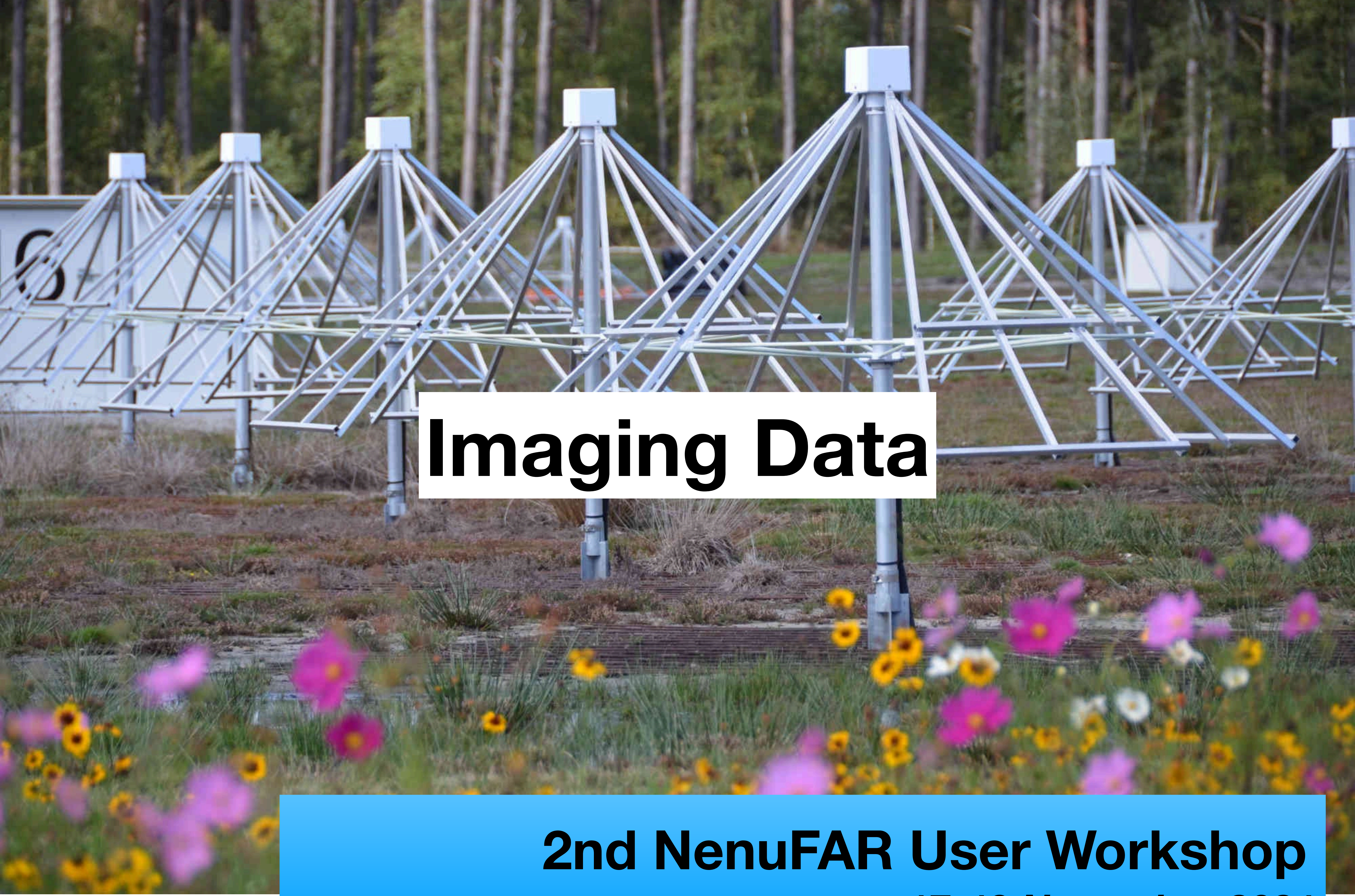
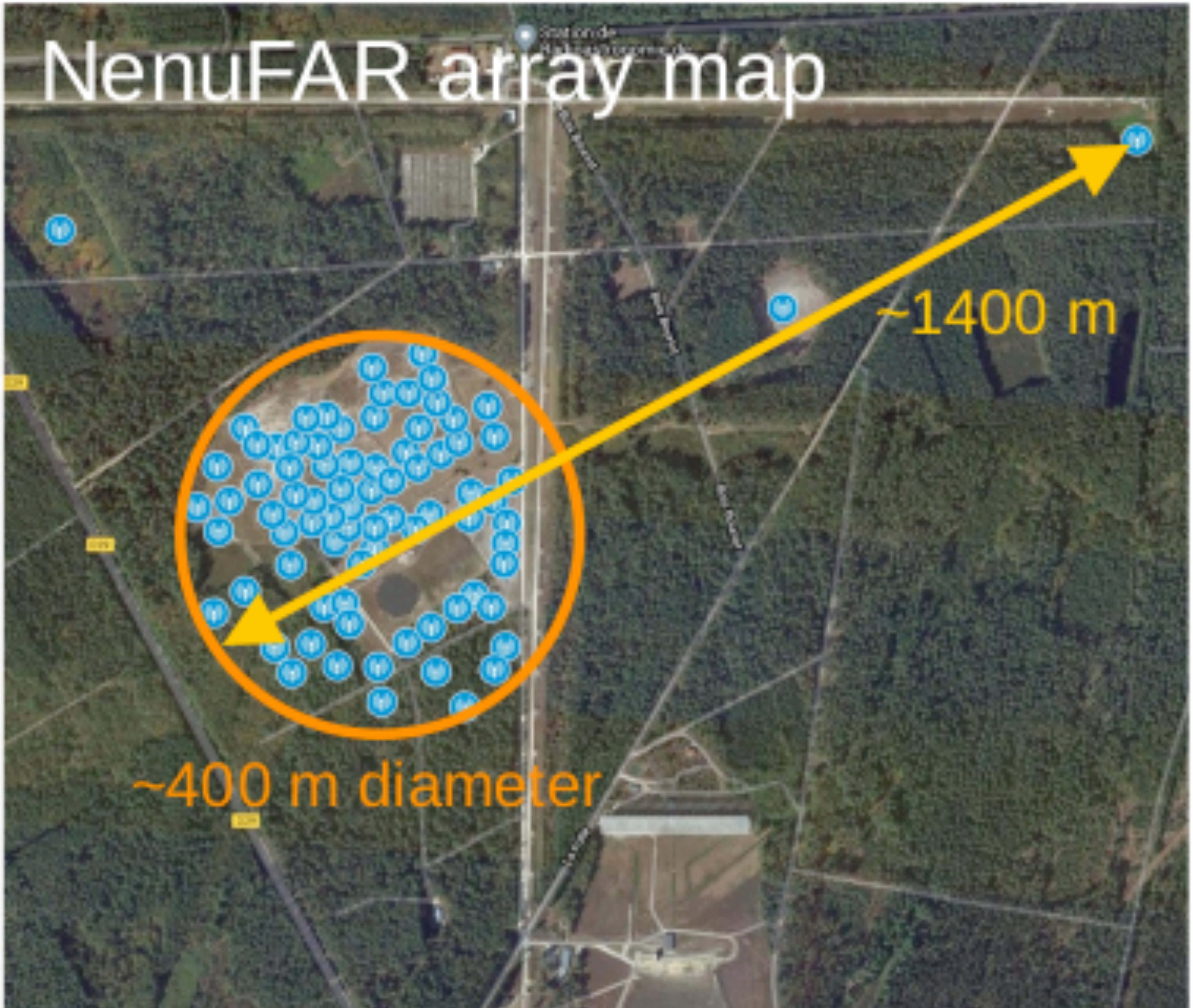


