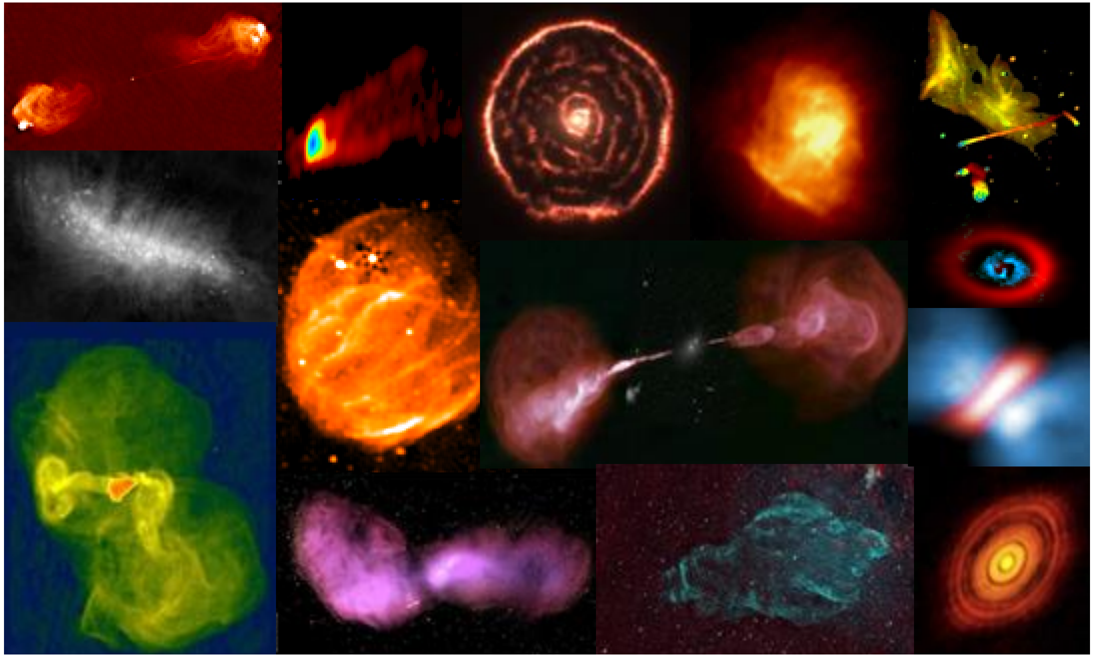
Imaging in Radio Astronomy



Urvashi Rau & Sanjay Bhatnagar

National Radio Astronomy Observatory, USA

National Radio Astronomy Observatory

Outline…

- Images in Radio Astronomy
- Signal measurement (RF power, front-end systems, EMI)
- K-space sampling (point spread functions)
- Image Reconstruction (signal equations, algorithms)
- Operational workflows
- Future directions

(Extra slides – History of radio astronomy, and telescopes of the world)

Imaging in Astronomy

Radio Infrared Visible Ultraviolet X-Ray Gamma

What we measure :

Intensity of the received power
EM Polarization
Spectral structure
Time-variability

Quantitative !

What we infer :

Temperature, Energetics,
Emission Physics, Chemical Composition
Magnetic Fields
Velocities , 3D structure
Age of the source

Why ? To study new Physics

Images in Radio Astronomy : 2D brightness distribution + B-fields

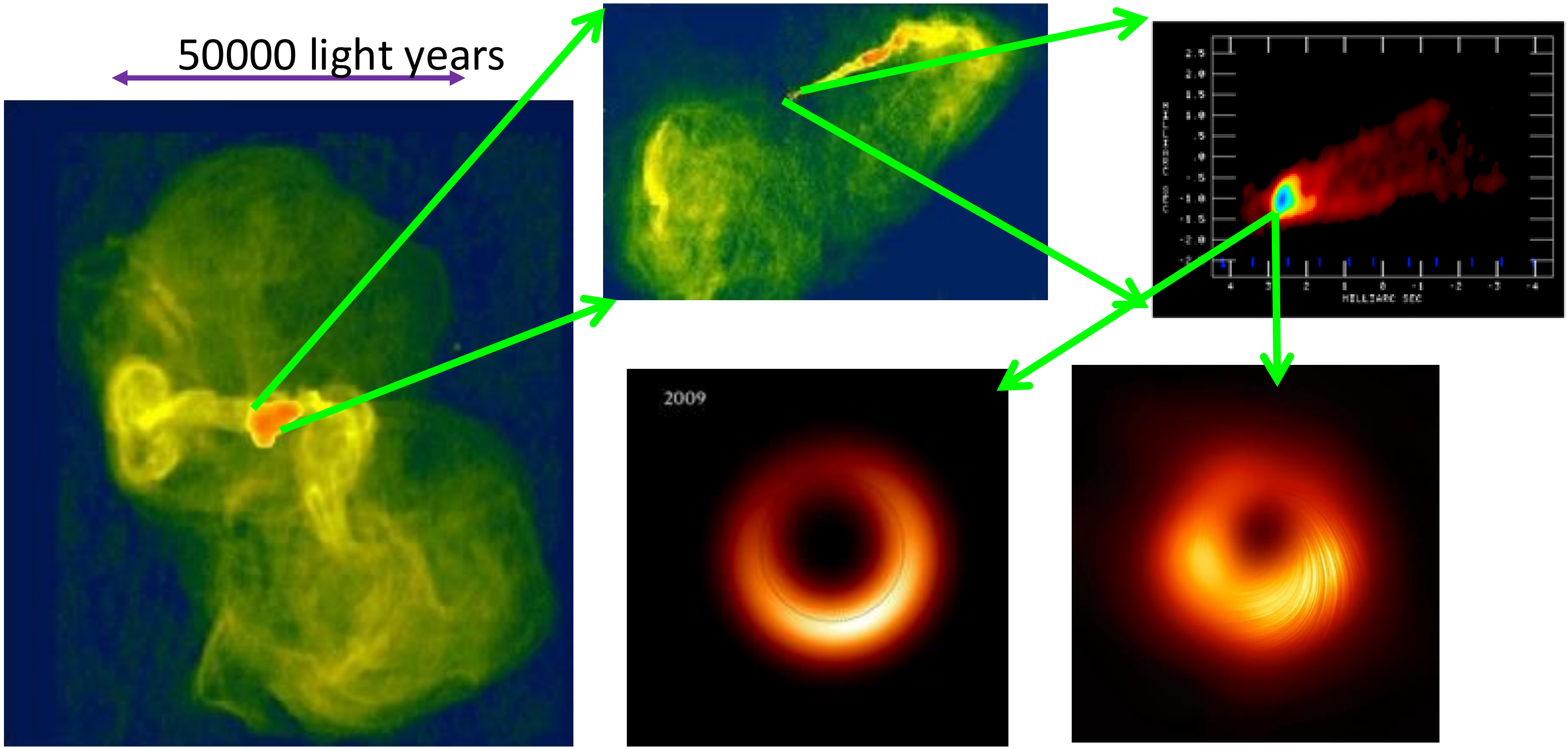
Space

Time

Frequency

Polarization

50000 light years



0.006 light years

Credits :
NRAO, ALMA,
Event Horizon Telescope collaboration

Images in Radio Astronomy : Spectral Lines + Doppler Shifts

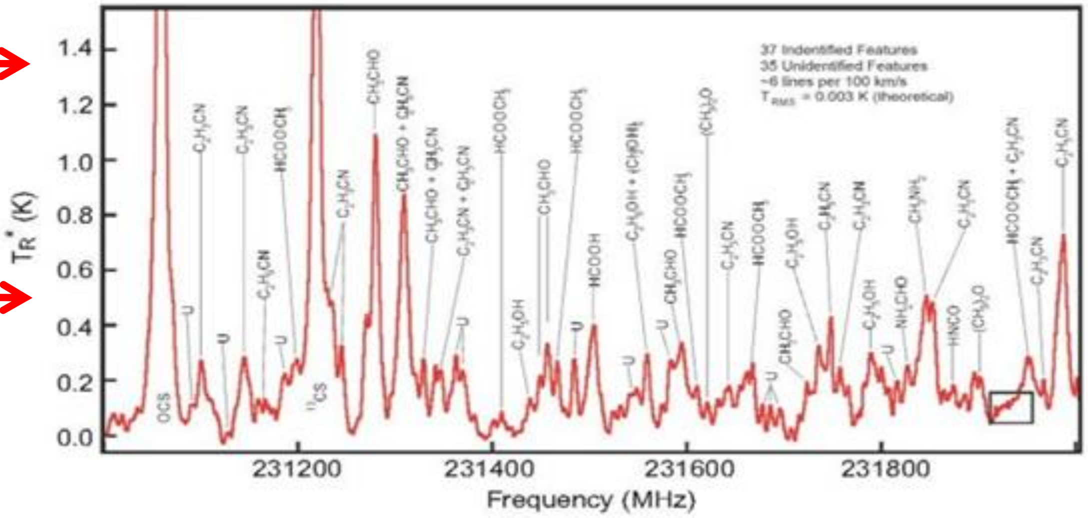
Space

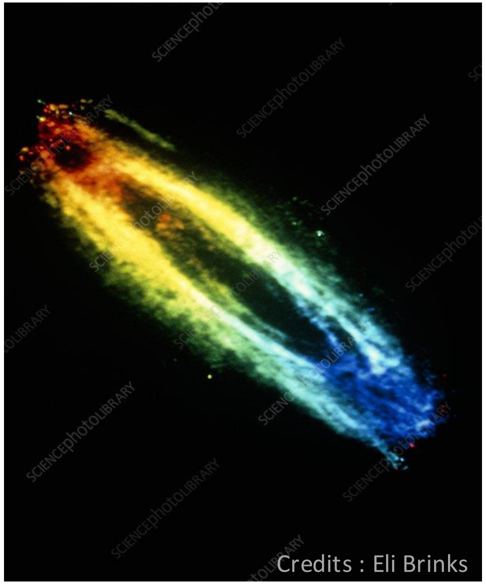
Time

Frequency

Polarization

Astro-chemistry tracers





Doppler shifts
trace physical velocity

M31 : Andromeda
Galaxy Rotation

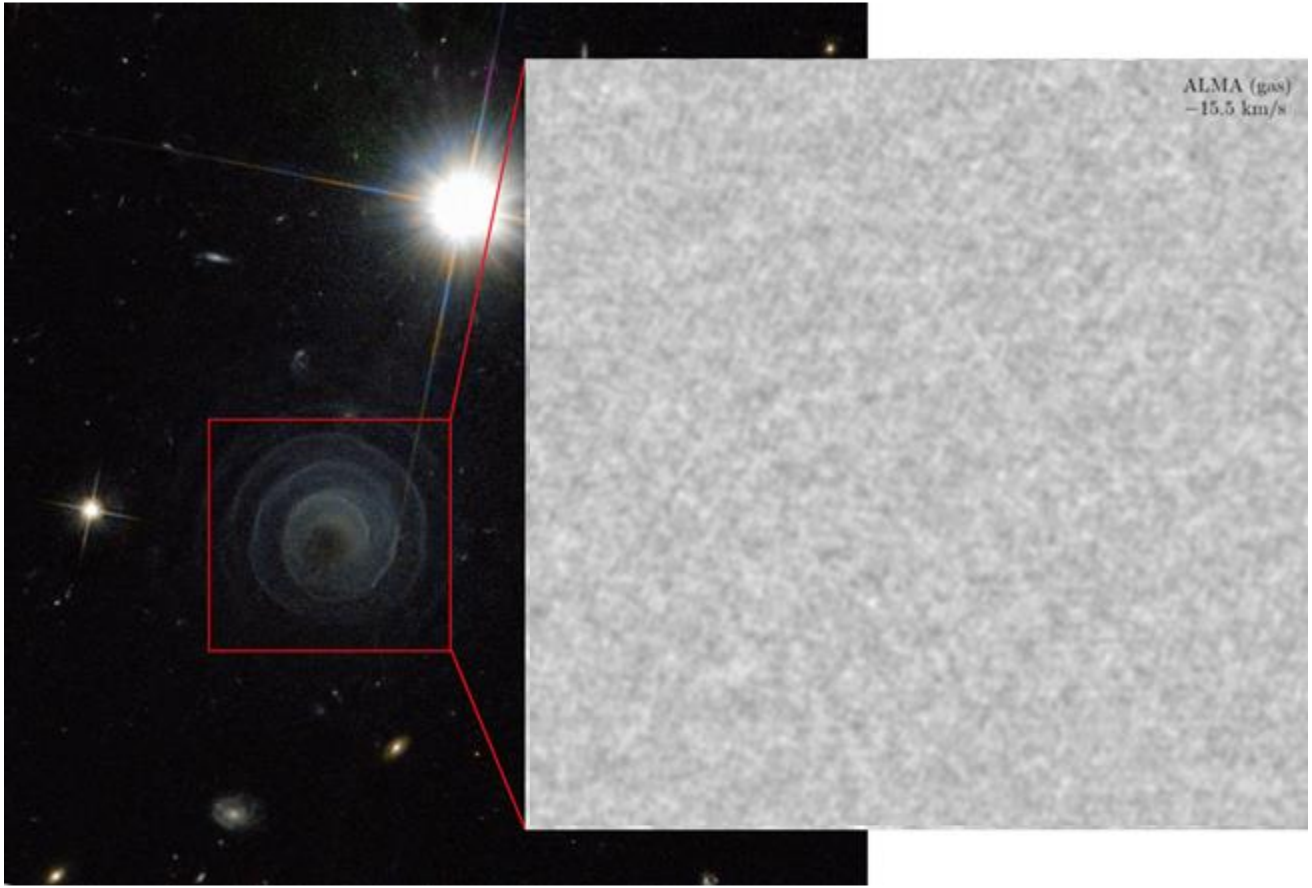
Images in Radio Astronomy : 3D velocity structures (Doppler)

Space

Time

Frequency

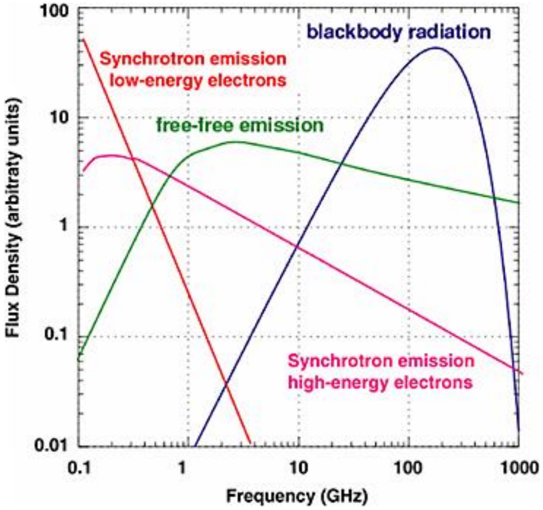
Polarization



CO emission showing a spiral-shell structure around the AGB star LL Pegasi and its stellar companion

(Kim et al, Nature Astro 2017.)

