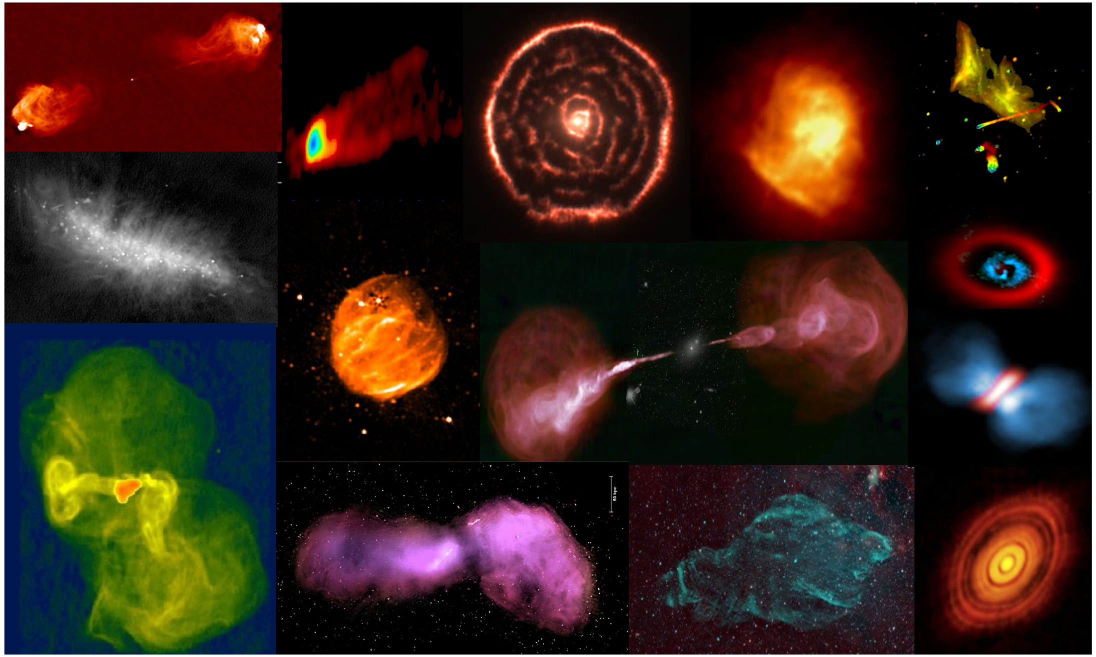
Introduction to Radio Astronomy (for Medical Imaging Professionals)



Urvashi Rau
National Radio Astronomy Observatory, Socorro, NM, USA

From Cells to Galaxies (13 October 2021)

Outline

- Images in radio astronomy

- Imaging with a radio interferometer
  - Image formation
  - The forward and inverse problems

- Current limits and future trends

Images in Radio Astronomy

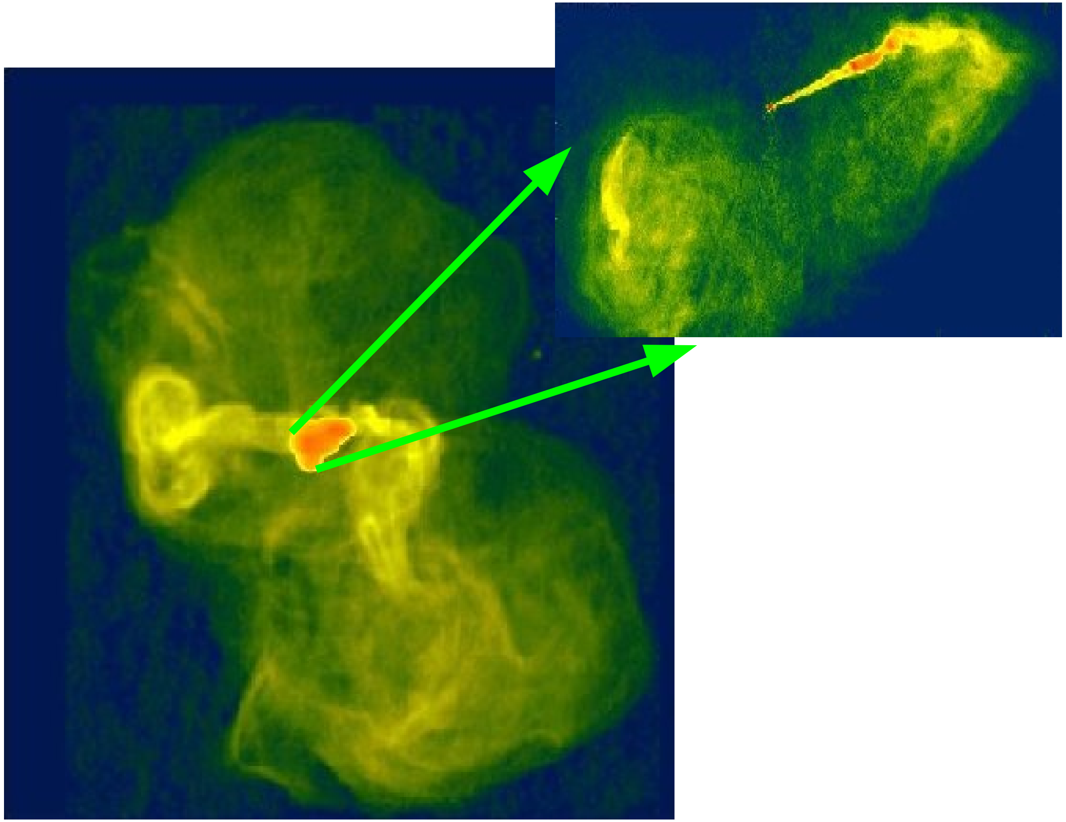
Flux Density : $\frac{10^{-26} W}{m^2 \, Hz \, Beam} = \frac{Jy}{Beam}$

Image pixel value

Images in Radio Astronomy

Flux Density : $\frac{10^{-26} W}{m^2\, Hz\, Beam} = \frac{Jy}{Beam}$

- Spatial Structure



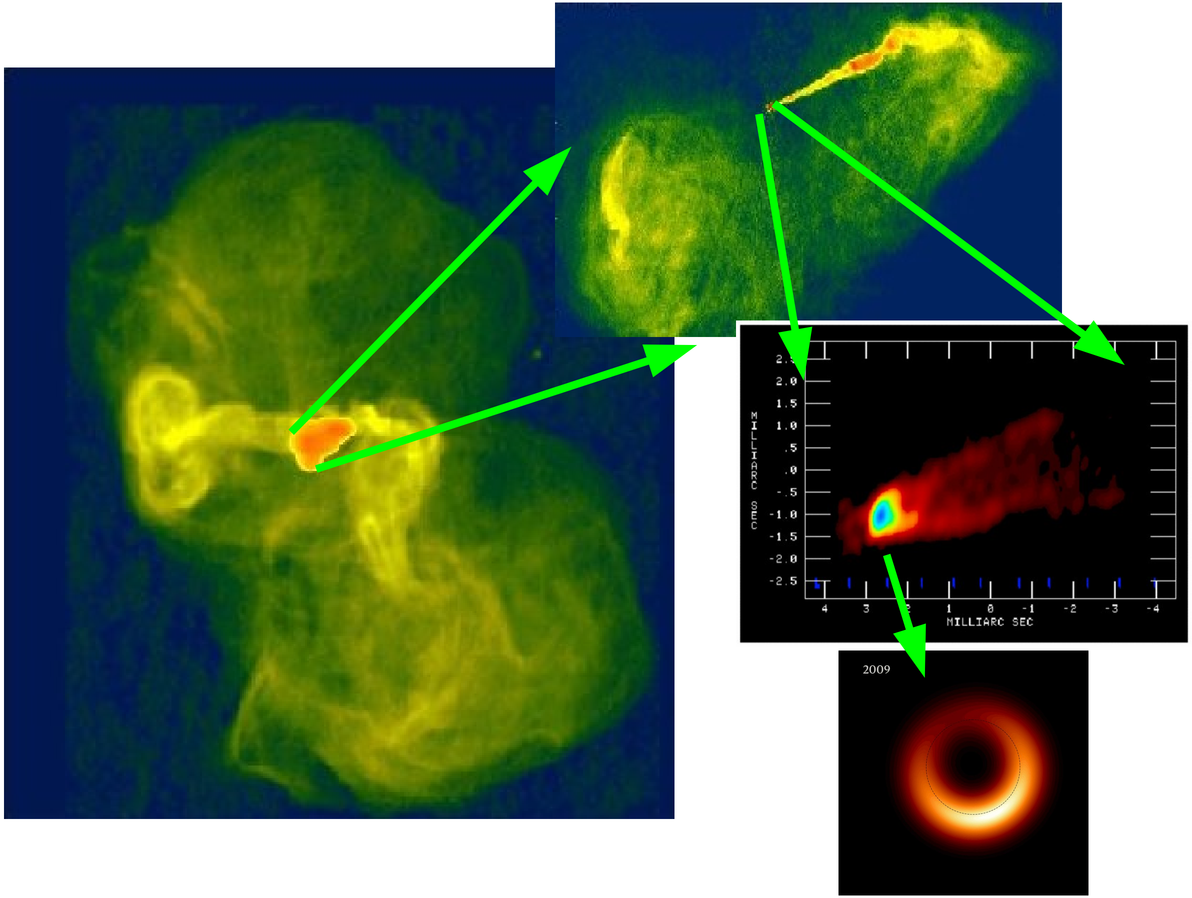
The M87 Radio Galaxy

Images in Radio Astronomy

Flux Density : $\frac{10^{-26} W}{m^2 \, Hz \, Beam} = \frac{Jy}{Beam}$

- Spatial Structure

- Time Variability

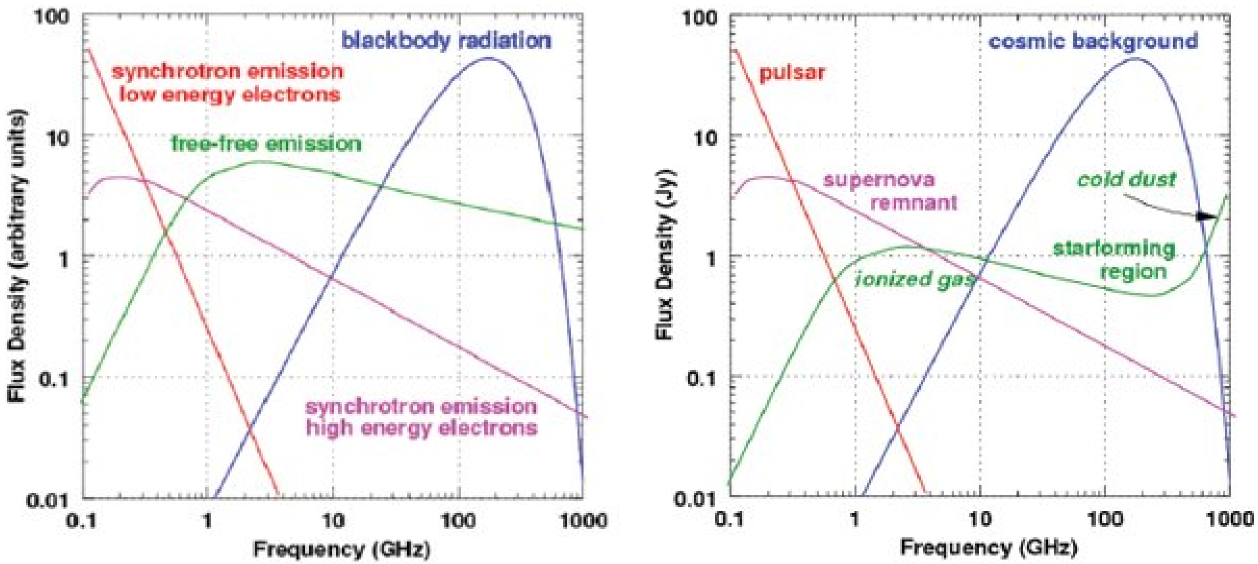


The M87 Radio Galaxy

Images in Radio Astronomy

Flux Density : $\frac{10^{-26} W}{m^2\, Hz\, Beam} = \frac{Jy}{Beam}$

- Spatial Structure
- Time Variability
- Spectral Structure
  - Continuum Emission



Continuum Spectrum :