Imaging Data

2nd NenuFAR User Workshop

17-19 November 2021


NenuFAR array map
~1400 m
~400 m diameter

N-antenna interferometer: (u,v) plane

$$N$$

antennas

$$\frac{N(N-1)}{2}$$

Independent baselines

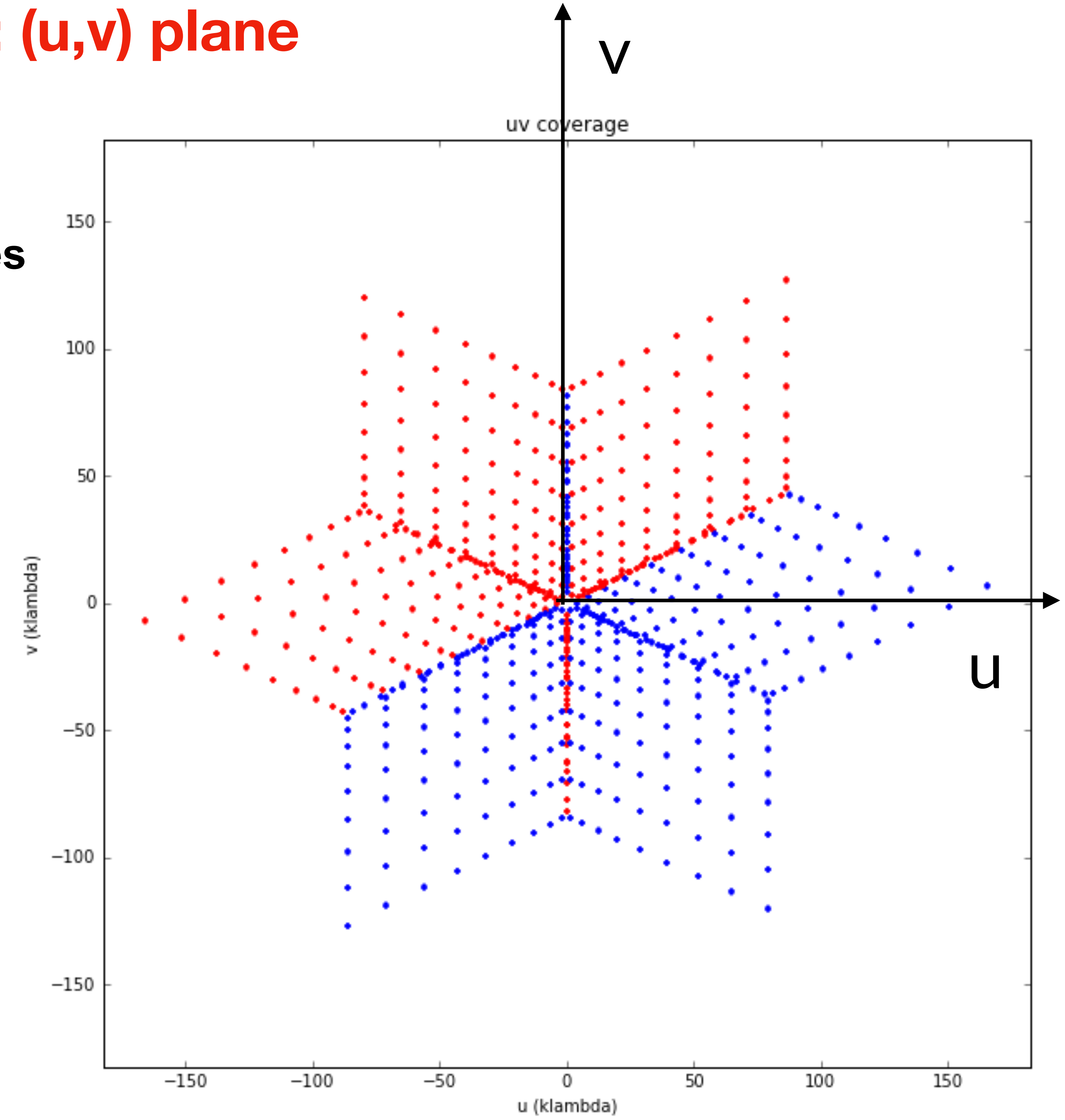
N-antenna interferometer: (u,v) plane

N

antennas

$$\frac{N(N-1)}{2}$$

Independent baselines



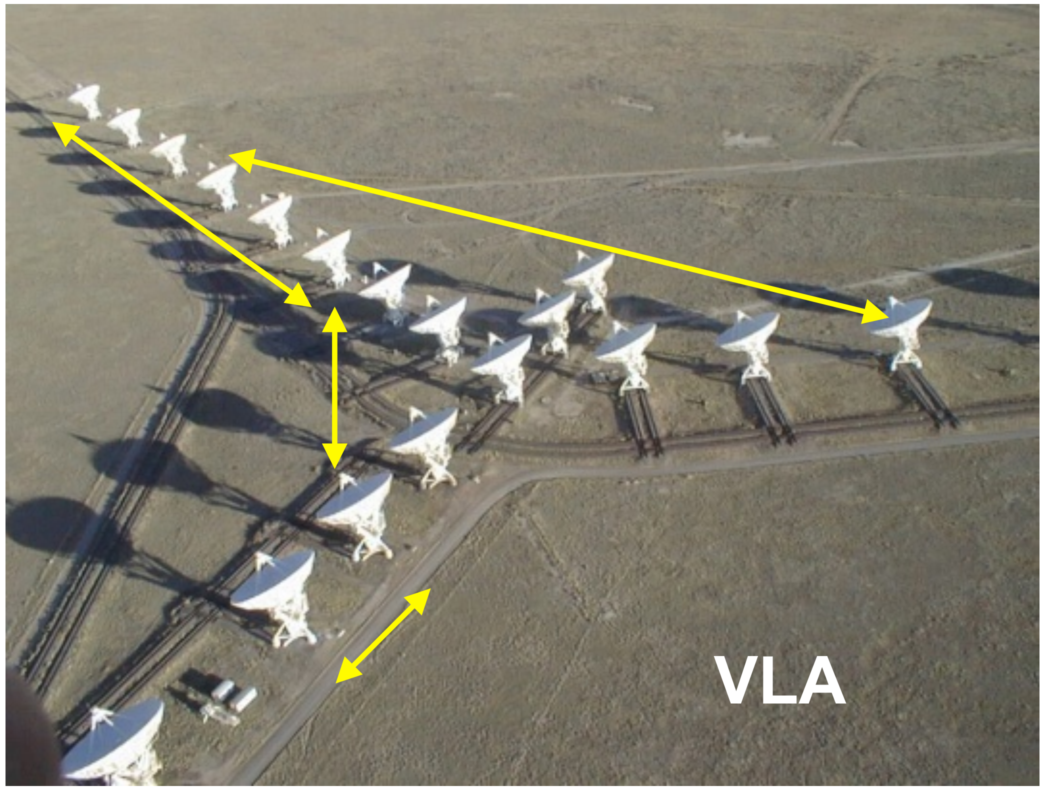
N-antenna interferometer: (u,v) plane

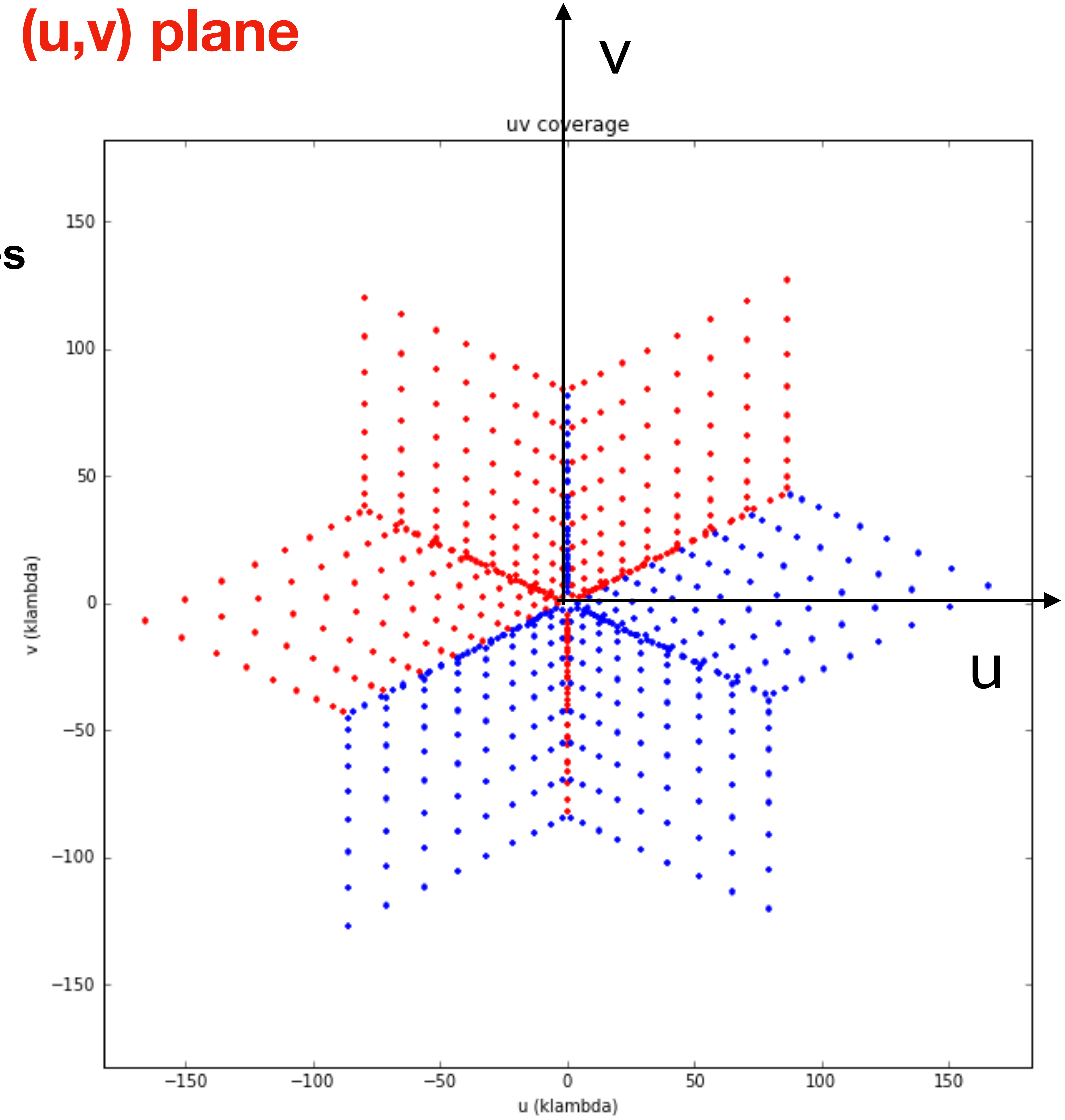
$$N$$

antennas

$$\frac{N(N-1)}{2}$$

Independent baselines





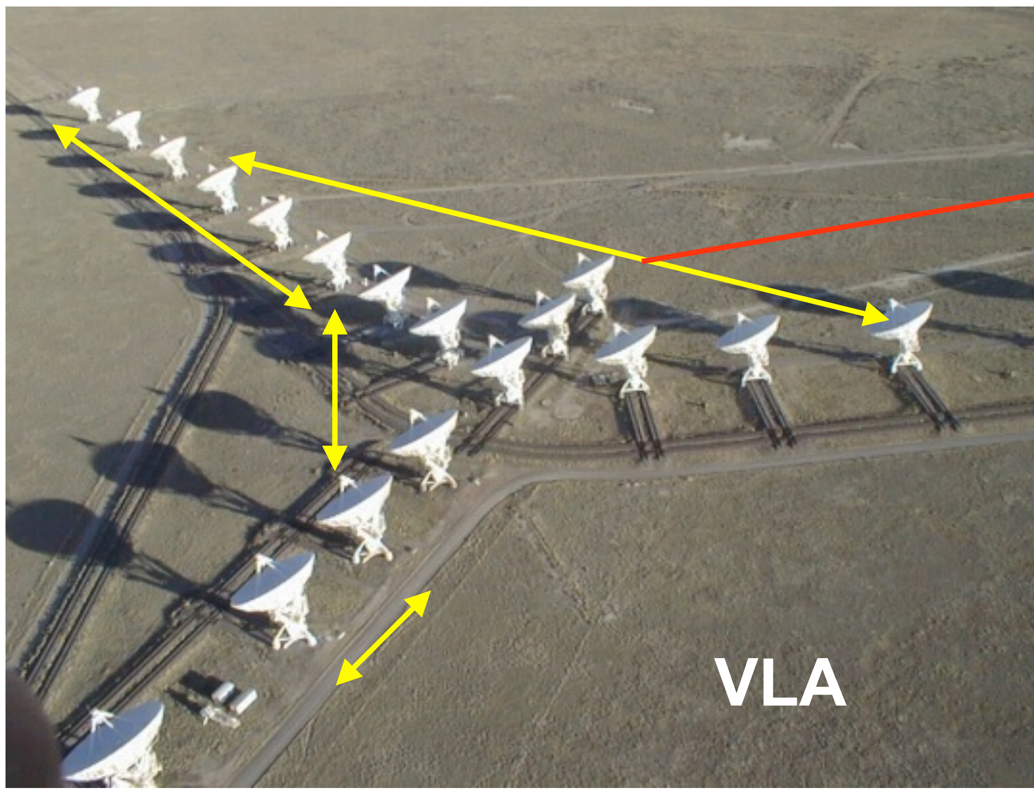
N-antenna interferometer: (u,v) plane

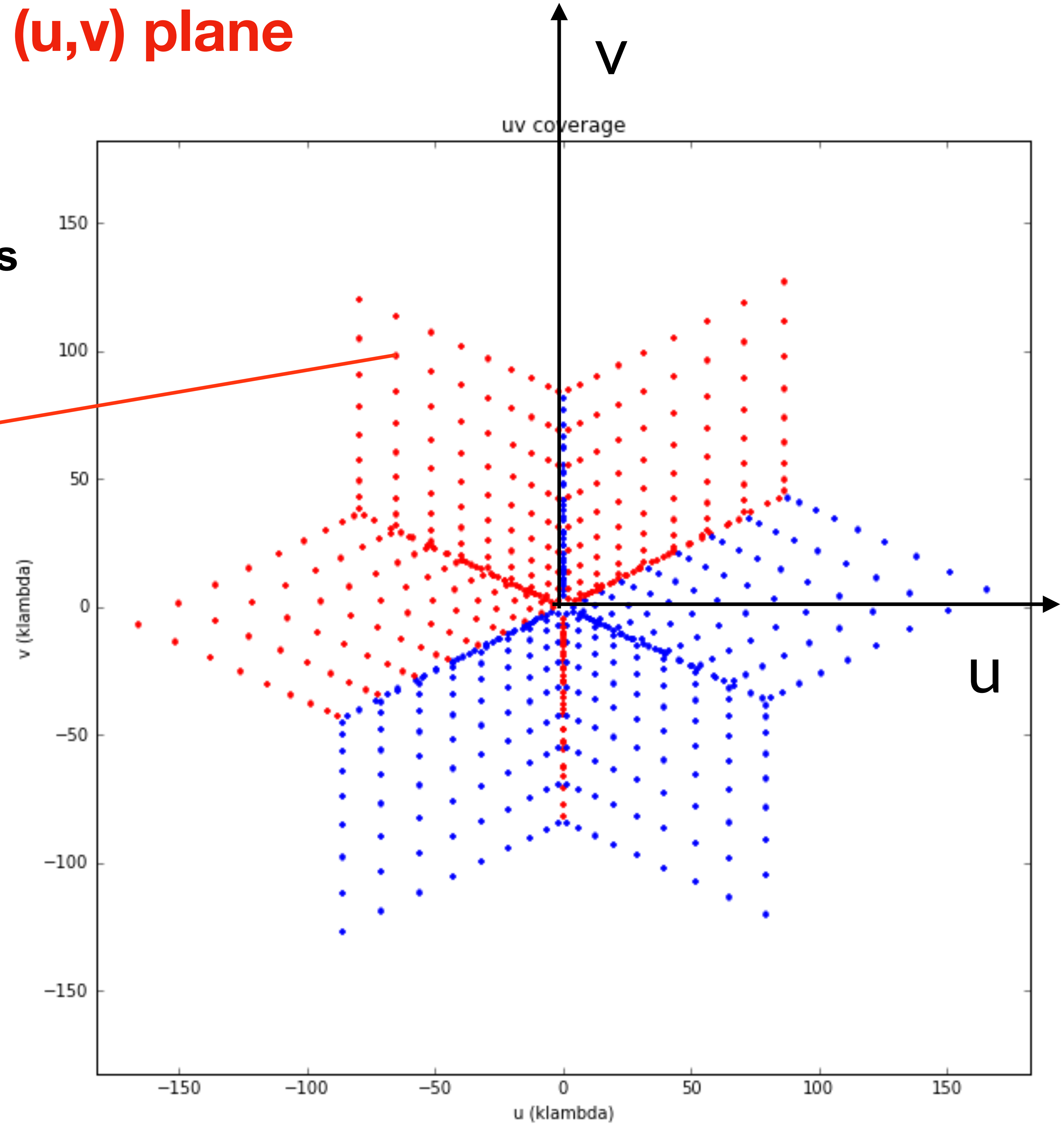
$$N$$

antennas

$$\frac{N(N-1)}{2}$$

Independent baselines





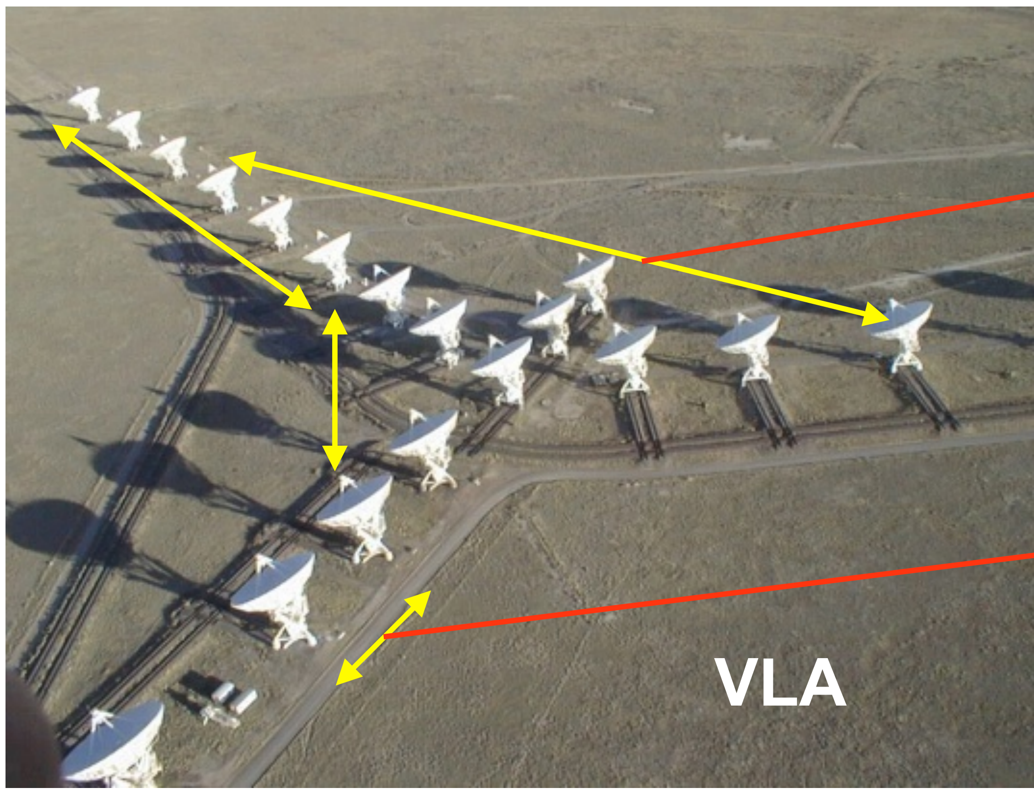
N-antenna interferometer: (u,v) plane

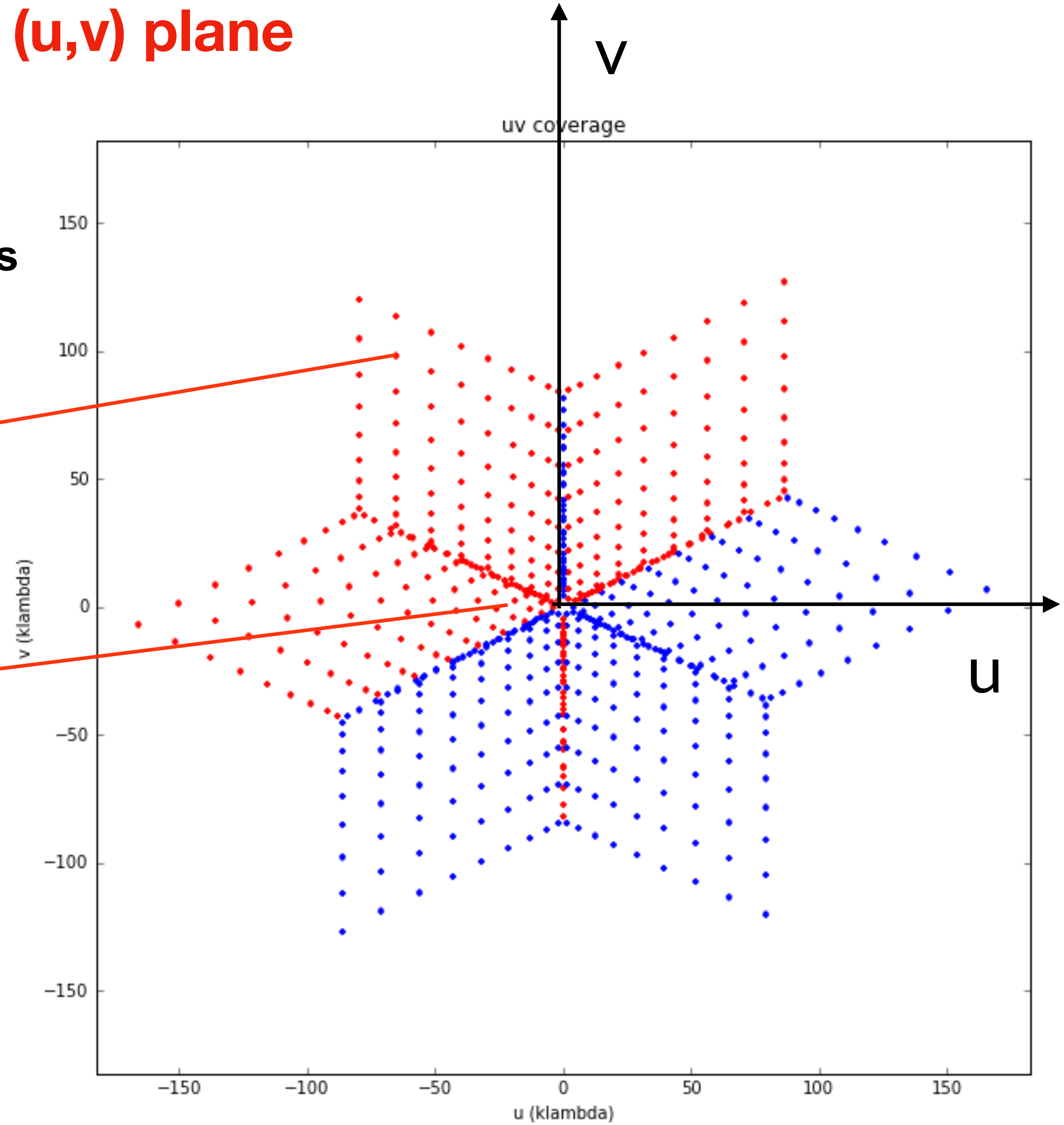
$$N$$

antennas

$$\frac{N(N-1)}{2}$$

Independent baselines





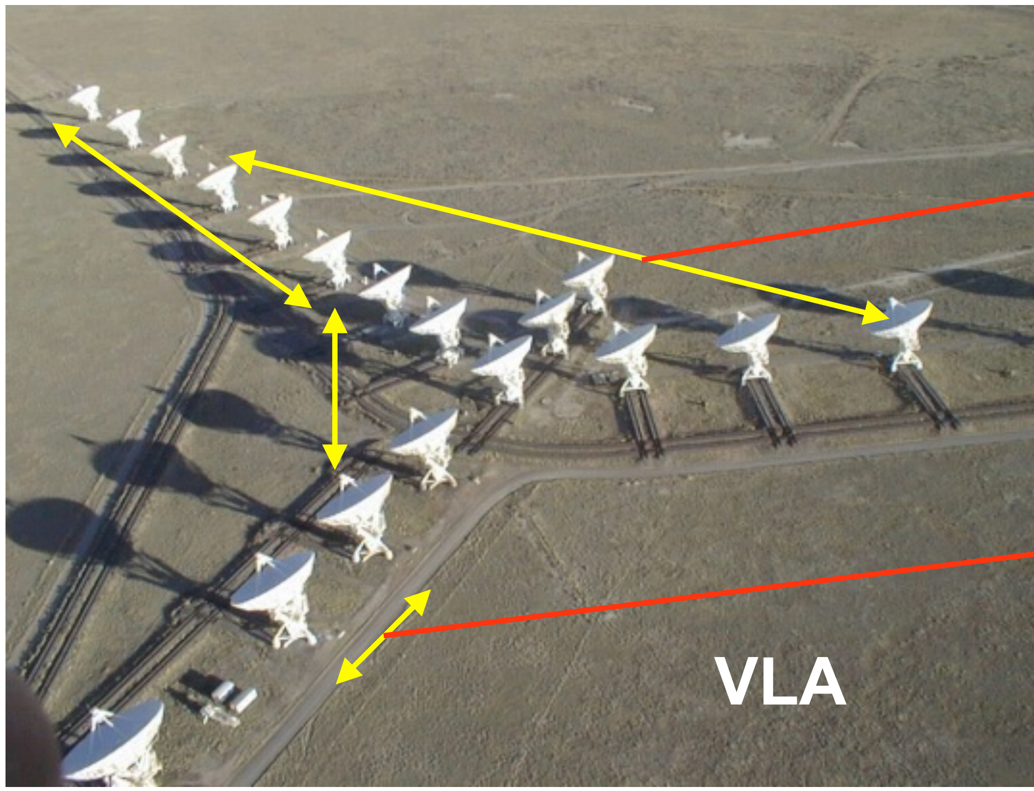
N-antenna interferometer: (u,v) plane

N

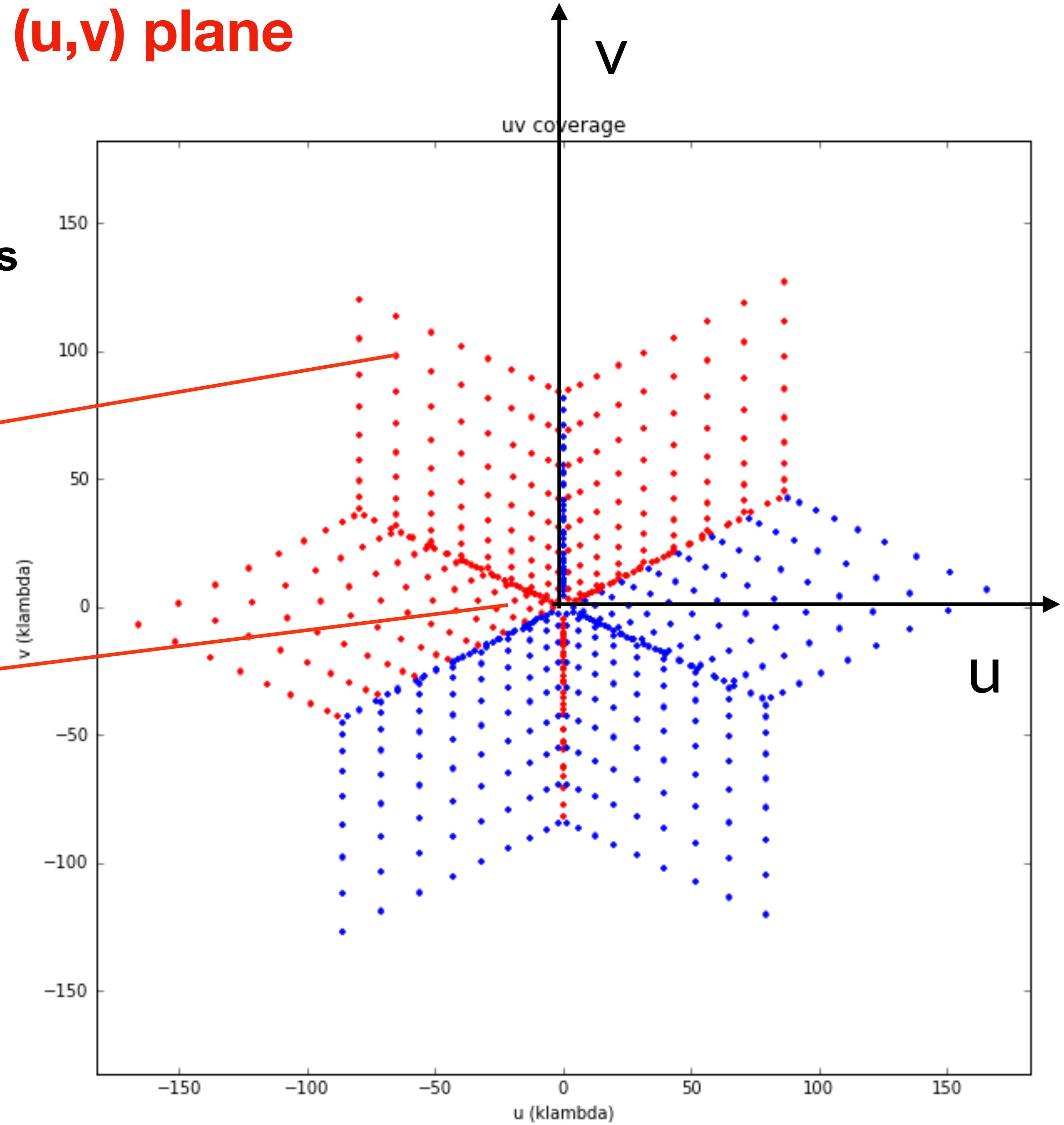
antennas

$$\frac{N(N-1)}{2}$$

Independent baselines



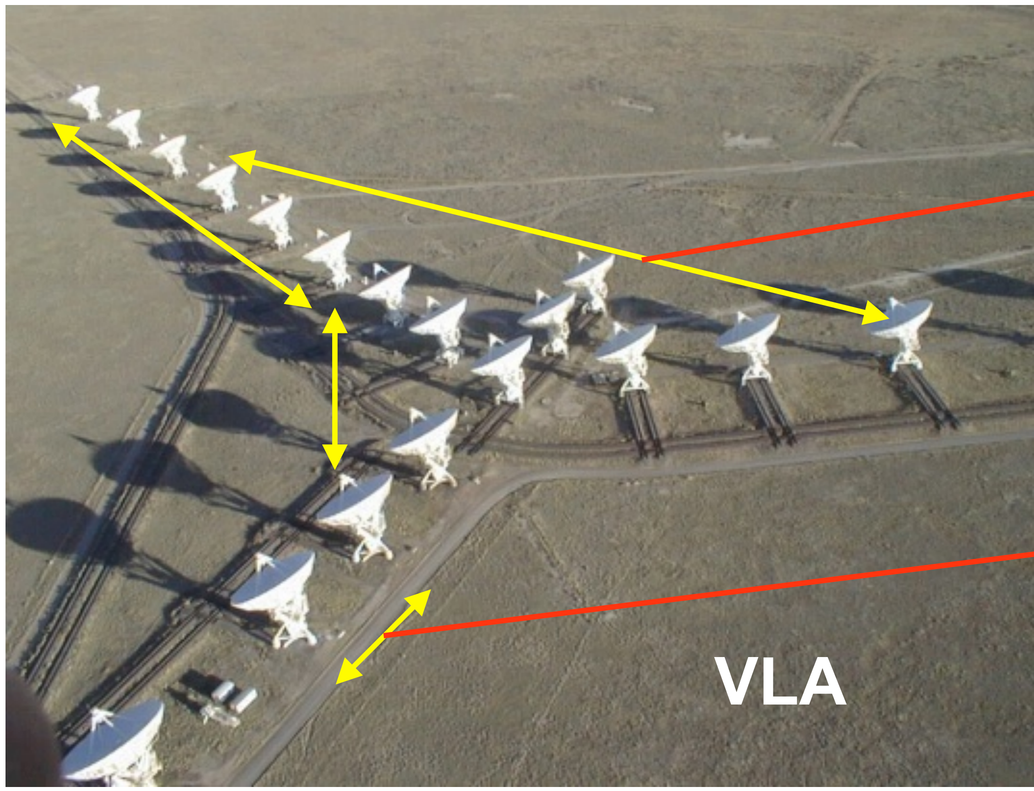
1 projected baseline
= 1 sample in the Fourier plane
(« u,v » plane)

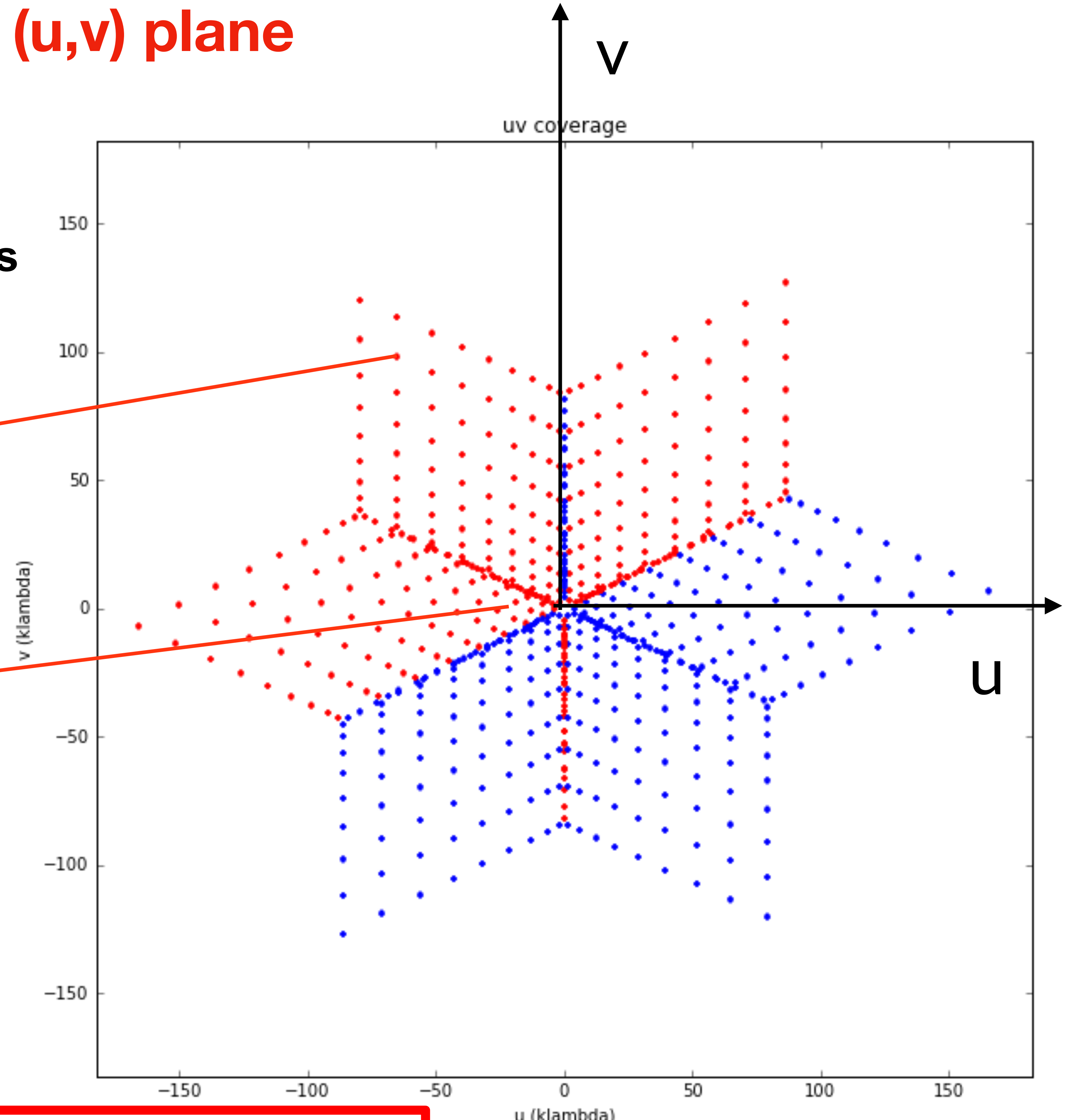


N-antenna interferometer: (u,v) plane

N **antennas**

$\frac{N(N-1)}{2}$ **Independent baselines**





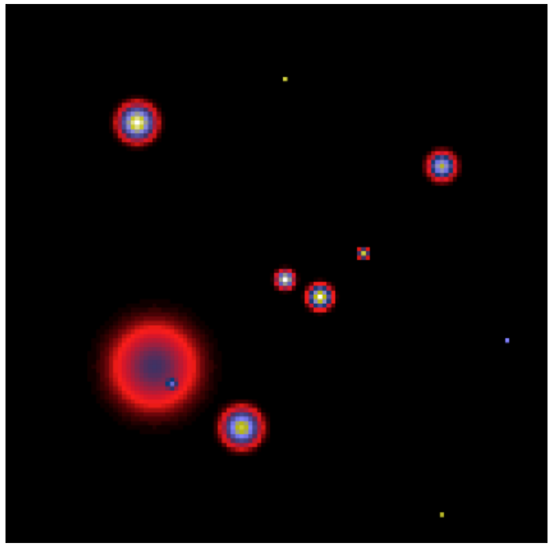
1 projected baseline
= 1 sample in the Fourier plane
(« u,v » plane)

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

Visibility function

(Simplification of the Van Cittert-Zernike Theorem)

Aperture synthesis imaging

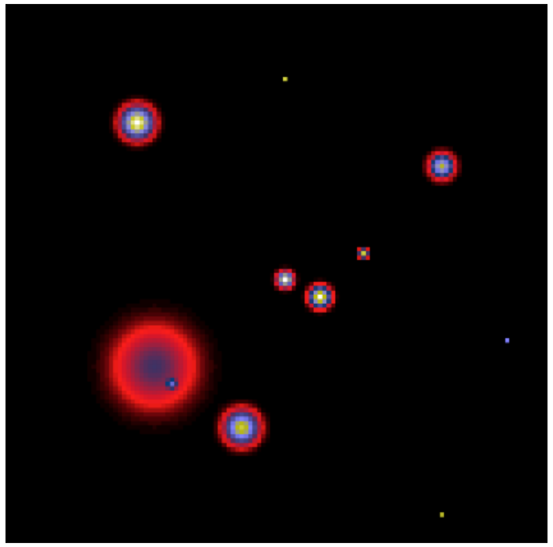


Brightness

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

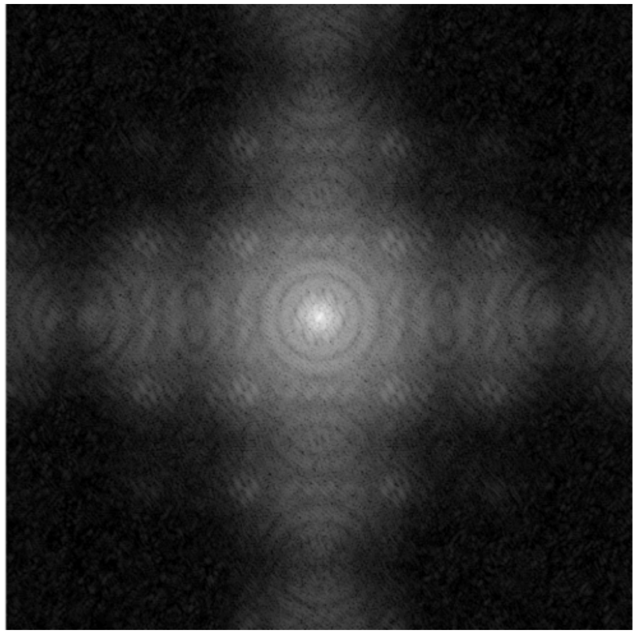
Aperture synthesis imaging

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



Brightness

FT

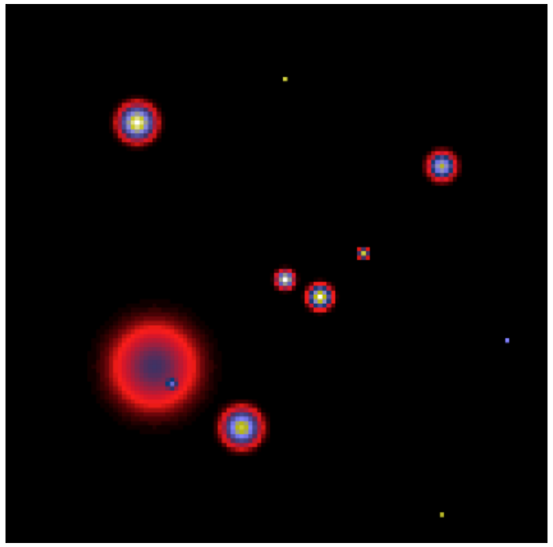


FT(Brightness)

Continuous "visibility" function

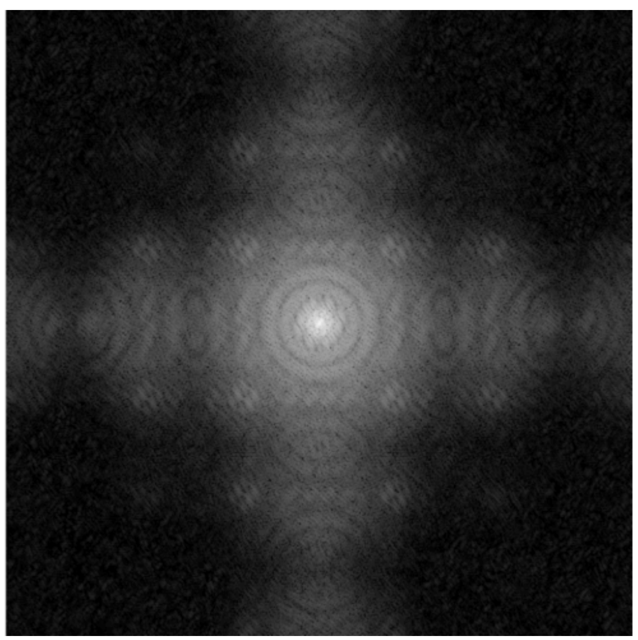
Aperture synthesis imaging

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



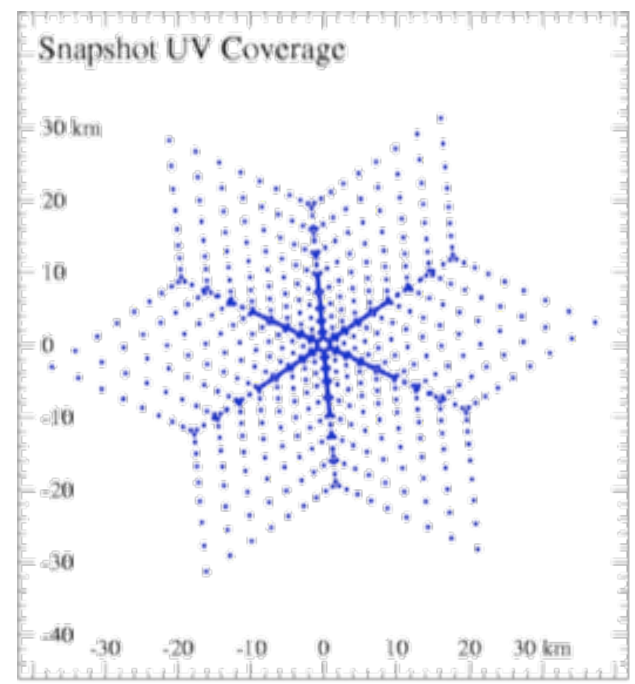
Brightness

FT



FT(Brightness)

