Radio Interferometry Fundamentals

John Conway

Onsala Space Obs and Nordic ALMA ARC-node

So far discussed only single dish radio/mm obs

- Resolution λ/D, for D=20m, is 30'' at mm-wavelengths and 30' (diameter of full moon) at cm (i.e. λ =18cm)

- Paradox - In fact despite radio/mm having the longest wavelengh it can achieve the highest angular resolution of any wavelength (up to 1 mas = 0.001'').

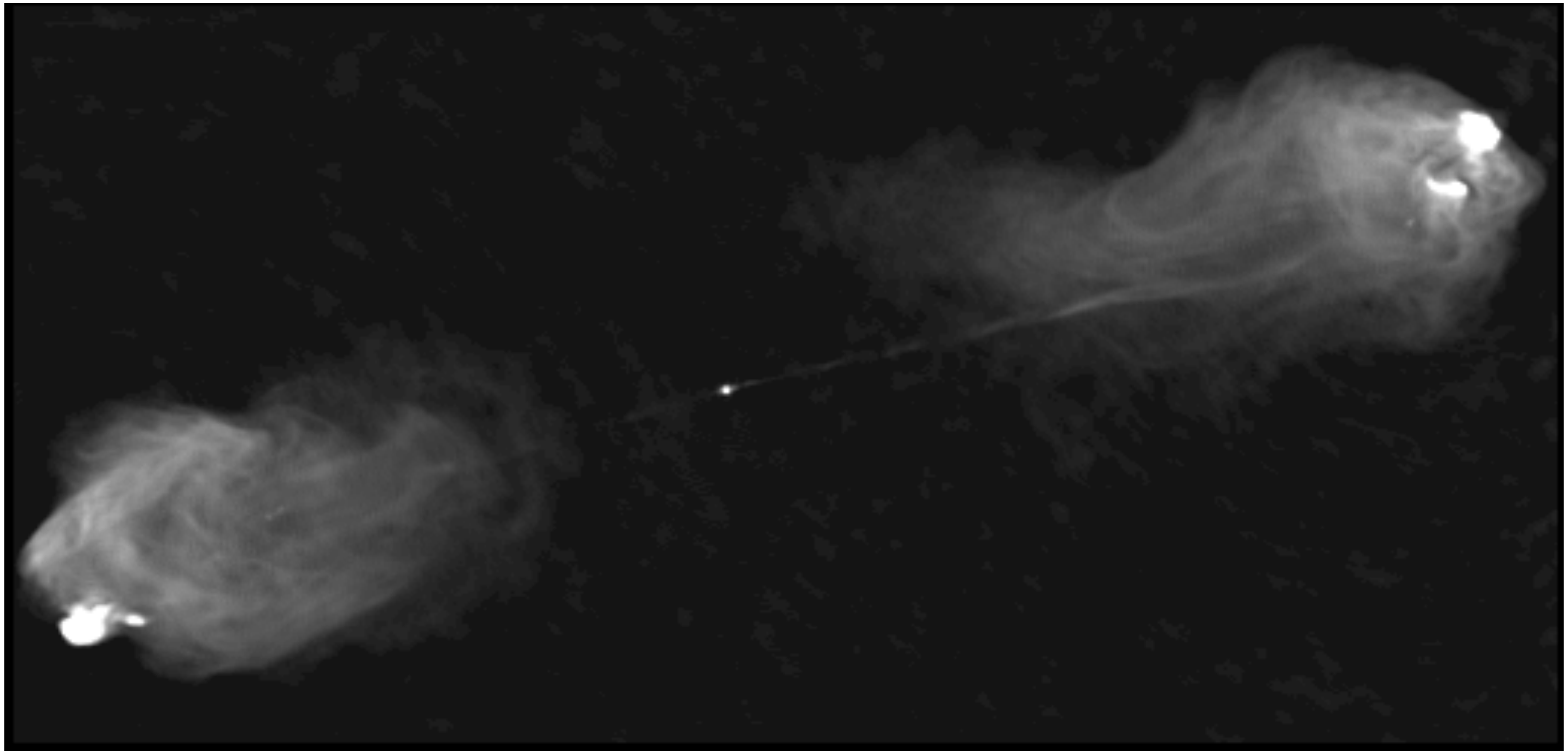
- Reason- Interferometry is relatively easy to do at radio and mm wavelengths

- Presently at cm 5% science single dish and 95% interferometry, at mm more 50%/50% but with ALMA interferometry will dominate at mm as well.

Very Large Array(VLA)

Overall View of the VLA

VLA Image – Radio Galaxy Cygnus A (500 million light years away)



Radio astronomers can make nice images too

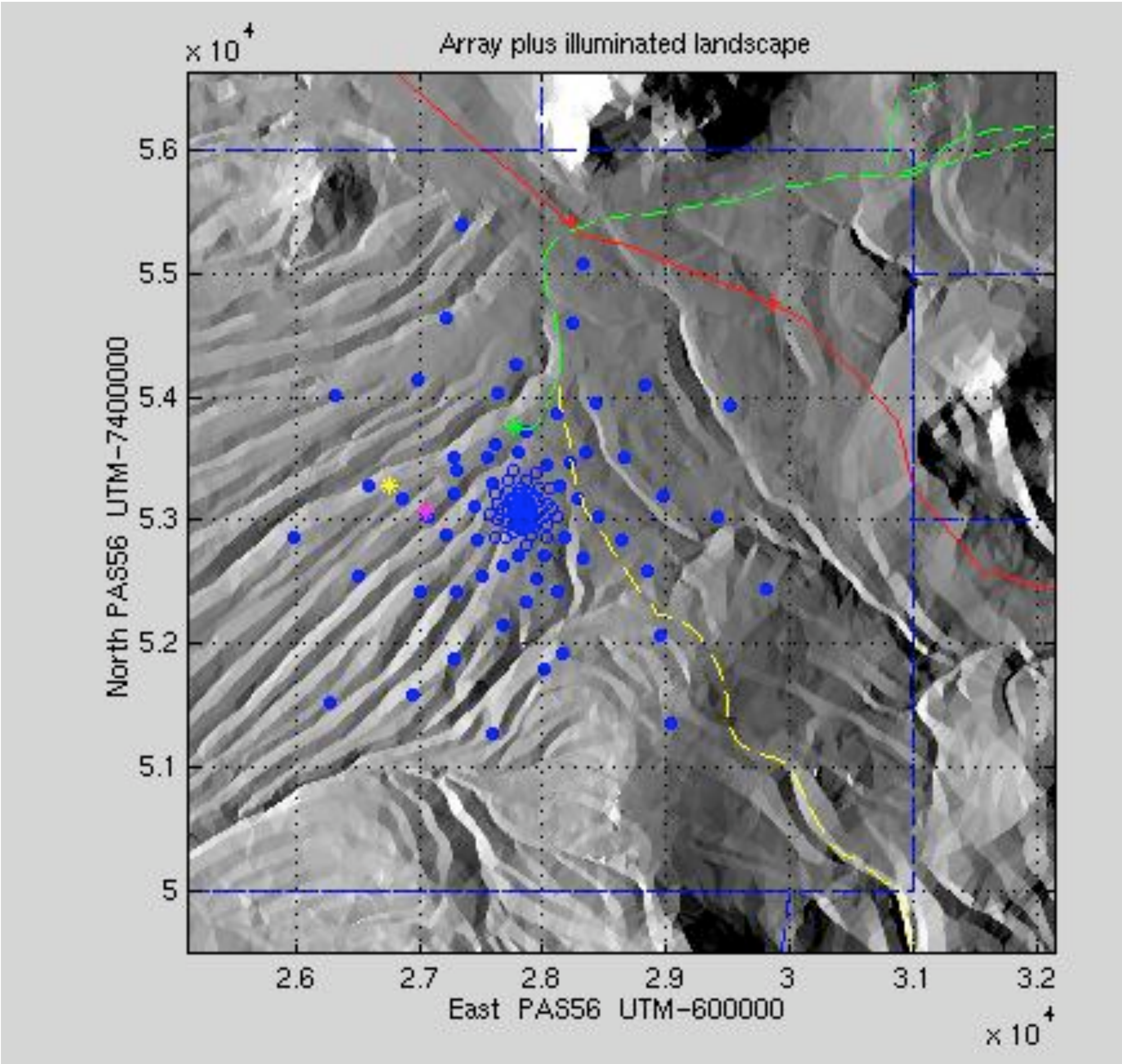
ALMA Atacama Large Millimetre Array

at 5000m elevation, Atacama Desert, Chile

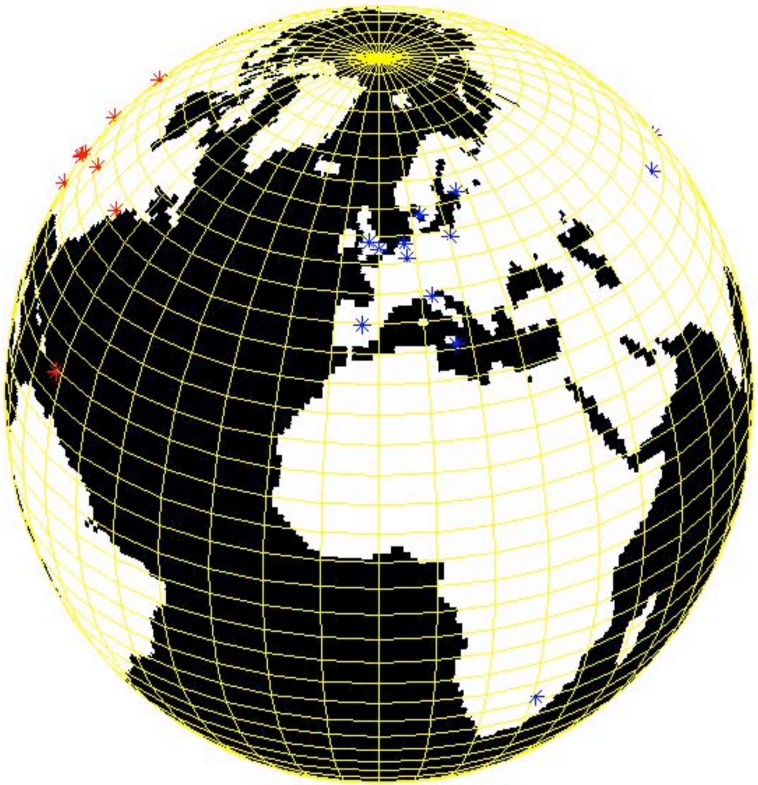
50 times 12m diameter dishes,moved around on 200 pads

Myself at the site in April 2001

ALMA Configuration layout – John Conway



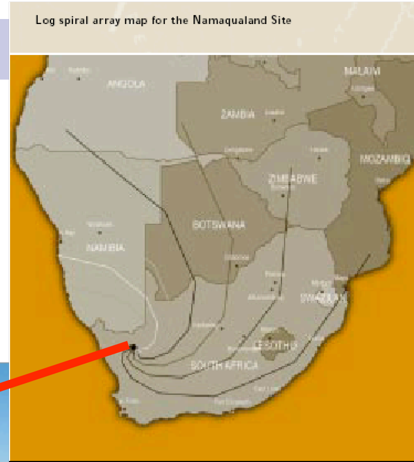
Very Long Baseline Interferometry (VLBI)