Images in Radio Astronomy : Emission Physics



Space

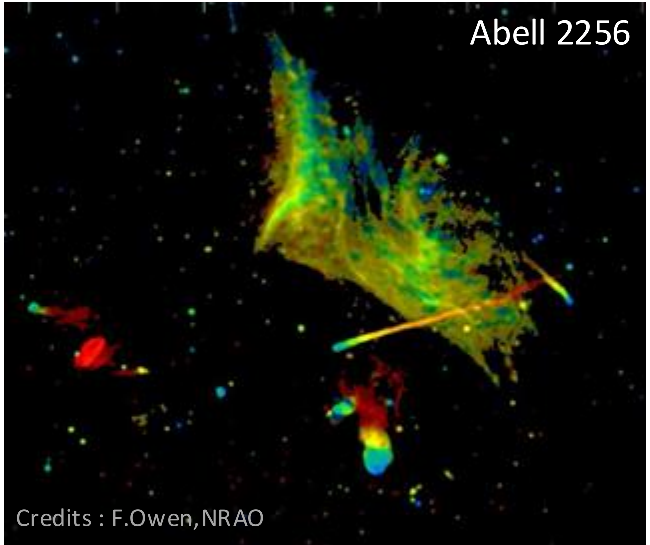
Time

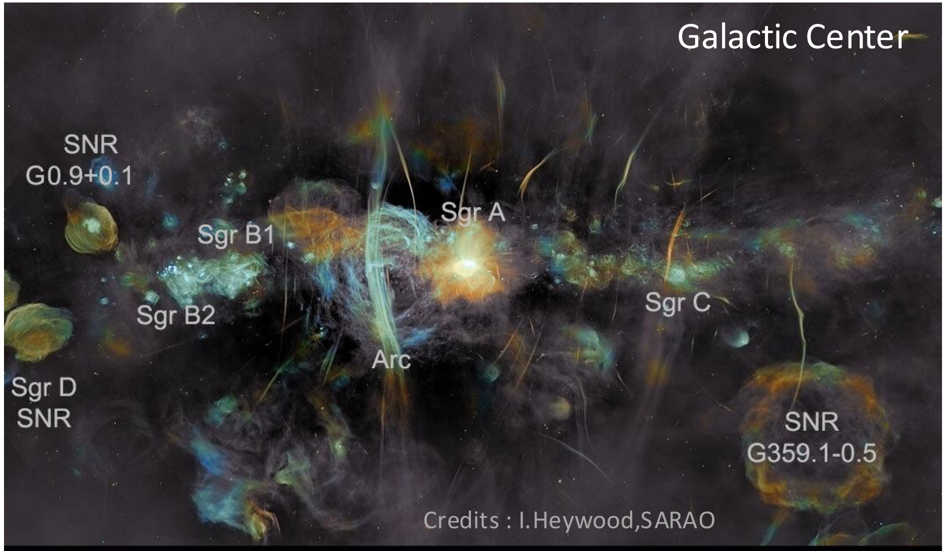
Frequency

Polarization

Color : Spectral slope

- Identify radiation process
- Tracer of "age"





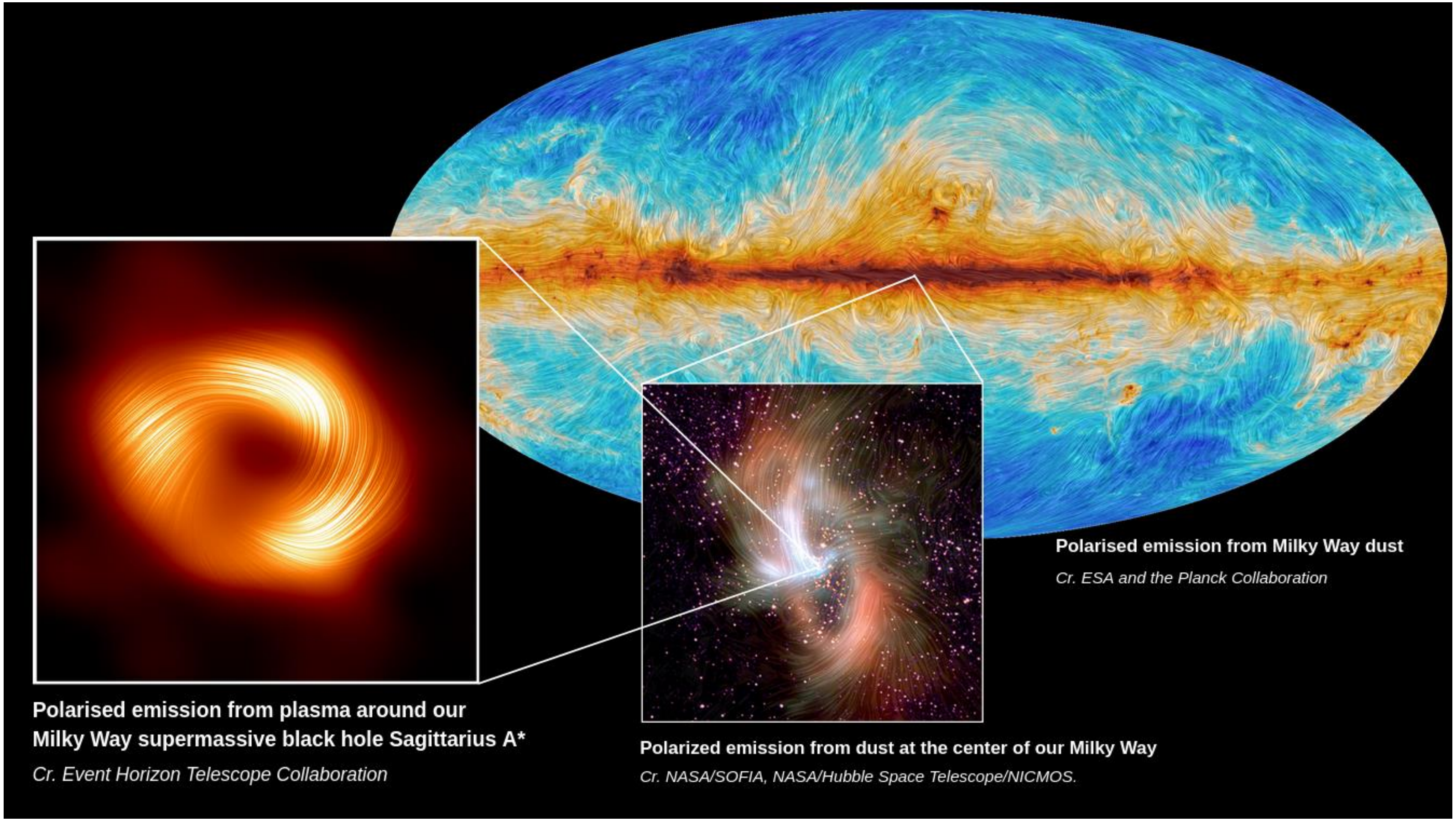
Images in Radio Astronomy : Magnetic Field Direction

Space

Time

Frequency

Polarization



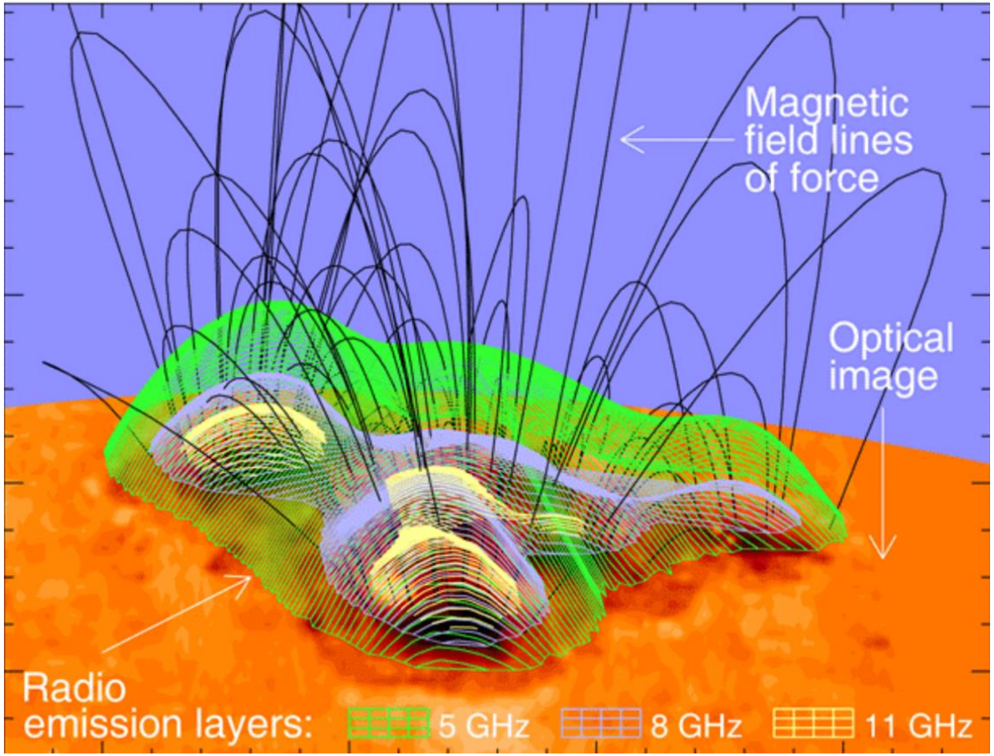
Images in Radio Astronomy : Coronal Magnetography

Space

Time

Frequency

Polarization



Gyro-synchrotron radio emission from the solar corona

Between 1 GHz and 20 GHz

Traces B-field strengths at difference heights above the surface of the sun.

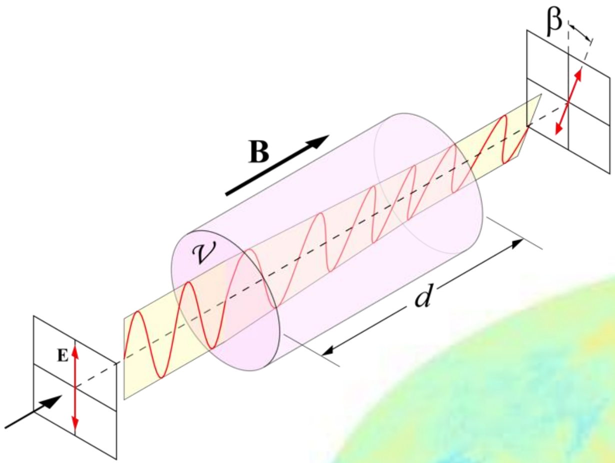
Images in Radio Astronomy : 3D Magnetic Tomography

Space

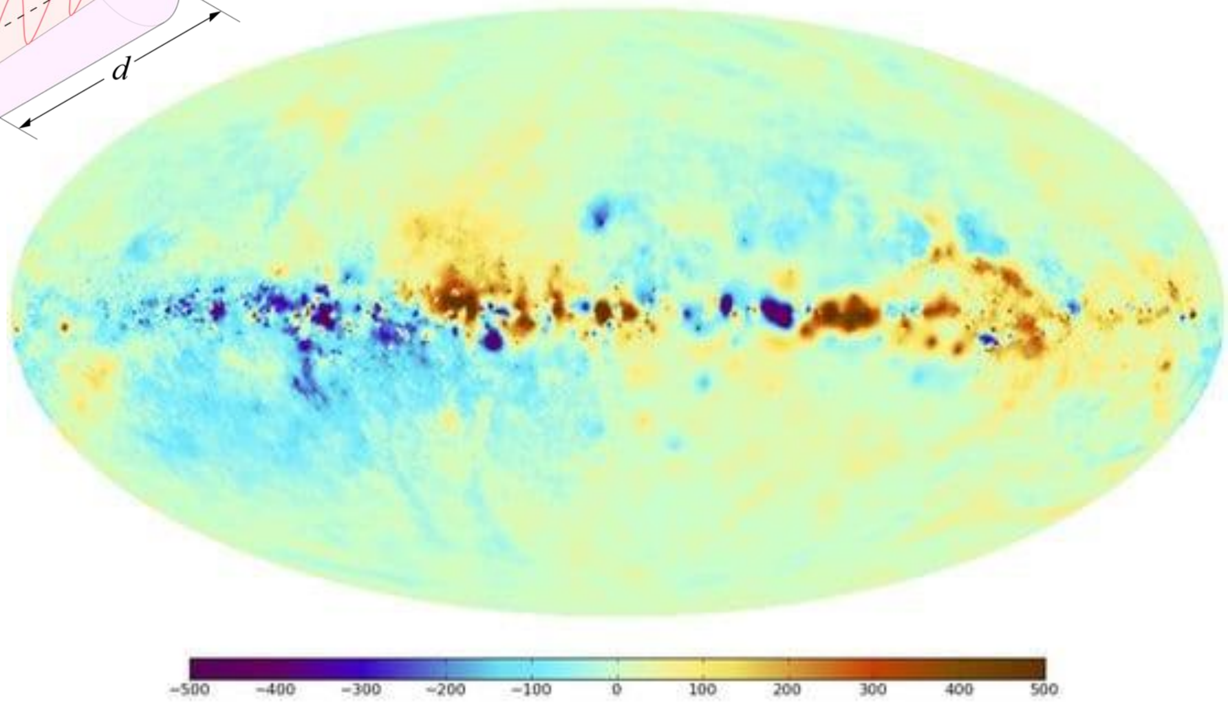
Time

Frequency

Polarization



Faraday Rotation and B-fields



All sky map of Faraday Depth, as a tracer of magnetic fields of the Milky Way.

Credits : Max Planck Institute

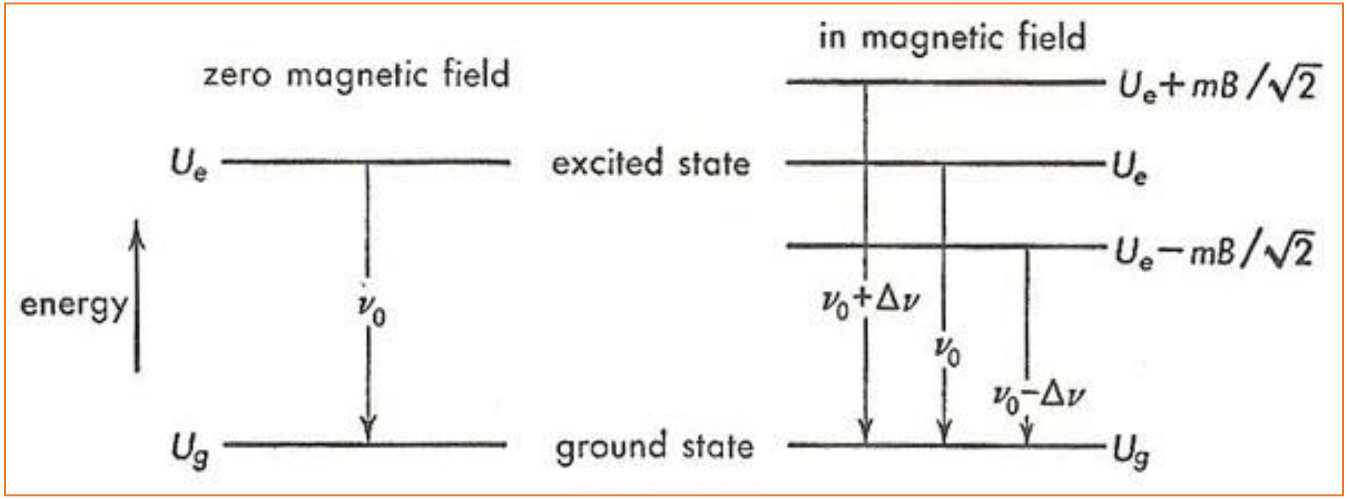
Images in Radio Astronomy : Zeeman Splitting & B-field strength

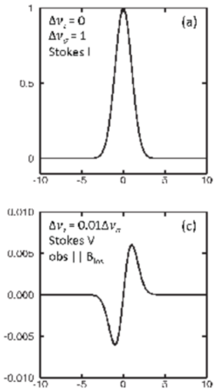
Space

Time

Frequency

Polarization

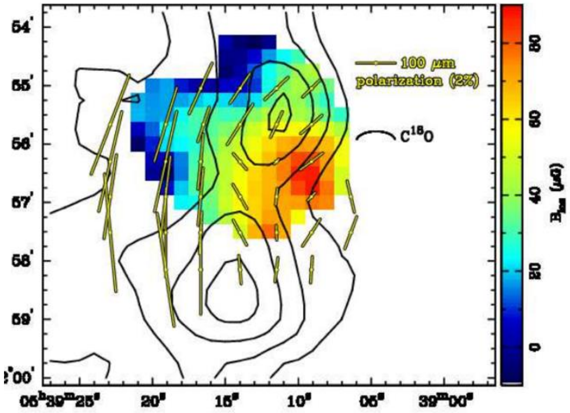




Stokes I

Stokes V

Frequency



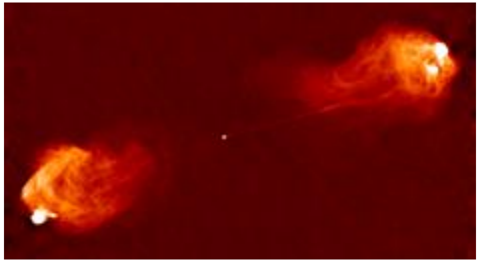
B-field from OH Zeeman lines

NGC2024 star-forming region

Credits : Crutcher & Kemball, 2019

Measurements – Power Levels and Frequency Ranges

Electromagnetic radiation from objects in space

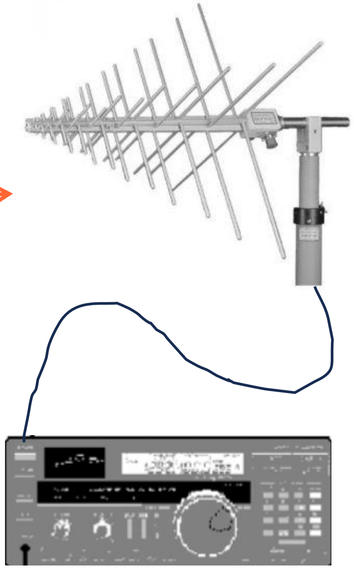


Spectral Power Flux Density

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

Measured range : 10^{4} Jy to 10^{-6} Jy

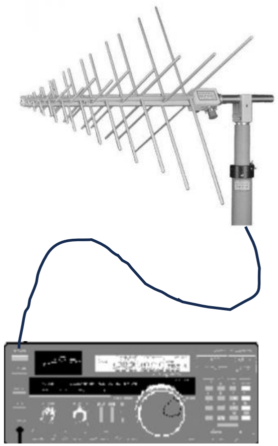
Measure Power Received at Radio Frequencies



Frequency Ranges

30 MHz -100 MHz	LOFAR
300 MHz – 1.5GHz	GMRT
900 MHz – 50 GHz	VLA
(40 GHz – 120 GHz)	(ngVLA)
100 GHz – 900 GHz	ALMA

Measurements – Front-end systems



Cooled Receivers

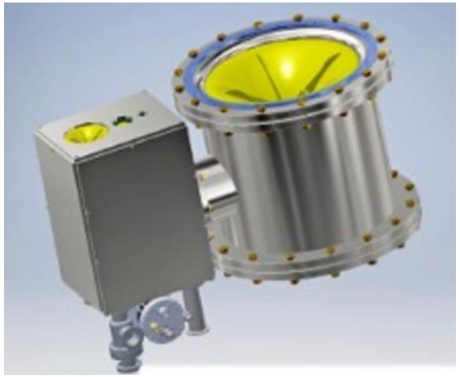
Low Noise Amplifiers

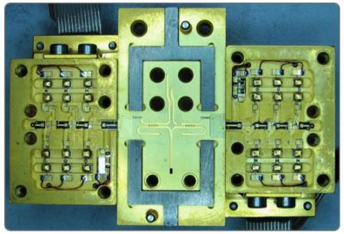
Sky : 2.7K
Ambient : 300K
Current instruments : ~ 20 K