- Energetics, Temperature
- Emission mechanism

Images in Radio Astronomy

Flux Density : $\dfrac{10^{-26} W}{m^2\, Hz\, Beam} = \dfrac{Jy}{Beam}$

- Spatial Structure
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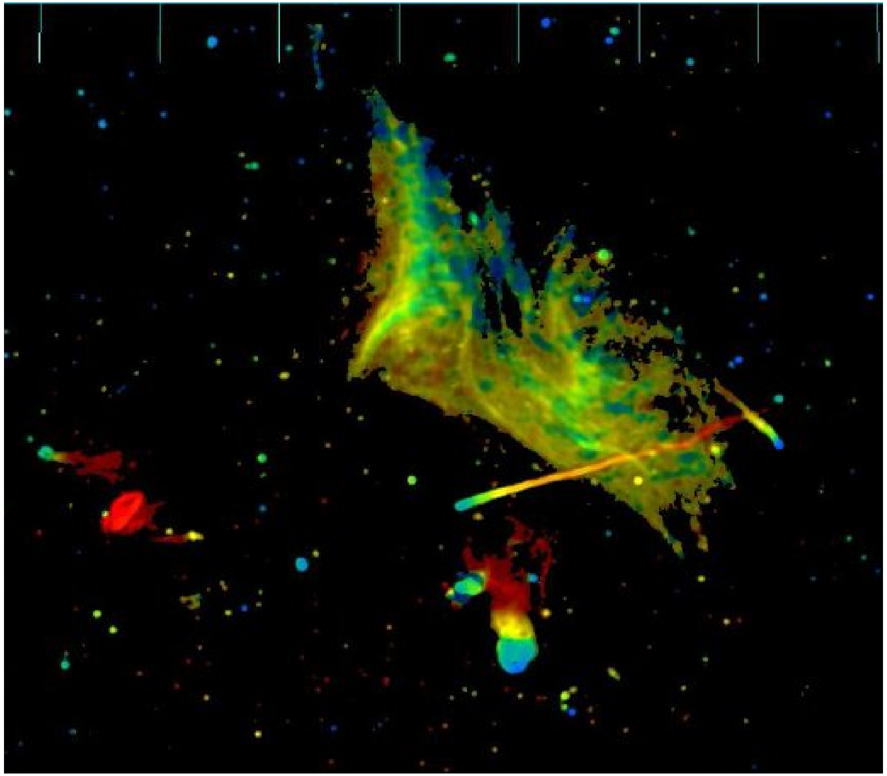


VLA Image of the synchrotron spectral slope in Abell 2256, a galaxy cluster radio relic

(credits : F.Owen, NRAO)

Images in Radio Astronomy

Flux Density : $\frac{10^{-26} W}{m^2\, Hz\, Beam} = \frac{Jy}{Beam}$

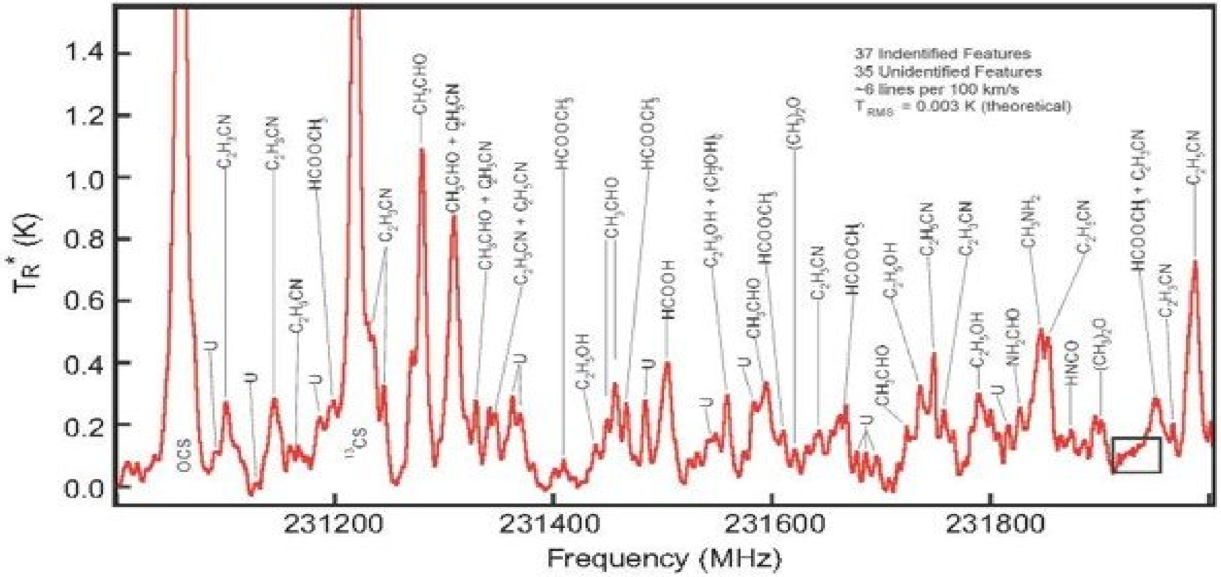
- Spatial Structure

- Time Variability

- Spectral Structure

  - Continuum Emission

  - Spectral Lines



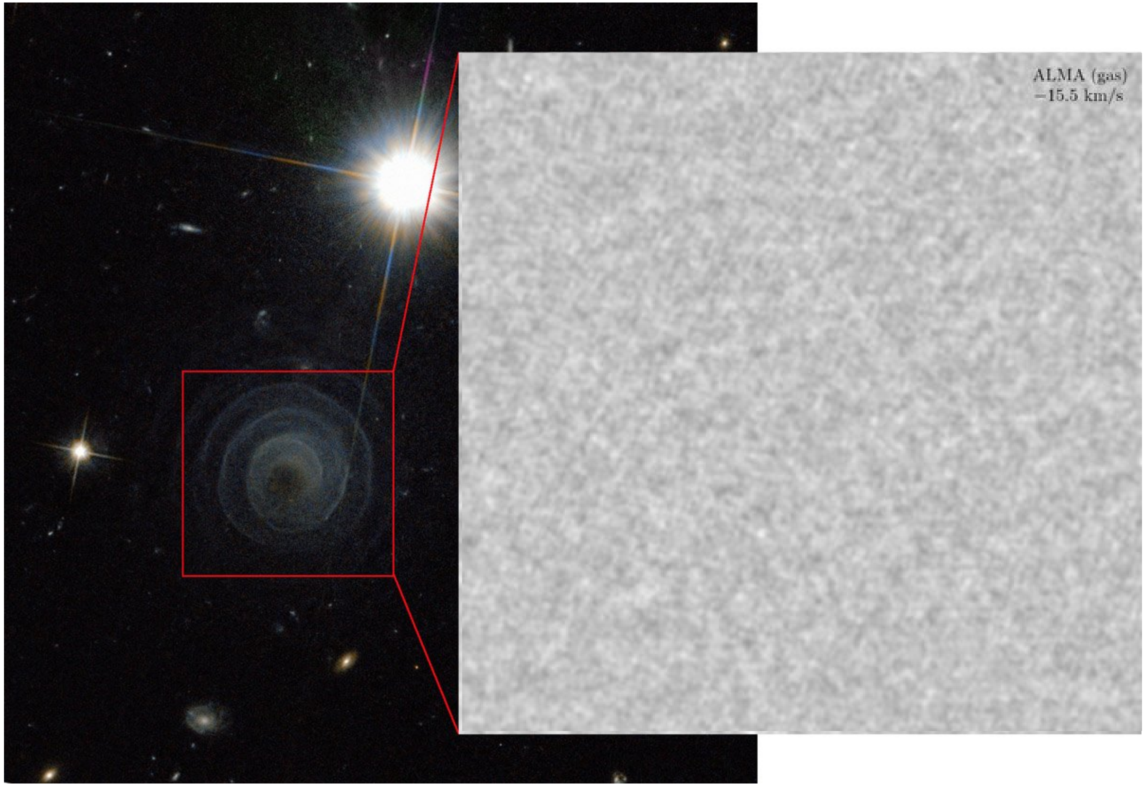
Spectral Lines :

- Astro-Chemistry
- Doppler shifts → 3D structure

Images in Radio Astronomy

Flux Density : $\frac{10^{-26} W}{m^2\, Hz\, Beam} = \frac{Jy}{Beam}$

- Spatial Structure
- Time Variability
- Spectral Structure
    - Continuum Emission
    - Spectral Lines



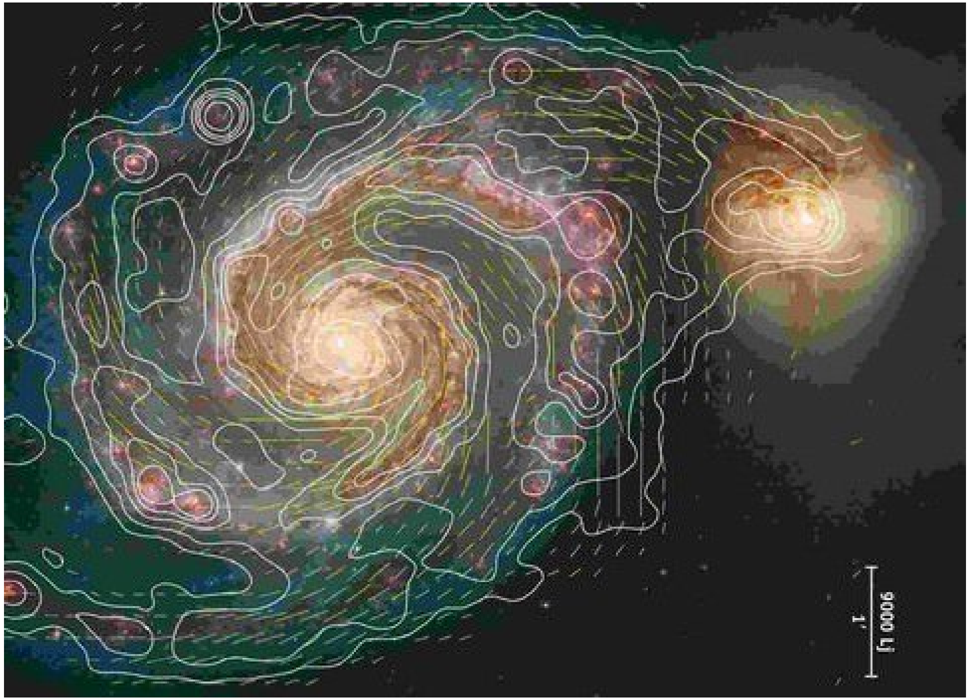
ALMA image of CO emission from the molecular shell around the AGB star LL Pegasi and its stellar companion

(Kim et al, Nature Astro 2017.)

Images in Radio Astronomy

Flux Density : $\dfrac{10^{-26}W}{m^2\,Hz\,Beam} = \dfrac{Jy}{Beam}$

- Spatial Structure
- Time Variability
- Spectral Structure
    - Continuum Emission
    - Spectral Lines
- Polarization (Stokes)



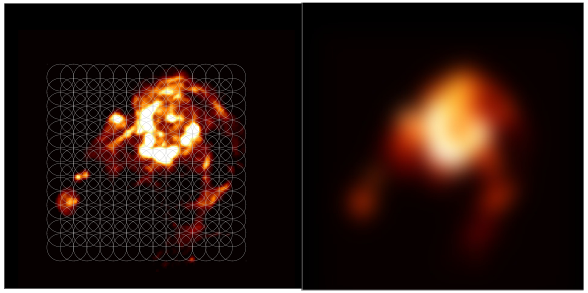
Magnetic Field direction in the Whirlpool Spiral Galaxy.

Imaging Instruments in Radio Astronomy

Imaging Instruments in Radio Astronomy

Single Dish

Image : Raster Scan on the Sky



Imaging Instruments in Radio Astronomy

Single Dish

Interferometer

Image : Raster Scan on the Sky

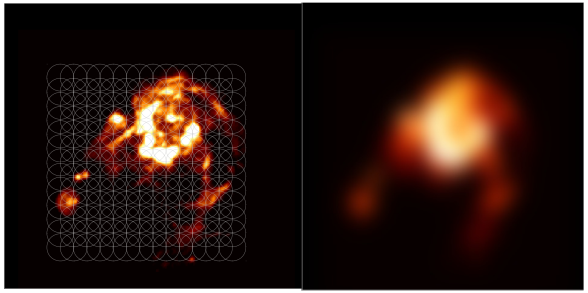
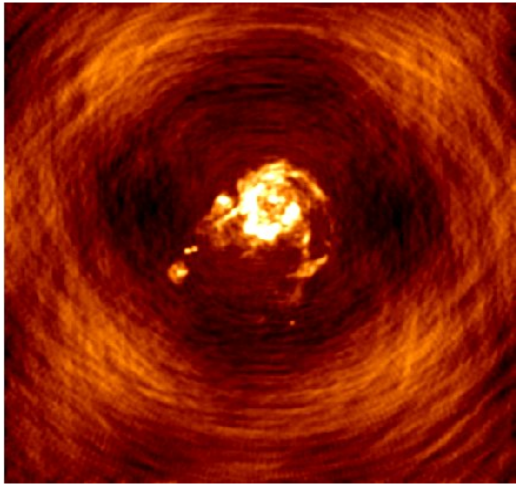


Image : iFFT of partially sampled
spatial frequency domain



Imaging Instruments in Radio Astronomy

Single Dish

Interferometer

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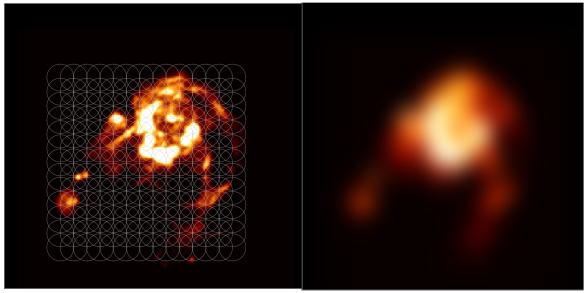