Make an interferometer the size of the Earth – combine signals from antennas all around Earth – Tape record data and combine later ’off-line’ or send in real -time over internet

Square Kilometer Array (SKA)

Future cm wavelength interferometer array



South africa

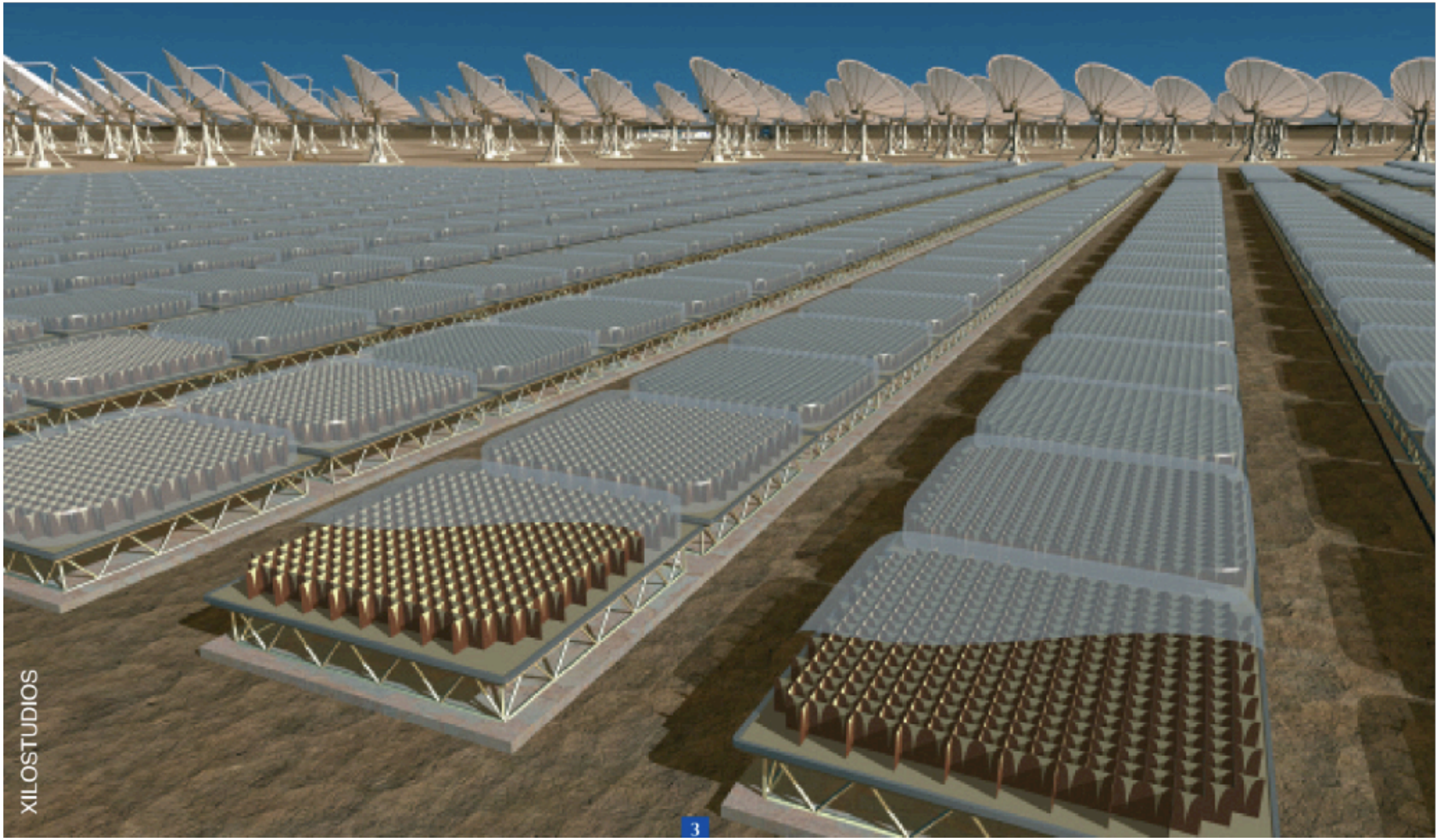
16

Australia

International project,
estimated cost 1.5 B€
phase 2 ready by 2020

Inner SKA core

Parabolas + aperture arrays, ...



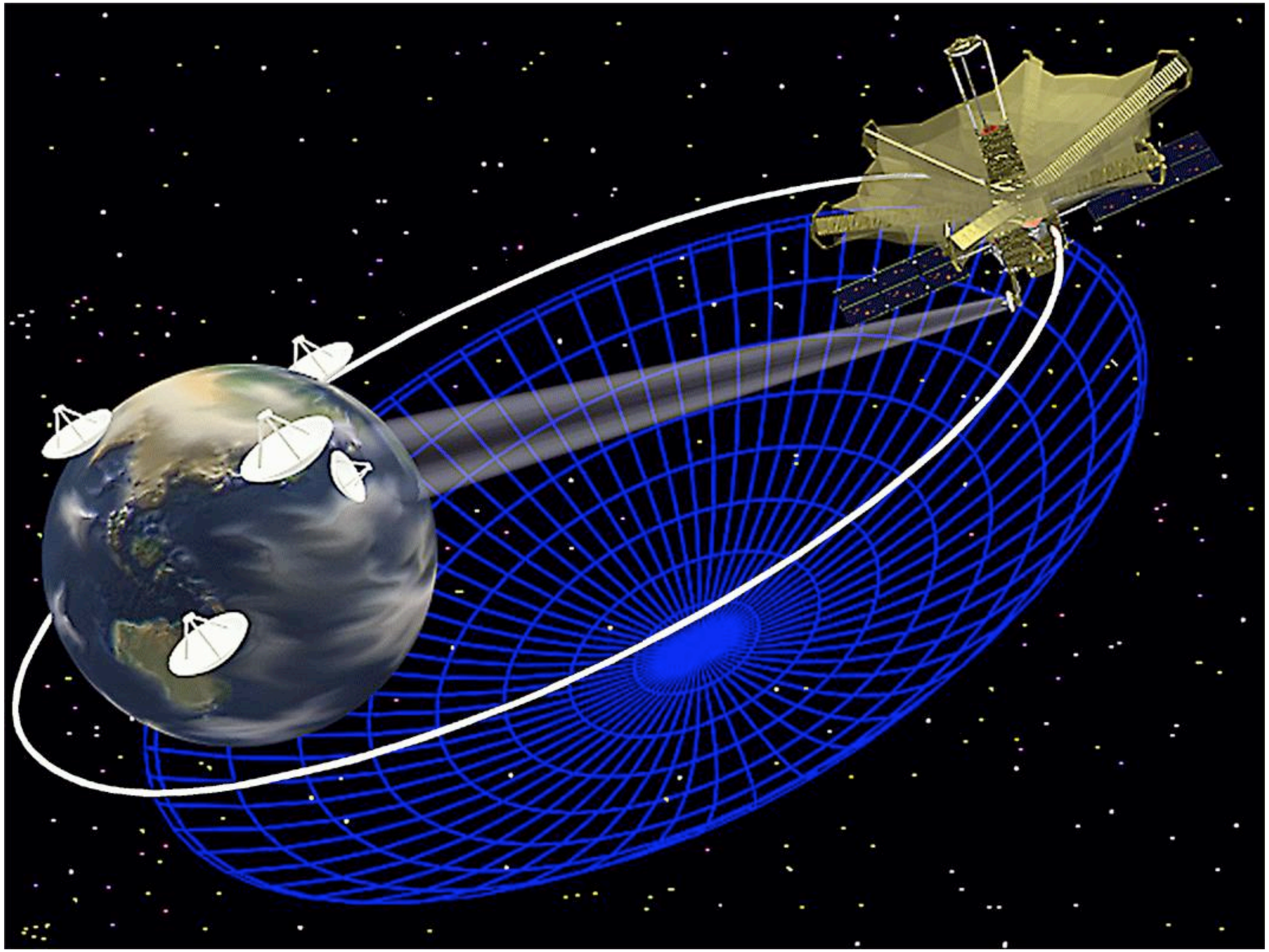
SN1993J in M81

VLBI Observations

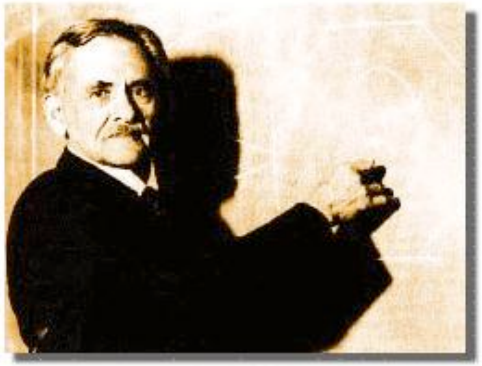
J.M. Marcaide, A. Alberdi, E. Ros,
et al.

Japanese 6m antenna on VSOP sattelite orbits the Earth out

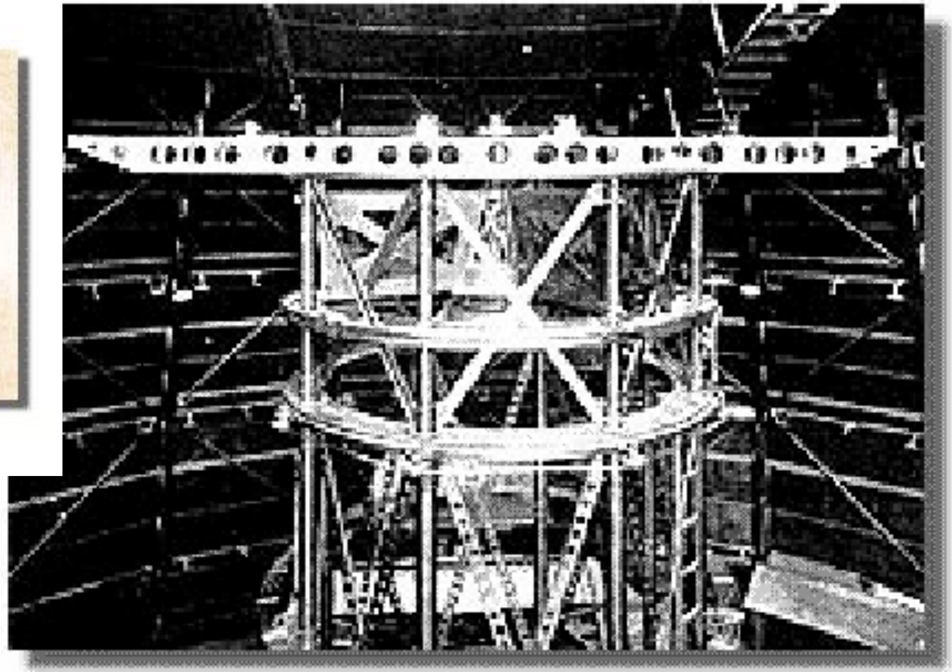
to 4 Diameters increasing the resolution of VLBI