Spectral Power Flux Density

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

Measured range : 10^4 Jy to 10^{-6} Jy

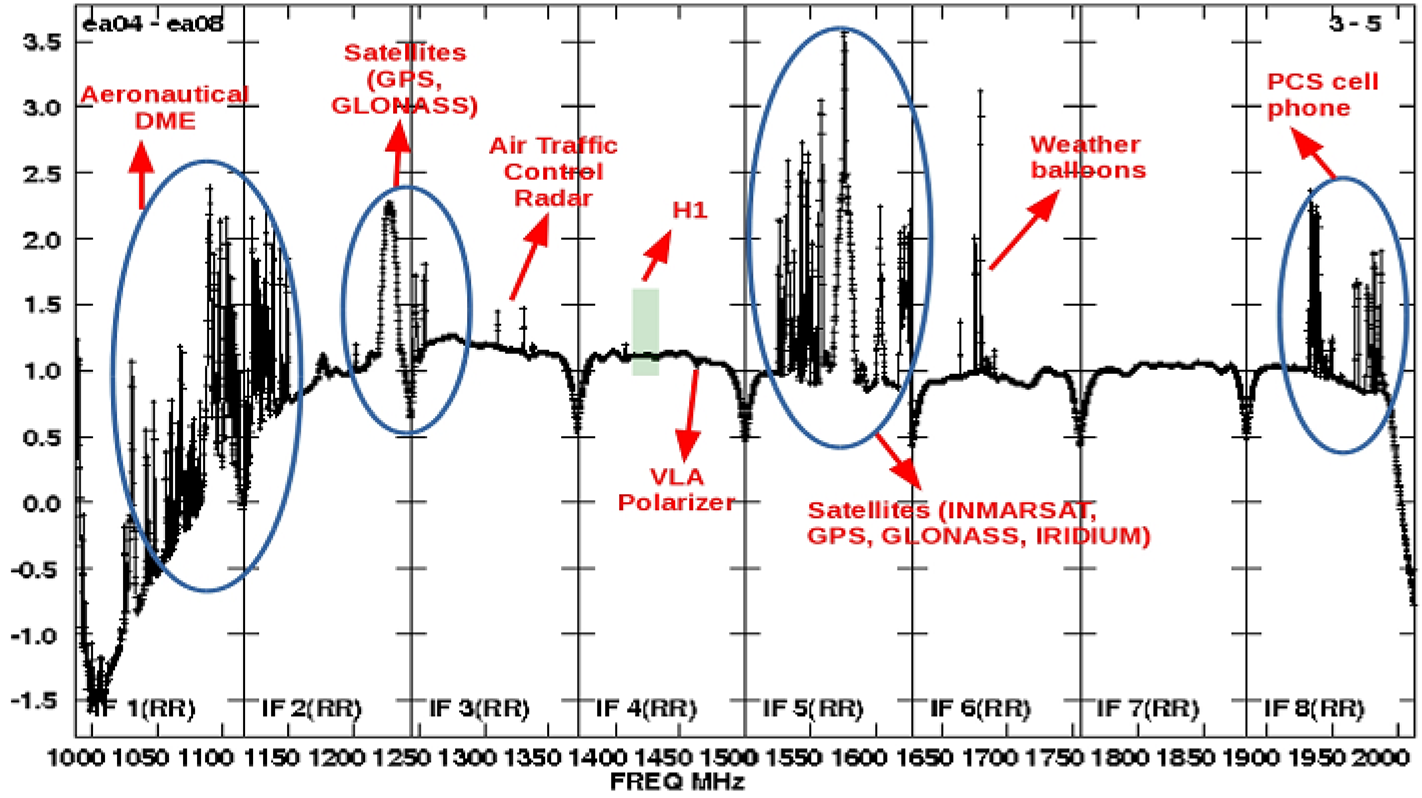




Central Dev Lab,
NRAO

LNAs, Cryogenics,
Mixers, waveguides,

Radio Frequency Interference



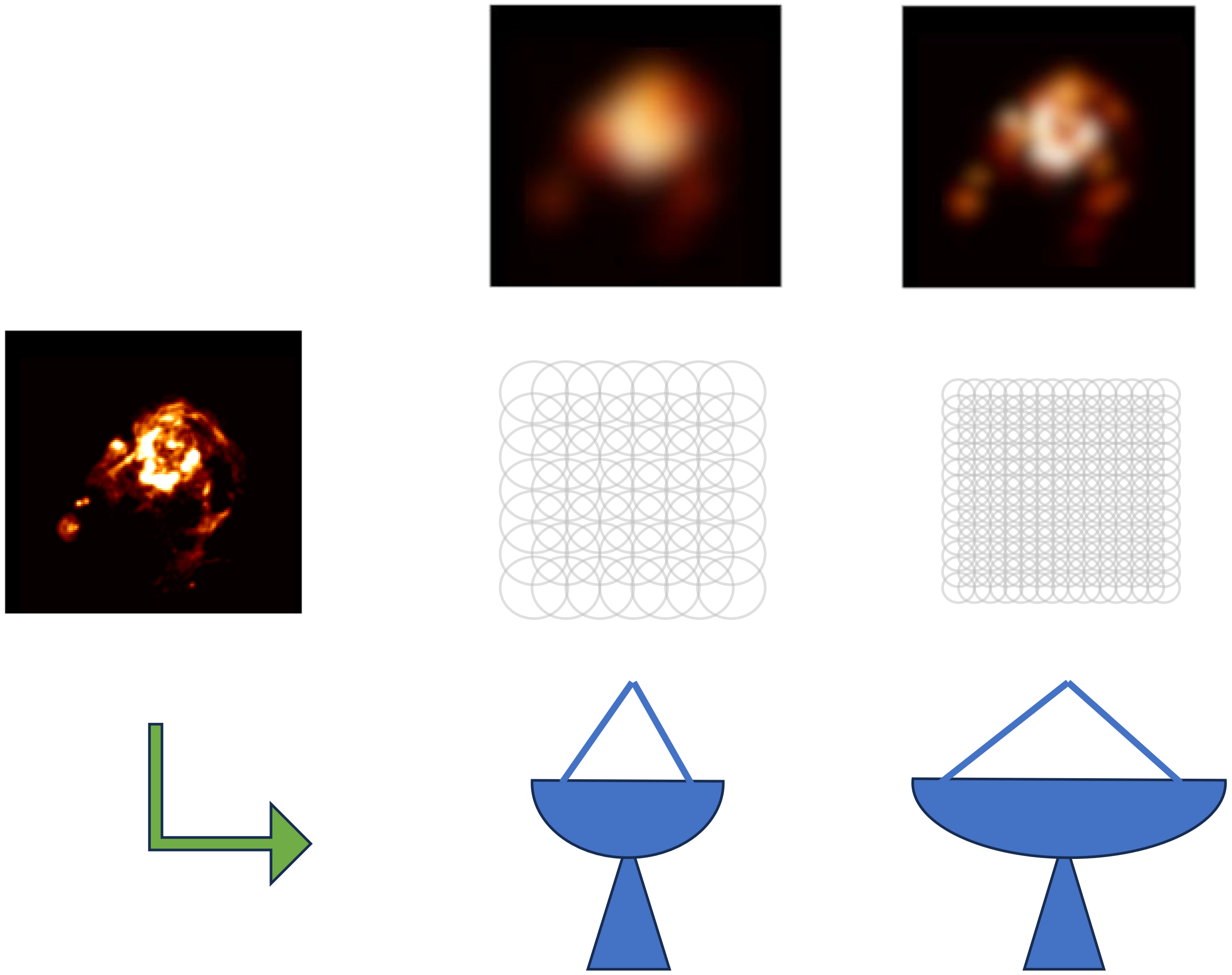
Man-made transmissions

- Satellite radio, internet, navigation comms, cell services, etc.
- Only very small protected bands

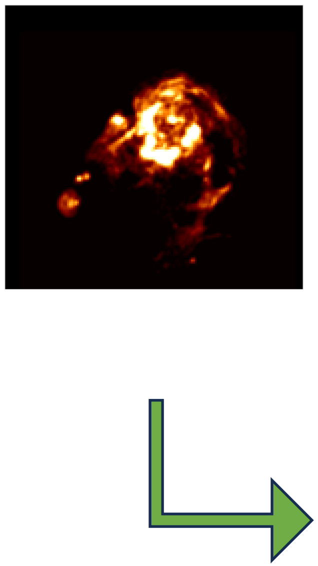
Algorithms : **Flagging** Outlier detection + discarding corrupted samples.

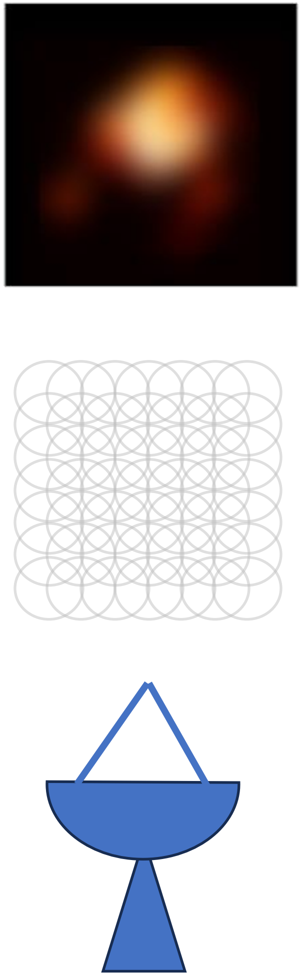
Challenges : ~30-40% data loss in commercial bands → R&D on ways to recover data

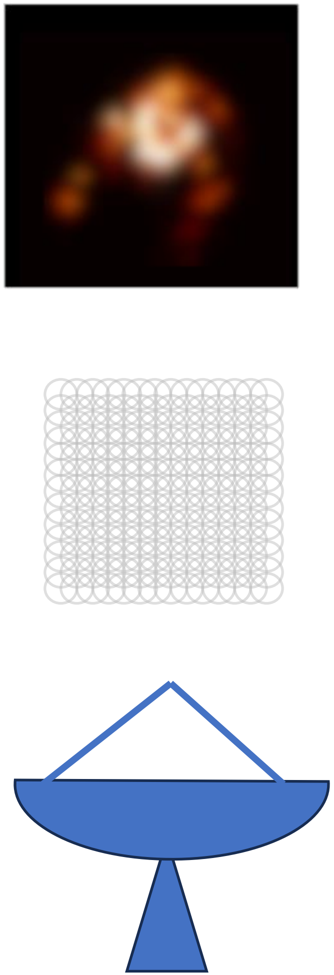
Images in Radio Astronomy

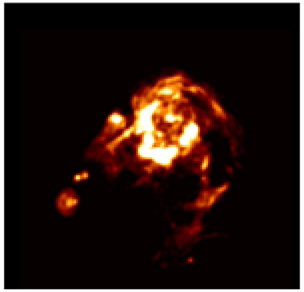


Images in Radio Astronomy





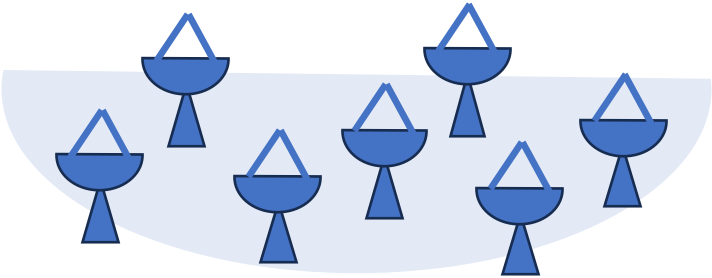




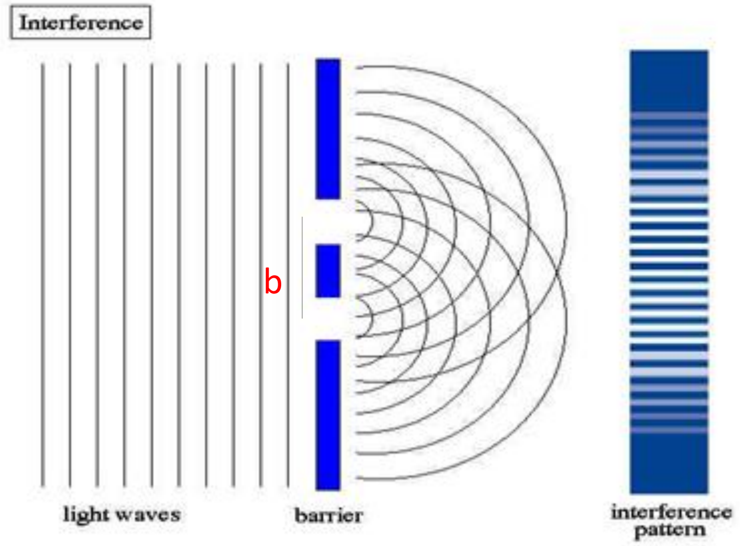
Aperture Synthesis

Measure spatial frequencies...

