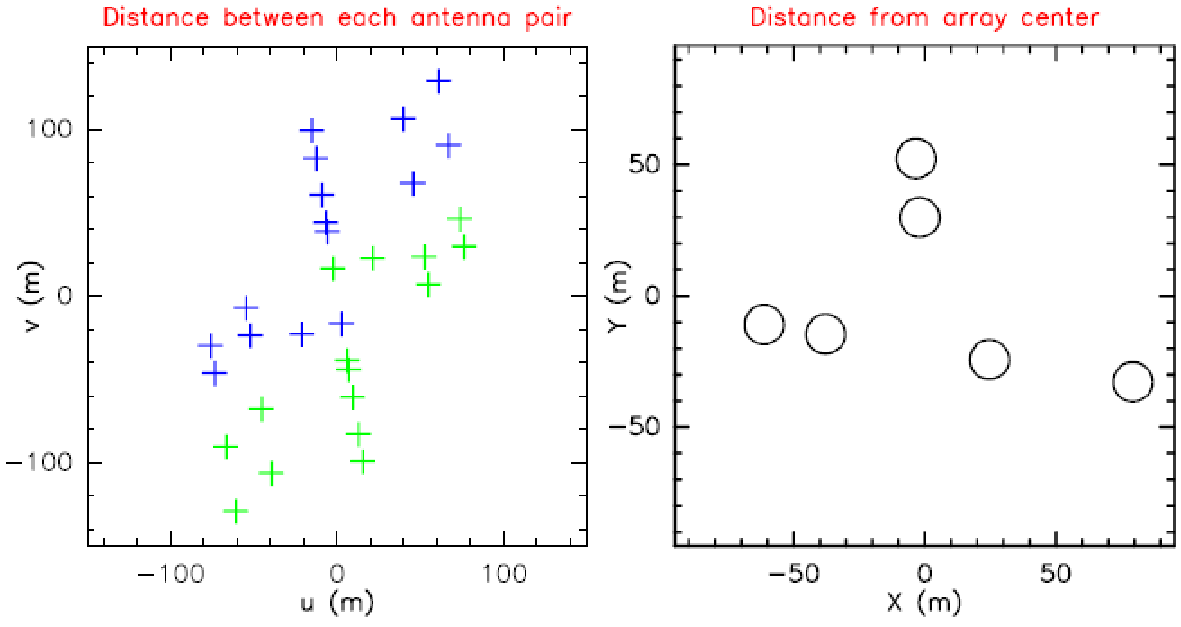
- τ_g is known from the antenna position, source direction, time –> could be corrected
- u,v depends on the hour angle – as the earth rotates and the source appears to move across the sky, the array samples different u,v at different times







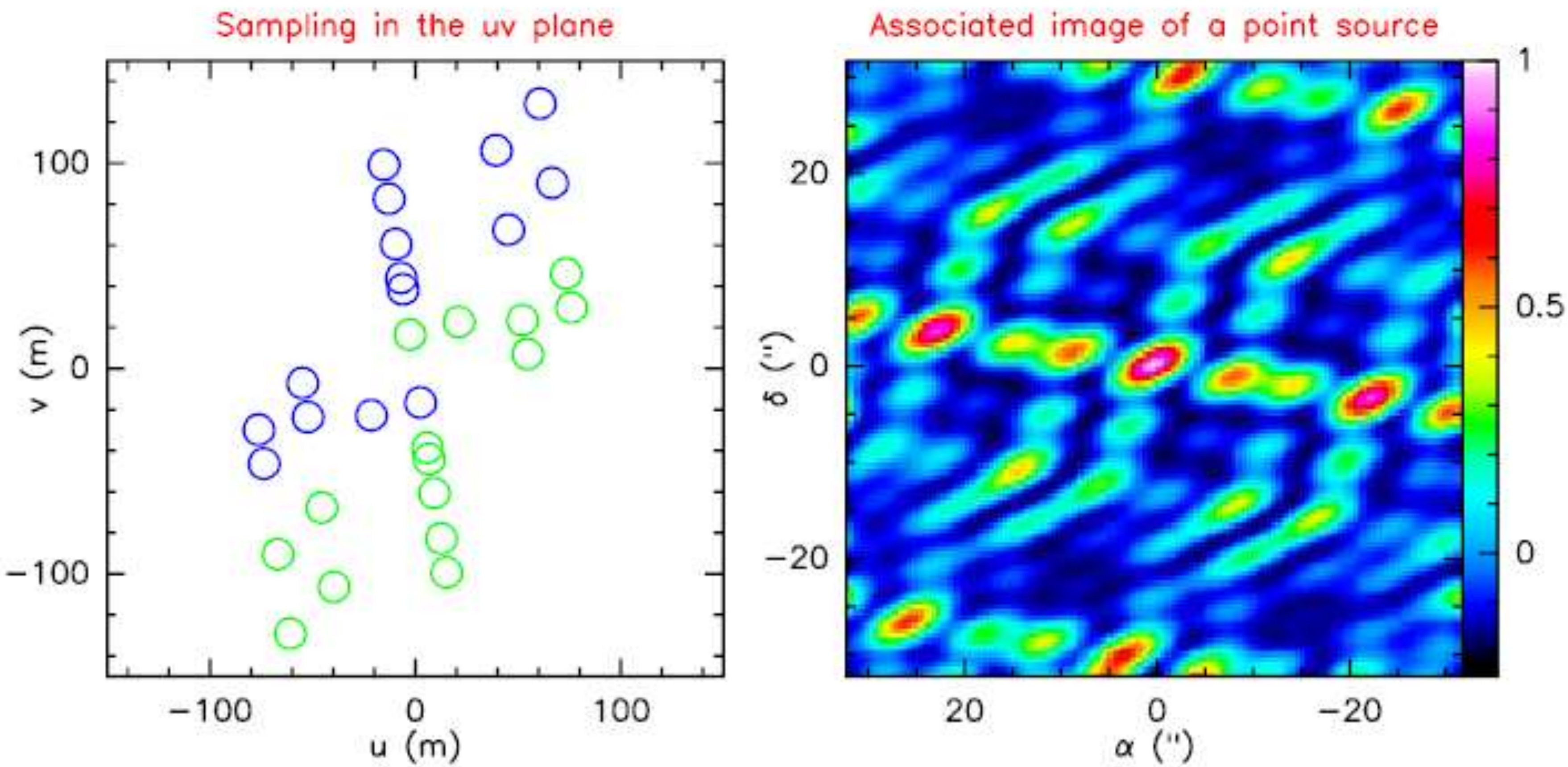




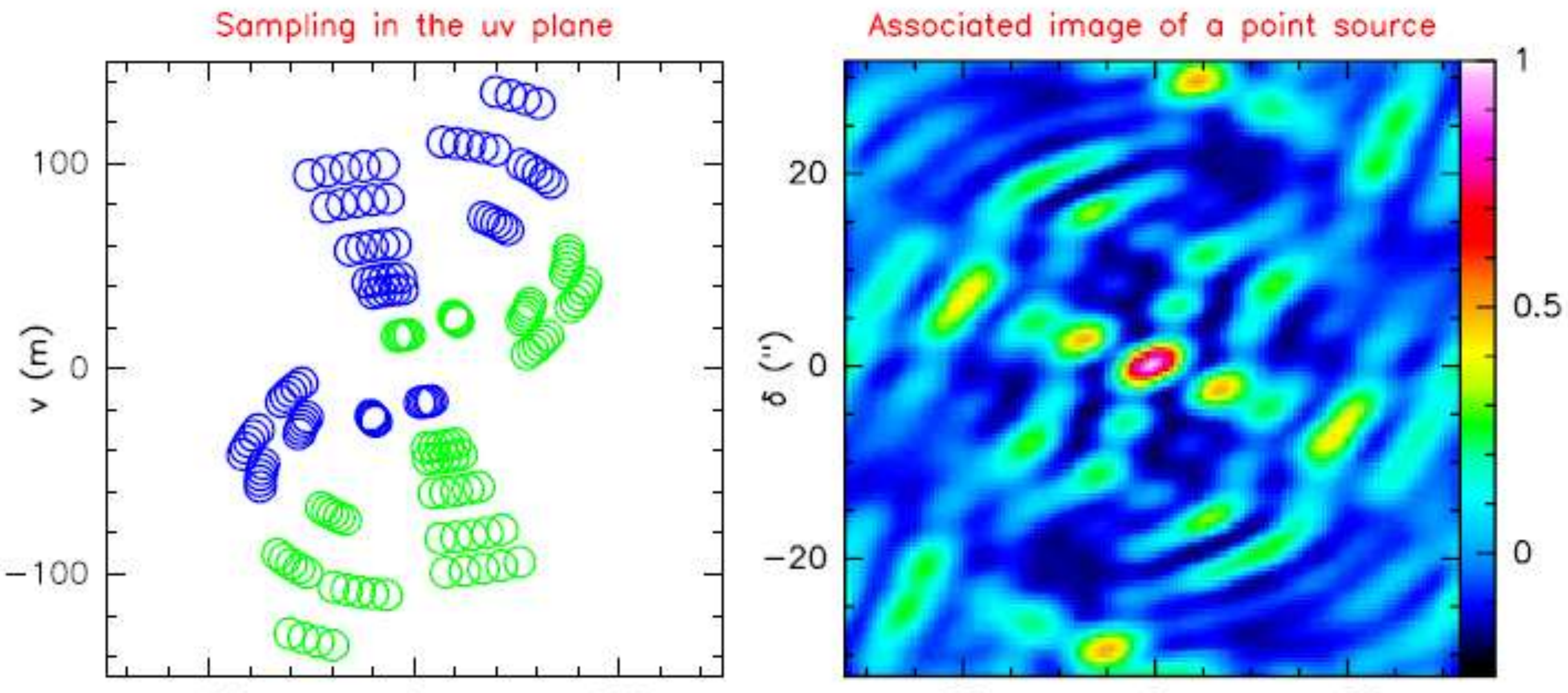
Distance between each antenna pair
100
0
−100
v (m)
−100
0
100
u (m)
Distance from array center
50
0
−50
Y (m)
−50
0
50
X (m)