Michelson Stellar Interferometer



Albert Michelson

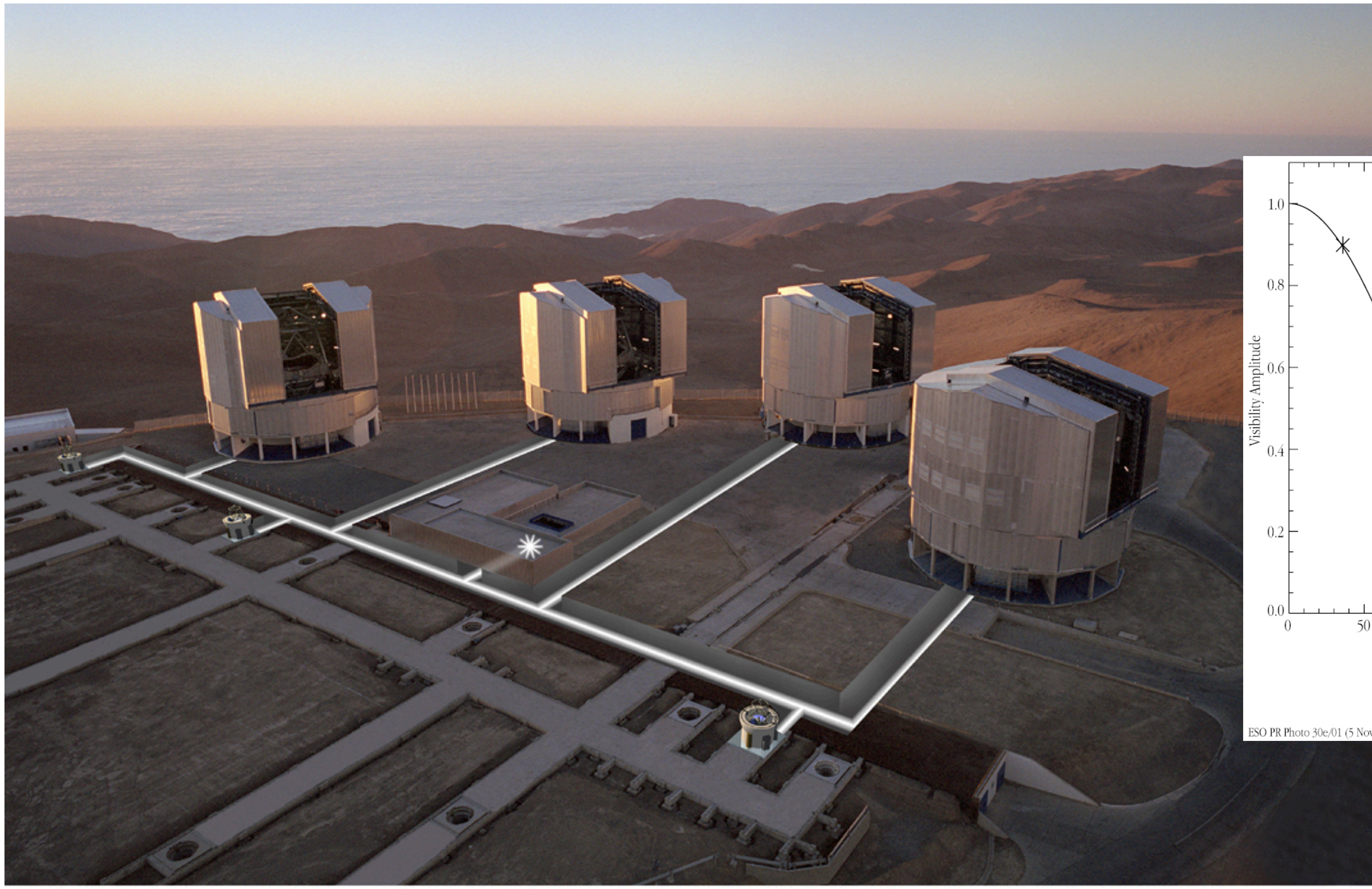


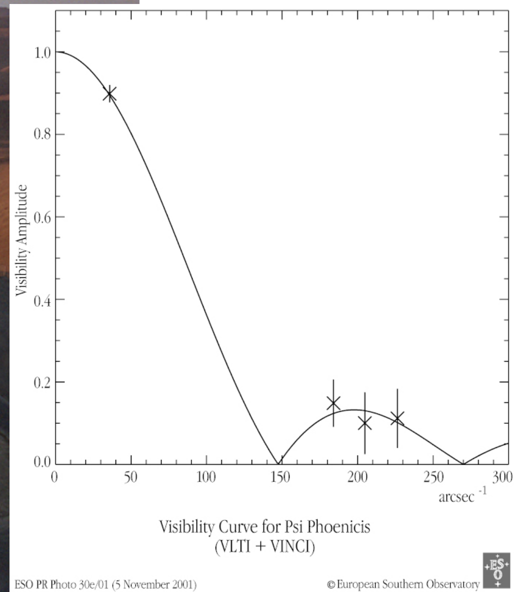
The 20-foot beam on top of the 100-inch Hooker Telescope on Mt. Wilson in Southern California.

First direct measurement of a stellar diameter.

Michelson and Pease (1921)

Very Large Telescope Interferometer (VLTI) - Paranal, Chile – optical interferometer

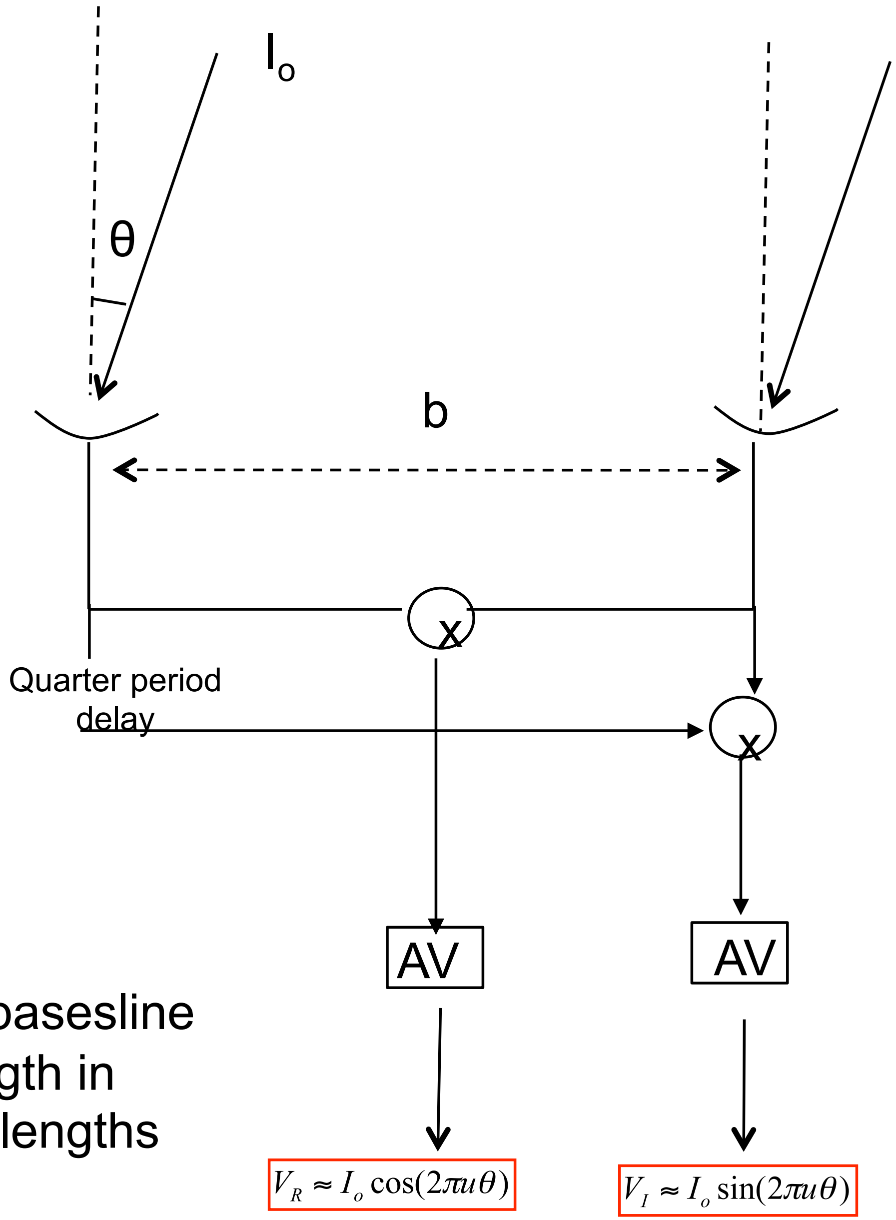




Aerial View of Paranal Observing Platform with VLTI Light Paths

ESO PR Photo 10f/01 (18 March 2001)

Radio Multiplying interferometer



Intereferometer response to a point source brightness I_o an angle θ from zenith

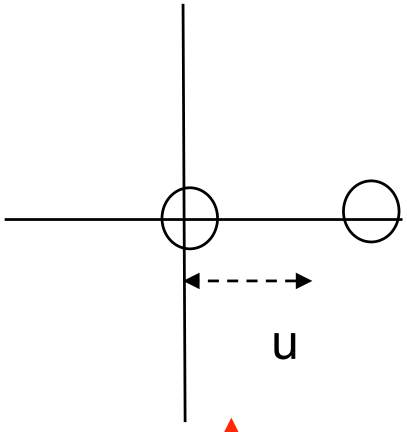
u= b/λ basesline length in wavelengths

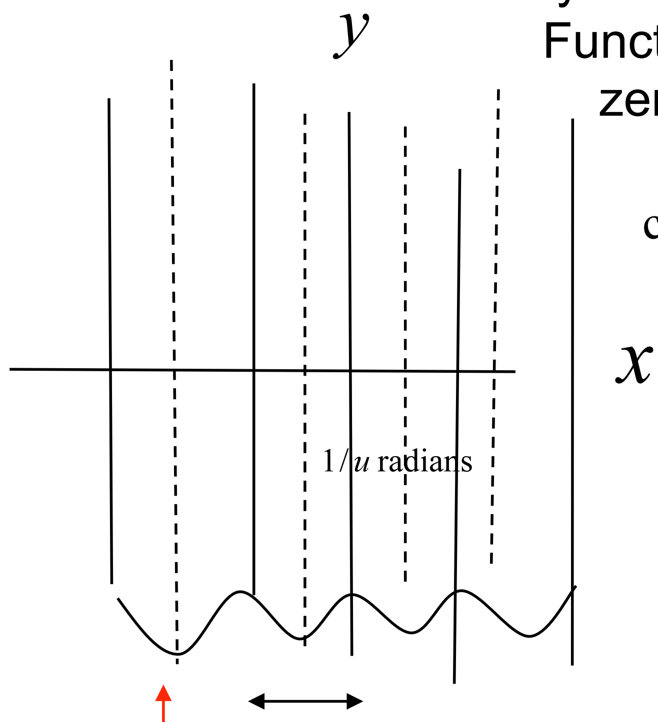
Form complex visibility V = $V_R - i\,V_I$. Amplitude of that visibility depends only on point source strength and phase on position