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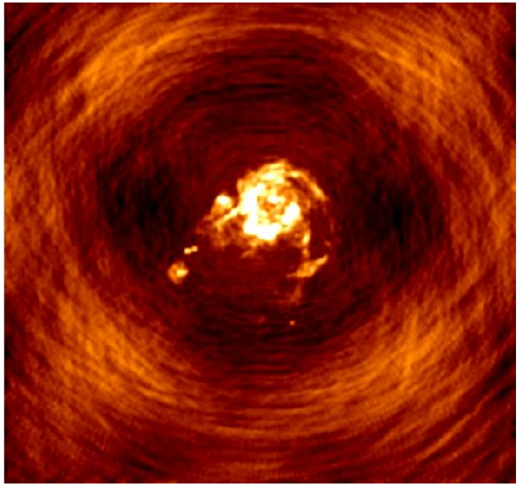


Single Dish + Interferometer

Mosaics :

- Single pixel/beam feeds
- Phased-Array Feeds

Tomography :

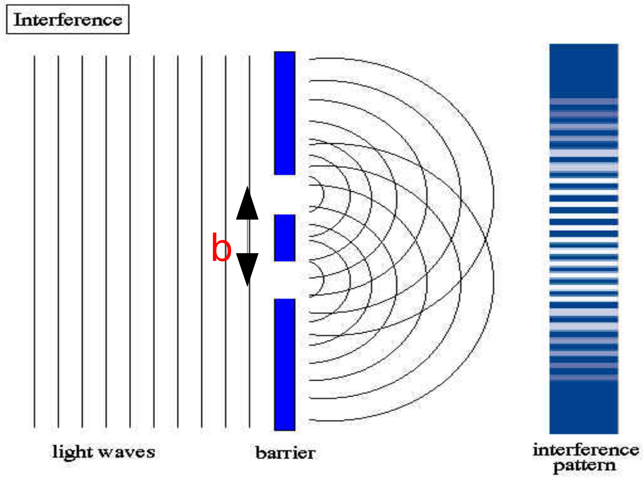
- e.g. Make images of a planet's emission region as it rotates

Outline

- – Images in radio astronomy
- – Imaging with a radio interferometer
  - – Image formation
  - – The forward and inverse problems
- – Current limits and future trends

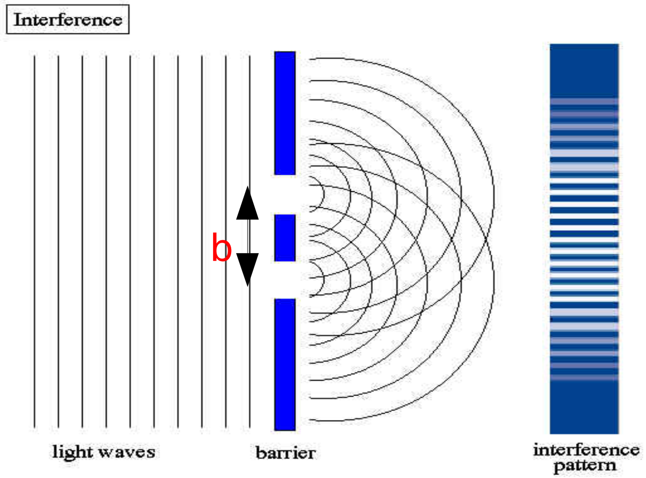
An indirect imaging device

Young's double slit experiment



An indirect imaging device

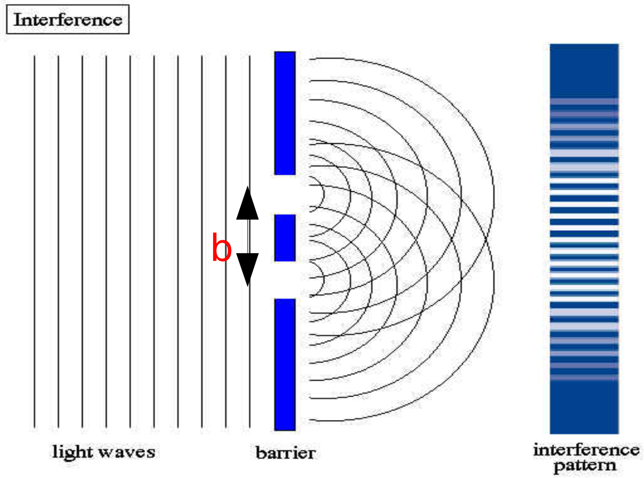
Young’s double slit experiment



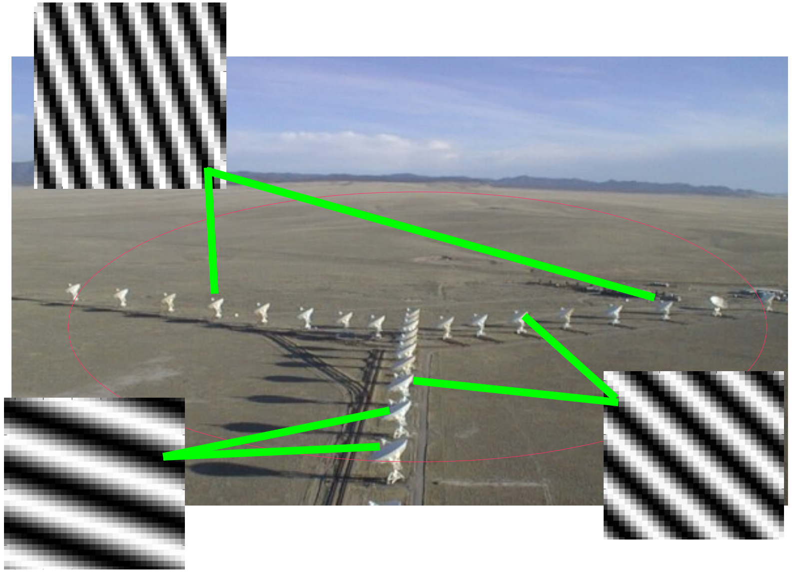
Instrument : An array of detectors

An indirect imaging device

Young’s double slit experiment



Each antenna-pair measures the parameters of one 'fringe'.

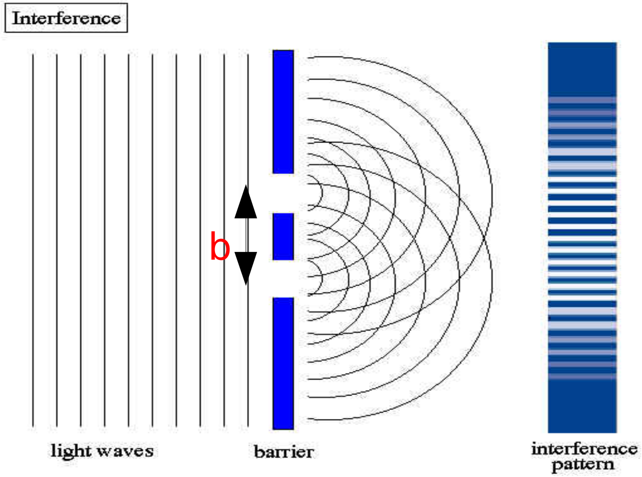


Measured Fringe Parameters :

Amplitude, Phase
Orientation, Wavelength

An indirect imaging device

Young’s double slit experiment



2D Fourier transform :

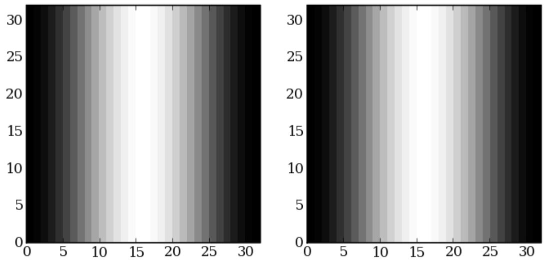
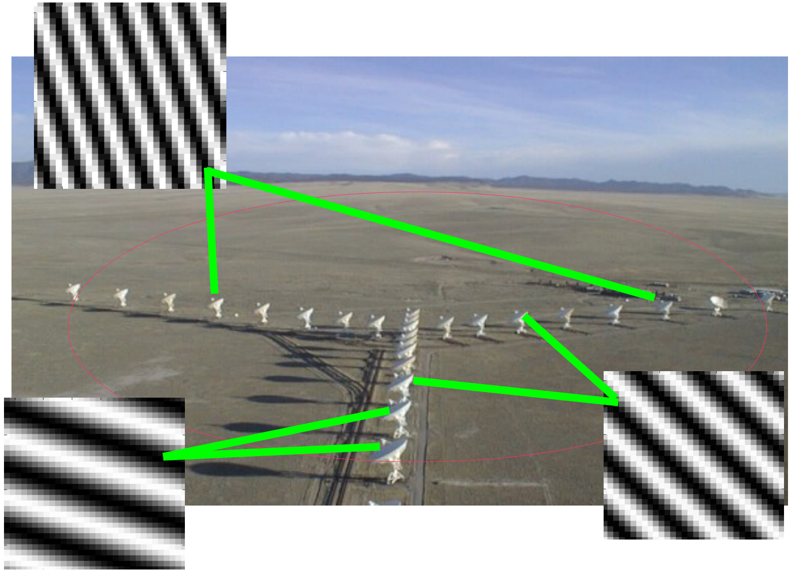


Image = sum of cosine 'fringes'.

Each antenna-pair measures the parameters of one 'fringe'.

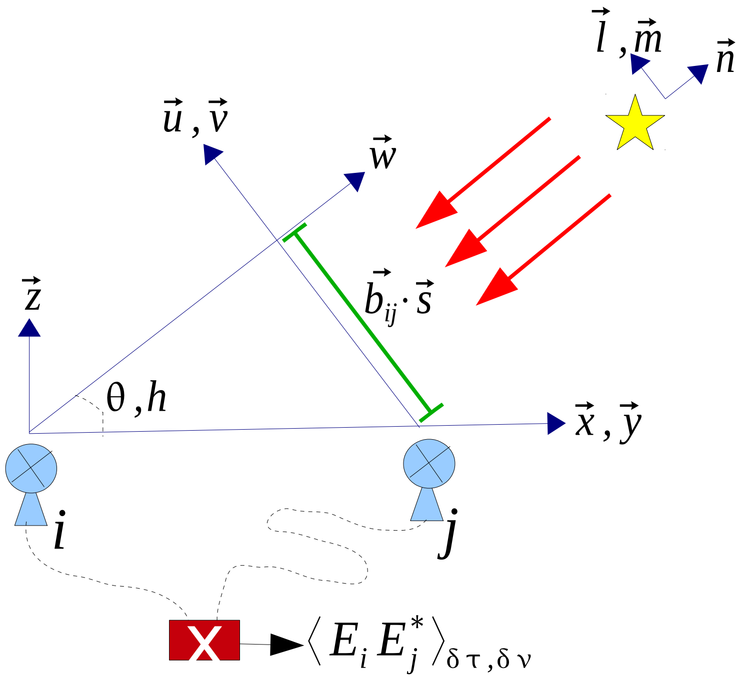


Measured Fringe Parameters :

Amplitude, Phase
Orientation, Wavelength

Measuring the visibility function

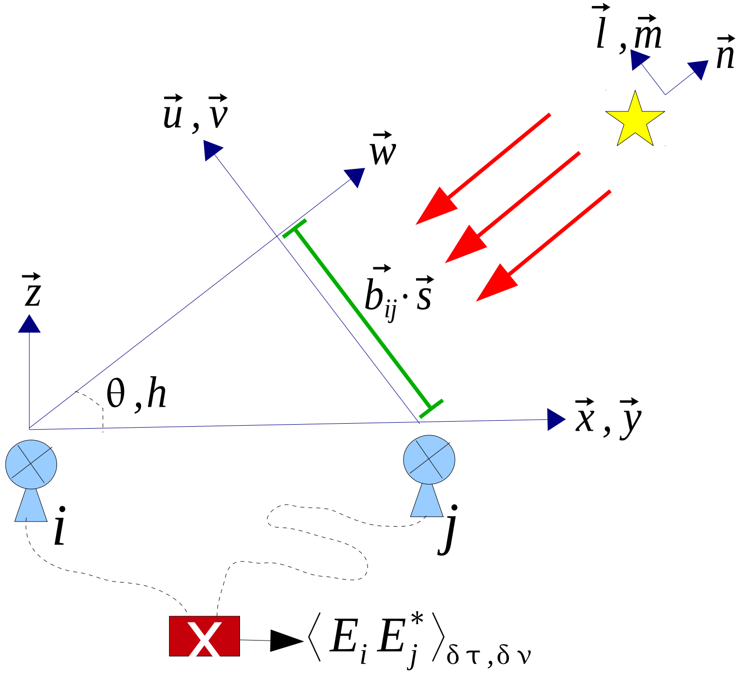
Measure the spatial correlation of the E-field
incident at each pair of antennas



N antennas
N(N-1)/2 antenna-pairs (baselines)

Measuring the visibility function

Measure the spatial correlation of the E-field incident at each pair of antennas



N antennas
N(N-1)/2 antenna-pairs (baselines)

Parameters of a Fringe :

Amplitude, Phase :

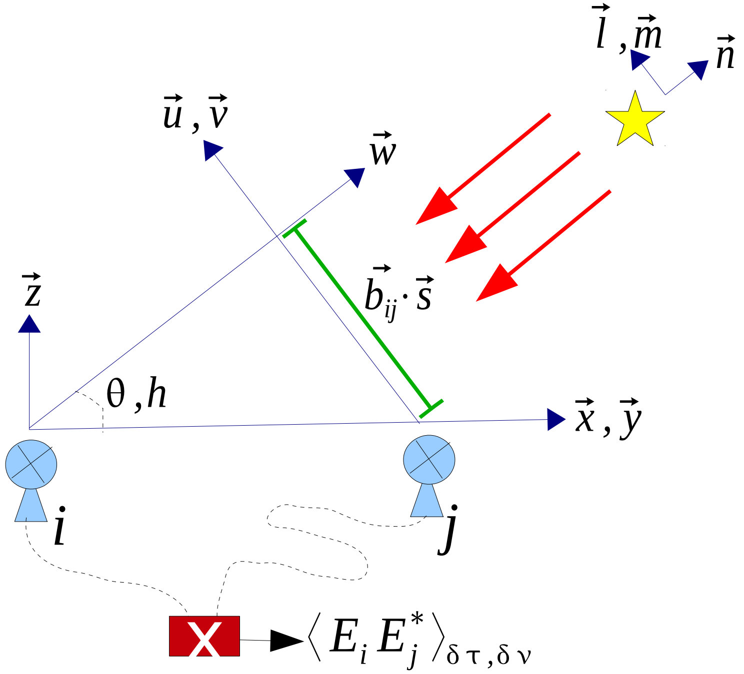
$\langle E_i E_j^* \rangle$ is a complex number.

