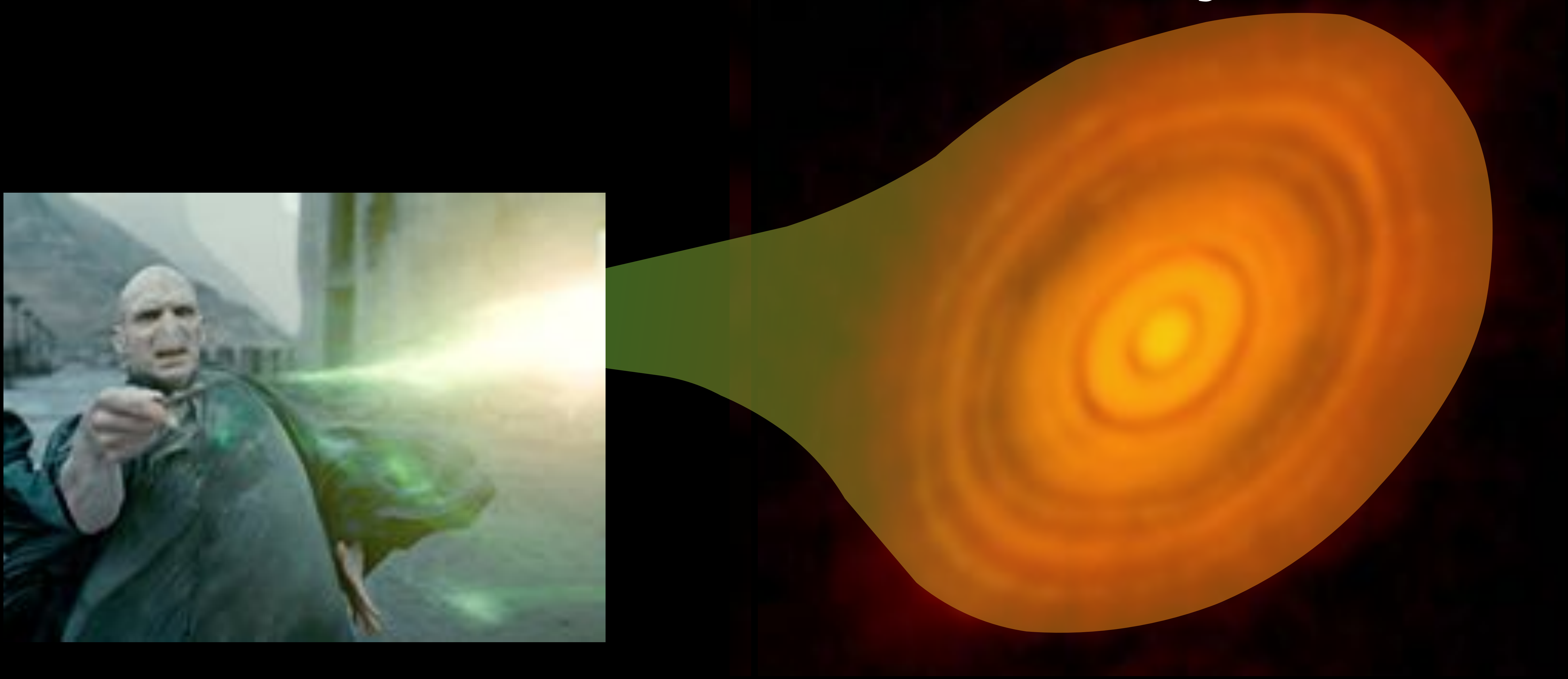
The Dark Magic of Radio Astronomy



Yao-Lun Yang
GSPS
11.20.15

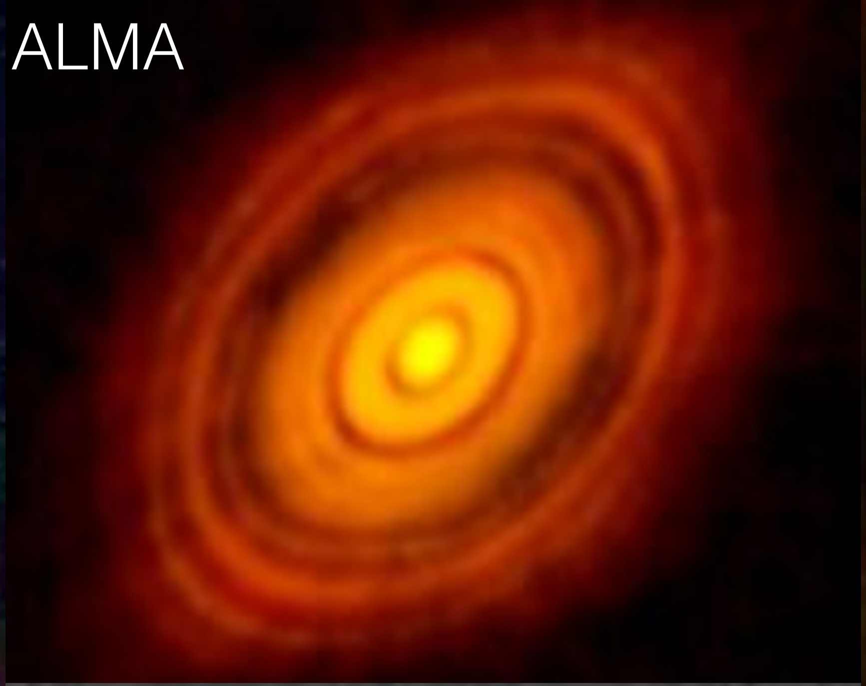
Radio Telescopes

Basics of Single-dish Antenna and Interferometry

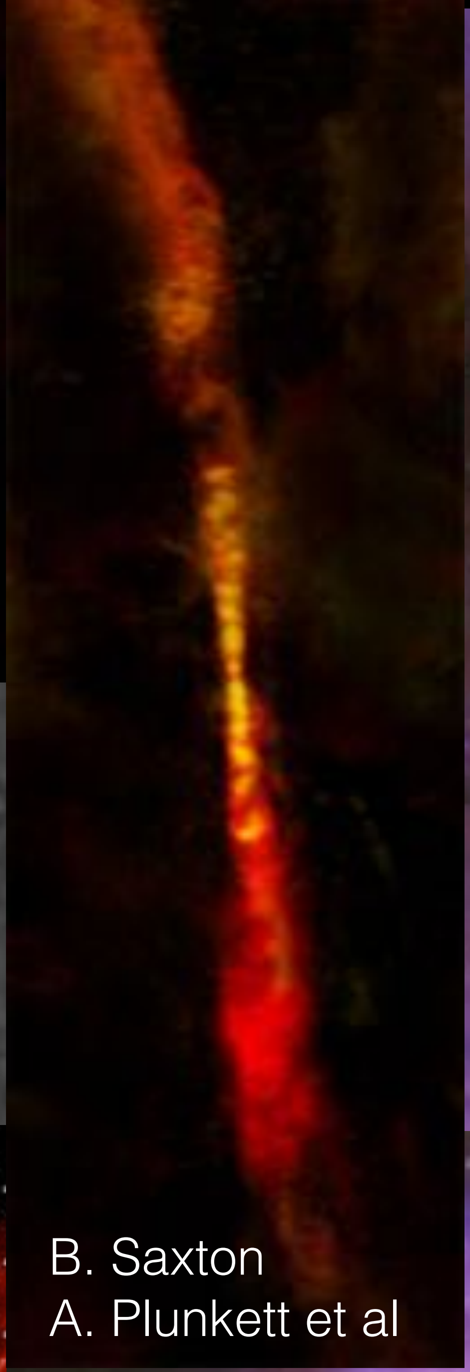
Calibration Techniques

Most of the slides are stolen from 2015 NAIC/NRAO single=dish and interferometry summer school

Chynoweth+09

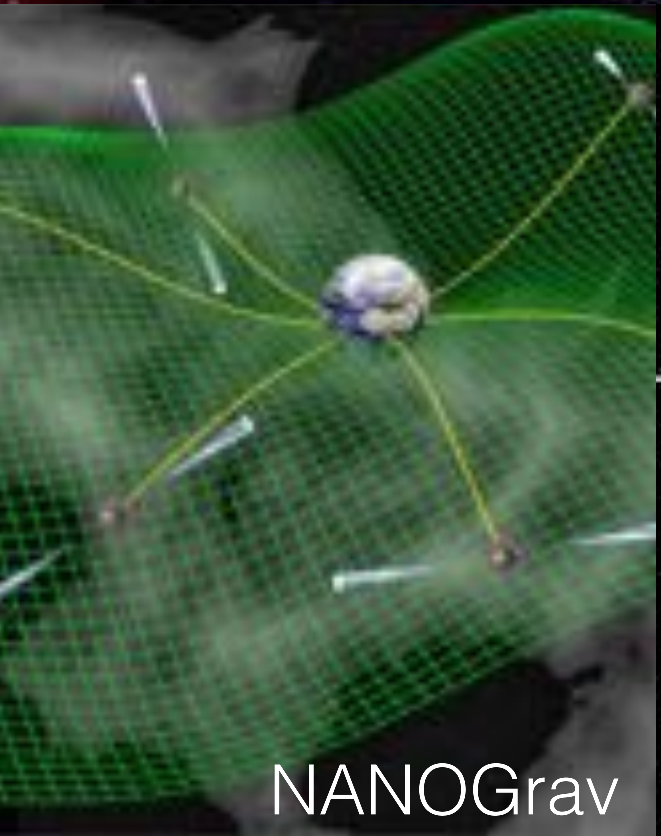


ALMA

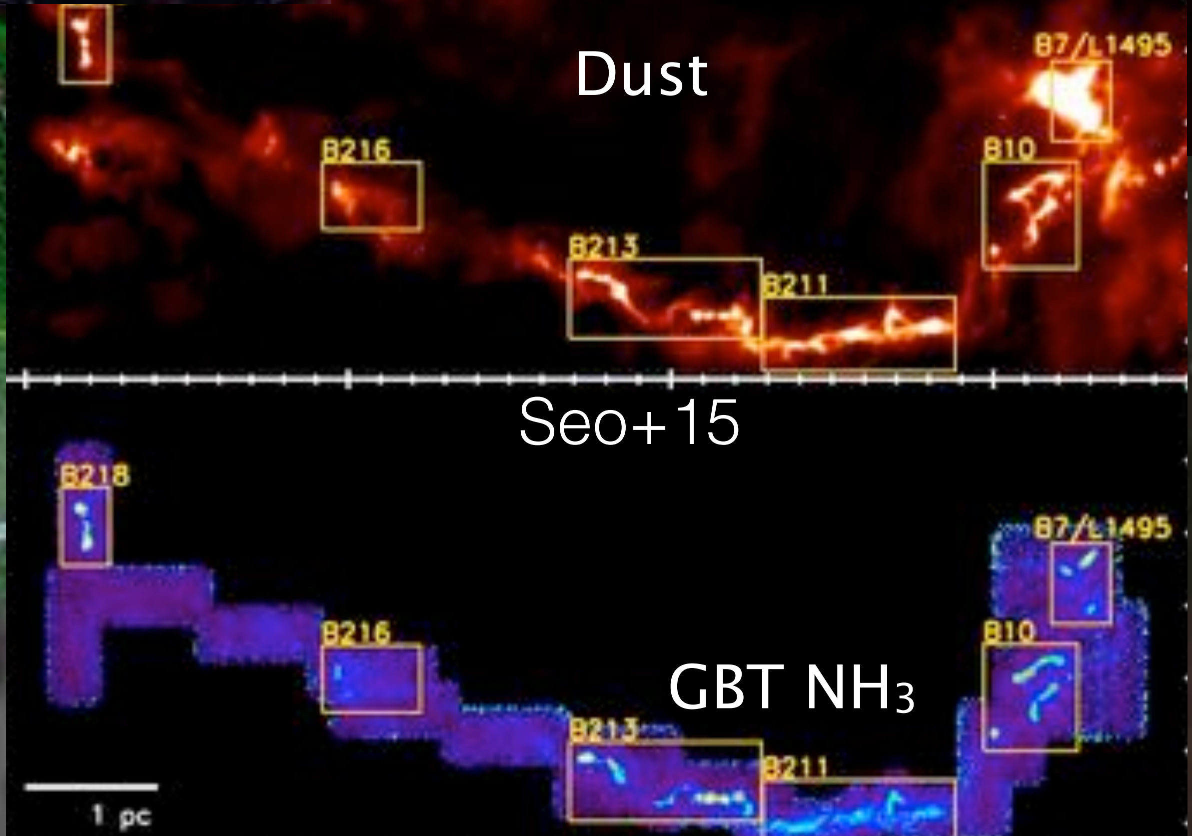


B. Saxton
A. Plunkett et al

Schnee+14



NANOGrav



Seo+15

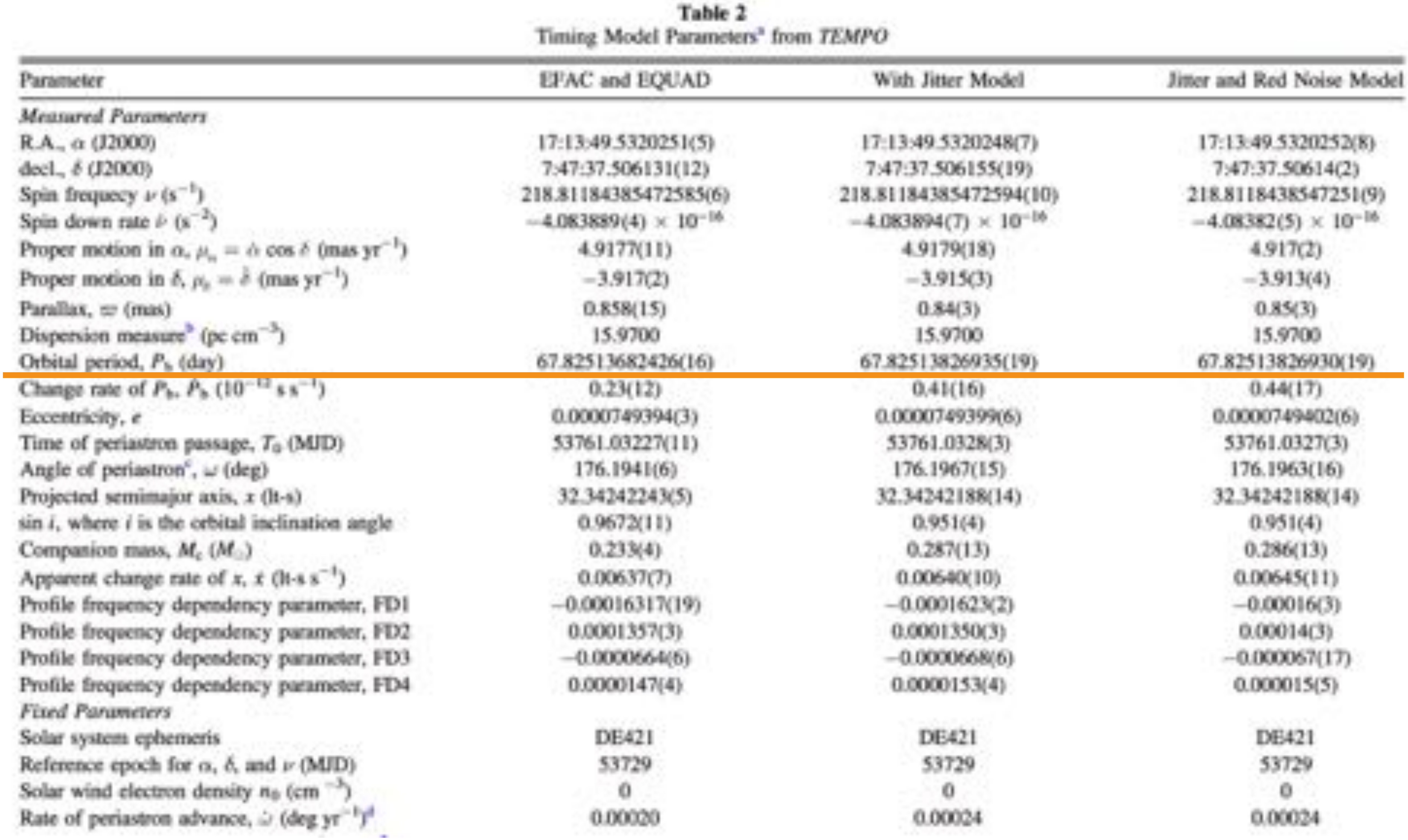
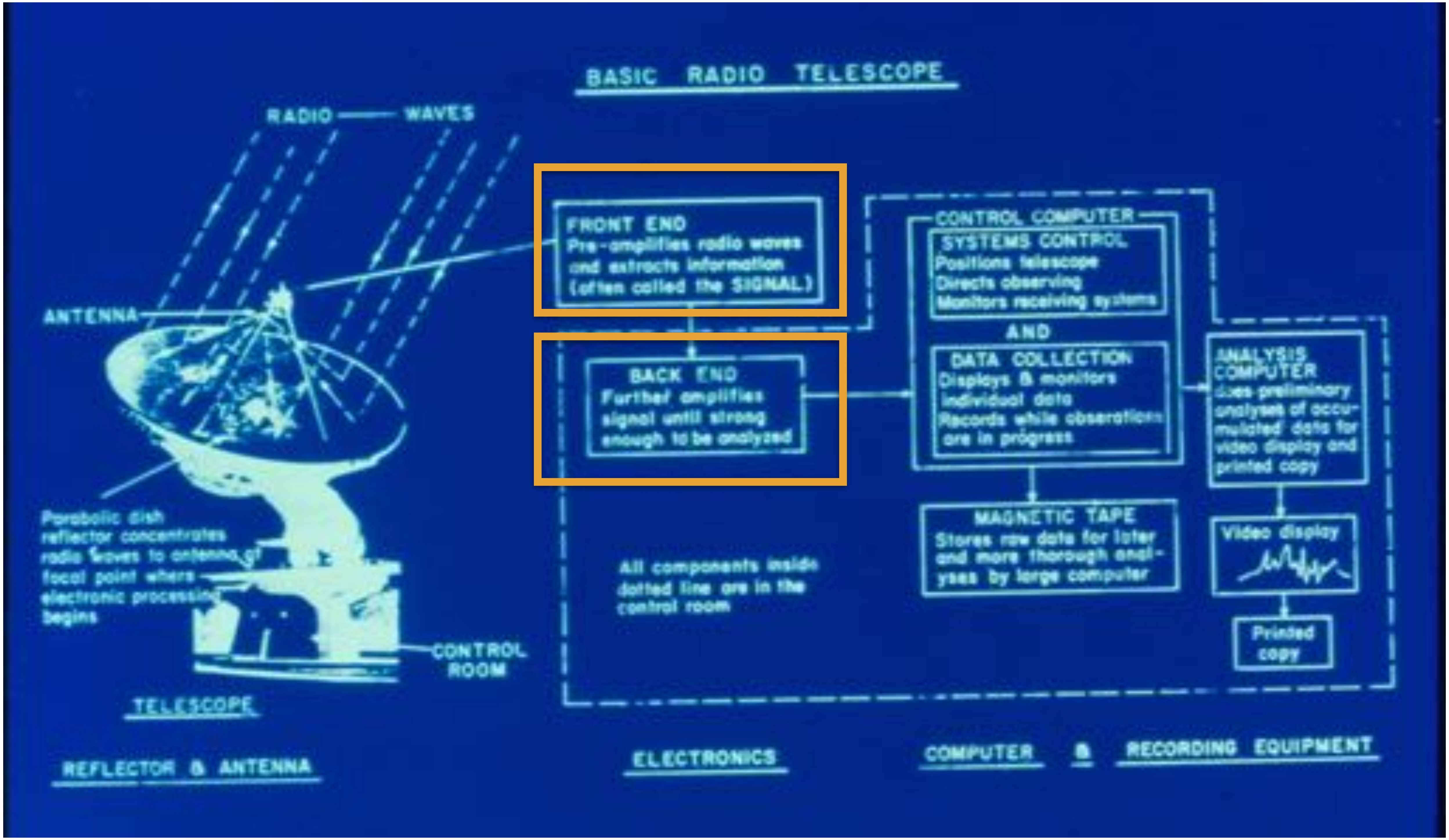


Table 2

Timing Model Parameters[a] from *TEMPO*

Parameter	EFAC and EQUAD	With Jitter Model	Jitter and Red Noise Model
Measured Parameters			
R.A., α (J2000)	17:13:49.5320251(5)	17:13:49.5320248(7)	17:13:49.5320252(8)
decl., δ (J2000)	7:47:37.506131(12)	7:47:37.506155(19)	7:47:37.50614(2)
Spin frequecy ν (s^{-1})	218.81184385472585(6)	218.81184385472594(10)	218.8118438547251(9)
Spin down rate $\dot{\nu}$ (s^{-2})	$-4.083889(4) \times 10^{-16}$	$-4.083894(7) \times 10^{-16}$	$-4.08382(5) \times 10^{-16}$
Proper motion in α, $\mu_\alpha = \dot{\alpha} \cos \delta$ (mas yr^{-1})	4.9177(11)	4.9179(18)	4.917(2)
Proper motion in δ, $\mu_\delta = \dot{\delta}$ (mas yr^{-1})	−3.917(2)	−3.915(3)	−3.913(4)
Parallax, ϖ (mas)	0.858(15)	0.84(3)	0.85(3)
Dispersion measure[b] (pc cm^{-3})	15.9700	15.9700	15.9700
Orbital period, P_b (day)	67.8251368242 6(16)	67.825138269 35(19)	67.825138269 30(19)
Change rate of P_b, $\dot{P}_b$ (10^{-12} s s^{-1})	0.23(12)	0.41(16)	0.44(17)
Eccentricity, e	0.0000749394(3)	0.0000749399(6)	0.0000749402(6)
Time of periastron passage, T_0 (MJD)	53761.03227(11)	53761.0328(3)	53761.0327(3)
Angle of periastron[c], ω (deg)	176.1941(6)	176.1967(15)	176.1963(16)
Projected semimajor axis, x (lt-s)	32.34242243(5)	32.34242188(14)	32.34242188(14)
sin i, where i is the orbital inclination angle	0.9672(11)	0.951(4)	0.951(4)
Companion mass, M_c ($M_\odot$)	0.233(4)	0.287(13)	0.286(13)
Apparent change rate of x, $\dot{x}$ (lt-s s^{-1})	0.00637(7)	0.00640(10)	0.00645(11)
Profile frequency dependency parameter, FD1	−0.00016317(19)	−0.0001623(2)	−0.00016(3)
Profile frequency dependency parameter, FD2	0.0001357(3)	0.0001350(3)	0.00014(3)
Profile frequency dependency parameter, FD3	−0.0000664(6)	−0.0000668(6)	−0.000067(17)
Profile frequency dependency parameter, FD4	0.0000147(4)	0.0000153(4)	0.000015(5)
Fixed Parameters			
Solar system ephemeris	DE421	DE421	DE421
Reference epoch for α, δ, and ν (MJD)	53729	53729	53729
Solar wind electron density n_0 (cm^{-3})	0	0	0
Rate of periastron advance, $\dot{\omega}$ (deg yr^{-1})[d]	0.00020	0.00024	0.00024

What is a radio telescope?