Earth-rotation aperture synthesis

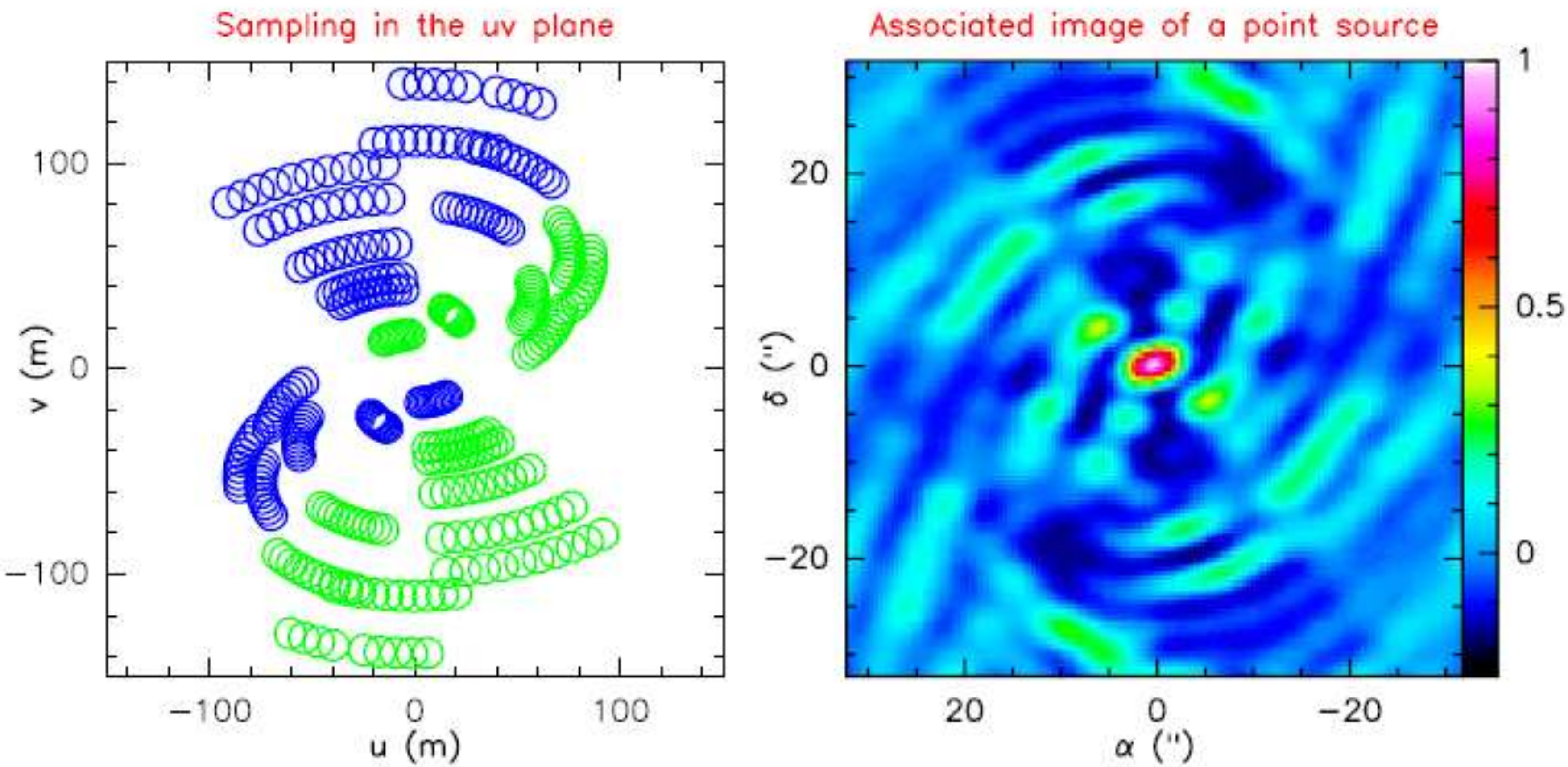
- Incomplete *uv* plane coverage



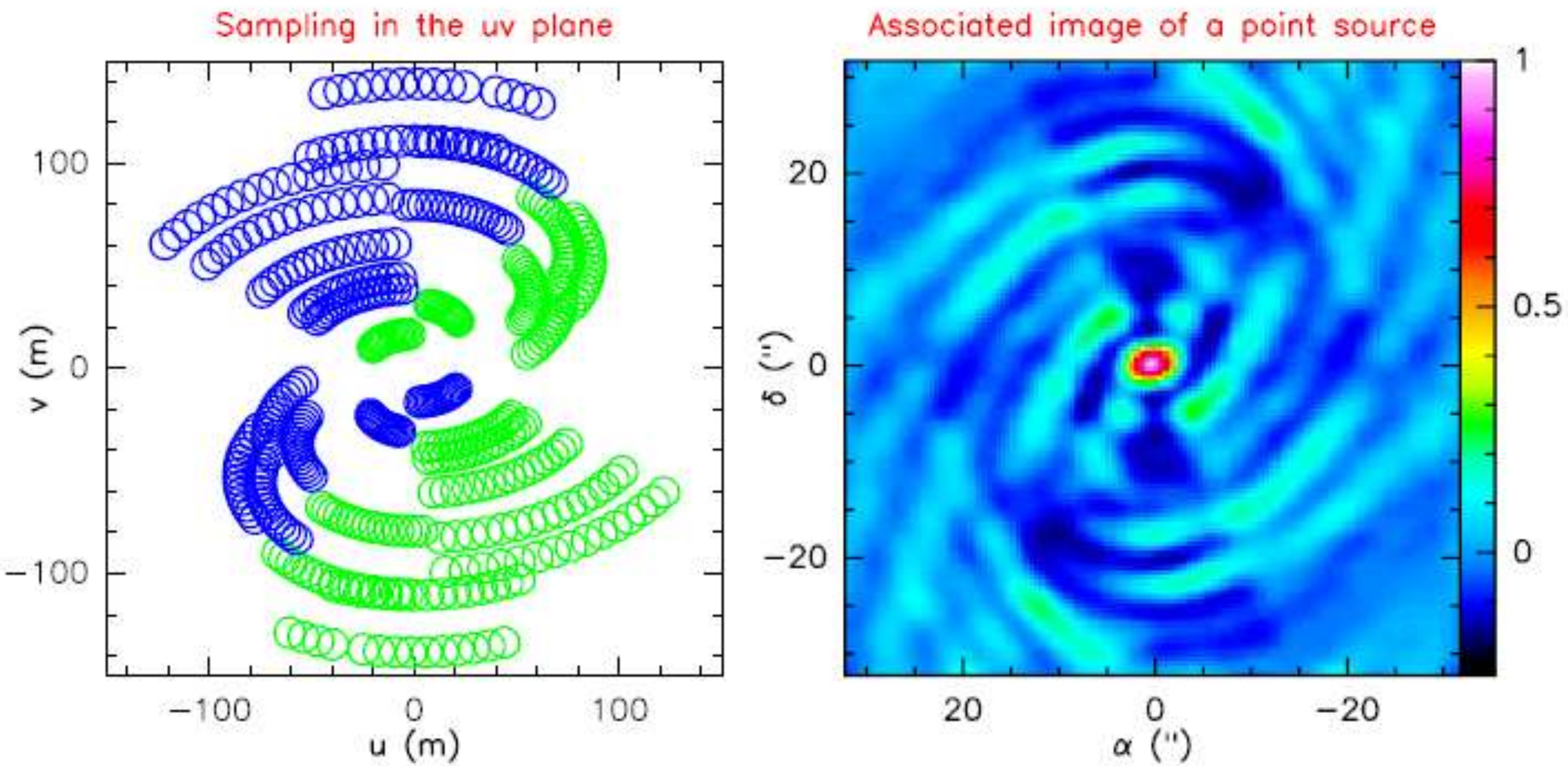
Earth-rotation aperture synthesis



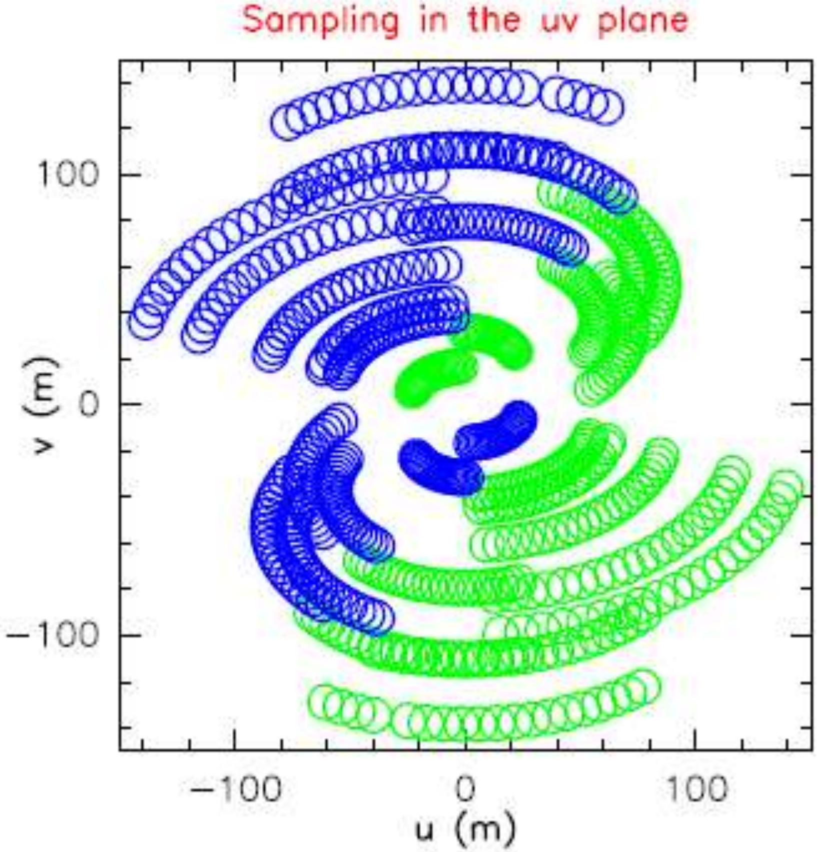
Earth-rotation aperture synthesis

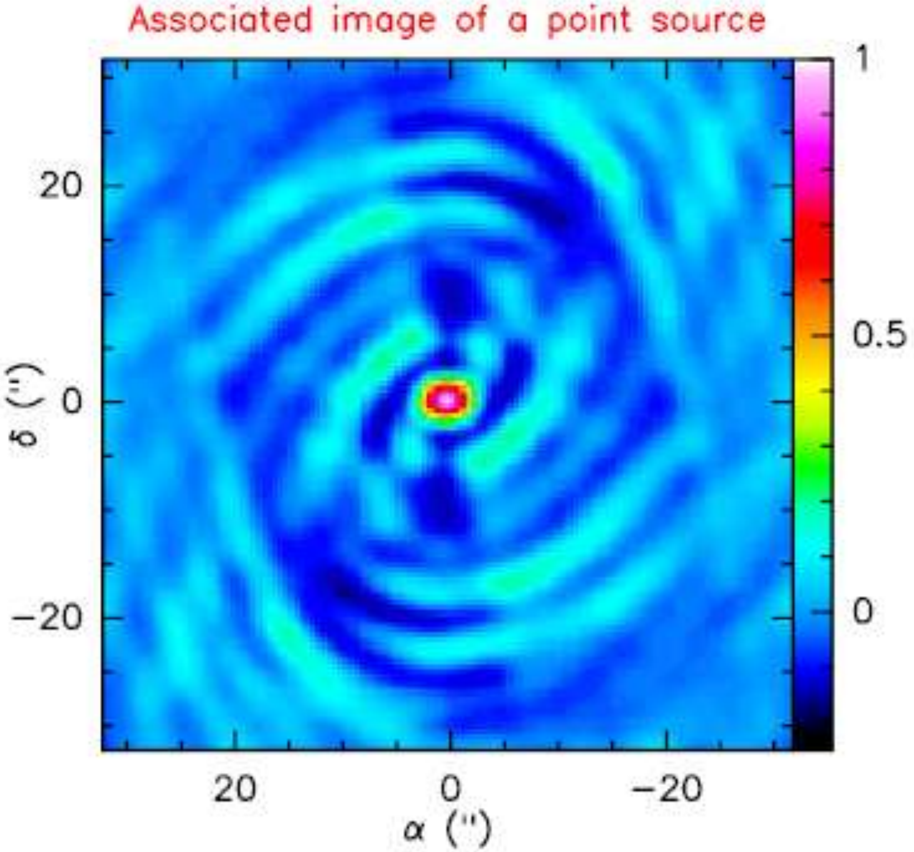


Earth-rotation aperture synthesis

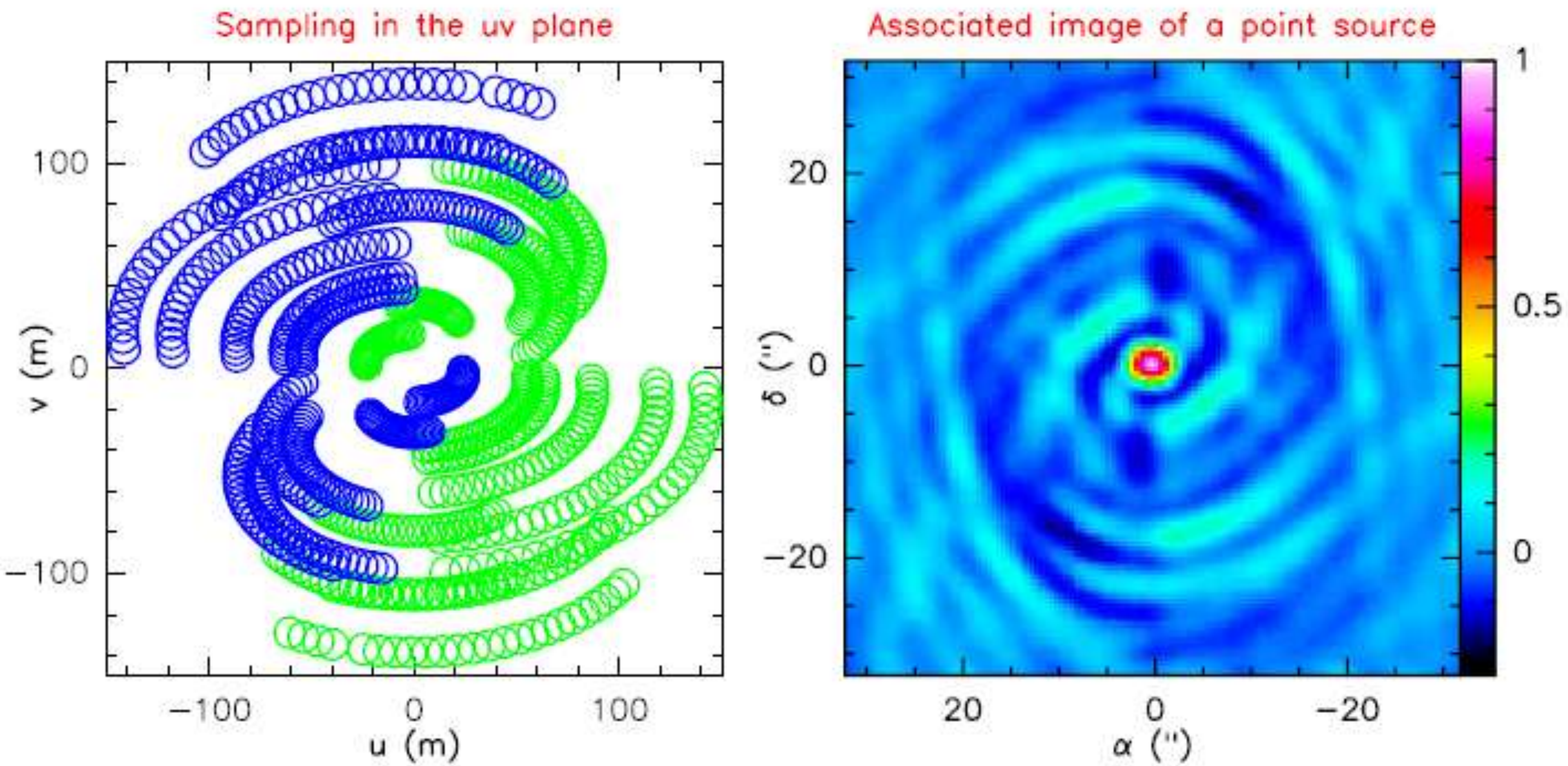


Earth-rotation aperture synthesis

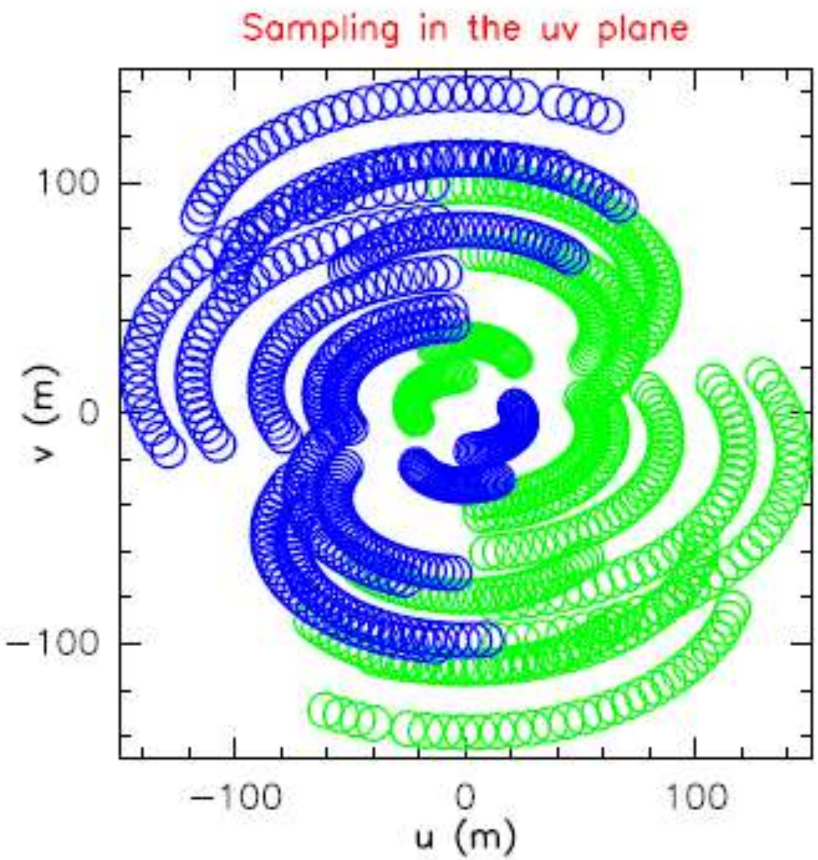


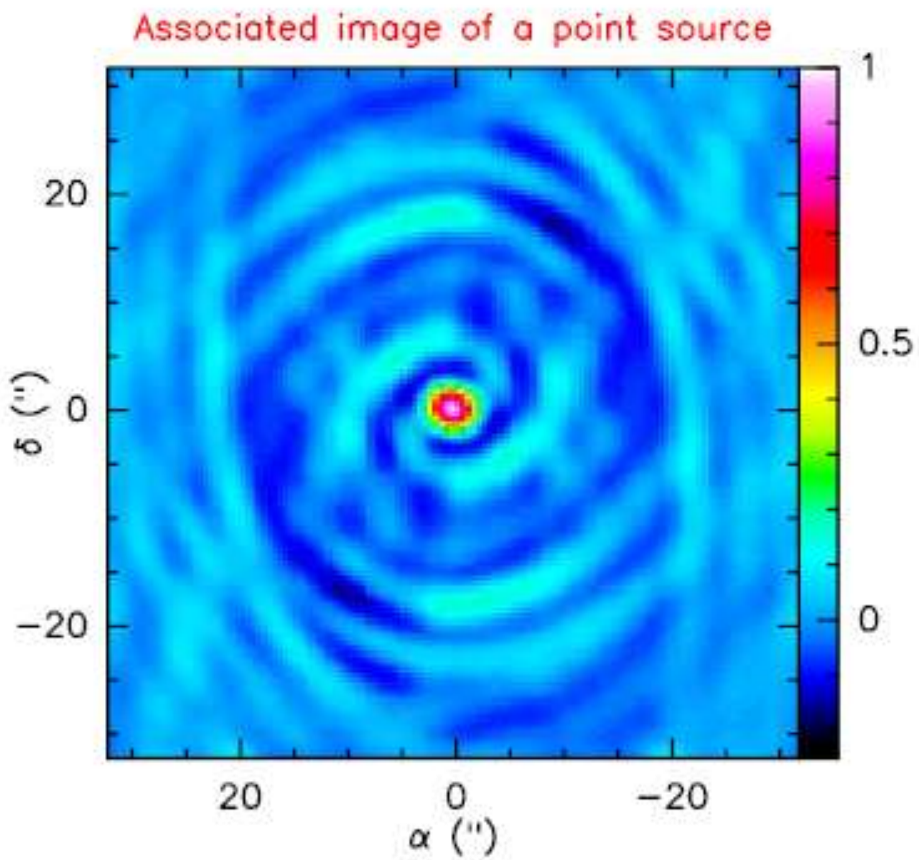


Earth-rotation aperture synthesis

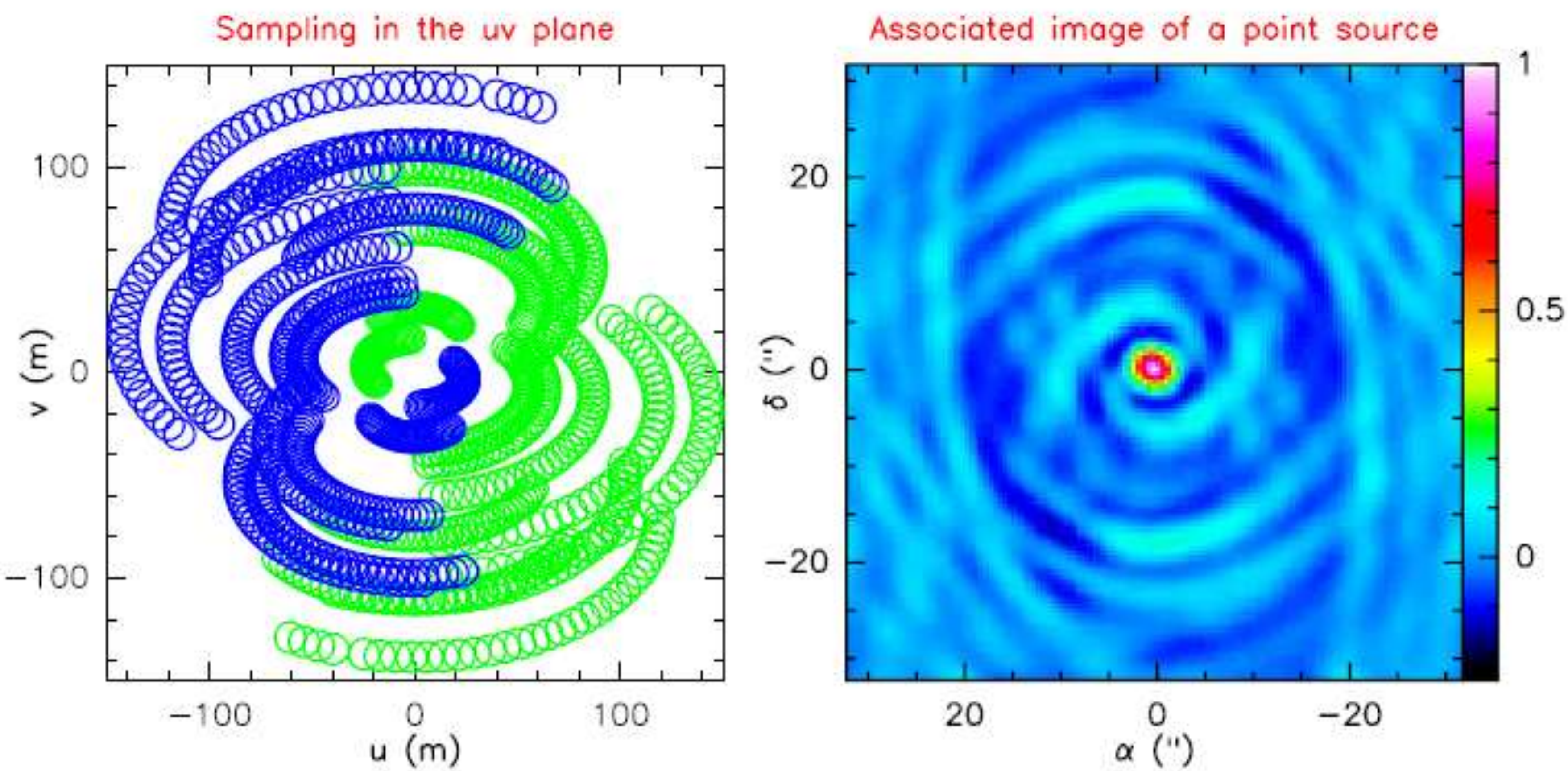


Earth-rotation aperture synthesis





Earth-rotation aperture synthesis

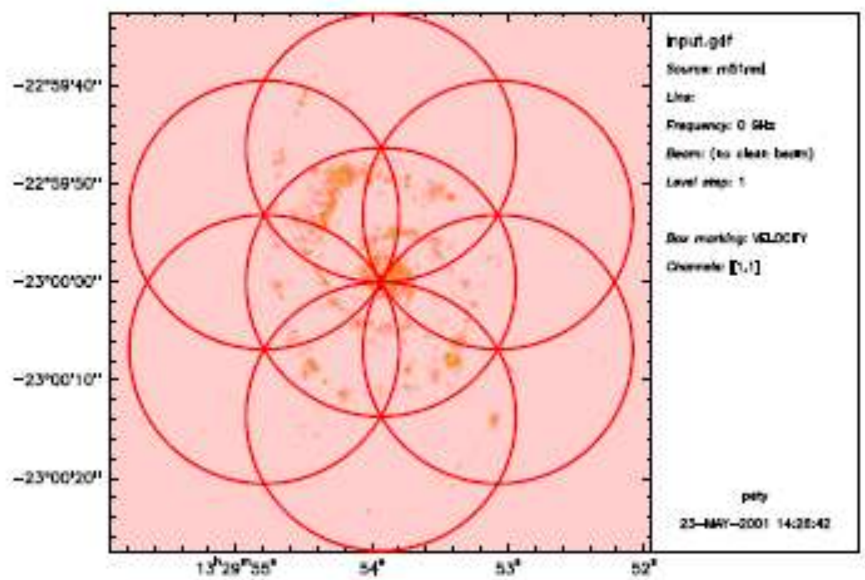


Atmosphere effects

- Atmospheric noise uncorrelated – correlation suppresses it!
- But transmission depends on weather and frequency
  - astronomical sources needed to calibrate the flux scale!
- Atmosphere is turbulent => phase noise
  - timescale of atmospheric phase random changes:
    - optical: 10-100 milli secondes;
    - radio: 10 minutes.
  - thus, radio permits phase calibration on a nearby point source (e.g. quasar)