Continuous "visibility" function

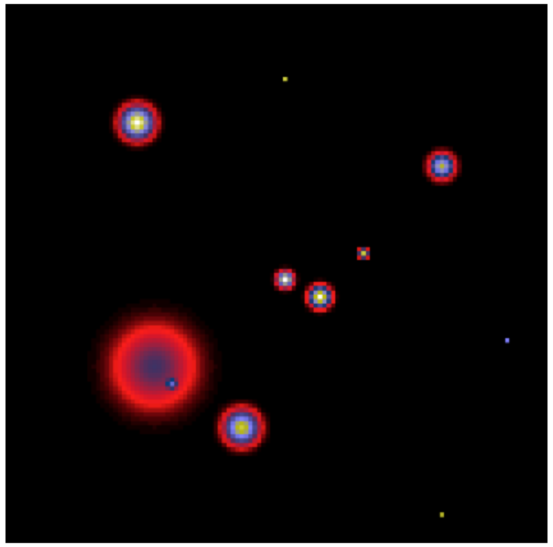


Discrete sampling by interferometer

FT^{-1}(Sampling function) = PSF

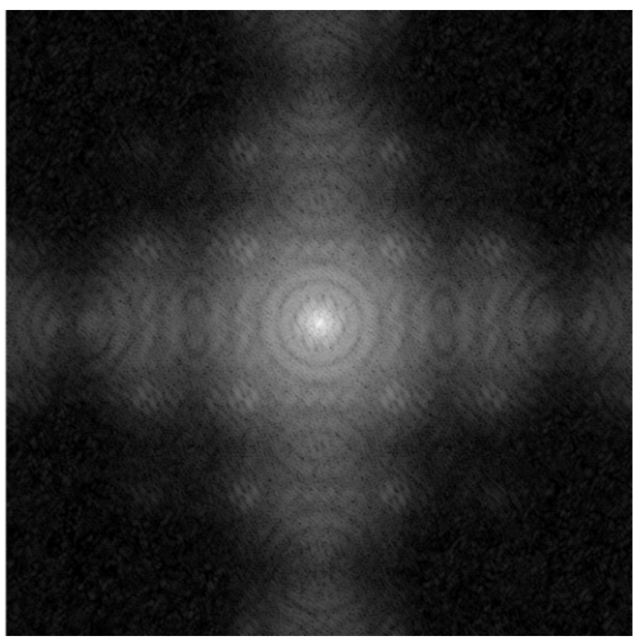
Aperture synthesis imaging

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



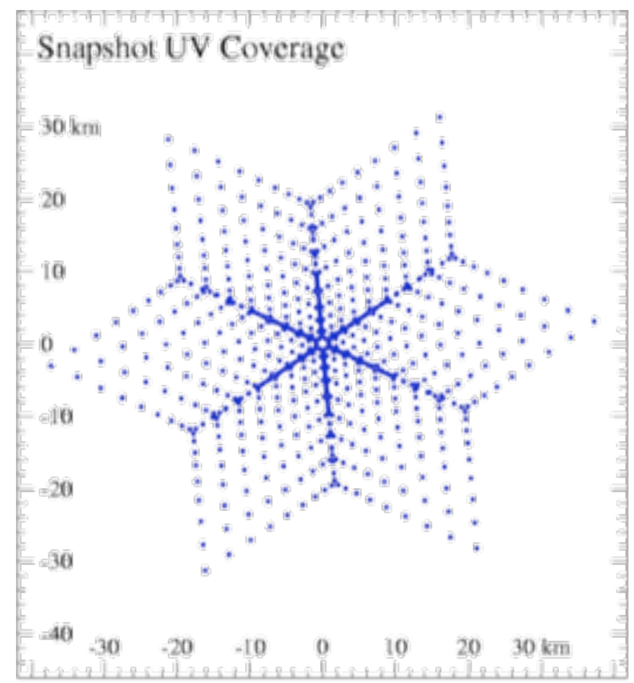
Brightness

FT



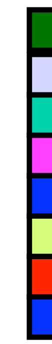
FT(Brightness)

Continuous "visibility" function



Discrete sampling by interferometer

FT^{-1}(Sampling function) = PSF

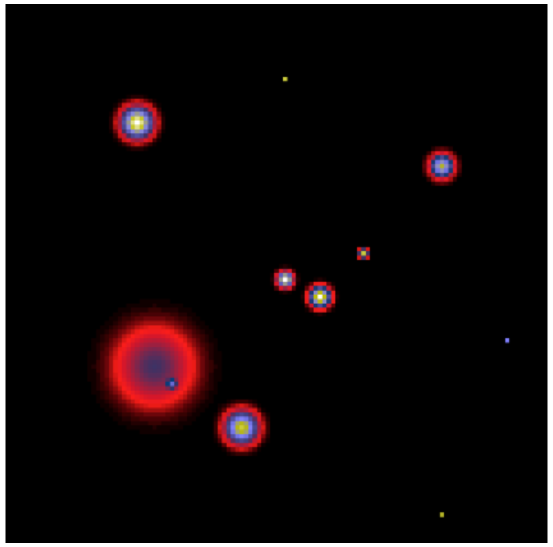


"Visibilities" = Fourier Samples

Dataset

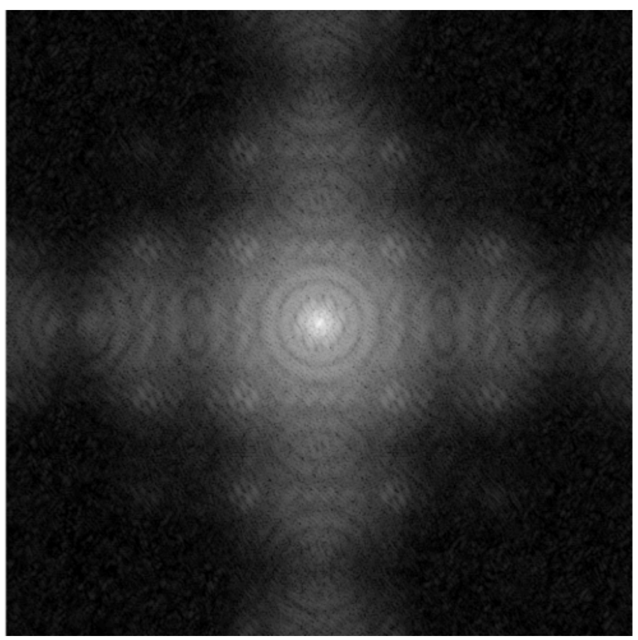
Aperture synthesis imaging

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



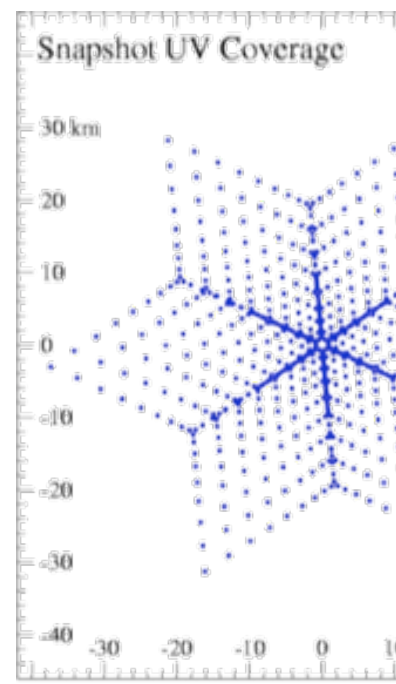
Brightness

FT



FT(Brightness)

Continuous "visibility" function



Discrete sam
interferom

FT^{-1}(Sampling function) = PSF

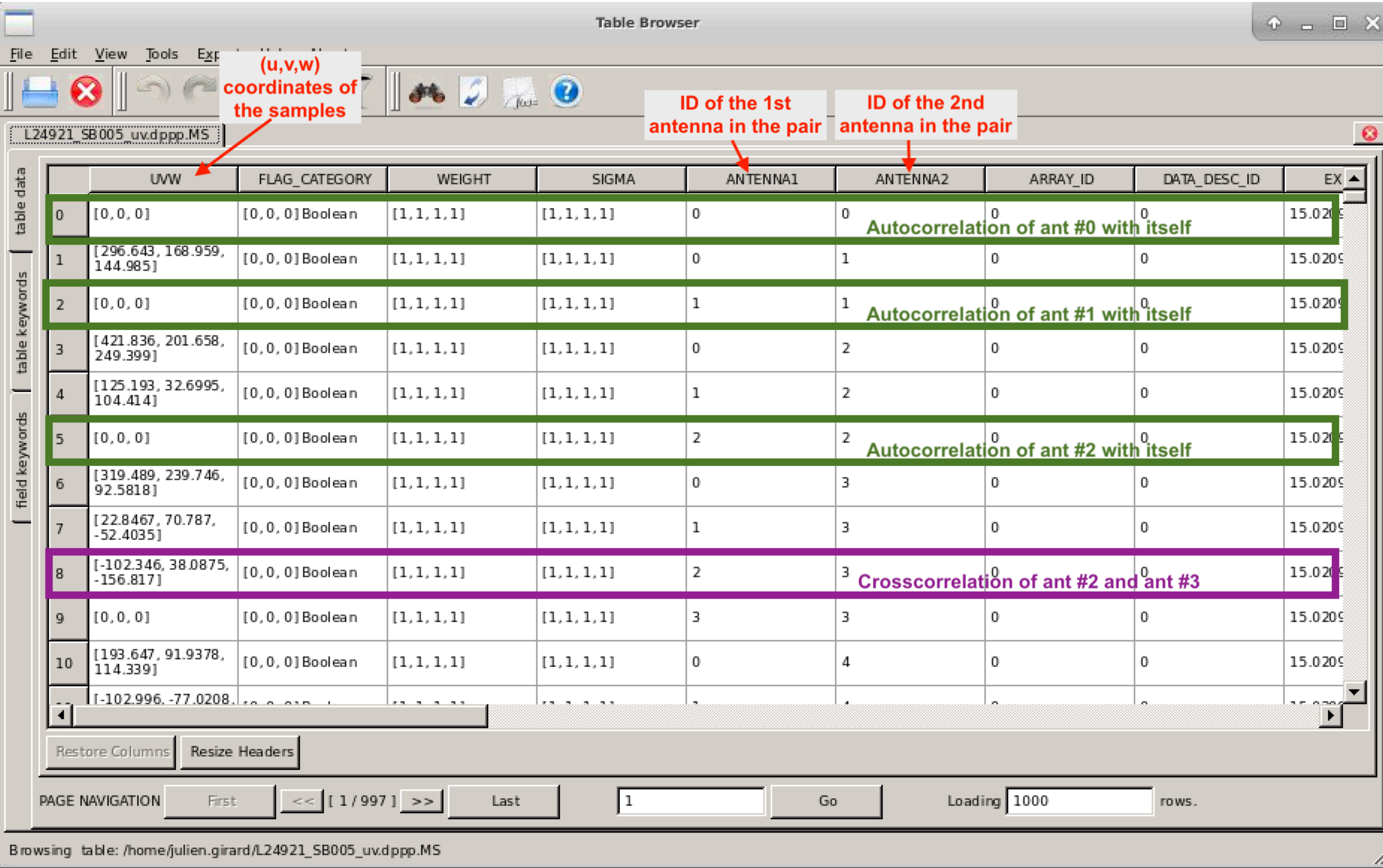
Dataset

Measurement Set format

NRAO Standard

Visibilities

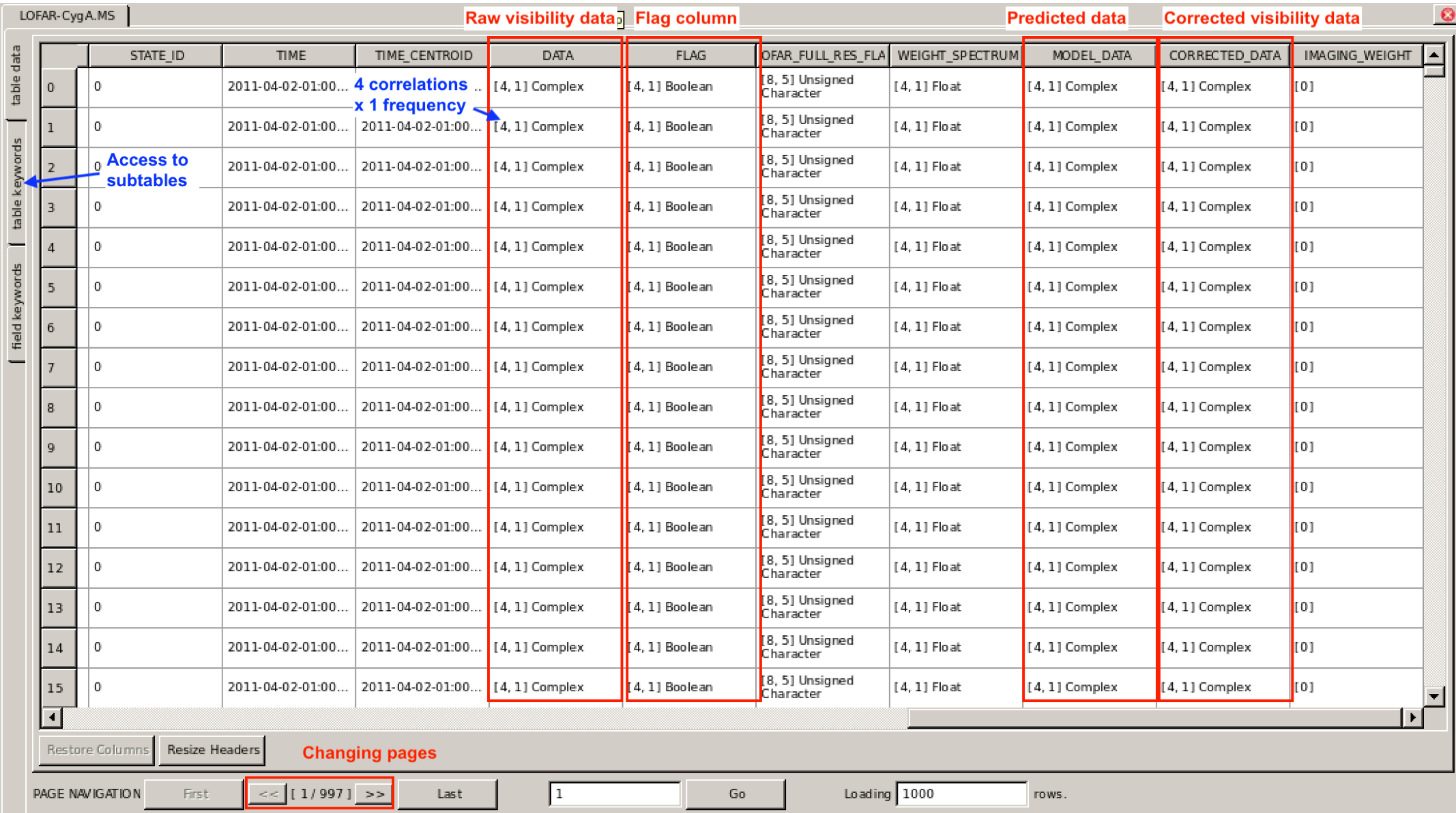
NICKEL "=" COBALT-II (LOFAR)



	UVW	FLAG_CATEGORY	WEIGHT	SIGMA	ANTENNA1	ANTENNA2	ARRAY_ID	DATA_DESC_ID	EX
0	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	0	0	0	15.020
1	[296.643, 168.959, 144.985]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	1	0	0	15.020
2	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	1	0	0	15.020
3	[421.836, 201.658, 249.399]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	2	0	0	15.020
4	[125.193, 32.6995, 104.414]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	2	0	0	15.020
5	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	2	2	0	0	15.020
6	[319.489, 239.746, 92.5818]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	3	0	0	15.020
7	[22.8467, 70.787, -52.4035]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	3	0	0	15.020
8	[-102.346, 38.0875, -156.817]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	2	3	0	0	15.020
9	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	3	3	0	0	15.020
10	[193.647, 91.9378, 114.339]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	4	0	0	15.020
11	[-102.996, -77.0208,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Measurement Set format

Data columns



	STATE_ID	TIME	TIME_CENTROID	DATA	FLAG	OFAR_FULL_RES_FLA	WEIGHT_SPECTRUM	MODEL_DATA	CORRECTED_DATA	IMAGING_WEIGHT
0	0	2011-04-02-01:00...	..	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
1	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
2	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
3	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
4	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
5	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
6	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
7	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
8	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
9	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
10	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
11	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
12	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
13	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]
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15	0	2011-04-02-01:00...	2011-04-02-01:00...	[4, 1] Complex	[4, 1] Boolean	[8, 5] Unsigned Character	[4, 1] Float	[4, 1] Complex	[4, 1] Complex	[0]

Measurement Set format

Subtables

Table Browser

File Edit View Tools Export Help About

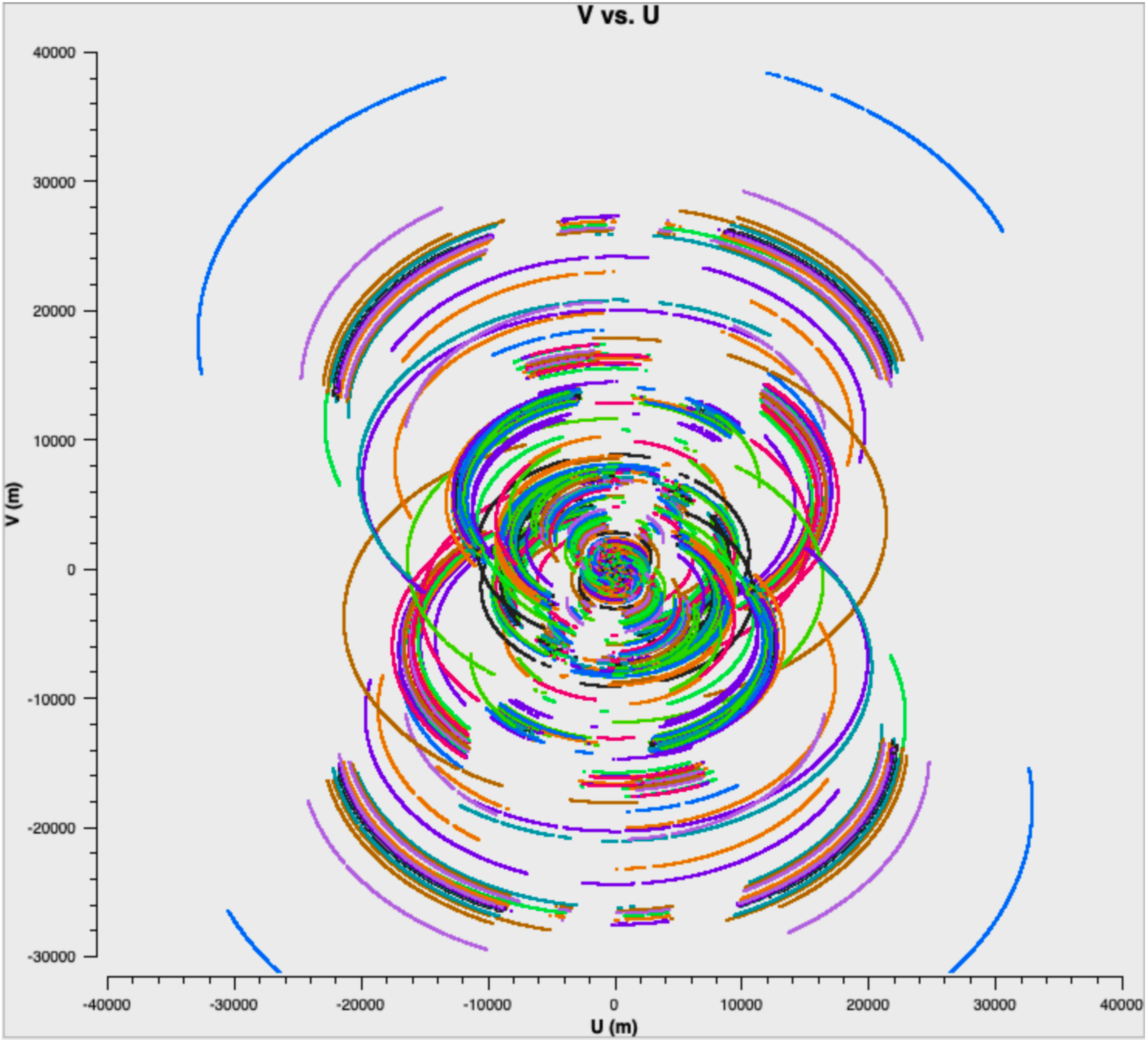
L24921_SB005_uv.dppp.MS

table data | table keywords | field keywords

	Keyword	Type	Value	Extra Information
1	MS_VERSION	Float	2	
2	ANTENNA	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/ANTENNA **contains information about the antennas (position, type, etc)**	Subtable has 27 rows.
3	DATA_DESCRIPTION	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/DATA_DESCRIPTION	Subtable has 1 rows.
4	FEED	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/FEED	Subtable has 27 rows.
5	FLAG_CMD	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/FLAG_CMD	Subtable has no rows.
6	FIELD	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/FIELD **definition of the fields**	Subtable has 1 rows.
7	HISTORY	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/HISTORY **all that happen to the MS**	Subtable has 2 rows.
8	OBSERVATION	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/OBSERVATION **Information on the observation (program N#, PI, etc.)**	Subtable has 1 rows.
9	POINTING	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/POINTING	Subtable has no rows.
10	POLARIZATION	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/POLARIZATION	Subtable has 1 rows.
11	PROCESSOR	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/PROCESSOR	Subtable has no rows.
12	SPECTRAL_WINDOW	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/SPECTRAL_WINDOW	Subtable has 1 rows.
13	STATE	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/STATE	Subtable has no rows.
14	LOFAR_STATION	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/LOFAR_STATION	Subtable has 27 rows.
15	LOFAR_ANTENNA_FIELD	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/LOFAR_ANTENNA_FIELD **LOFAR specific subtables**	Subtable has 27 rows.
16	LOFAR_ELEMENT_FAILURE	Table	/home/julien.girard/L24921_SB005_uv.dppp.MS/LOFAR_ELEMENT_FAILURE	Subtable has no rows.

Browsing table: /home/julien.girard/L24921_SB005_uv.dppp.MS

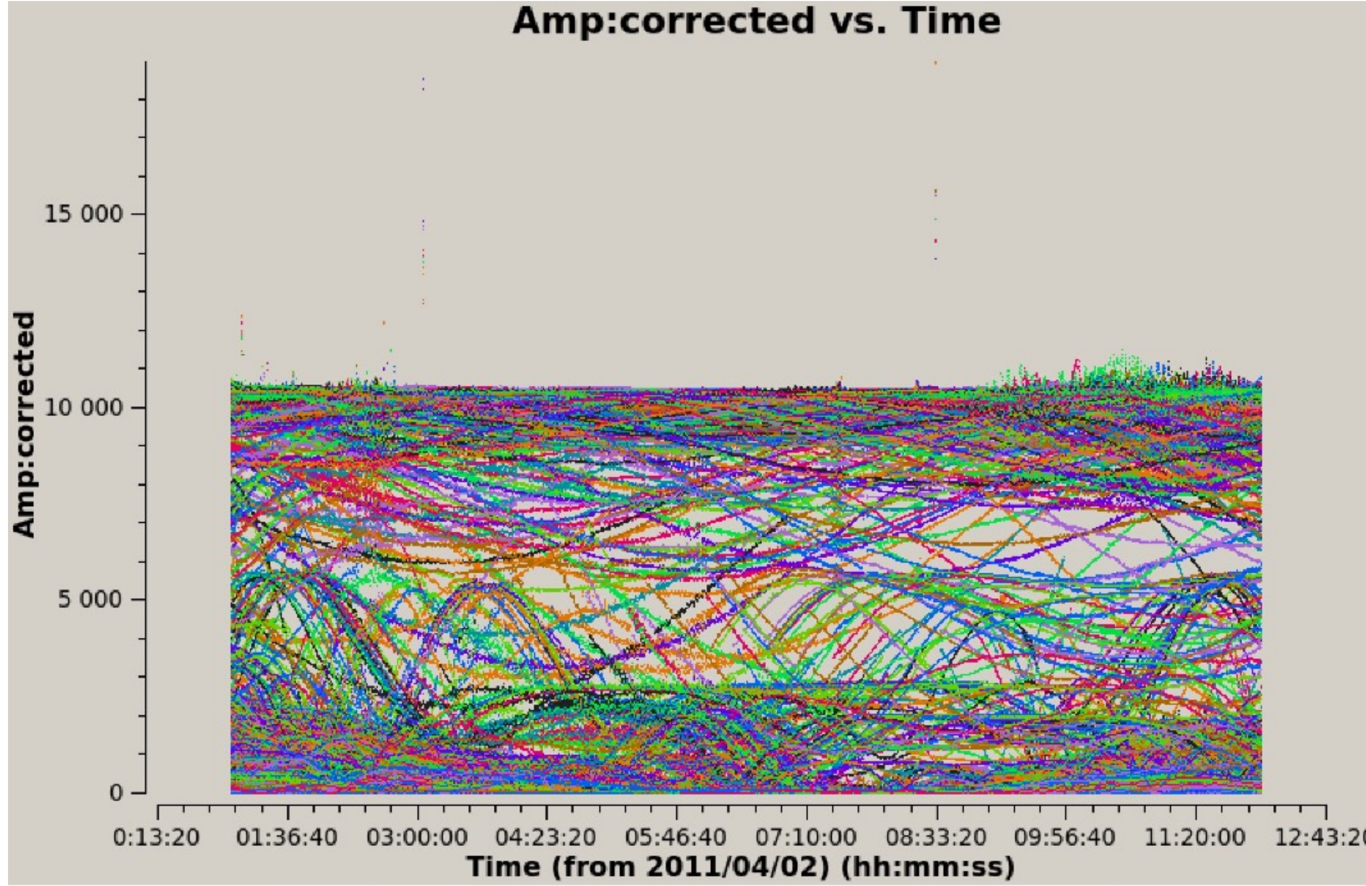
UV plane



V vs. U
40000
30000
20000
10000
0
-10000
-20000
-30000
V (m)
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000
U (m)

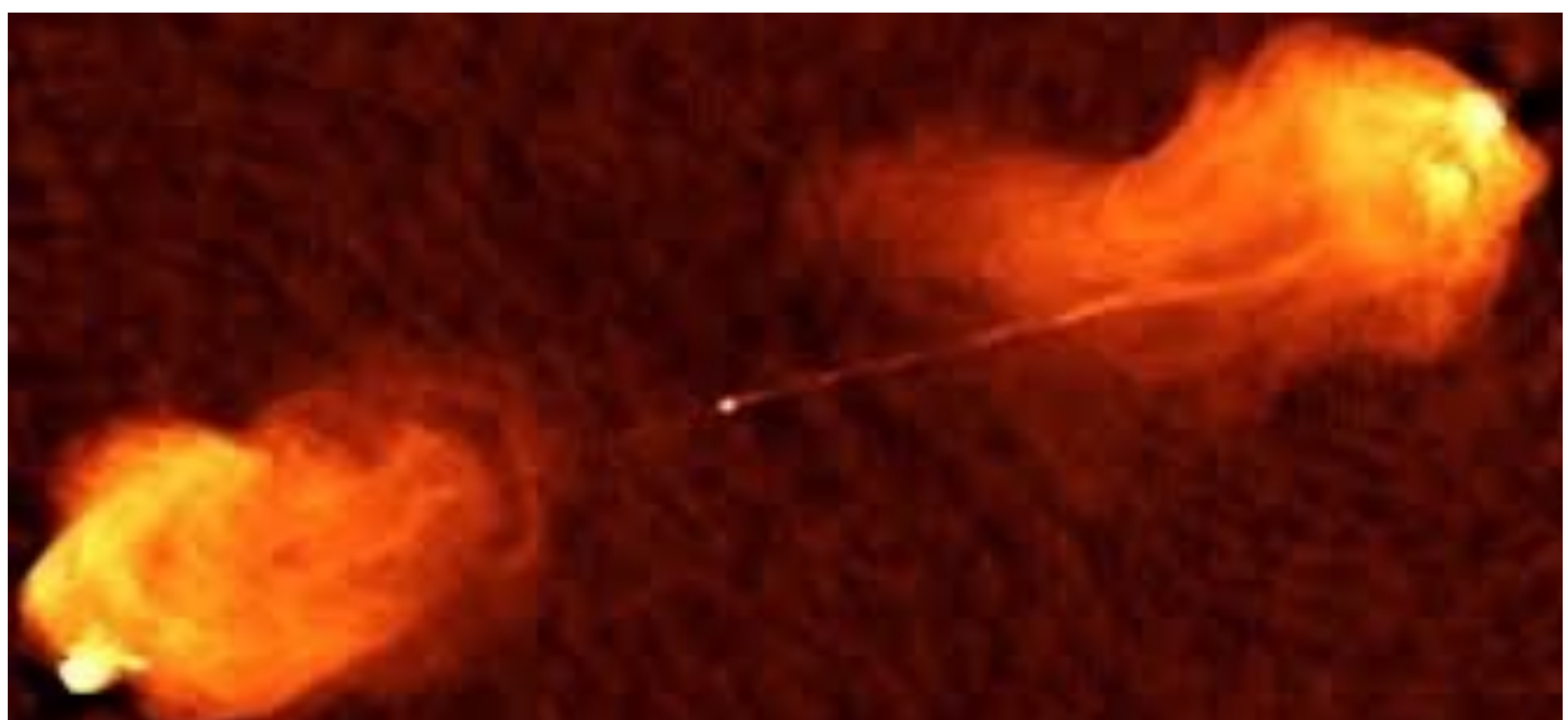
From visibilities to images?