BASIC RADIO TELESCOPE

FRONT END
Pre-amplifies radio waves and extracts information (often called the SIGNAL)

BACK END
Further amplifies signal until strong enough to be analyzed

CONTROL COMPUTER

SYSTEMS CONTROL
Positions telescope
Directs observing
Monitors receiving systems

AND

DATA COLLECTION
Displays & monitors individual data
Records while observations are in progress

ANALYSIS COMPUTER
does preliminary analyses of accumulated data for video display and printed copy

MAGNETIC TAPE
Stores raw data for later and more thorough analyses by large computer

Parabolic dish reflector concentrates radio waves to antenna at focal point where electronic processing begins

All components inside dotted line are in the control room

REFLECTOR & ANTENNA

ELECTRONICS

COMPUTER & RECORDING EQUIPMENT

From the slide of Frank Ghigo at SDSS15. “Verschuur, 1985. Slide set produced by the Astronomical Society of the Pacific, slide #1.”

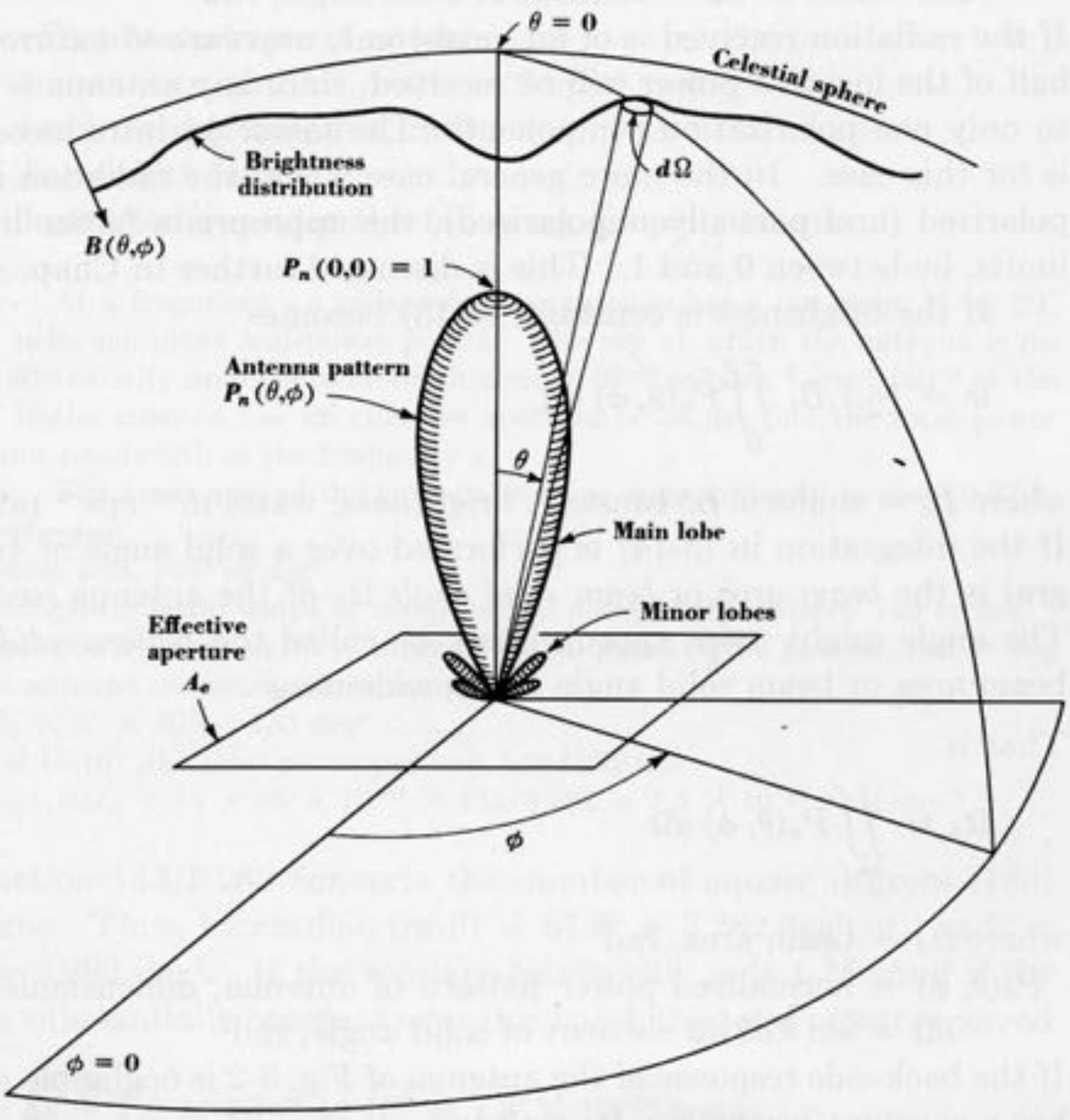
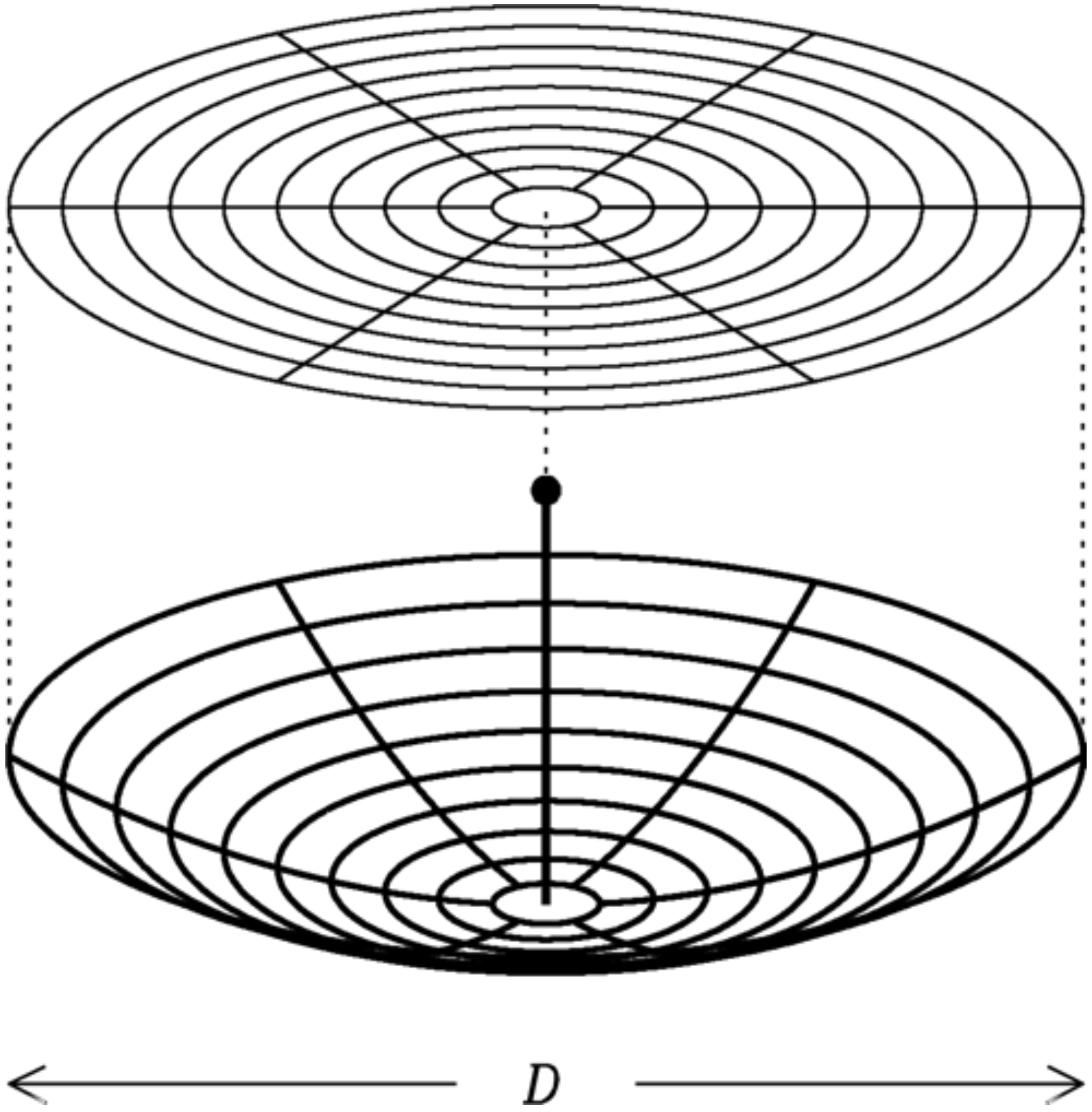
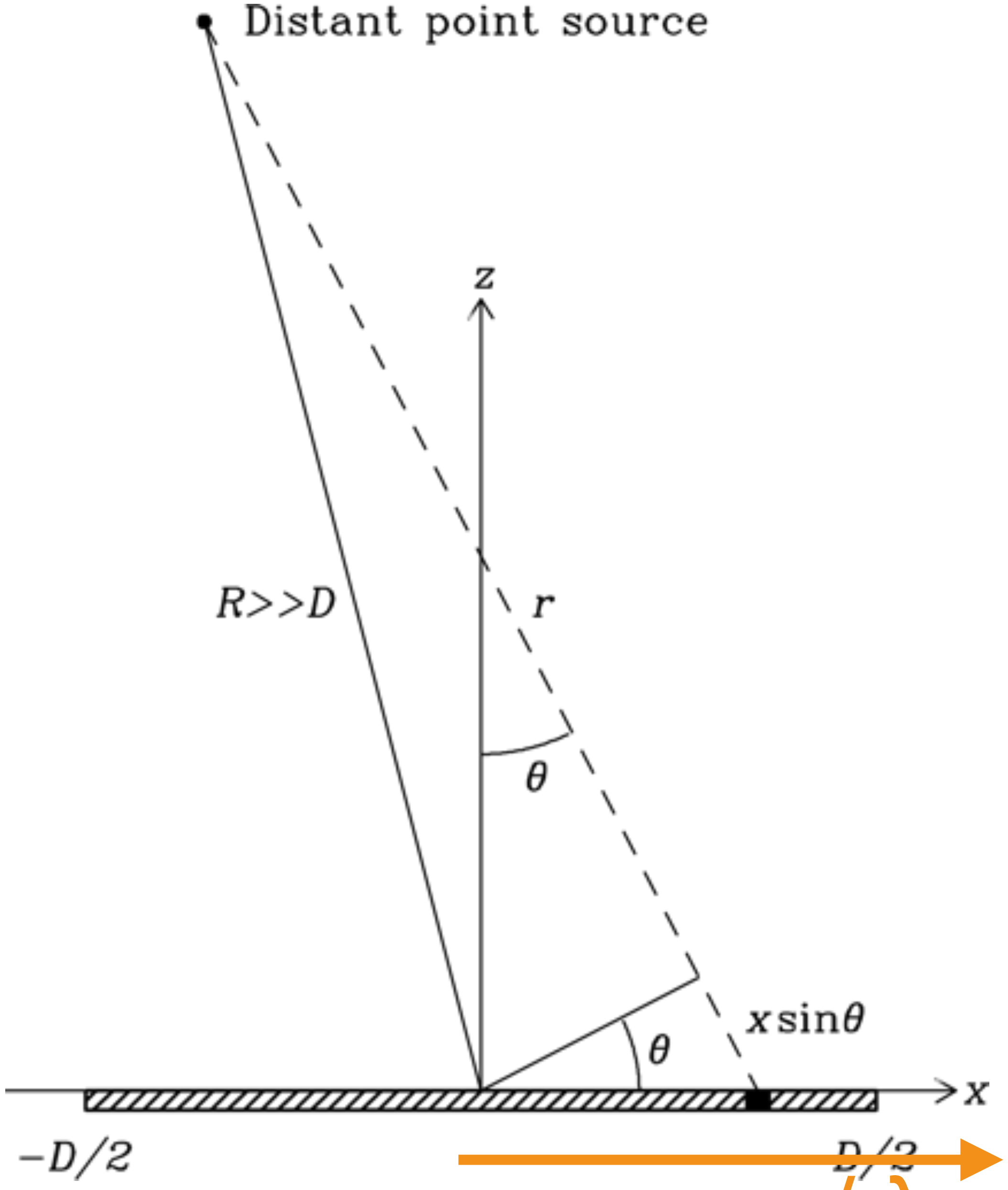


Fig. 3-2. Relation of antenna pattern to celestial sphere with associated coordinates.