Field of view

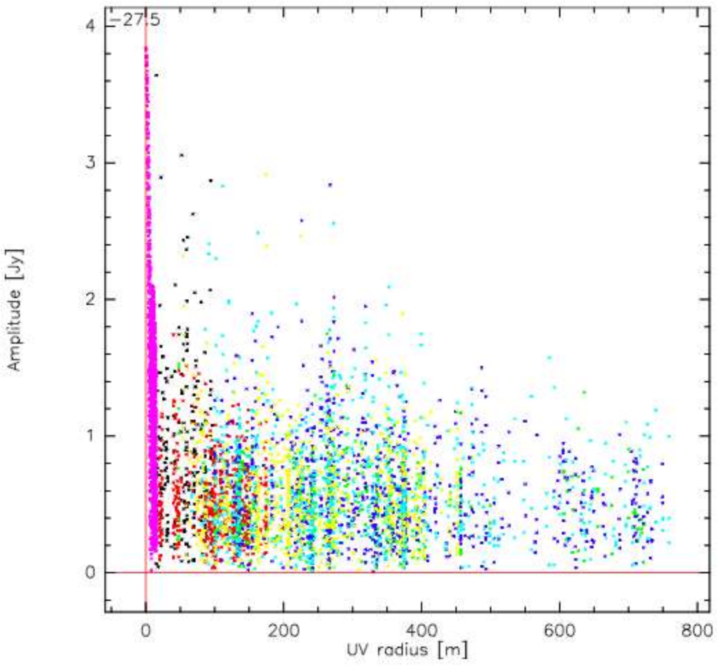
- One pixel detector:
  - Single Dish: one image pixel/telescope pointing;
  - Interferometer: numerous image pixels/telescope pointing
    - Field of view = Primary beam size;
    - Image resolution = Synthesized beam size.
- Wide-field imaging => mosaicing

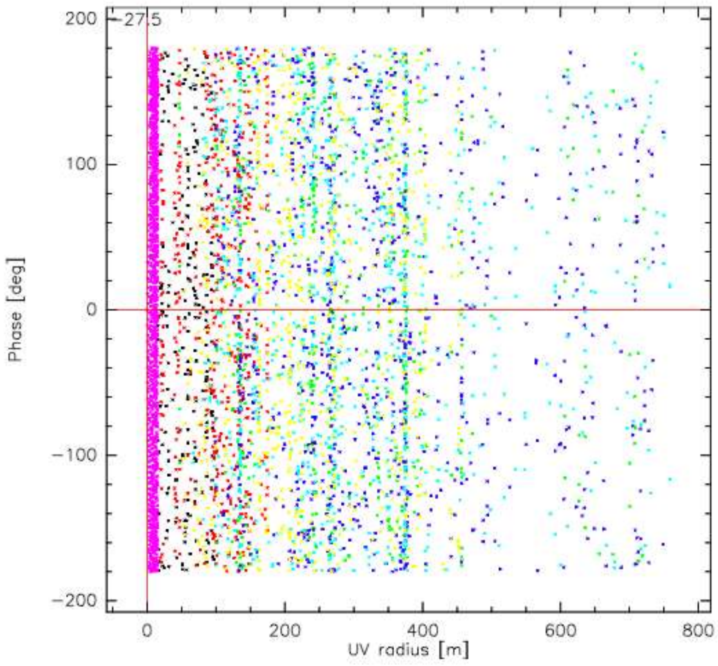


LECTURE 3

Interferometer output

- (calibrated) visibilities in the uv-plane
- to get from uv-plane to image plane, mathematical transforms needed





Mapping: inverse FT

- We measure the interferometer response V(u,v)

$$V(u,v) = \int I(l,m) \exp[-i2\pi(ul+vm)]dldm$$

- We can take the inverse FT to obtain the sky brightness

$$I(l,m) = \int V(u,v) \exp[i2\pi(ul+vm)]dudv$$

- However, the uv-plane is not fully sampled (only by available baselines)
- Thus introducing a sampling function S(u,v) for the uv coverage

$$S(u,v) = \sum_{\text{baselines}} \delta(u-u_k, v-v_k)$$

- we have a dirty image

$$I_D(l,m) = \int S(u,v)V(u,v) \exp[i2\pi(ul+vm)]dudv$$

- Thus what we really have is the image brightness convolved with the dirty beam
- To retrieve the image brightness, we need deconvolution by the dirty beam

Mapping: inverse FT

- FT of sampling function is convolved with brightness distribution

$$I_D = FT\{S(u,v)V(u,v)\} = FT\{S(u,v)\} * FT\{V(u,v)\}$$

- FT of sampling function = dirty beam (or Point Spread Function)
- main lobe of dirty beam can be fitted by a Gaussian beam and is called the synthesized beam

- To calculate the dirty image
  - direct FT – would require $2MN^2$ multiplications, where M … number of u,v points, N … linear dimension of the image in pixels. In practice, M~N, so costs go as N^4
  - FFT – requires only $N^2 \ln N$ operations
    - this requires gridding the u,v data

- visibilities $V_{ij}(b_{ij}) = \overset{\mathrm{FT}}{\Leftrightarrow} B_{\mathrm{primary}} I_{\mathrm{source}}$

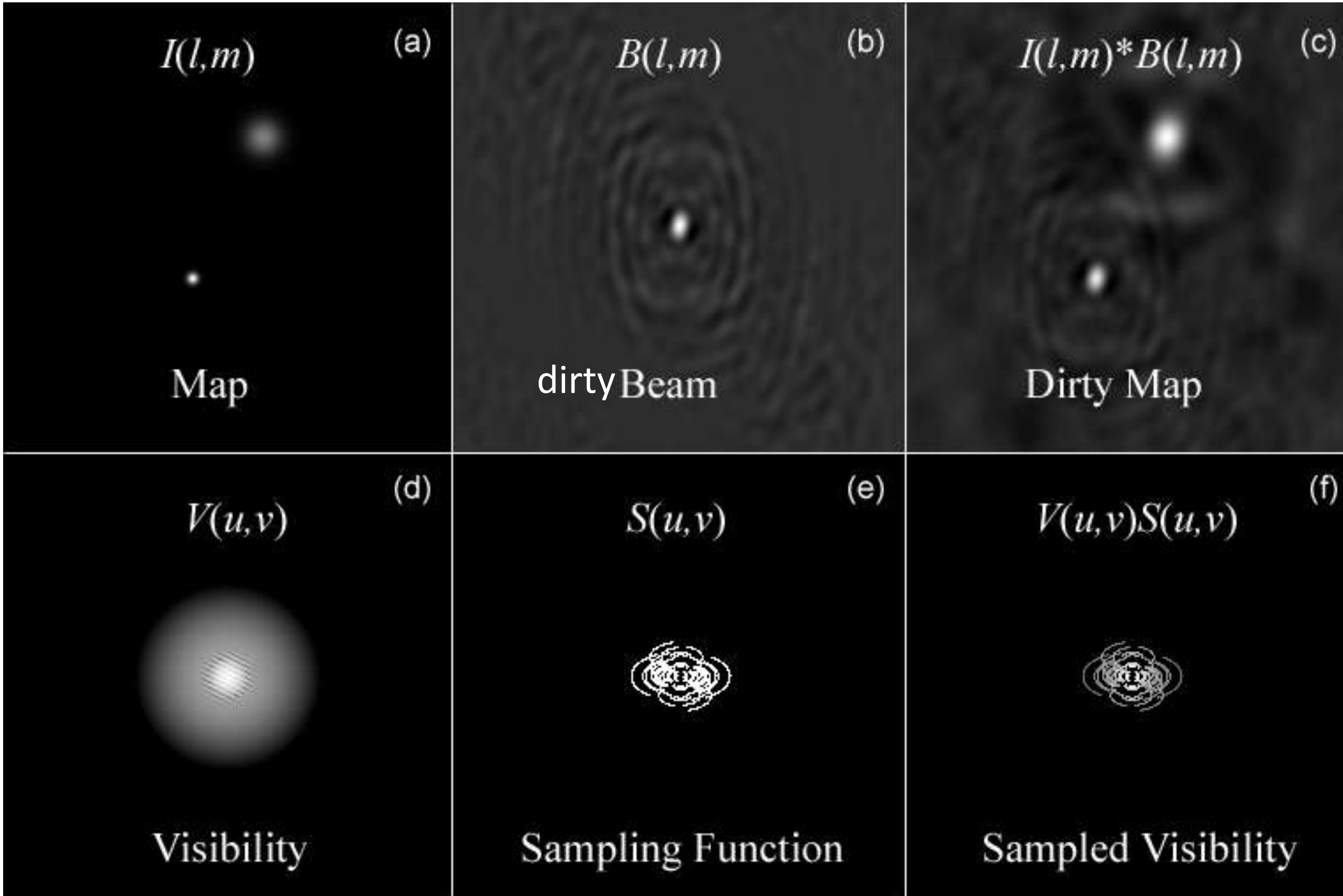
- dirty beam (PSF) $B_{\mathrm{dirty}} = FT^{-1}\{S(u,v)\}$

- dirty image $I_{\mathrm{dirty}} = FT^{-1}\{S(u,v)V(u,v)\} =$

$$FT^{-1}\{S(u,v)\} * FT^{-1}\{V(u,v)\}$$

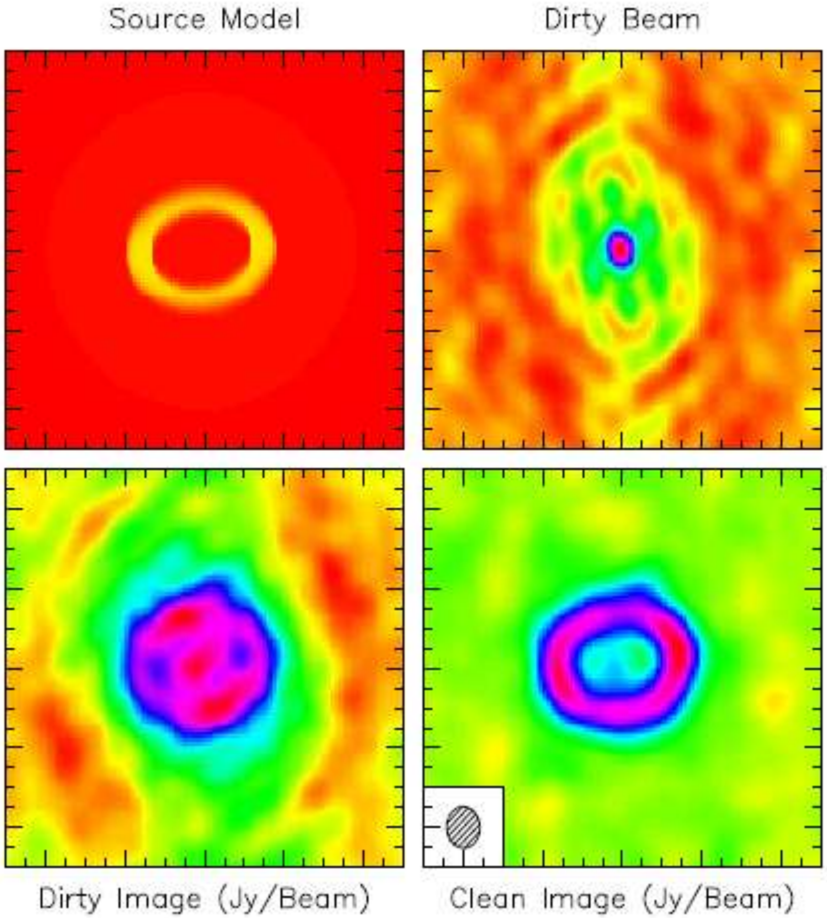
$$I_{\mathrm{dirty}} = B_{\mathrm{dirty}} * FT^{-1}\{V(u,v)\}$$

- deconvolution of dirty image => clean image to do science with



I(l,m)
(a)
Map
B(l,m)
(b)
dirty Beam
I(l,m)*B(l,m)
(c)
Dirty Map
V(u,v)
(d)
Visibility
S(u,v)
(e)
Sampling Function
V(u,v)S(u,v)
(f)
Sampled Visibility

Mapping



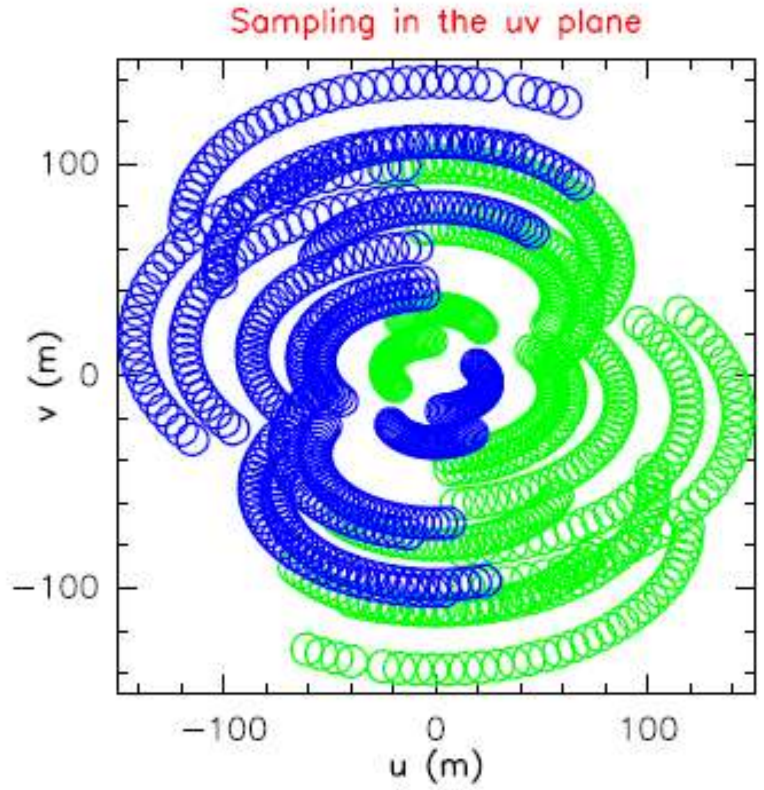
- Difficult to do science on dirty image.
- Deconvolution ⇒ a clean image compatible with the sky intensity distribution.

- Some image reconstruction techniques must be used to recover the missing spacings
- CLEANing of a dirty image

Imaging

$$V_{i,j}(b_{i,j}) = FT\{B_{\text{primary}} I_{\text{source}}\}(b_{i,j}) + \text{noise}$$

- irregular, incomplete sampling
- distorted primary beam
- procedure:
  - from calibrated visibilities **via FT** to dirty beam and image
  - then **via deconvolution** to clean beam and image
  - then visualization and scientific image analysis



- Direct FT is slow
- Fast FT (FFT)
  - an algorithm to compute the discrete Fourier transform
  - quick for images of sizes $2^M x 2^N$
  - needs a regular sampling
    - artifacts due to gridding – periodic replication and aliasing
      - gridding must be fine enough and image must be large enough
    - pixel size: between 1/4 and 1/5 of the synthesized beam
    - image size: at least twice the primary beam (i.e. Nyquist’s criterion in uv plane)

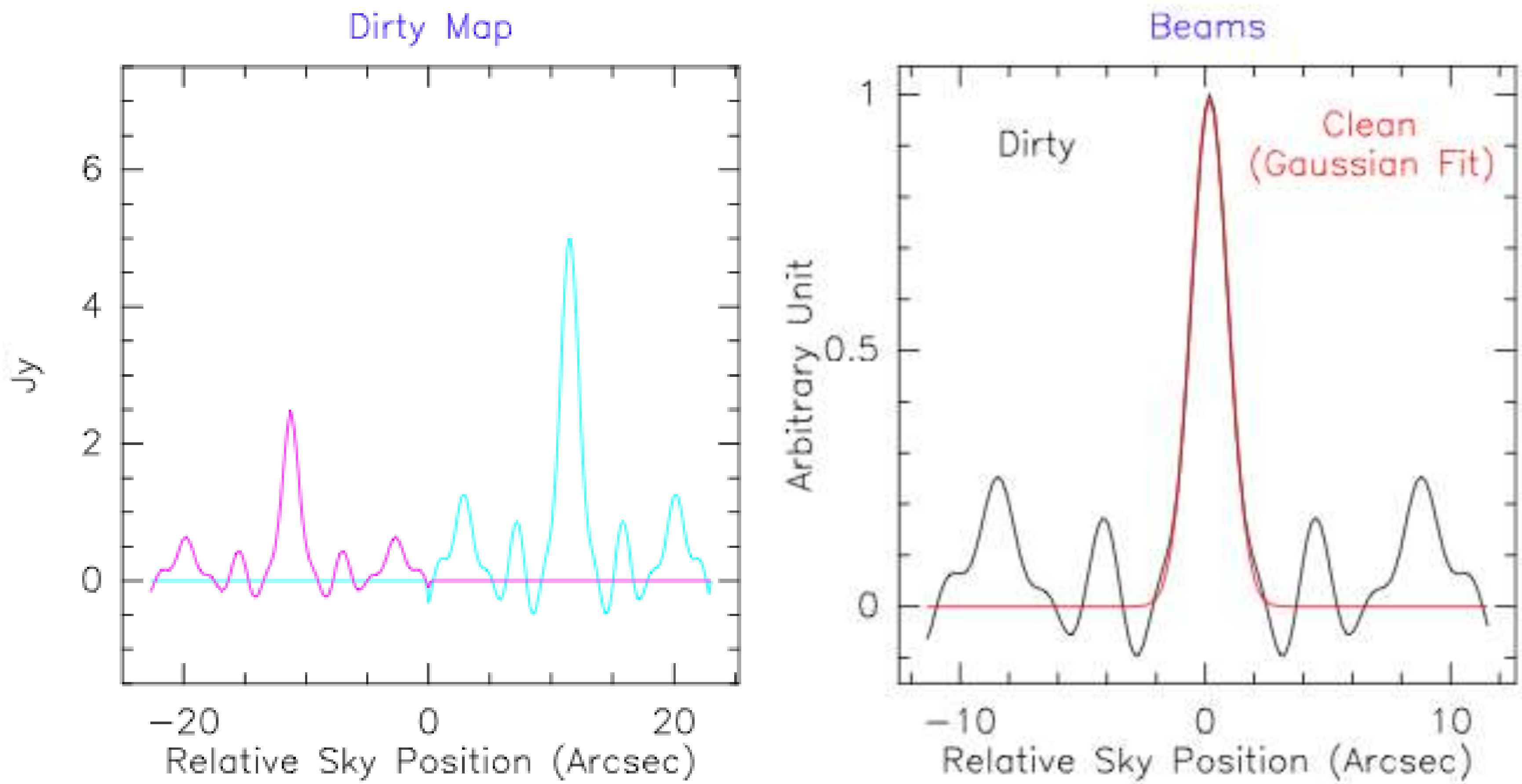
Deconvolution

$$I_{\mathrm{dirty}} = B_{\mathrm{dirty}} * (B_{\mathrm{primary}} I_{\mathrm{source}}) + \mathrm{noise}$$

