NenuFAR array map

~1400 m

~400 m diameter
N-antenna interferometer: (u,v) plane

\[
\frac{N \cdot (N - 1)}{2}
\]

antennas

Independent baselines

VLA
N-antenna interferometer: \((u,v)\) plane

\[ N \frac{N(N-1)}{2} \]

antennas

Independent baselines

VLA

uv coverage
N-antenna interferometer: \((u,v)\) plane

\[
\frac{N(N-1)}{2}
\]

antennas

Independent baselines

VLA
N-antenna interferometer: (u,v) plane

\[ \frac{N(N - 1)}{2} \]

antennas

Independent baselines

VLA
N-antenna interferometer: \((u,v)\) plane

\[
\frac{N(N - 1)}{2}
\]

antennas

Independent baselines

VLA
N-antenna interferometer: \((u,v)\) plane

\[
N \frac{N(N-1)}{2}
\]

antennas

Independent baselines

1 projected baseline

= 1 sample in the Fourier plane

\((\sim u,v)\) plane

VLA

uv coverage

150

100

50

0

-50

-100

-150

u (\lambda)

v (\lambda)

\(u\) and \(v\) are the baseline coordinates in the Fourier plane, which represent the differences in position between pairs of antennas. The formula \(N \frac{N(N-1)}{2}\) calculates the number of independent baselines for \(N\) antennas, indicating how many unique measurements can be made in the Fourier plane. The VLA (Very Large Array) is an example of such an interferometer array.
N-antenna interferometer: \((u,v)\) plane

\[
\frac{N(N-1)}{2}
\]

\(N\) antennas

Independent baselines

1 projected baseline
= 1 sample in the Fourier plane
\((\sim u,v)\) plane

\[
V(u,v) = \int \int T(l,m)e^{-2i\pi(ul+vm)}dldm
\]

Visibility function

(Simplification of the Van Cittert-Zernike Theorem)
Aperture synthesis imaging

In 1st approximation, an interferometer samples the sky Fourier transform

Brightness
Aperture synthesis imaging

In 1st approximation, an interferometer samples the sky Fourier transform

Brightness

FT\text{(Brightness)}

Continuous "visibility" function
Aperture synthesis imaging

In 1st approximation, an interferometer samples the sky Fourier transform

$$\text{Discrete sampling by interferometer}$$

$$\text{Continuous "visibility" function}$$

$$\text{FT}(\text{Brightness})$$

$$\text{FT}^{-1}(\text{Sampling function}) = \text{PSF}$$
Aperture synthesis imaging

In 1st approximation, an interferometer samples the sky Fourier transform

\[ \text{FT} \]

\[ \text{Brightness} \]

\[ \text{FT(Brightness)} \]

Continuous "visibility" function

Discrete sampling by interferometer

\[ \text{FT}^{-1}(\text{Sampling function}) = \text{PSF} \]

"Visibilities" = Fourier Samples

Dataset
Aperture synthesis imaging

In 1st approximation, an interferometer samples the sky Fourier transform.

Brightness $\rightarrow$ $\text{FT}$

**Continuous "visibility" function** $\text{FT}(\text{Brightness})$

**Discrete sample interferometer** $\text{FT}^{-1}(\text{Sampling function}) = \text{PSF}$

Dataset
## Measurement Set format

### Visibilities

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<tr>
<th>UVW</th>
<th>FLAG_CATEGORY</th>
<th>WEIGHT</th>
<th>SIGMA</th>
<th>ANTENNA1</th>
<th>ANTENNA2</th>
<th>ARRAY_ID</th>
<th>DATA_DESC_ID</th>
<th>EX</th>
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**NRAO Standard**

**NICKEL "=" COBALT-II (LOFAR)**
# Measurement Set format

## Data columns

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<th>MODEL_DATA</th>
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<th>IMAGING_WEIGHT</th>
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## Measurement Set format

### Subtables

<table>
<thead>
<tr>
<th>Table data data</th>
<th>Table keywords data</th>
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<tbody>
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<td><strong>Table Browser</strong></td>
<td><strong>L24921_SB005_uv.dppp.MS</strong></td>
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</table>

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<th>Extra Information</th>
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<td>Float 2</td>
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<td><strong>ANTENNA</strong></td>
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<tr>
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<td><strong>7</strong></td>
<td><strong>HISTORY</strong></td>
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<td><strong>OBSERVATION</strong></td>
<td>Table /home/julien.girard/L24921_SB005_uv.dppp.MS/OBSERVATION Information on the observation (program N#, PI, etc.) Subtable has 1 rows.</td>
</tr>
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</tr>
</tbody>
</table>

Browsing table: /home/julien.girard/L24921_SB005_uv.dppp.MS
From visibilities to images?