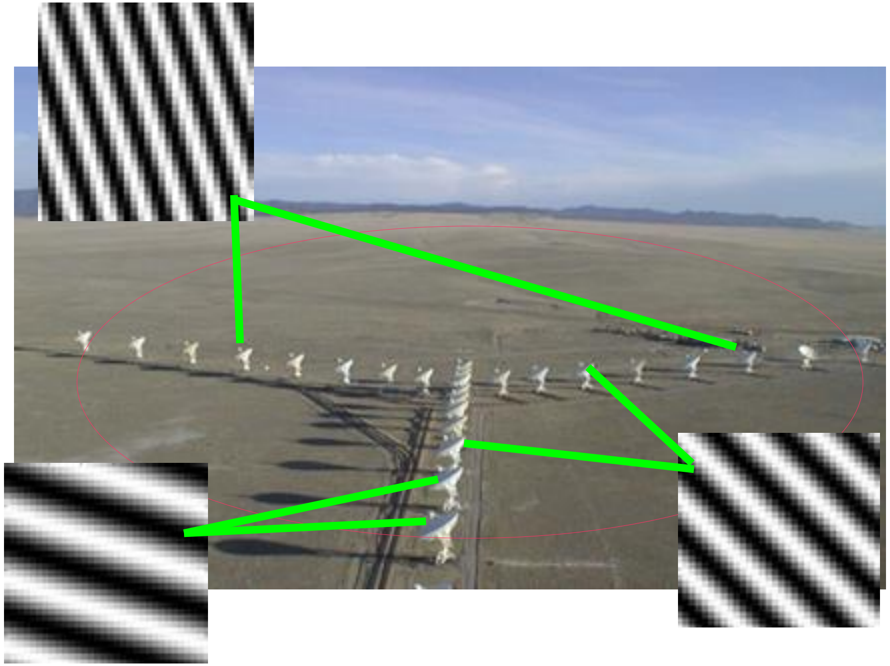
“ K-space Sampling “



An indirect imaging device

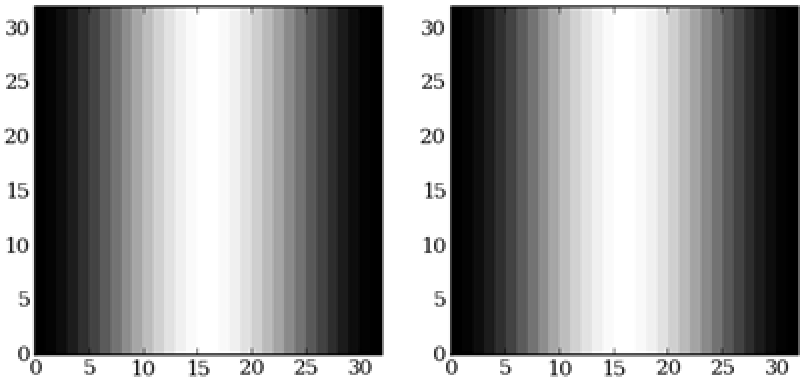


Young's double slit experiment

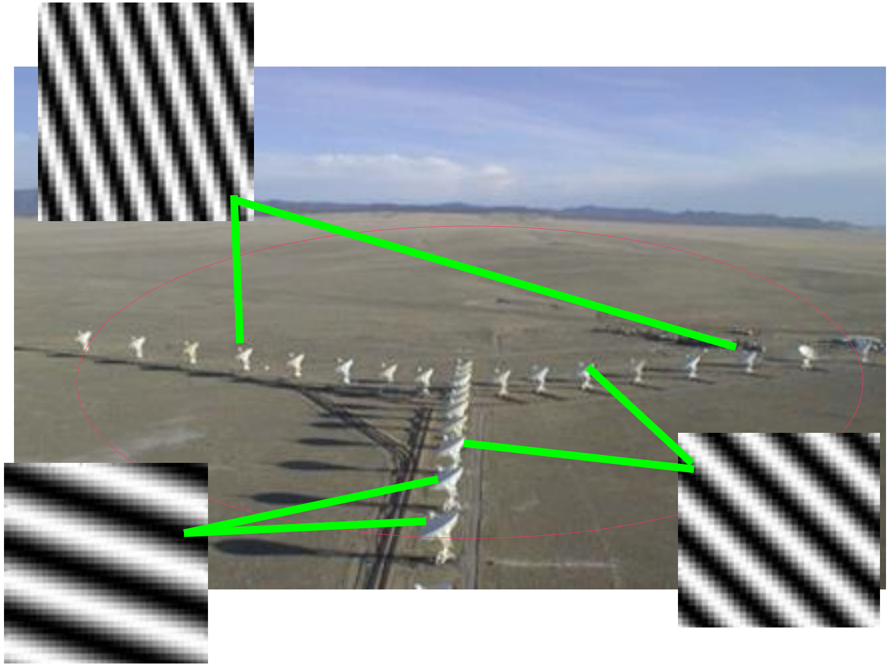


Imaging Interferometer : A detector array

An indirect imaging device

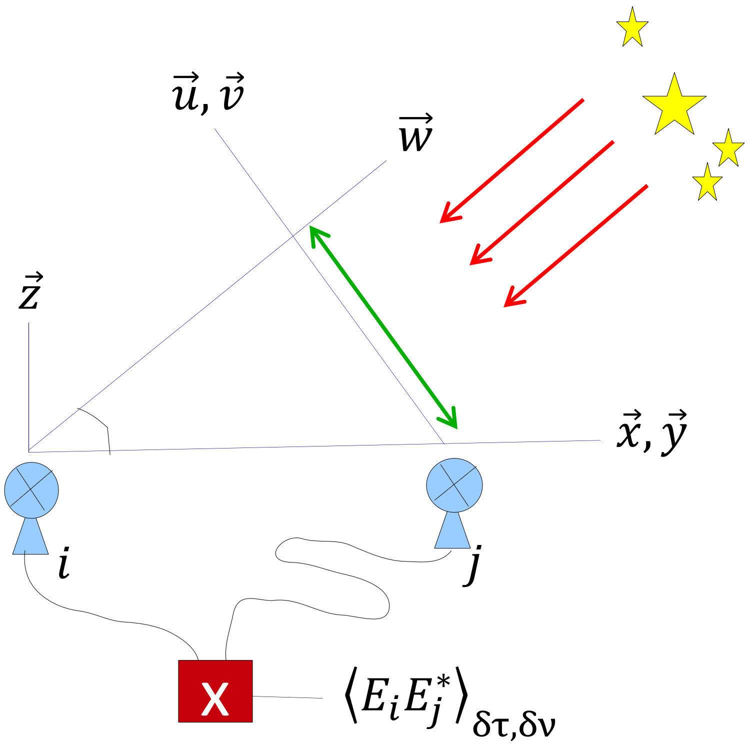


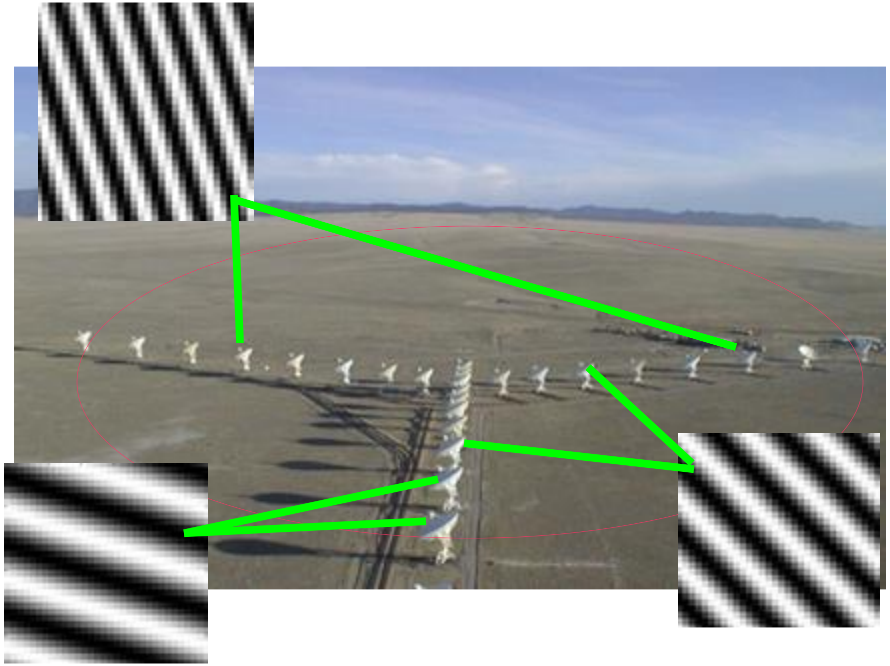
2D Fourier Series



Imaging Interferometer : A detector array

Measuring spatial frequency components

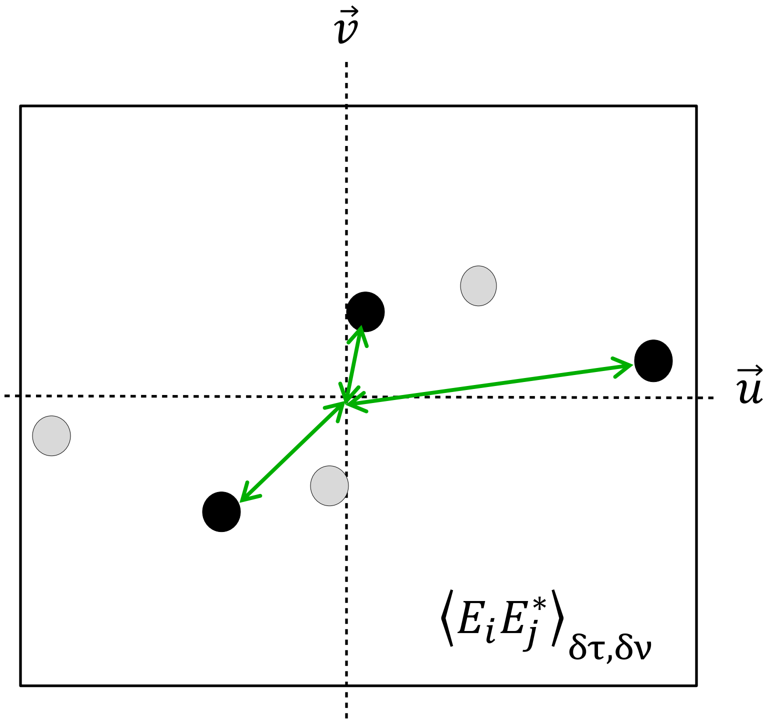




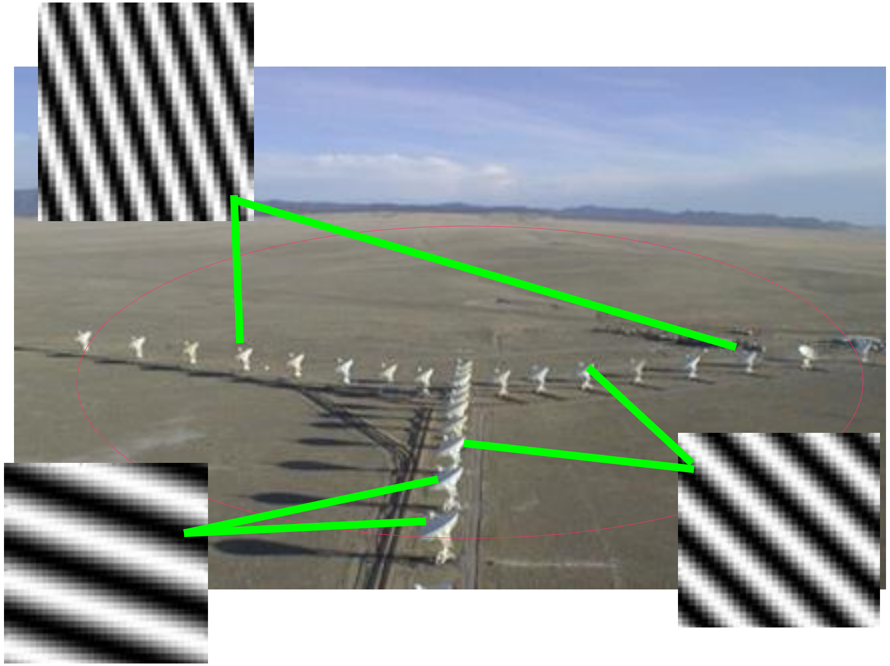
Imaging Interferometer : A detector array

Measure spatial coherence of incident E-field

Filling up the K-space



Sampling the " K-Space "



Imaging Interferometer : A detector array

(Spatial Frequency Domain, UV-domain)

Spatial Frequency (uv) coverage + Observed Image

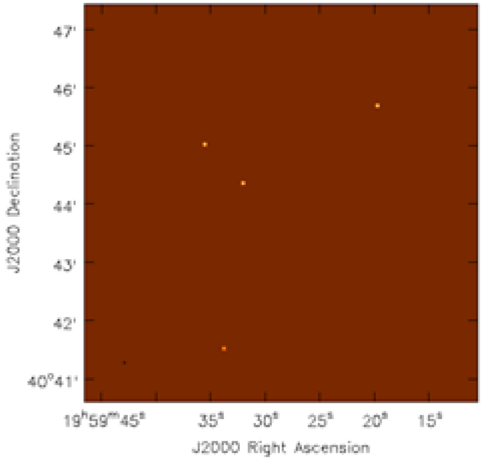
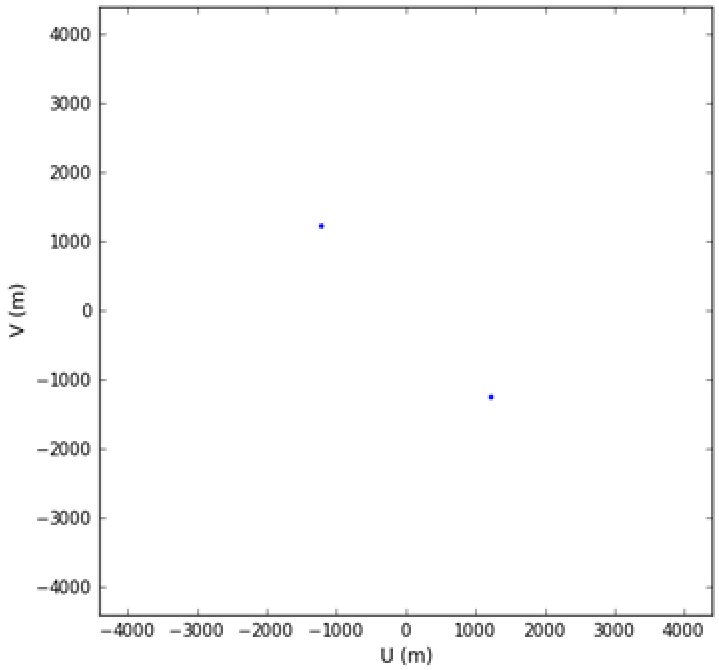
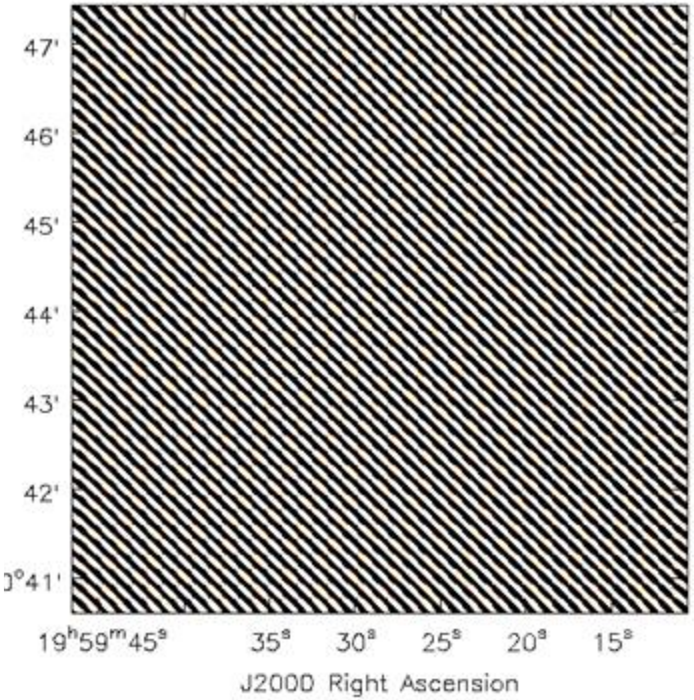


Image of the sky using **2** antennas

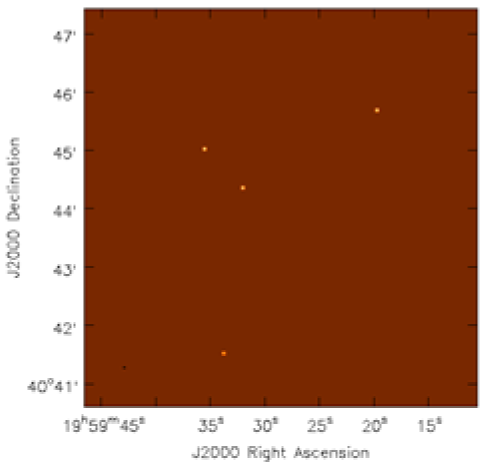
$S(u,v)$



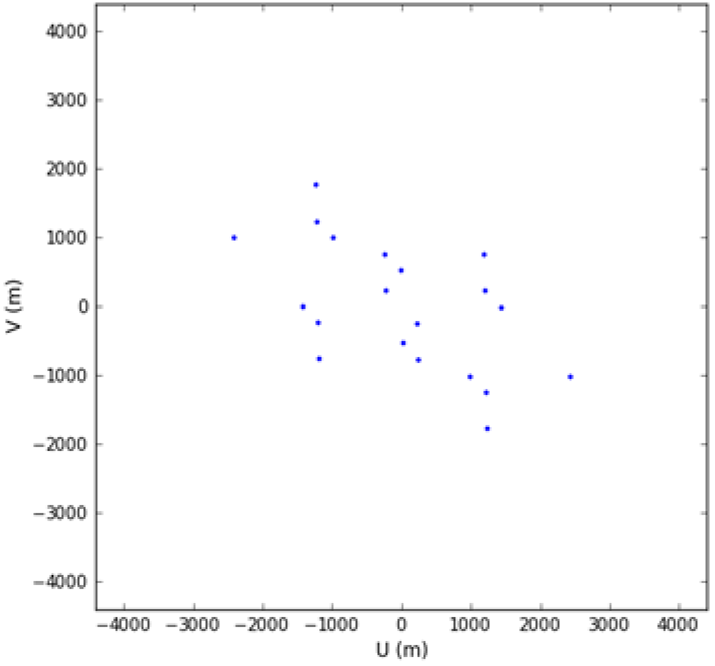
$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image



$S(u, v)$



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

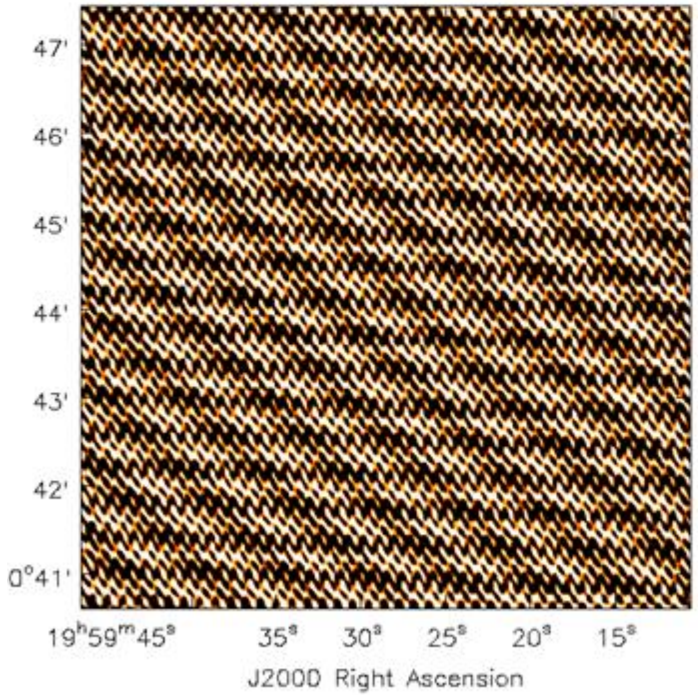


Image of the sky using **5** antennas

"Aperture Synthesis"

Spatial Frequency (uv) coverage + Observed Image

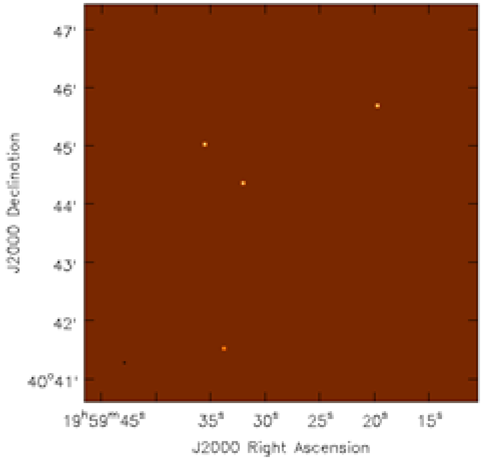
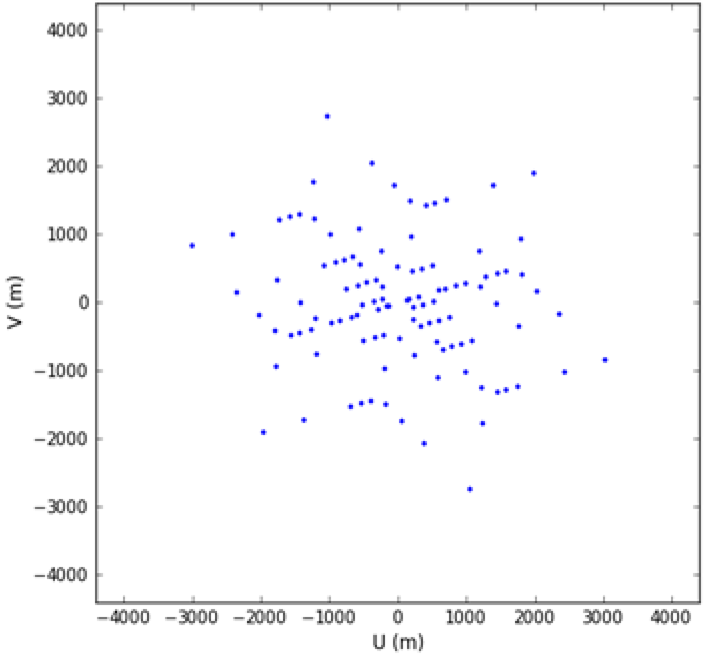