From Frank Ghigo at SDSS15

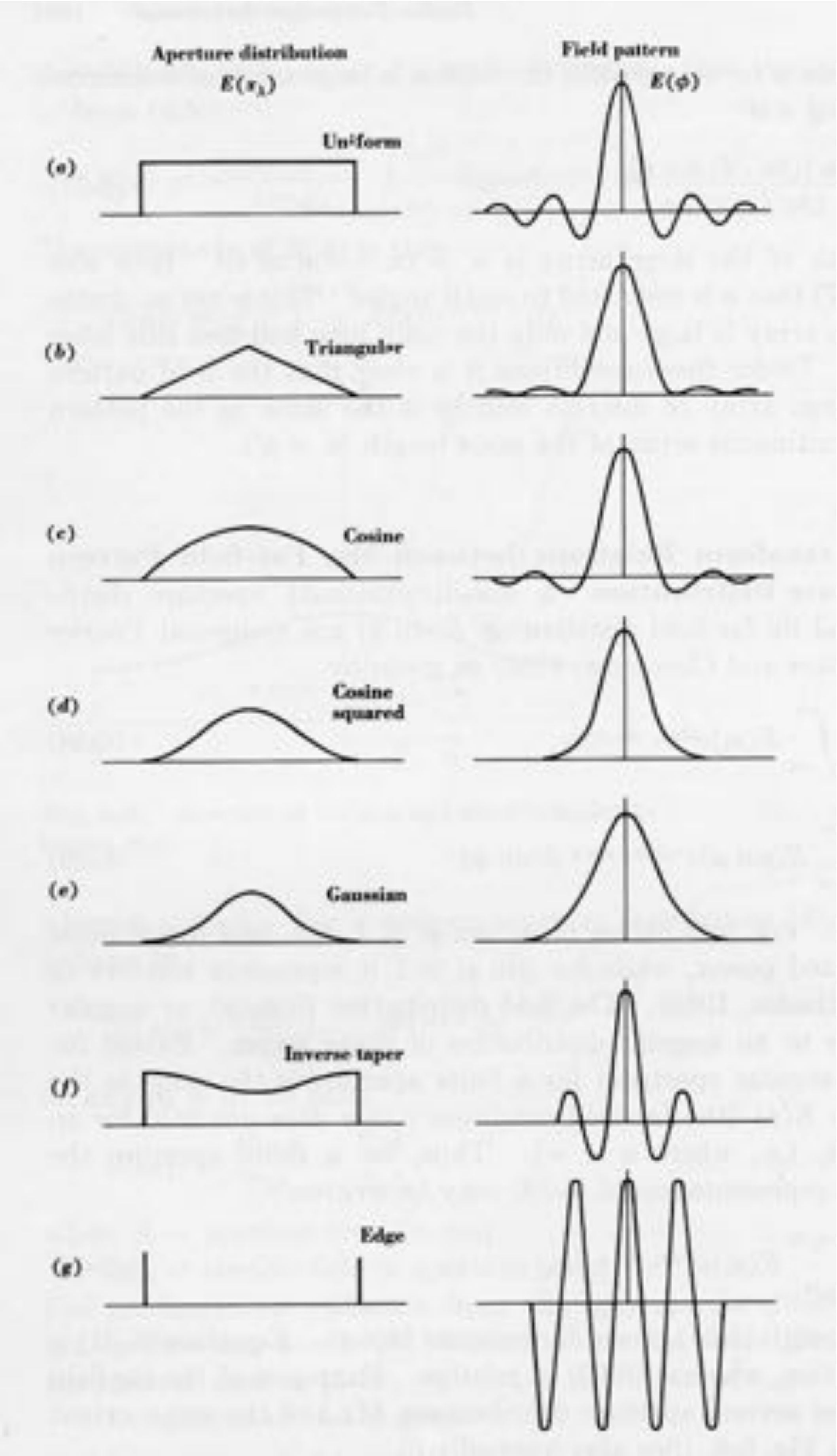
Aperture





$u = x / \lambda$

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



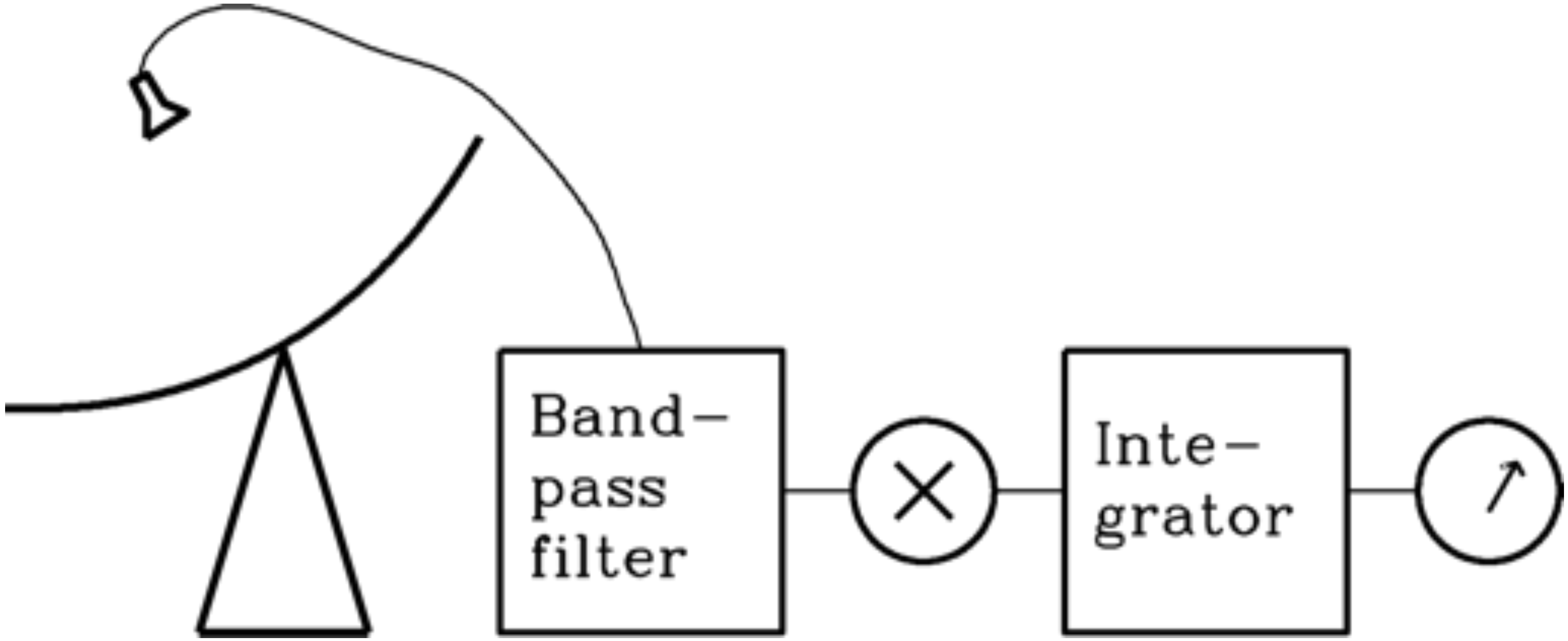
From Frank Ghigo at SDSS15


140-ft at GBT

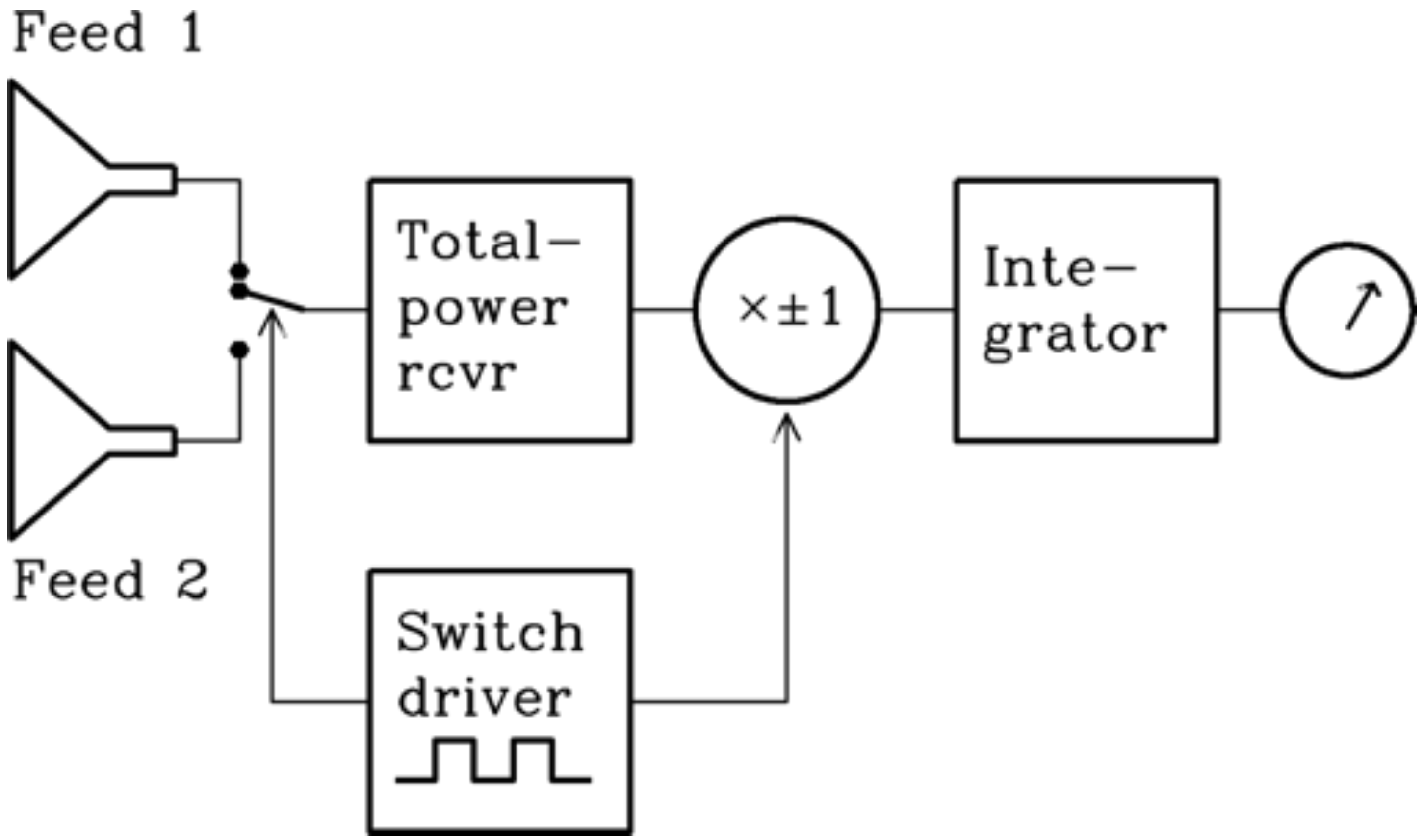
Green Bank Telescope

Radiometers

The simplest radiometer



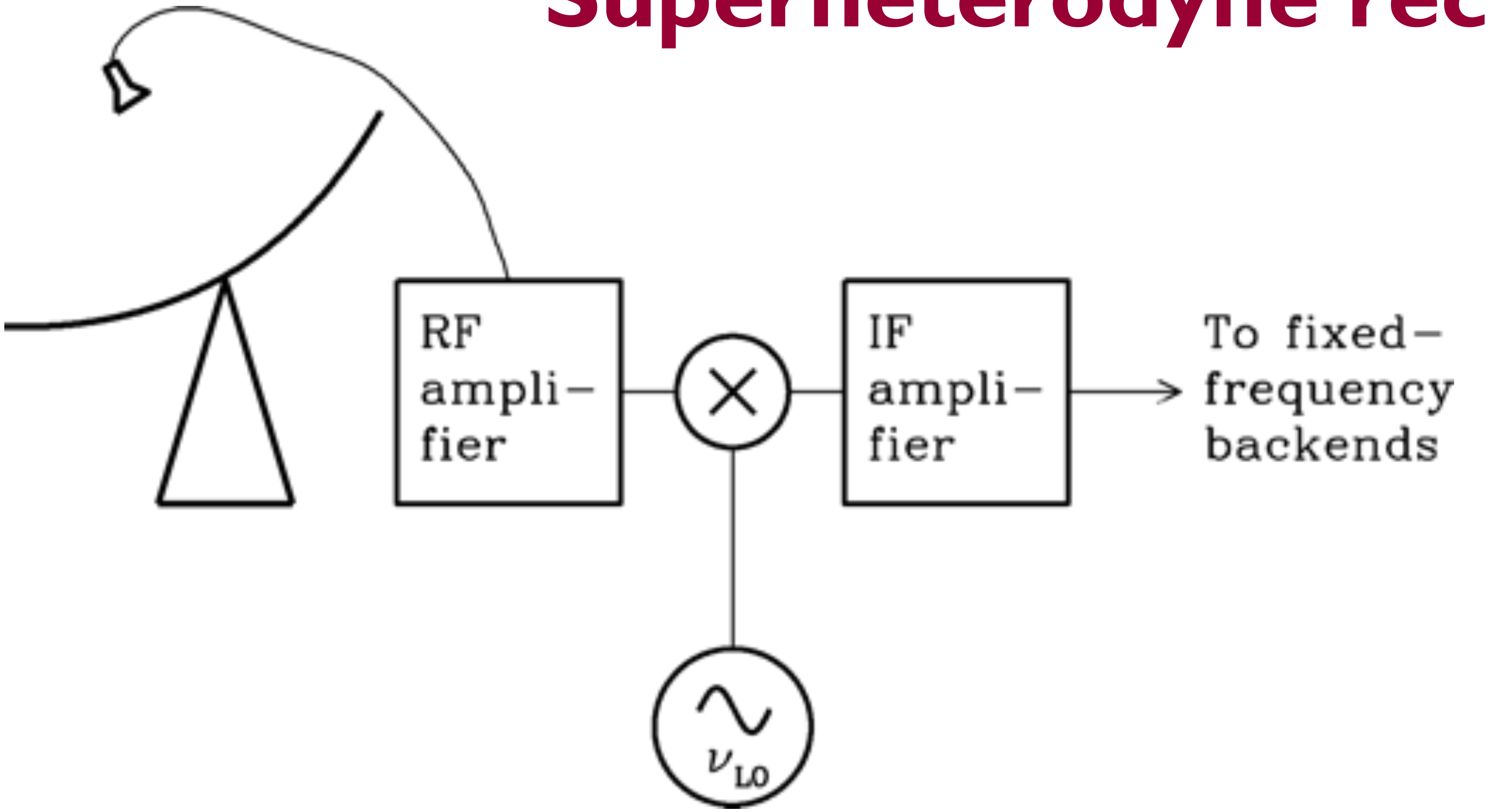
Differential radiometer



$$\boxed{\sigma_{\mathrm{T}} = \frac{2T_{\mathrm{s}}}{\sqrt{\Delta\nu\,\tau}}}$$

Jim Condon

Superheterodyne receiver



RF amplifier

IF amplifier

To fixed-frequency backends

$$2\sin(2\pi\nu_{\rm LO}t)\times\sin(2\pi\nu_{\rm RF}t)=$$
$$\cos[2\pi(\nu_{\rm LO}-\nu_{\rm RF})t]-\cos[2\pi(\nu_{\rm LO}+\nu_{\rm RF})t]$$

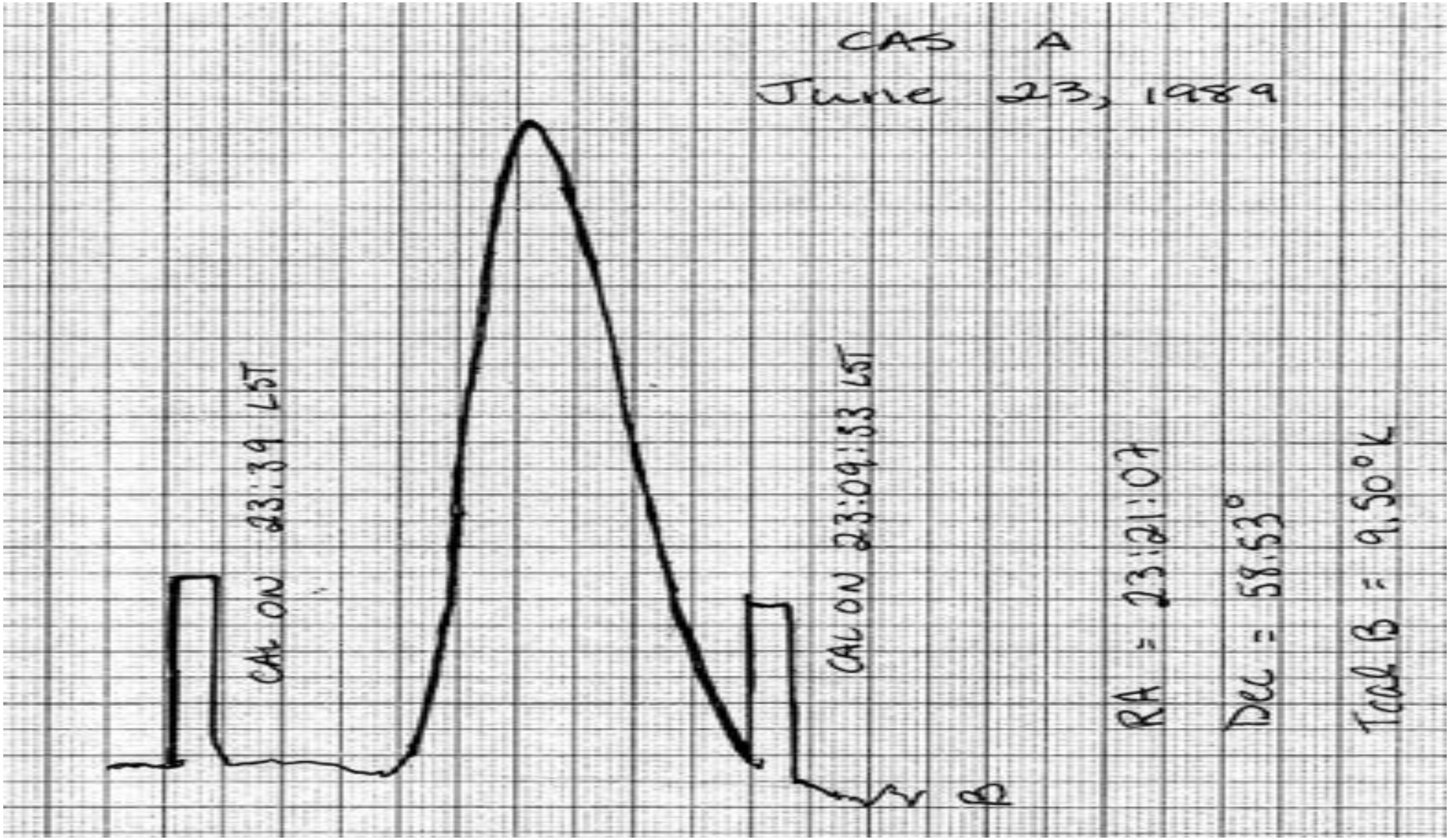
System Temperature

$$T_R \equiv \frac{\lambda^2}{2k} I_\nu$$

Radiation Temperature

$$T_{sys} = T_{ant} + T_{rcvr} + T_{atm}(1 - e^{-\tau a}) + T_{spill} + T_{CMB} + \cdots$$

$$\Delta T = k_1 \frac{T_{sys}}{\sqrt{\Delta\nu \cdot t_{\mathrm{int}}}}$$

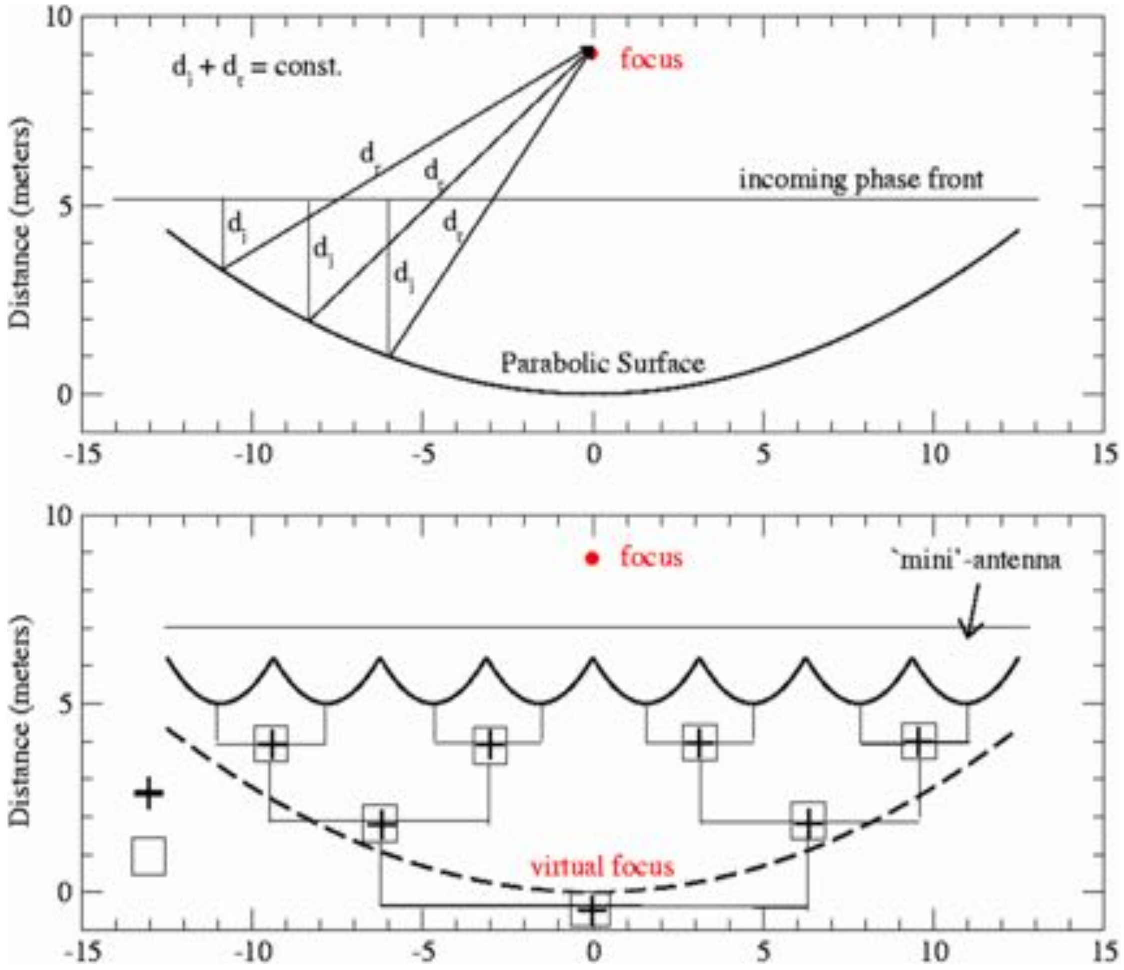


From Frank Ghigo at SDSS15

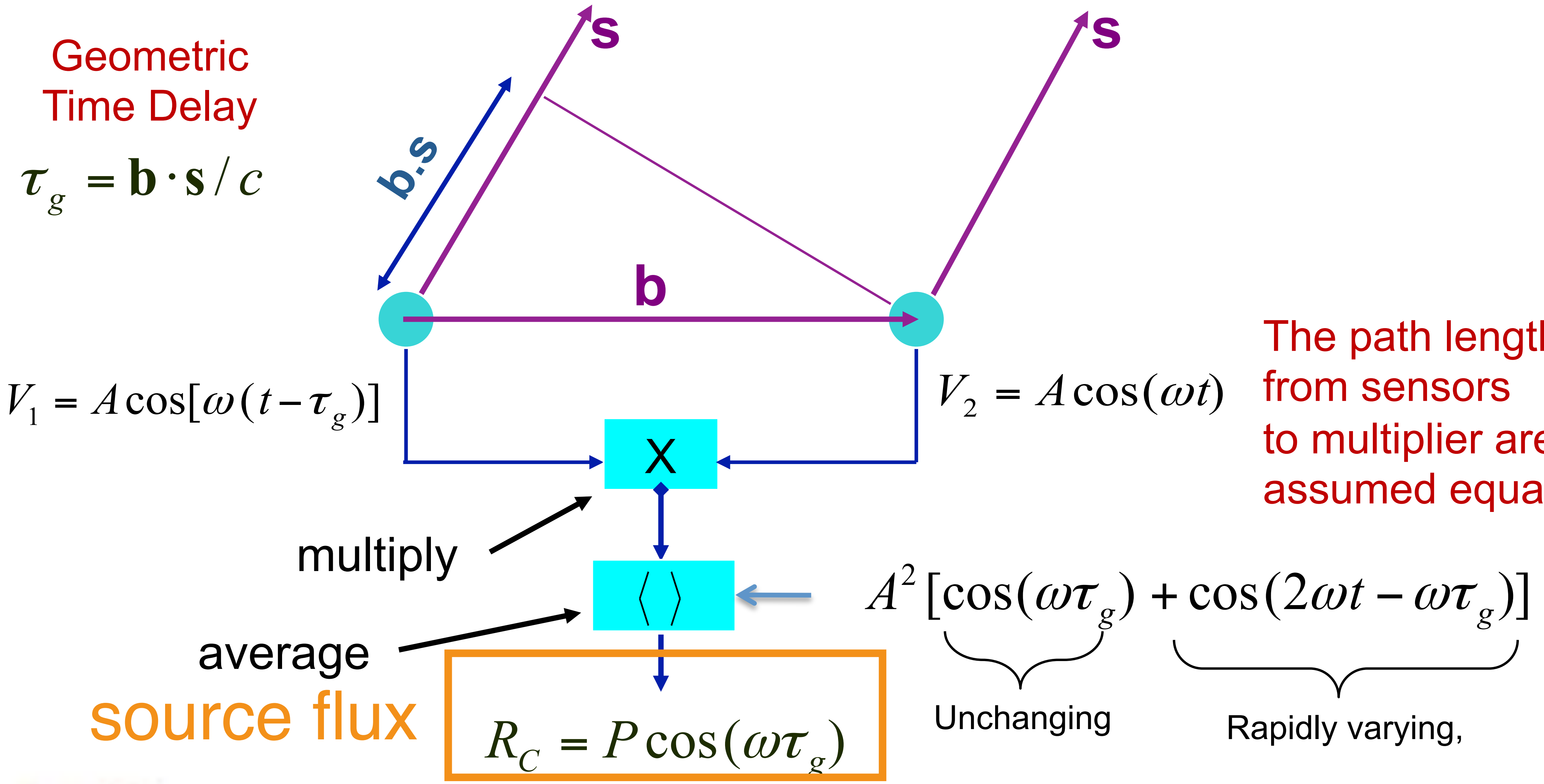
Alright, ready for interferometry?

The Purposes of Interferometry

- Increase the spatial resolution
- Interferometry has to **correlate** E-fields at spatially separated locations



The Stationary, Quasi-Monochromatic Radio-Frequency Interferometer



Geometric Time Delay

$$\tau_g = \mathbf{b}\cdot\mathbf{s}/c$$

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

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

The path lengths from sensors to multiplier are assumed equal!

$$\langle\ \rangle$$

$$A^2[\underbrace{\cos(\omega\tau_g)}_{\text{Unchanging}} + \underbrace{\cos(2\omega t-\omega\tau_g)}_{\text{Rapidly varying,}}]$$

source flux

$$\boxed{R_C = P\cos(\omega\tau_g)}$$

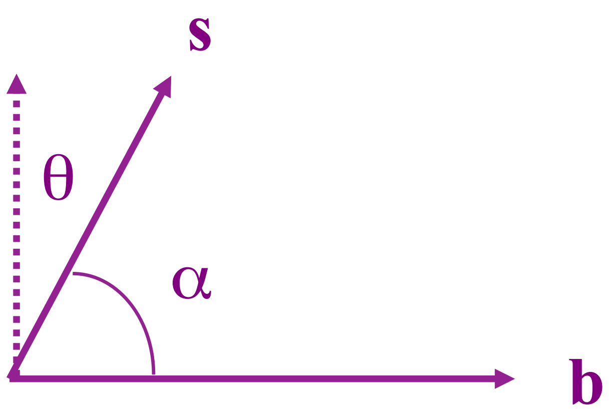
Note: R_c is not a function of time or location!

Nomenclature, and Direction Cosines

- To illustrate the response, expand the dot product in one dimension:

$$\frac{2\pi \mathbf{b} \bullet \mathbf{s}}{\lambda} = 2\pi \frac{b}{\lambda} \cos\alpha = 2\pi u \sin\theta = 2\pi u l$$

  - Where u = b/λ is the baseline length in wavelengths,
  - α is the angle w.r.t. the baseline vector
  - $l = \cos\alpha = \sin\theta$ is the direction cosine for the direction **s**.