2D Response function of Interferometer Baseline close to the zenith is

Sky Resonpse Function at zenith

North Pole





$\cos(2\pi(ux))$

Telecope layout

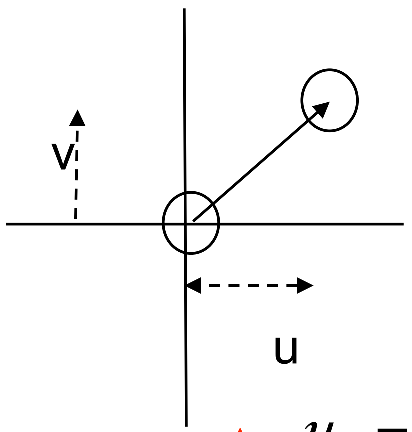
Real channel response function at zenith. 'Corrugated Roof' with spatial frequency u,v

If the two telescope are not East-West

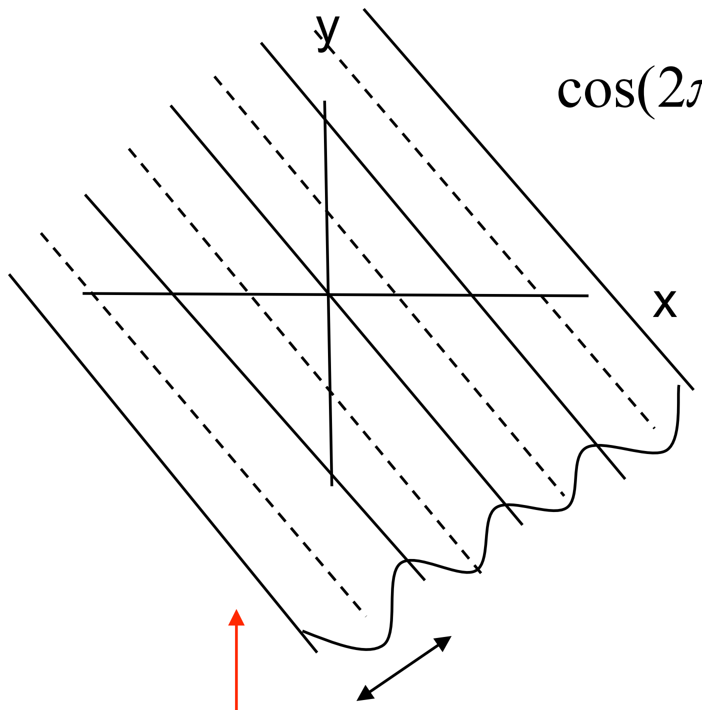
Real Resonse Function on sky

$$\cos(2\pi(ux + vy))$$

North



$$u_r = \sqrt{u^2 + v^2}$$



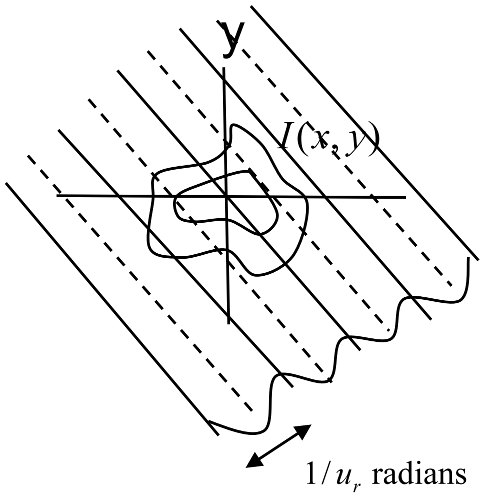
$1/u_r$ radians

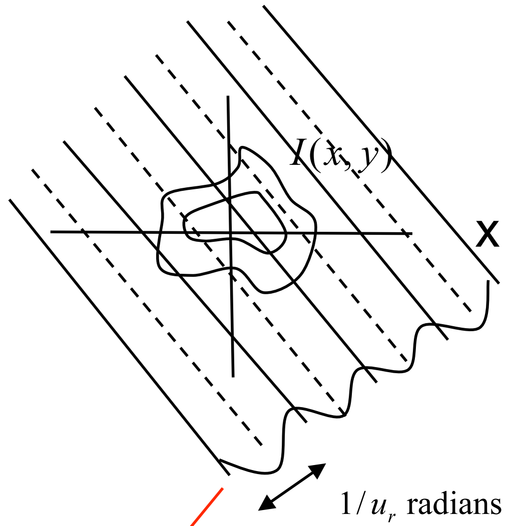
Telecope layout

Real channel response function at zenith. 'Corrugated Roof' with spatial frequency u,v

$$V_R = \iint I(x,y)\cos(2\pi(ux+vy))dxdy$$

$$V_I = \iint I(x,y)\sin(2\pi(ux+vy))dxdy$$





Real part

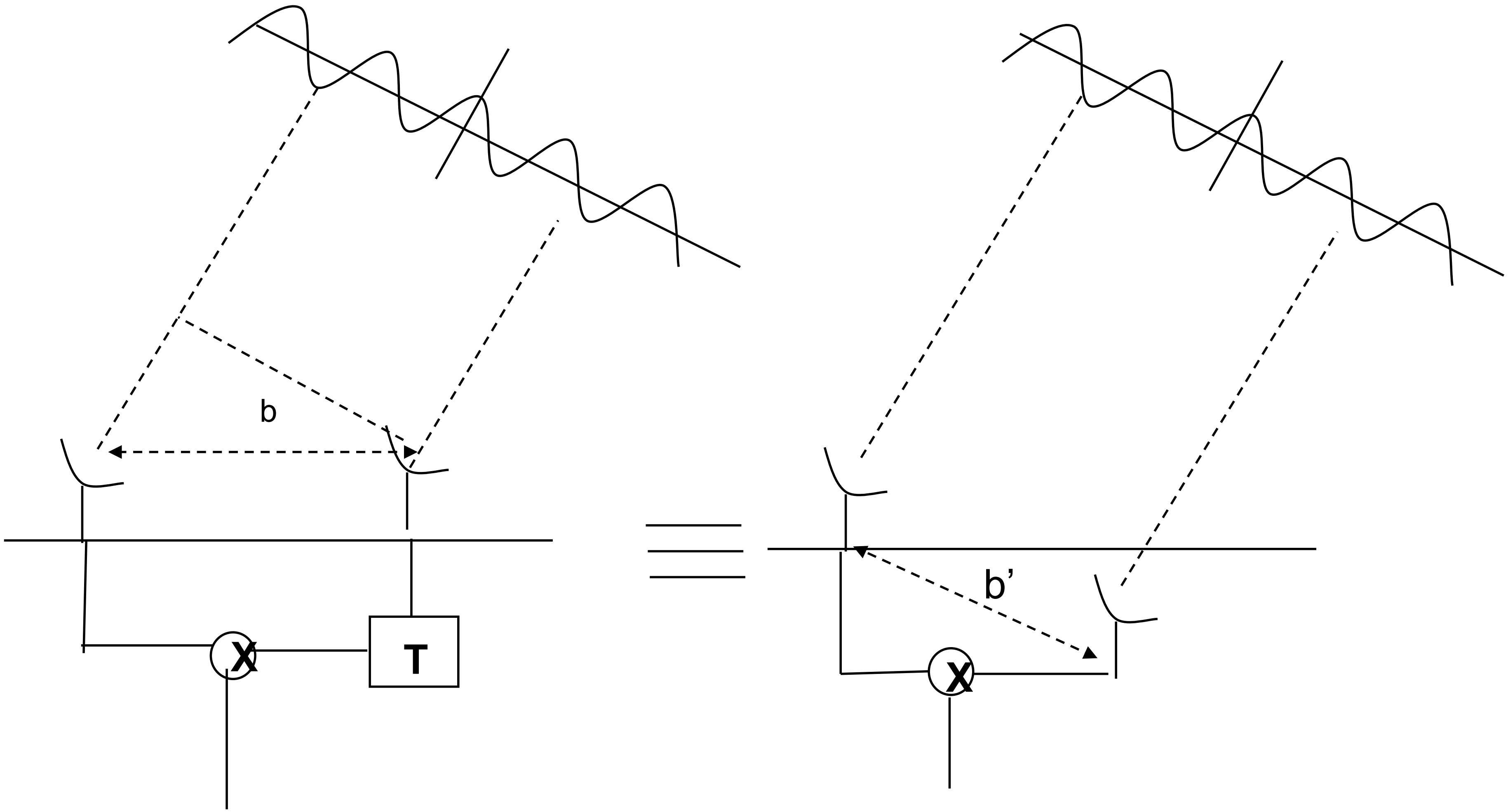
Imaginary part

$$V(u,v) = \int\int I(x,y)\exp(-2\pi i(ux+vy))dxdy$$

Van Cittert – Zernicke theoreom

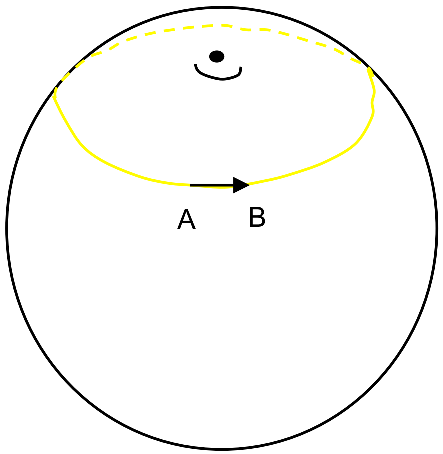
Interferometer outputs 2 numbers, signal in real channel (Vr) and in imaginary (Vi), together give complex visibility V(u,v) – this equals the 2D FT of I(x,y) evaluated at a u,v given by the projected baseline coordinates EW and NS measured in wavelengths. Have many baselines can collect lots of information about the 2D FT of the source.

To observe not at zenith and track source across sky add delay T to compensate extra geometrical path, equivalent to moving an antenna so its in the plane perpendicular to ray



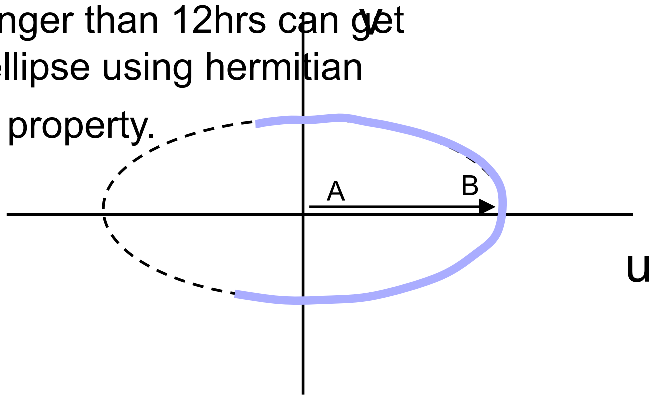
Electronic delay moves centre of fringe pattern so its always centred on the source, and hence ‘tracks’ its position. Fringe spacing on the sky depends on PROJECTED BASELINE measured in wavelengths u = b’/lambda as seen from source. .Rotation of Earth helps us collect more data.