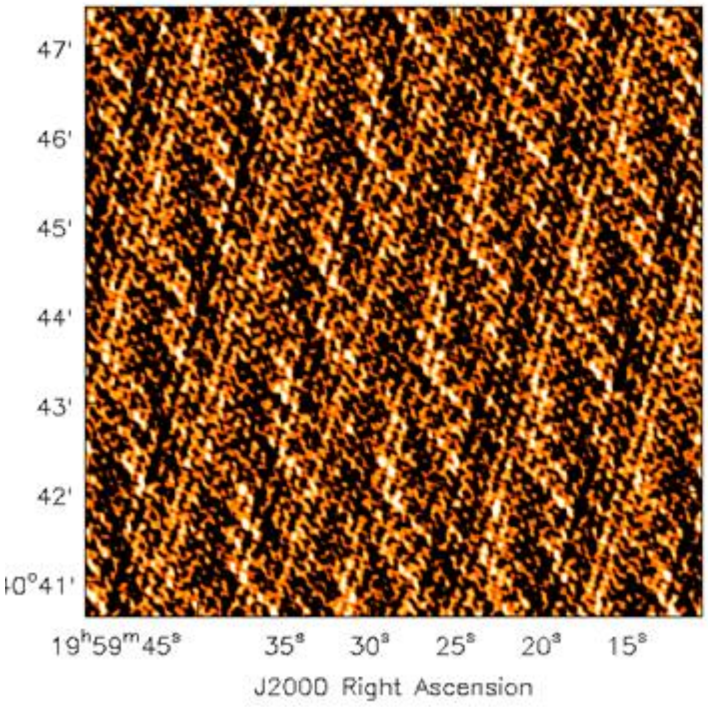
Image of the sky using **11** antennas

"Aperture Synthesis"

$S(u,v)$



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



Spatial Frequency (uv) coverage + Observed Image

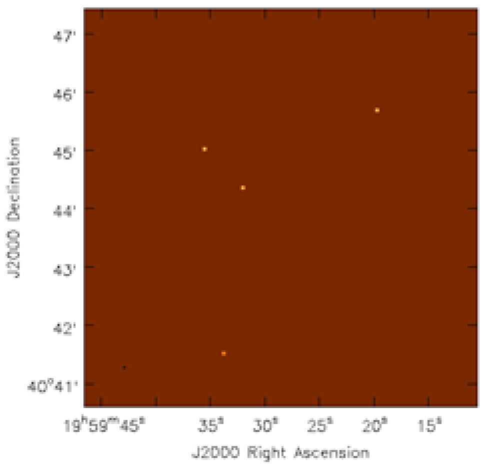
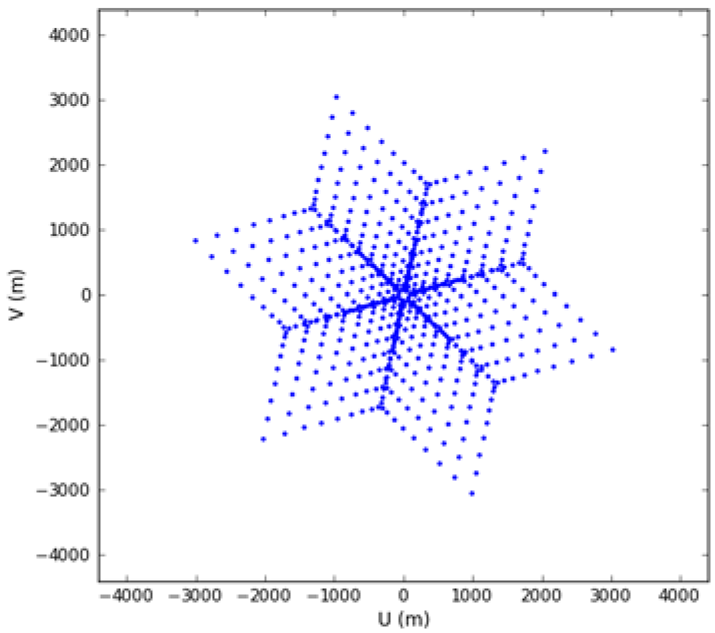


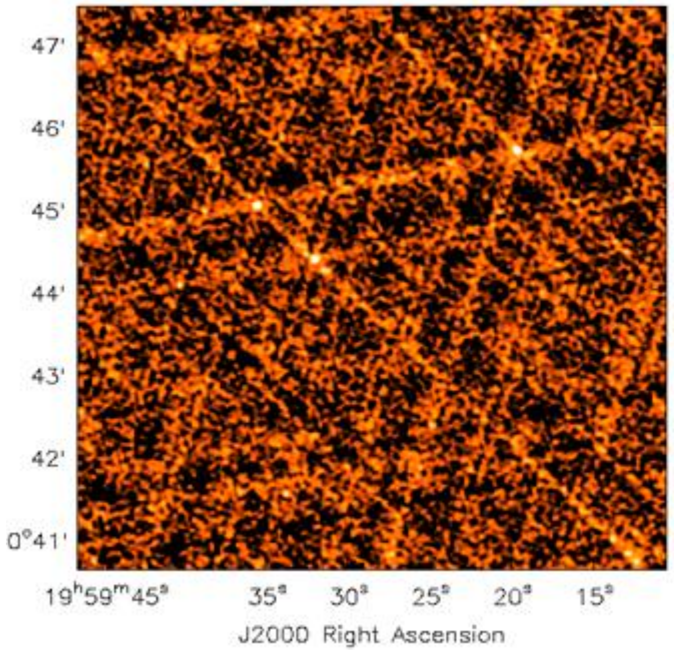
Image of the sky
using **27** antennas

“Aperture Synthesis”

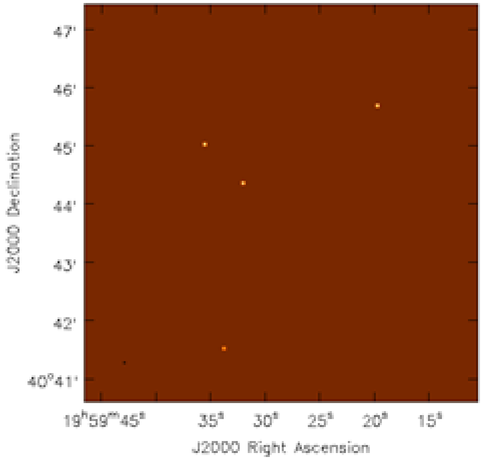
$S(u,v)$



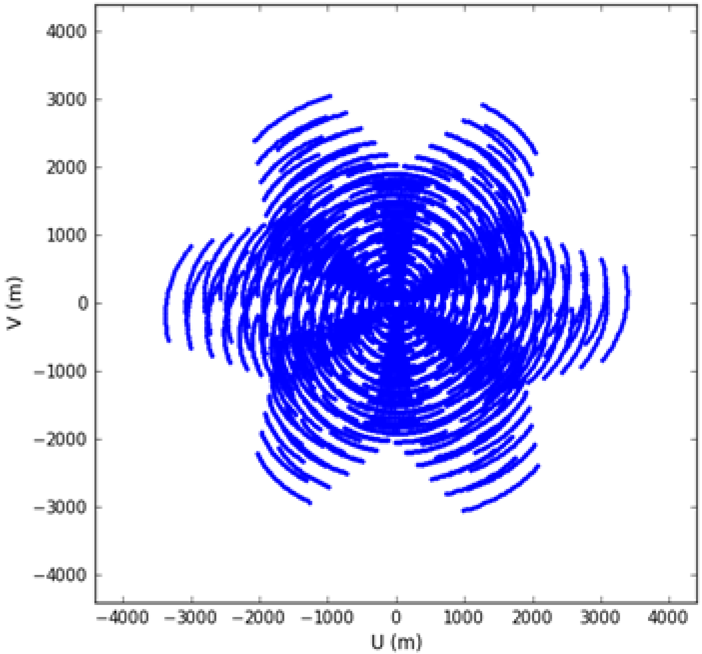
$I^{obs}(l,m)$



Spatial Frequency (uv) coverage + Observed Image



$S(u, v)$



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

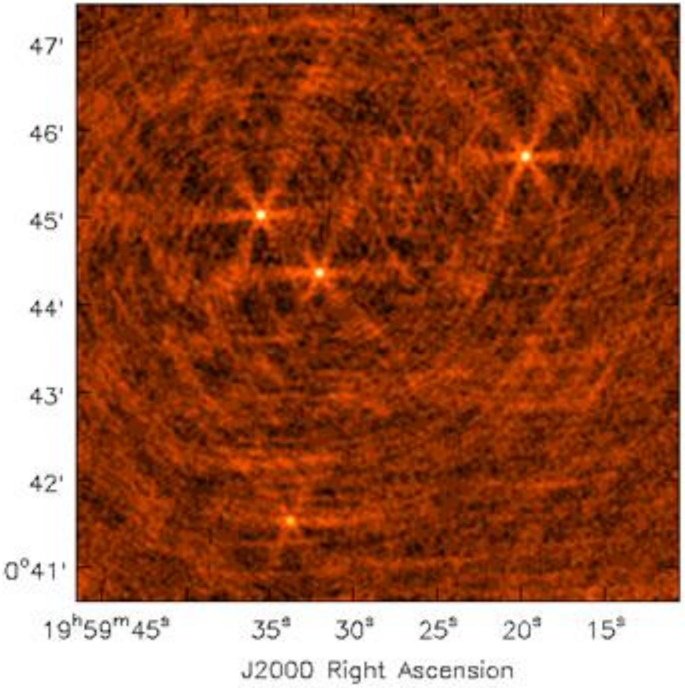


Image of the sky
using 27 antennas

Observation : **2 hours**

“Earth Rotation Synthesis”

Spatial Frequency (uv) coverage + Observed Image

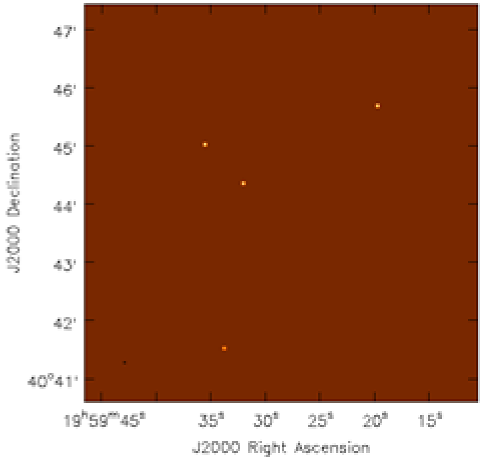
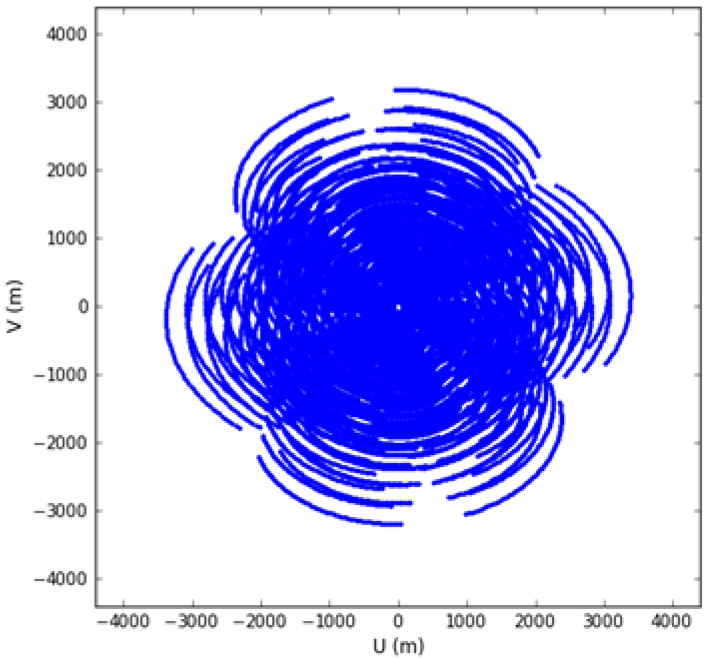


Image of the sky
using 27 antennas

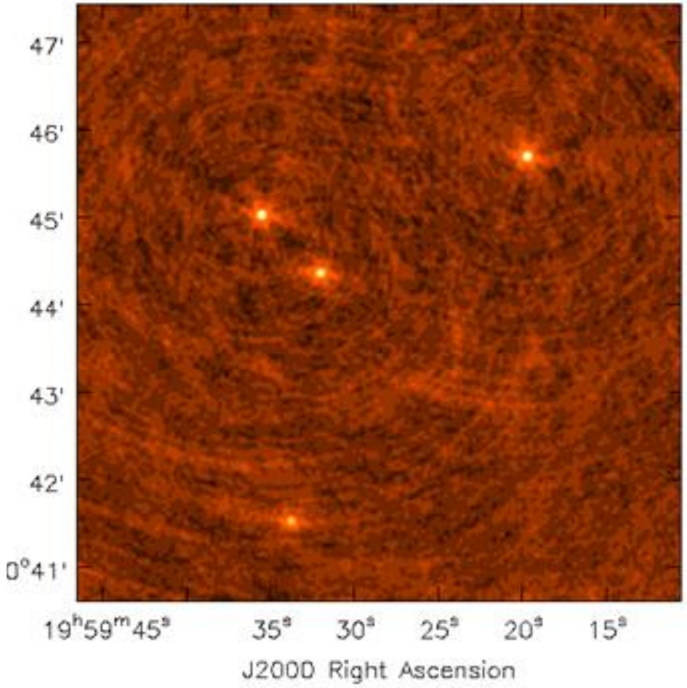
Observation : **4 hours**

"Earth Rotation Synthesis"

$S(u,v)$



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



Spatial Frequency (uv) coverage + Observed Image

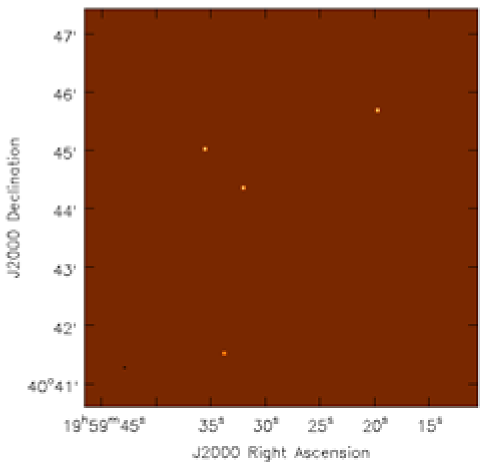
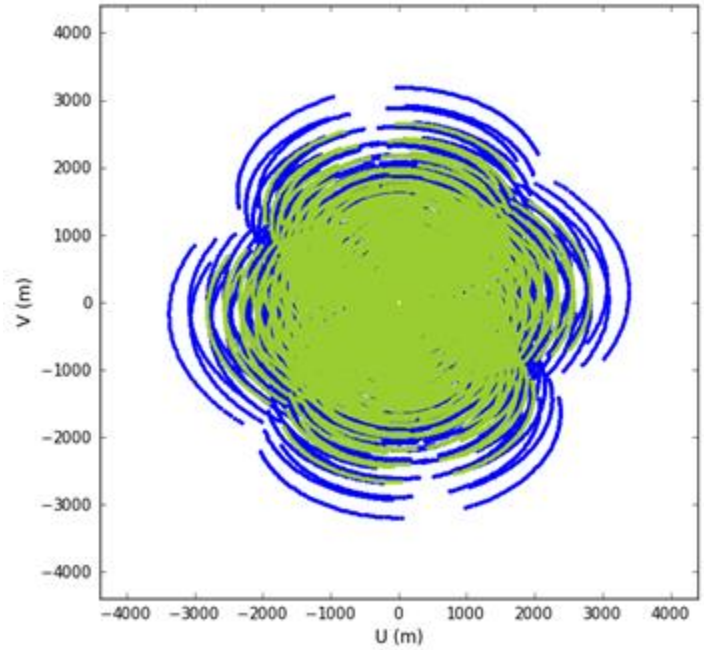
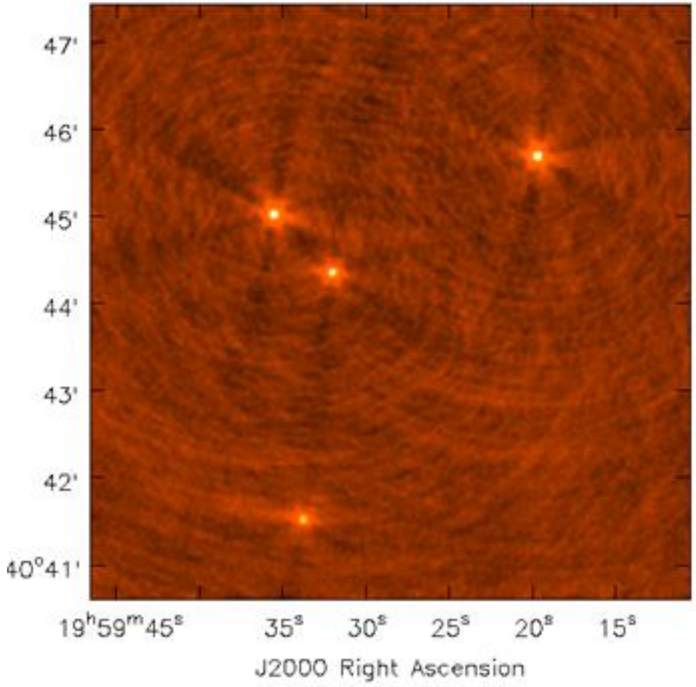