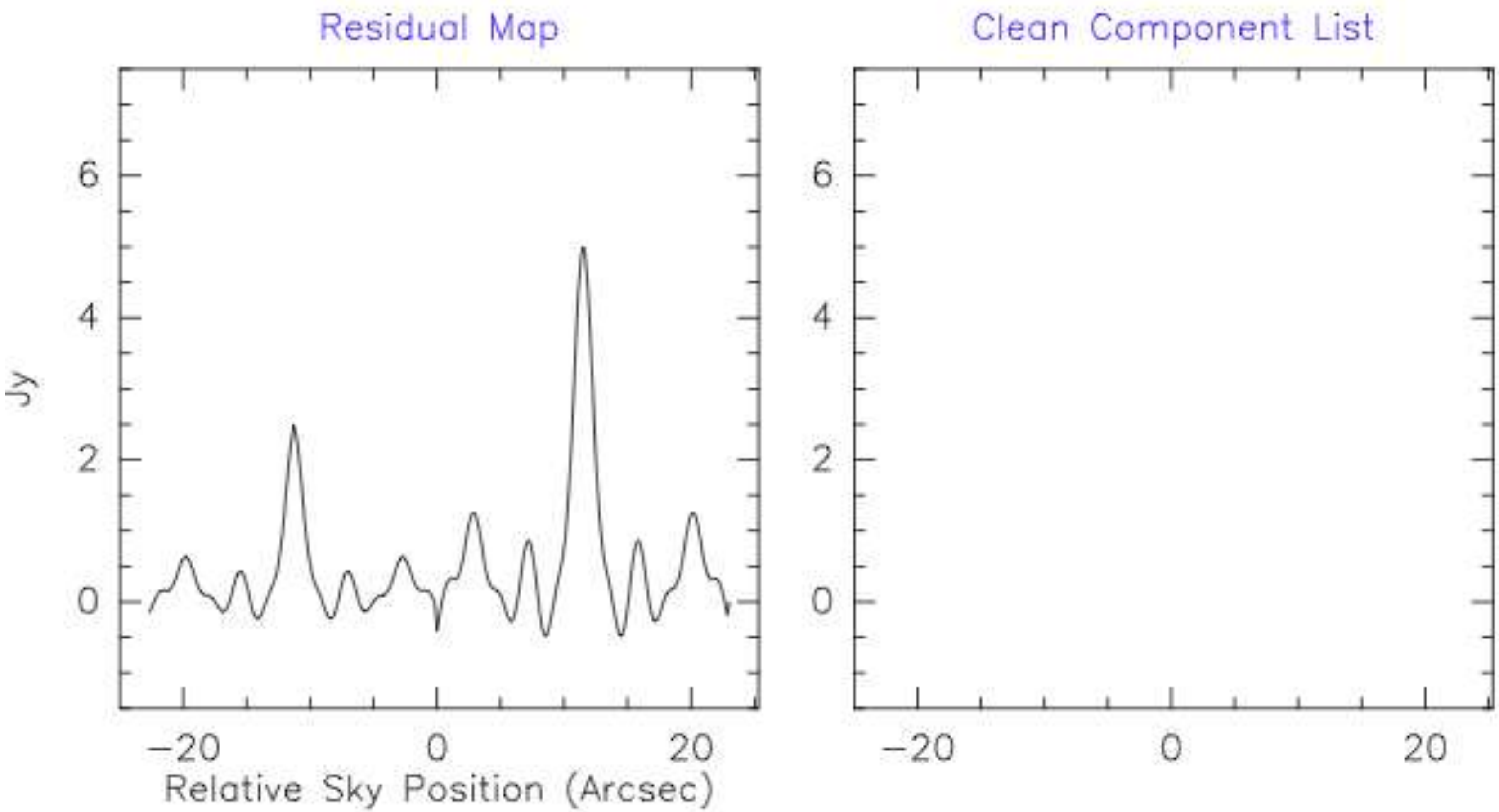
- Irregular, incomplete sampling + noise => impossible to recover the true source structure…
  - improve dirty beam…
  - if B_{dirty} is Gaussian, no deconvolution needed
- Deconvolution needs some a priori assumptions about the source intensity distribution
- goal is to find a sensible intensity distribution compatible with the intrinsic source one

- <u>CLEAN algorithm</u>
  - assumption that source is collection of point sources
  - identify pixel of max. intensity in residual map (dirty map) as a point source
  - add this to a clean component list
  - subtract from residual map
  - repeat until a criterion is matched
  - convolution by clean beam

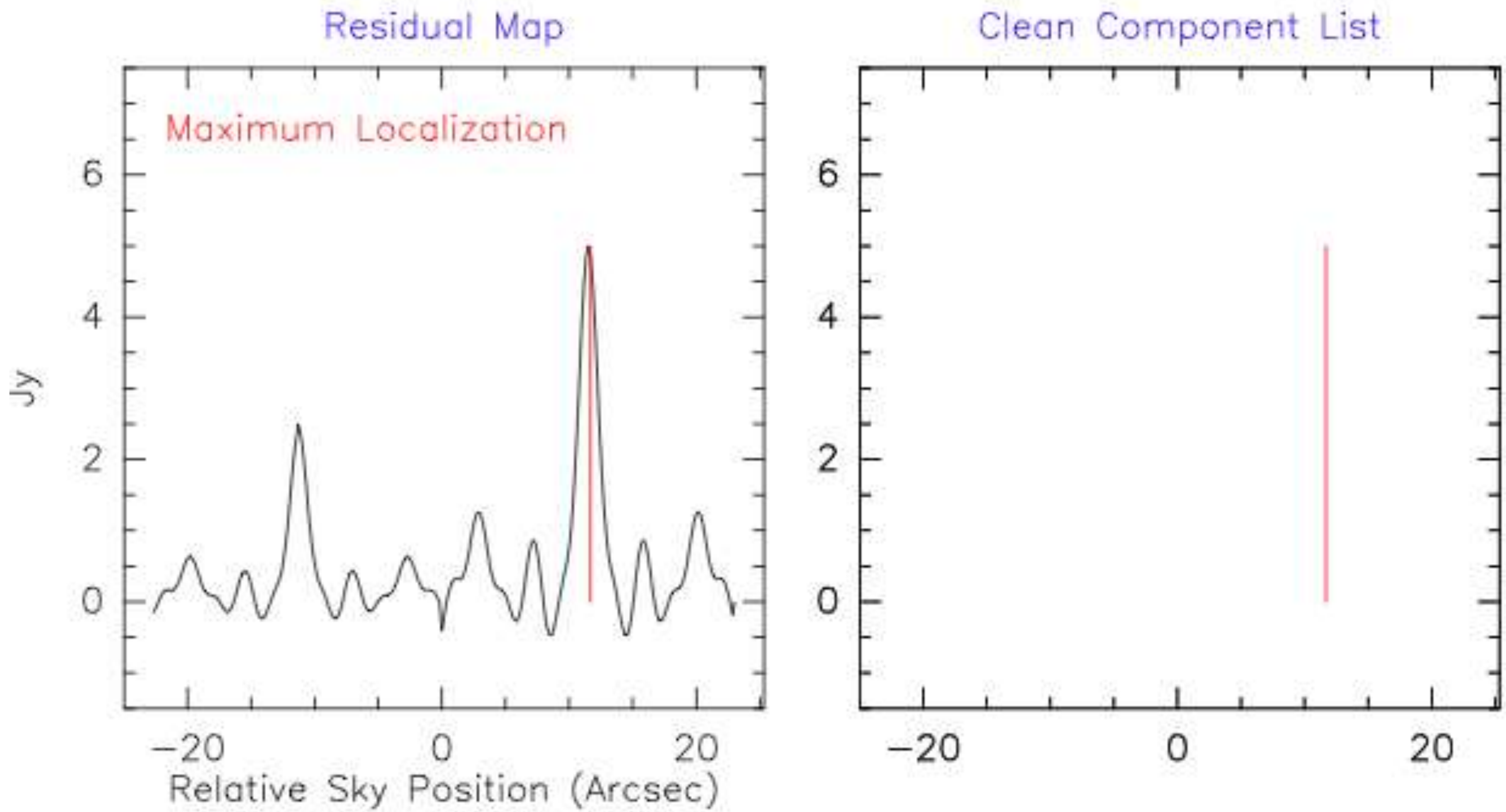
Clean algorithm

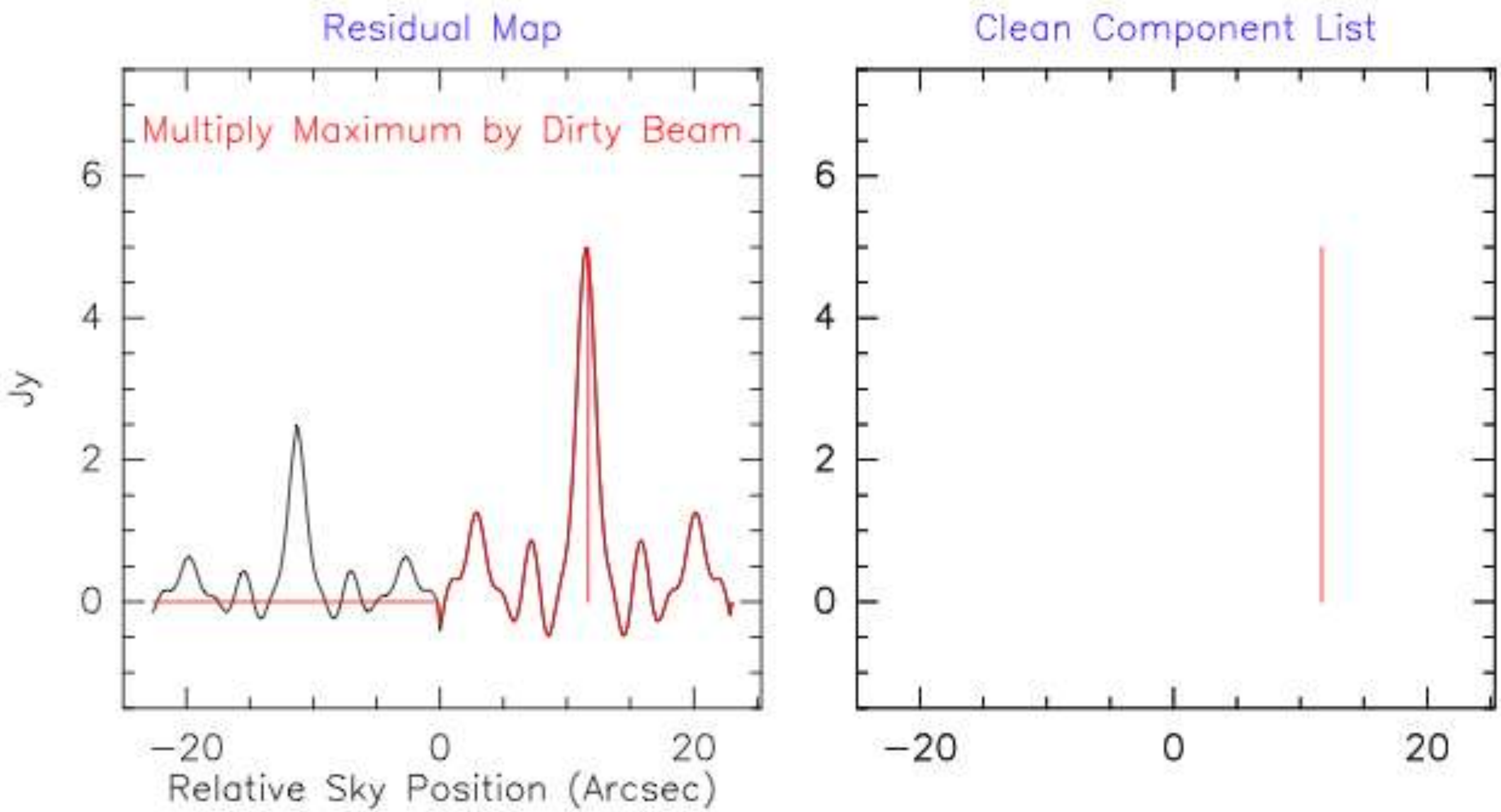


clean

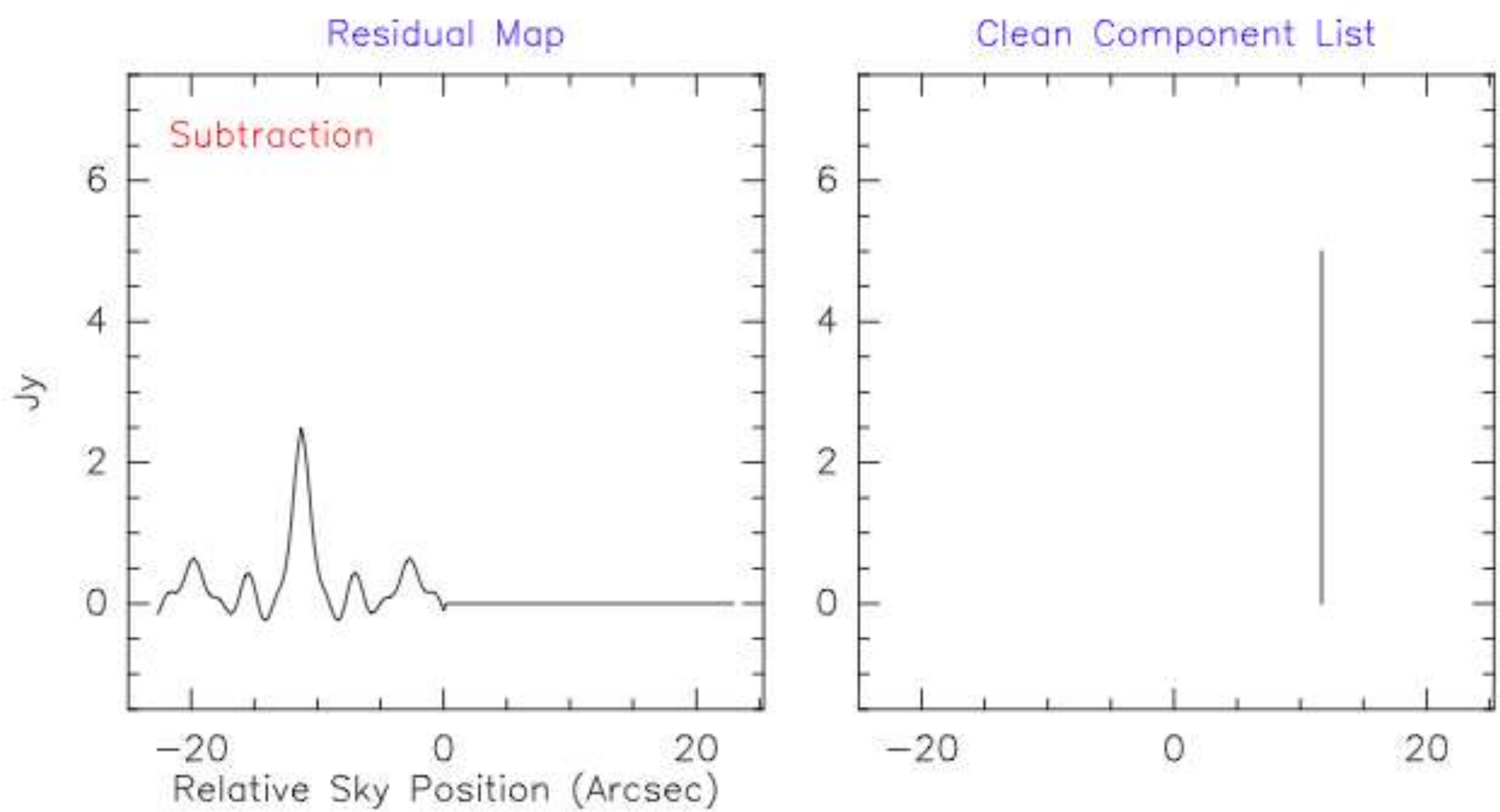


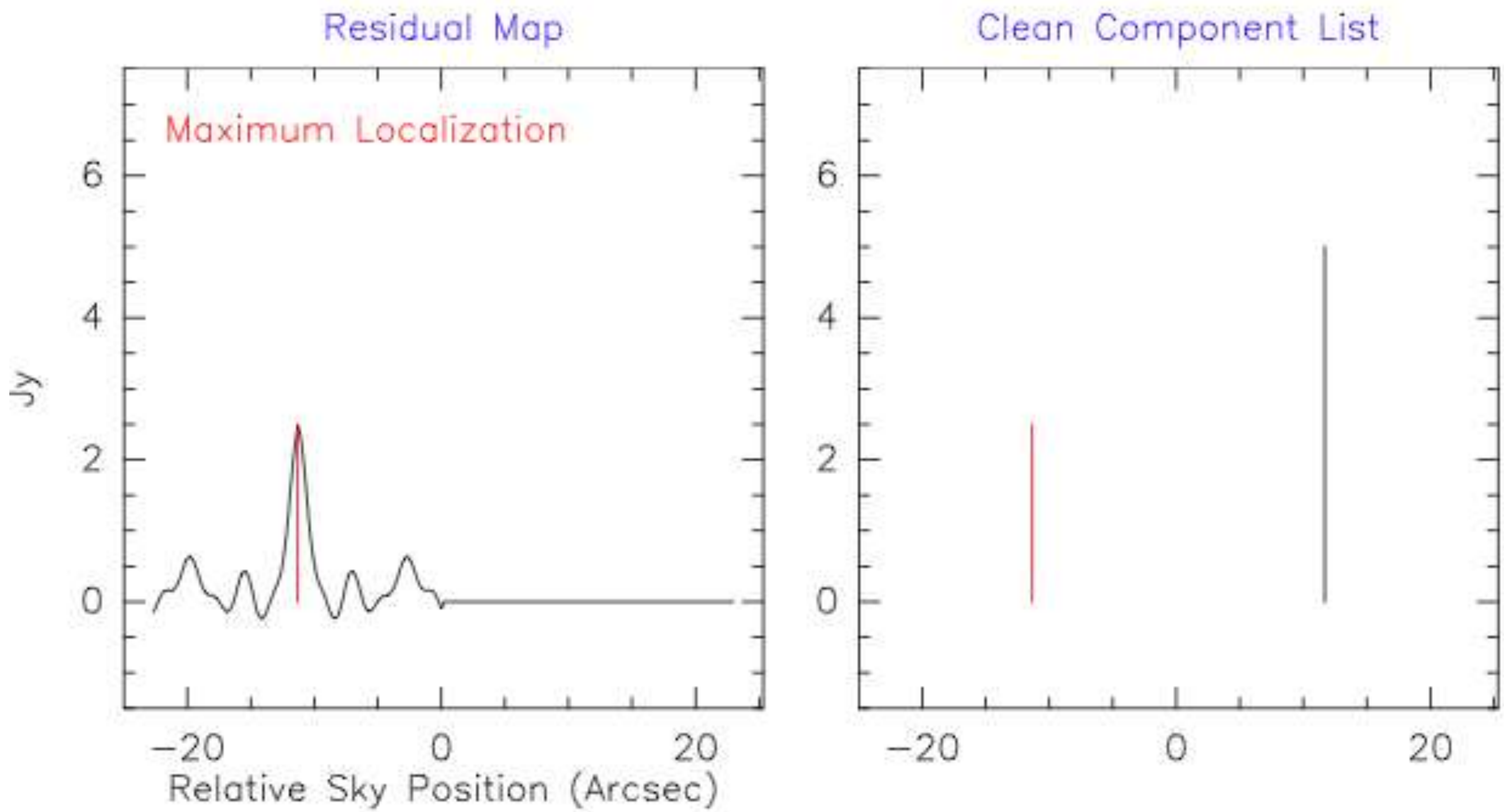
Residual Map
Clean Component List
Jy
6
4
2
0
−20
0
20
Relative Sky Position (Arcsec)