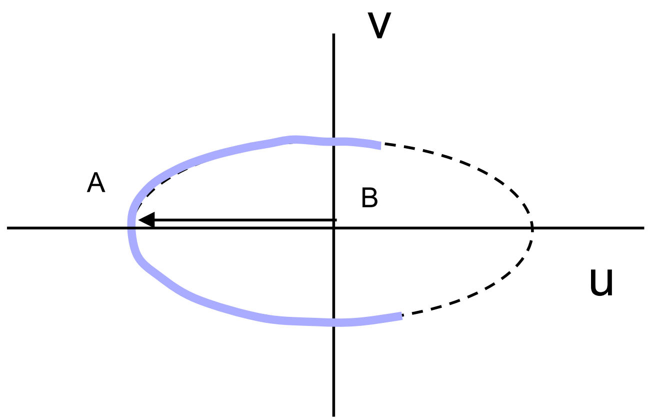
Earth Rotation
East-West baselines
Source at declination
Delta = +30

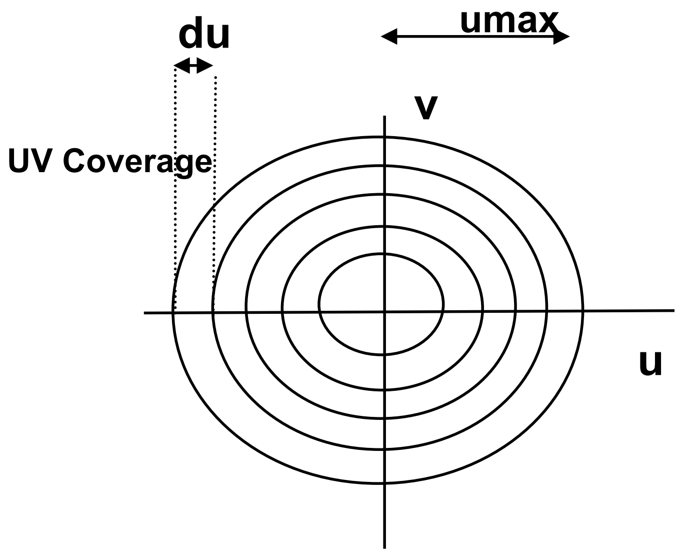


View of East
-West baseline as
Earth rotates

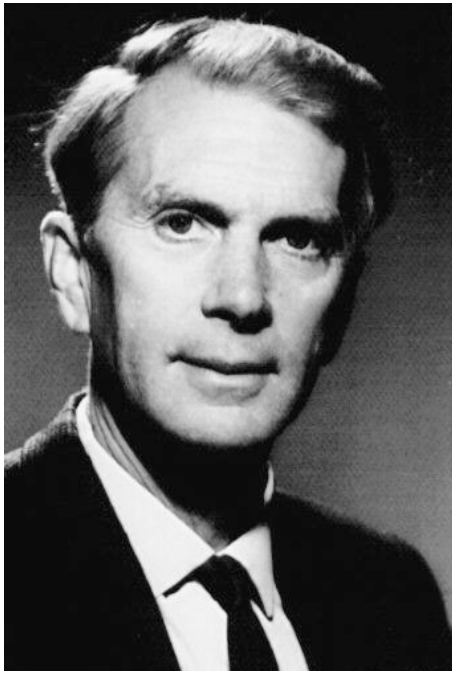
uv tracks are ellipses – squashed by cos(delta), cannot usually observe for 24hrs because most sources not above horizon that long, but if above horizon for longer than 12hrs can get complete ellipse using hermitian property.





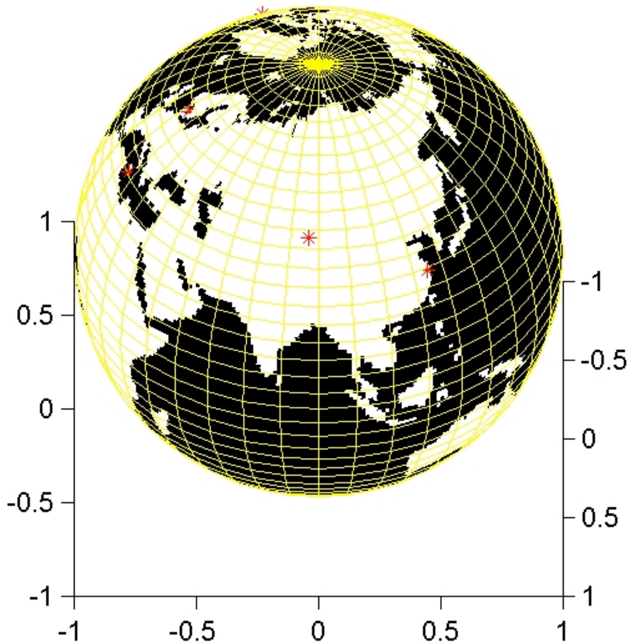


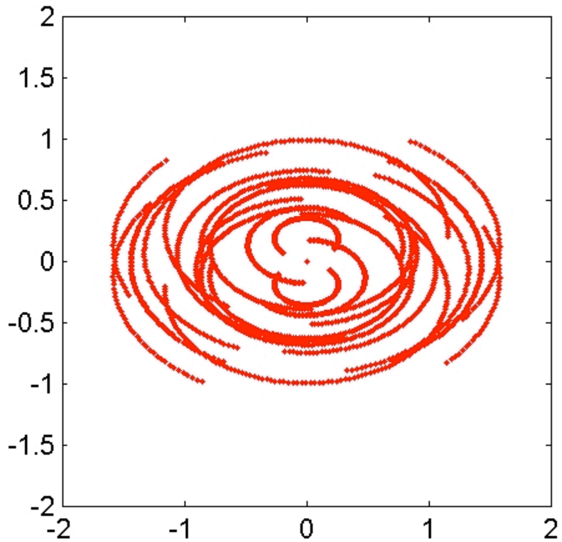
uv coverage and imaging simplest for E-W arrays, but also have some disadvantages



1974 Nobel Prize in Physics to Martin Ryle (Cambridge) for development of Aperture Synthesis

Example – Small VLBI array, gives an irregular uv coverage. Each baseline gives an elliptical track, but not centred on origin.





Interferometry Difficulty 1 - The Inverse Problem

We know how visibility is related to source structure

$$V(u,v) = \bar{I}(u,v) = \int\int I(x,y)\exp(-2\pi i(ux + vy))dxdy$$

If we had complete information on V(u,v) at all u,v then inverting the problem is easy

$$I'(x,y) = \int\int V(u,v)\exp(2\pi i(ux + vy))dudv$$

Unfortunately we don't know value of V(u,v) everywhere.

‘Dirty Imaging’

$V'(u,v) = S(u,v)V(u,v)$

Where $V(u,v)$ is the true visibility $S(u,v)$ the sampling function and $V'(u,v)$ the sampled visibility

The visibility is related to the image via

$V(u,v) = FT(I(x,y))$

If we take the IFT of $V'(u,v)$ then using the convolution theorem we get

$IFT(V') = IFT(S) * FT(V)$

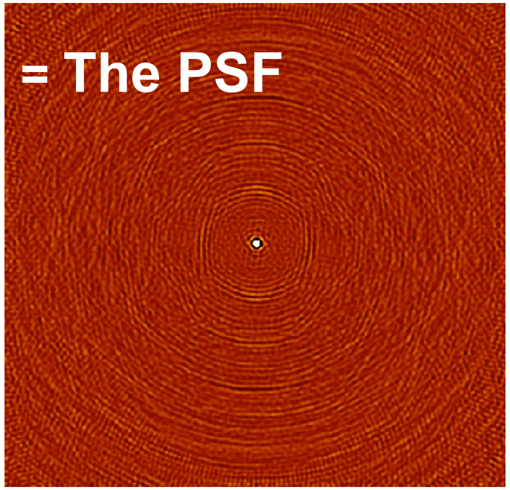
where $*$ indicates convolution

$IFT(V') = B(x,y) * I(x,y)$

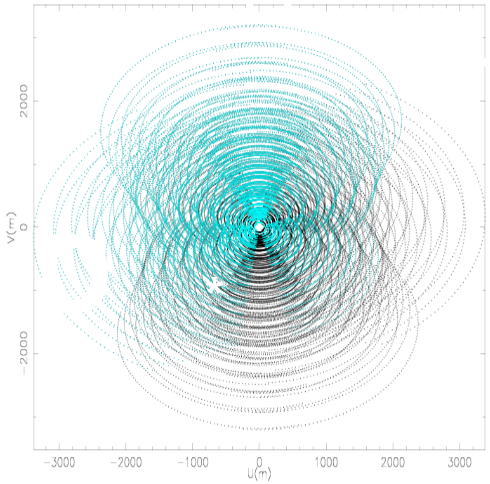
where $B(x,y) = IFT(S(u,v))$ is the 'dirty beam' and $*$ is convolution (copying of the beam, at every point on the source).