Set of complex visibilities

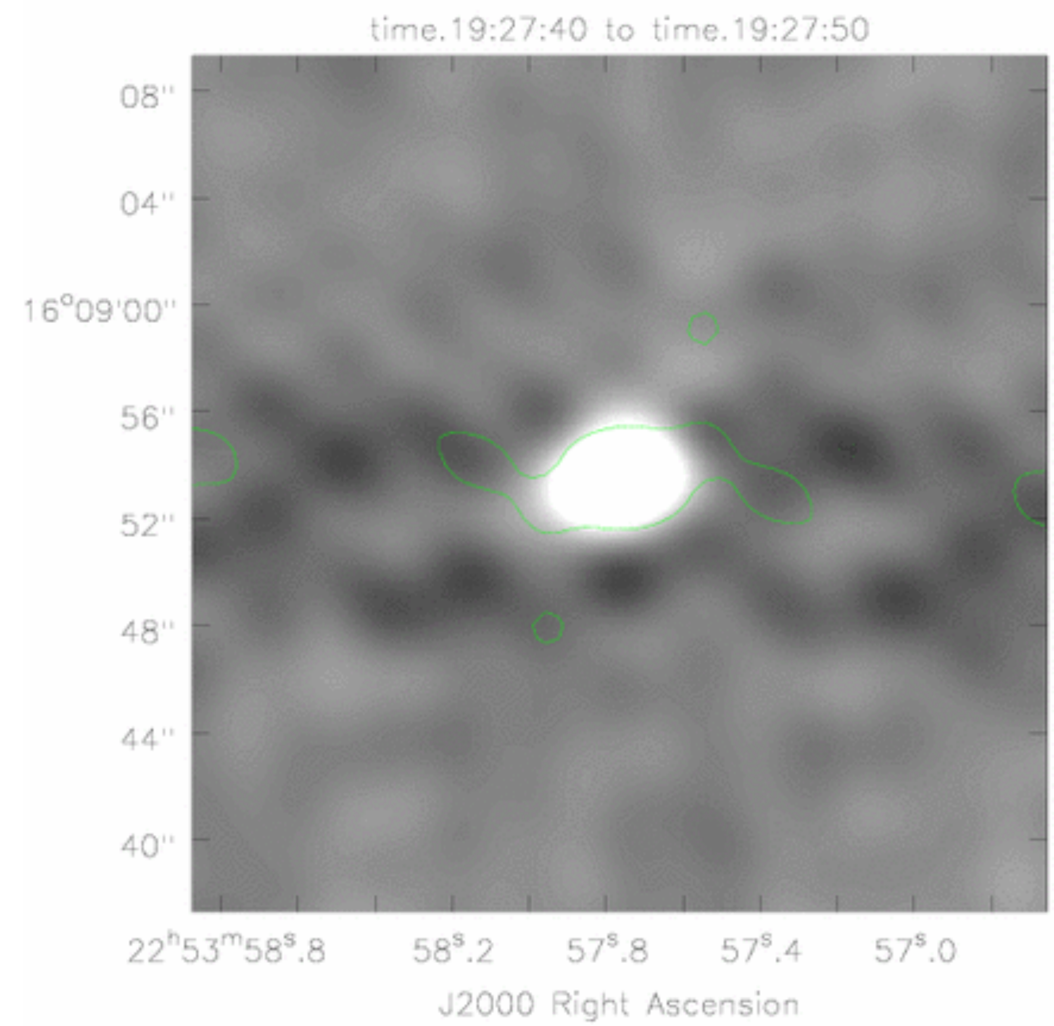


Calibration & Imaging & deconvolution

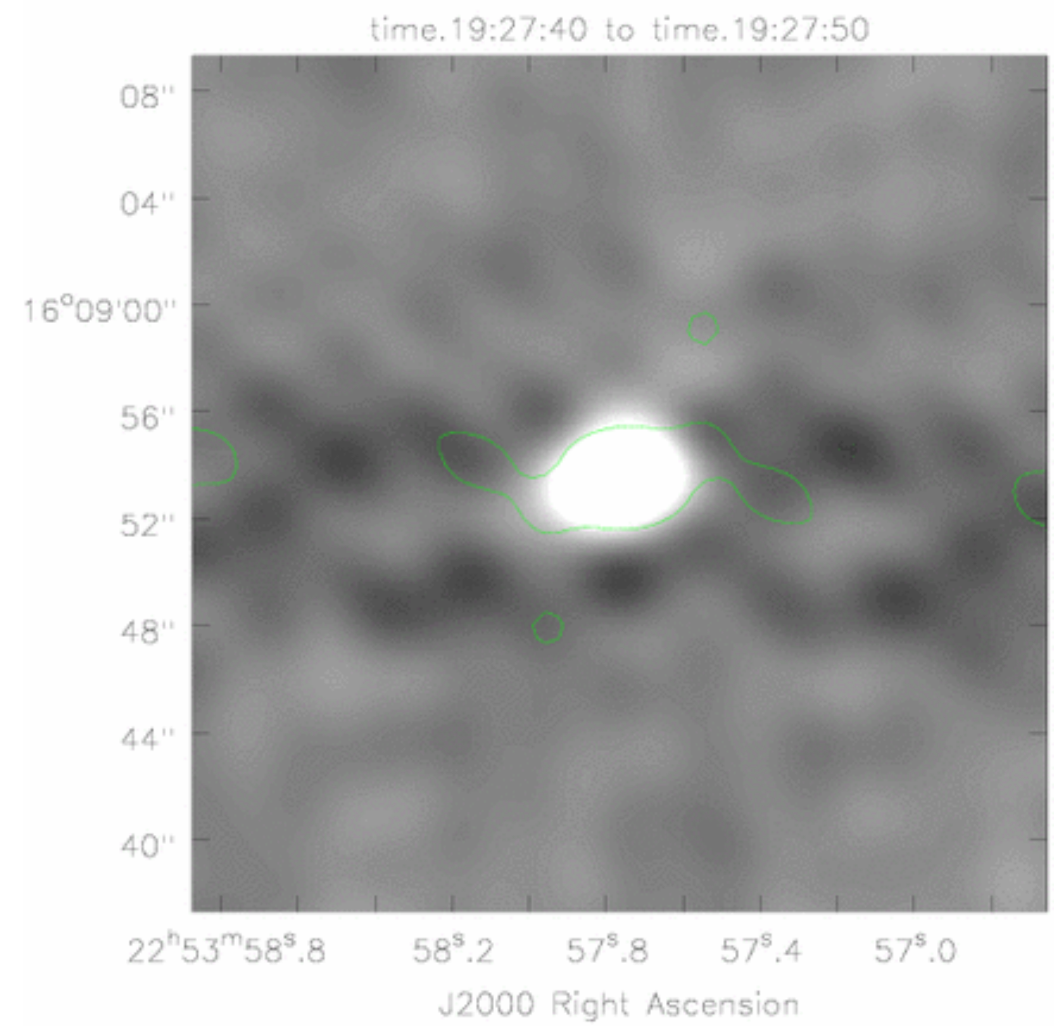
Brightness distribution



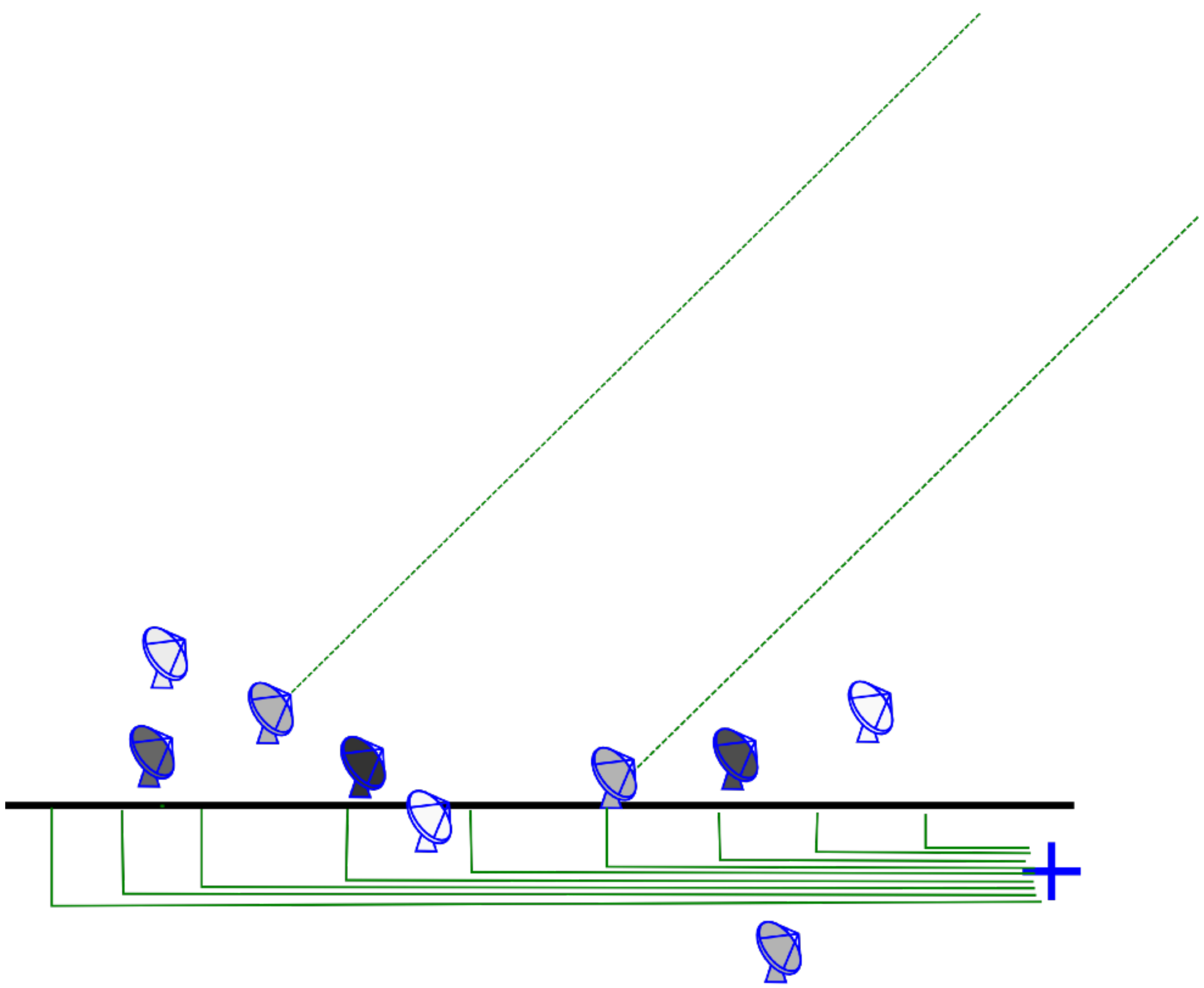
Calibration

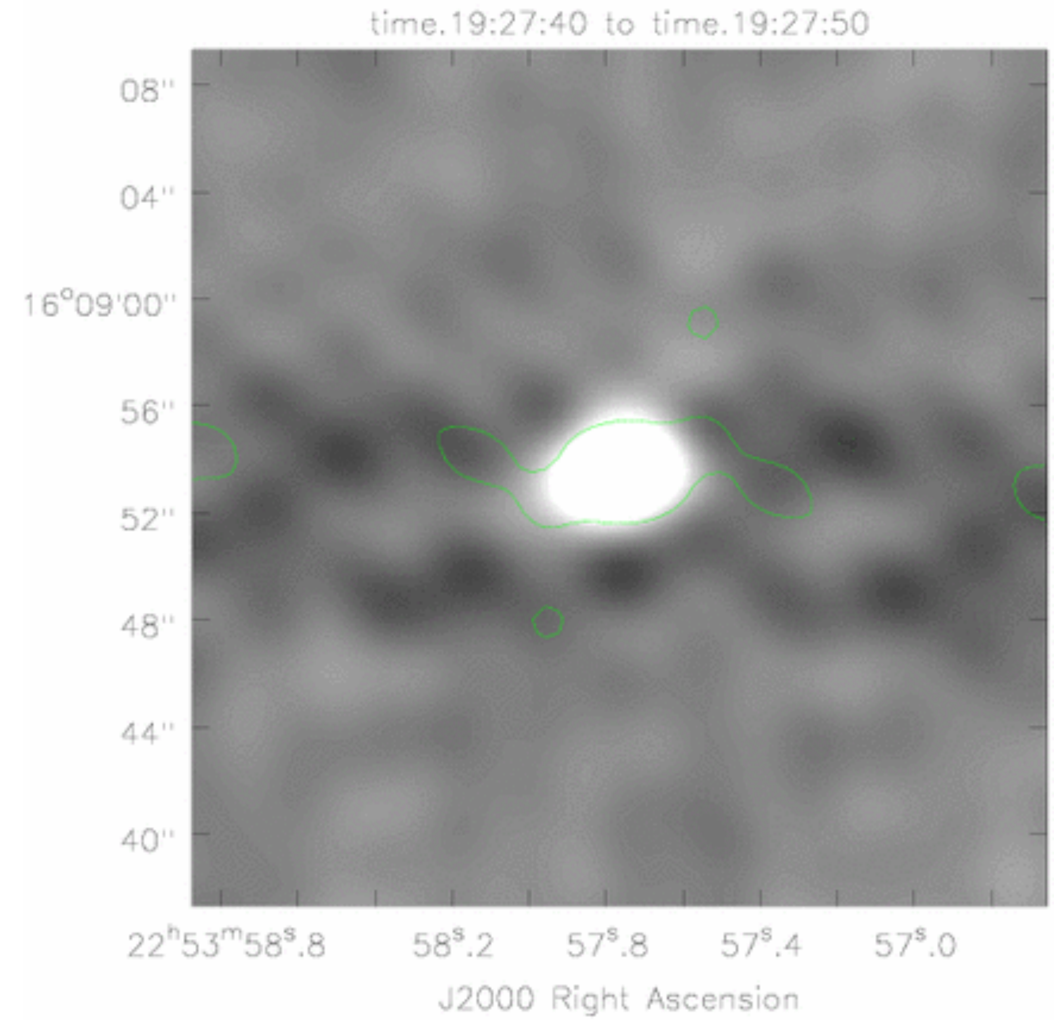


Calibration



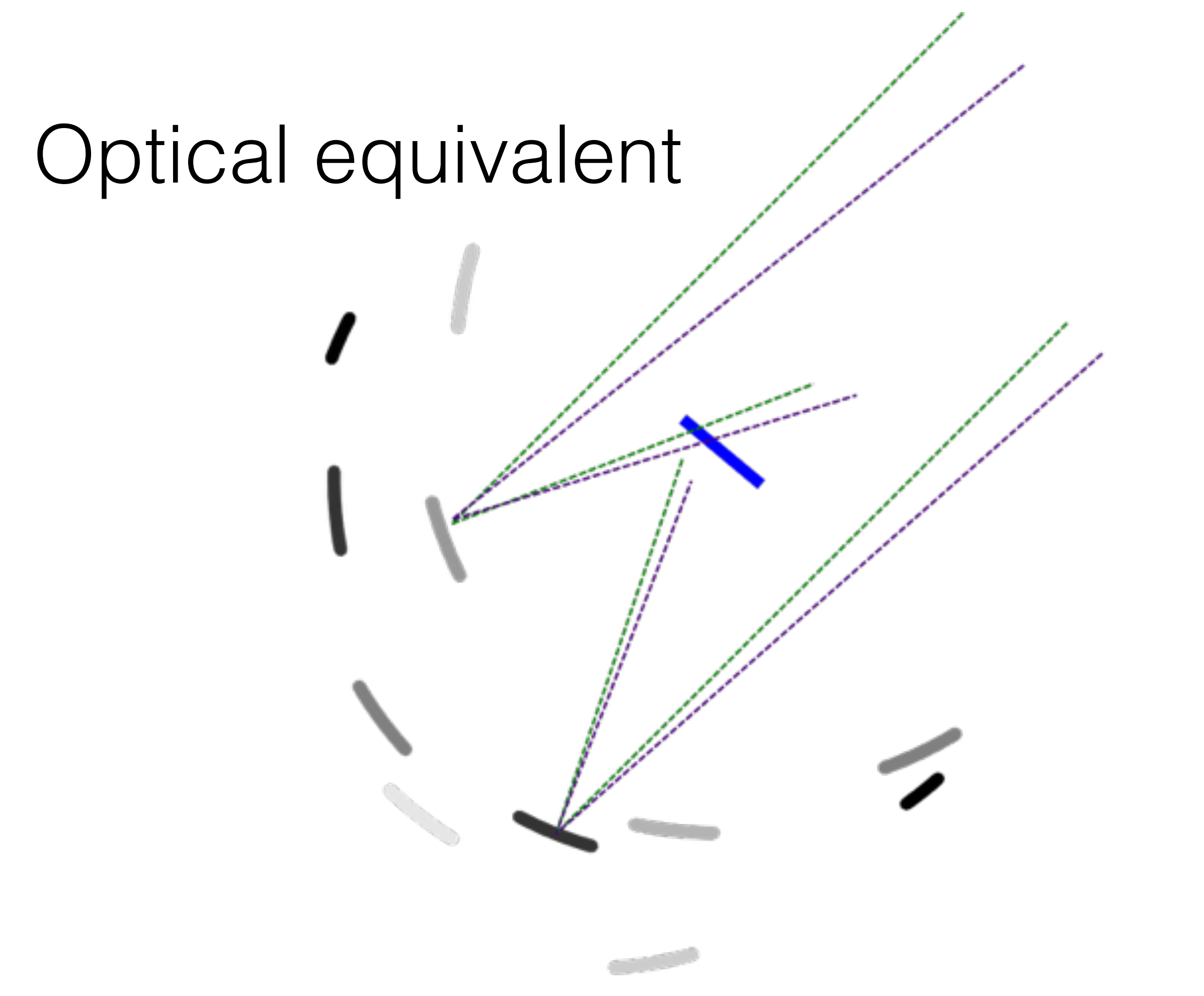
Calibration

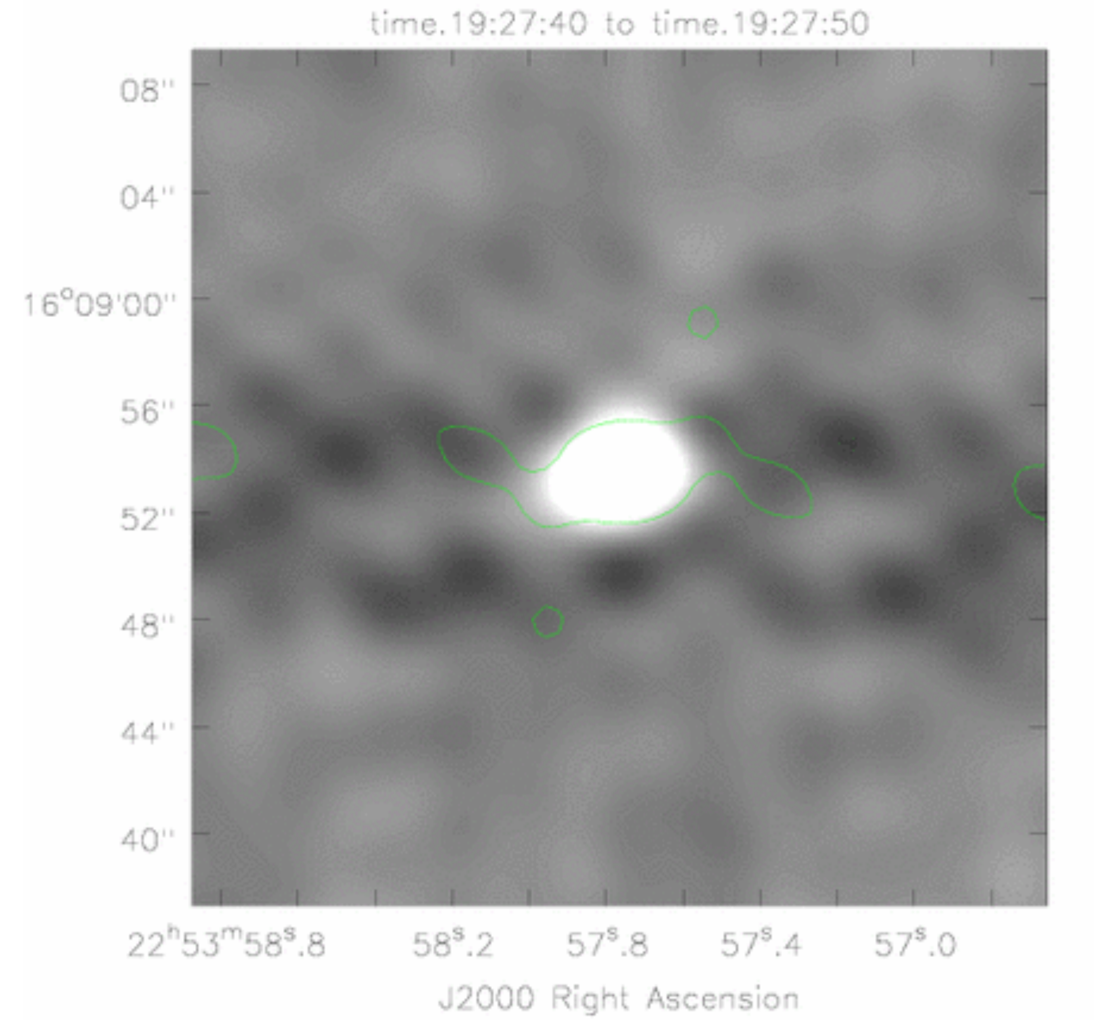




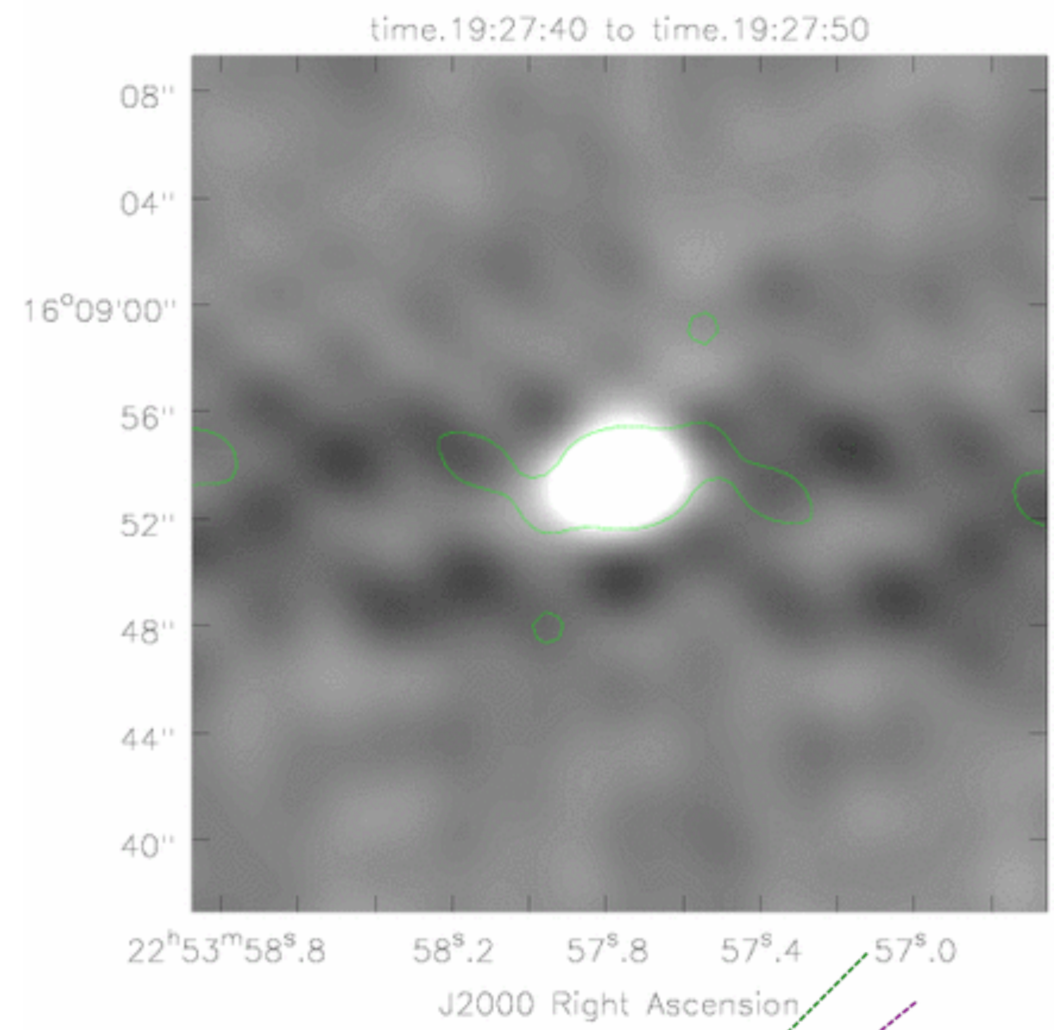
Calibration

Optical equivalent

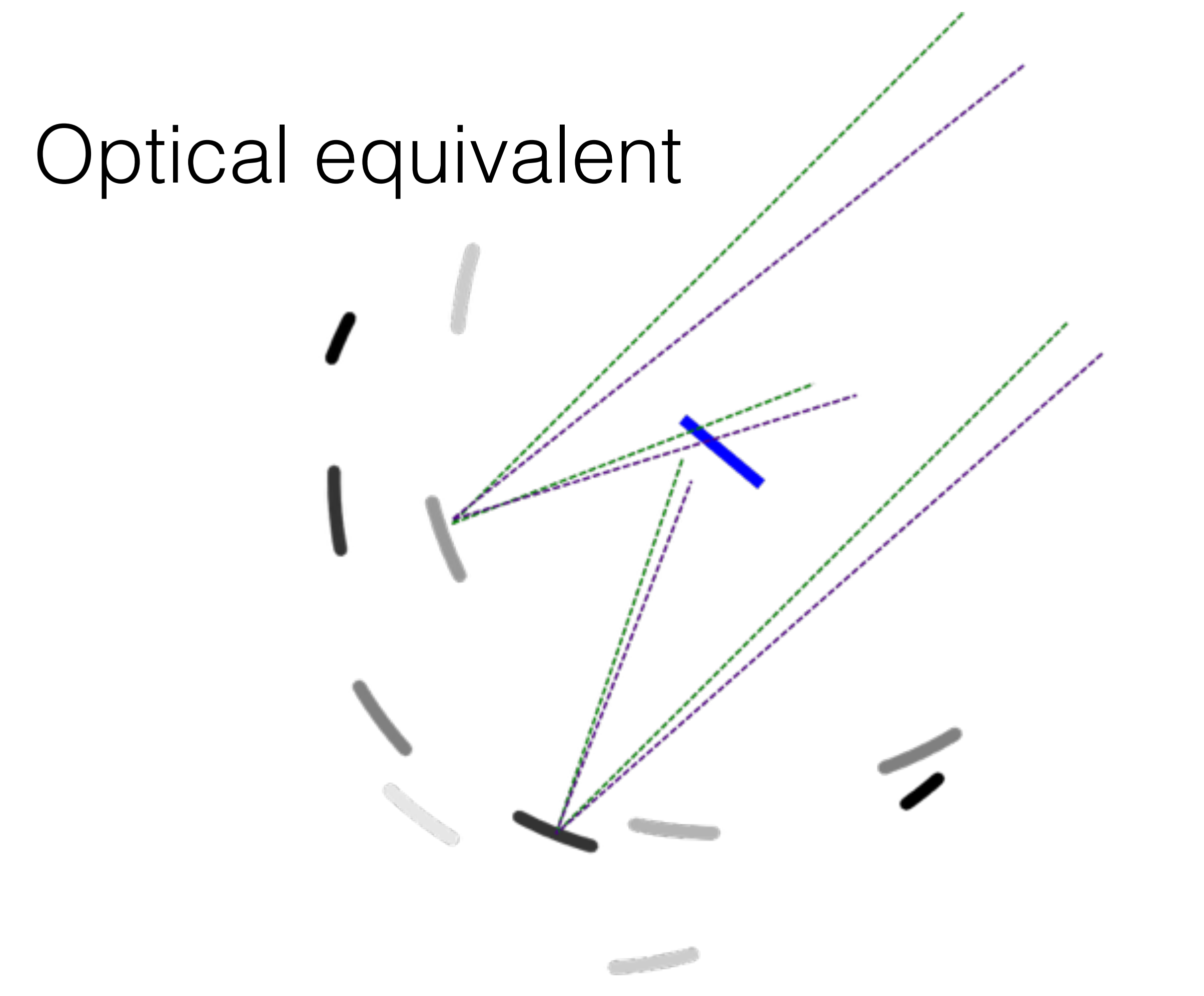


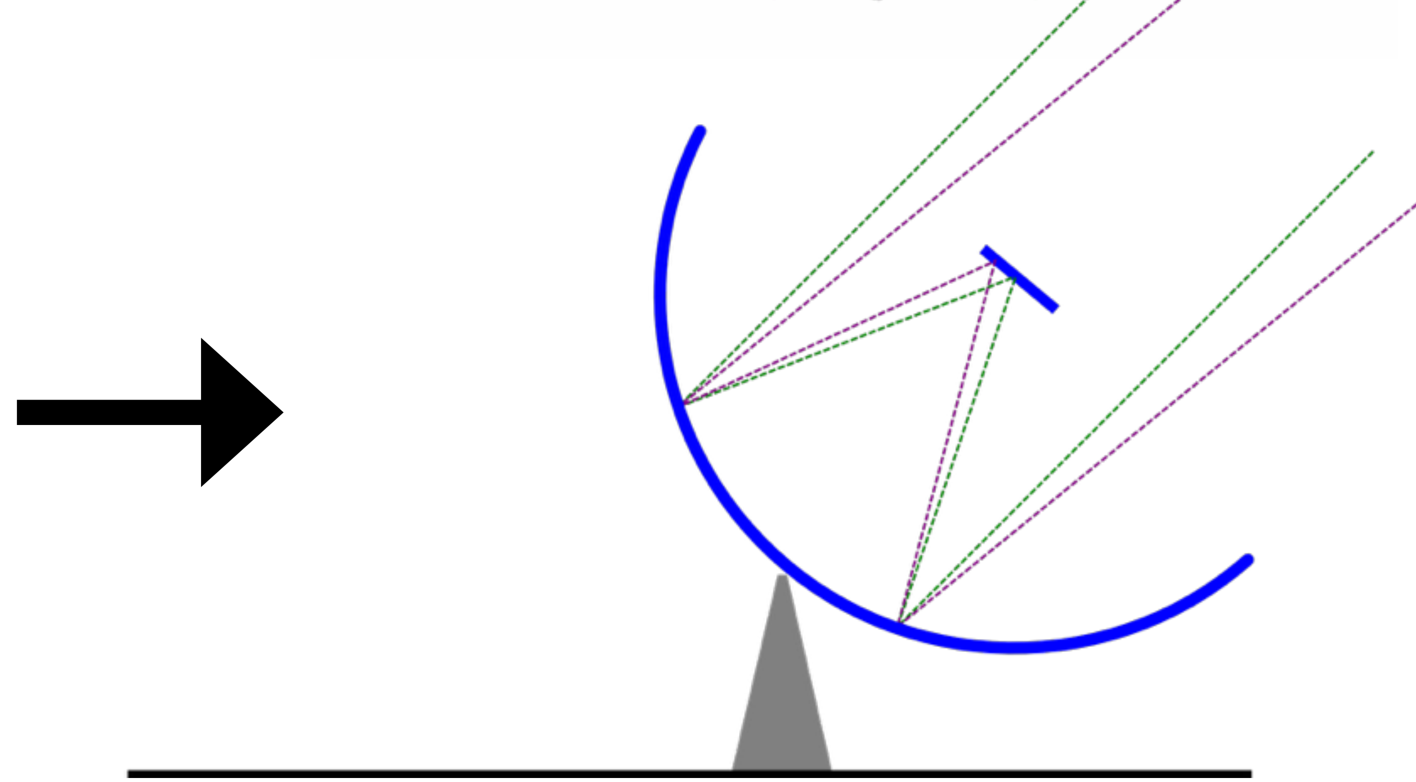


Calibration

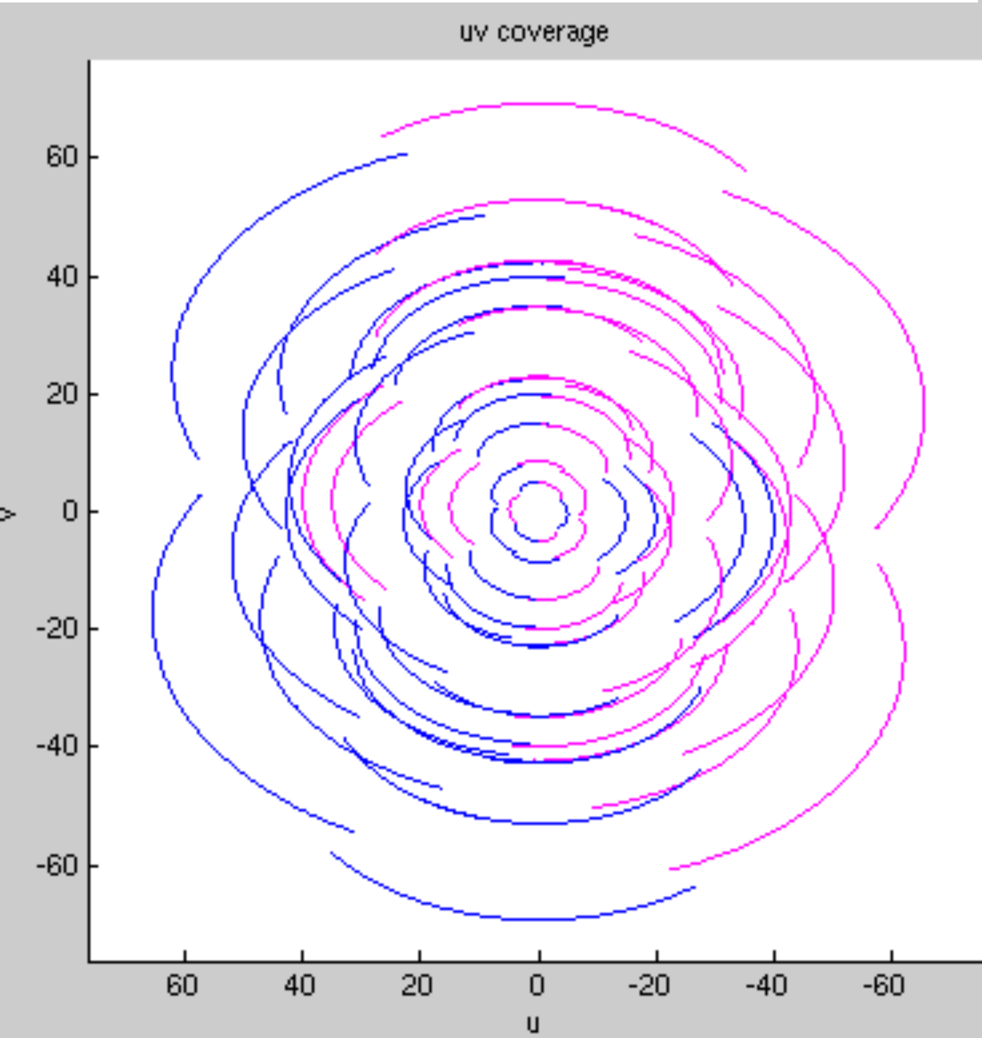


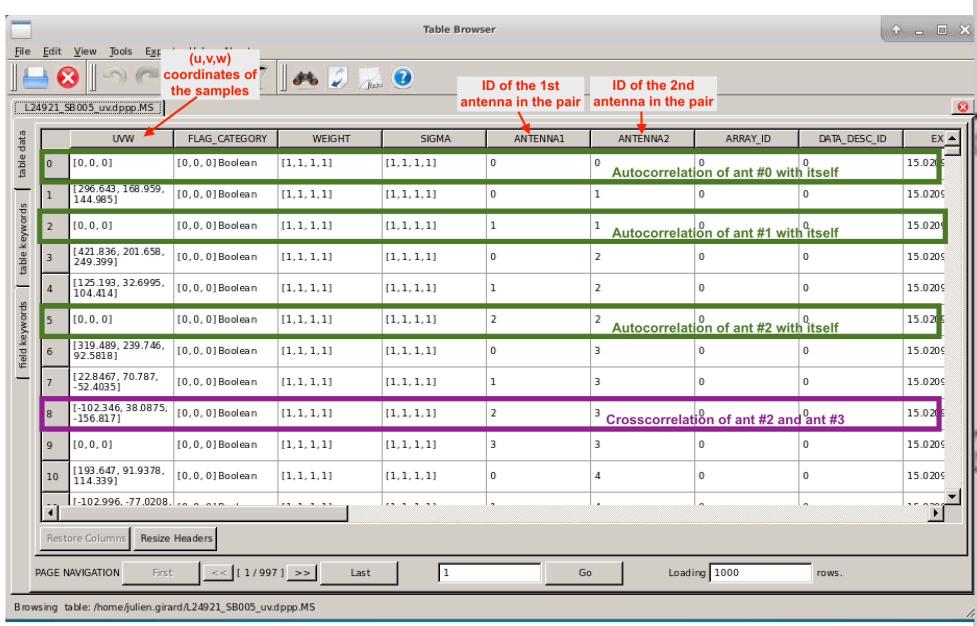
Optical equivalent



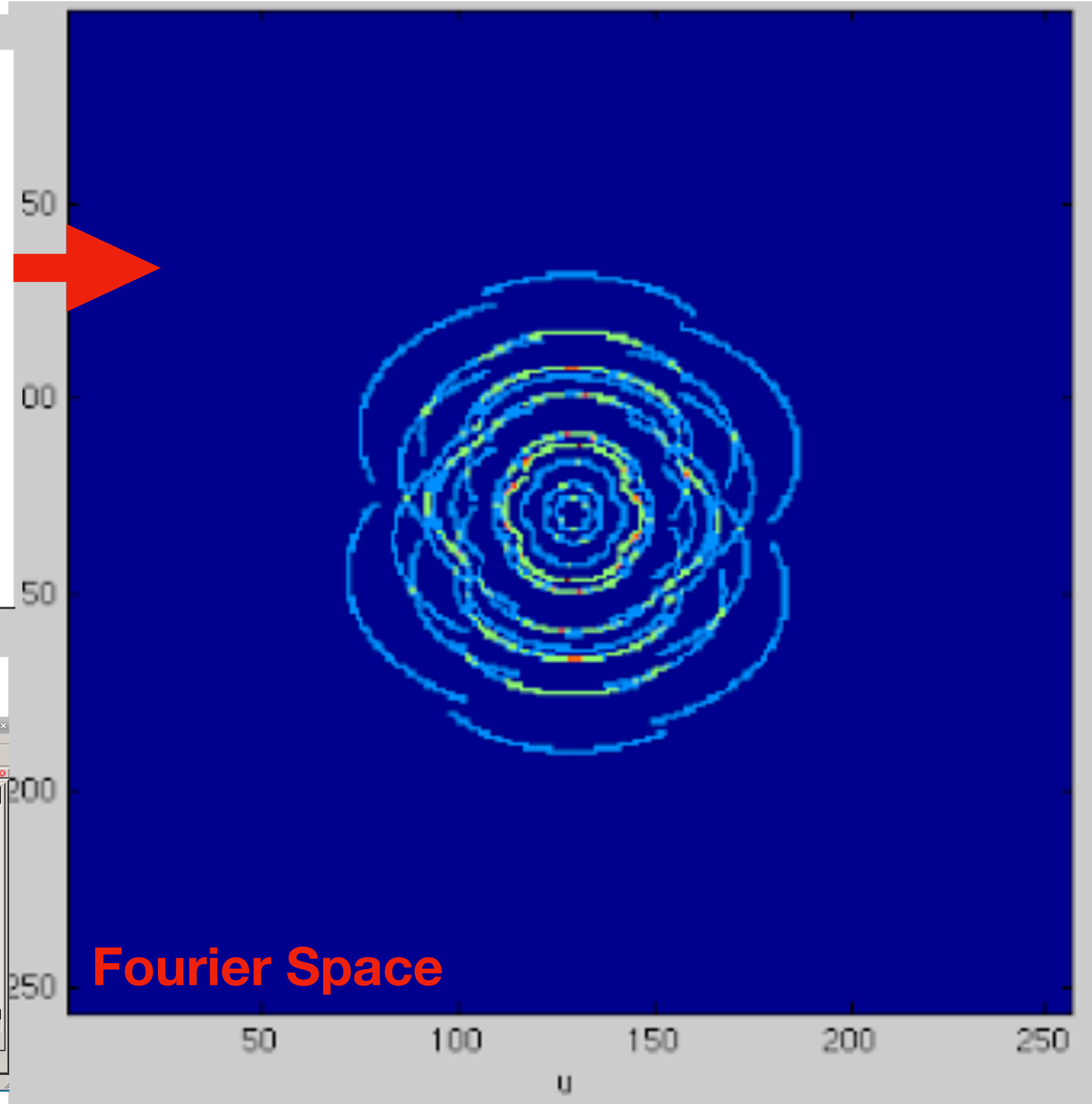


Imaging   Combining calibrated visibilities into an image





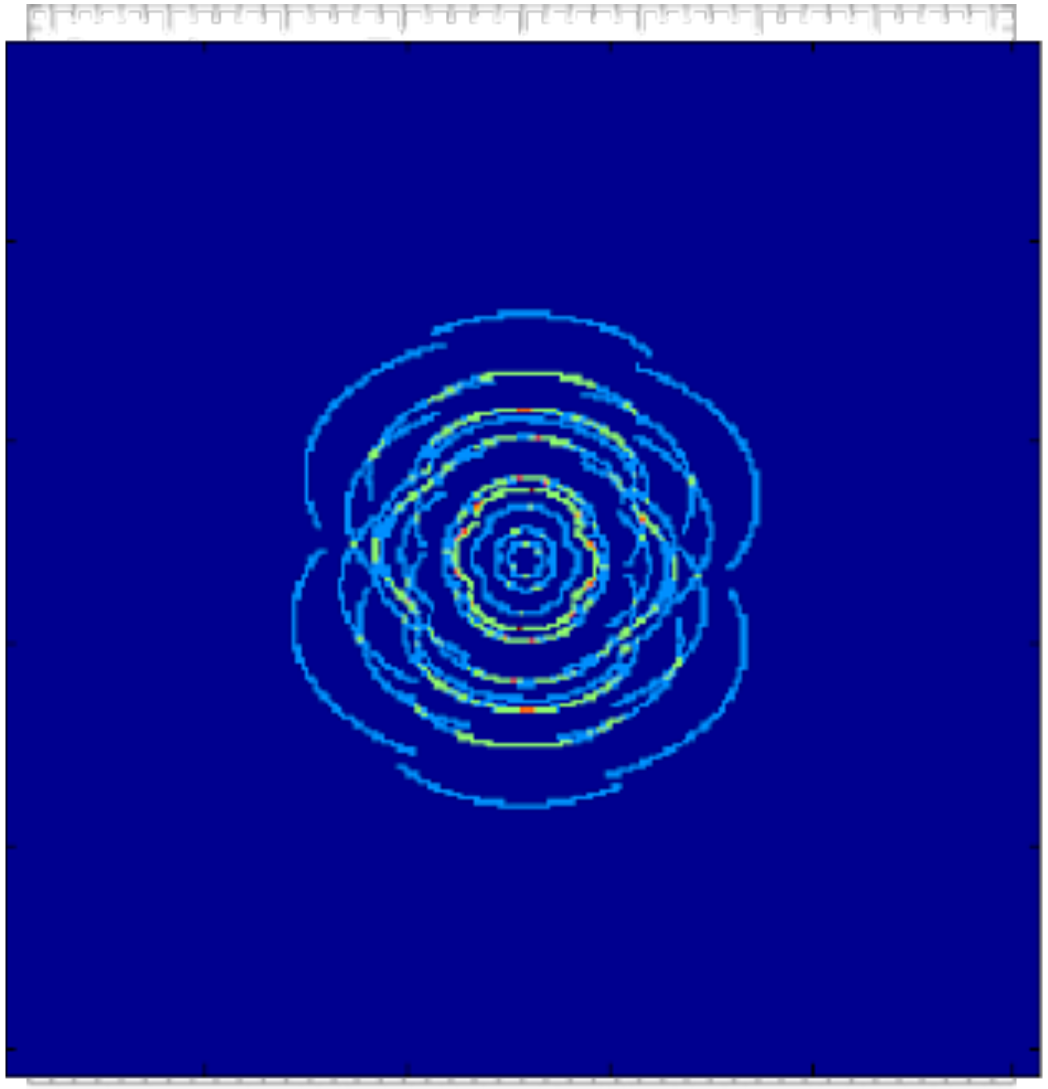
	UVW	FLAG_CATEGORY	WEIGHT	SIGMA	ANTENNA1	ANTENNA2	ARRAY_ID	DATA_DESC_ID	EX
0	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	0	0	0	15.020
1	[296.643, 168.959, 144.985]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	1	0	0	15.020
2	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	1	0	0	15.020
3	[421.836, 201.658, 249.399]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	2	0	0	15.020
4	[125.193, 32.6995, 104.414]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	2	0	0	15.020
5	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	2	2	0	0	15.020
6	[319.489, 239.746, 92.5818]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	3	0	0	15.020
7	[22.8467, 70.787, -52.4035]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	1	3	0	0	15.020
8	[-102.346, 38.0875, -156.817]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	2	3	0	0	15.020
9	[0, 0, 0]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	3	3	0	0	15.020
10	[193.647, 91.9378, 114.339]	[0, 0, 0] Boolean	[1, 1, 1, 1]	[1, 1, 1, 1]	0	4	0	0	15.020



Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage

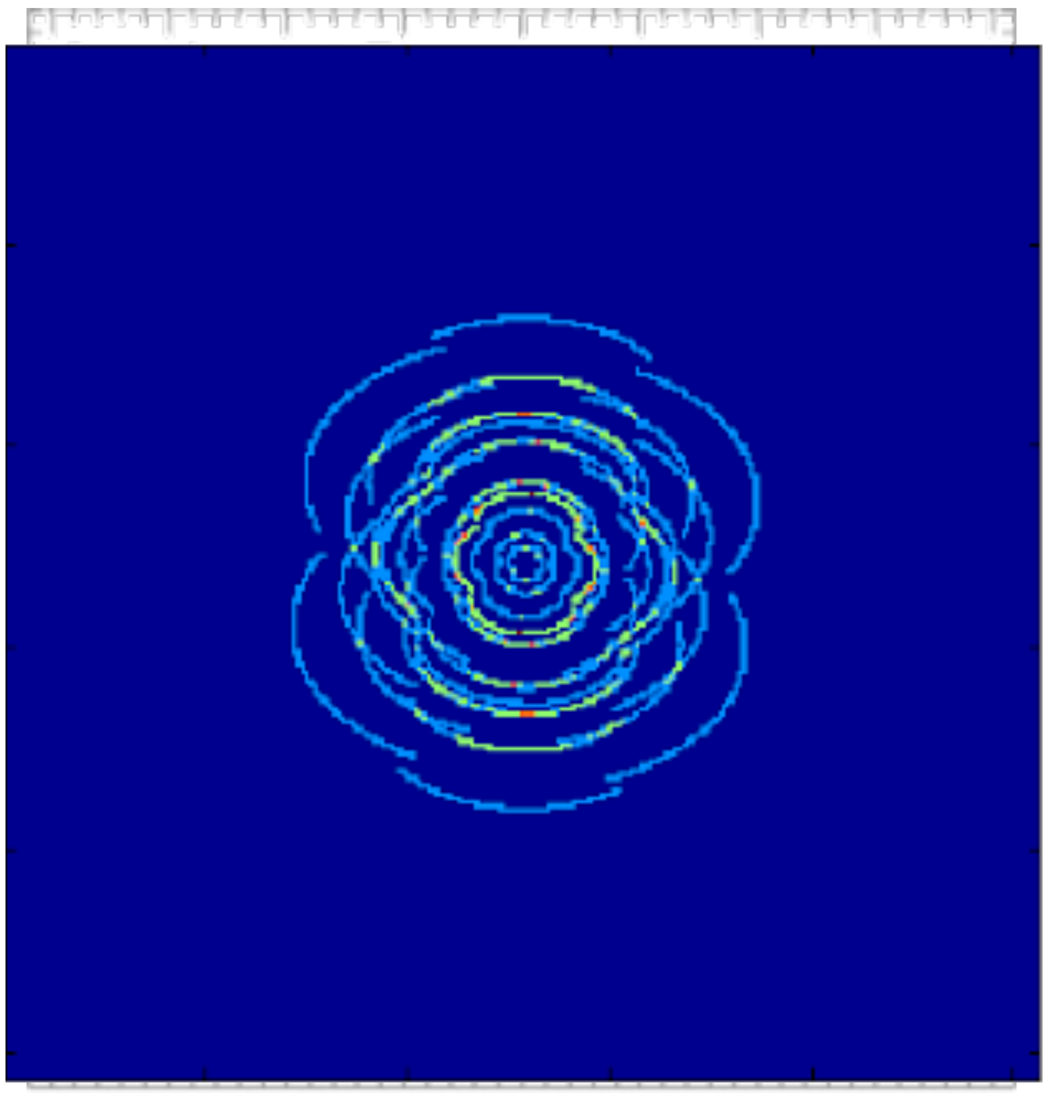


Discrete sampling of the Fourier space

Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage



Discrete sampling of the Fourier space

$\sim FT^{-1}$

image domain

Images from D. Wilner, NRAO

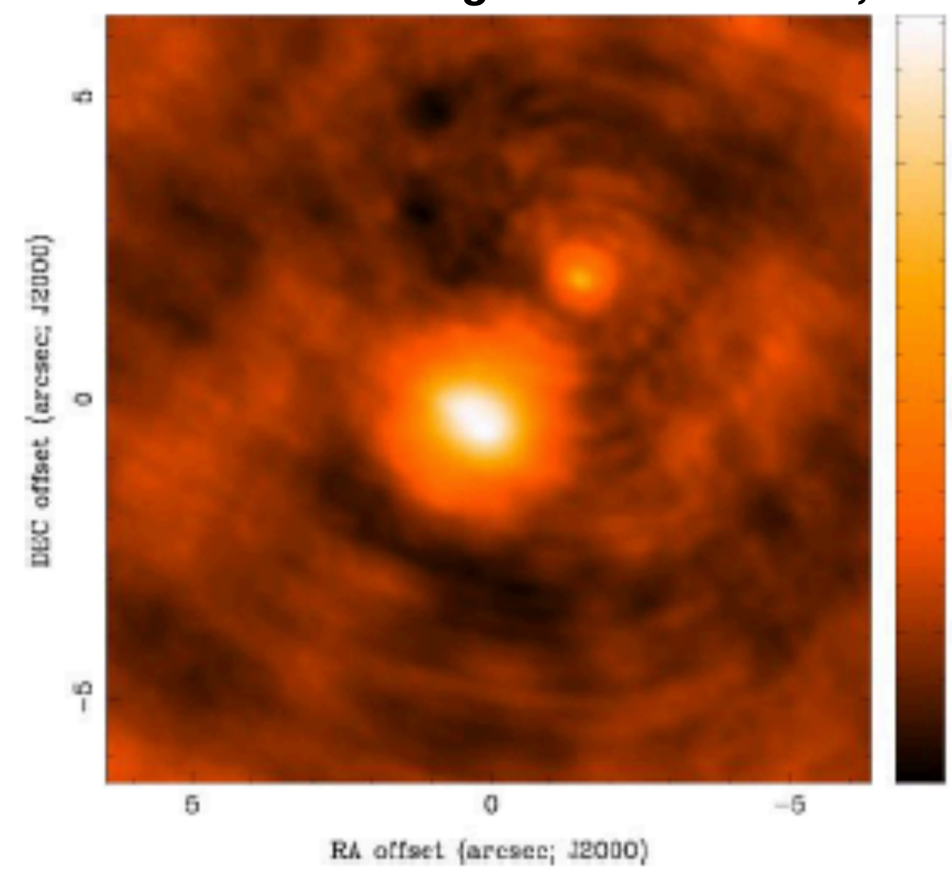


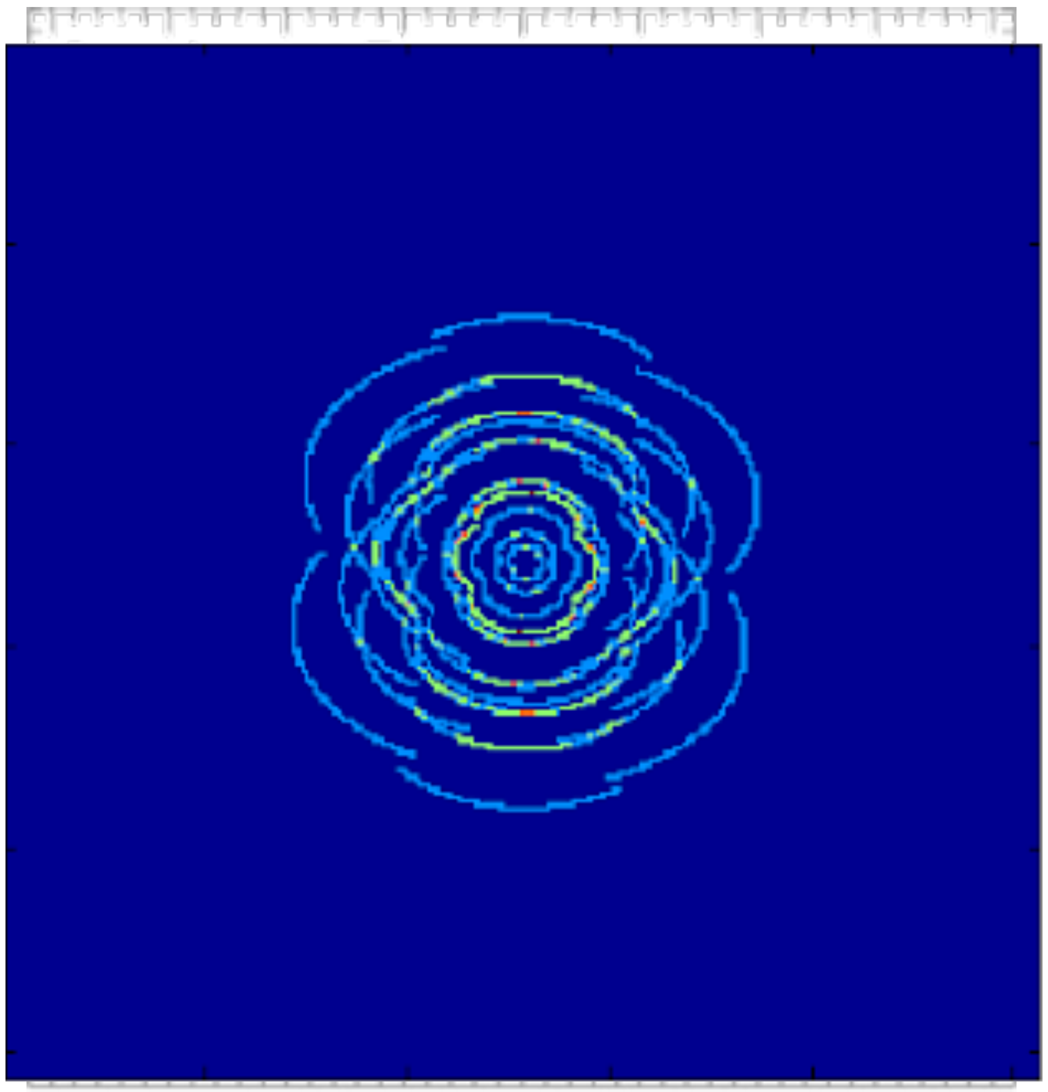
Image from Data =
« True » sky * PSF =

"Dirty" image

Deconvolution

Imagerie / Inverse problem

Fourier plane
Snapshot (u,v) Coverage



Discrete sampling of the Fourier space

$\sim FT^{-1}$

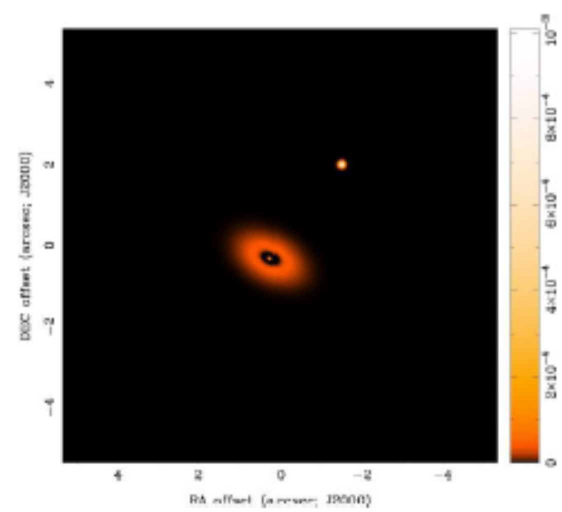
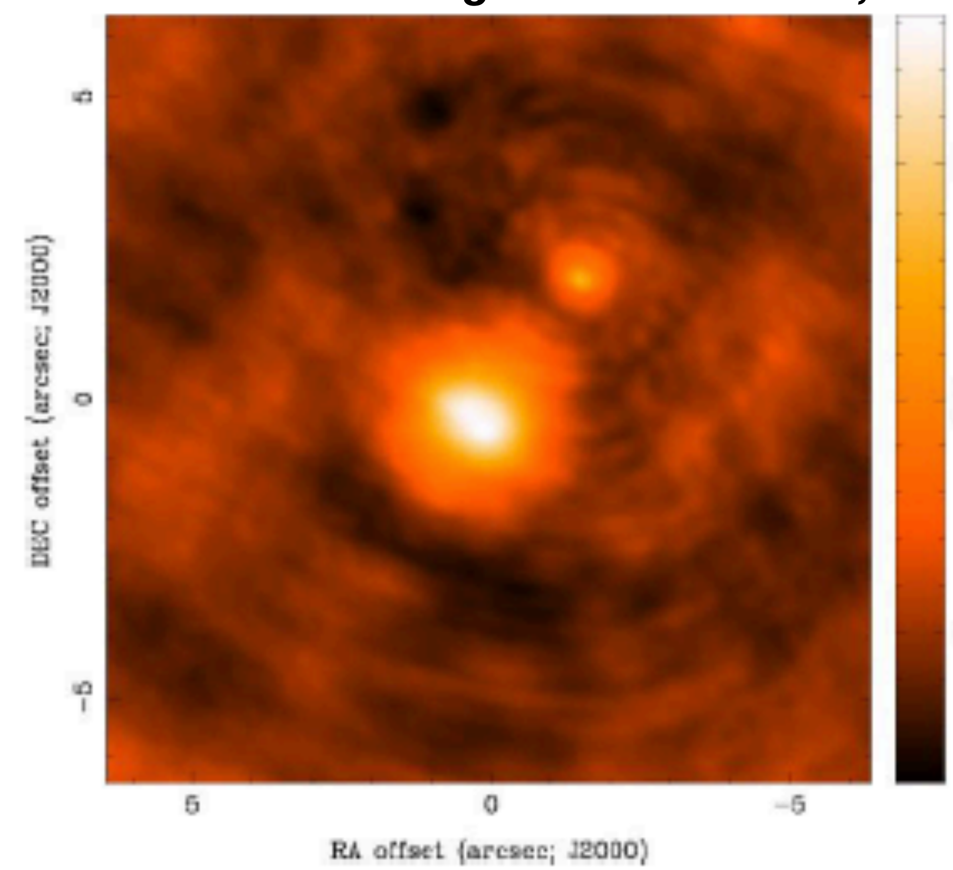


image domain

Images from D. Wilner, NRAO



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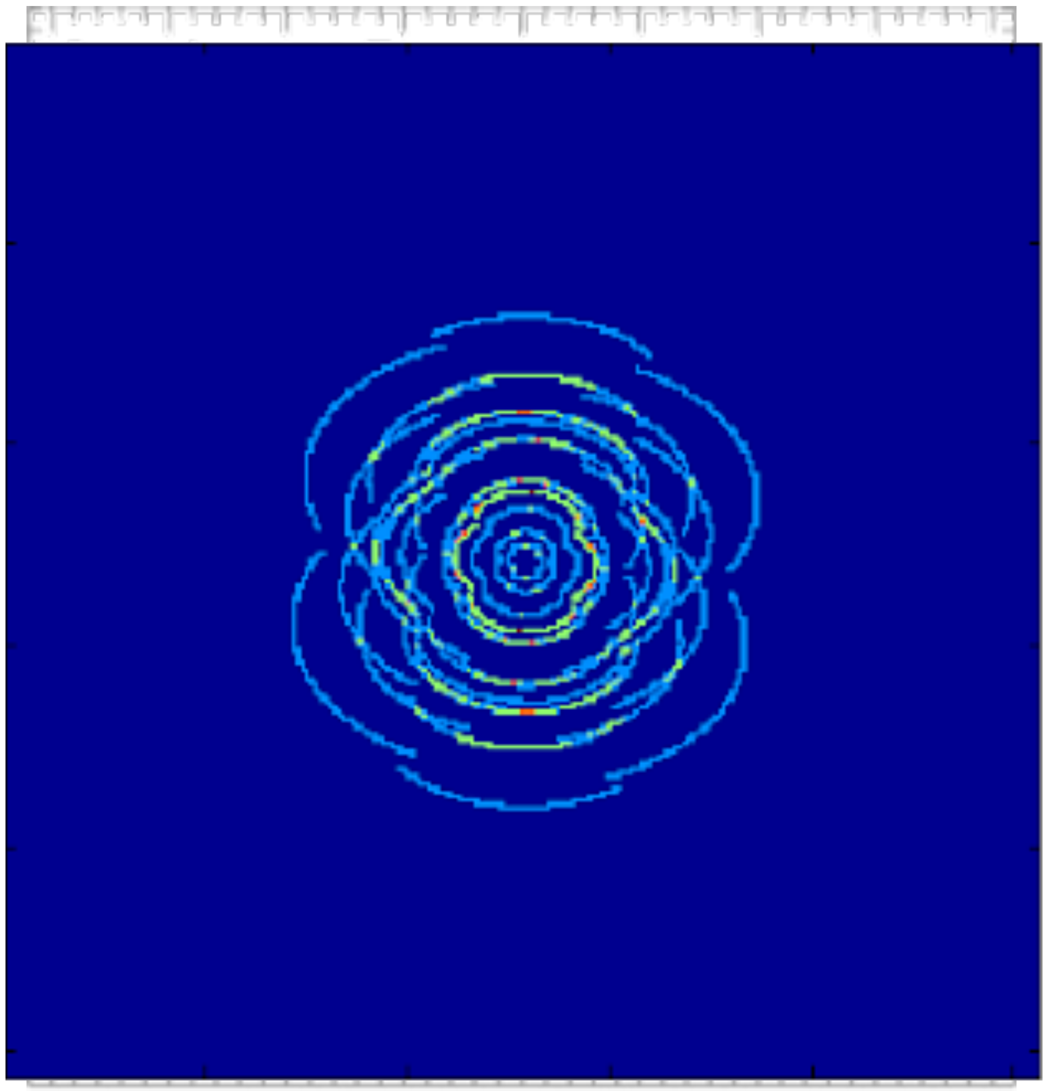
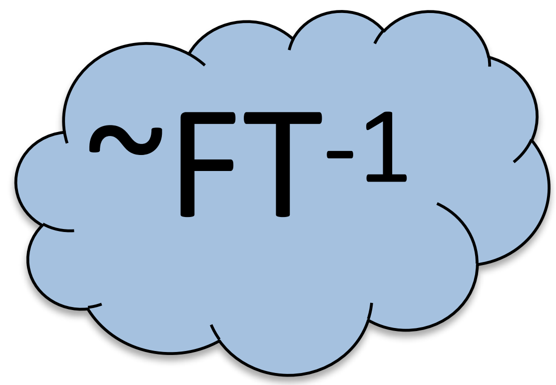


Discrete sampling of the Fourier space



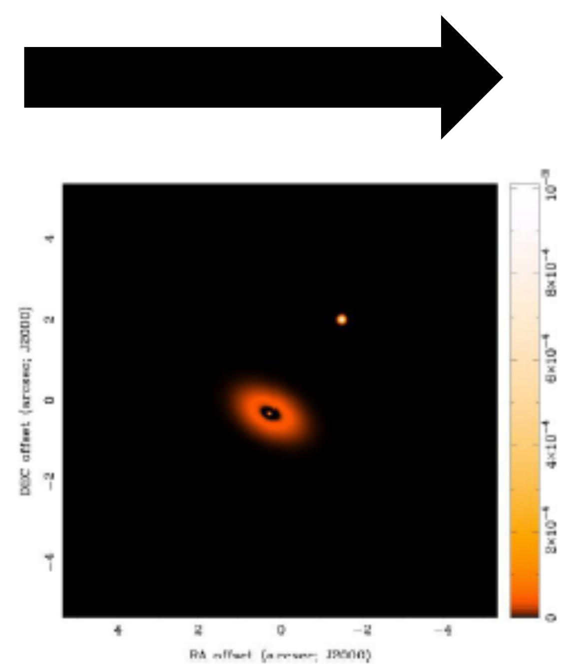


image domain

Images from D. Wilner, NRAO

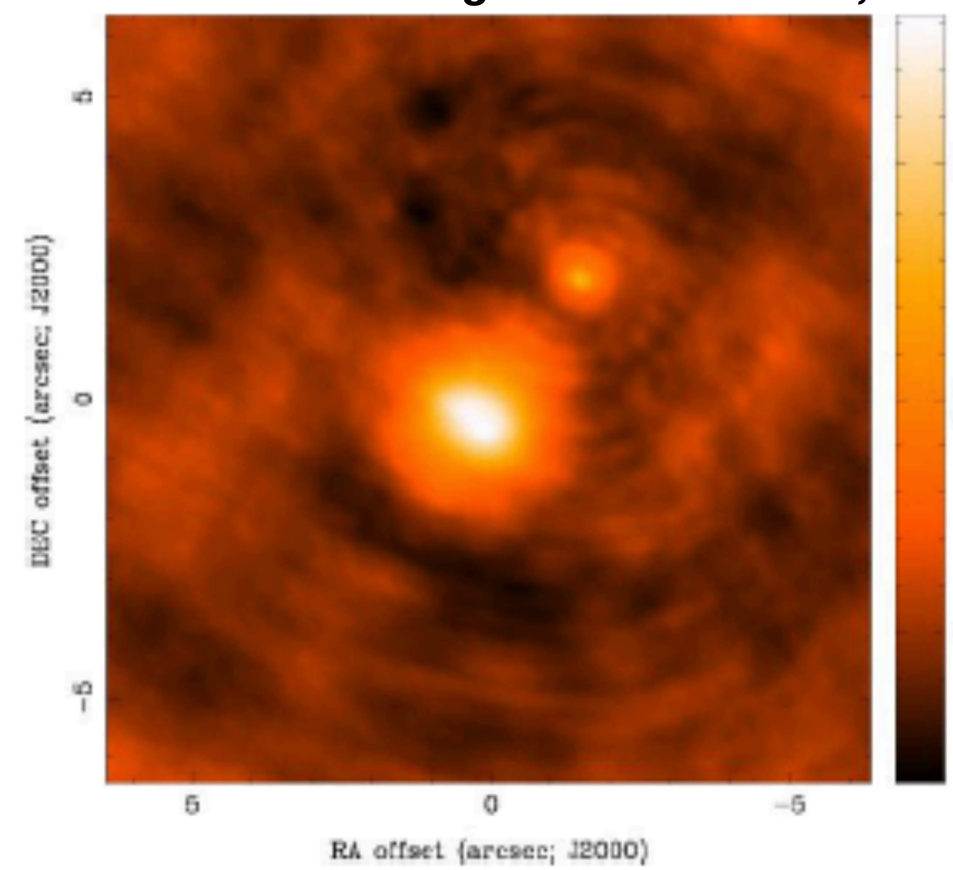


Image from Data =
« True » sky * PSF =

"Dirty" image

Usually:

- bad sampling in Fourier space — *Unsufficient sampling*
- not really a Fourier transform — *Non-coplanarities*
- simplifying hypothese no longer valid — *Small field approximation*

} ***Hard Inverse problem***

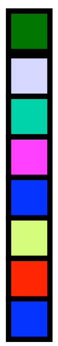
+ all direction-dependent effects (DDE) (Beam,ionosphere…)

Deconvolution

Imaging / Inverse problem

$$H$$

y



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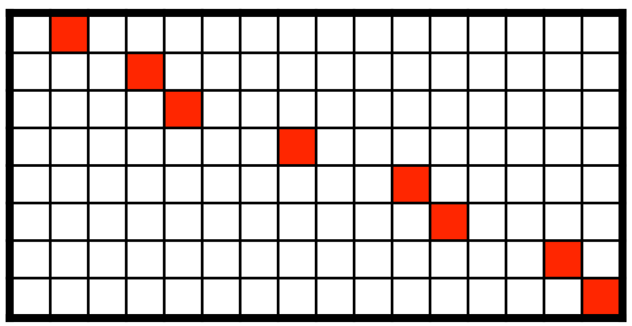
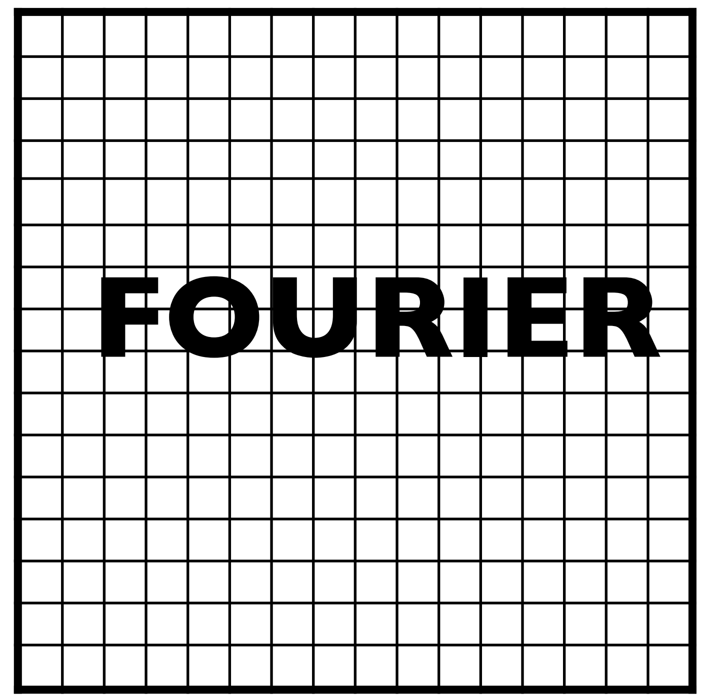
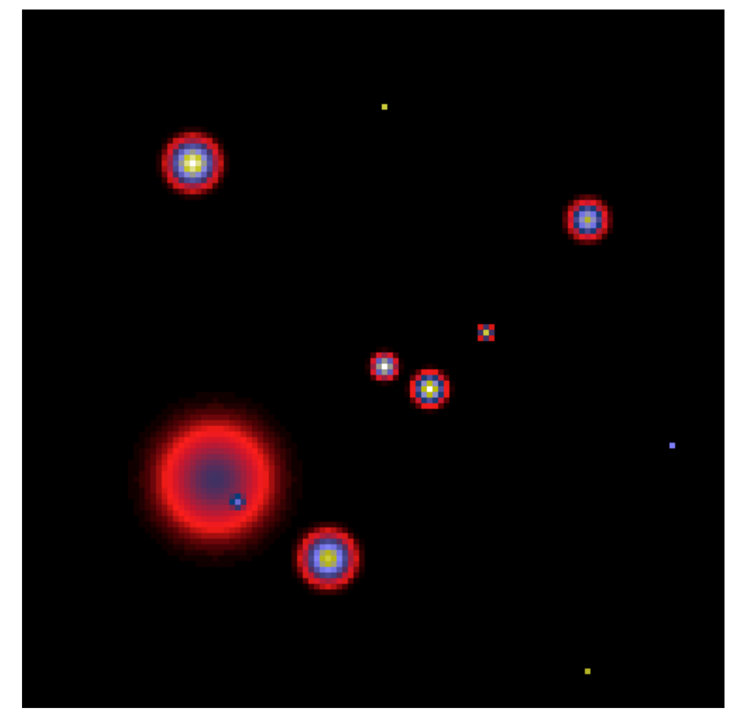
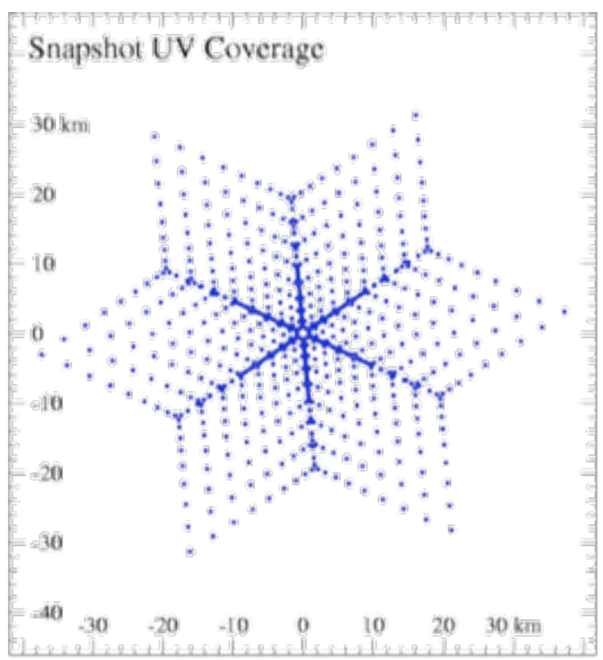






Visibilities



Measurement matrix (Fourier + Sampling)