Orientation, Wavelength :

$\vec{u}, \vec{v}, \vec{b}$ (geometry)

Measuring the visibility function

Measure the spatial correlation of the E-field incident at each pair of antennas



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Parameters of a Fringe :

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$\langle E_i E_j^* \rangle$ is a complex number.

Orientation, Wavelength :

$\vec{u}, \vec{v}, \vec{b}$ (geometry)

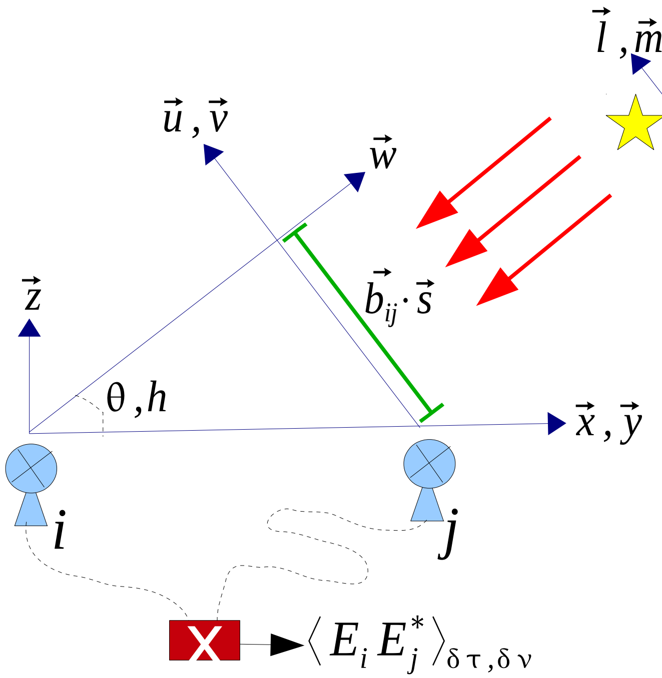
Van Cittert Zernicke theorem (far-field)

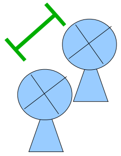
$$\langle E_i E_j^* \rangle \propto V_{ij}(u,v) = \iint I^{sky}(l,m) e^{2\pi i (ul+vm)} dl dm$$

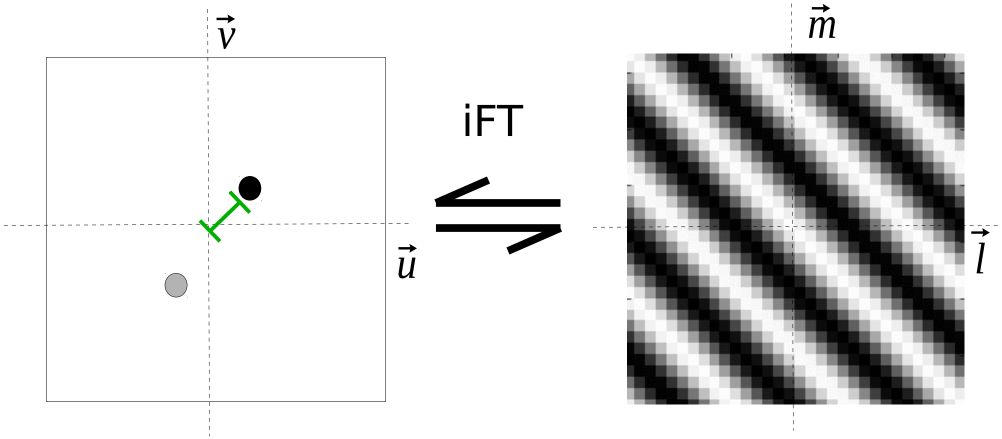
General Form : $V(\vec{b}_{ij}) = \iiint I^{sky}(\vec{s}) e^{2\pi i (\vec{b}_{ij} \cdot \vec{s})} d^3\vec{s}$

Visibilities on the UV plane

Measure the spatial correlation of the E-field incident at each pair of antennas







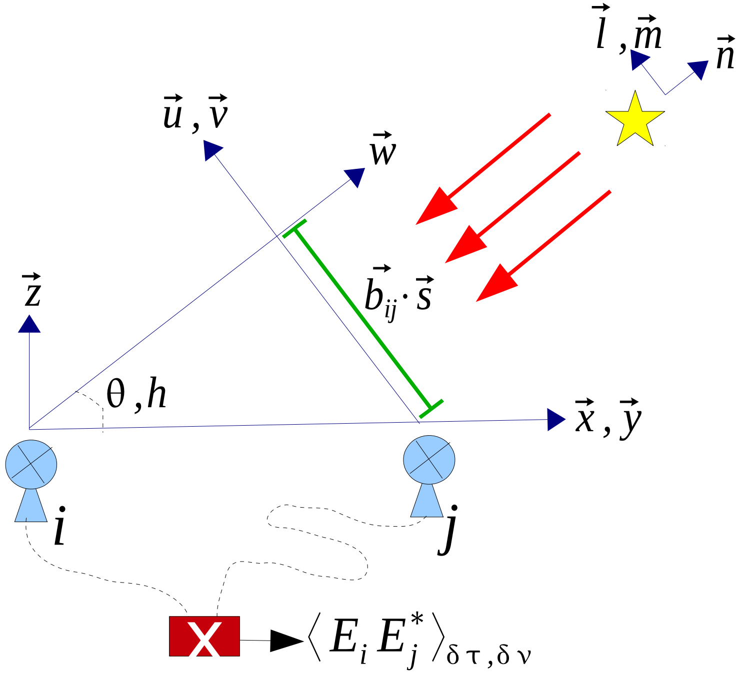
UV domain (spatial frequency)

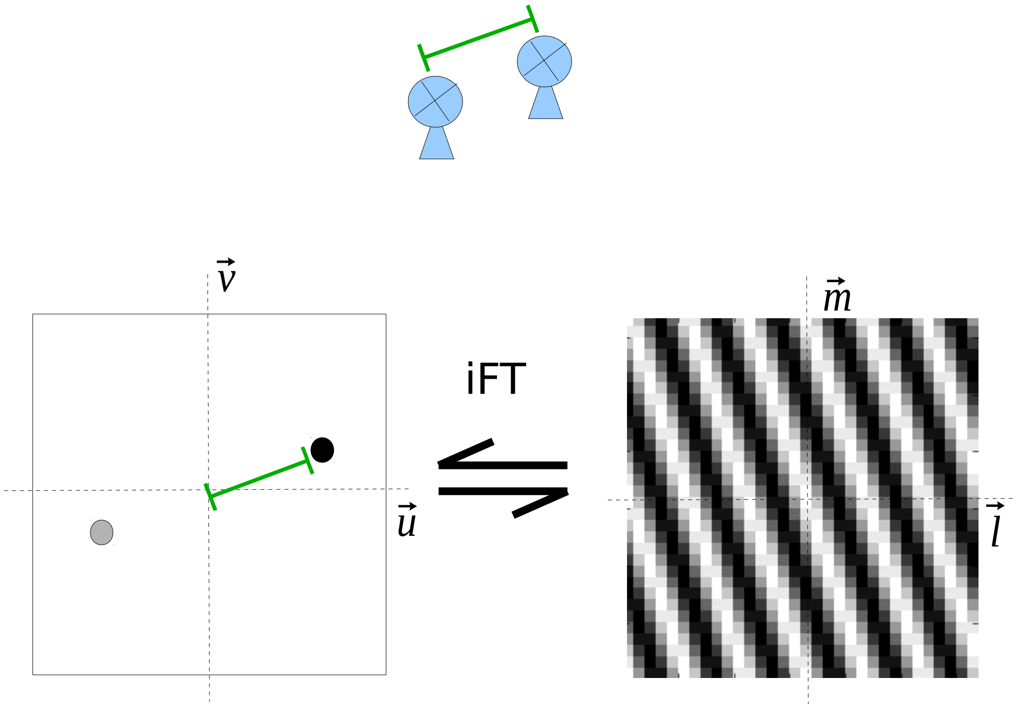
Image domain (directions on sky)

N antennas
N(N-1)/2 antenna-pairs (baselines)

Visibilities on the UV plane

Measure the spatial correlation of the E-field incident at each pair of antennas



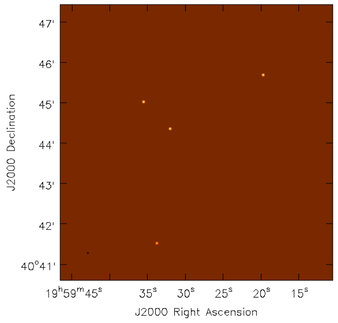


UV domain
(spatial frequency)

Image domain
(directions on sky)

N antennas
N(N-1)/2 antenna-pairs (baselines)

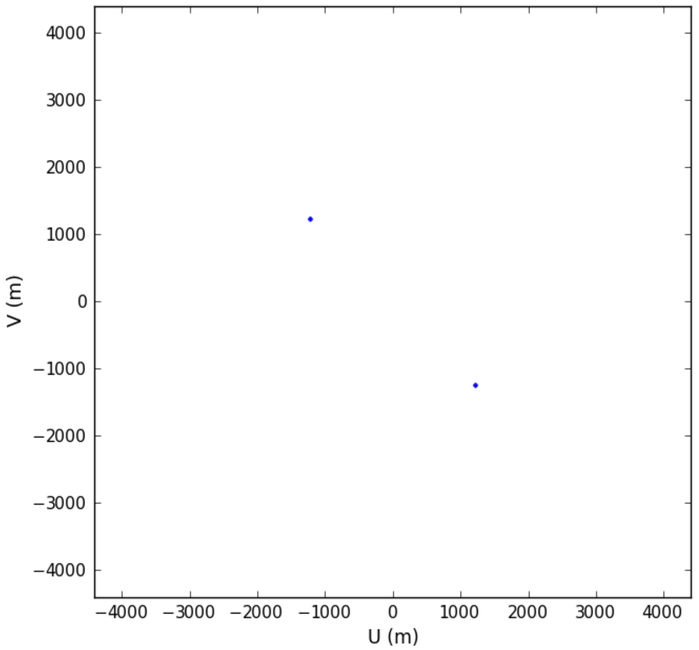
Spatial Frequency (uv) coverage + Observed Image



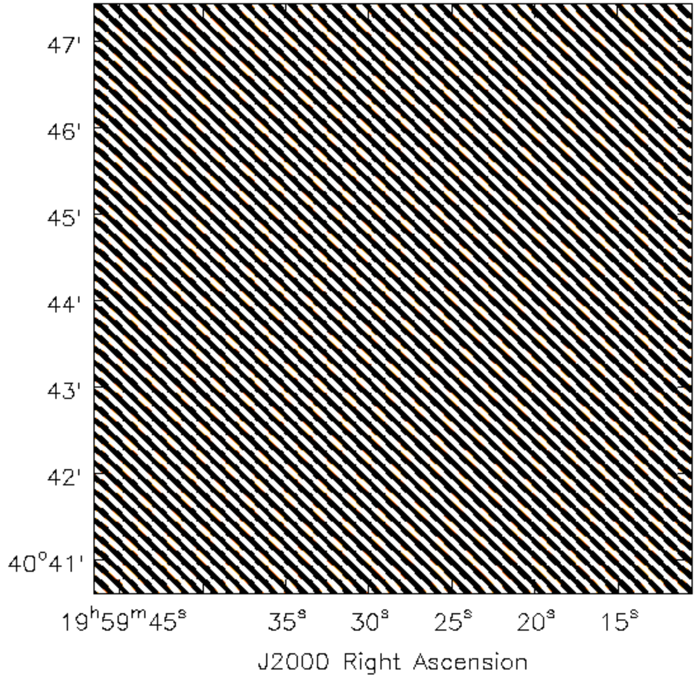
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