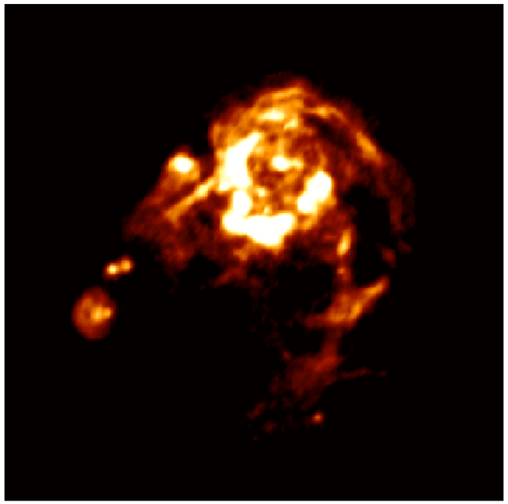
The Dirty Image

Dirty beam

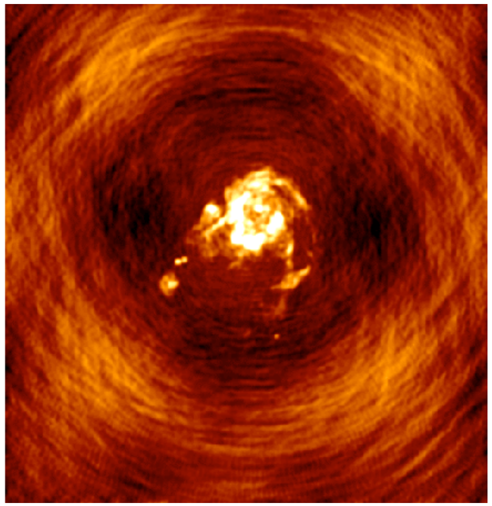


FT



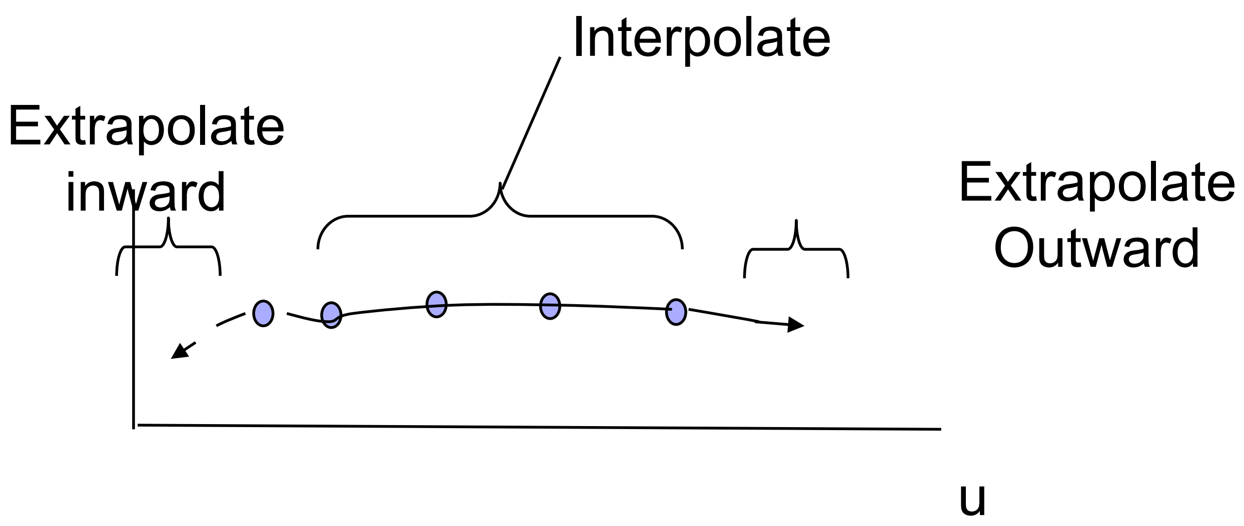


True image



Dirty Image = True Image convolved with dirty beam

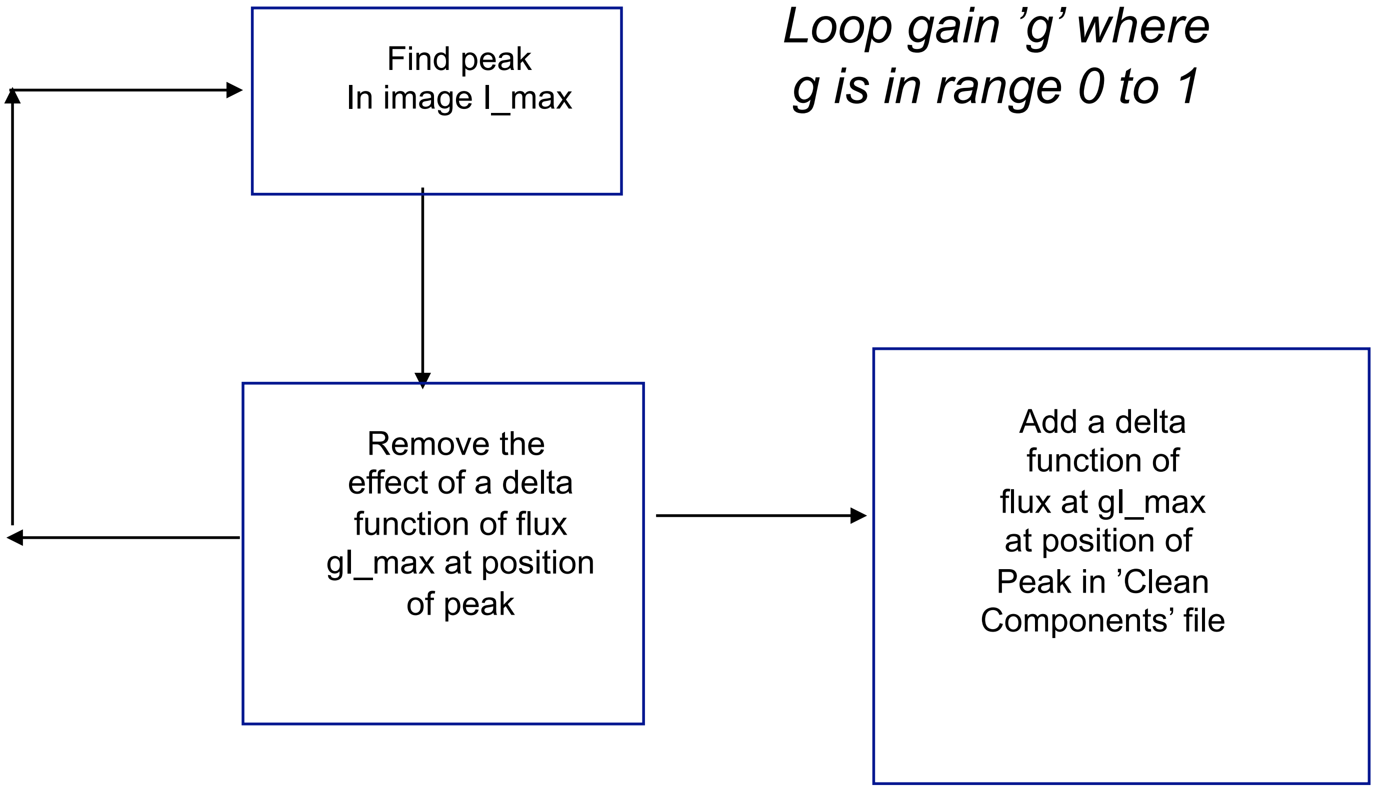
Need for Deconvolution



To improve image further must both ’interpolate between measured visibilities and ’extrapolate’ beyond outer edge and into inner hole. ’Interpolation’ removes effects of far sidelobes and the ’Extrapolation’ that of Inner sidelobes and central bowl.

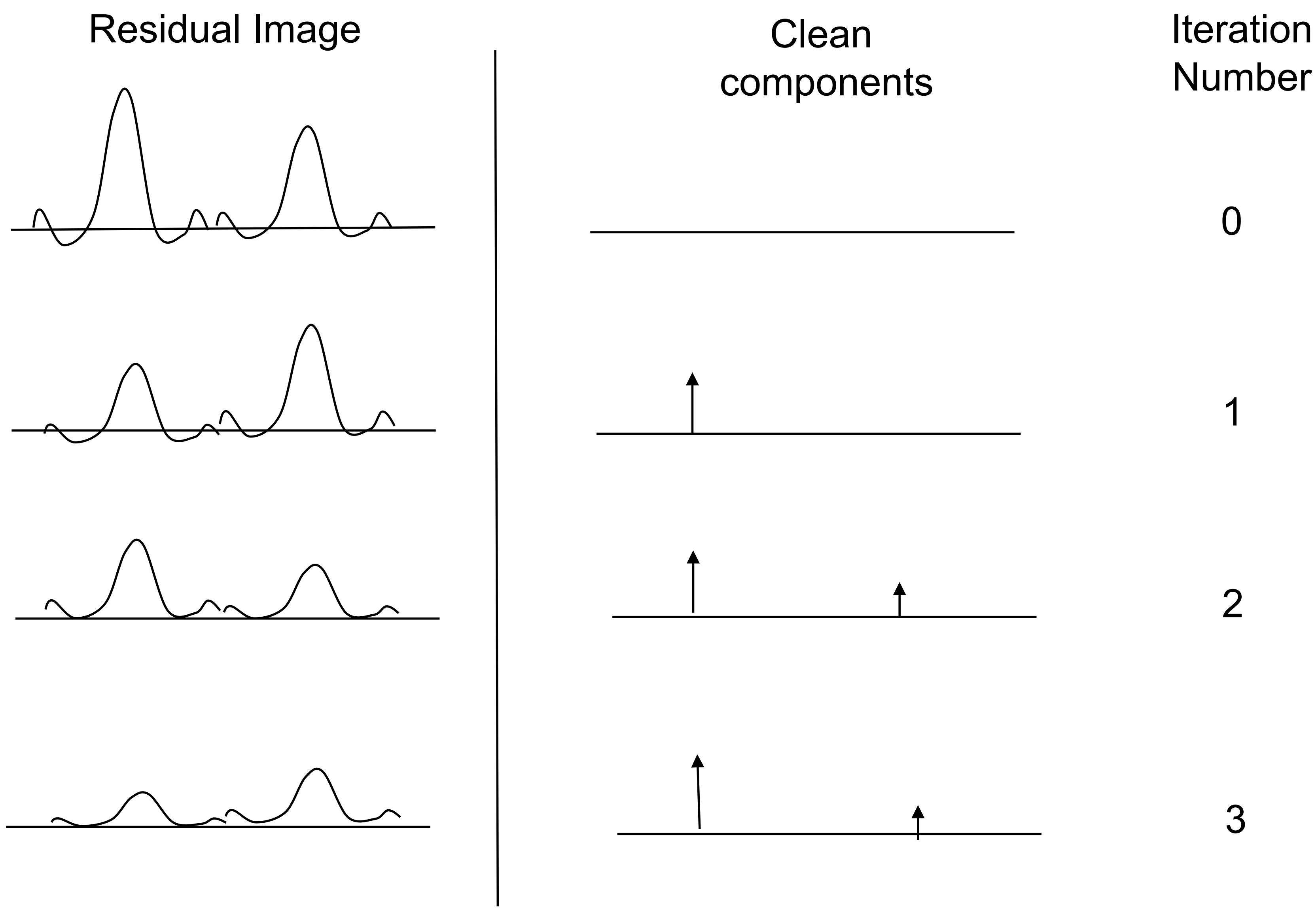
CLEAN Algorithm (Nordic invention Högbom 1974 – one of top 10 cited AA papers)

Loop gain 'g' where g is in range 0 to 1



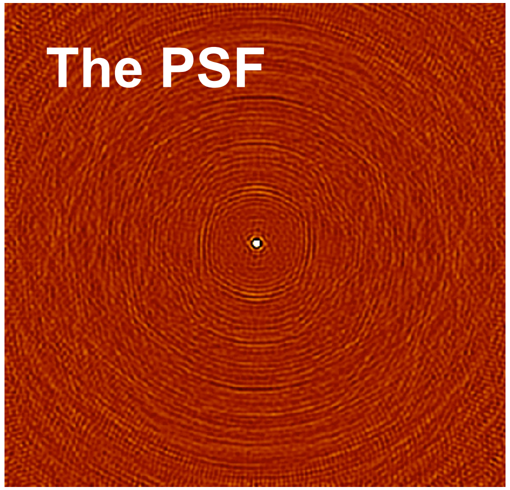
Interate until nothing but noise is left in 'residual' Image- usually convolve 'clean components' by a gaussian 'restoring' beam