Sky

$$X$$

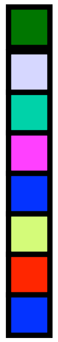
$$Y = HX + N$$

Deconvolution

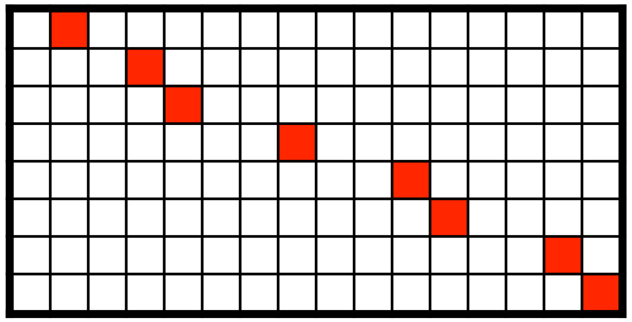
Imaging / Inverse problem

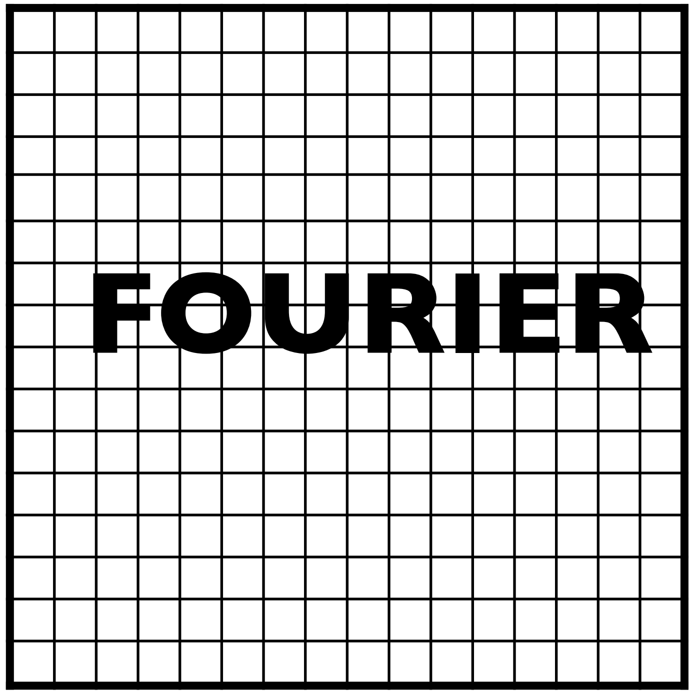
$$H$$

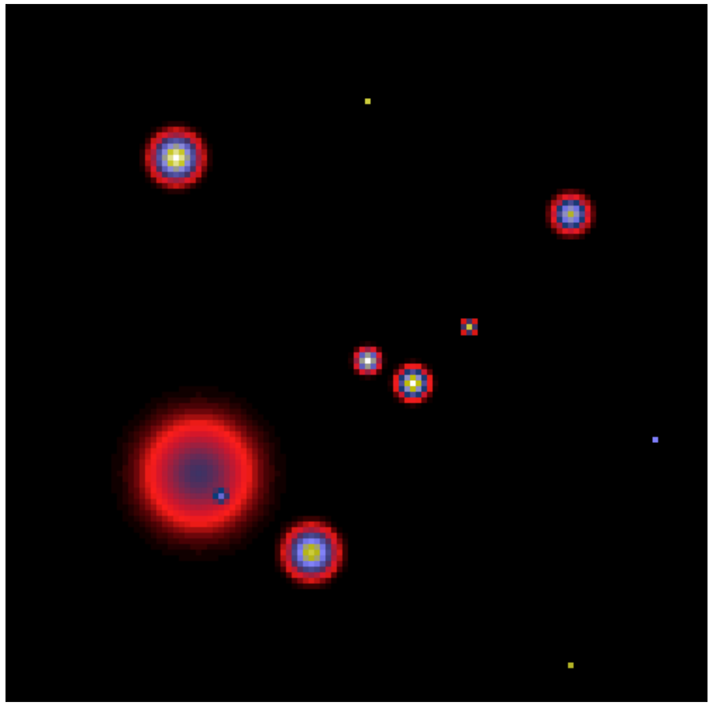
y



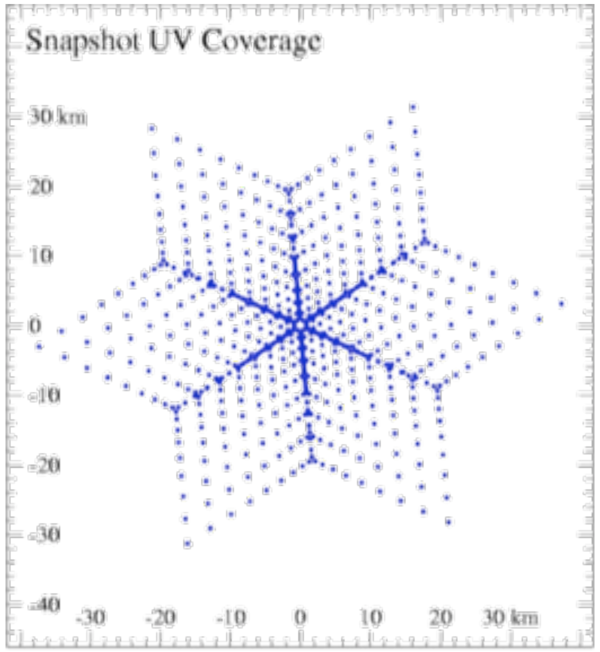
$=$







Visibilities



Measurement matrix (Fourier + Sampling)

Sky

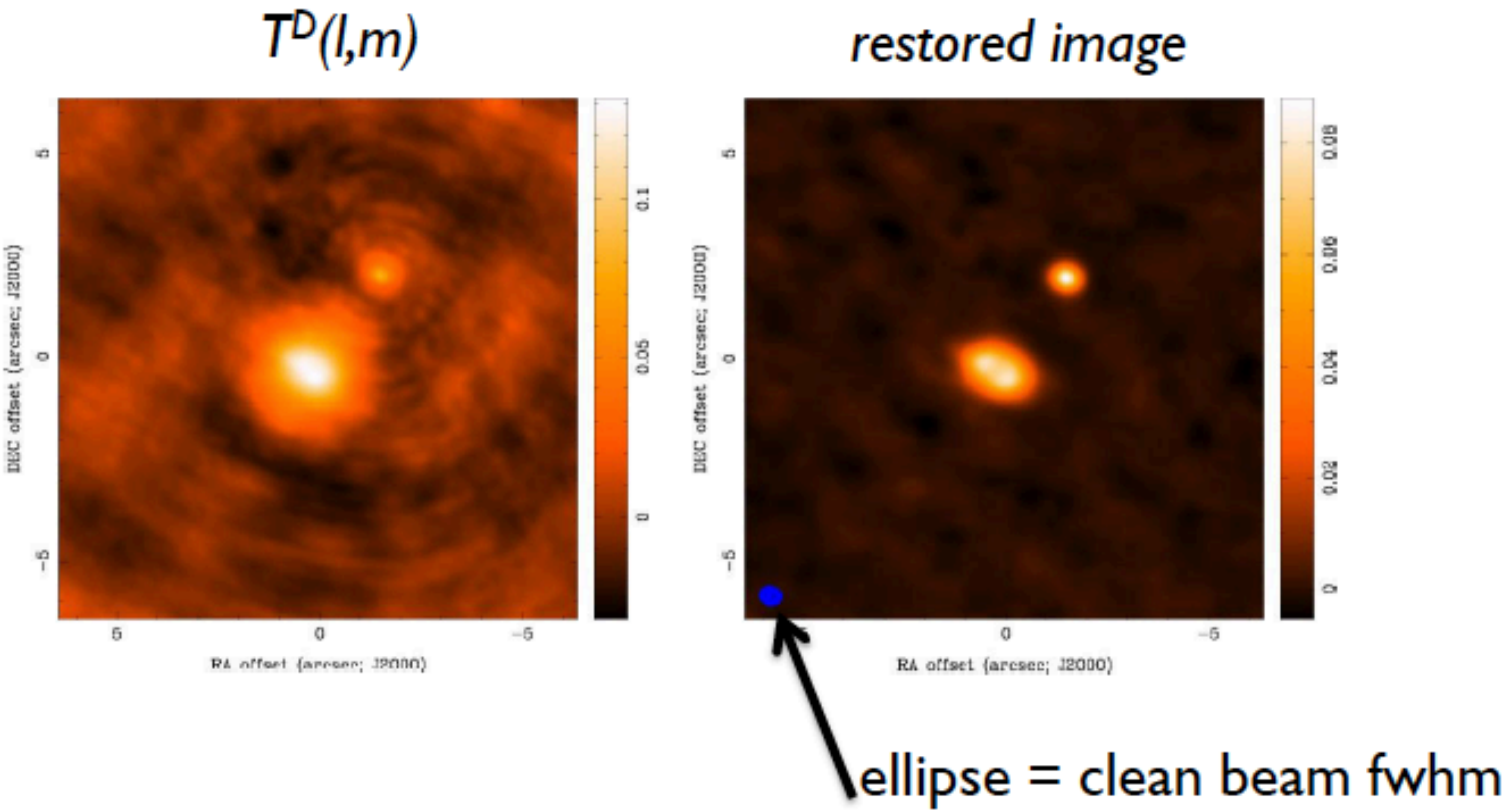
X

$$Y = HX + N$$

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

Deconvolution

Imaging / Inverse problem



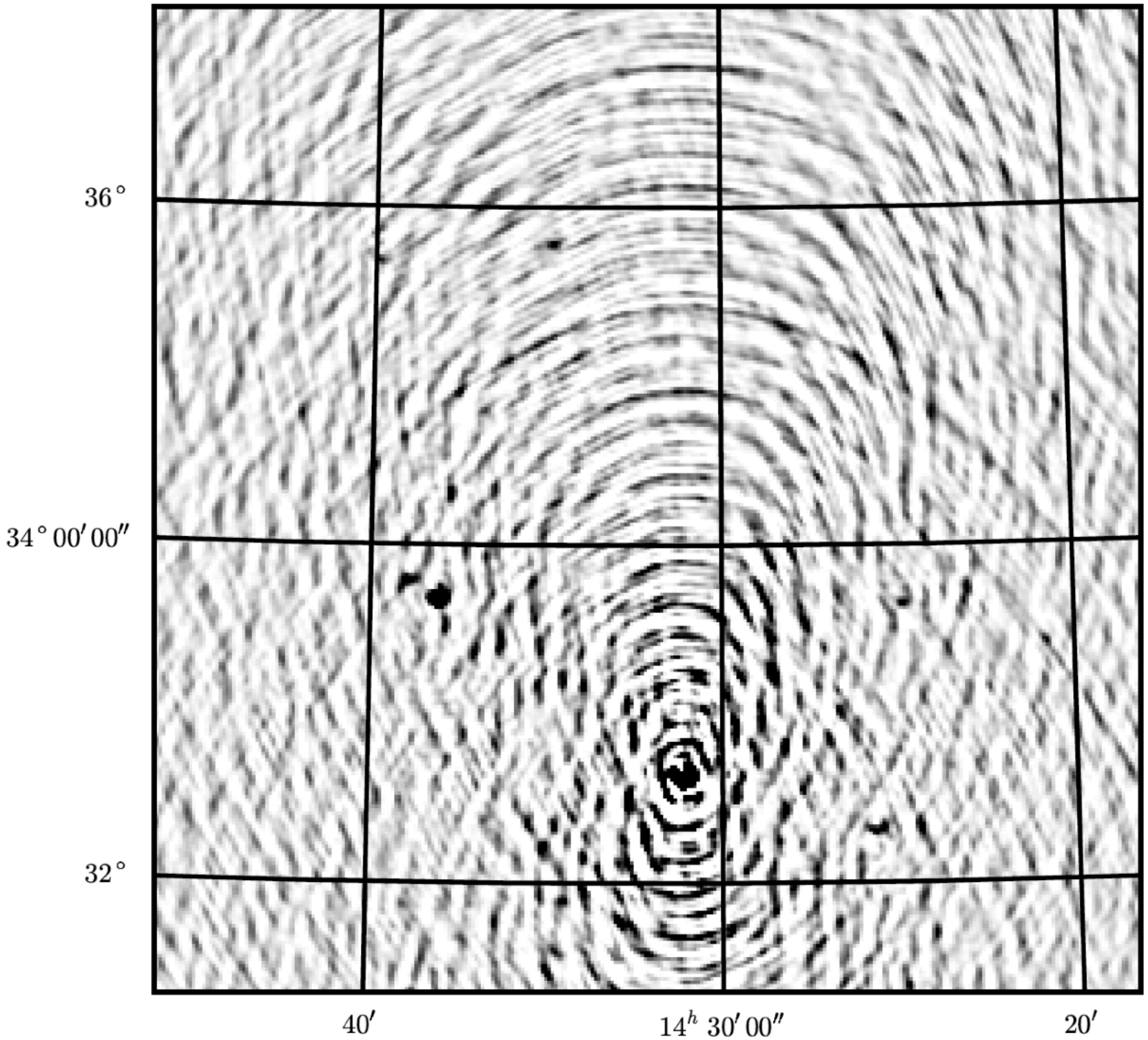
Images from D. Wilner, NRAO

Deconvolution - Algorithms beyond CLEAN

- ~40 years of development

Multifrequency, Multiscale CLEAN…

W-term only (Casa)



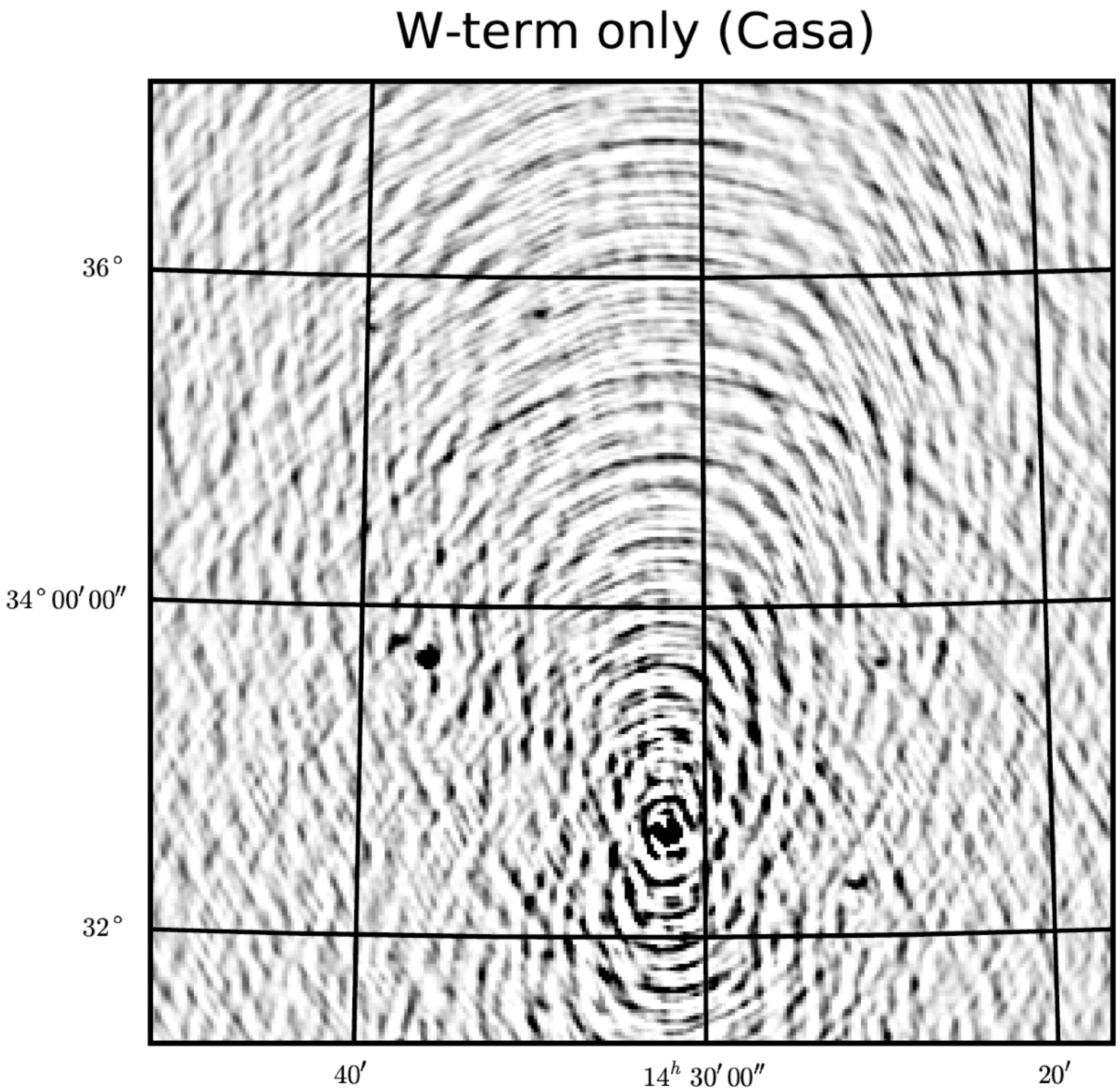
Array factor only (PSF)

Tasse et al. 2012

Deconvolution - Algorithms beyond CLEAN

- ~40 years of development *Multifrequency, Multiscale CLEAN…*

- Today, accounting for Direction-dependent effects *Imaging ~ Calibration*



Array factor only (PSF)

Tasse et al. 2012

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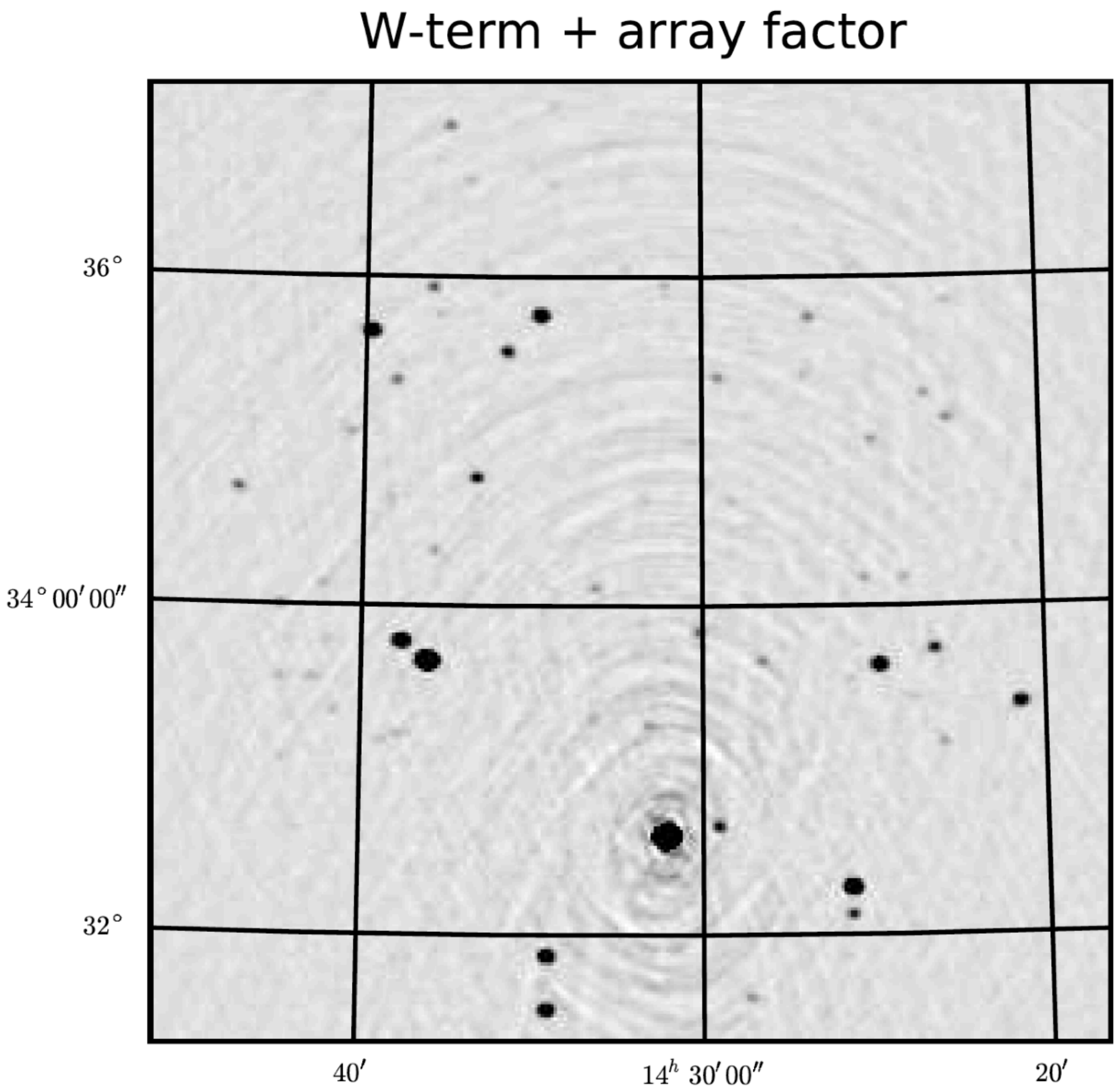


Array factor only (PSF)

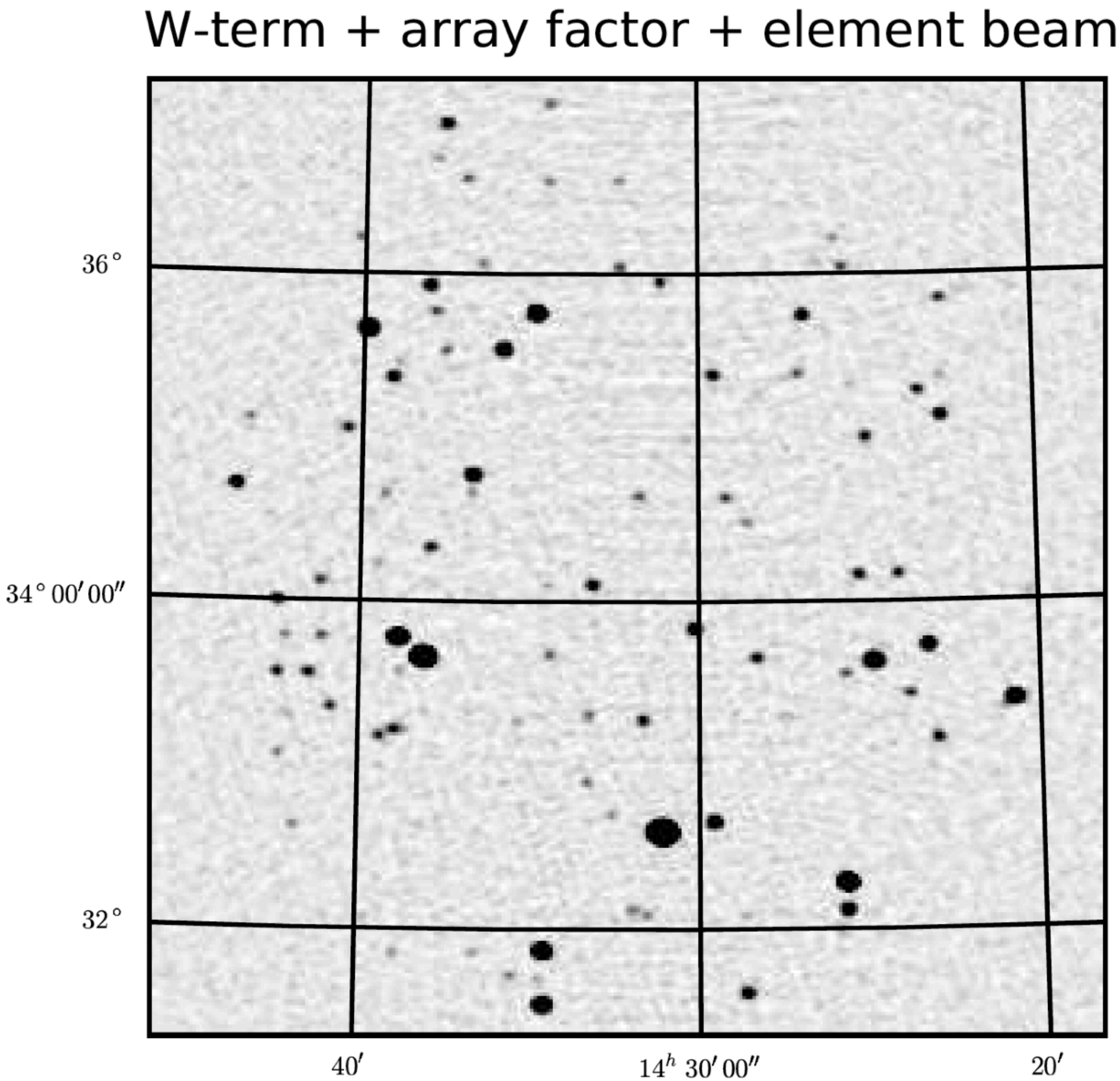
+

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

Tasse et al. 2012

Deconvolution - Algorithms beyond CLEAN

- **~40 years of development** *Multifrequency, Multiscale CLEAN…*
- **Today, accounting for Direction-dependent effects** *Imaging ~ Calibration*



Array factor only (PSF)

+

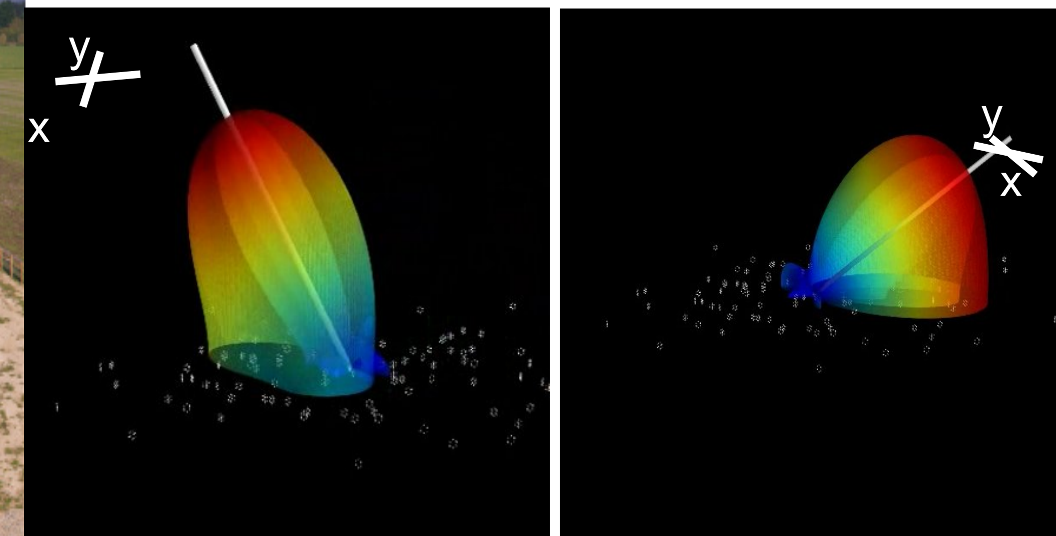
Non-coplanarity (and/or wide field of view) ("W-term" ≠ 0)

+

Antenna beam pattern ("E-term")