Image of the sky
using 27 antennas

$S(u, v)$



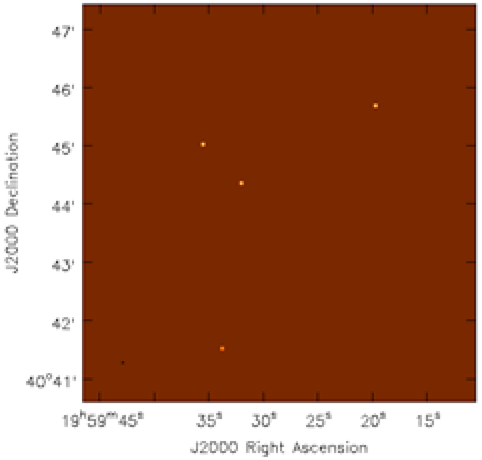
$I^{obs}(l, m)$



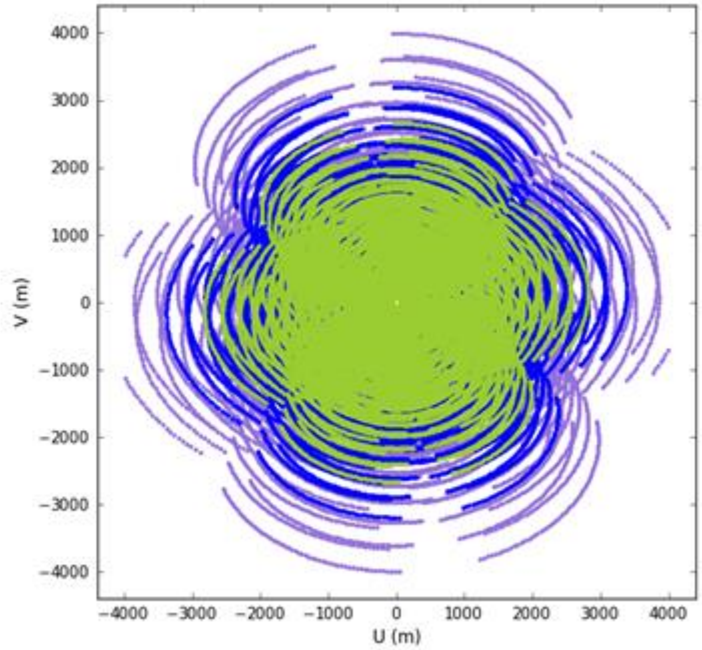
Observation : 4 hours, **2 frequency channels**

"Multi-Frequency Synthesis"

Spatial Frequency (uv) coverage + Observed Image



$S(u,v)$



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

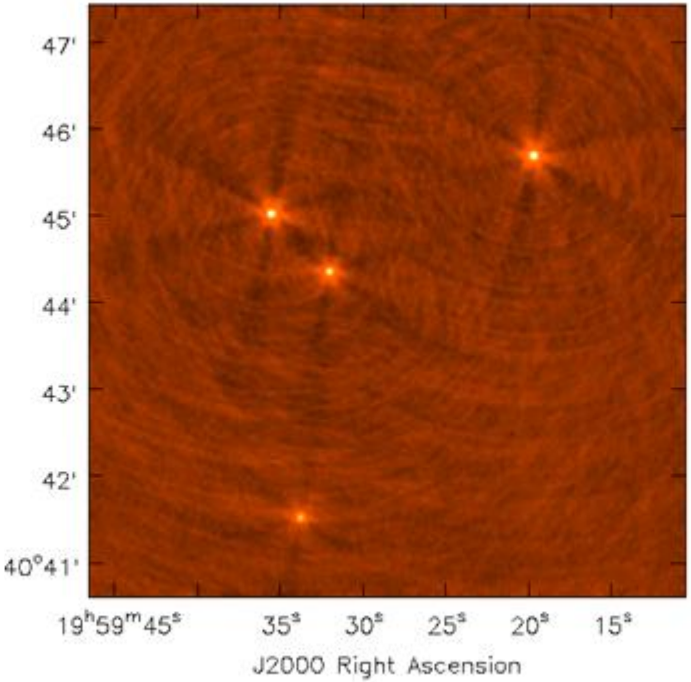


Image of the sky
using 27 antennas

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

"Multi-Frequency Synthesis"

The forward problem

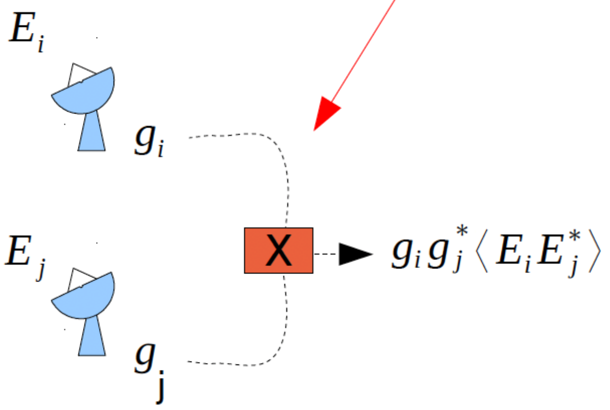
$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm$$

- $V_{ij}^{obs}(\nu,t)$ → Observed 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

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

The forward problem

- Observed visibilities (Data)
- Direction Independent Gains
- UV sampling pattern
- Sky Brightness (Image)
- Fourier transform kernel



Calibration

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

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

The forward problem

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

- $V_{ij}^{obs}(\nu,t)$: 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}

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

The forward problem

Observed or Calibrated visibilities (Data)

Direction Independent Gains

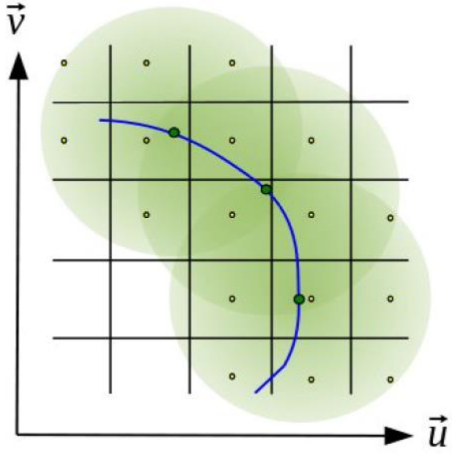
UV sampling pattern

Sky Brightness (Image)

Fourier transform kernel

Gridding
+
IFFT
+
Normalization

I^{obs}



Convolutional resampling

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

The forward problem

- $V_{ij}^{obs}(\nu,t)$: 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

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

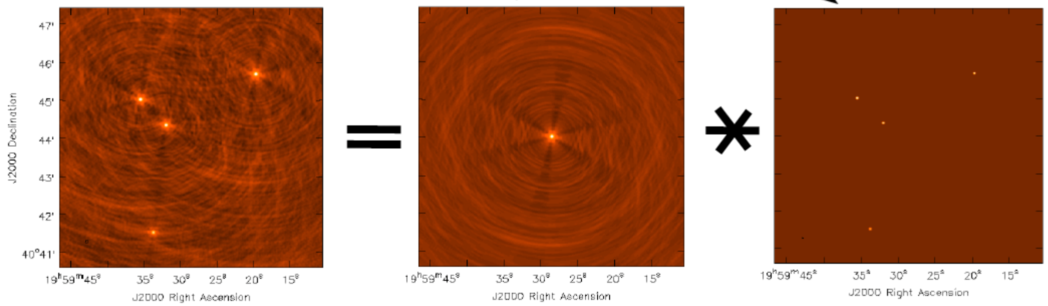


Image Reconstruction (deconvolution)

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} dl\, dm\, dn$$

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} \, dl \, dm \, dn$$

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.

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} \, dl \, dm \, dn$$

Direction Independent Gains

Direction Dependent Effects

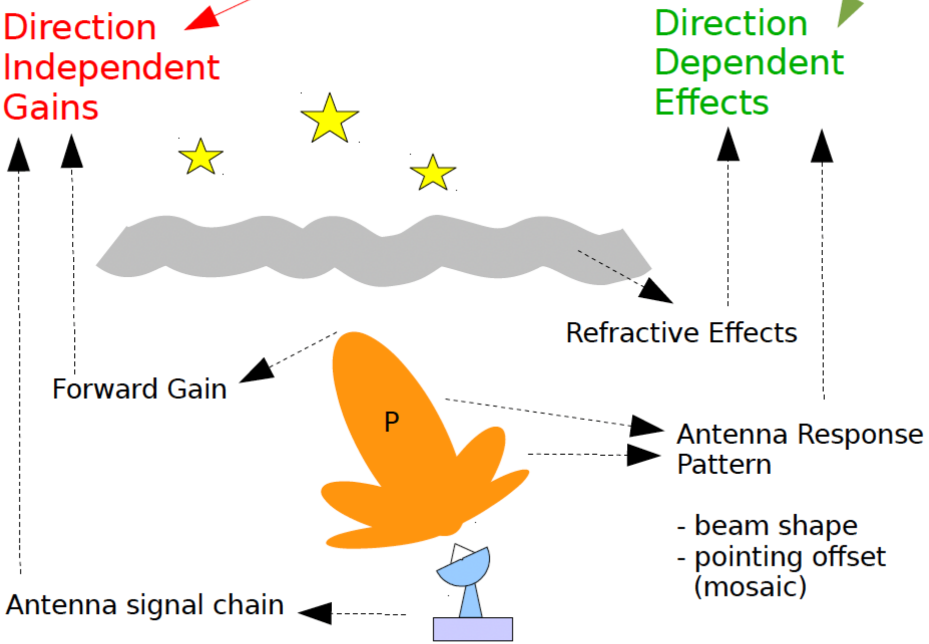
Sky-brightness varies with frequency (time)

W-Term

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i (ul+vm+w(n-1))} dl\, dm\, dn$$



The generalized forward problem

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

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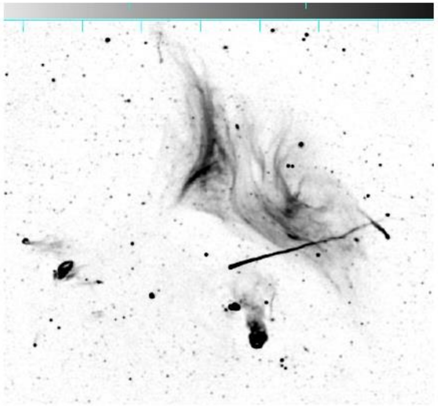
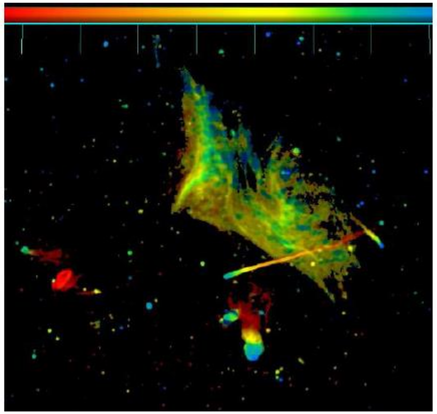
Sky-brightness varies with frequency

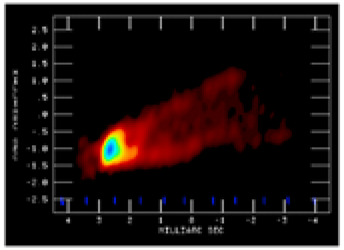
and time



Intensity



Intensity weighted Spectral Index



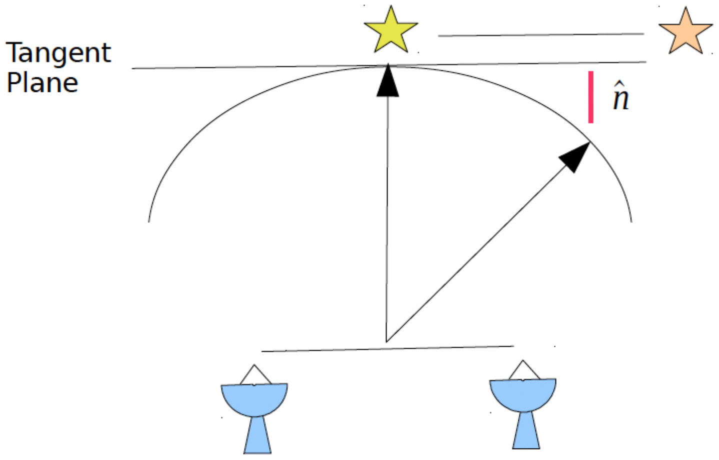
$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm$$

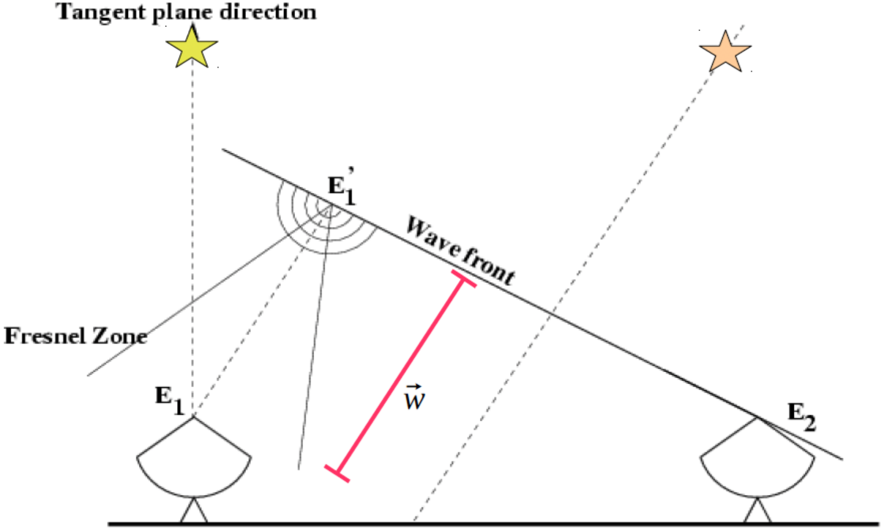
The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} dl\, dm\, dn$$

W-Term

Effect of Sky Curvature





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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} dl\, dm\, dn$$

Direction Independent Gains

UV sampling function

Direction Dependent Effects

Sky-brightness varies with frequency and time

W-Term

How do we solve these systems of 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 generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} dl\, dm\, dn$$

Direction Independent Gains

UV sampling function

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Sky-brightness varies with frequency and time

W-Term

Calibration

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))}\, dl\, dm\, dn$$

Direction Independent Gains

UV sampling function

Direction Dependent Effects

Sky-brightness varies with frequency and time

W-Term

Calibration

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

Inverse Imaging

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

The generalized forward problem

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t)\, I(l,m,\nu,t)\, e^{2\pi i(ul+vm+w(n-1))}\, dl\, dm\, dn$$

Direction Independent Gains

UV sampling function

Direction Dependent Effects

Sky-brightness varies with frequency and time

W-Term

Calibration

Image Reconstruction

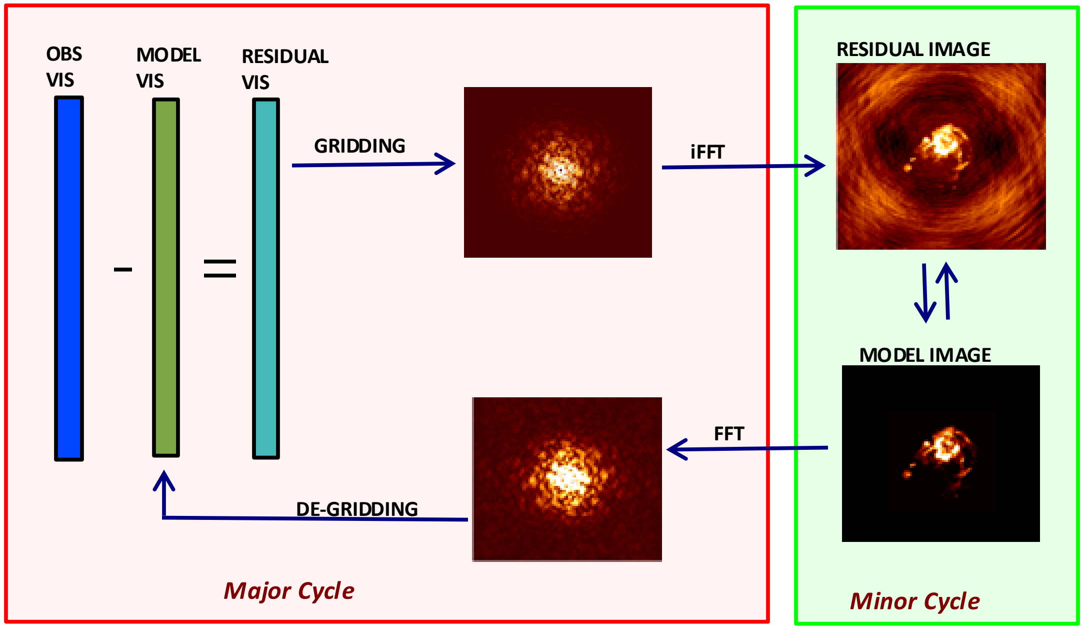
(De)convolution in the image domain

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

Inverse Imaging

Forward and Inverse Problems : Iterative Optimization algorithms

$$V^{obs} = [A] I^m + n \quad \Rightarrow \quad I^m = [A]^{-1} V^{obs}$$



Data regularization : L2 (chi-square)