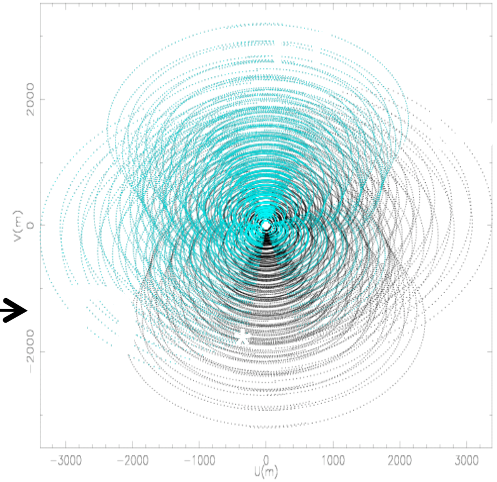
Example – in ID, Gain = 0.5

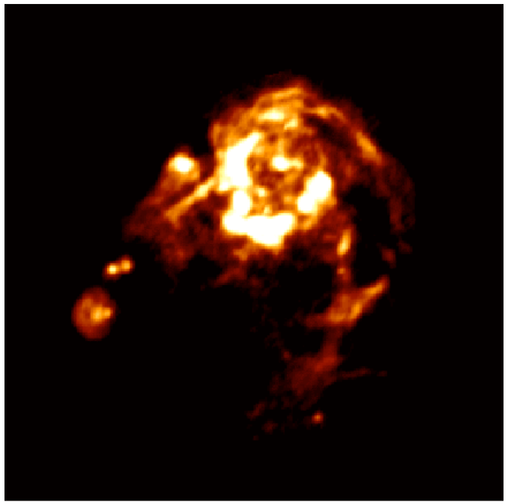


The Dirty Image

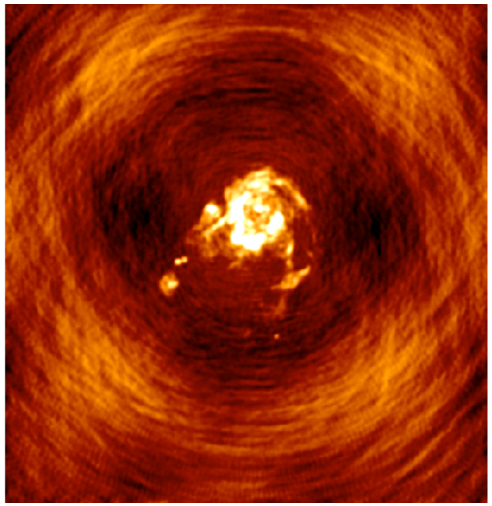
Dirty beam







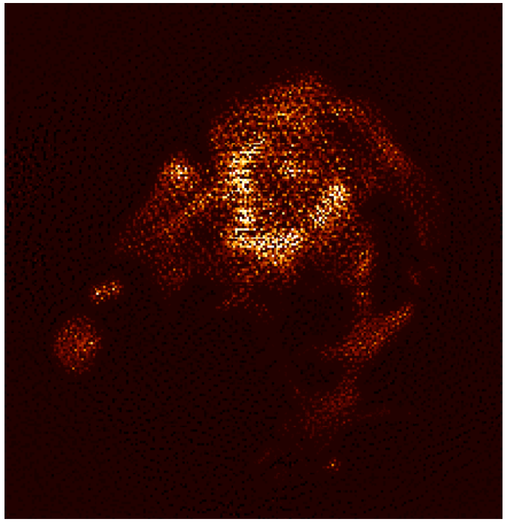
True image

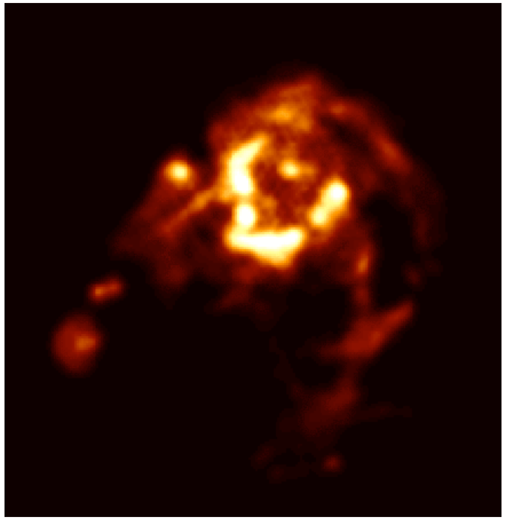


Dirty Image

Clean: Example

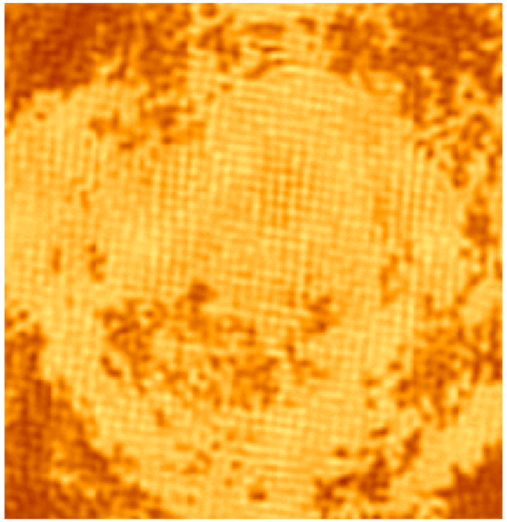
Clean components found

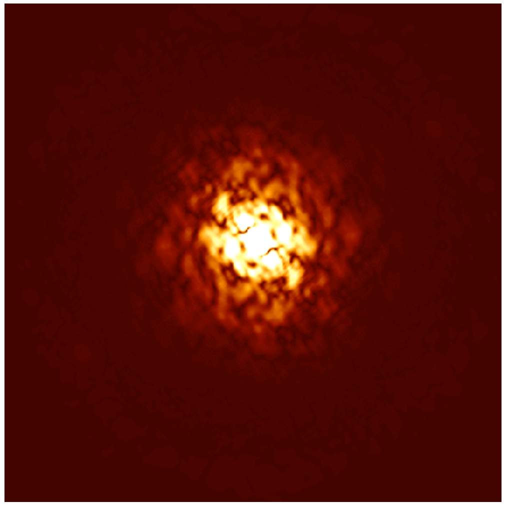




Clean components convolved with Gaussian ‘restoring beam’ (X=FWHM), our estimated source structure at resolution X

FT of Clean components, model visibility

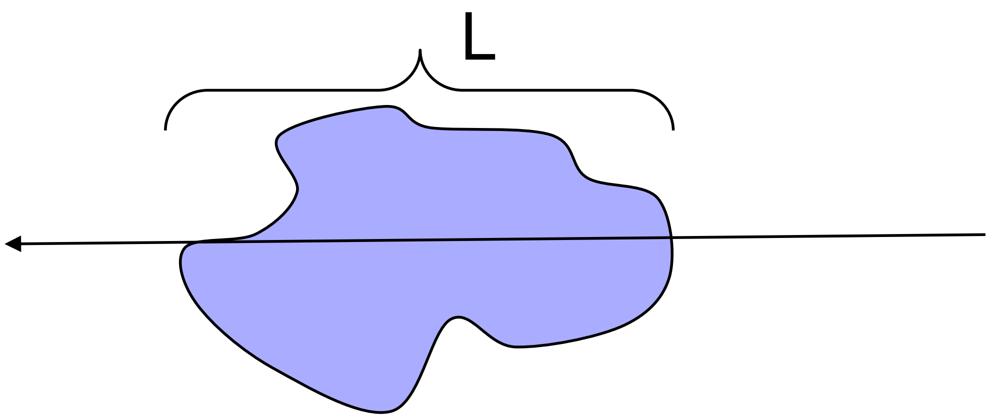




FT of restored image

Interferometry Difficulty 2 – Phase errors

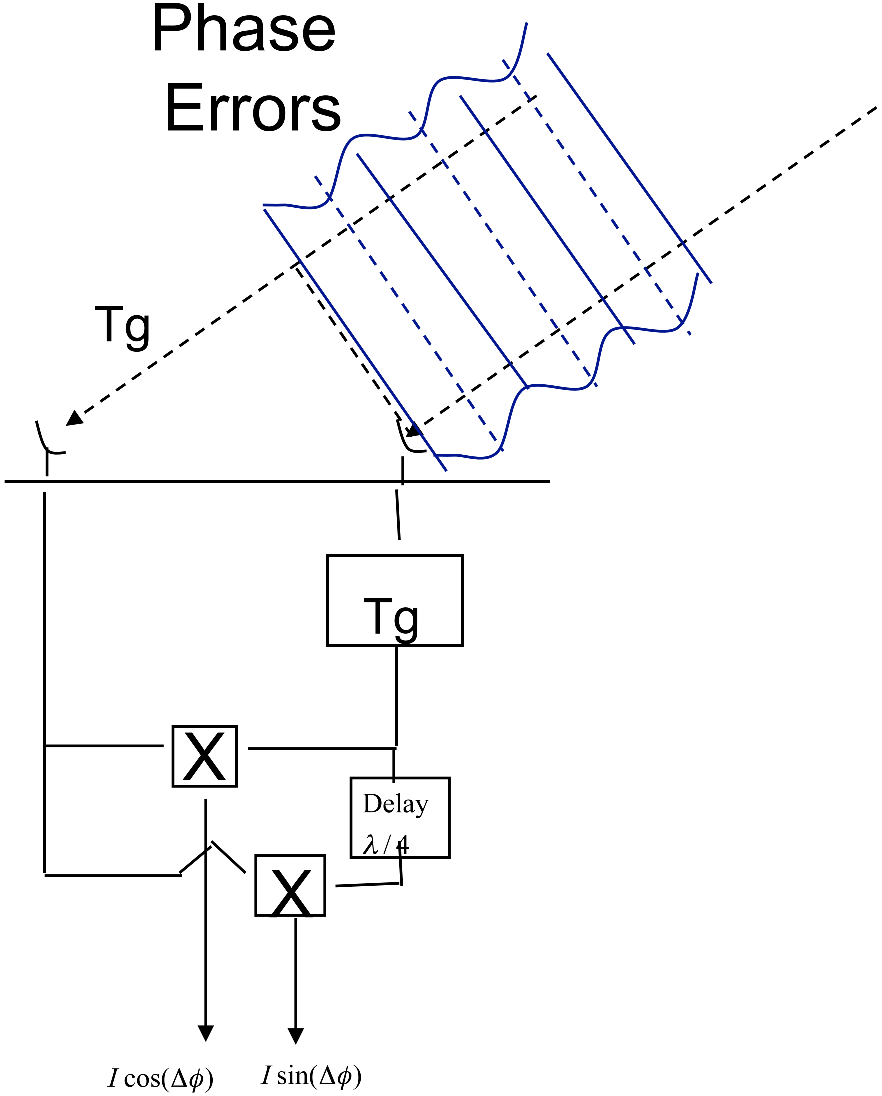
Clouds of water vapour in atmosphere or ionised gas in ionosphere cause the 'refective index' (n) for radio waves to be different from 1, hence radio waves travel slightly slower than the speed of light by a factor 1/n.