Set of complex visibilities

Calibration & Imaging & deconvolution

Brightness distribution
Calibration
Calibration
Calibration
Calibration

Optical equivalent
Imaging

Combining calibrated visibilities into an image

Fourier Space
Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage

Discrete sampling of the Fourier space
Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage

Image from Data = « True » sky * PSF = "Dirty" image
Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage

Discrete sampling of the Fourier space

Image from Data = "True" sky * PSF = "Dirty" image

\[ \sim FT^{-1} \]
Fourier plane
Snapshot (u,v) Coverage

Image from Data = « True » sky * PSF = "Dirty" image

Deconvolution
Imagerie / Inverse problem

Usually:
• bad sampling in Fourier space
• not really a Fourier transform
• simplifying hypothesis no longer valid

Unsufficient sampling
Non-coplanarities
Small field approximation

+ all direction-dependent effects (DDE) (Beam, ionosphere...)

Hard Inverse problem
Deconvolution

Imaging / Inverse problem

\[ y = H x + n \]
Deconvolution

Imaging / Inverse problem

\[ Y = HX + N \]

Visibility
dey 😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊😊 noexcept)

We will use "CLEAN" (Hogbom, 1964 and recent derivates)
Deconvolution

Imaging / Inverse problem

\[ T^D(l,m) \]

restored image

ellipse = clean beam fwhm

Images from D. Wilner, NRAO
Deconvolution - Algorithms beyond CLEAN

- ~40 years of development

Array factor only (PSF)

W-term only (Casa)

Multifrequency, Multiscale CLEAN…

Tasse et al. 2012
Deconvolution - Algorithms beyond CLEAN

- ~40 years of development
- Today, accounting for Direction-dependent effects

W-term only (Casa)

Array factor only (PSF)

Tasse et al. 2012
Deconvolution - Algorithms beyond CLEAN
- ~40 years of development
- Today, accounting for Direction-dependent effects

W-term + array factor

Array factor only (PSF)

Non-coplanarity (and/or wide field of view) ("W-term" ≠ 0)

Tasse et al. 2012
Deconvolution - Algorithms beyond CLEAN

- ~40 years of development
- Today, accounting for Direction-dependent effects

W-term + array factor + element beam

Array factor only (PSF)

Non-coplanarity (and/or wide field of view) ("W-term" ≠ 0)

Antenna beam pattern ("E-term")

Tasse et al. 2012
Diagramme d’antenne

Direction-Dependent Effects

100-250 MHz

30-80 MHz

Direction 1 affecte le gain

la polarisation

Direction 2
Diagramme d’antenne

Fluctuations ionosphériques/atmosphériques

Direction-Dependent Effects

100-250 MHz

30-80 MHz

Direction 1
affecte le gain
la polarisation

Direction 2

Plan d’onde incident

Ionosphere

Plan d’onde émergent

affecte le gain
la phase
la polarisation

PSF

PSF + ionosphère
Direction-Dependent Effects

$V_{pq}$
Direction-Dependent Effects
Direction-Dependent Effects

\[ J^p = J_n \ J_{n-1} \ldots \ J_2 \ J_1 \]

\[ J^q = J_n \ J_{n-1} \ldots \ J_2 \ J_1 \]
Direction-Dependent Effects

\[ J = J_n J_{n-1} \ldots J_2 J_1 \]

From the source to the antenna

\[ J = B G D E P T \]
Direction-Dependent Effects

Radio Interferometer Measurement Equation

\[ V_{pq} = J_p \mathcal{B} J_q^H \]

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]
Direction-Dependent Effects

Radio Interferometer Measurement Equation

\[ V_{pq} = J_p \mathbf{B} J_q^H \]

- Visibility from baseline pq
- Effects from the source to antenna p
- Brightness
- Effects from the source to antenna q

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]
Direction-Dependent Effects

Radio Interferometer Measurement Equation

\[ V_{pq} = J_p \mathbf{\beta} J_q^H \]

Visibility from baseline pq  Effects from the source to antenna p  Brightness  Effects from the source to antenna q

Compact, intuitive and linear representation of propagation effects
Now Mandatory for the calibration of large interferometers
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Thursday
Hands-on

Basic tutorial  First light NenuFAR Data  Vir A

Data statistics quicklook  Aoqplot (AOflagger)
Flagging  DPPP
Calibration (DI)  DPPP
Solution inspection  LoSoTo
Imaging / Deconvolution  WSClean
(Source finding)  Pybdsf

Advanced Imaging tutorial  NCP NenuFAR Data

Data statistics quicklook
Impact of A-team
Building Sky model
Calibration (DDE)
Imaging
A-team subtraction
Source finding

Mix of python, DPPP, LoSoTo, …