Residual Map
Maximum Localization
Jy
6
4
2
0
−20
0
20
Relative Sky Position (Arcsec)
Clean Component List
6
4
2
0
−20
0
20

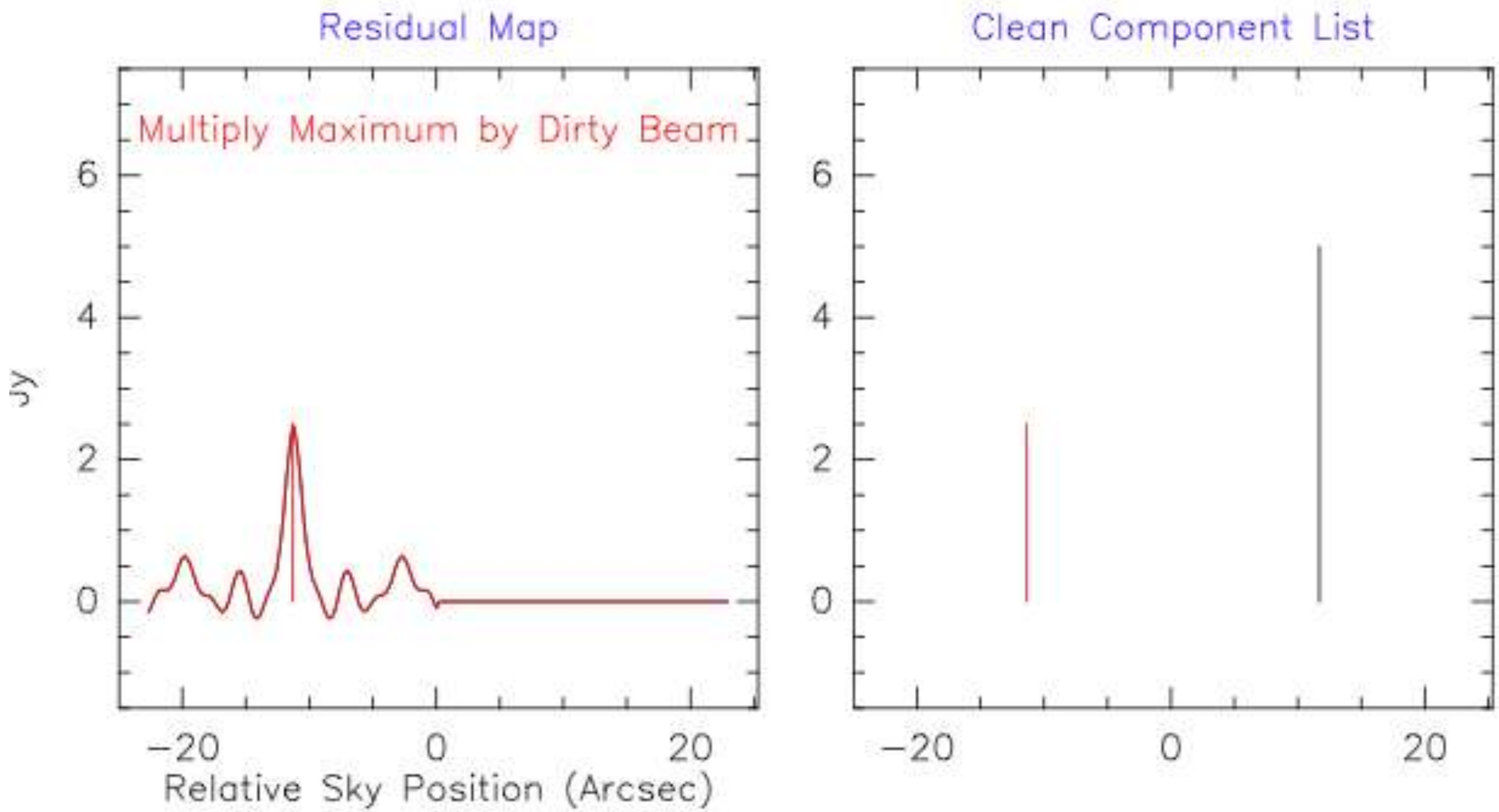


Residual Map
Multiply Maximum by Dirty Beam
Jy
6
4
2
0
−20
0
20
Relative Sky Position (Arcsec)
Clean Component List
6
4
2
0
−20
0
20

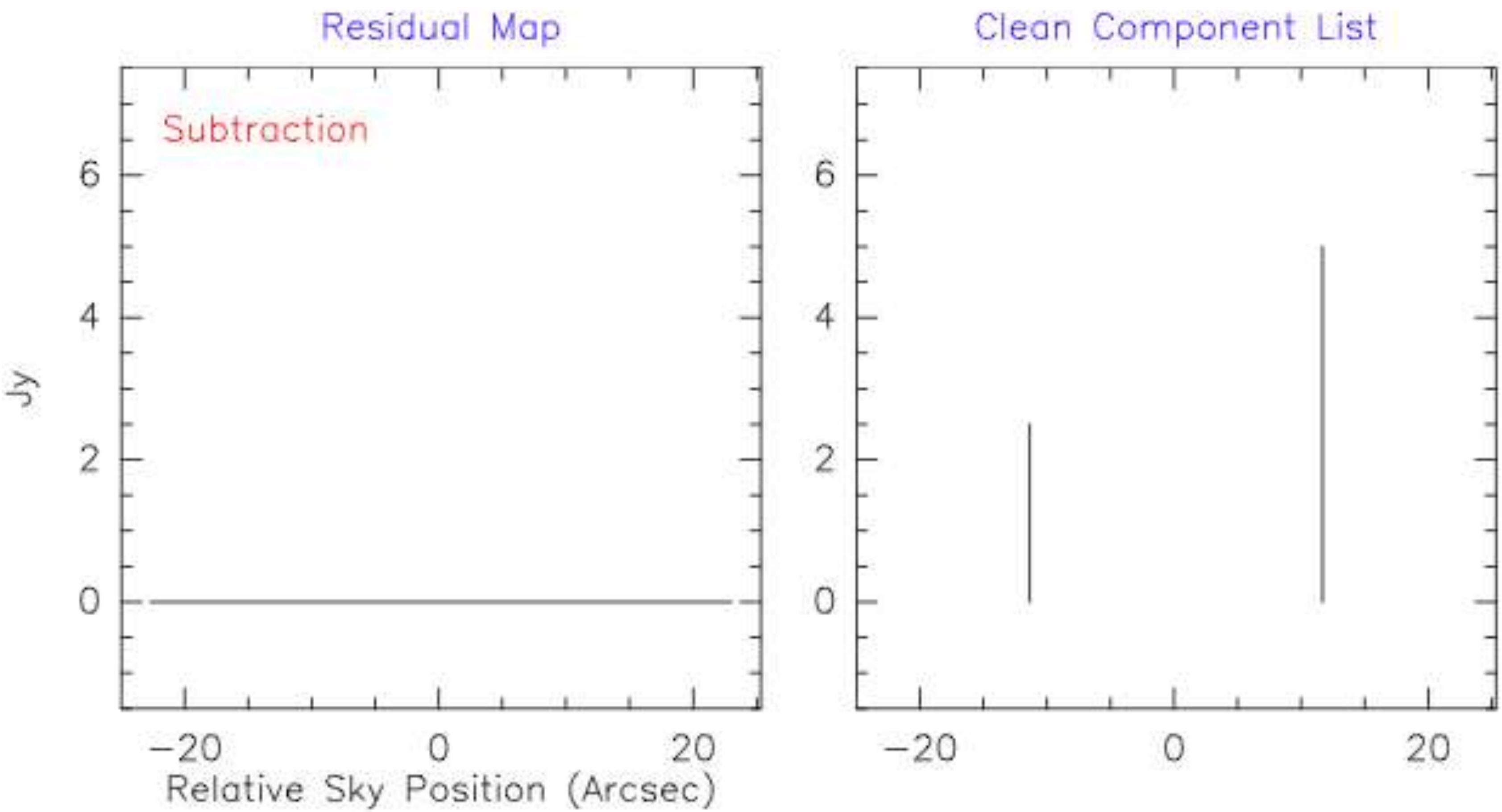

Residual Map
Subtraction
Clean Component List
Jy
6
4
2
0
-20
0
20
Relative Sky Position (Arcsec)



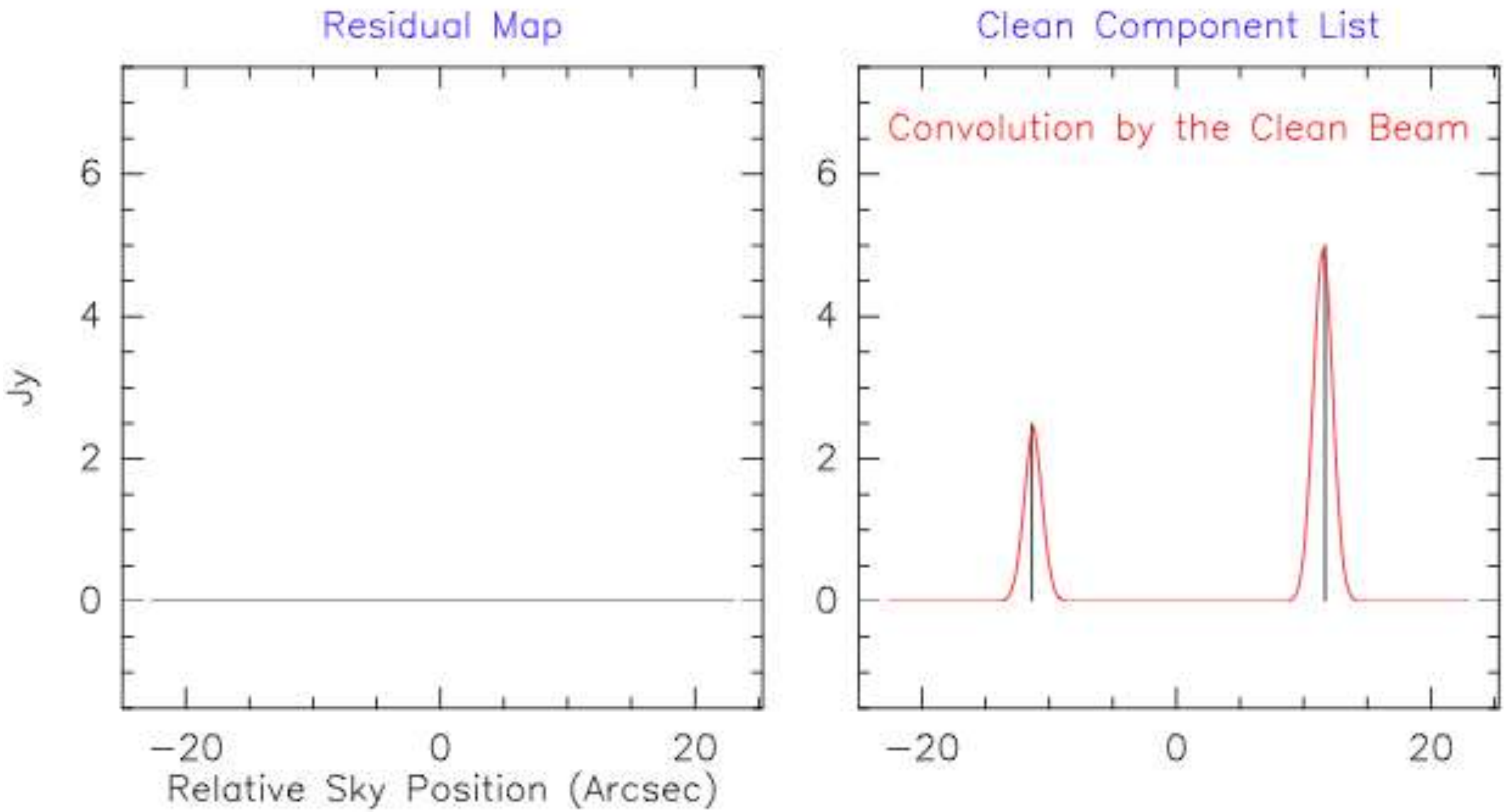
Residual Map
Maximum Localization
Jy
6
4
2
0
−20
0
20
Relative Sky Position (Arcsec)
Clean Component List
6
4
2
0
−20
0
20



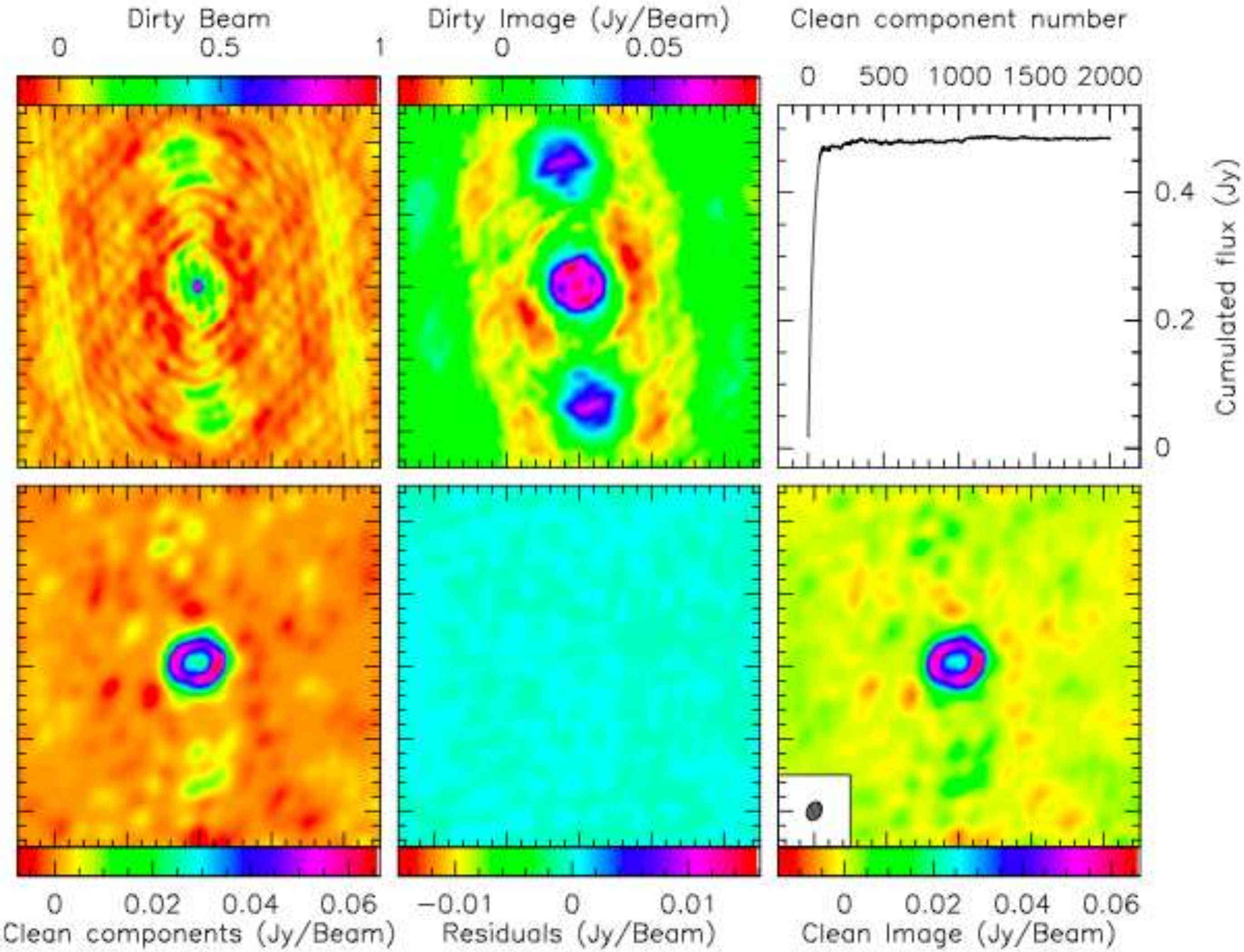
Residual Map
Multiply Maximum by Dirty Beam
Jy
Relative Sky Position (Arcsec)
Clean Component List



Residual Map
Subtraction
Jy
Relative Sky Position (Arcsec)
Clean Component List


Residual Map
Clean Component List
Convolution by the Clean Beam
Jy
6
4
2
0
−20
0
20
Relative Sky Position (Arcsec)

- Stopping criterion
  - total number of components
  - maximum intensity < fraction of noise
  - maximum int. < fraction of dirty map maximum



Sensitivity (noise)