Sky model

- Delta functions, Gaussians, Wavelets, etc, etc..
- Multi-frequency and time-variable models
- Astrophysics models (non-imaging)

Constrained Optimization

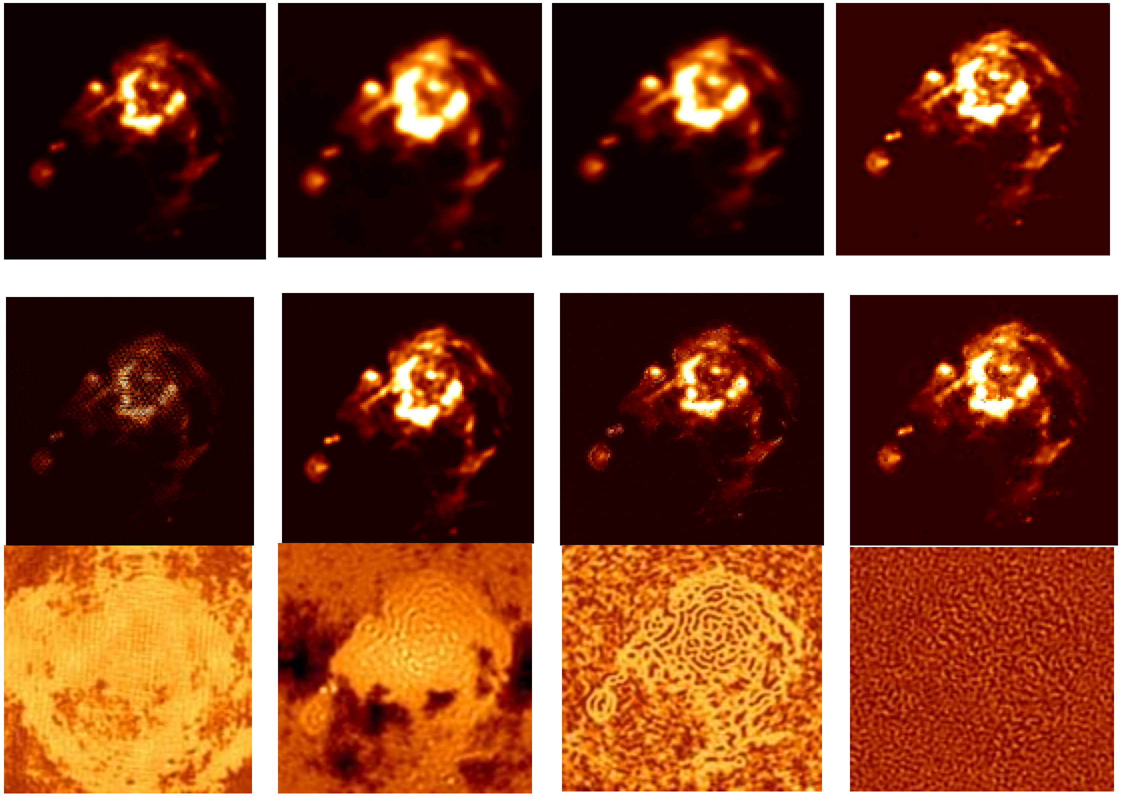
- Log power spectrum, positivity, smoothness
- Manual constraints : spatial masks, iteration control
- Greedy algorithms vs Parameterized solvers
- L1 , TV norm, etc...

Instrumental corrections

- Wide-field and wide-band antenna response patterns,
- Ionospheric refraction corrections
- 3D to 2D effects, K-space 'hole' effects.

Forward and Inverse Problems : Algorithm Variability

$$V^{obs} = [A]I^m + n \quad \longrightarrow \quad I^m = [A]^{-1}V^{obs}$$



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Instrumental corrections

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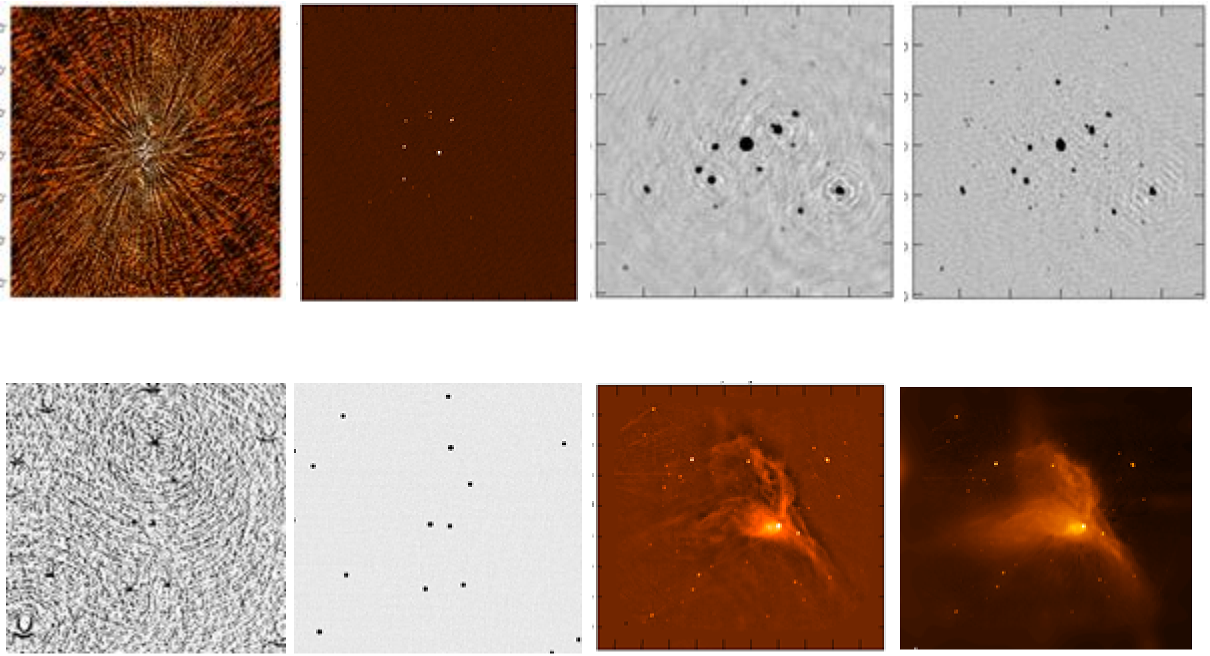
- Ionospheric refraction corrections
- 3D to 2D effects, K-space 'hole' effects.

Forward and Inverse Problems : Instrumental Corrections

$$V^{obs} = [A]I^m + n \quad \Rightarrow \quad I^m = [A]^{-1}V^{obs}$$



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Instrumental corrections

- Wide-field and wide-band antenna response patterns,
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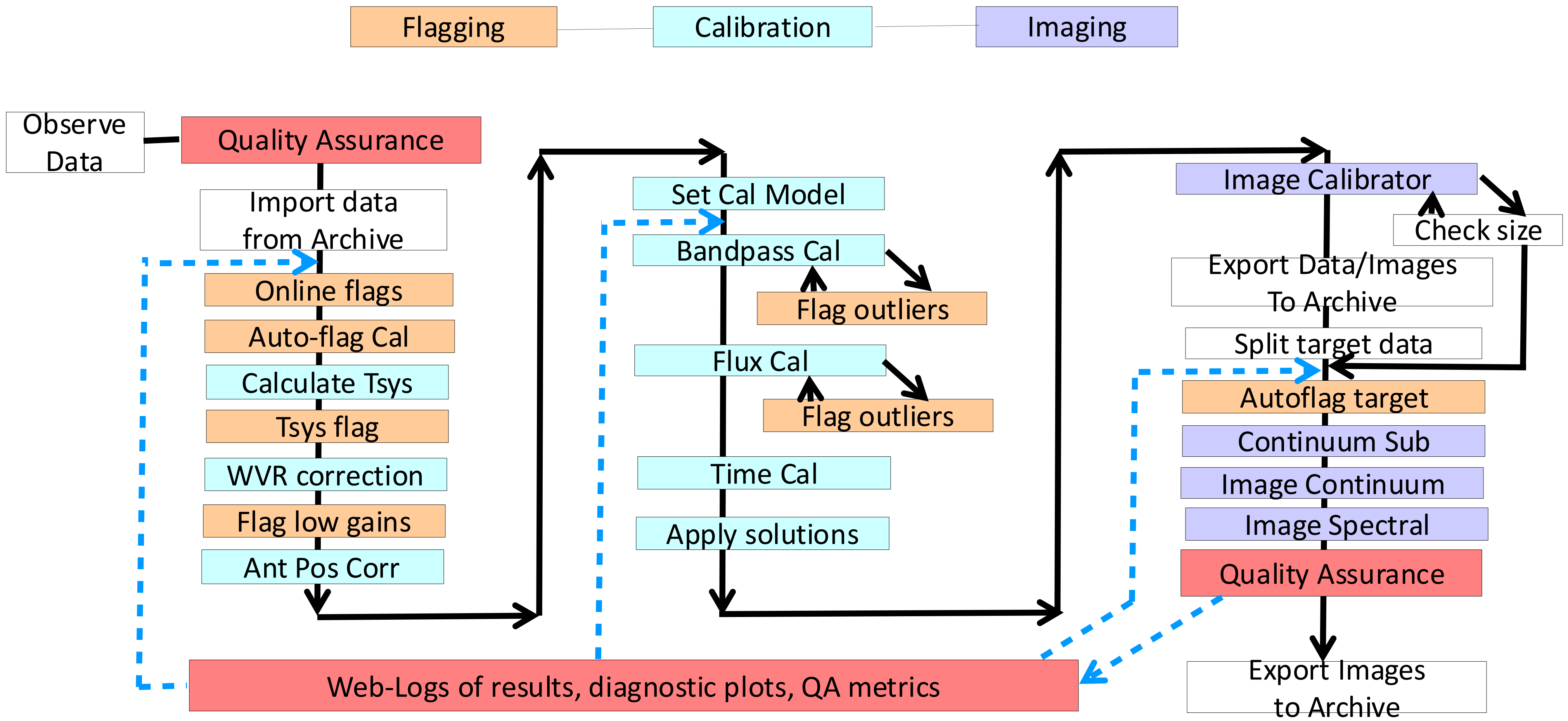
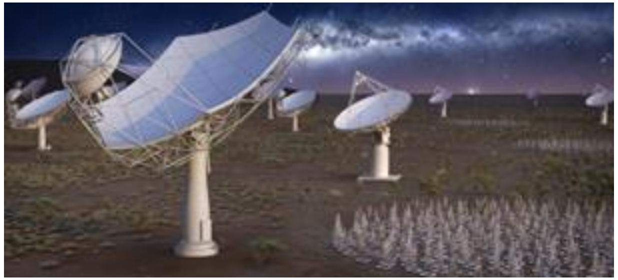
Operational Workflows



The R&D frontier

New Instruments : More sensitive, Lower image noise, Detect Fainter Sources
Larger Data Volume, Greater Algorithm Complexity



Square Kilometer Array (skatelescope.org)

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

Algorithms :

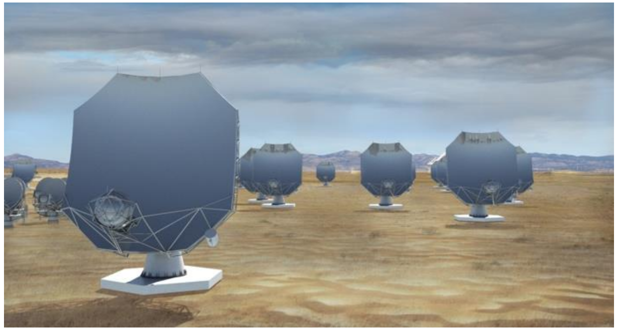
- A variety of sky models, instrument models, objective functions and regularizers, optimization strategies, the use of priors, etc..

=> Increased exploration of Machine Learning.

Compute Load :

- Data volumes : 10s to 100s of GB ➔ ngVLA/SKA : TeraBytes/PetaBytes/ExaBytes
- Image sizes : 10kx10k ➔ 200k x 200k pixels (with 10k channels and 4 pols)

=> High Performance and High Throughput Computing



Next Generation VLA (ngvla.nrao.edu)

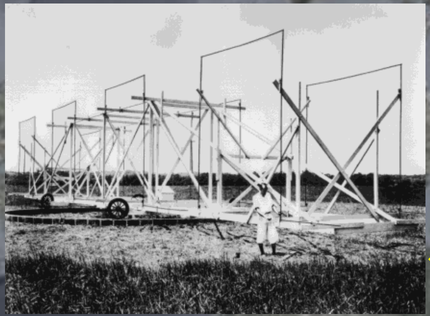
263 dishes (2 types) , 1-100 GHz

Workflow Automation :

- Data analysis pipelines that tune parameters for each dataset

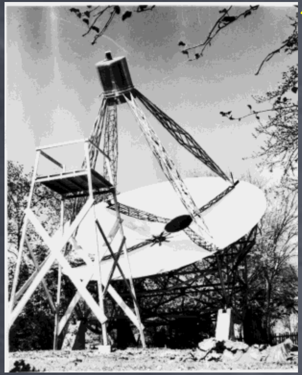
Radio Telescopes around the World

Radio Telescopes around the World



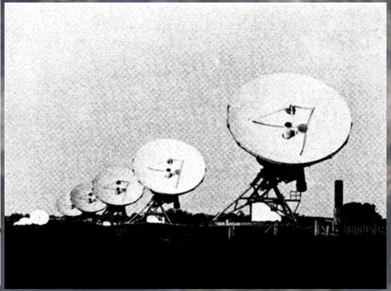
Karl Jansky (1933)

"Radio Waves from the Milky Way"



Grote Reber (1936)

"First All-Sky Radio Map"



Martin Ryle (1960+)

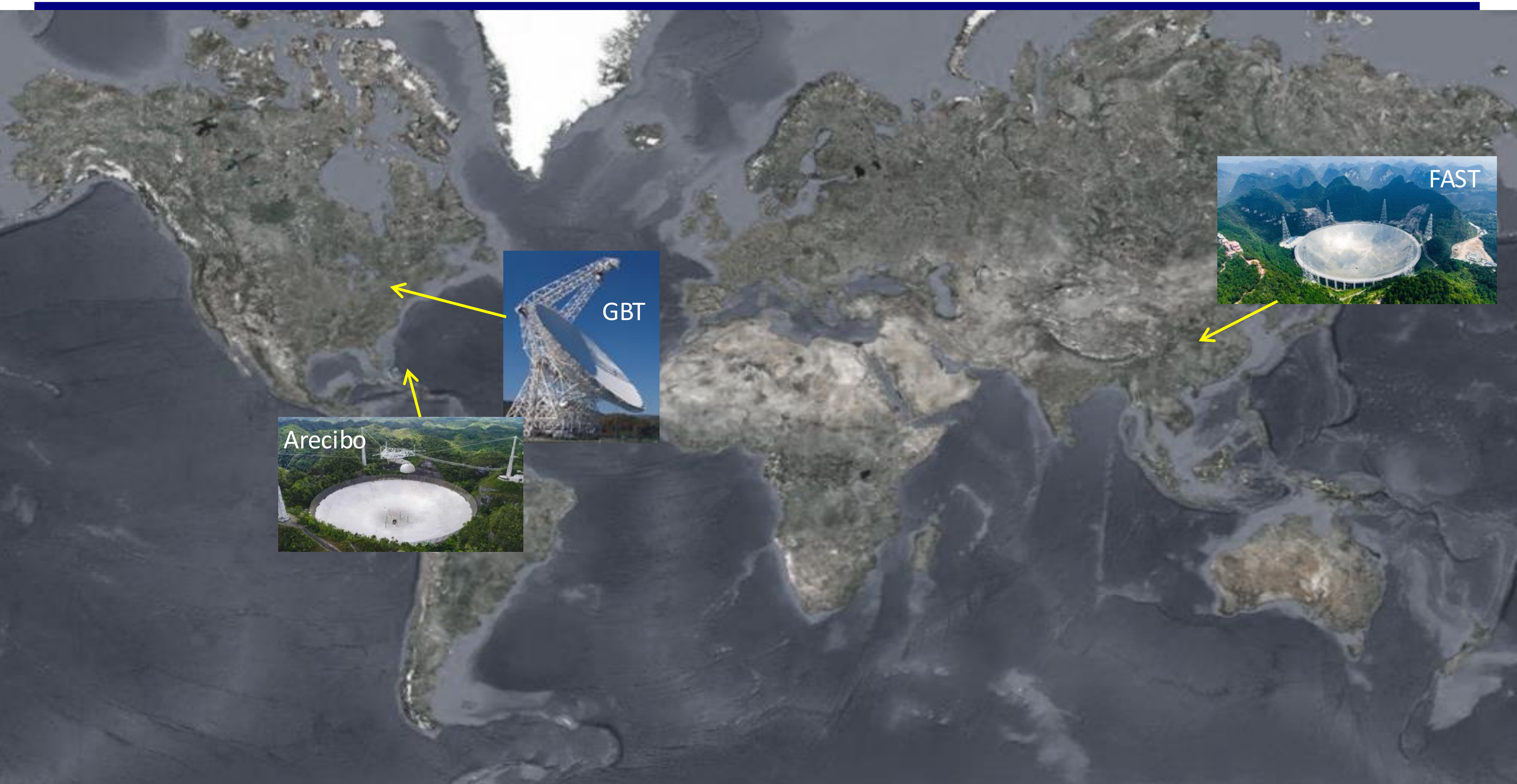
"First intentional sampling of spatial frequency (k-space) in radio astronomy"