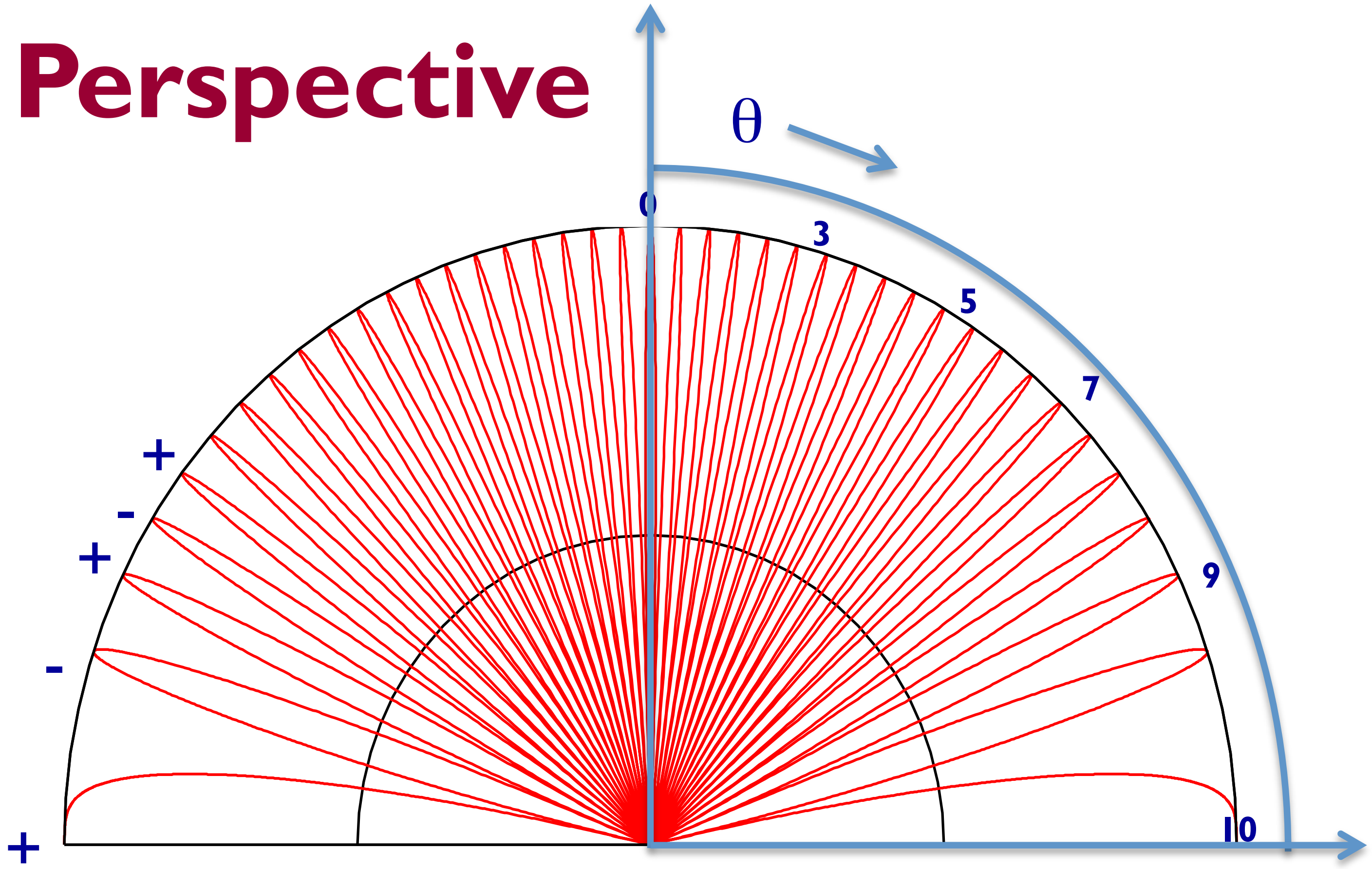


From an Angular Perspective

Top Panel:

The absolute value of the response for u = 10, as a function of angle.

The 'lobes' of the response pattern alternate in sign.

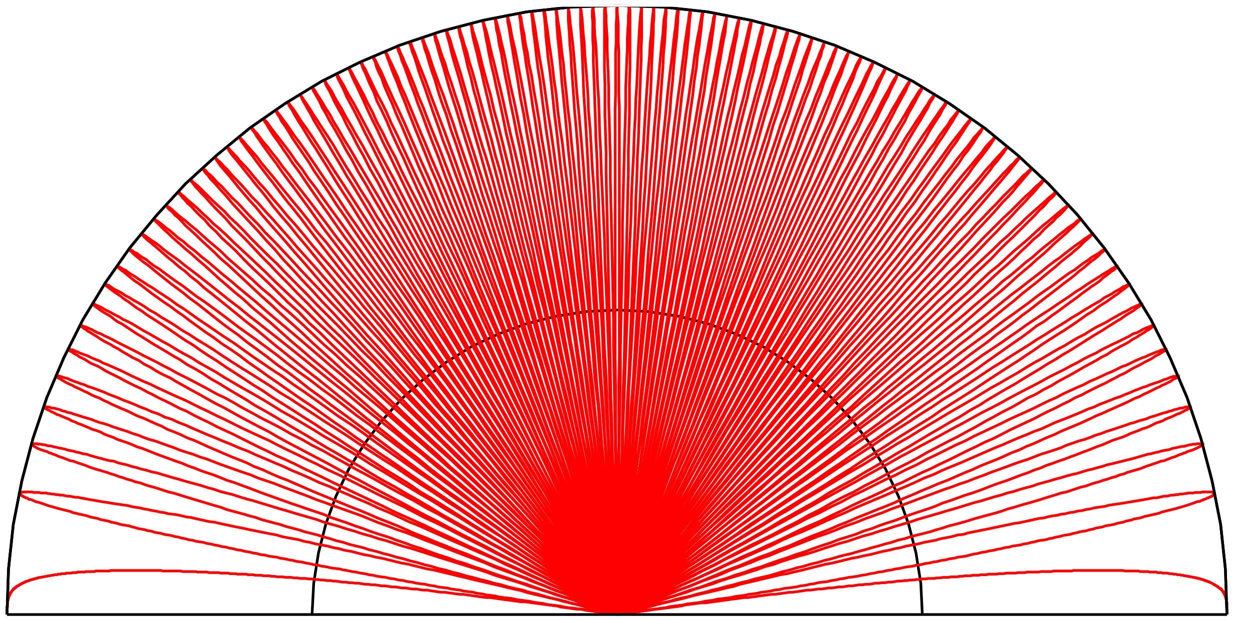


Bottom Panel:

The same, but for u = 25.

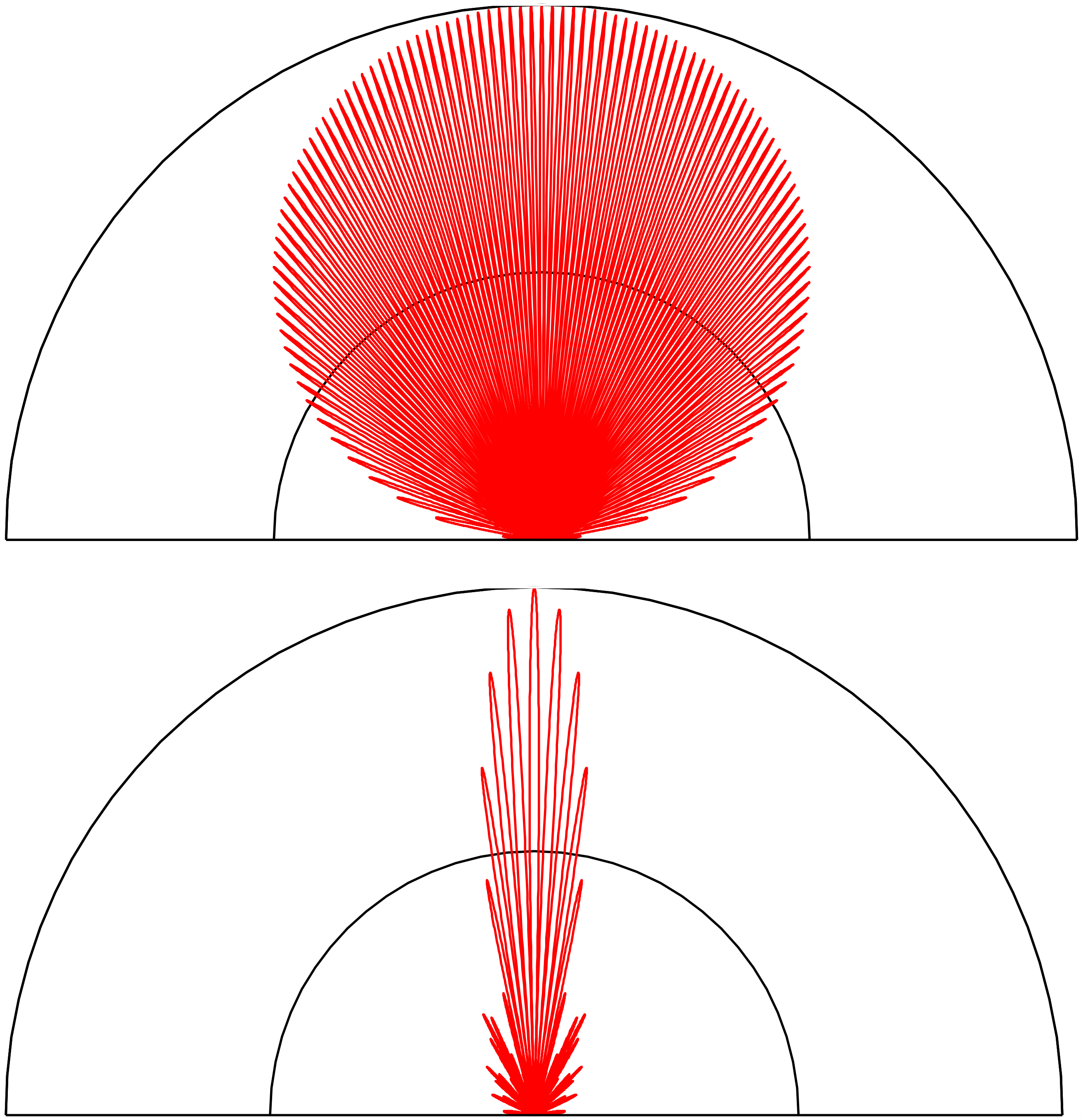
Angular separation between lobes (of the same sign) is

$\delta\theta \sim 1/u = \lambda/b$ radians.



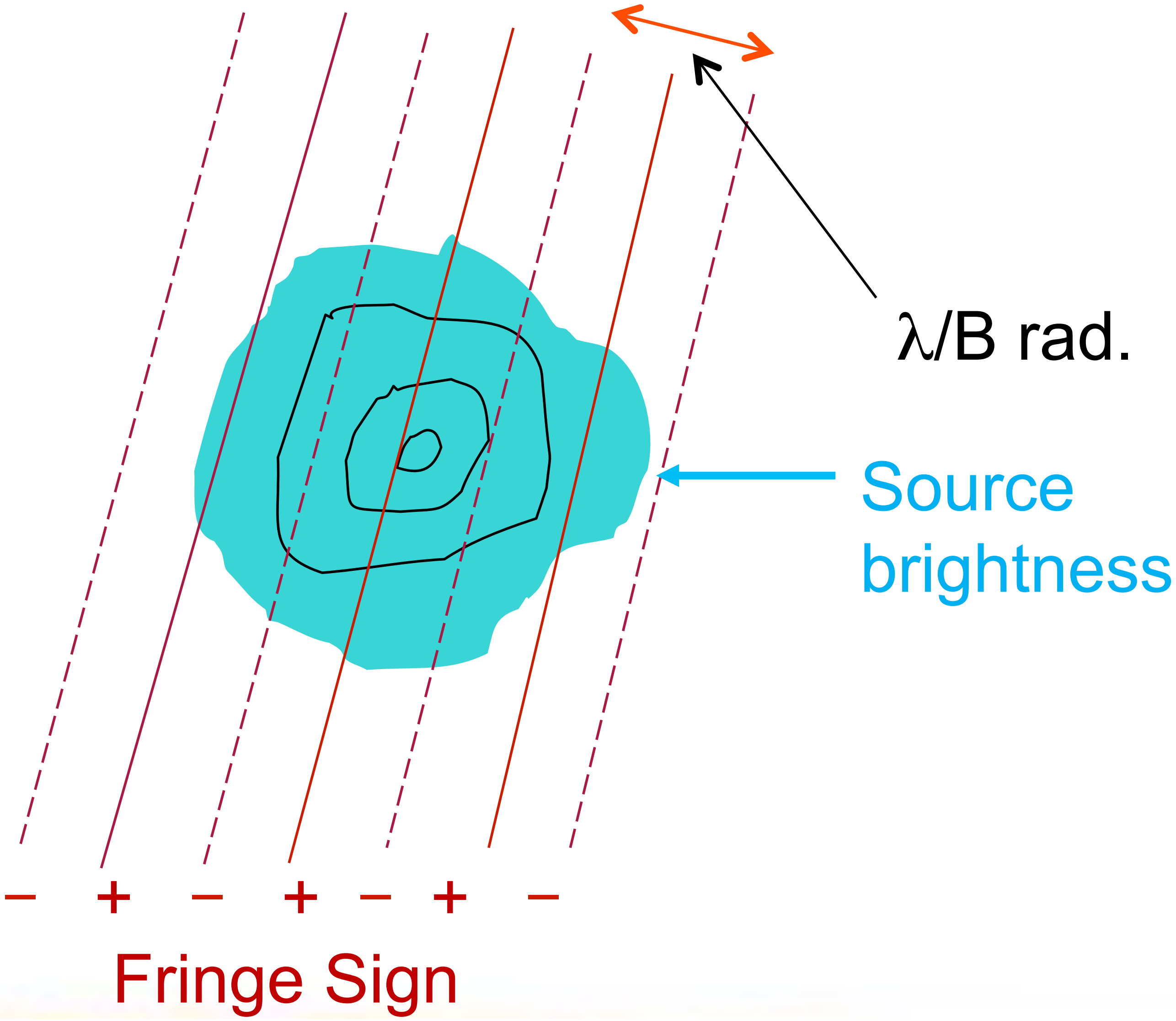
The Effect of Sensor Patterns

- Sensors (or antennas) are not isotropic, and have their own responses.
- **Top Panel:** The interferometer pattern with a cos(θ)-like sensor response.
- **Bottom Panel:** A multiple-wavelength aperture antenna has a narrow beam, but also sidelobes.
- Note that the phase will also be modified.



$$R_C = \iint I_\nu(\mathbf{s}) \cos(2\pi\nu \mathbf{b}\cdot\mathbf{s}/c)\, d\Omega$$

The response from an extended source with isotropic sensor



Define the Complex Visibility

- We now DEFINE a complex function, the complex visibility, V, from the two independent (real) correlator outputs R_C and R_S:

$$V = R_C - iR_S = Ae^{-i\phi}$$

where

$$A = \sqrt{R_C^2 + R_S^2}$$

$$\phi = \tan^{-1}\left(\frac{R_S}{R_C}\right)$$

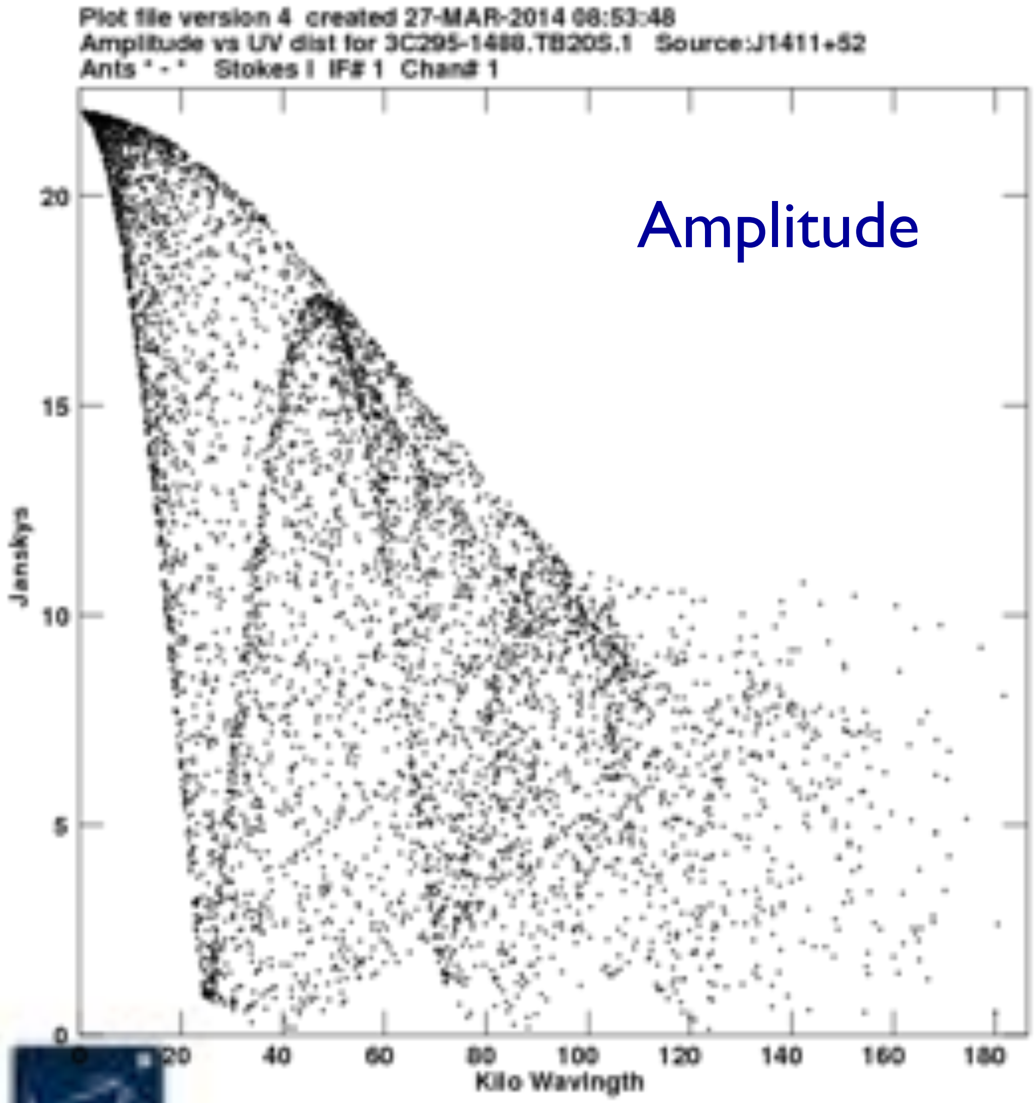
- This gives us a beautiful and useful relationship between the source brightness, and the response of an interferometer:

$$V_\upsilon(\mathbf{b}) = R_C - iR_S = \iint I_\nu(s)\, e^{-2\pi i\nu\, \mathbf{b}\cdot\mathbf{s}/c}\, d\Omega$$

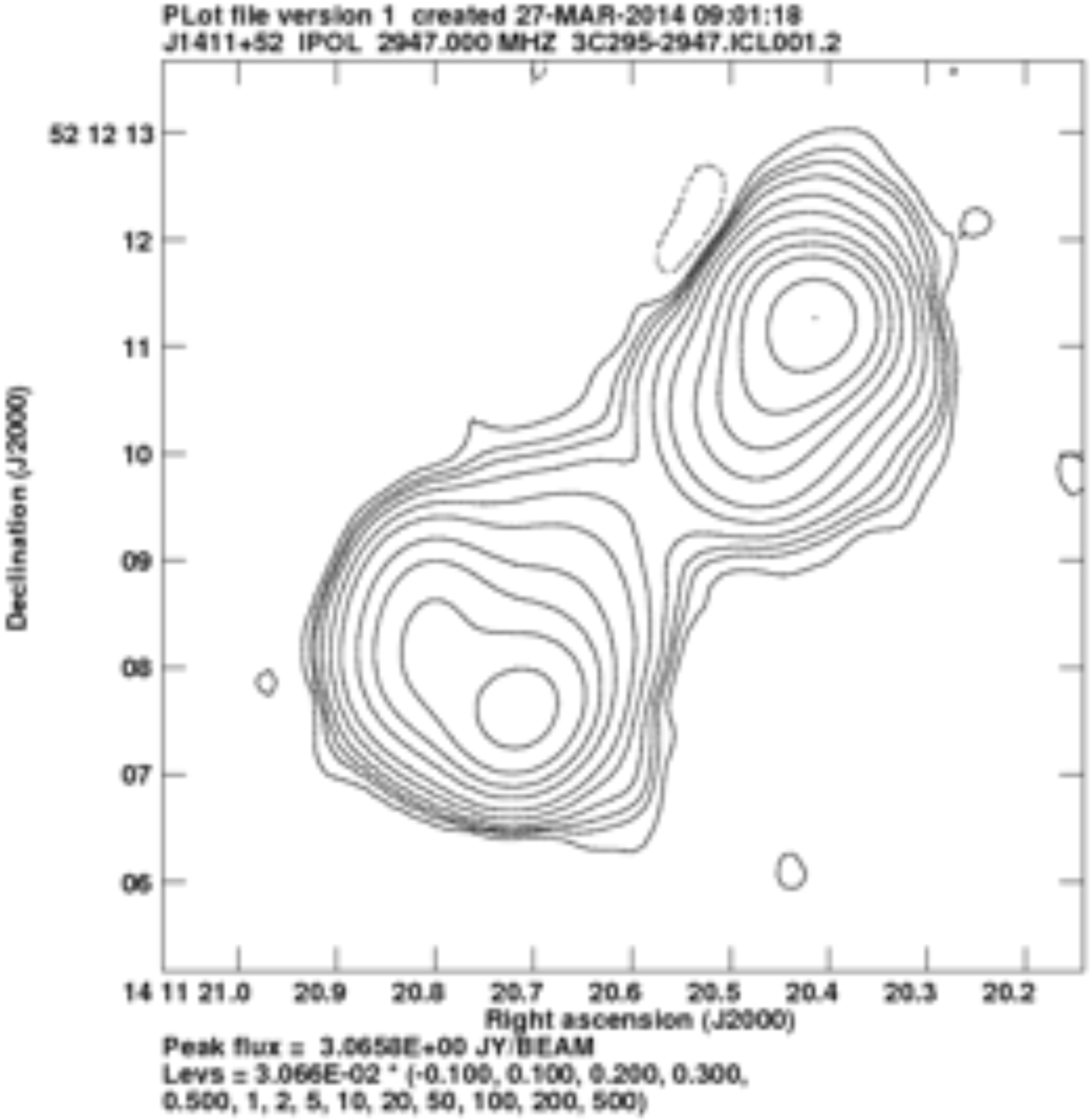
- This is a Fourier transform – but with a quirk: The visibility distribution is in genera a function of the three spatial dimension, while the brightness distribution is only 2-dimensional. More on this, later.

Examples of Visibilities – a Well Resolved Object

- The flux calibrator 3C295



Amplitude



Move on to a more realistic interferometry

The 2-d Fourier Transform Relation

Then, $\nu\mathbf{b}.\mathbf{s}/c = ul + vm + wn = ul + vm$, from which we find,

$$V_\nu(u,\mathrm{v}) = \iint I(l,m)e^{-i2\pi(ul+vm)}\ dldm$$

which is a **2-dimensional Fourier transform** between the brightness and the spatial coherence function (visibility):

$$I_\nu(l,m) \Leftrightarrow V(u,\mathrm{v})$$

And we can now rely on two centuries of effort by mathematicians on how to invert this equation, and how much information we need to obtain an image of sufficient quality.