- Radiometer equation

$$\sigma = \frac{2kT_{\rm sys}}{A_{\rm eff}\,(\Delta\nu\Delta t)^{1/2}}$$

$$\sigma = \frac{2kT_{\rm sys}}{A_{\rm eff}\,[N(N-1)\Delta\nu\Delta t]^{1/2}}$$

where

σ [Jy] flux noise

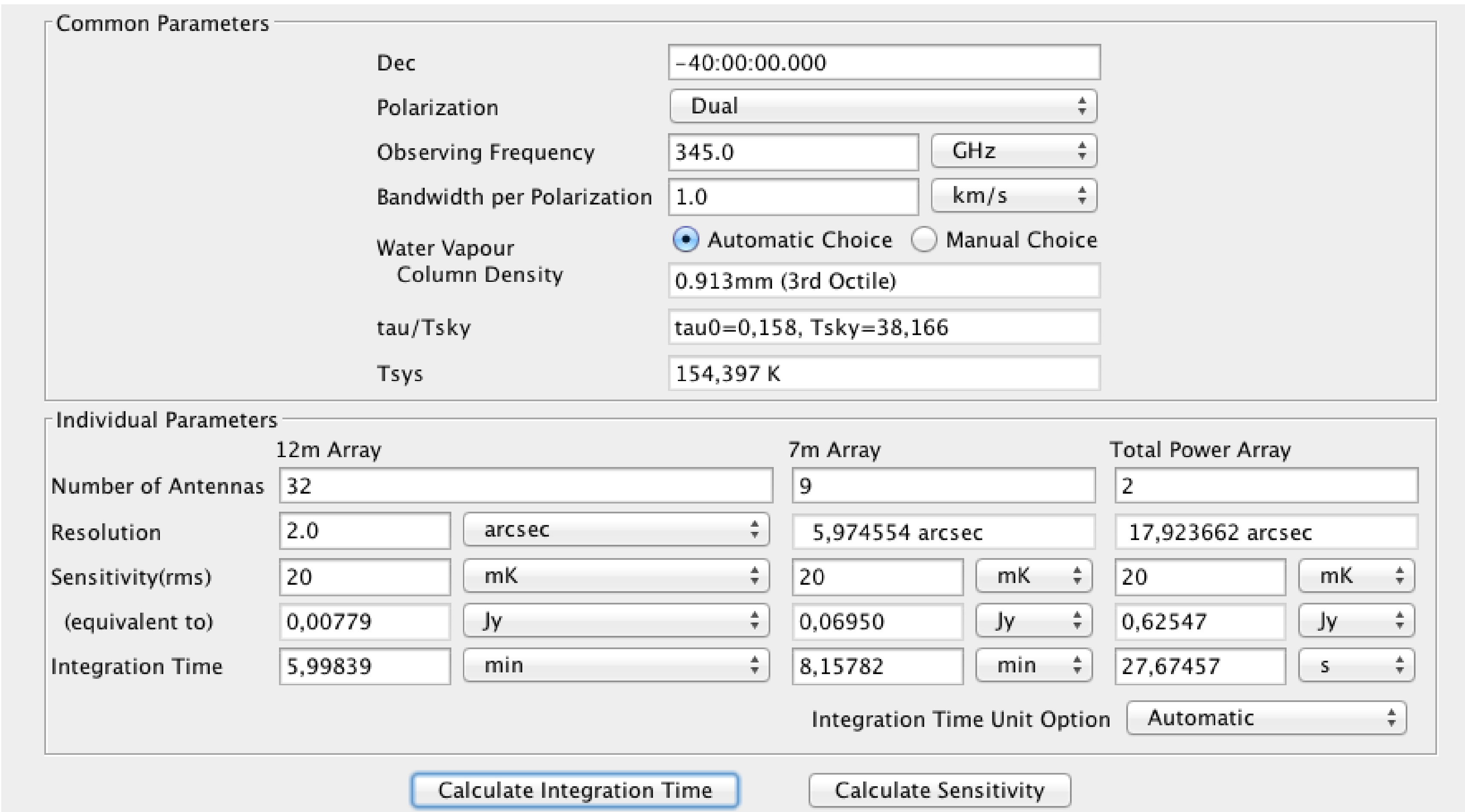
T_{sys} system temperature

$\Delta\nu$ channel bandwidth

Δt on-source integration time

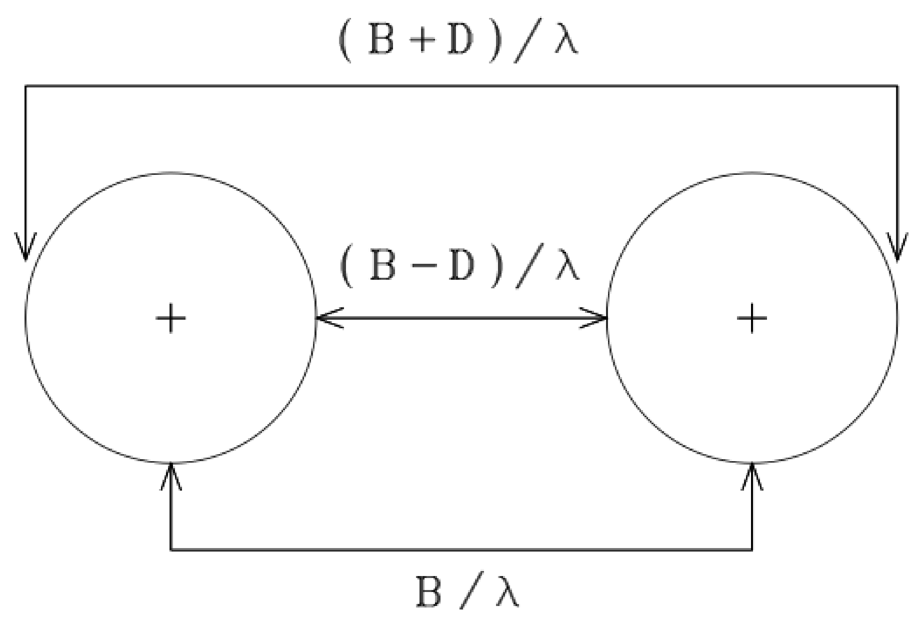
N_{ant} number of antennas

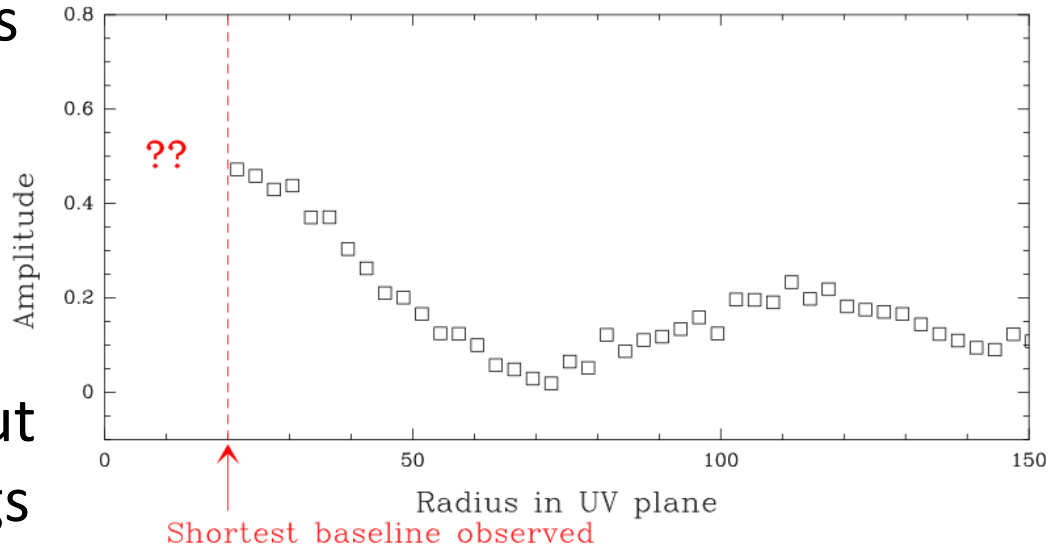
ALMA sensitivity calculator



Short-spacing

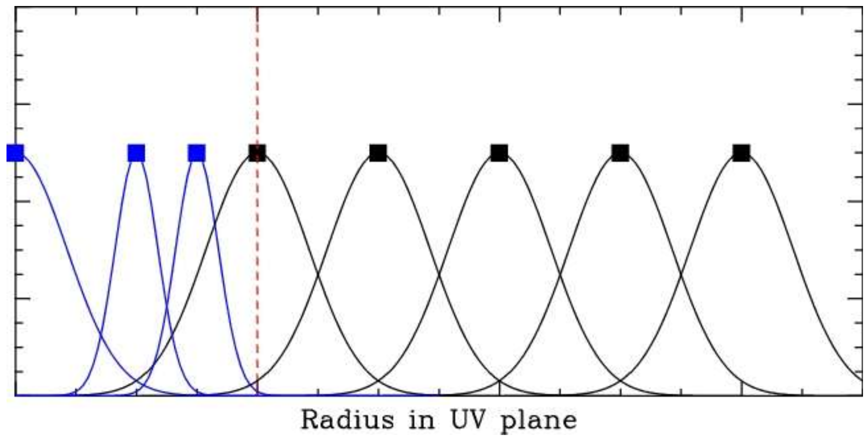
- Single-dish is sensitive to spatial frequencies from *0* to *D*
- Interferometer is sensitive to spatial frequencies from *B-D* to *B+D*
- interferometer cannot sample all spatial frequencies: the shortest baseline distance defines the shortest spatial frequency that is measured (vertical red line)
- The most extended structures are filtered out
- => need of short spacings

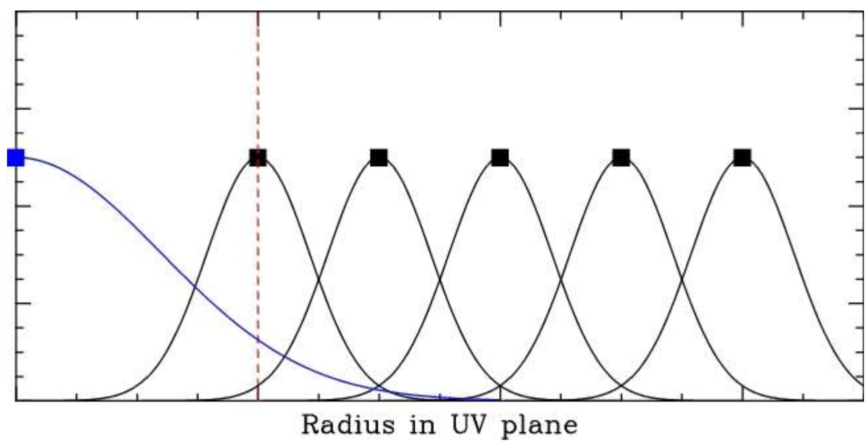




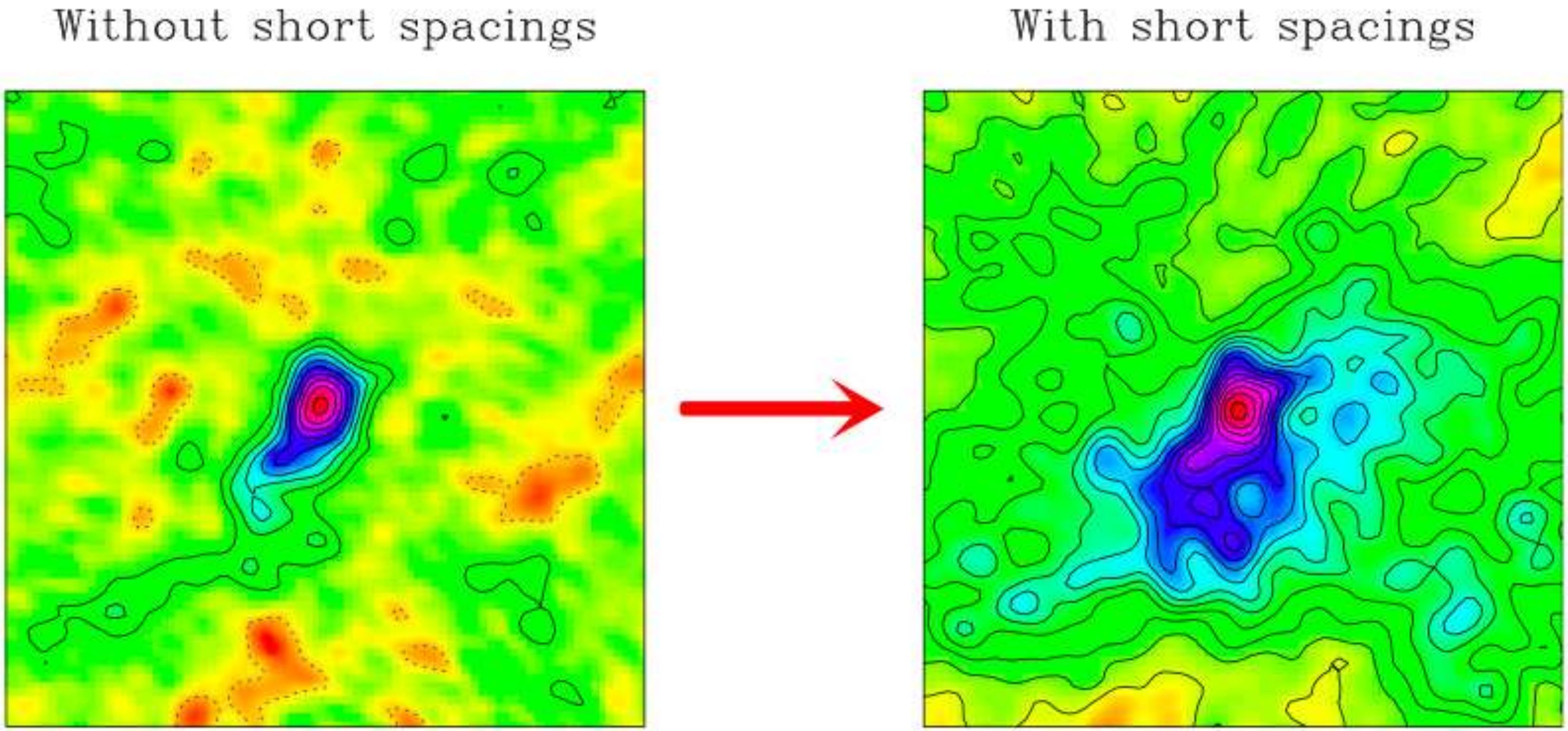
Short-spacing

- Each measurement is actually a local average of the visibilities, weighted by the transfer function of each individual antenna (approximated by Gaussian)
- The largest structures that can be mapped are ~ 2/3 of the primary beam (field of view)
- Structures larger than ~ 1/3 of the primary beam may already be affected
- ALMA + ACA + single-dish antennas





example



^{13}CO (1–0) in the L 1157 protostar (Gueth et al. 1997)

Cycle 1 12-m Array configurations

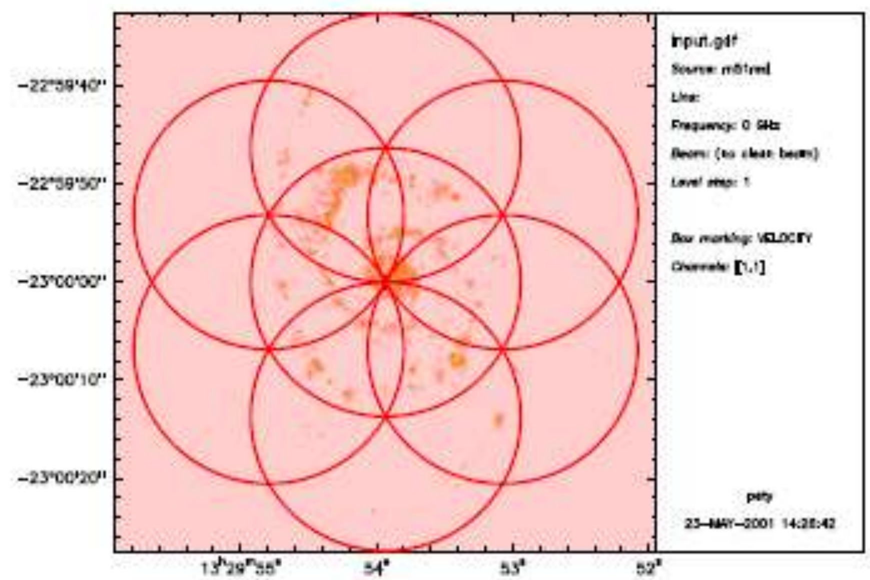
	C32-1		C32-2		C32-3		C32-4		C32-5		C32-6	
Band (freq)	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale
Band 3 (100GHz)	3.7"	25"	2.0"	25"	1.4"	17"	1.1"	17"	0.75"	14"	0.57"	8.6"
Band 6 (230GHz)	1.6"	11"	0.89"	11"	0.61"	7.6"	0.48"	7.6"	0.33"	6.2"	0.25"	3.7"
Band 7 (345GHz)	1.1"	7.1"	0.59"	7.1"	0.40"	5.0"	0.32"	5.0"	0.22"	4.1"	0.16"	2.5"
Band 9 (675GHz)	0.55"	3.6"	0.30"	3.6"	0.21"	2.6"	0.16"	2.6"	0.11"	2.1"	0.08"	1.3"

12-m Array & ACA combinations

	C32-1 & ACA 7-m Array		C32-2 & ACA 7-m Array		C32-3 & ACA 7-m Array		C32-4 & ACA 7-m Array	
Band (freq)	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale	Ang Res	Max Ang Scale
Band 3 (100 GHz)	3.7"	44"	2.0"	44"	1.4"	44"	1.1"	44"
Band 6 (230 GHz)	1.6"	19"	0.89"	19"	0.61"	19"	0.48"	19"
Band 7 (345 GHz)	1.1"	13"	0.59"	13"	0.40"	13"	0.32"	13"
Band 9 (675 GHz)	0.55"	6.5"	0.30"	6.5"	0.21"	6.5"	0.16"	6.5"

mosaicking

- field of view is limited by the antenna primary beam width => observe a mosaic of several adjacent overlapping fields
- spacing = half the primary beam FWHM
- fields are observed in a loop, each one during a few minutes → similar atmospheric conditions (noise) and similar uv coverages (dirty beam, resolution) for all fields



almascience.org

Atacama Large Millimeter/submillimeter Array
In search of our Cosmic Origins

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Welcome to the Science Portal at ESO

Overview

The Atacama Large Millimeter/submillimeter Array (ALMA) is a major new facility for world astronomy. When completed in 2013, ALMA will consist of a giant array of 12-m antennas, with baselines up to 16 km, and an additional compact array of 7-m and 12-m antennas to greatly enhance ALMA's ability to image extended targets. ALMA will be outfitted with state-of-the-art receivers that cover atmospheric windows from 84–950 GHz (3mm – 300 micron). Construction of ALMA started in 2003 and will be completed in 2013. The ALMA project is an international collaboration between Europe, East Asia and North America in cooperation with the Republic of Chile. More details can be found via the ***About ALMA*** link in the left menu.

This is the website for **The ALMA Science Portal**, served from one of the **ALMA Regional Centers (ARCs)** of the ALMA partner organizations: ESO, NRAO or NAOJ. You may switch between the different instances of the portal through the links to the appropriate ALMA partner at the top banner. Through this portal you can find details about the technical capabilities of ALMA, how to propose for observing time, and how to access ALMA data. It includes links to all official ALMA documents and tools, including those for preparing and submitting proposals and processing ALMA data. In order to access some of the tools, users must register with the project and login to the portal via the links at the top banner.