Image of the sky
using **2** antennas

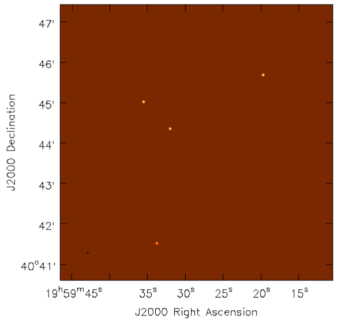
$S(u,v)$



$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image



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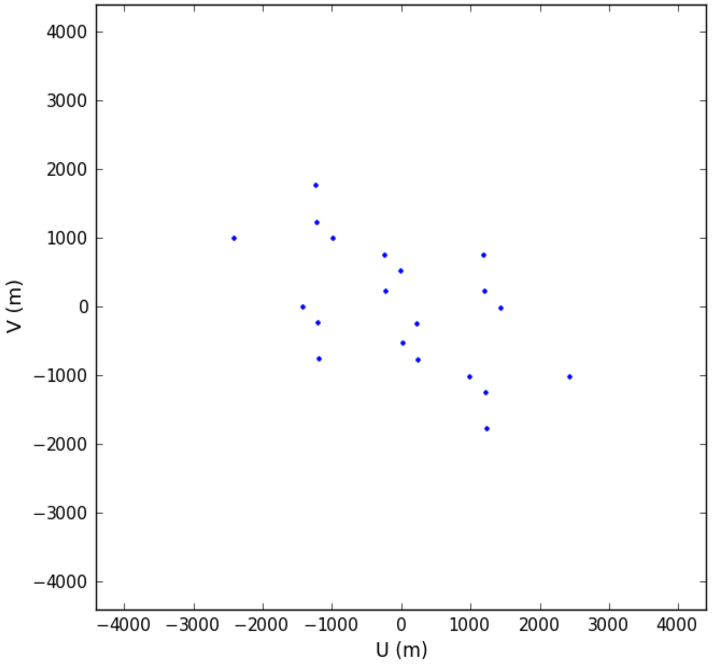


$I^{obs}(l,m)$

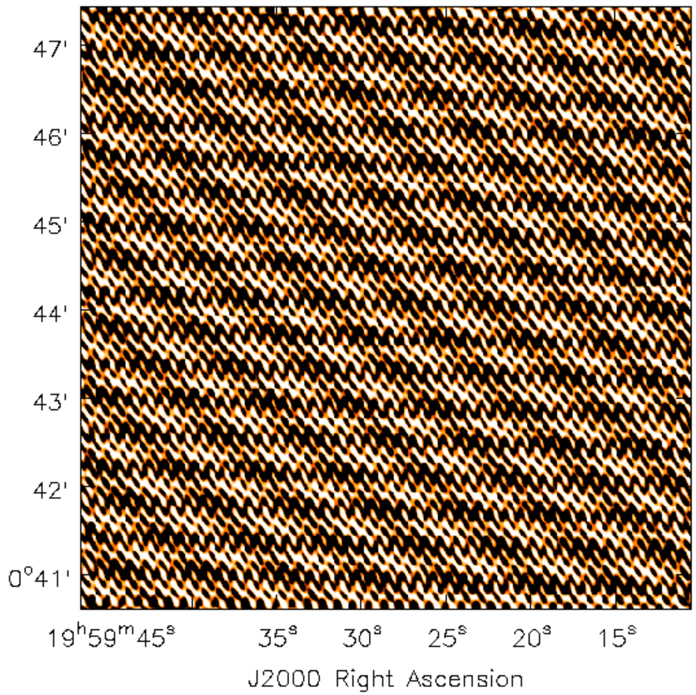
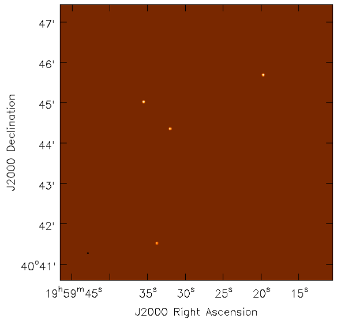


Image of the sky
using **5** antennas

"Aperture Synthesis"

Spatial Frequency (uv) coverage + Observed Image

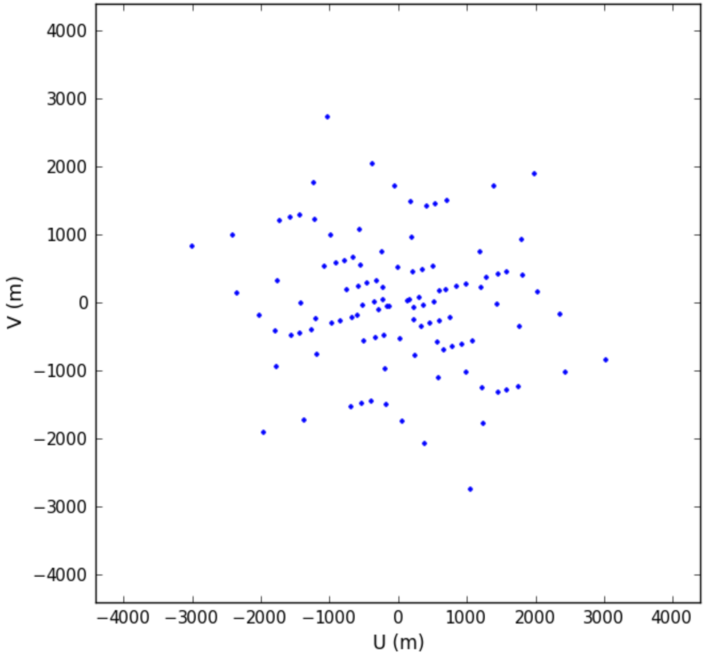


$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

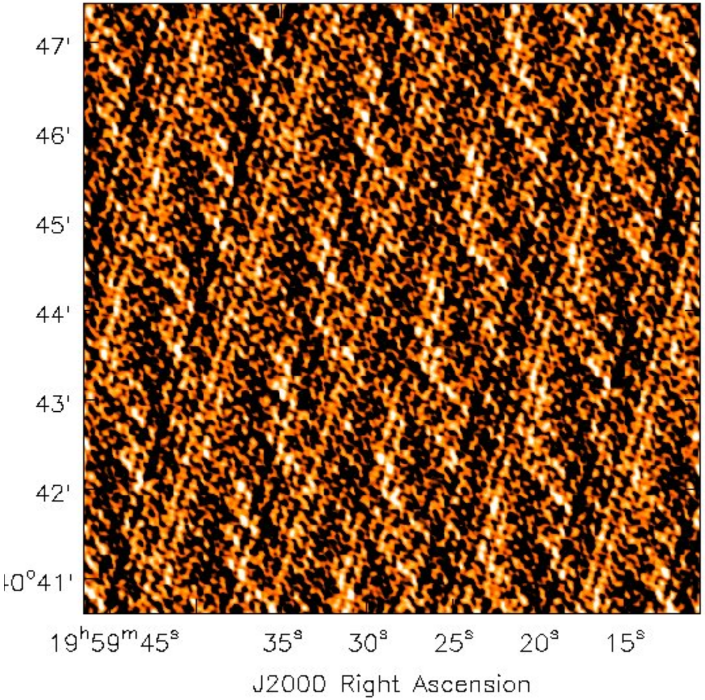
Image of the sky
using **11** antennas

“Aperture Synthesis”

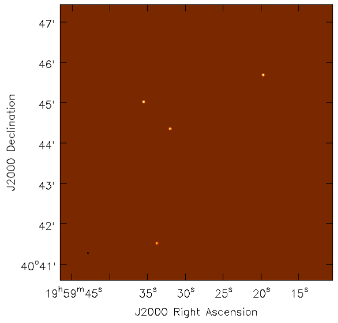
$S(u,v)$



$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image

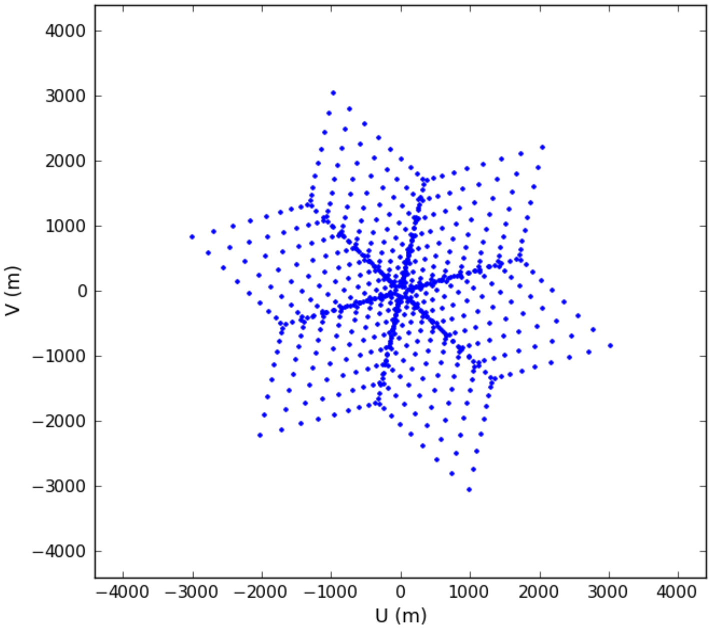


$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

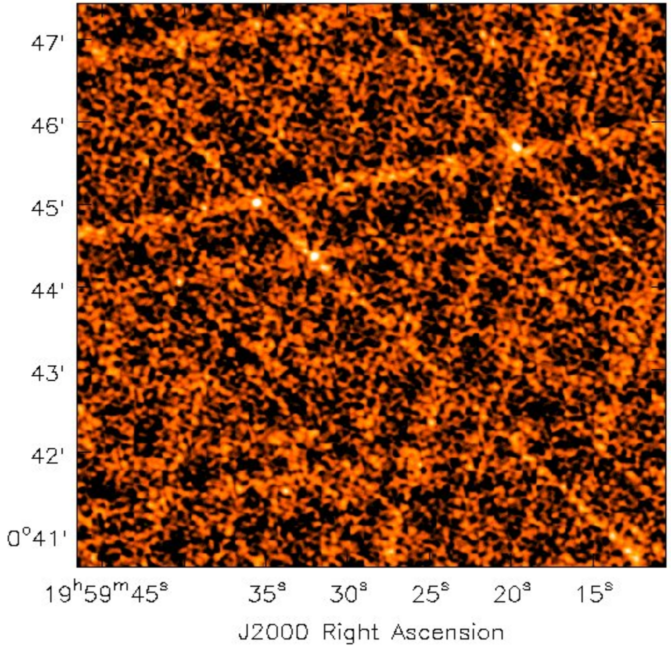
Image of the sky
using **27** antennas

“Aperture Synthesis”

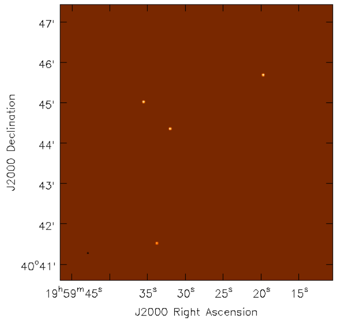
$$S(u,v)$$



$$I^{obs}(l,m)$$



Spatial Frequency (uv) coverage + Observed Image



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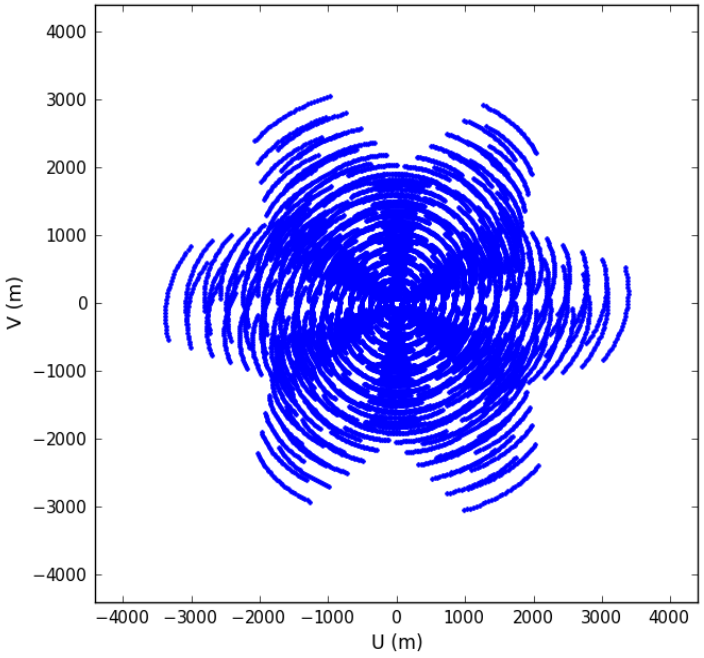
$S(u,v)$



$I^{obs}(l,m)$

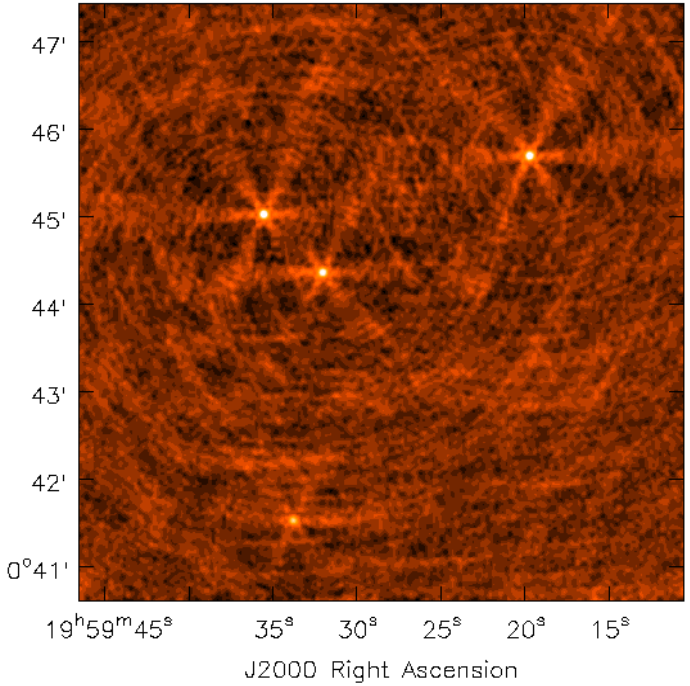


Image of the sky
using 27 antennas

Observation : **2 hours**

"Earth Rotation Synthesis"