Tasse et al. 2012

Direction-Dependent Effects



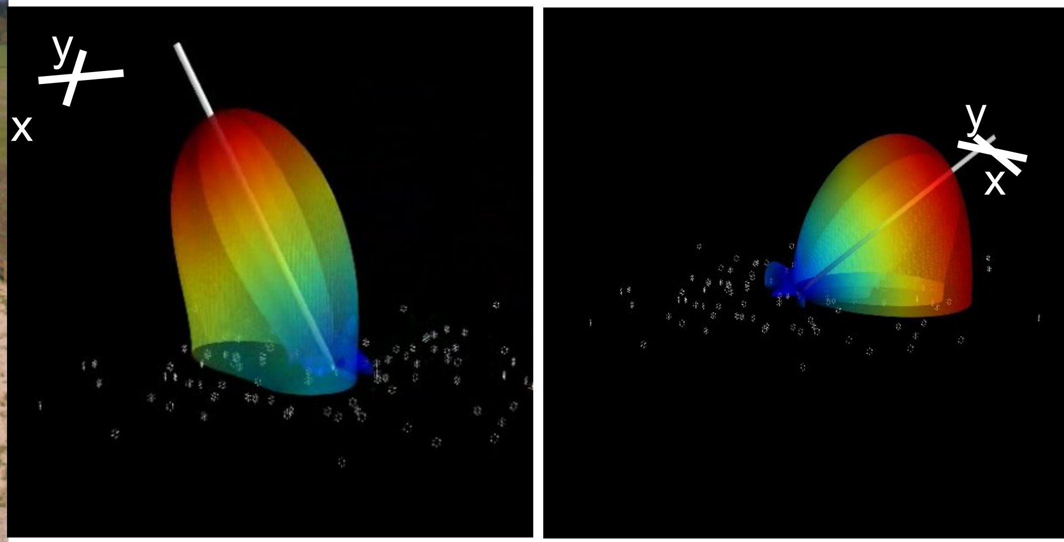
Direction 1 Direction 2

affecte le gain

la polarisation

Diagramme d’antenne

Direction-Dependent Effects

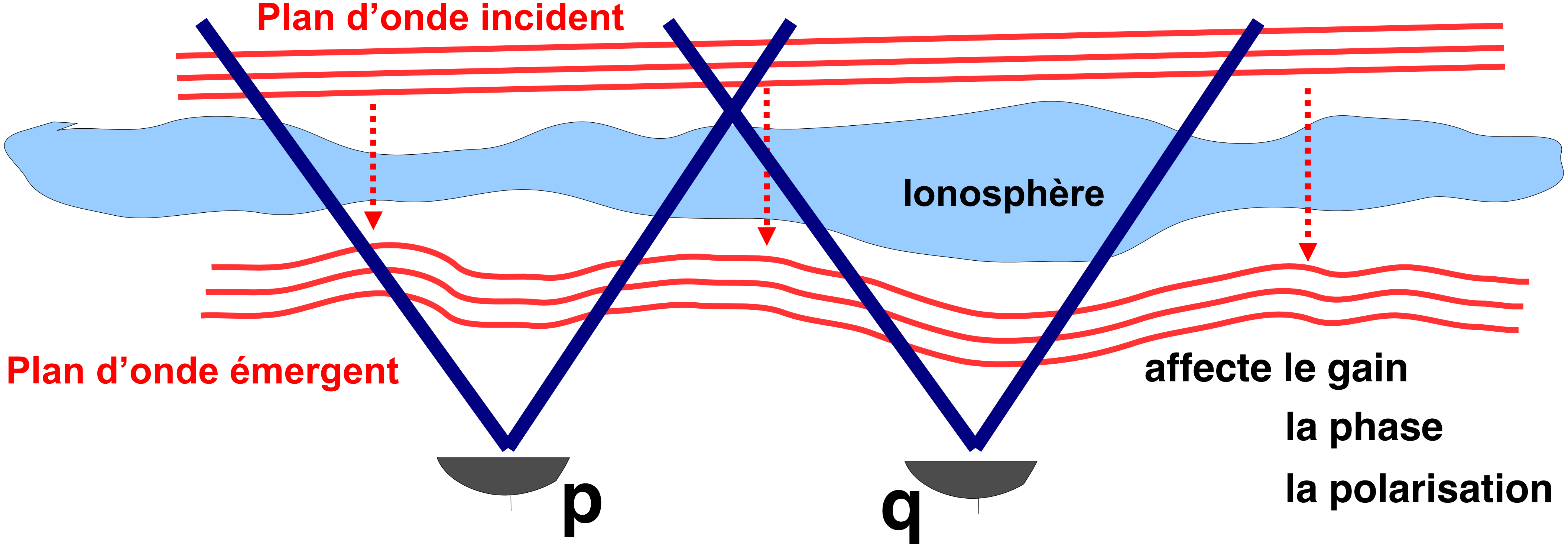


Direction 1 Direction 2

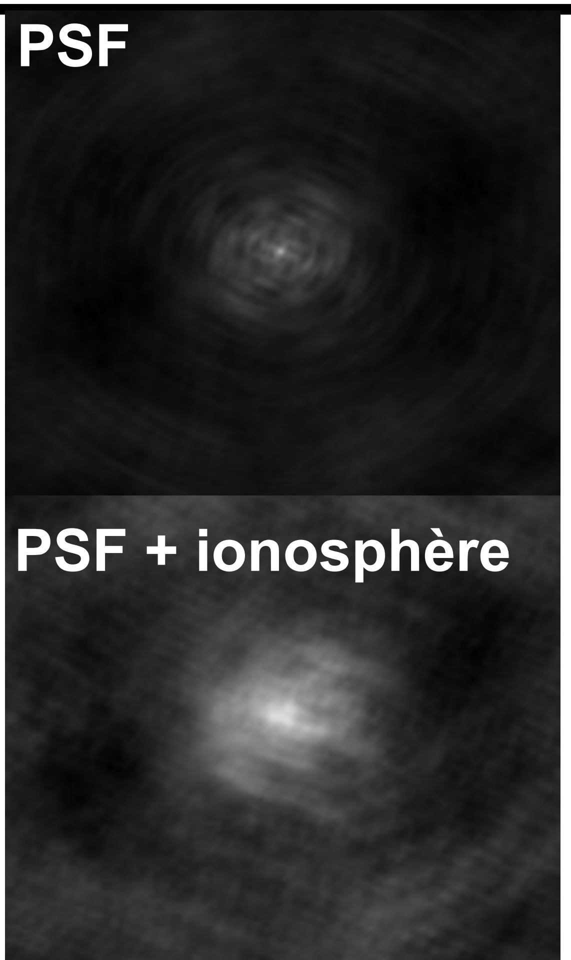
affecte le gain
la polarisation

Diagramme d’antenne

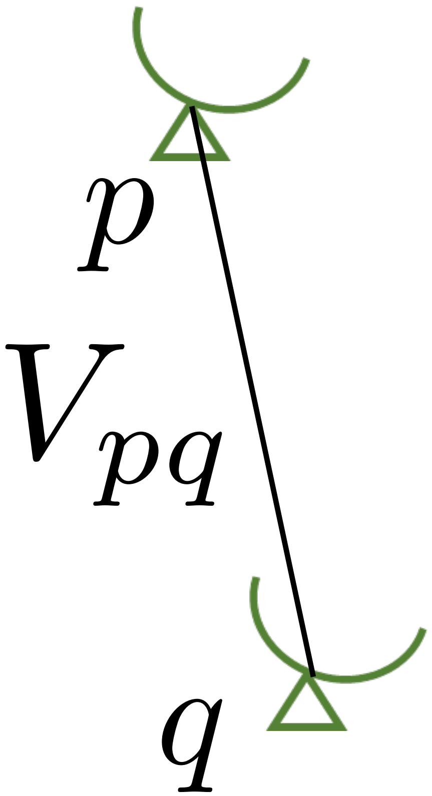
Fluctuations ionosphériques/atmosphériques



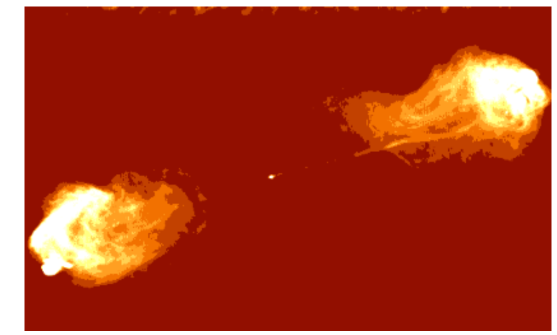
affecte le gain
la phase
la polarisation



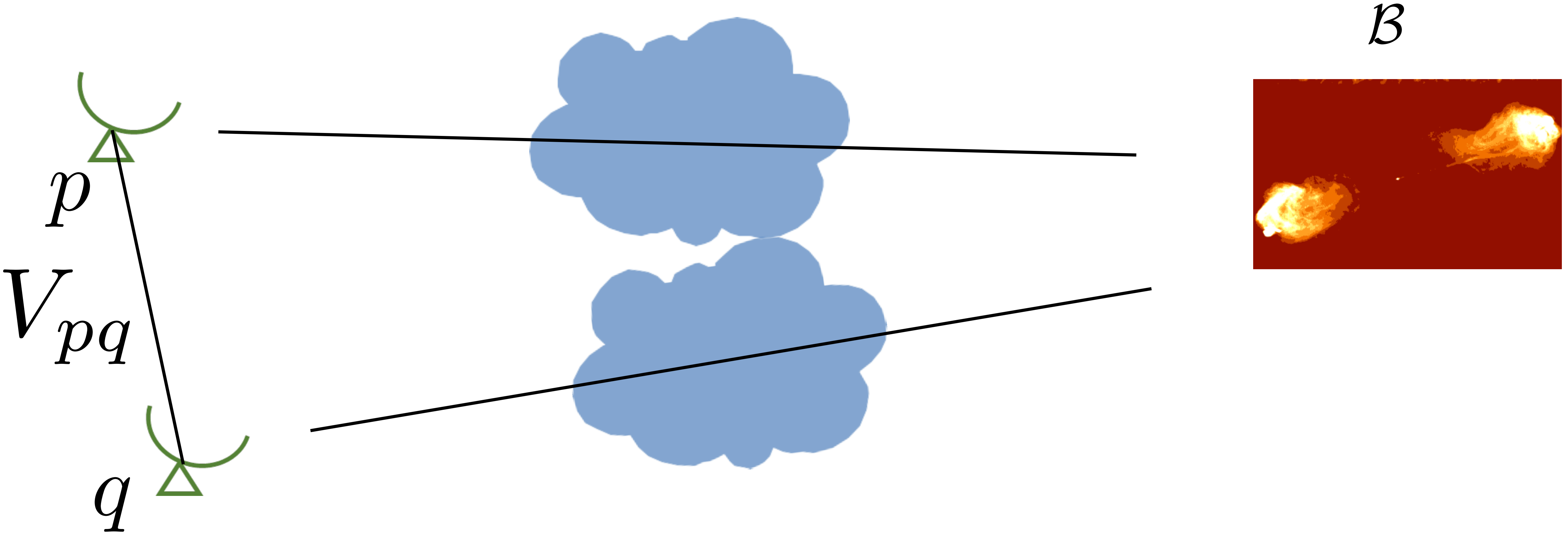
Direction-Dependent Effects



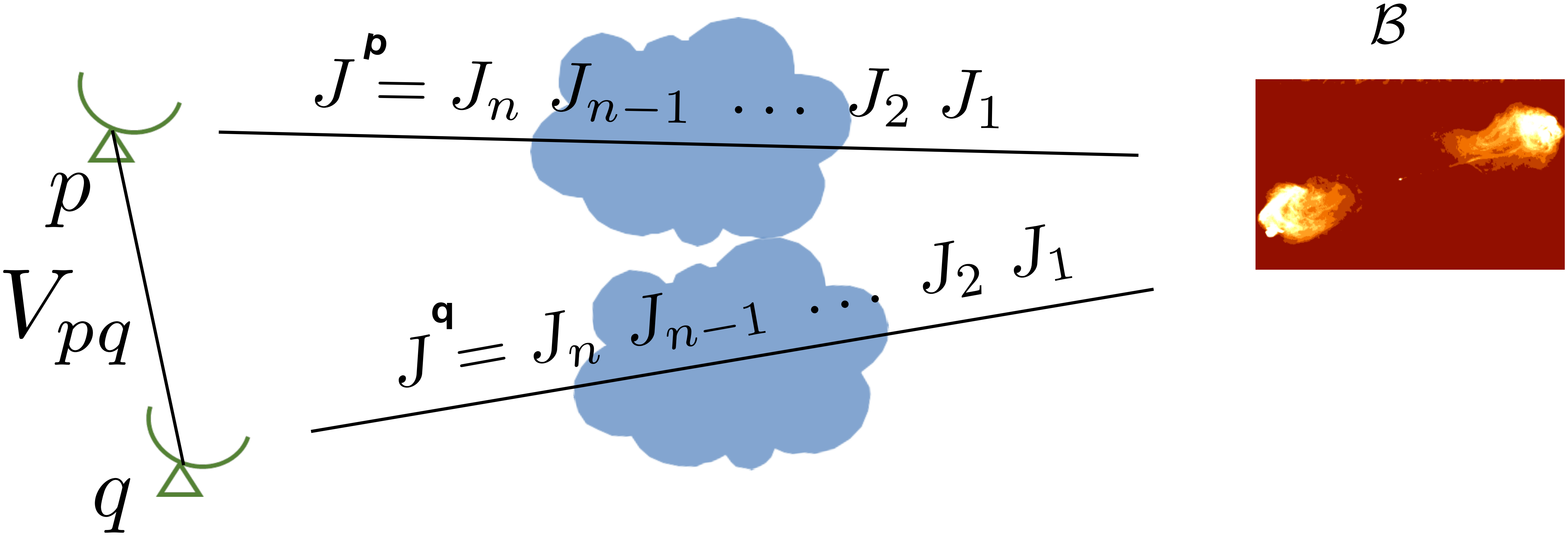
$\mathcal{B}$



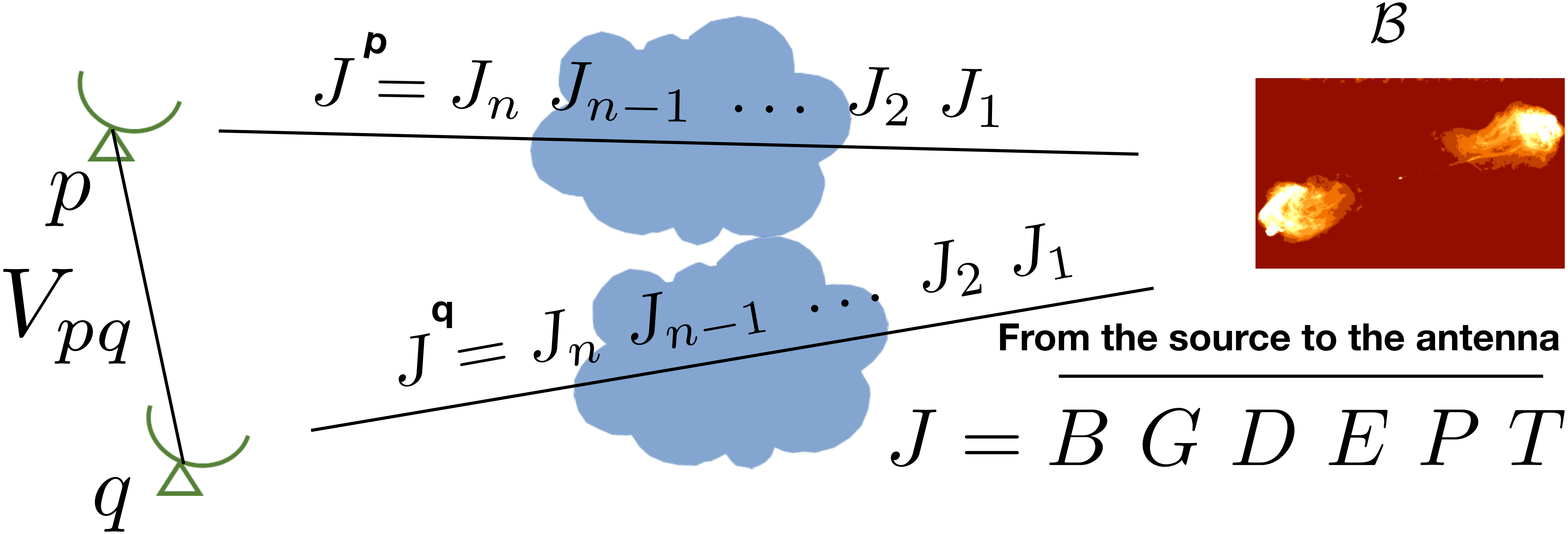
Direction-Dependent Effects



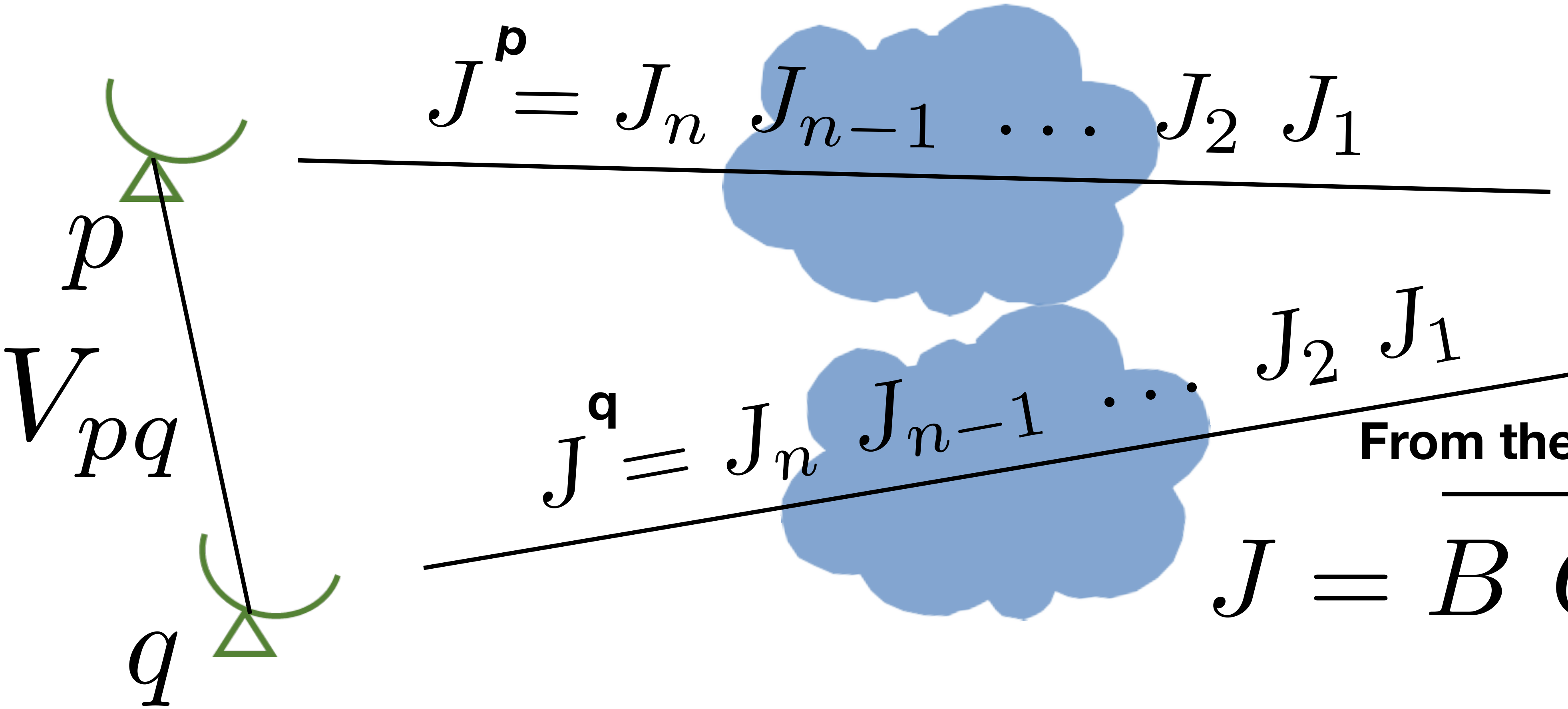
Direction-Dependent Effects



Direction-Dependent Effects



Direction-Dependent Effects



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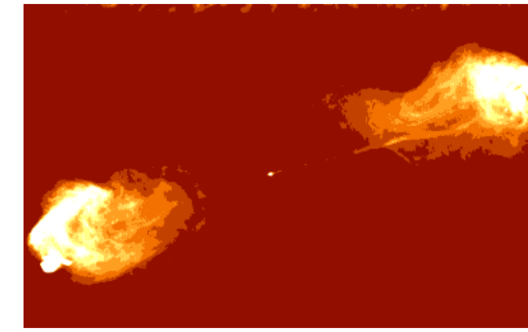


From the source to the antenna

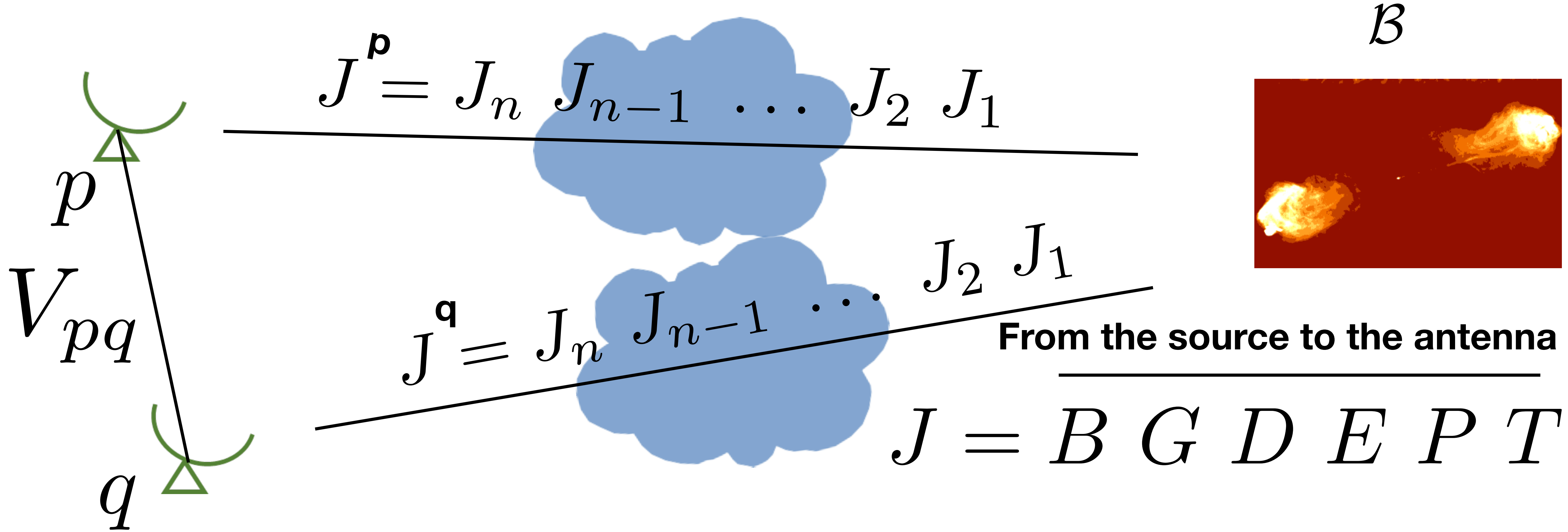
$$J = B \; G \; D \; E \; P \; T$$

Radio Interferometer Measurement Equation

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

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]

Direction-Dependent Effects



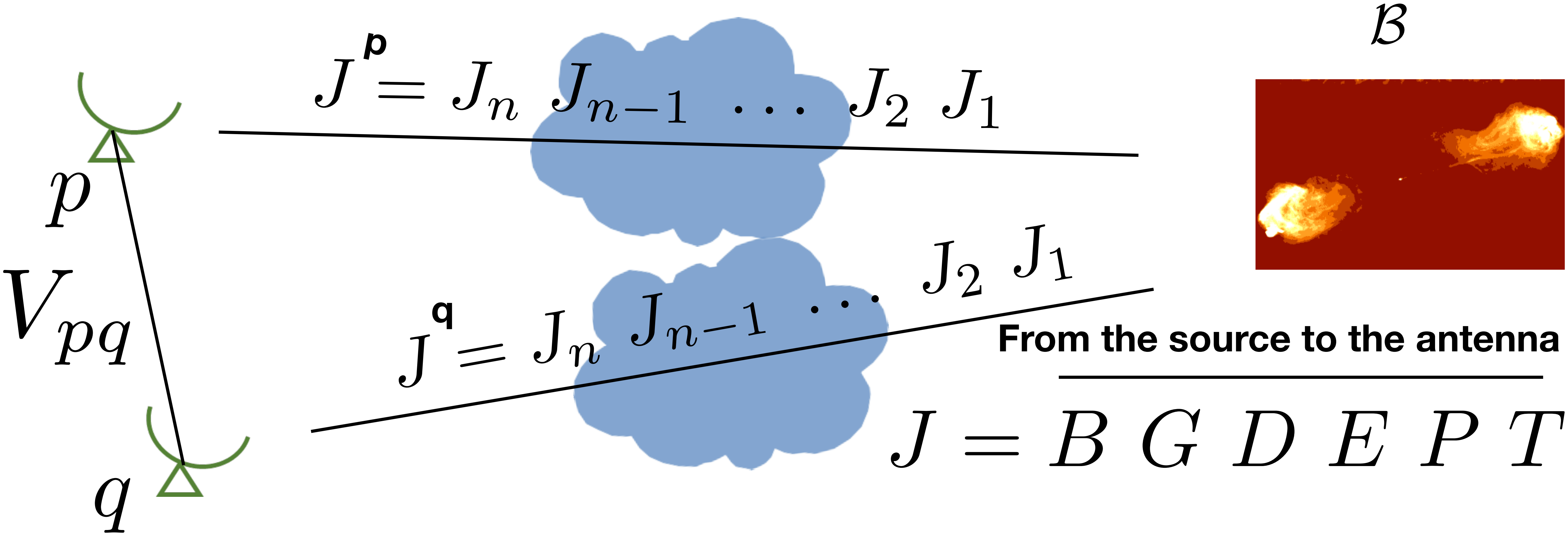
Radio Interferometer Measurement Equation

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

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]

- **Visibility from baseline pq** (V_{pq})
- **Effects from the source to antenna p** (J_p)
- **Brightness** ($\mathcal{B}$)
- **Effects from the source to antenna q** (J_q^H)

Direction-Dependent Effects



Radio Interferometer Measurement Equation

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

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]

- V_{pq}: **Visibility from baseline pq**
- J_p: **Effects from the source to antenna p**
- $\mathcal{B}$: **Brightness**
- J_q^H: **Effects from the source to antenna q**

Compact, intuitive and linear representation of propagation effects

Now Mandatory for the calibration of large interferometers

Hands-on

Basic tutorial First light NenuFAR Data Vir A

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

Hands-on

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Imaging / Deconvolution	*WSClean*		
(Source finding)	*Pybdsf*		
Advanced Imaging tutorial	NCP NenuFAR Data		
Data statistics quicklook			
Impact of A-team			Friday
Building Sky model	*Mix of python, DPPP, LoSoTo, …*		
Calibration (DDE)			
Imaging			
A-team subtraction			
Source finding			