ALMA Newsletter

Newsletter No. 9
May 23, 2012

More…

General News

ALMA Early Science Cycle 1: Outcome of the Proposal Review Process
Nov 27, 2012

New release of ALMA Science Verification data
Oct 23, 2012

Announcement of intent to release a new installment of Science Verification data
Oct 16, 2012

Update on ALMA Cycle 0 observations
Oct 08, 2012

More…

Local News

Cycle 1 preparation workshops throughout

Call for ALMA proposals

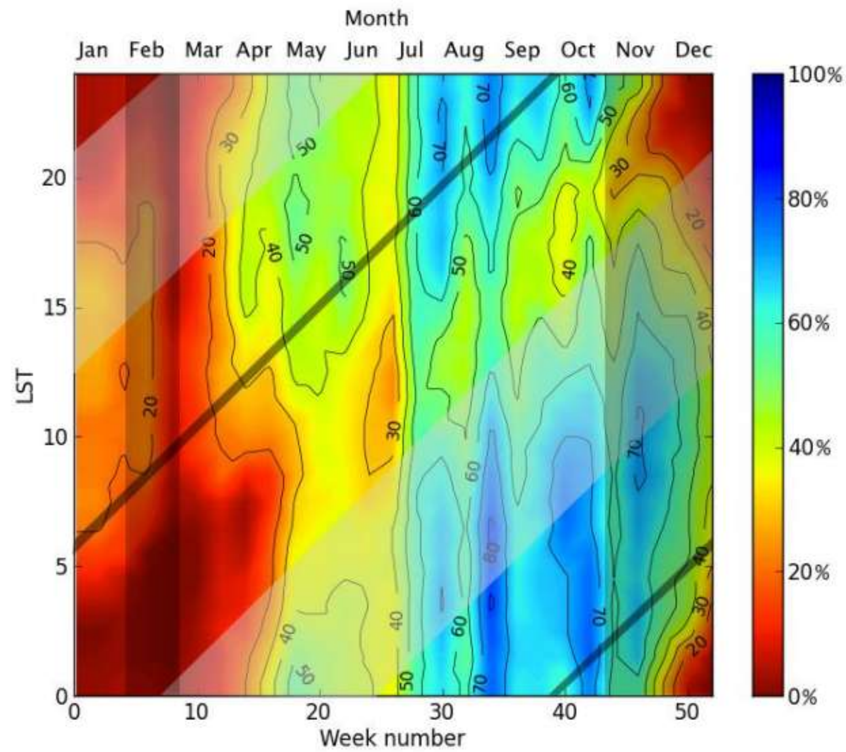
- http://almascience.eso.org/documents-and-tools
- ALMA Proposers Guide
- ALMA Technical Handbook
- Early Science Primer
- ALMA Proposal Template
- Observing Tool
- Guides to ALMA Regional Centers
- ALMA Sensitivity Calculator
- CASA
- CASA Simulator
- Splatalogue
- …

ALMA

- partnership of Europe, North America and East Asia in cooperation with the Republic of Chile
- ALMA construction and operations are led on behalf of Europe by ESO
- 66 high-precision antennas
  - 50 of these will be 12-meter dishes in the 12-m Array, used for sensitive, high-resolution imaging
  - complemented by the Atacama Compact Array (ACA) composed of 12 closely spaced 7-meter antennas (7-m Array), and four 12-meter antennas for single dish observations (Total Power Array), to enhance wide-field imaging
- At full operational capability, wavelengths covered by ALMA will range from 0.3 mm to 3.6 mm (frequency coverage of 84 GHz to 950 GHz)
- ALMA is located at latitude = 23.029°, longitude = 67.755°
- Targets as far north as declination +40° (i.e., maximum source elevation at Chajnantor of ~25°), can in principle be observed
  - shadowing by adjacent antennas becomes an increasing problem at low elevations
  - imaging capability, as well as the time on source, will also be limited for such northern sources

ALMA Proposer's Guide

- ALMA overview
- percentage of time with pwv<1mm
- Fraction of time suitable for observing in each band
- ALMA Regional centers
- ALMA Proposal Eligibility
  - 22.5% for East Asia
  - 33.75% for Europe
  - 33.75% for North America
  - 10% for Chile
- ALMA HelpDesk



ALMA Band	Band 3	Band 6	Band 7	Band 9
Fraction of time	100%	70%	40%	10%

Current observing cycle – Cycle 1

- thirty-two 12-m antennas, the Atacama Compact Array (ACA) composed of nine 7-m antennas and two 12-m antennas for single dish observations
- receiver bands 3, 6, 7 & 9 (wavelengths of about 3, 1.3, 0.8 and 0.45 mm)
- several array configurations with maximum baselines ranging from ~160 m to ~1 km
- single field imaging and mosaics of up to 150 pointings, and a set of correlator modes that will allow both continuum and spectral line observations simultaneously, as well as a mixed spectral setup mode

Current observing cycle – Cycle 1

- about 800 hours of 12-m Array time will be allocated for the highest priority Cycle 1 projects
- as much as one-third of this time will be available for observations that require both the 12-m Array
- and the ACA
- for Cycle 1 the OT allocates three times as much time on the ACA than is needed for the corresponding 12-m Array observations
- about 200 highest priority projects are expected to be prepared for scheduling
- thus the average 12-m Array observing time per proposal is likely to be about four hours (with a large range)
- only a small number of proposals requiring substantially more time than the average can be
- accepted, and these must be scientifically compelling
- maximum observing time per proposal is 100 hours
- there is no guarantee that a project will be completed.

Proposal types

- Standard
- Target of Opportunity (ToO)
  - should be used to observe targets that can be anticipated but not specified in detail
  - target list may be left unspecified, observing modes and sensitivity requests must be specified in detail
  - reaction time for its execution may be as long as 3 weeks (shorter reaction times - few days – may be possible but are not guaranteed)
- Director Discretionary Time (DDT)
  - proposals requiring the immediate observation of a sudden and unexpected astronomical event
  - proposals requesting observations on highly competitive scientific topic, motivated by developments that have taken place after the regular proposal submission deadline
  - proposals asking for follow-up observations of a program recently conducted with ALMA or any other observing facility, where a quick implementation is expected to provide breakthrough results
  - may be submitted at any time during Cycle 1
  - must be submitted using a special version of the Observing Tool
  - DDT proposals will be approved for execution by the ALMA Director,

Science categories

1. cosmology and the high redshift universe
2. galaxies and galactic nuclei
3. ISM, star formation and astrochemistry
4. circumstellar disks, exoplanets and the solar system
5. stellar evolution and the Sun

Writing a proposal

- Science case
- Technical justification
- Figures, tables and references (optional)
- A brief statement on the likely potential for publicity (e.g. images, press releases etc.) arising from the proposed scientific observations
- shall be submitted as a single PDF document written in English. The total length of this document is limited to 5 pages

Observing Tool (OT)

- Java application for preparation and submission of ALMA proposal materials
  - Phase I (observing proposal)
  - Phase II (telescope runfiles for accepted proposals)
- Webstart or manual installation
- current *Cycle 1* release configured for the Early Science Capabilities of ALMA
- In order to submit proposals you have to register with the ALMA Science Portal

ALMA full array

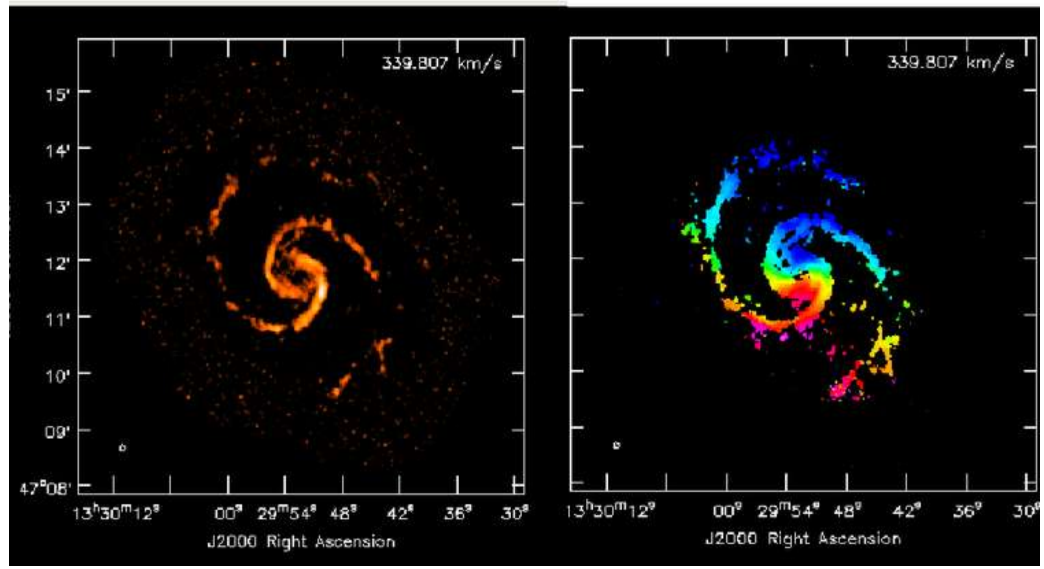
Full Science Capabilities						Most Compact		Most Extended	
Band	Frequency (GHz)	Wave-length (mm)	Primary Beam (FOV; ")	Ap-prox. Max. Scale (")	Contin-uum Sen-sitivity (mJy/ beam)	Angular Resolu-tion (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
1‡	*31.3-45*	*6.7-9.5*	*145-135*	*93*	*‡*	*13-9*	*‡*	*0.14-0.1*	*‡*
2‡	*67-90*	*3.3-4.5*	*91-68*	*53*	*‡*	*6-4.5*	*‡*	*0.07-0.05*	*‡*
3	*84-116*	*2.6-3.6*	*72-52*	*37*	*0.07*	*4.9-3.6*	*0.04*	*0.05-0.038*	*430*
4	*125-163*	*1.8-2.4*	*49-37*	*32*	*0.06*	*3.3-2.5*	*0.048*	*0.035-0.027*	*330*
5	*163-211*	*1.4-1.8*	*37-29*	*23*	*	*	*	*	*
6	*211-275*	*1.1-1.4*	*29-22*	*18*	*0.09*	*2.0-1.5*	*0.05*	*0.021-0.016*	*490*
7	*275-373*	*0.8-1.1*	*22-16*	*12*	*0.15*	*1.5-1.1*	*0.08*	*0.016-0.012*	*814*
8	*385-500*	*0.6-0.8*	*16-12*	*9*	*0.40*	*1.07-0.82*	*0.28*	*0.011-0.009*	*1900*
9	*602-720*	*0.4-0.5*	*10-8.5*	*6*	*1.4*	*0.68-0.57*	*0.9*	*0.007-0.006*	*8900*
10	*787-950*	*0.3-0.4*	*7.7-6.4*	*5*	*1.2*	*0.52-0.43*	*1.6*	*0.006-0.005*	—

CASA

- casa.nrao.edu
- CASA = *Common Astronomy Software Applications* package
- data post-processing needs of the next generation of radio astronomical telescopes such as ALMA and EVLA
- Can process both interferometric and single dish data
- The CASA infrastructure consists of a set of C++ tools bundled together under an iPython interface as a set of data reduction tasks.
- This structure provides flexibility to process the data via task interface or as a python script. In addition to the data reduction tasks, many post-processing tools are available for even more flexibility and special purpose reduction needs.
- The latest CASA release is 4.0.0

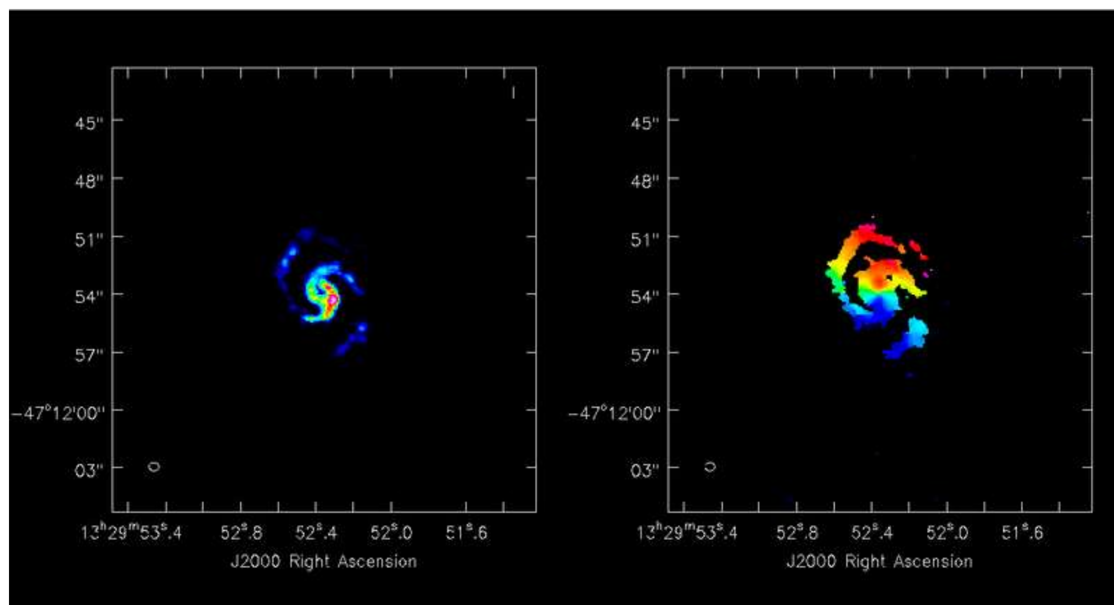
CASA Simulator

M51 in CO(1-0) located at 9Mpc



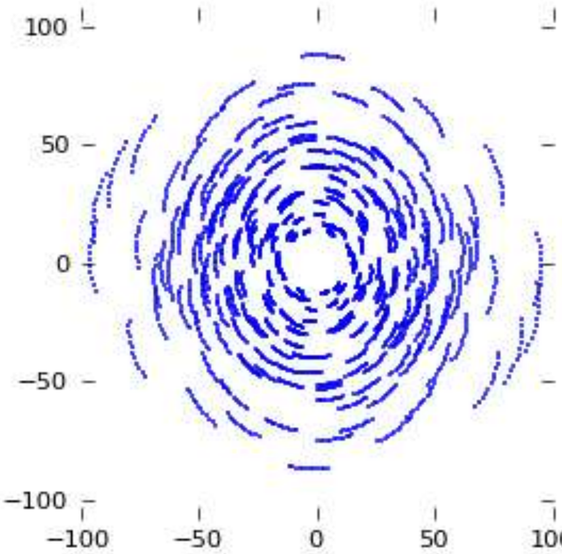
Tasks simobserve() and
simanalyze()

model at z=0.1 (460Mpc)
- noise in the model
- sky coordinates
- flux density scaling
- angular size scaling
- map size, mosaicking
- integration, total time
- array configuation

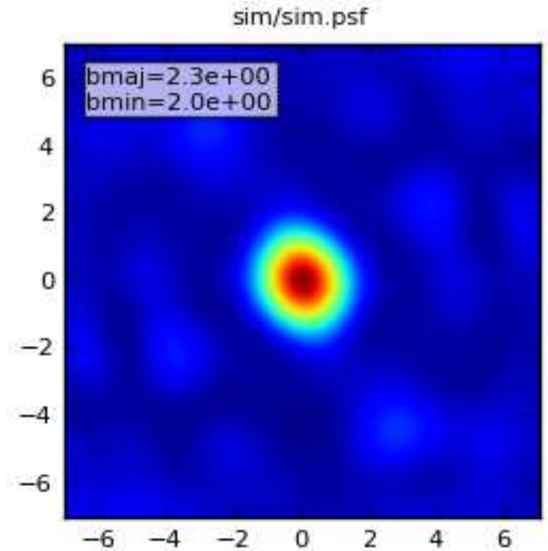


CASA simulator (30 Doradus)

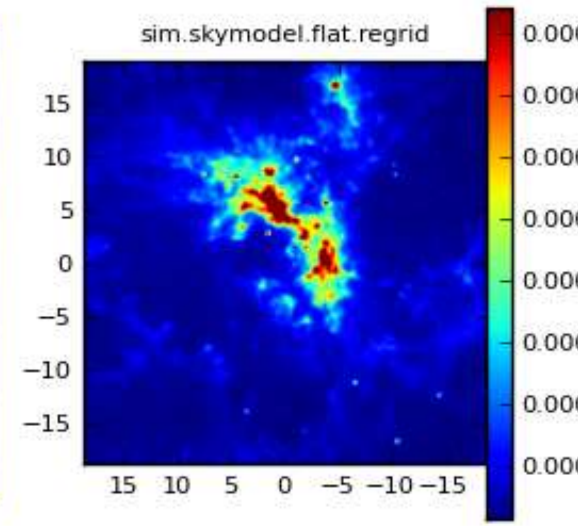
uv coverage



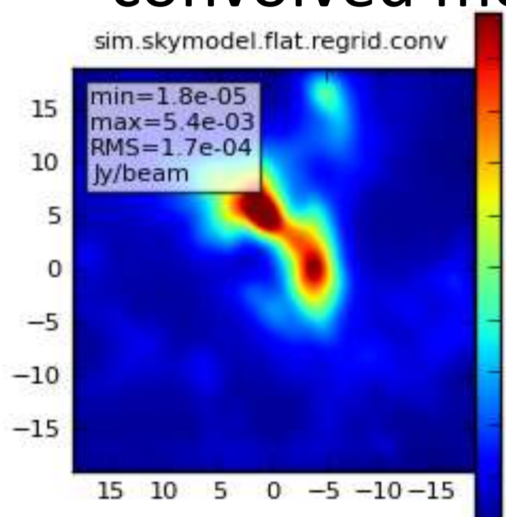
dirty beam



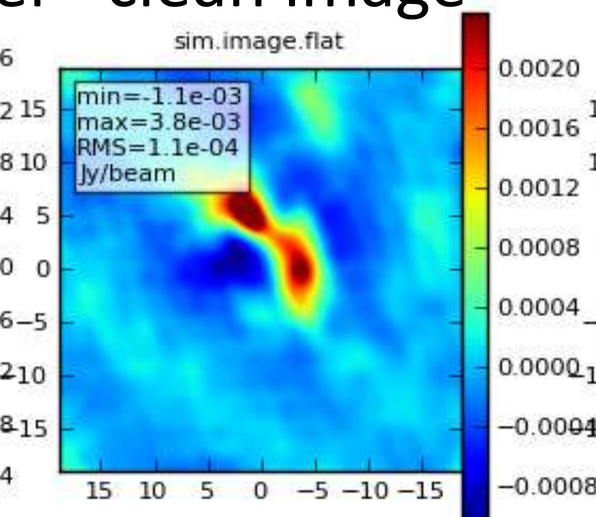
sky model



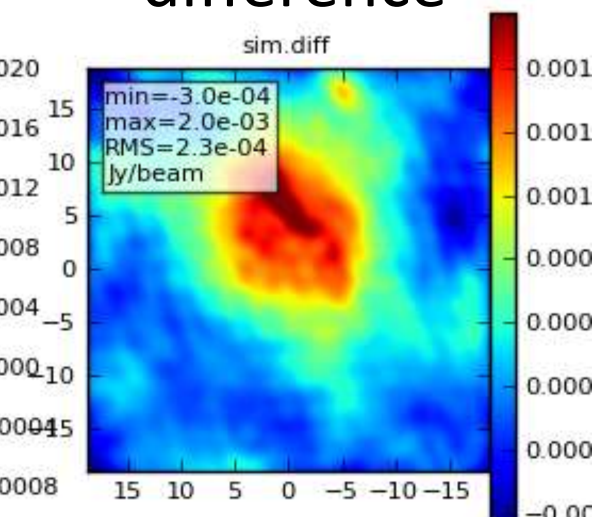
convolved model



clean image



difference



Proposal submission

Before you propose

- Target and Science motivation
- Observing strategy:
  - Single integration
  - Mosaic
  - Continuum
  - Spectral lines
- Is there any existing mm/sub-mm observation?
- Frequency, bandwidth, velocity resolution
- Desired spatial resolution and largest angular scale (use of ACA?)
- Sensitivity needed etc.
- is uv-coverage important for you?
- Find out more about actual cycle capabilities