Spatial Frequency (uv) coverage + Observed Image

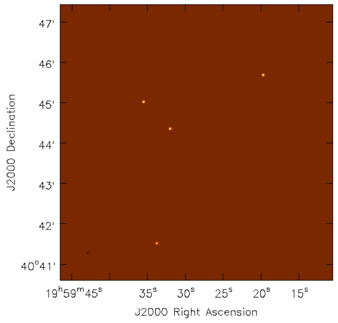


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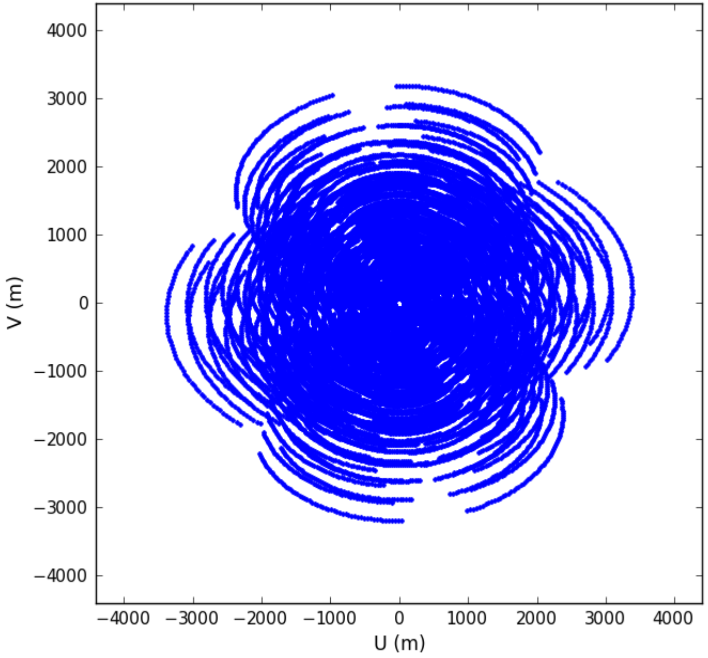
Image of the sky
using 27 antennas

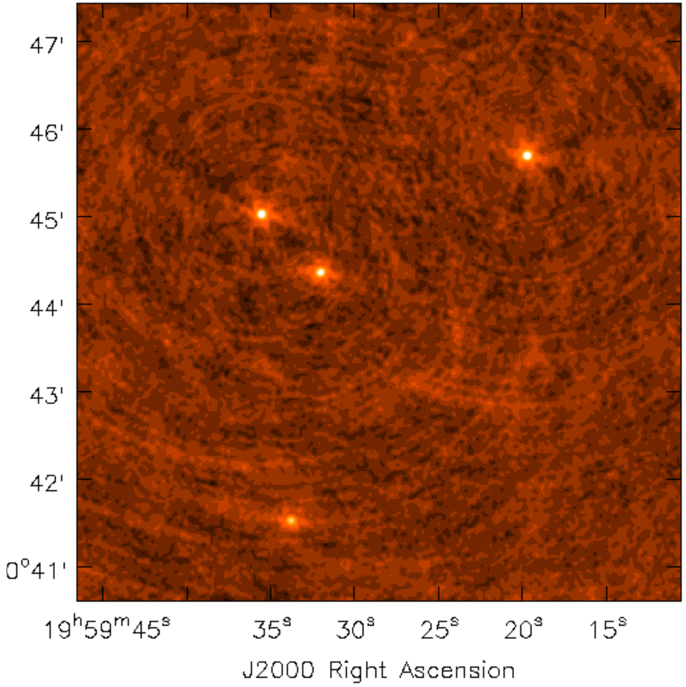
Observation : **4 hours**

"Earth Rotation Synthesis"

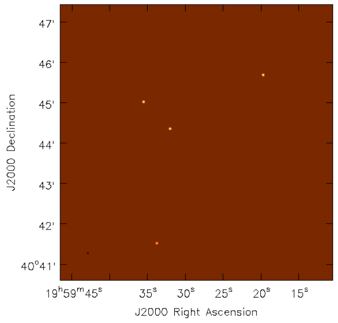
$S(u,v)$



$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image



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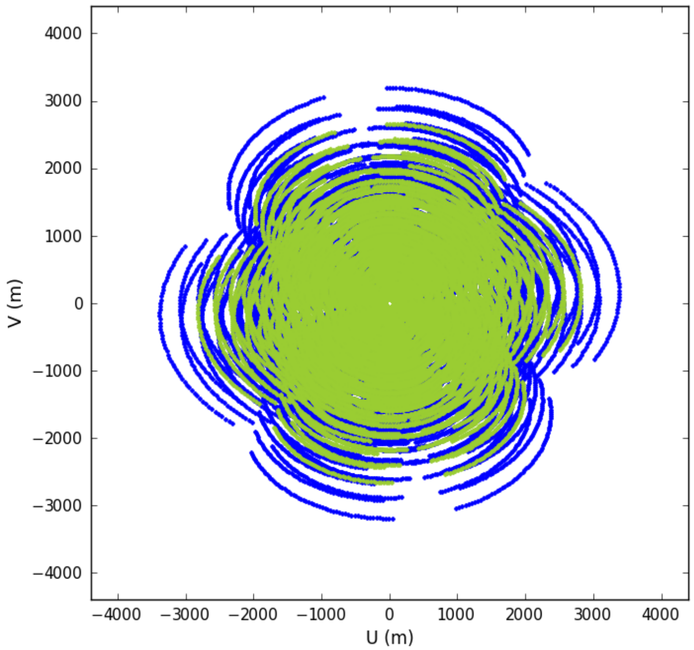
$S(u,v)$



$I^{obs}(l,m)$

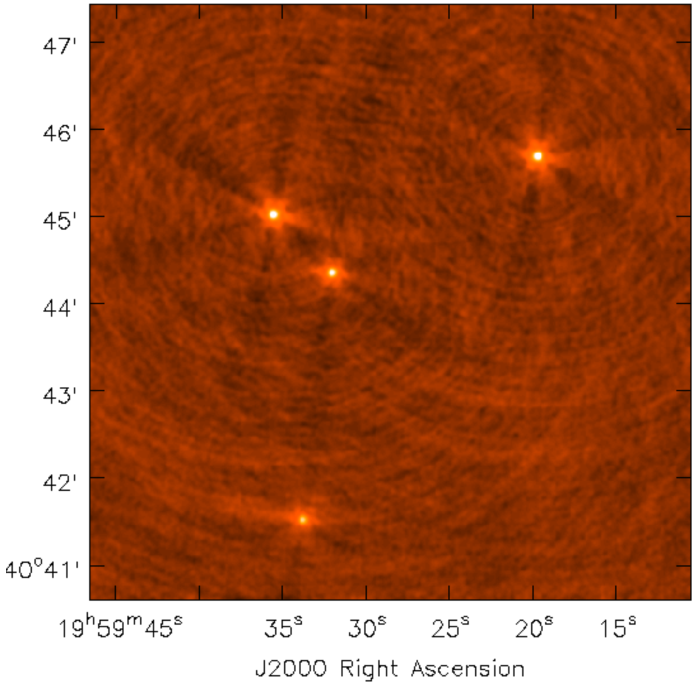


Image of the sky
using 27 antennas

Observation : 4 hours, **2 frequency channels**

"Multi Frequency Synthesis"

Spatial Frequency (uv) coverage + Observed Image

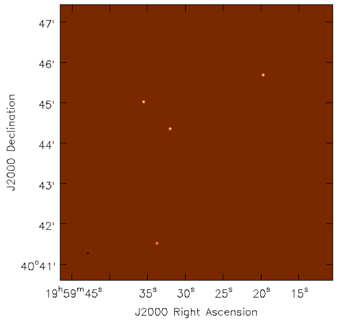


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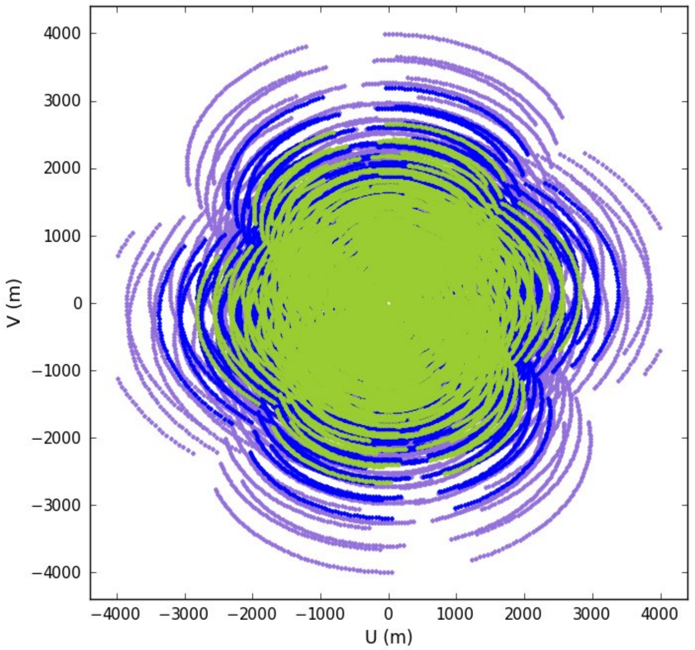
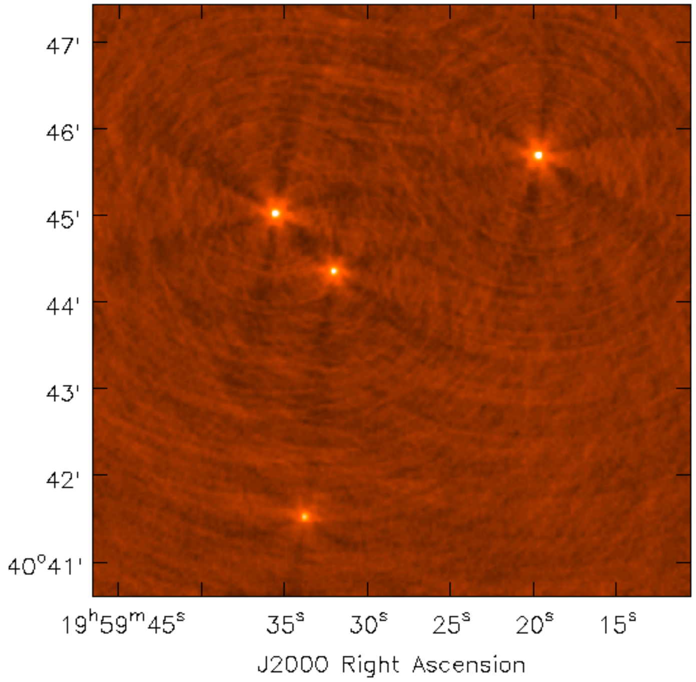
Image of the sky
using 27 antennas

$S(u,v)$



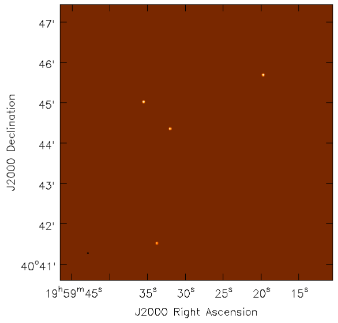
$I^{obs}(l,m)$



Observation : 4 hours, **3 frequency channels**

"Multi Frequency Synthesis"

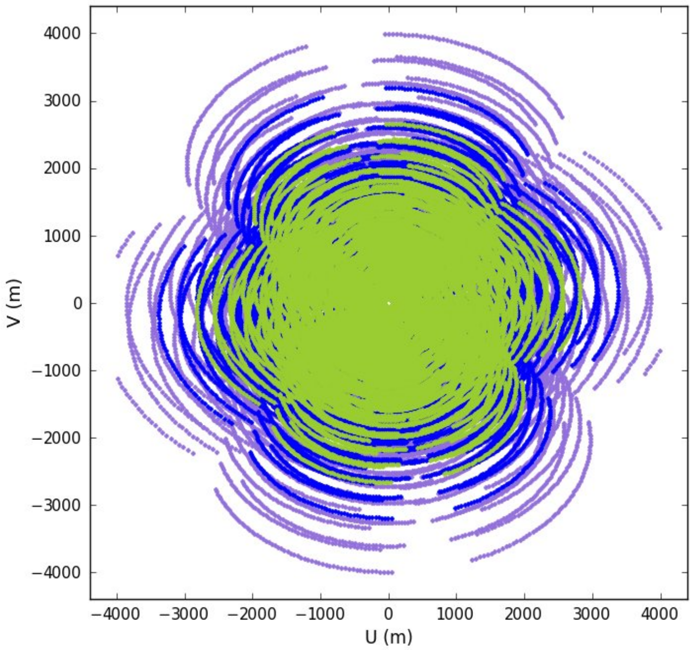
Spatial Frequency (uv) coverage + Observed Image