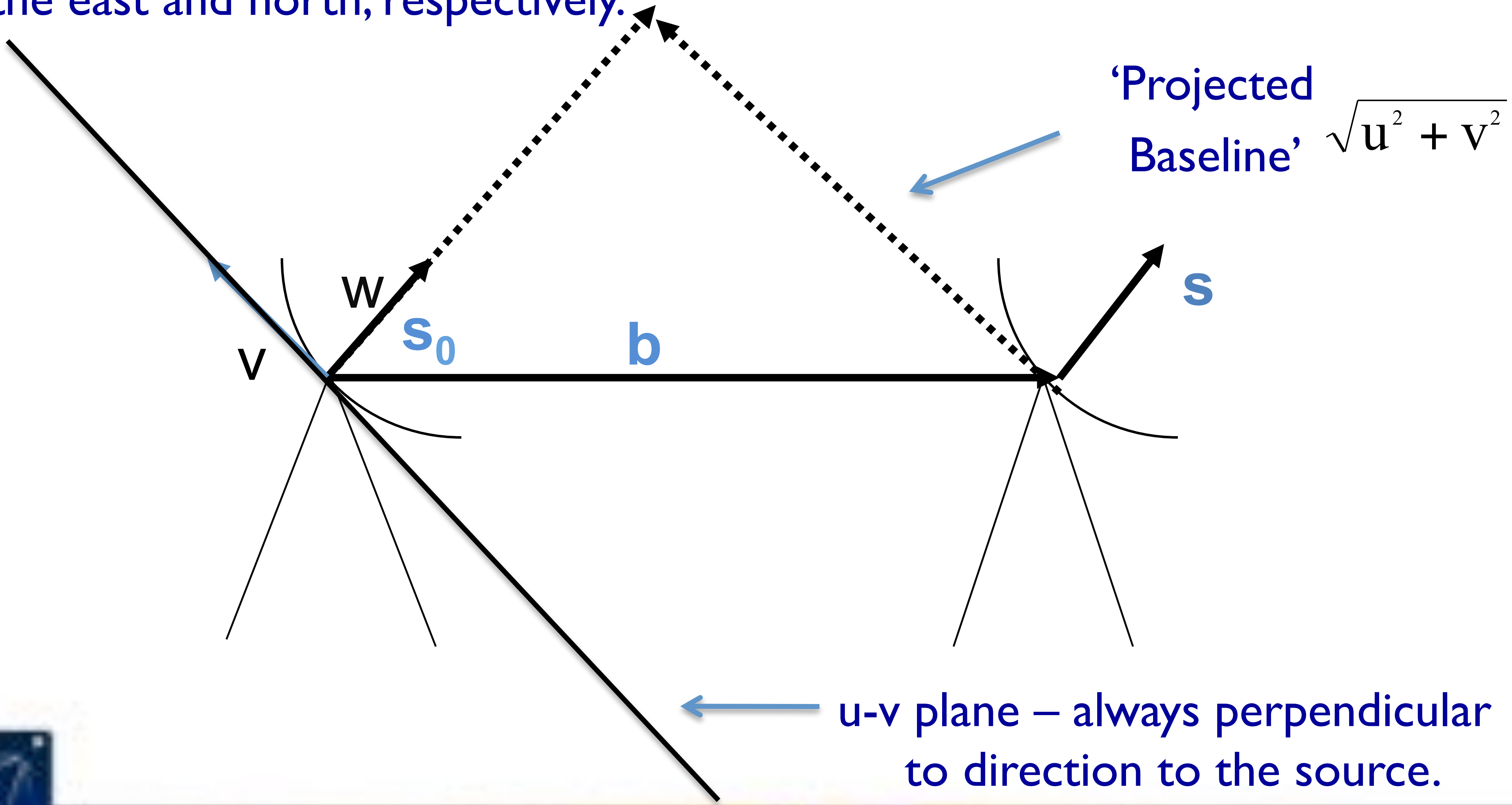
Formally,

$$I_\nu(l,m) = \iint V_\nu(u,v)e^{i2\pi(ul+\mathrm{v}m)}dud\mathrm{v}$$

In physical optics, this is known as the 'Van Cittert-Zernicke Theorem'.

General Coordinate System

- This is the coordinate system in most general use for synthesis imaging.
- **w** points to, and follows the source, **u** towards the east, and **v** towards the north celestial pole. The direction cosines *l* and m then increase to the east and north, respectively.

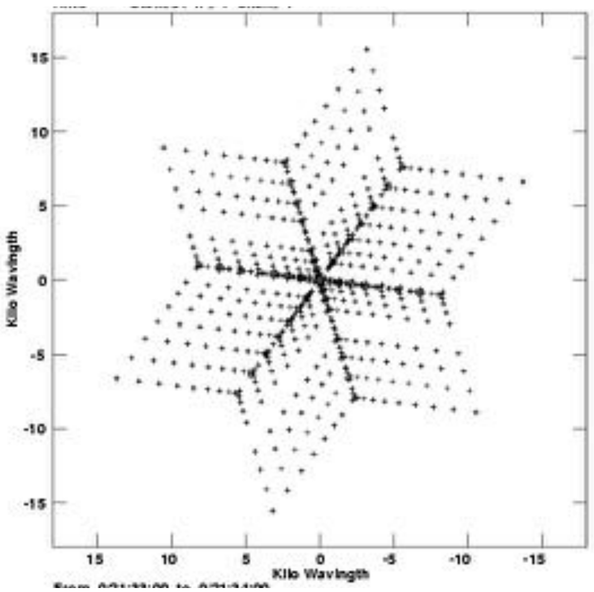


'Projected Baseline' $\sqrt{u^2 + v^2}$

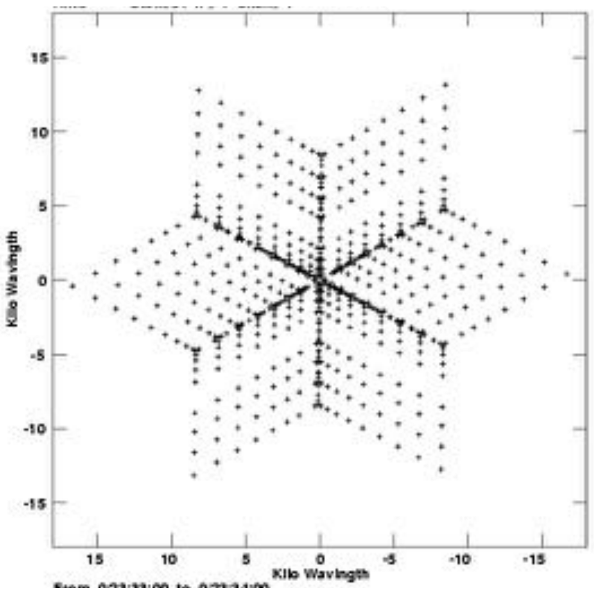
u-v plane – always perpendicular to direction to the source.

Sample VLA (U,V) plots for 3C147 (δ = 50)

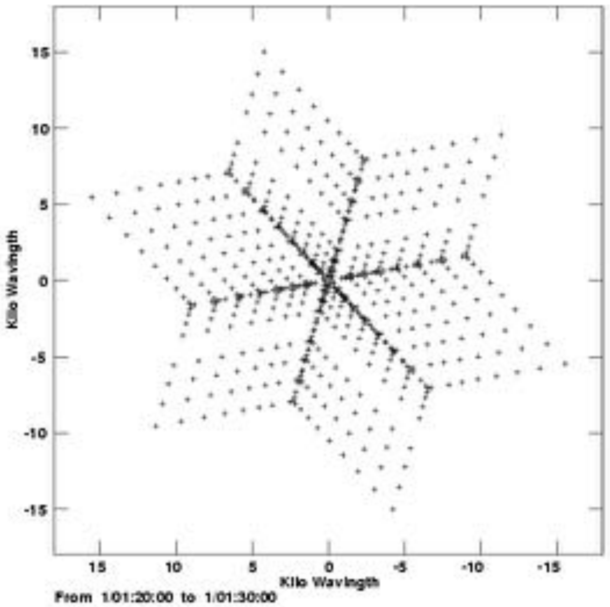
- Snapshot (u,v) coverage for HA = -2, 0, +2 (with 26 antennas).



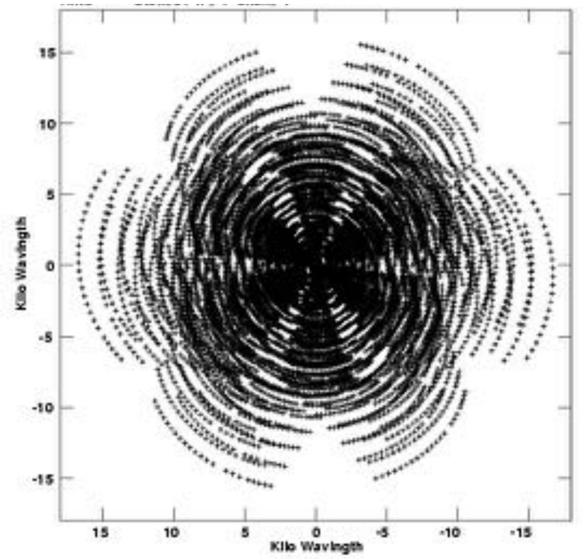
HA = -2h



HA = 0h

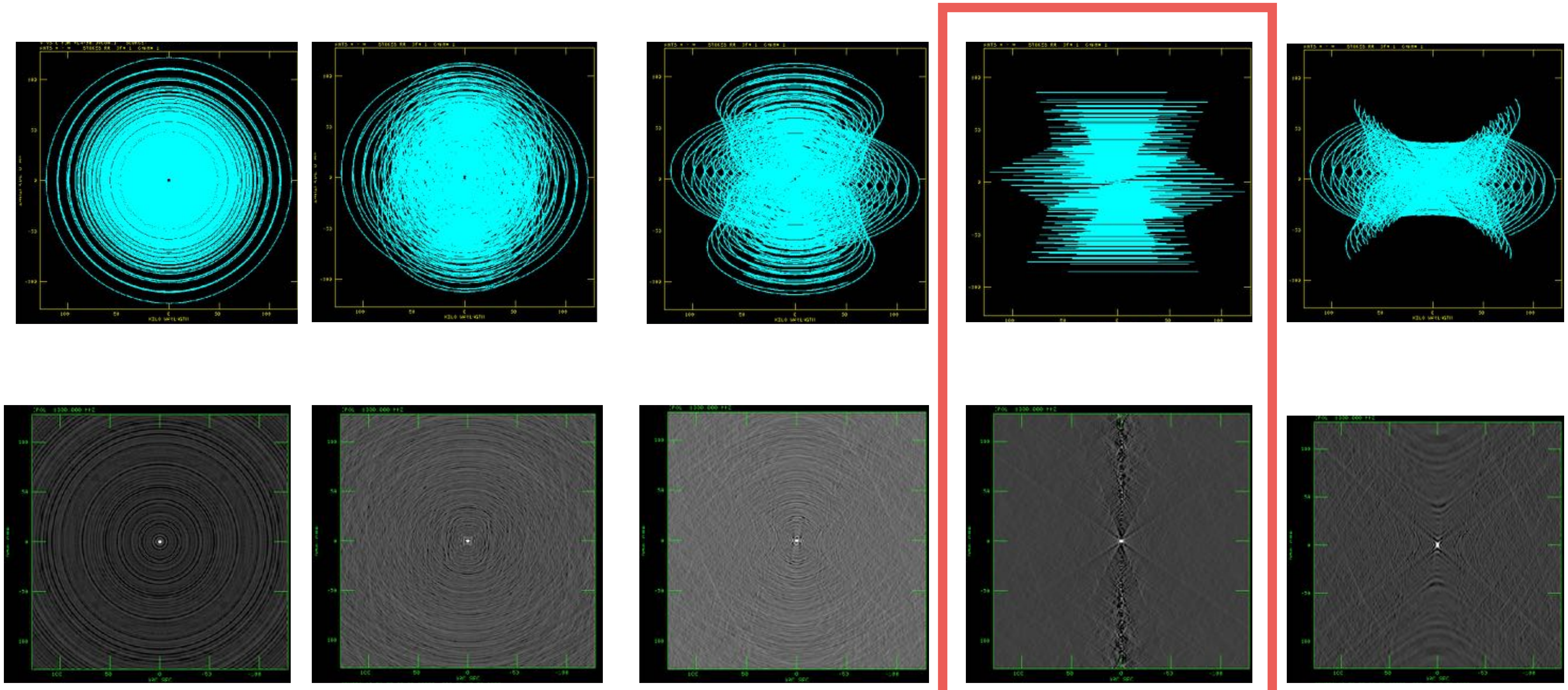


HA = 2h



Coverage over all four hours.

VLA Coverage and Beams

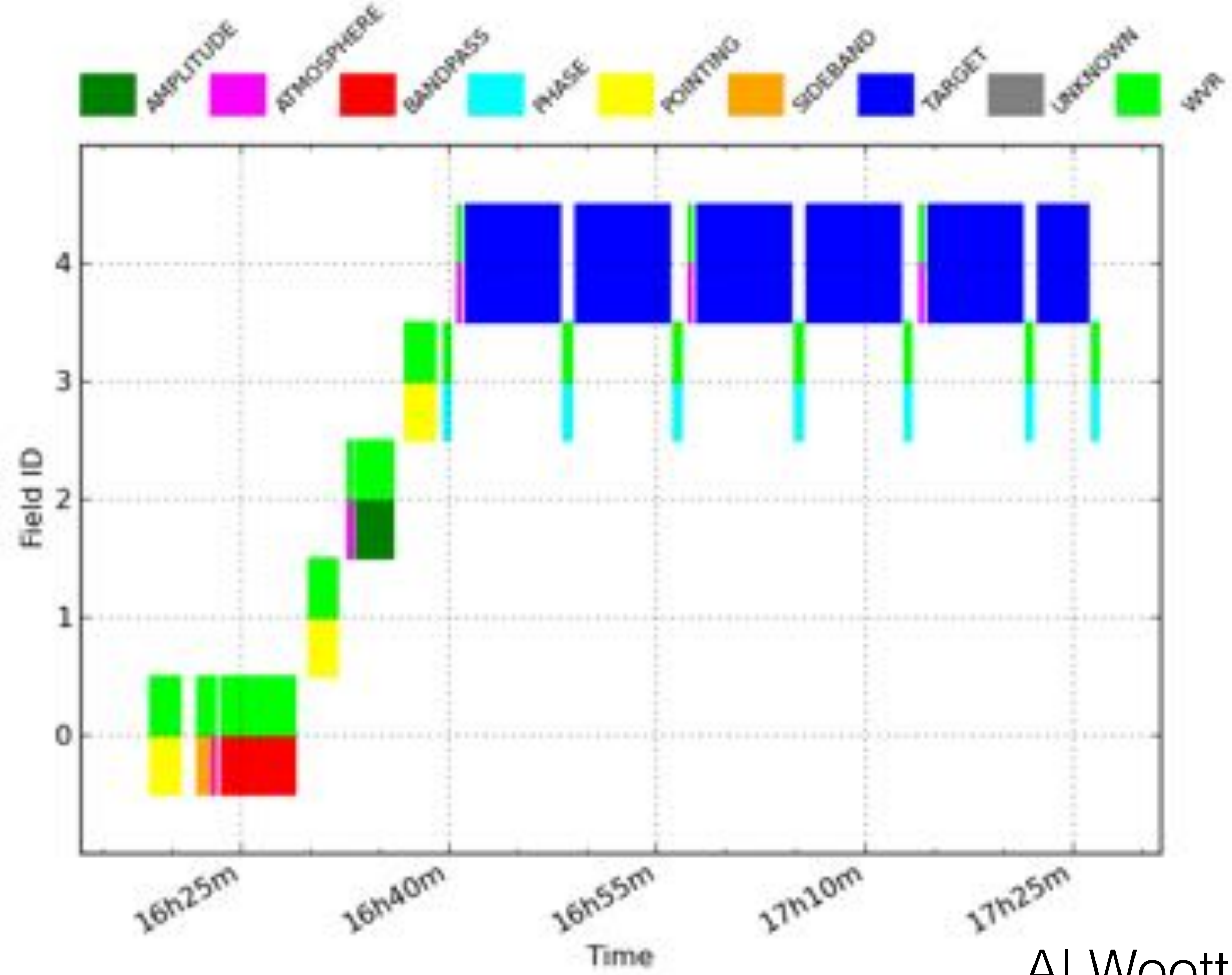


$\delta=90$ $\delta=60$ $\delta=30$ $\delta=0$ $\delta=-30$

- Good coverage at all declinations, but troubles near $\delta=0$ remain.

Calibration, Deconvolution, and Analysis

Graphic Representation (1 SB)



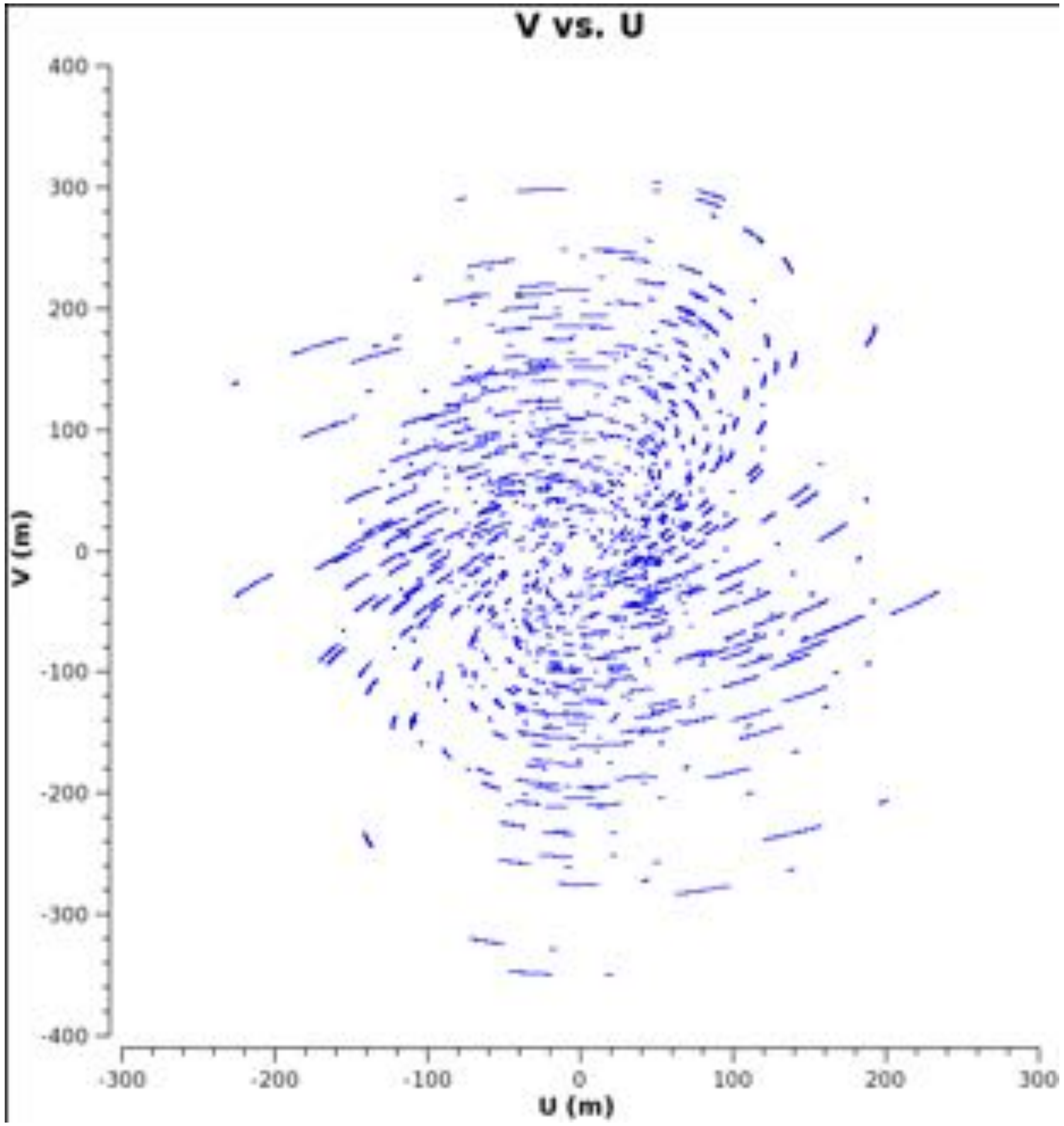
Al Wootten

U-v Source Coverage

Earth carries the antennas as it turns beneath the source

Sweeping out samples in the Fourier plane. Sampling is rather sparse on this short track but the source is probed on many spatial scales.

Note the missing samples near the center to be supplied by single ALMA elements, or by the Morita Array of 7m antennas.