Technical case

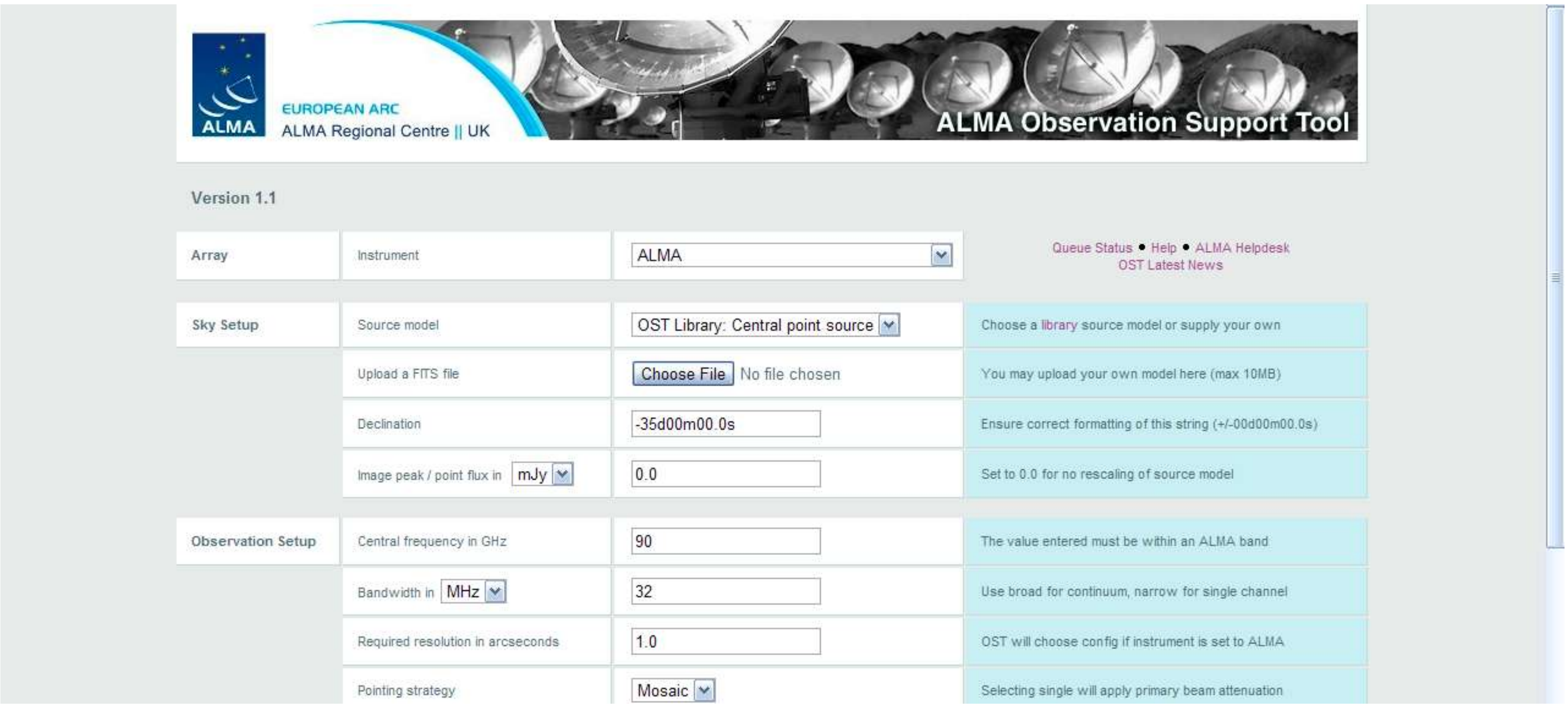
- Receiver Band(s) – spectral line or continuum?
- Angular resolution – configuration (compact/extended)
  - “*The desired angular resolution of 2.3" is by a factor of 10 better than that of previous observations.*”
- number of pointings (mosaic?)
- correlator mode – spectral resolution
  - e.g., “*correlator mode 7 provides 1.875GHz x 2basebands = 3.75GHz of spectral bandwidth in each sideband with 488kHz channels (976kHz resolution).*”
- spectral resolution
  - “*the very high spectral resolution of this correlator mode is not necessary for our science goal so we will smooth to 10km/s channels…*”
- number of spectral windows
  - e.g., “*four spectral windows will be set, one centered on the CO line in the USB and three covering basically the remainder of the full width of the sidebands. The line-free parts of the bandwidth will be used for mapping continuum*”
- desired rms + required time
  - “*this translates to a sensitivity goal of 5.8mJy per channel…*”

ALMA sensitivity calculator

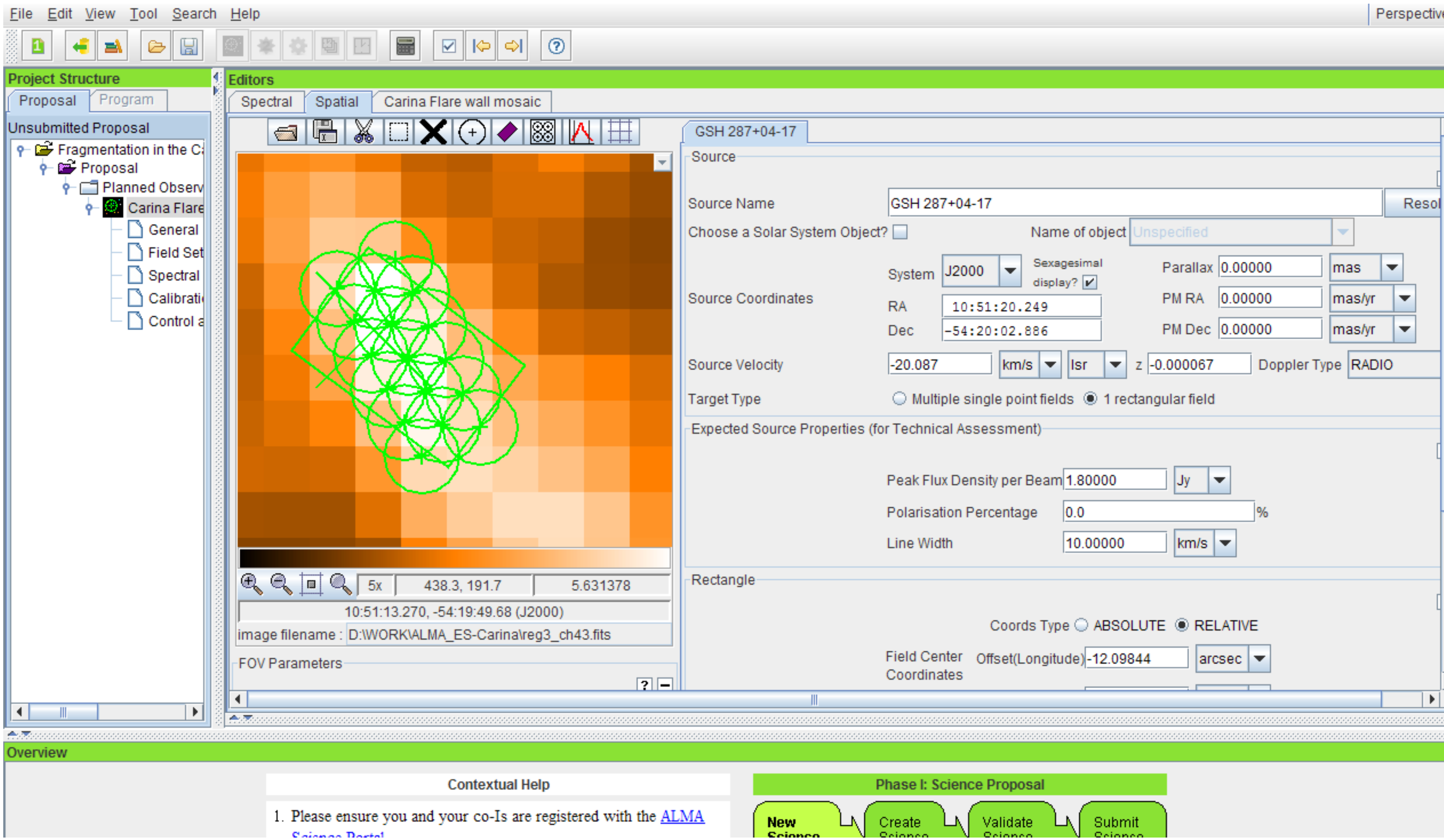
- radiometric formula: $\Delta S \propto \frac{T_{sys}}{D^2[n_p N(N-1)\Delta\nu\Delta t]^{1/2}} \mathrm{Wm^{-2}Hz^{-1}}$
  - *"Using the ALMA sensitivity calculator, for 16 antennas in compact configuration with 2.3" angular resolution and 13 mK rms per 10 km/s frequency channels, the required observing time per pointing is about 14 min. For the whole mosaic of 17 points the on-source time is about 4 hrs which yields the total required time of 5 hrs, including all overheads. The total integration time ensures a sufficient uv-coverage."*
- almascience.eso.org/call-for-proposals/sensitivity-calculator

ALMA simulators

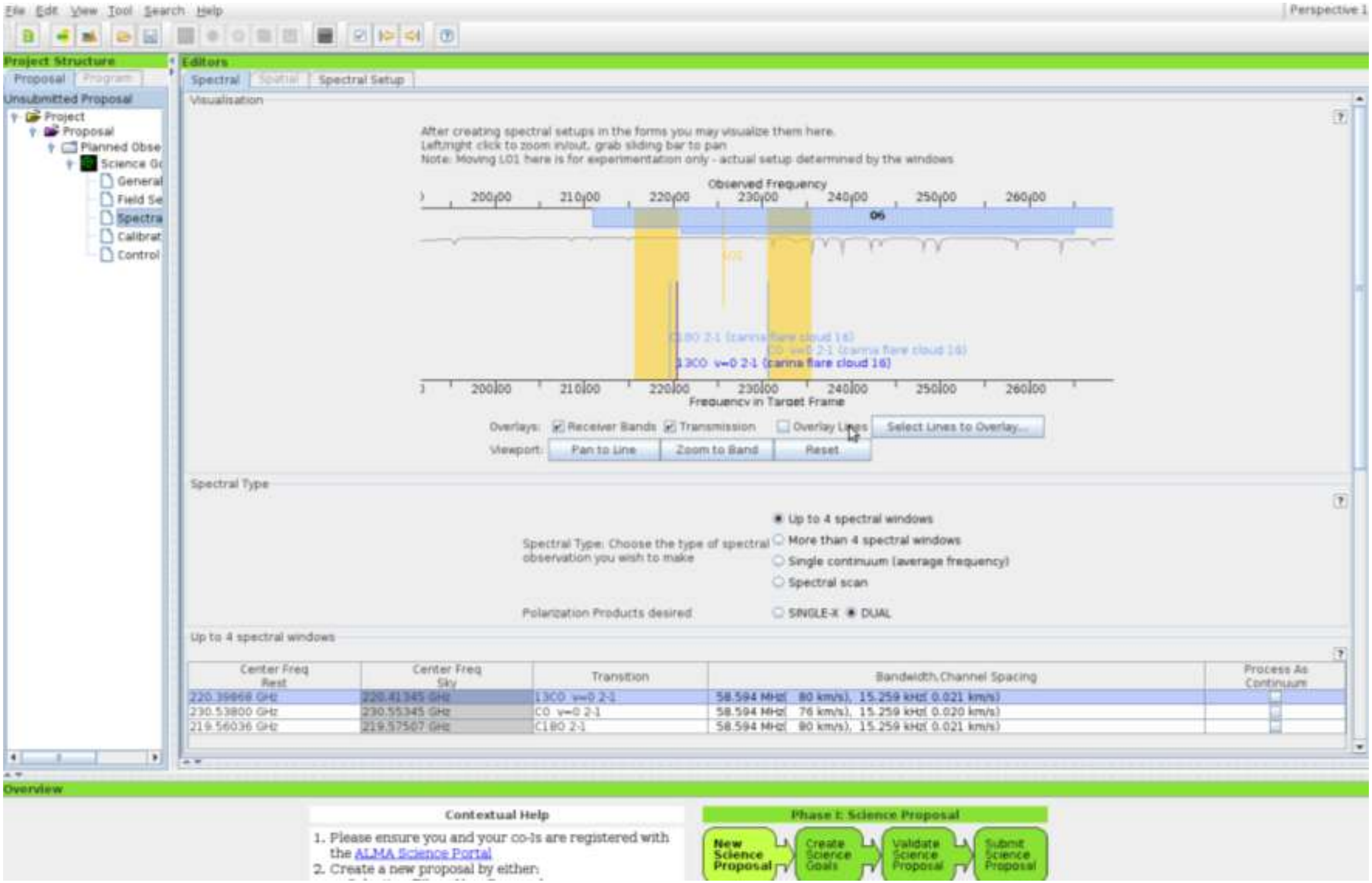
- http://almaost.jb.man.ac.uk/ (http://almaost.jb.man.ac.uk/beta)
- new tasks in CASA 3.3: sim_observe & sim_analyze



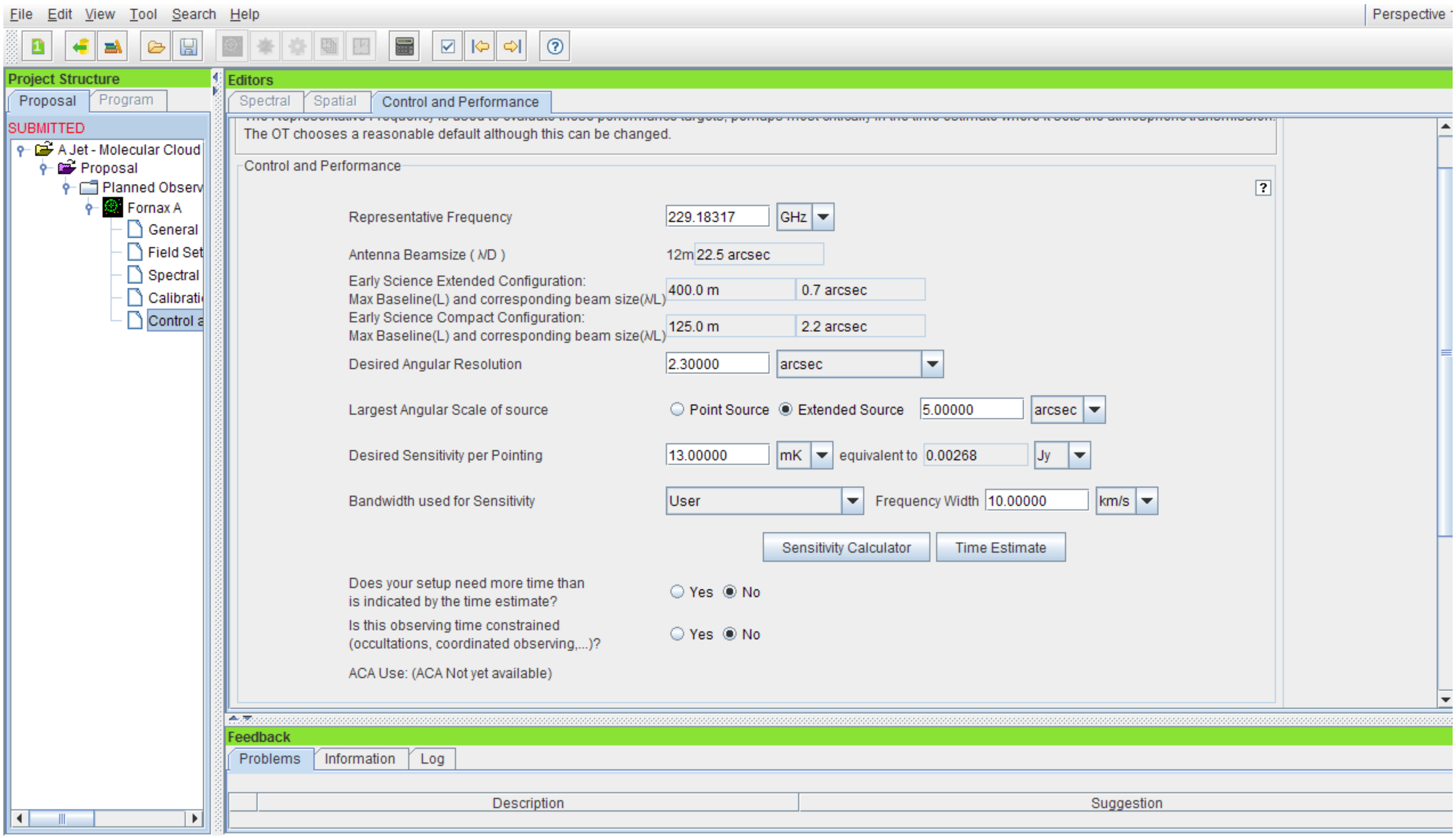
Spatial setup



Spectral setup



Control and performance



Once submitted

Congratulations!

Your project has been successfully submitted.

PI Name	Your name
Project Name	Your project name
Project Code	2011.0.00427.S
Date Submitted	2011-06-29 23:14:37 GMT
Internal Project ID	uid://A001/X3b/Xab1

Your ALMA Cycle 0 Proposal 2011.0.00XXX.S

- Dear Dr. XY,

  The ALMA Early Science Cycle 0 Proposal Review Process has now been completed. The demand for ALMA in its first ever period of scientific observing is extraordinarily high. The quality of the proposals is excellent, as is the breadth of science represented.

  The assessments have been carried out by fifty independent scientists from all over the world through a unified process coordinated by the Joint ALMAObservatory. The number of proposals submitted exceeds the number likely to be executed by a factor of about nine. It follows that many very good projects will not be observed. PIs are being informed that their proposals are either: of the highest priority to be observed; a filler project which will be observed only if the conditions do not allow any higher priority project to be executed; very unlikely to be observed; or technically infeasible.

  Following its scientific assessment by the ALMA Proposal Review Committee (see below), your ALMA proposal

  2011.0.00XXX.S was ranked in the 40-70%/10-20% band of all submitted proposals, and in the 40-70%/10-20% band of the proposals submitted by PIs from Europe.

  Ranking information is provided in the following bands: Top 10%, 10-20%, 20-40%, 40-70%, bottom 30%;

  relative to the global pool, which indicates the assessed scientific value in the context of all the proposals. When relevant, the same information is provided for your regional pool, which determines the likelihood that yourproject will be observed since ALMA time will be apportioned as follows: 33.75% for Europe, 33.75% for North America, 22.5% for East Asia and 10%for Chile. Proposals from other regions are considered solely according to their scientific assessment.

  As a result of its ranking, your project is very unlikely to be observed.

Your ALMA Cycle 0 Proposal 2011.0.00XXX.S

- The following comments on your proposal from the assessors are intended to provide you with constructive feedback. We hope that the comments arehelpful.
  - This proposal identifies an interesting region to study …
  - however at the distance to the Carina Flare, the resolution at 3mm will not be adequate to resolve the smallest clumps.
  - The proposal would have been much stronger if it had contained a simulation demonstrating how the short integrations will sample the relevant spatial scales,
  - … a discussion of how the data will be compared to the models and a better explanation of how the model parameter scan be constrained.
  - The proposal is well written, and motivates the choice of target and the importance for studying…
  - There is a large amount of ancillary data, and the proposal describes very well the previous work
  - Nevertheless, the proposal would have been strengthened by a discussion of the specific scientific aims and choice of transition (why CO(2-1) was chosen over other CO lines).
  - There was also some concern that 5 arcsec was an underestimate of the source size.
  - Technically, the use of a sub-Nyquist sampling in the proposed mosaic is not sufficiently justified