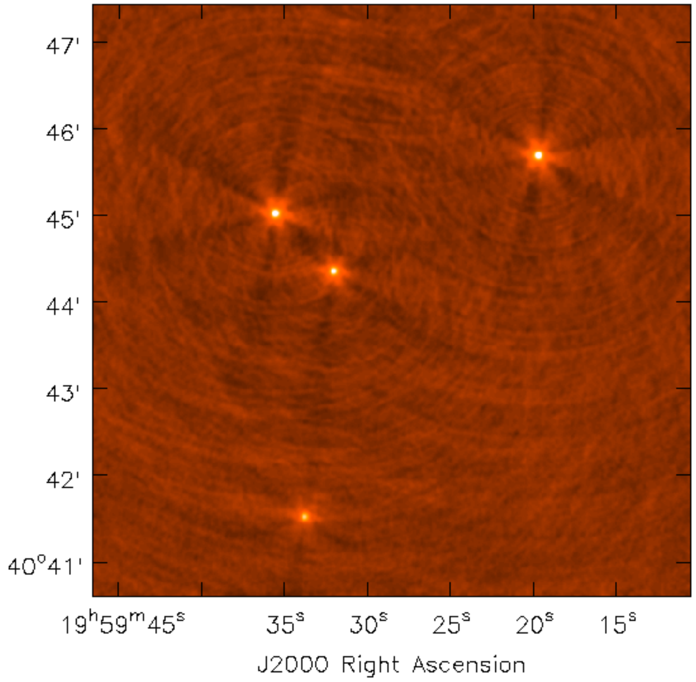
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\lambda} \begin{bmatrix} R(h,\theta) \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

Image of the sky
using 27 antennas

$S(u,v)$



$I^{obs}(l,m)$



Observation : 4 hours, 3 frequency channels

Point Spread Function

=> Imaging Properties

Outline

- Images in radio astronomy
- Imaging with a radio interferometer
  - Image formation
  - The forward and inverse problems
- Current limits and future trends

Radio Interferometry – Measurement Equations

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm$$

The forward problem

Observed visibilities (Data)

Direction Independent Gains

UV sampling pattern

Sky Brightness (Image)

Fourier transform kernel

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$$V_{ij}^{obs}(\nu, t) \approx M_{ij}(\nu, t) S_{ij}(\nu, t) \iint I(l, m) e^{2\pi i(ul+vm)} \, dl \, dm$$

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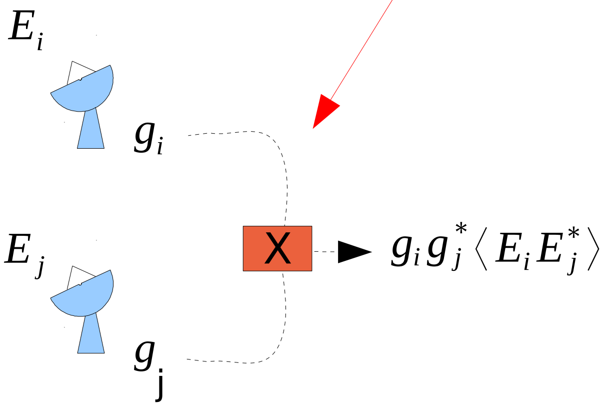

Calibration

Solve for g_i and divide out $g_i g_j^*$

N antennas
N(N-1)/2 antenna-pairs (baselines)

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- $S_{ij}(\nu,t)$ → UV sampling pattern
- $I(l,m)$ → Sky Brightness (Image)
- $e^{2\pi i(ul+vm)}$ → Fourier transform kernel

Observed or Calibrated visibilities (Data)

↓

Gridding
+
IFFT
+
Normalization

↓

I^{obs}

Radio Interferometry – Measurement Equations

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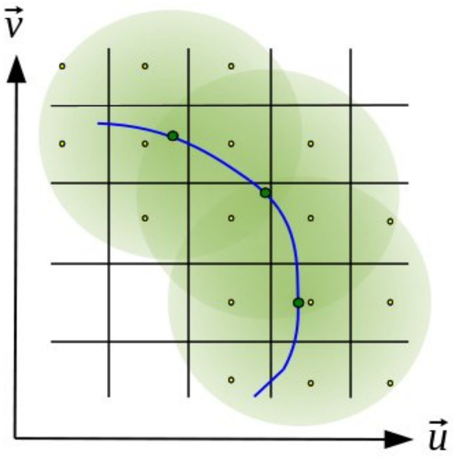
I^{obs}



Convolutional resampling

Radio Interferometry – Measurement Equations

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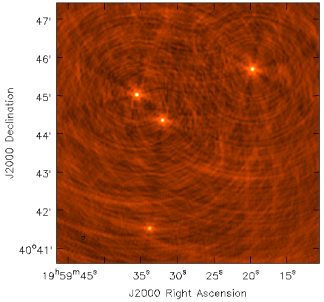
The forward problem

- $V_{ij}^{obs}(\nu,t)$: Observed or Calibrated visibilities (Data)
- $M_{ij}(\nu,t)$: Direction Independent Gains
- $S_{ij}(\nu,t)$: UV sampling pattern
- $I(l,m)$: Sky Brightness (Image)
- $e^{2\pi i(ul+vm)}$: Fourier transform kernel

Observed or Calibrated visibilities (Data) → Gridding + IFFT + Normalization → I^{obs}

The inverse problem

$$I^{obs}(l,m) = I^{PSF}(l,m) * I^{sky}(l,m)$$



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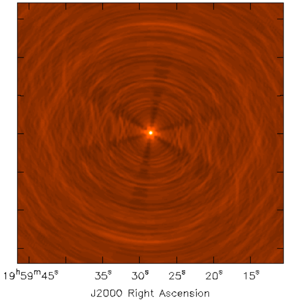

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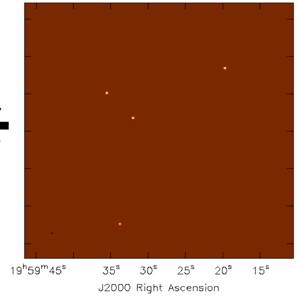

Image Reconstruction (deconvolution)

Radio Interferometry – Measurement Equations

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General Form : $V(\vec{b}_{ij}) = \iiint I^{sky}(\vec{s}) e^{2\pi i(\vec{b}_{ij}\cdot\vec{s})} d^3\vec{s}$

$$V(\vec{b}_{ij}) = \iiint M(\vec{s},t) I^{sky}(\vec{s},t) e^{2\pi i(\vec{b}_{ij}\cdot\vec{s})+\phi(\vec{s},t)} d^3\vec{s}$$

Interferometry & MRI share the same functional form (with different Physics)

=> Interesting overlap in solution techniques.

Radio Interferometry – Measurement Equations

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Direction Independent Gains

Direction Dependent Effects

Sky-brightness varies with frequency (time)

W-Term

Radio Interferometry – Measurement Equations

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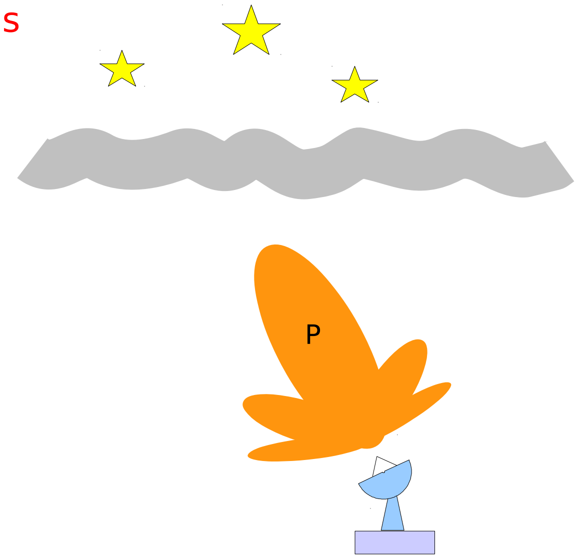

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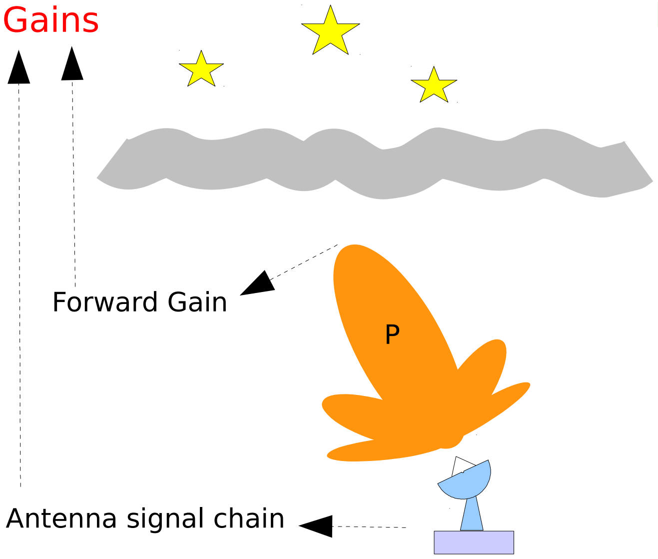

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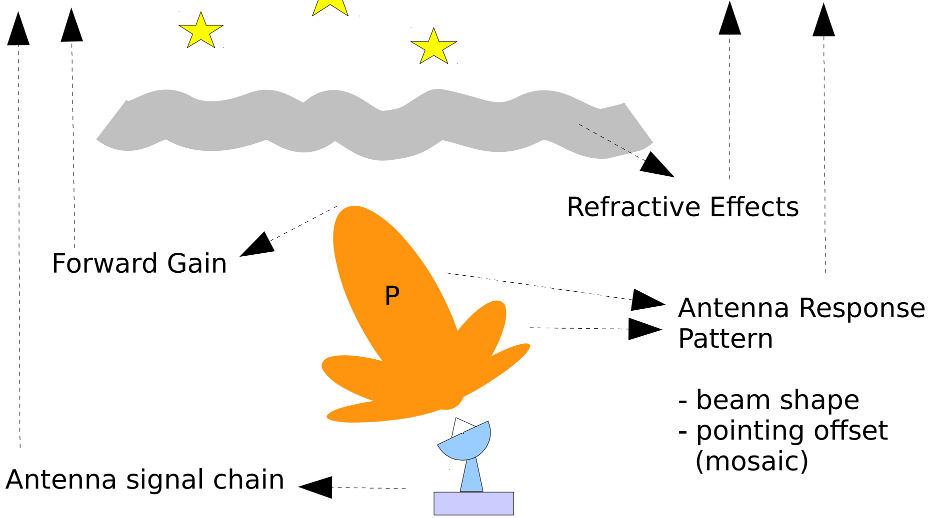

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Sky-brightness varies with frequency and time

W-Term

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Sky-brightness varies with frequency

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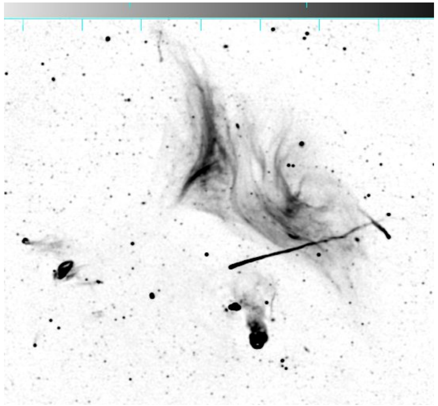
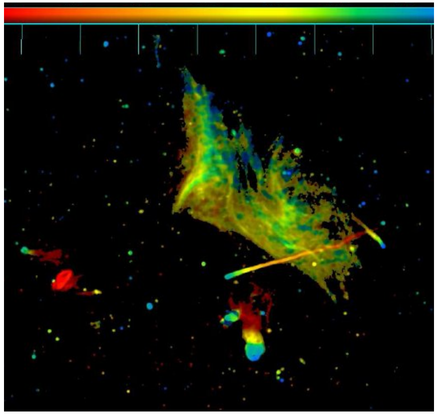
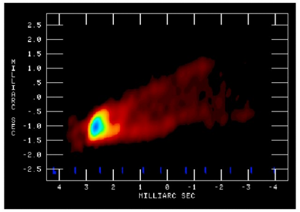


Intensity



Intensity weighted Spectral Index



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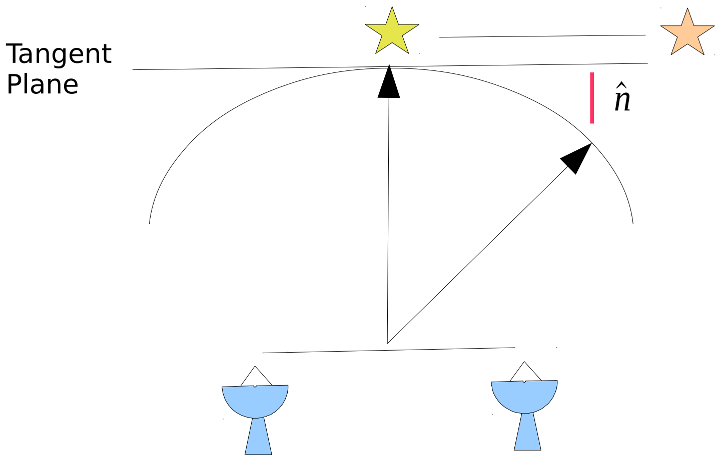
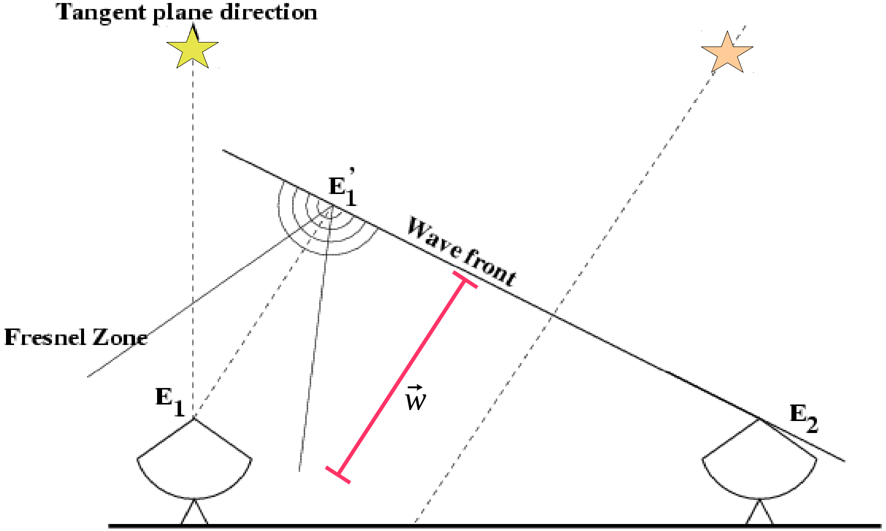
W-Term

Effect of Sky Curvature





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Direction Independent Gains

UV sampling function

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W-Term

How do we solve these systems of equations ?