Al Wootten

The take-home message

Interferometers measure cross-correlations between antennas = visibilities

Visibilities are samples of the Fourier transform of the sky brightness distribution

Imaging and deconvolution aim at

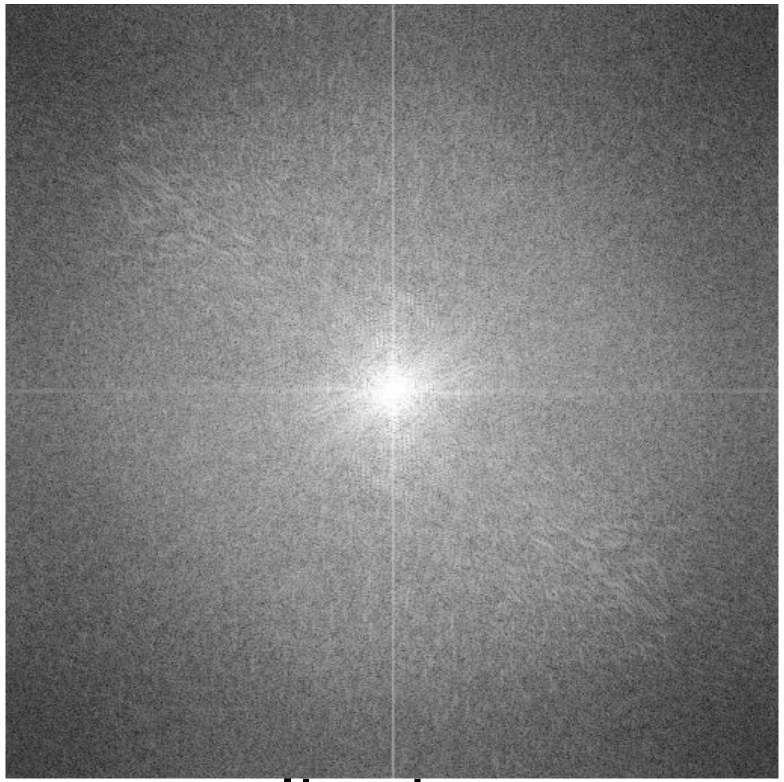
- retrieving an image of the original sky brightness distribution
- minimize the telescope footprint related to the incomplete sampling of the Fourier plane

Interferometers “see” very differently than cameras and eyes

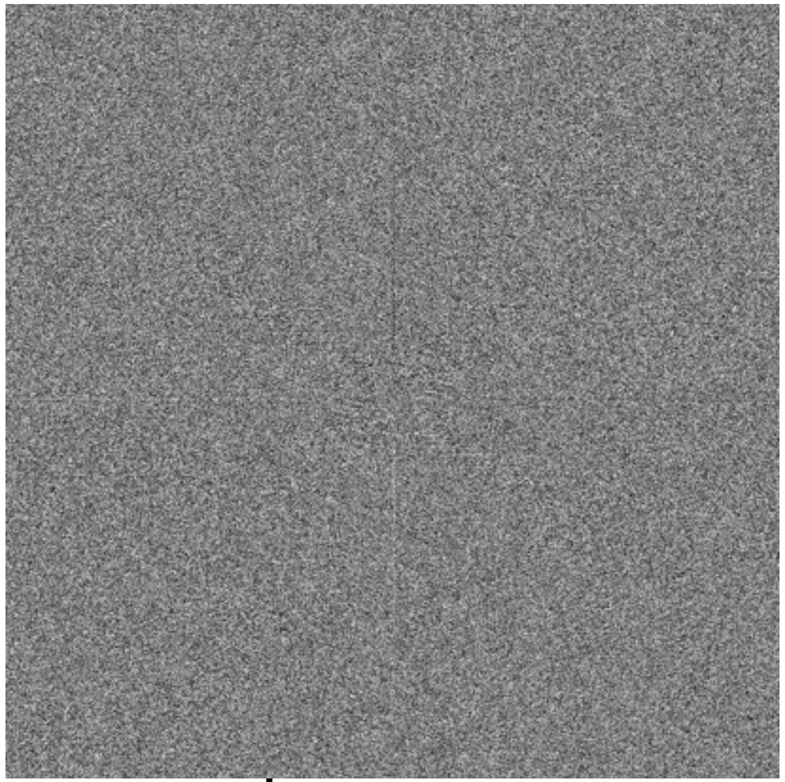
Interferometers measure complex numbers: visibilities

Absolute value: ‘Amplitude’

Argument: ‘Phase’



amplitude



phase

This is a NRAO director

(as seen by a perfect interferometer)

Arielle Moullet

Interferometers “see” very differently than cameras and eyes

Interferometers measure complex numbers: visibilities

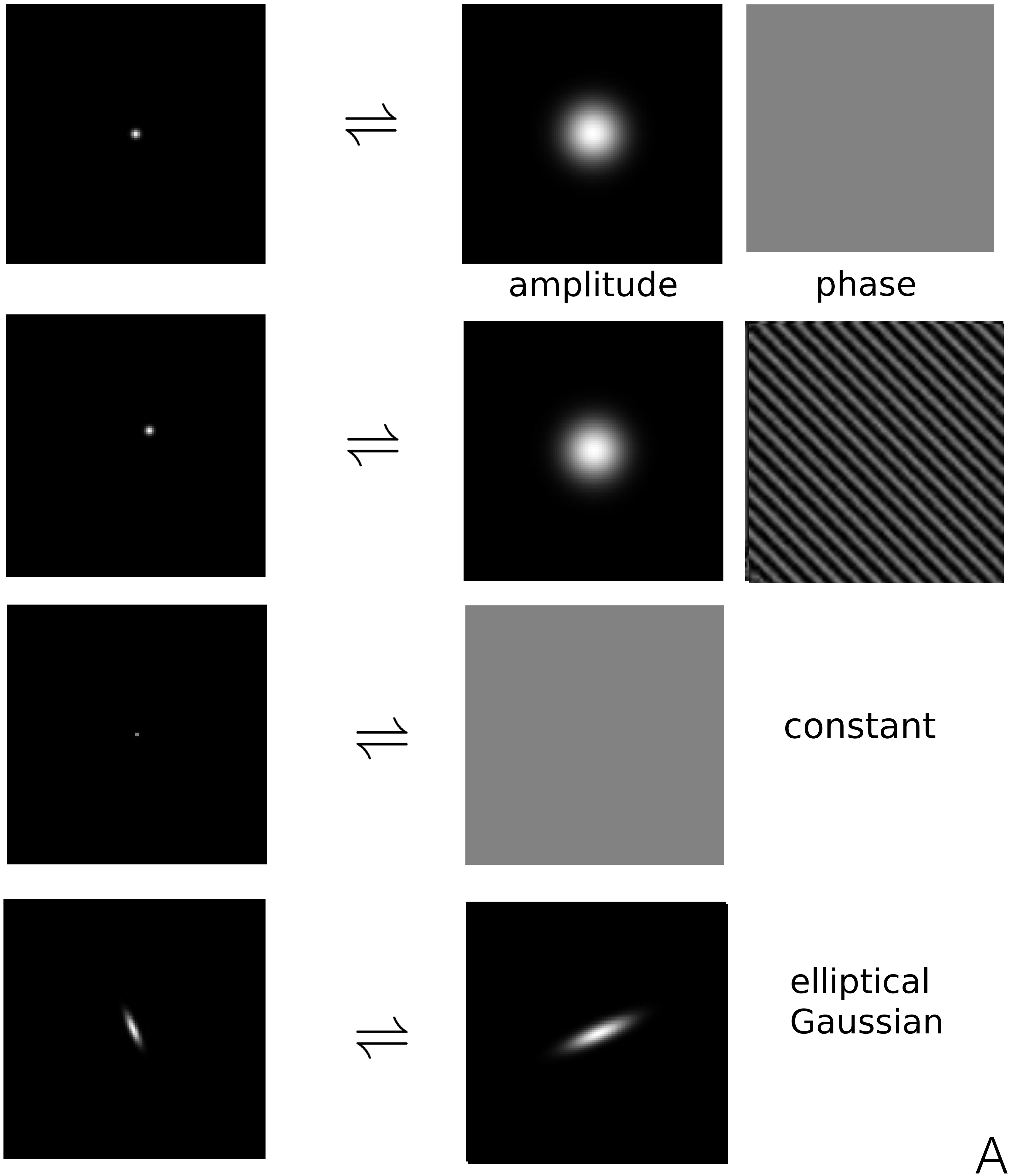
Absolute value: ‘Amplitude’

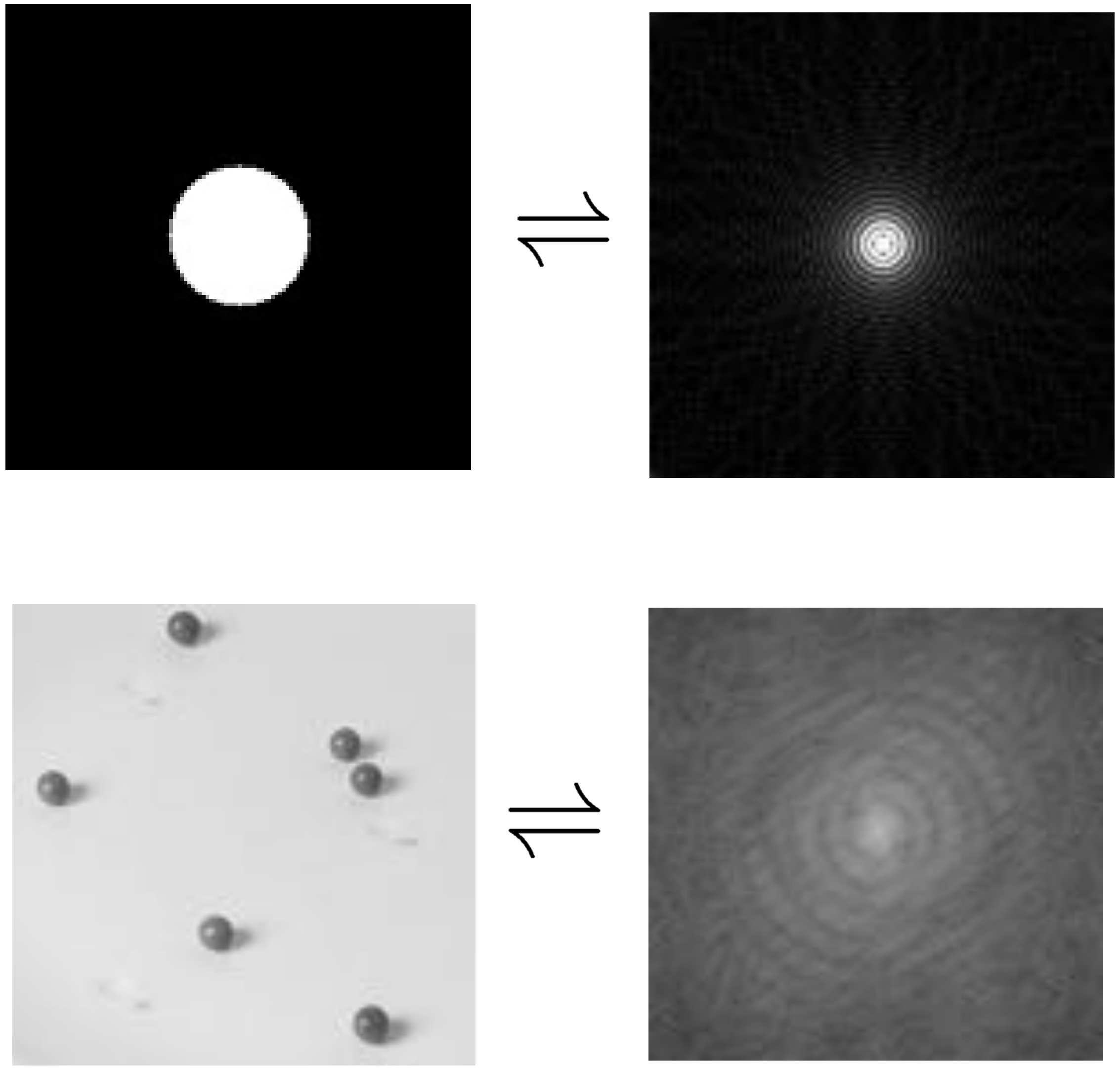
Argument: ‘Phase’

This is a NRAO director

(as seen by a camera)

Arielle Moullet





T(x,y) amp{V(u,v)}

disk $\rightleftharpoons$ Bessel

$\rightleftharpoons$

sharp edges result in many high spatial frequencies

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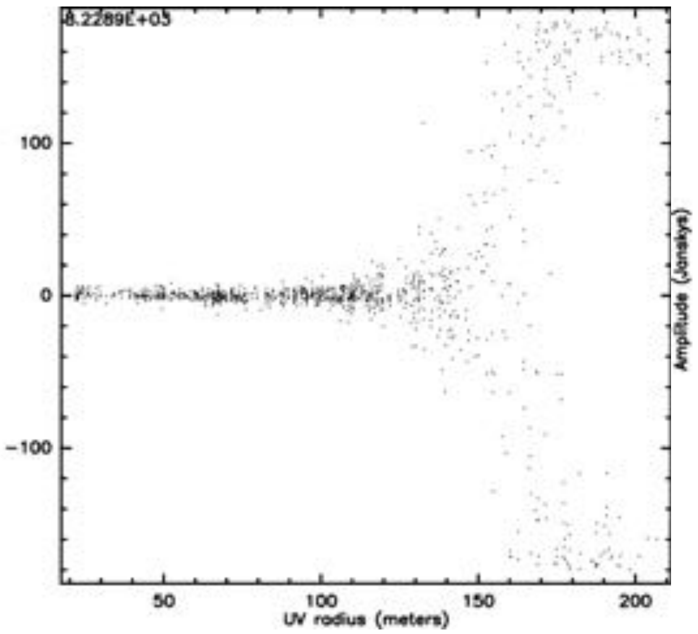
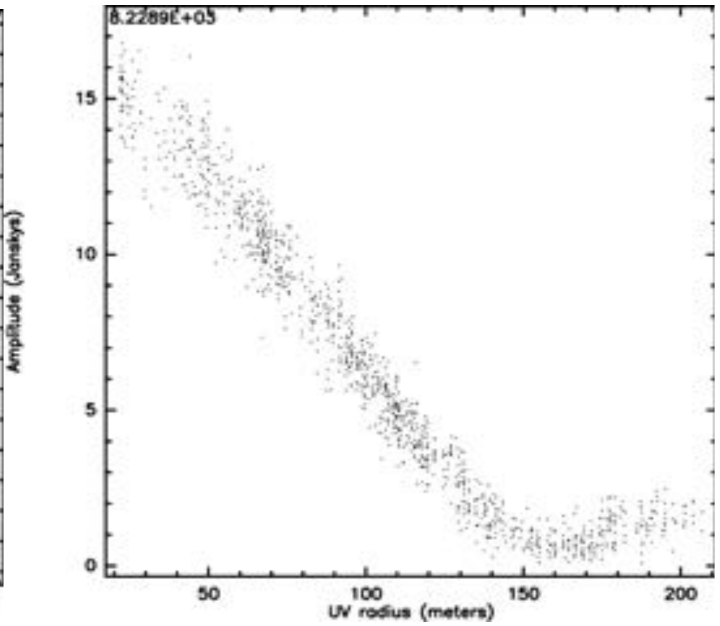
What was the original sky brightness distribution?

the inverse Fourier transform of the sampled visibilities yields **the dirty image** = true sky map convolved with footprint of the array

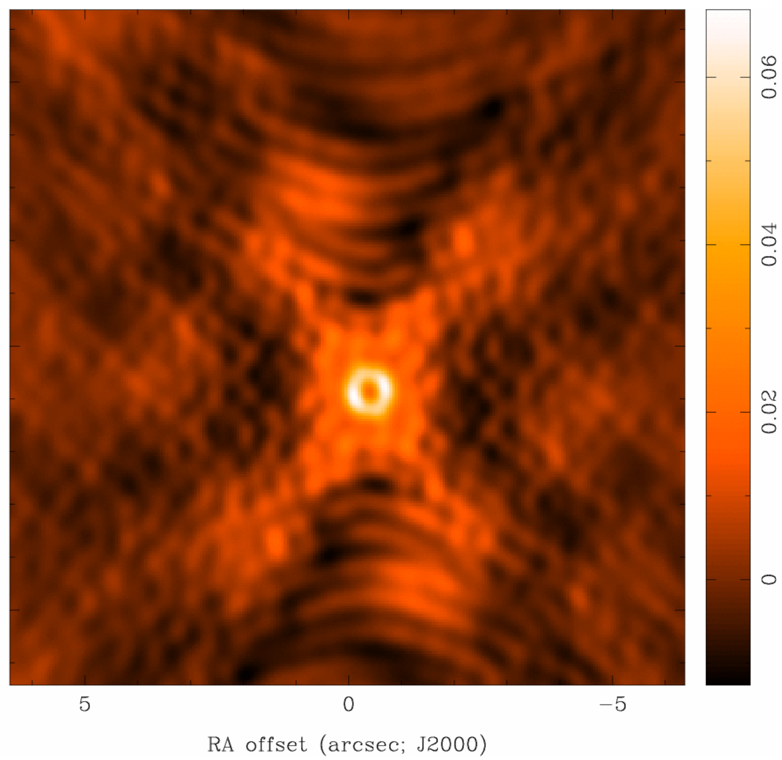


Phase



Amplitude

$\xrightarrow{\mathrm{FT}^{-1}}$



Dirty image

The footprint of the array is clearly apparent!

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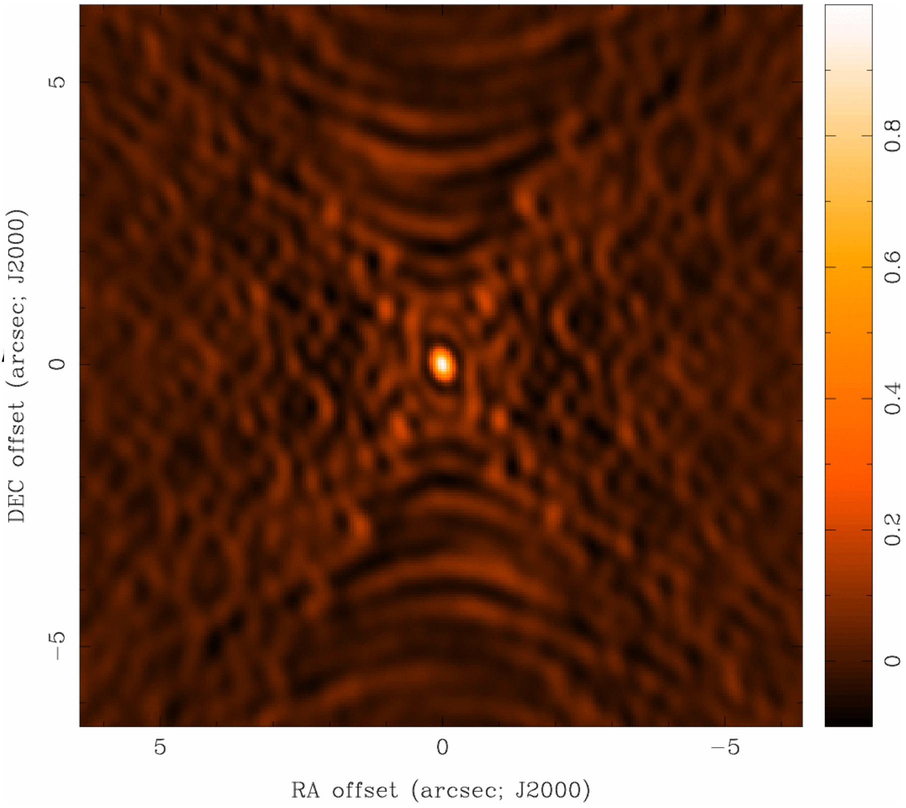
The dirty beam

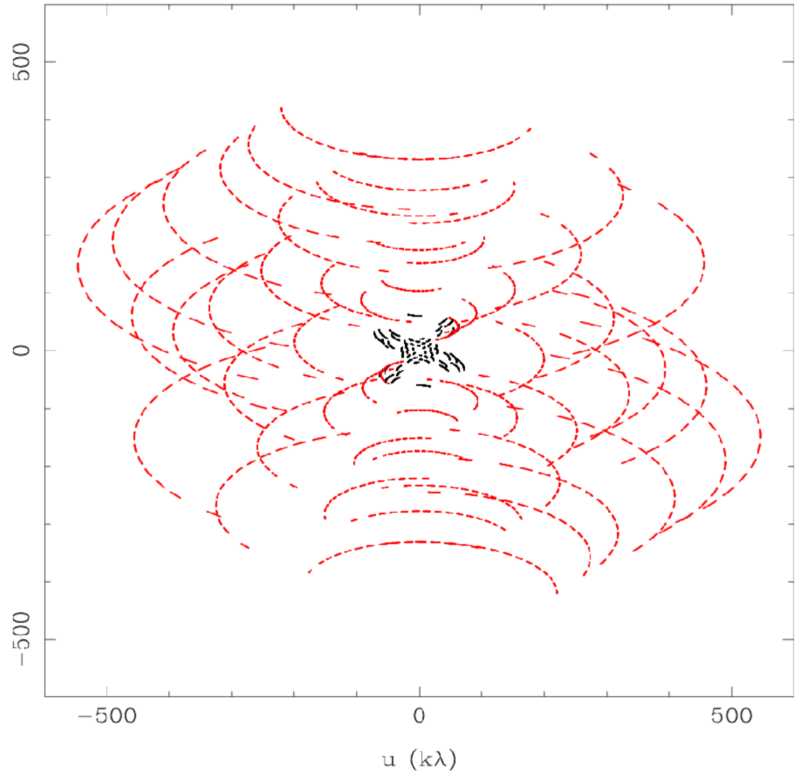
The footprint / point spread function (dirty beam) of the array is the Fourier transform of the uv-coverage.