Physics Nobel Prize : 1974

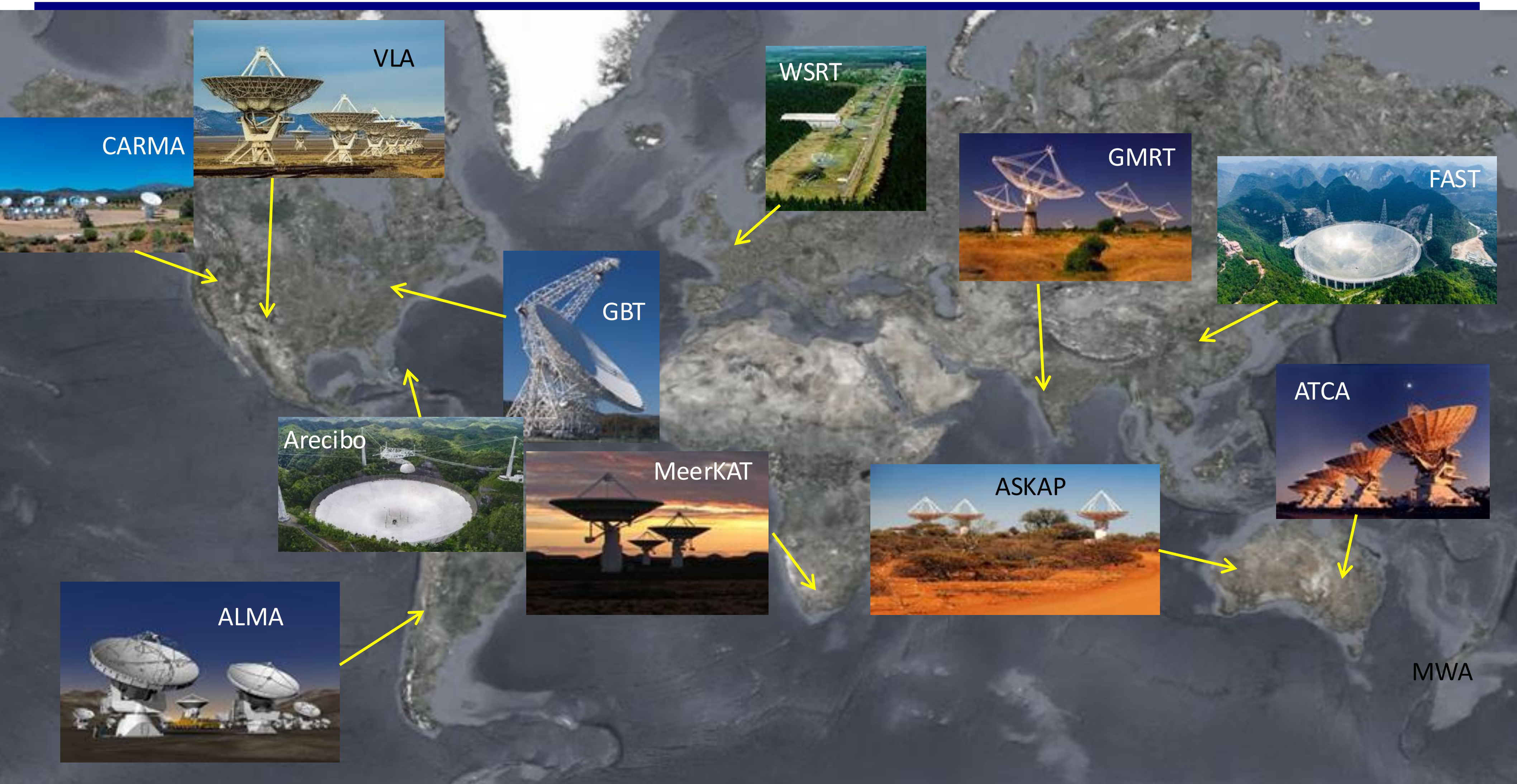
McCready, Pawsey, Payne-Scott. (1946)

"Used wave interference to infer spatial scale"

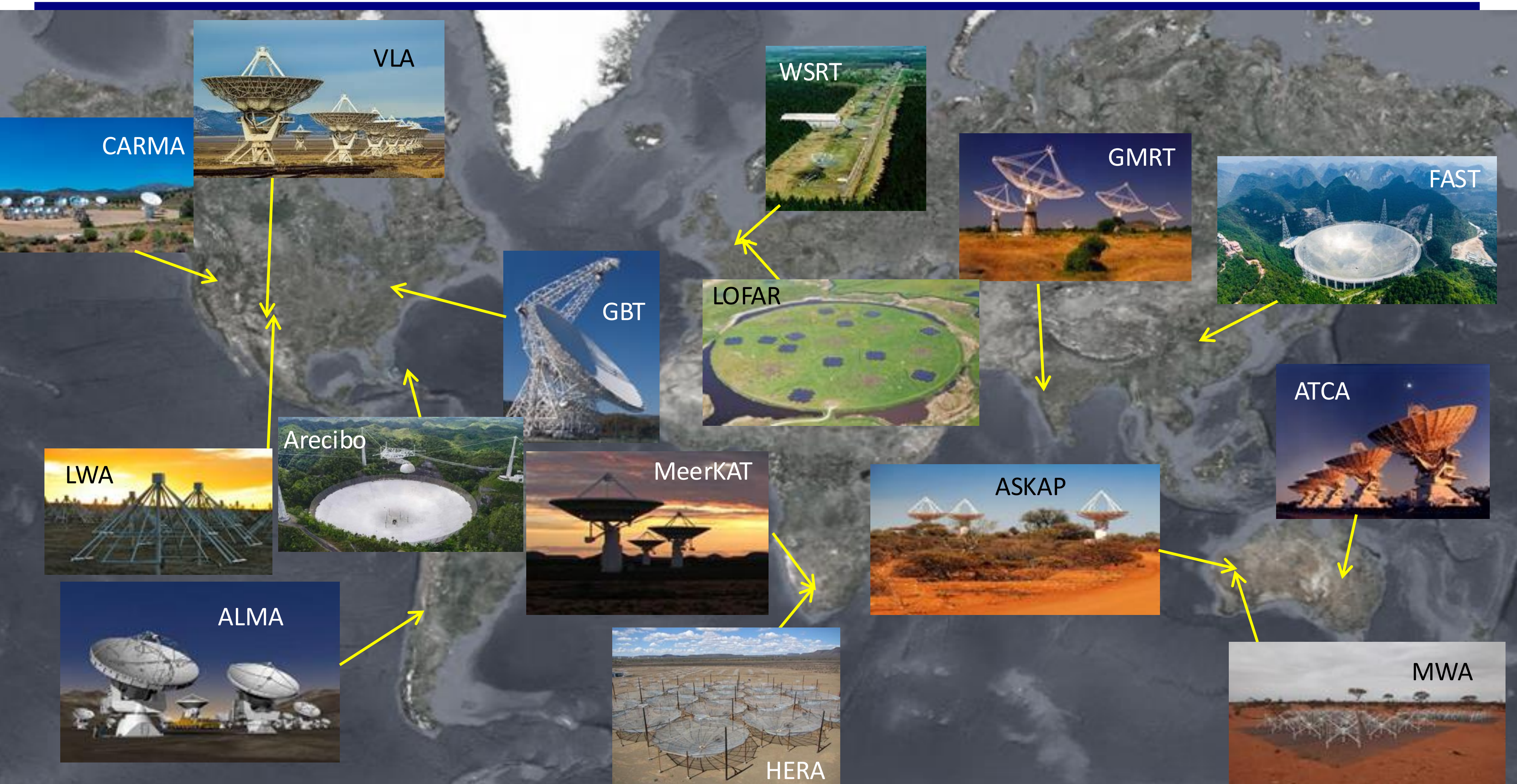
Radio Telescopes around the World



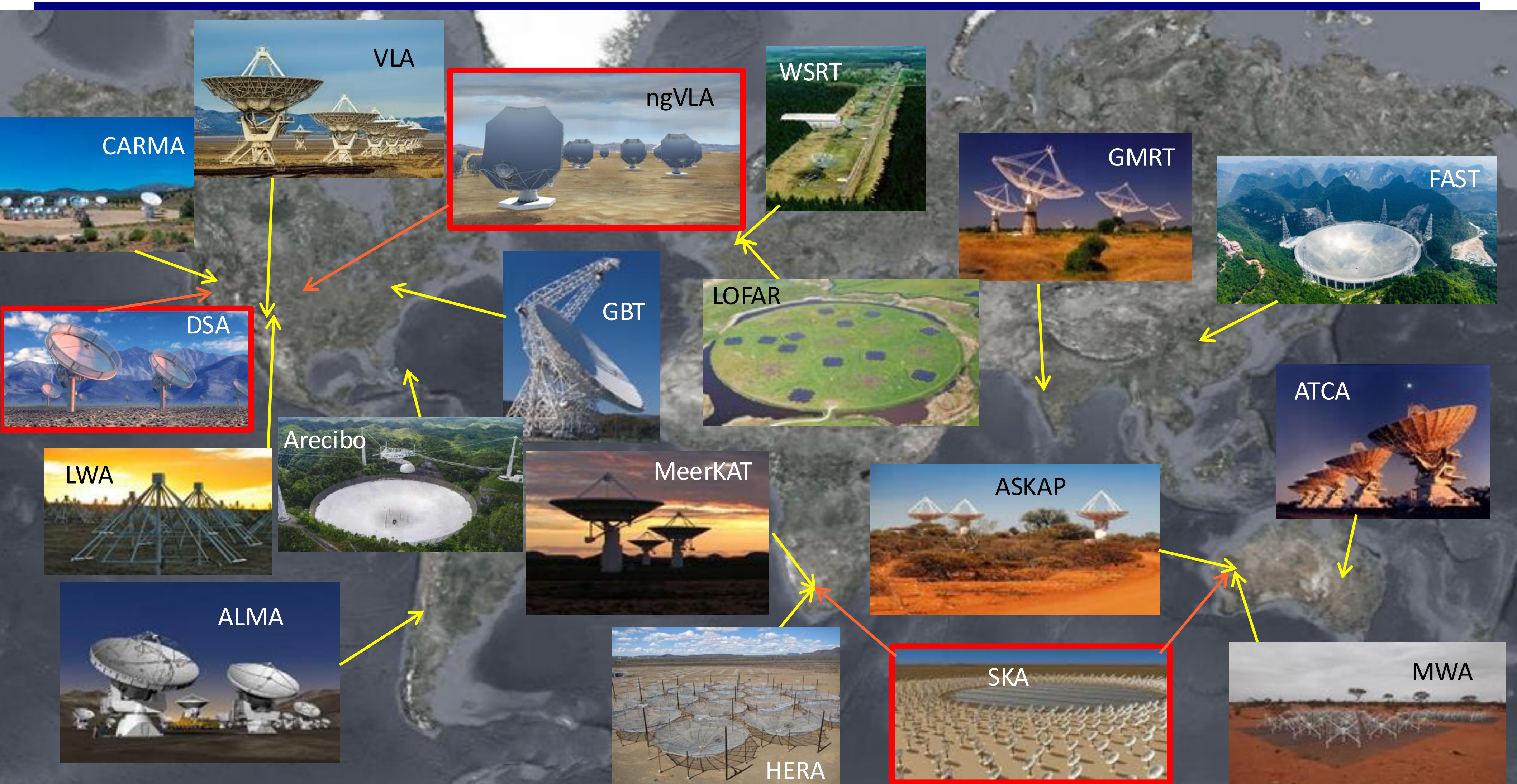
Radio Telescopes around the World



Radio Telescopes around the World

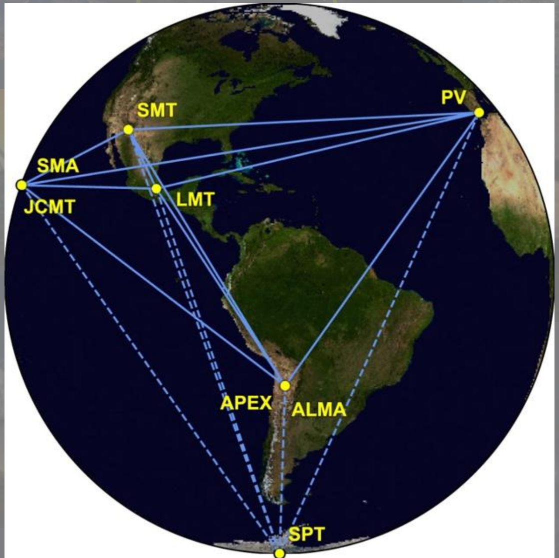


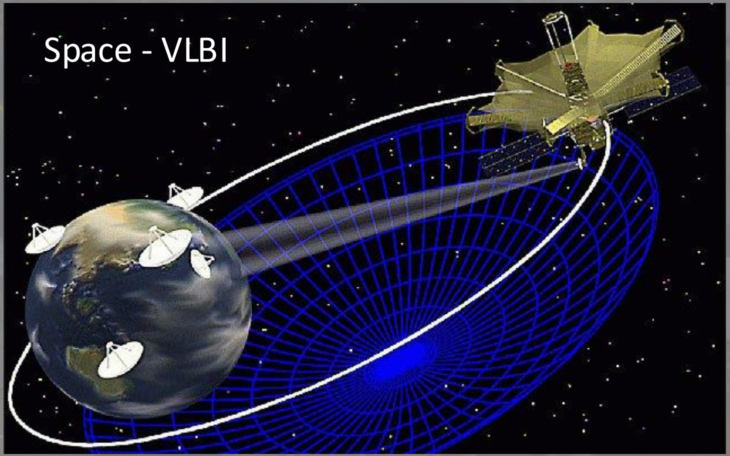
Radio Telescopes around the World



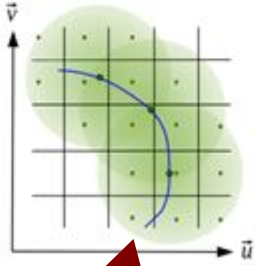
Radio Telescopes around the World

Event Horizon Telescope





Compute Cost



Gridding : Convolutional resampling

O(N_data) x (nxn) complex multiply/add (n=5 - 100)

Example : Major cycle : 1hr → 10 days (Diff Algorithms)

Data volume

N_data =
N_ant^2 x N_time
x N_chan x N_pol

Complex numbers

Lustre I/O

Example :
8hr data 300 GB

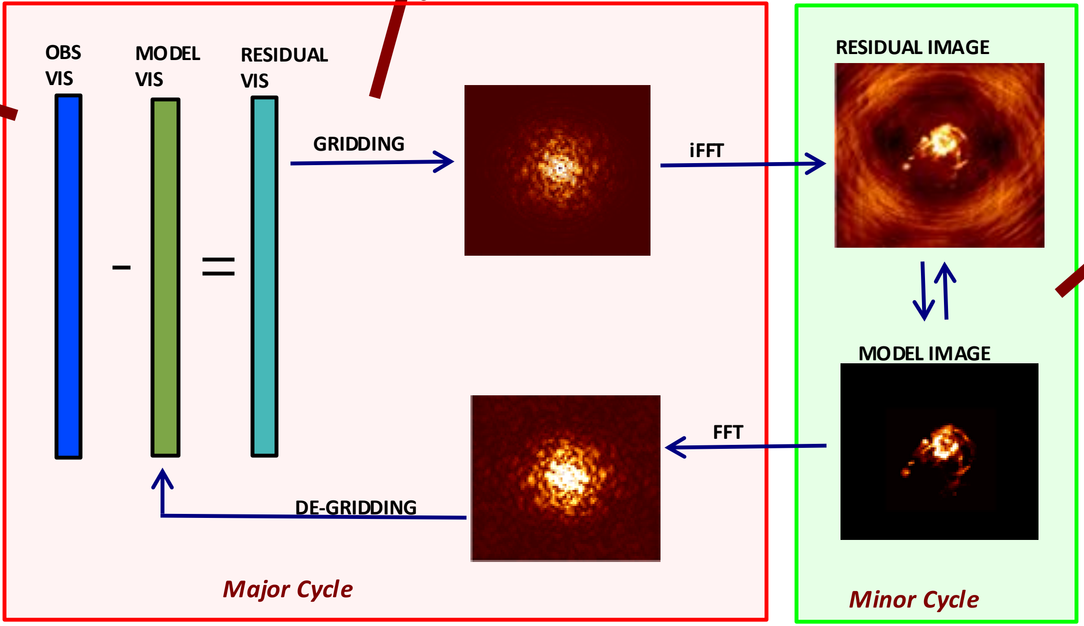


Image sizes

N_pix = Nx x Ny x
N_chan x N_pol

FFTs : O(NlogN)
Pixel math: O(N^2)
Mem : ~8 copies

Nx : 1k → 40k
N_chan : 200 - 16K

Example :
1K x 1K x 256
~1 GB per image

Number of iterations : 5 – 10 outer loops , 10^2 to 10^4 for regularization
Runtime varies by 1-2 orders of magnitude. Depends on data.