Radio Interferometry – Measurement Equations

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Calibration

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Calibration

=> Multiplicative effect in the image domain
=> Convolutions in the visibility domain
(corrected during gridding + iFFT + normalization)

Inverse Imaging

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Direction Independent Gains

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W-Term

Calibration

Image Reconstruction

(De)convolution in the image domain

=> Multiplicative effect in the image domain
=> Convolutions in the visibility domain
(corrected during gridding + iFFT + normalization)

Inverse Imaging

Iterative Image Reconstruction

The generalized forward problem $V^{obs} = [A] I^m + n$

The generalized inverse problem $I^m = [A]^{-1} V^{obs}$

L2 data regularization

+ Sky model (multiscale, wideband, timevar)
+ Solver/Optimizer with constraints/biases

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Forward and Reverse transforms

Calc $\frac{\delta \chi^2}{\delta I^m}$

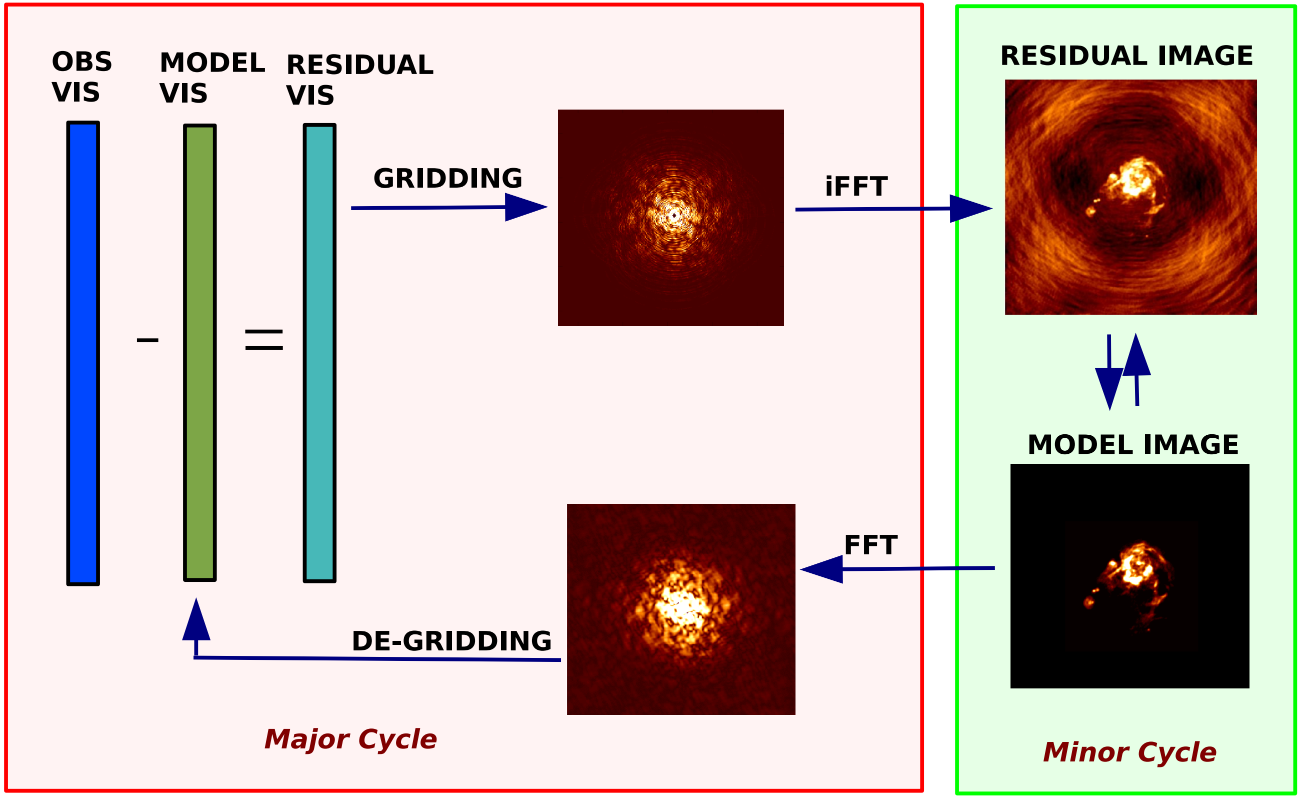


Image Reconstruction

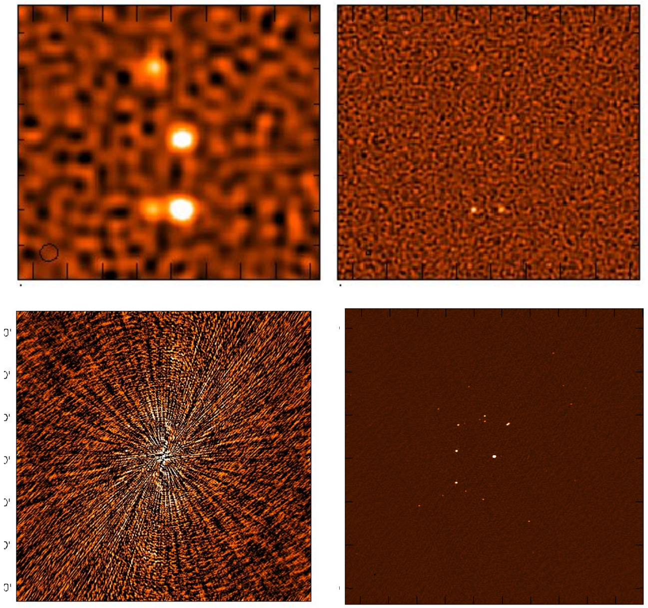
Sky models
- Delta function
- Gaussians
- .....

Algorithms
- Clean (greedy)
- Many other CS ideas

Outline

- Images in radio astronomy
- Imaging with a radio interferometer
    - Image formation
    - The forward and inverse problems
- Current limits and future trends

Limits of Interferometric Imaging



Signal-to-noise ratio (SNR)

Angular resolution & sensitivity

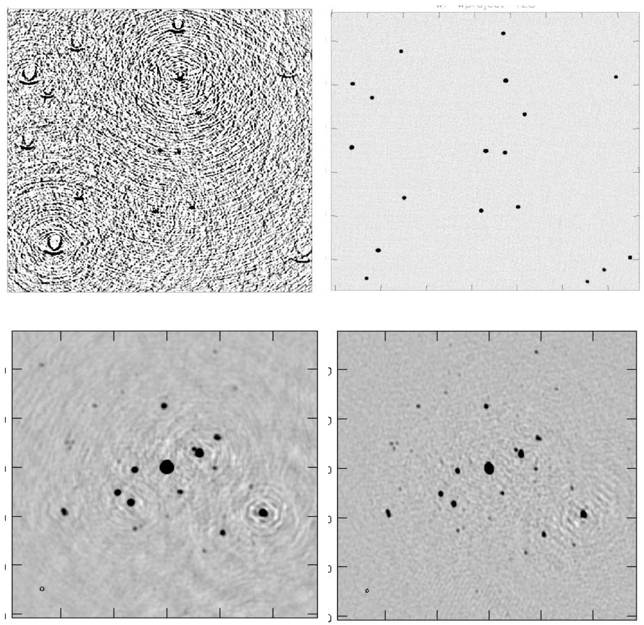
Dynamic range (CNR)

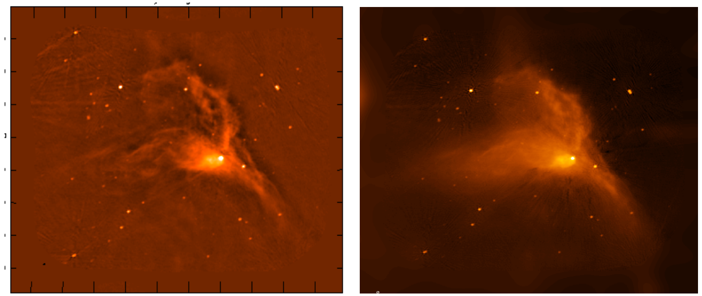
Un-measured large spatial scales

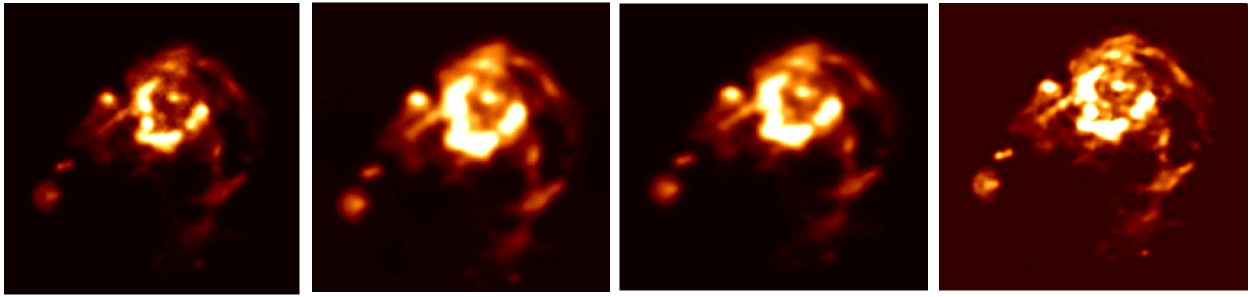
Accuracy of instrument models

Algorithmic variability

Data volume and compute cost





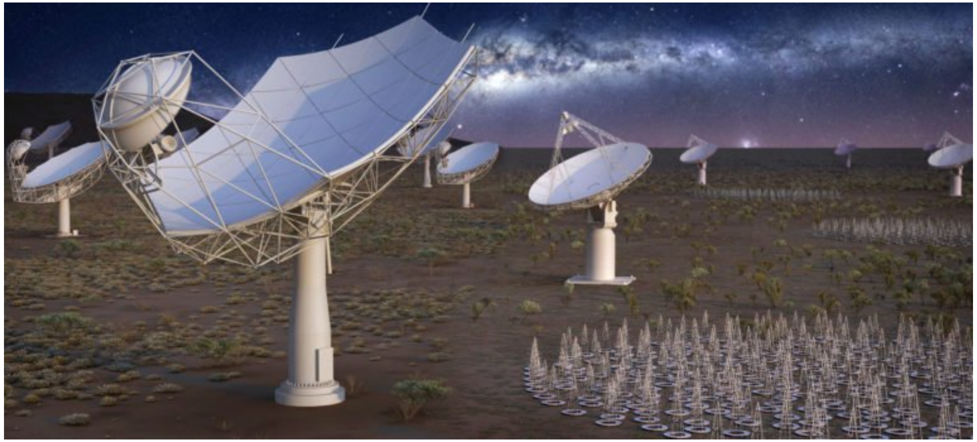


Going forward……

Data volumes will only increase (e.g. ngVLA, SKA….)

=> image noise reduces   => instrumental effects easily seen => need complex algorithms

=> compute cost increases => manual intervention is harder => need HPC and automation



Square Kilometer Array (skatelescope.org)

2K dishes, 1M antennas , 50 MHz – 30 GHz

Next Generation VLA   (ngvla.nrao.edu)

263 dishes (2 types) ,   1-100 GHz

The R&D frontier

Algorithms :

- A variety of sky models, instrument models, objective functions and regularizers, optimization strategies, the use of prior knowledge versus unknowns to solve for, etc..
- Talks by Maxim Voronkov and Kazunori Akiyama

Compute Load :

- Parallelization of data and algorithms, GPUs for the gridding compute hotspot, etc..
- Talk by Kumar Golap

Automation :

- Data analysis pipelines that know how to tune the details of each step (data editing, calibration, imaging) to each specific dataset

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Acknowledgements : Daniel Sodickson
Sanjay Bhatnagar
NRAO
C2G organizers