Deconvolving the dirty beam retrieve a ‘clean’ image

b(x,y)
“dirty beam”



$\rightleftharpoons$



B(u,v)

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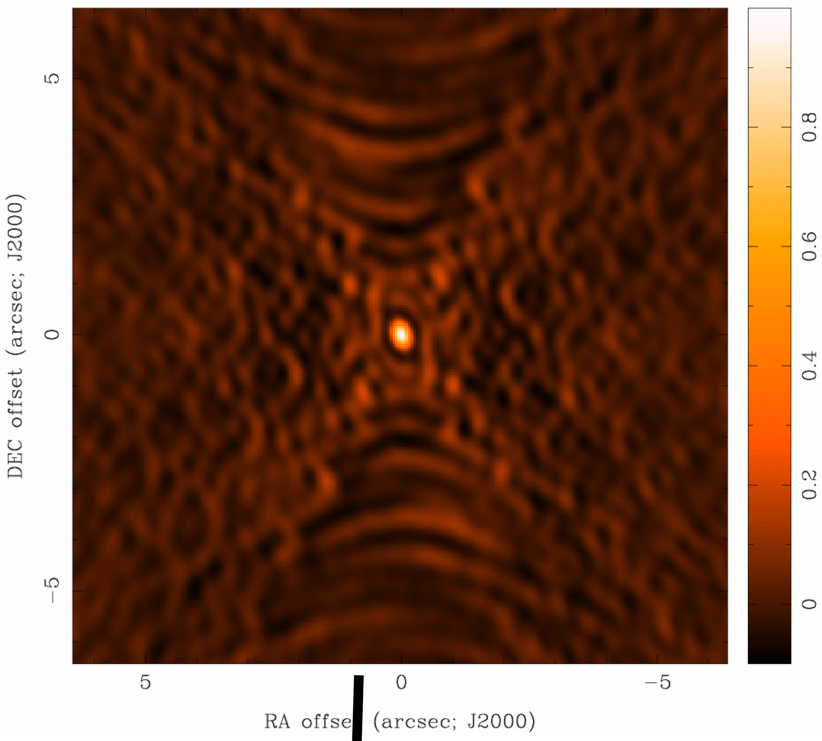
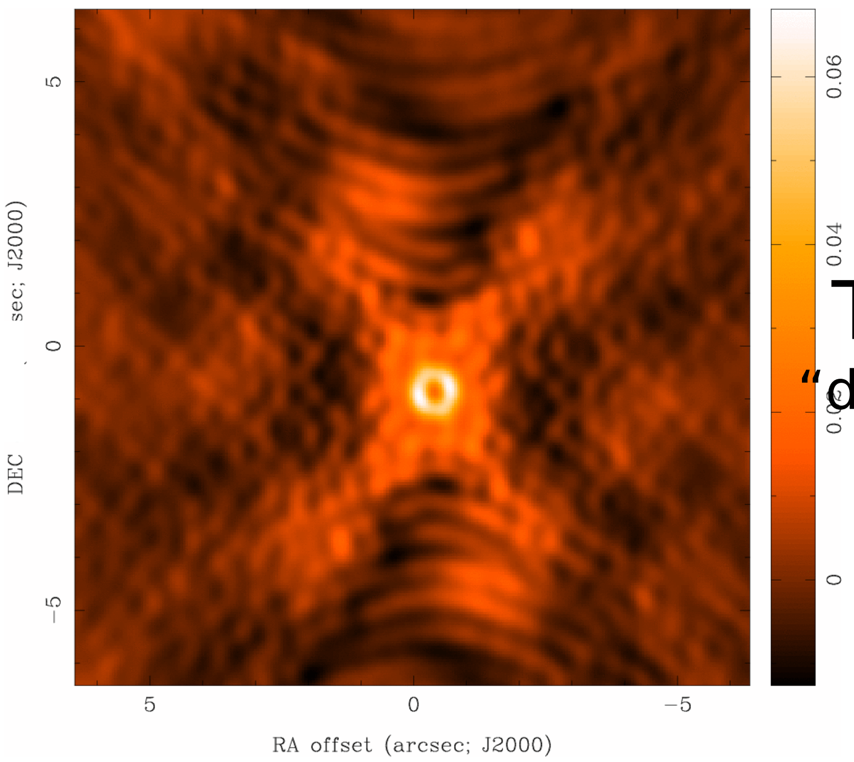
Dirty beam deconvolution

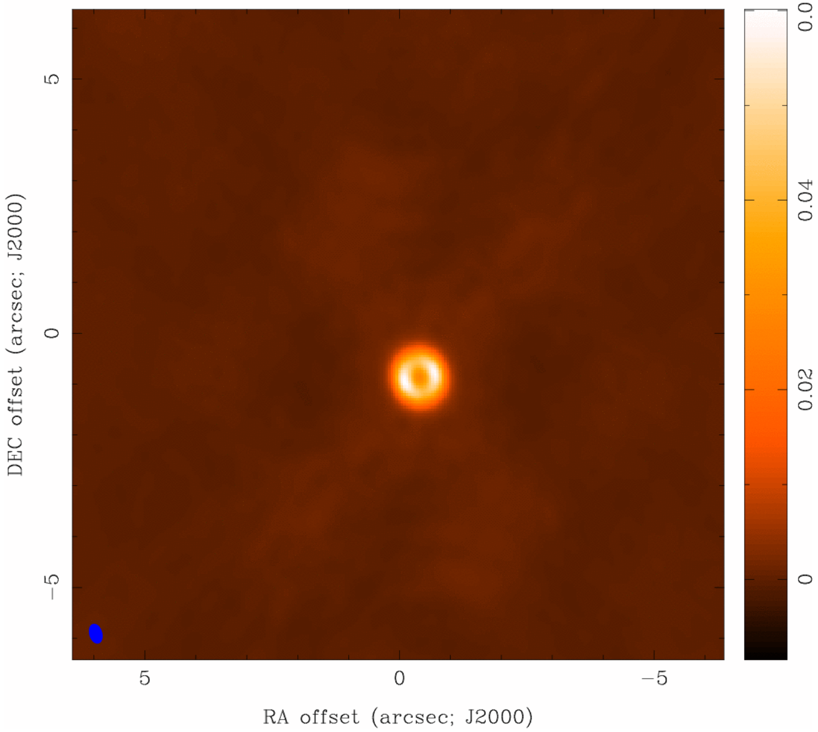
b(x,y)
“dirty beam



⇌



TD(x,y)
“dirty image”



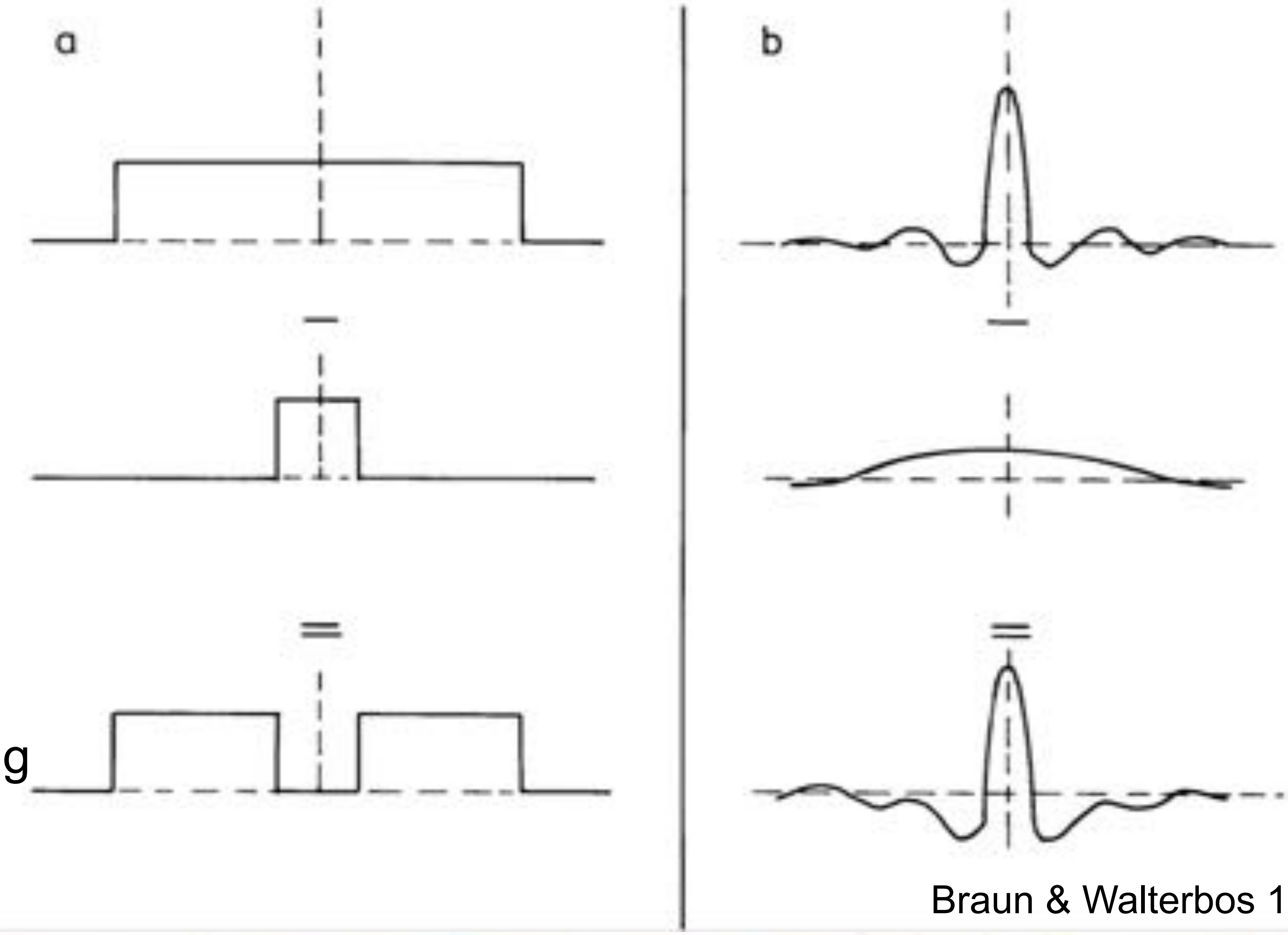
The clean image!

Arielle Moullet

What happens when you have missing short spacings?

Observed Spatial Frequencies

Instrumental Response



Ideal

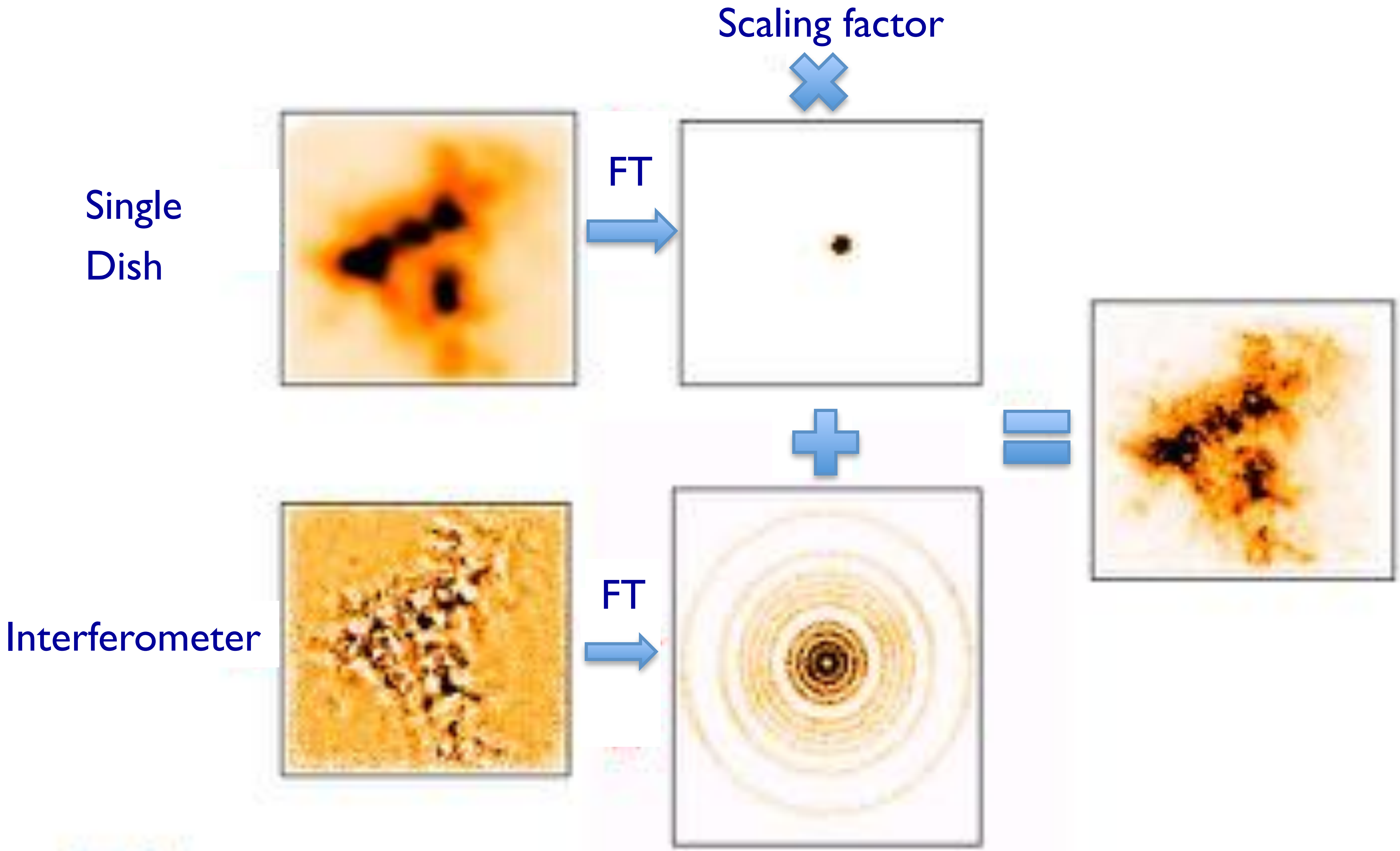
Minus Short Spacing

Effect of missing short spacing

Braun & Walterbos 1985

A. Kepley

Feather combines data in the UV plane.



Scaling factor

Single Dish

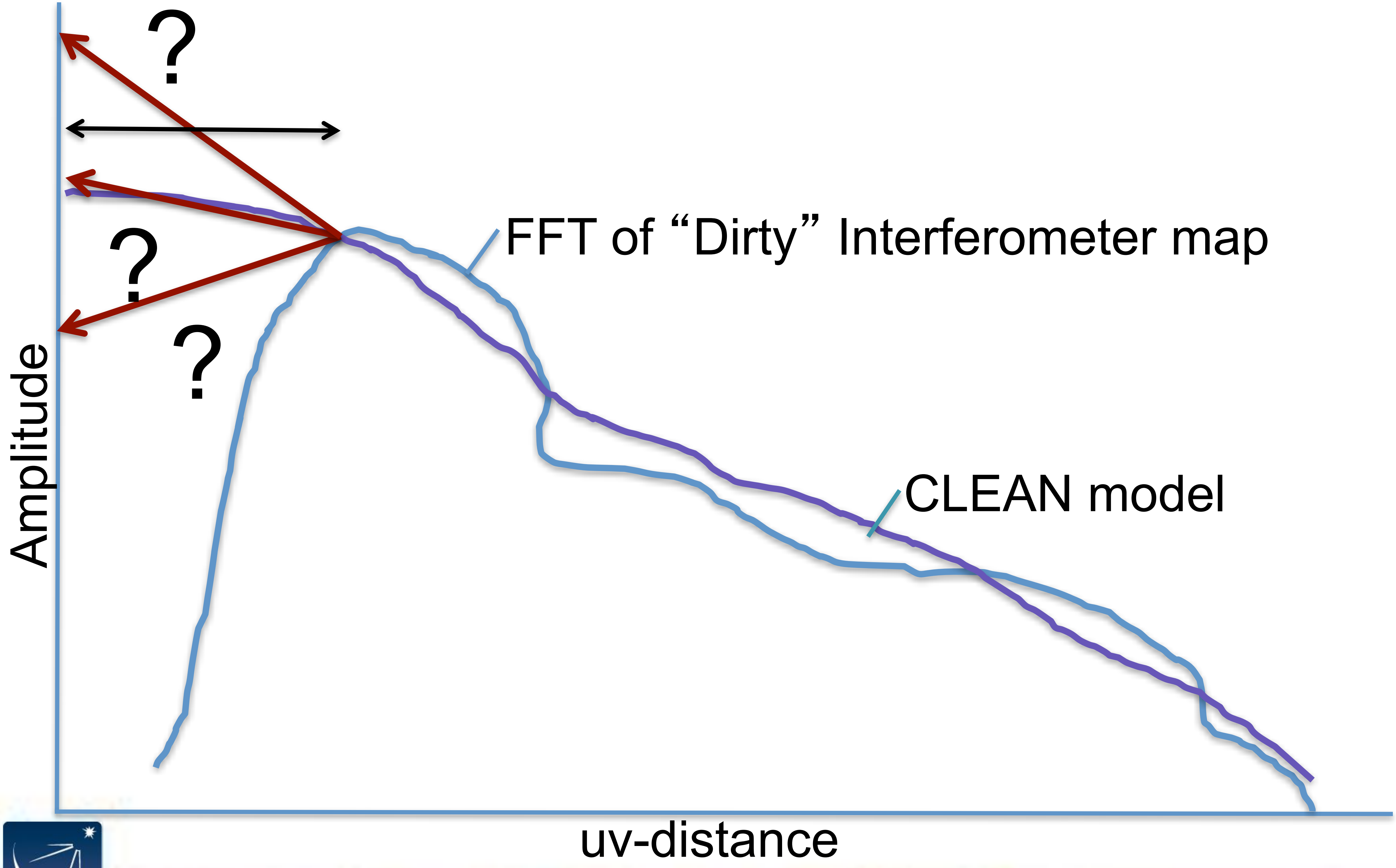
FT

Interferometer

FT

Stanimirovic 2002

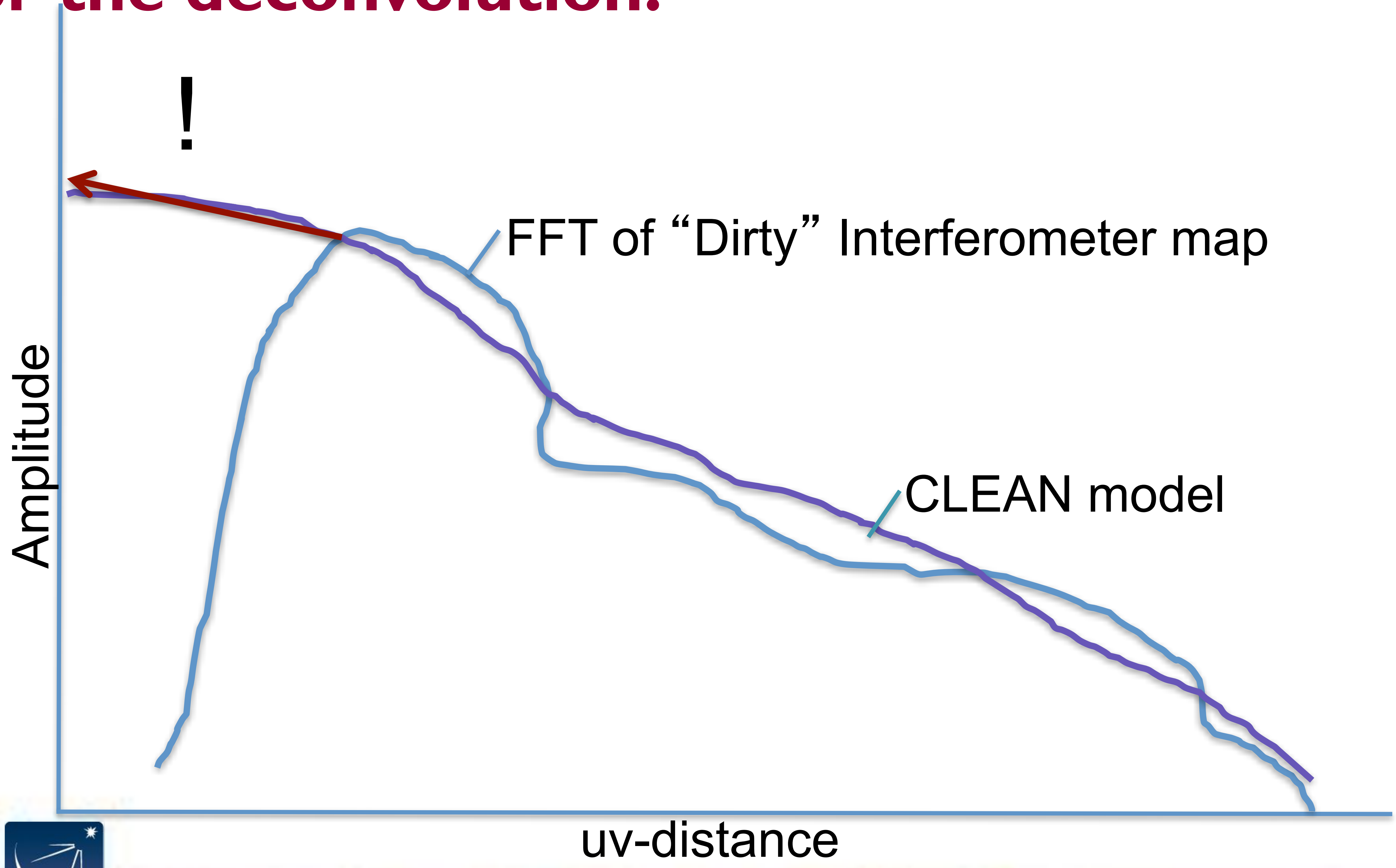
Devolution extrapolates inner flux.



A. Kepley

Deconvolution is done via clean, but MEM can provide similar results.

You can use the single dish data as a model for the deconvolution.

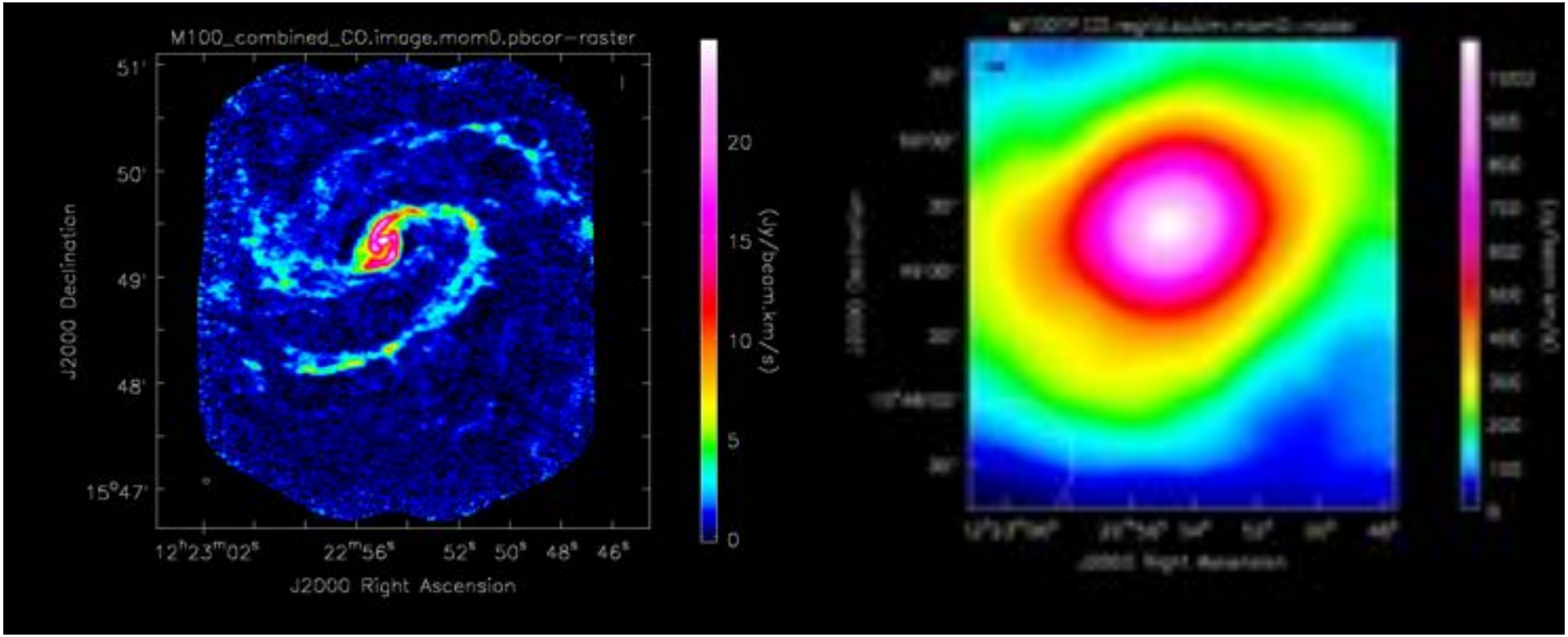


A. Kepley

Let's combine interferometric and single dish images using feather in CASA.

Interferometer

Single Dish

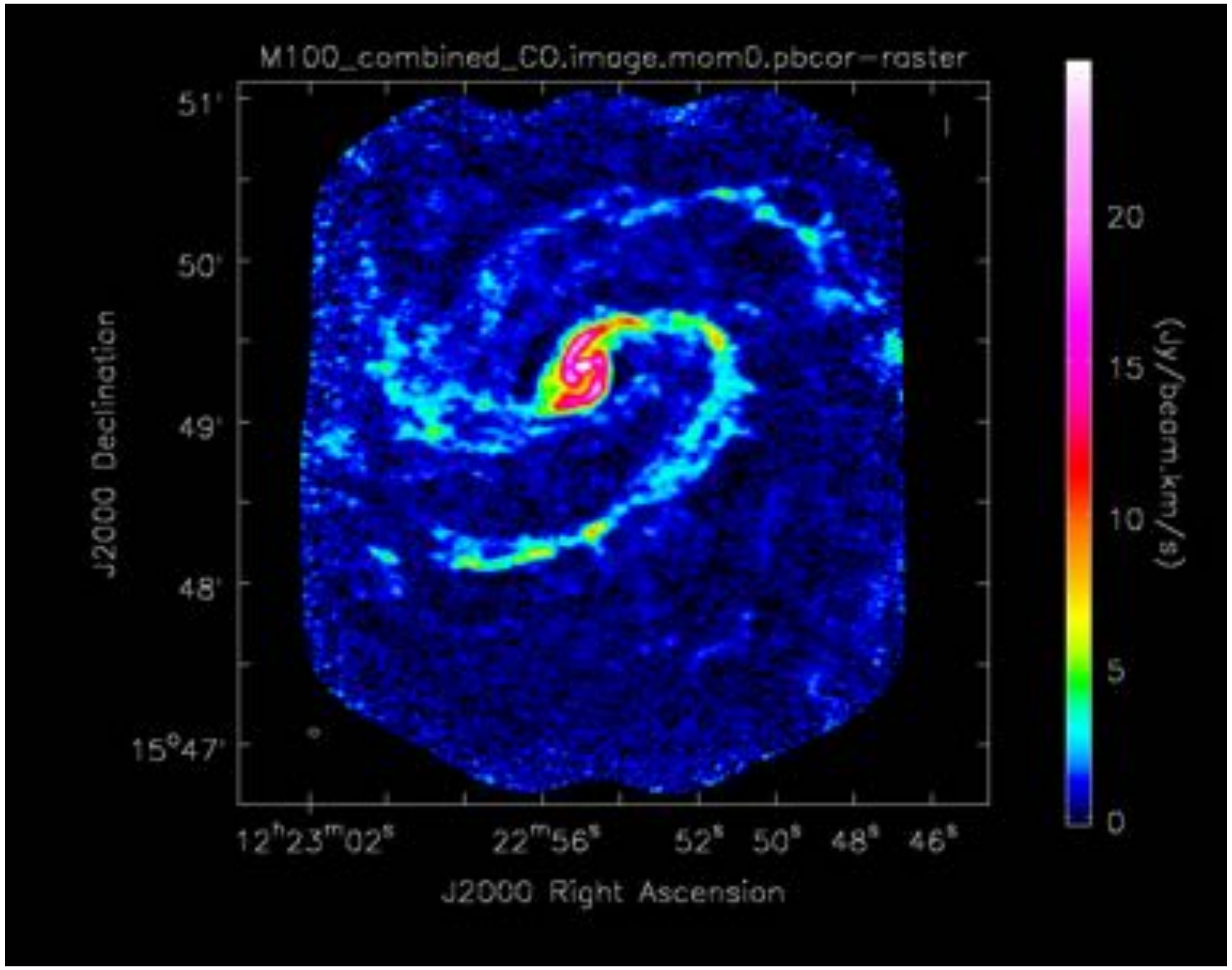


Images taken from forthcoming M100 ALMA Casaguide by Crystal Brogan, Jennifer Donovan Meyer, and Tsuyoshi Sawada.

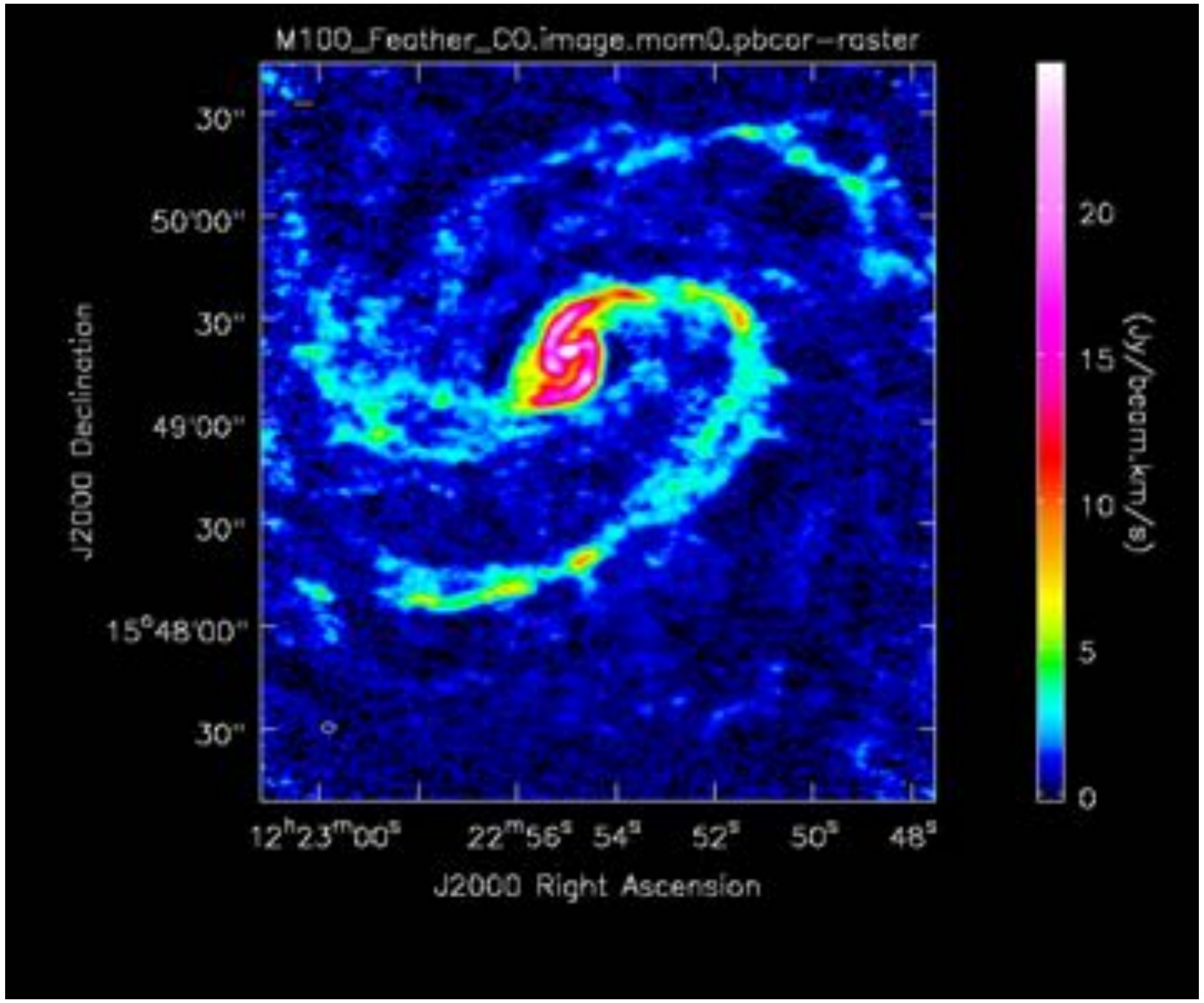
A. Kepley

Step 6. Science!

Interferometer Only

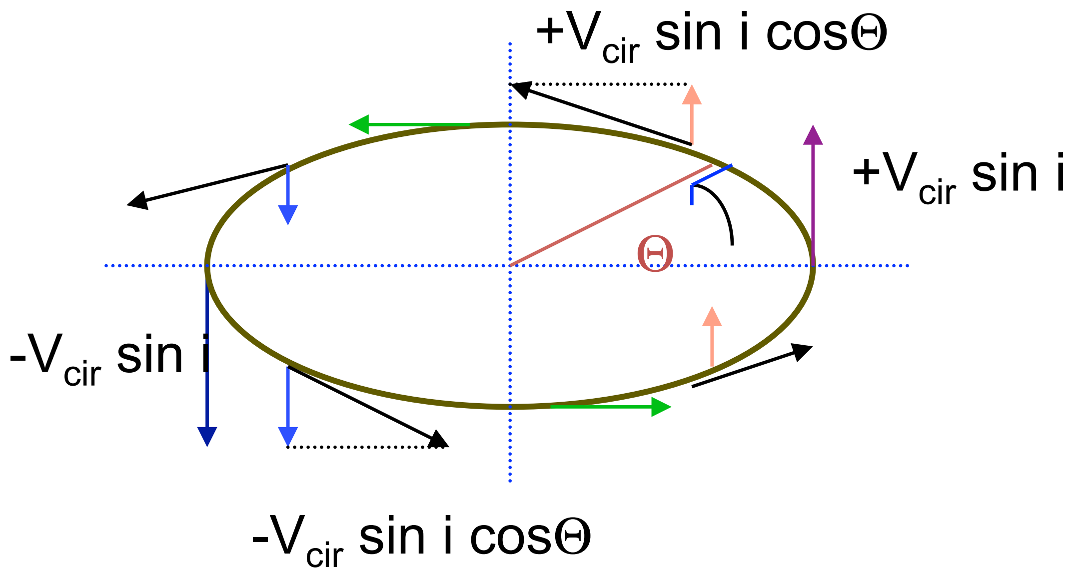


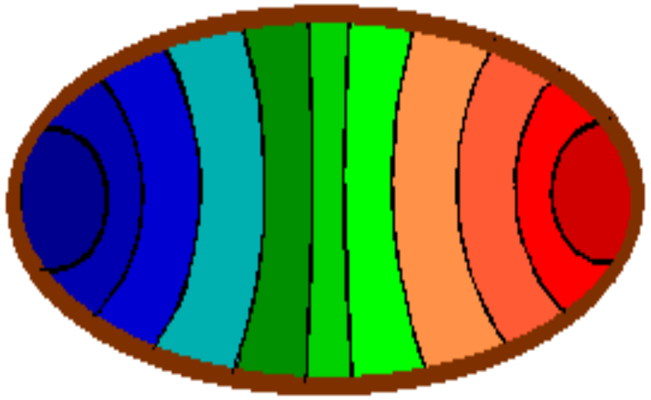
Interferometer+Single Dish



A. Kepley

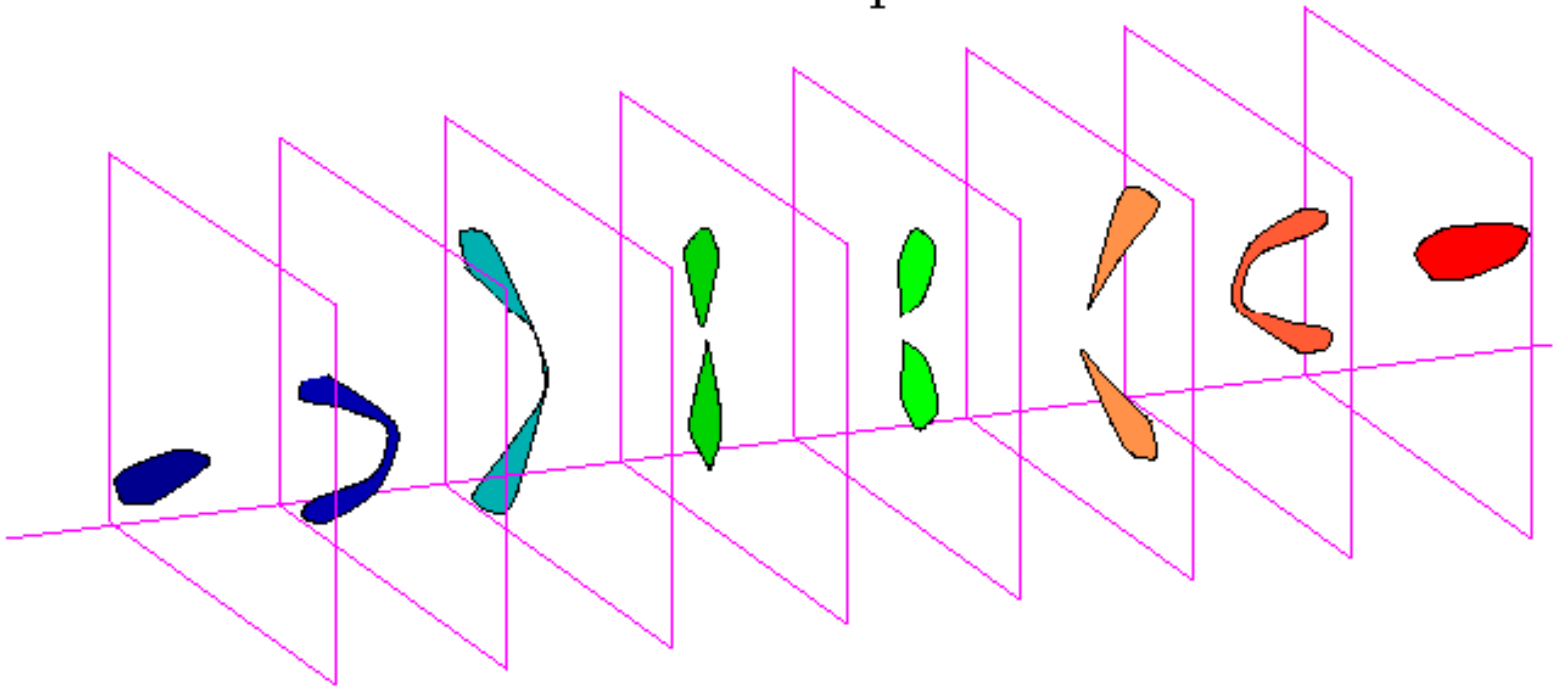
Example: A thin, tilted rotating disk





Mean Velocity Field

Channel Maps

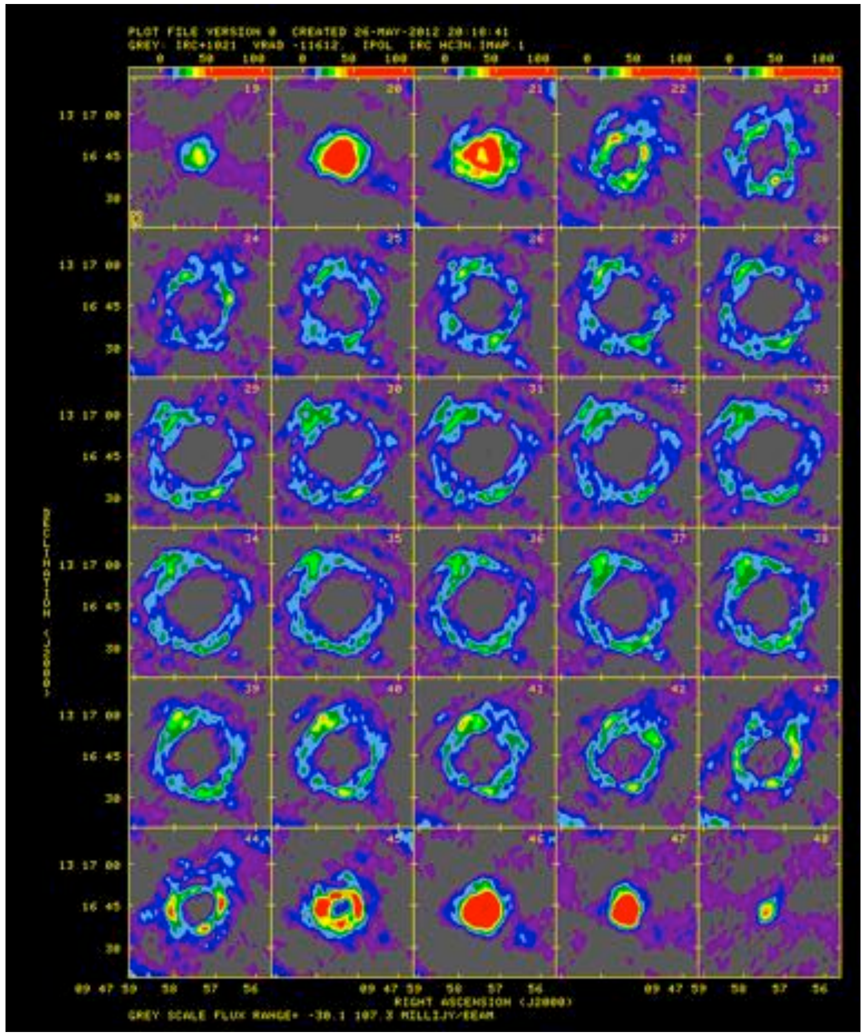


Jim Braatz

Channel maps give dynamical information

- IRC 10216 is a 16th mag AGB star but brightest star at 5 µm
- Expanding shell is clearly delineated in channel maps showing emission from the linear molecule HC_3N

HC_3N – IRC 10216



Jim Braatz

The ALMA correlator – world's highest supercomputer

Jim Braatz

ALMA Reduction Tutorials

ALMAguides

How to use these CASA Tutorials

Imaging Tutorials for CASA beginners

If you are new to CASA, start with the following tutorials. ALMA data are delivered with standard calibrations applied and they are ready for imaging. These guides cover the basic steps required for imaging and self-calibration.

- A first look at imaging in CASA This guide gives a first look at imaging and image analysis in CASA.
- A first look at self-calibration in CASA This guide demonstrates continuum self-cal.
- A first look at spectral line imaging in CASA This guide shows imaging of a spectral line.
- A first look at image analysis in CASA This guide demonstrates moment creation and basic image analysis.

Guides for reducing ALMA Science Verification data

The links below lead to overview pages for each science verification observation. The guides themselves are linked from the overview pages. These guides are a useful tools for those who would like to learn the process of calibration and imaging in detail.

The following ALMA science verification guides have been validated for CASA version 4.3. They should also work for CASA version 4.4, and they will be validated for version 4.4 soon.

- TWHydraBand7: The protoplanetary disk source TW Hya at Band 7 (0.87 mm)
- NGC3256Band3: The galaxy merger NGC 3256 at Band 3 (3 mm)
- AntennaeBand7: Mosaic of the galaxy merger NGC 4038/4039 (Antennae) at Band 7 (0.87 mm)
- IRAS16293Band9: Mosaic of the protostellar cluster IRAS16293-2422 at Band 9 (0.45 mm)
- File:BR1202 SV Band7 Calibration notes.pdf: Supplemental notes on the calibration of Science Verification target BR1202-0725 in CASA 3.3
- ALMA2014_LBC_SVDATA: Imaging scripts and details for the 2014 ALMA Long Baseline Campaign science verification data for Juno, Mira, HL Tau, and SDP.81.
- M100_Band3: Demonstration of combining 12m-array, 7m-array, and Total Power data for M100 using CASA 4.3.1
- 3C286_Polarization: Demonstration of the reduction of ALMA continuum polarization toward the quasar 3C286

Resources

NAIC/NRAO Single-Dish and Interferometry Summer School
https://science.nrao.edu/science/meetings/2015/summer-schools/interferometry-program

Essential Radio Astronomy, J. J. Condon and S. M. Ransom
http://www.cv.nrao.edu/course/astr534/ERA.shtml

CASA Guides
https://casaguides.nrao.edu/index.php/Main_Page

Synthesis Imaging in Radio Astronomy II, G. B. Taylor, C. L. Carilli, and R. A. Perley (aka. The White Book)

Splatalogue: database for astronomical spectroscopy
http://www.cv.nrao.edu/php/splat/