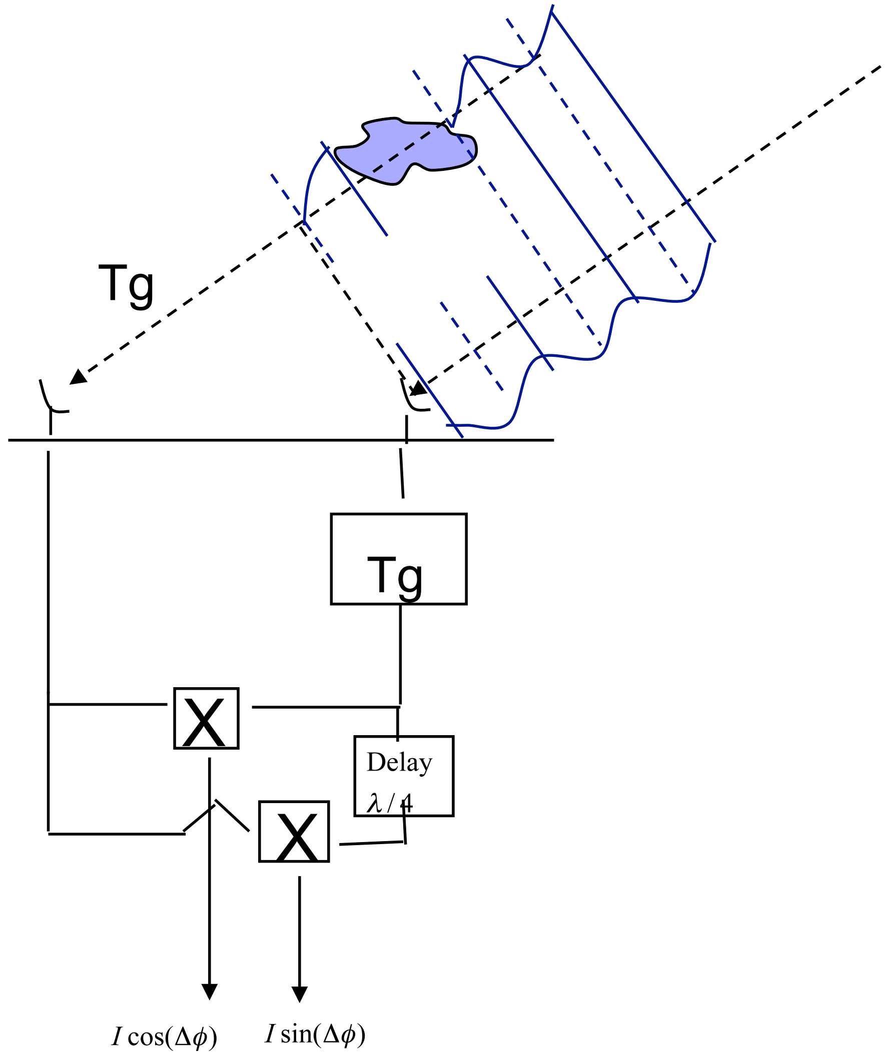
A ray passing a length L through a cloud causes a change in phase compared to free space propogation of

$$\Delta\phi = 2\pi L(n-1)/\lambda$$

Phase Errors

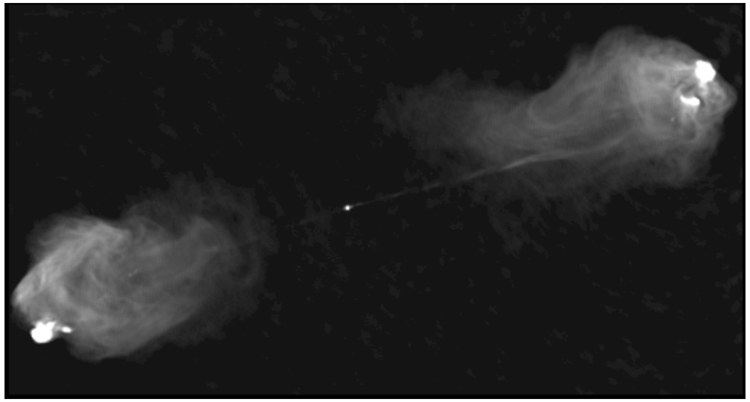


Visibility output depends on relative Phase of E-field on wavefront, in this case zero.



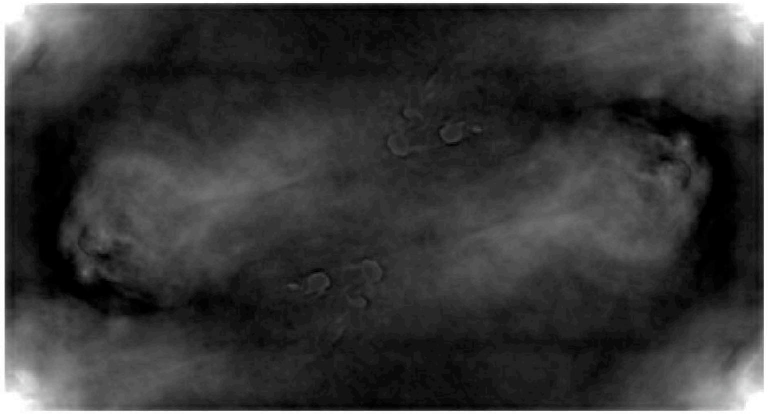
If there is cloud above one antenna which delays signal then relative phase of E-field on wavefront and hence visibility phase effected

True Image

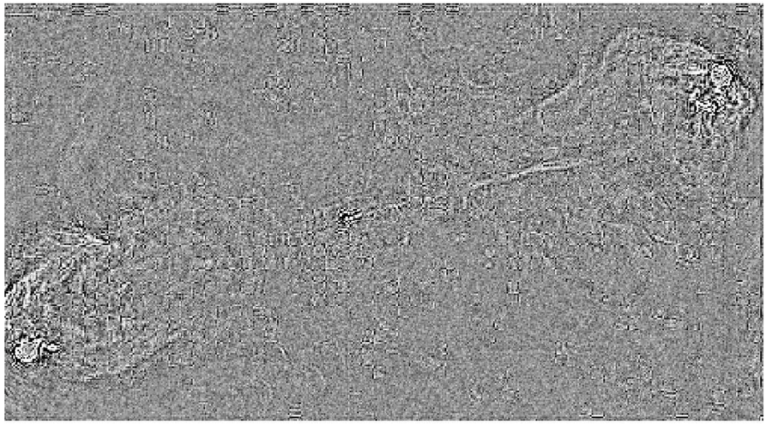


Fourier Phase
Is more important than
Amplitude for
finding source
structure

Reconstruction from FT
amplitude



Reconstruction from FT
phase



Closure Phase

Consider the measured phase of the visibility θ' and the true phase of the visibility θ on each baseline

$$\theta'_{12} = \theta_{12} + \Delta\phi_1 - \Delta\phi_2$$

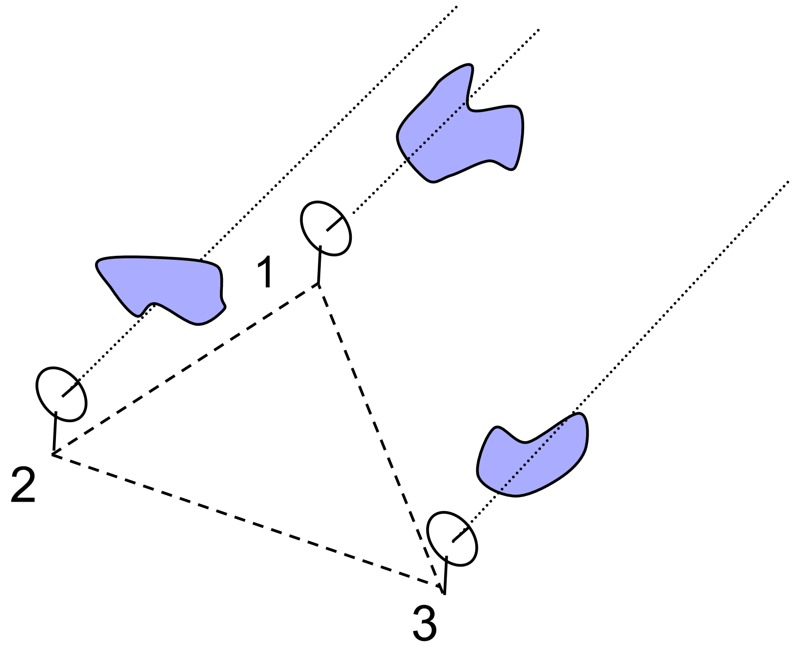
$$\theta'_{23} = \theta_{23} + \Delta\phi_2 - \Delta\phi_3$$

$$\theta'_{31} = \theta_{31} + \Delta\phi_3 - \Delta\phi_1$$

We can form a 'closure phase' by adding the phase on a closed loop of baselines

$$C_{123} = \theta'_{12} + \theta'_{23} + \theta'_{31} = \theta_{12} + \theta_{23} + \theta_{31}$$

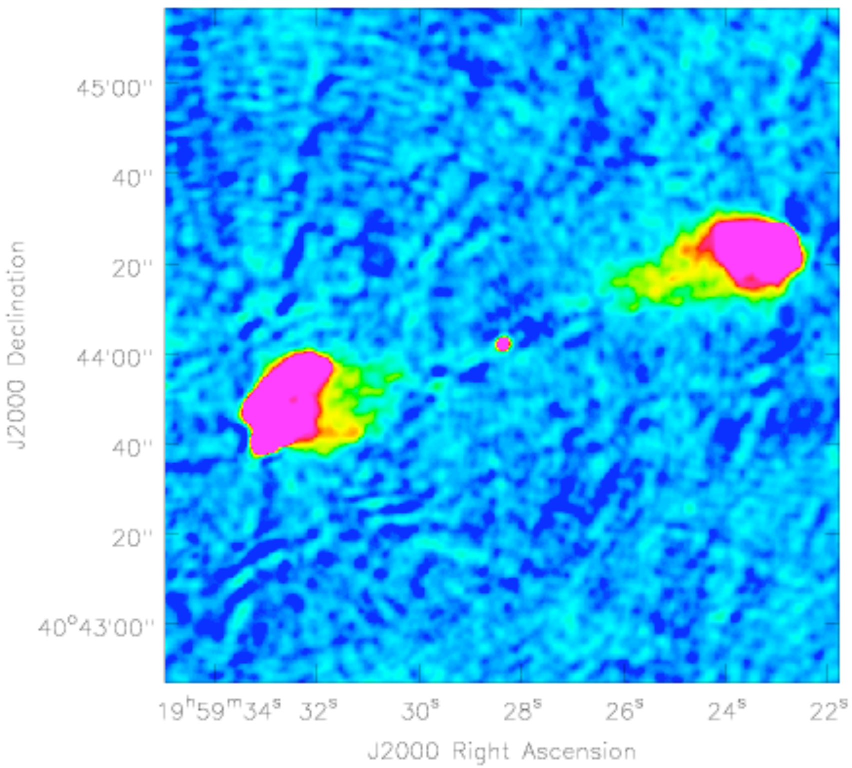
This 'Closure phase' depends only on the source structure and is independant of the atmosphere!



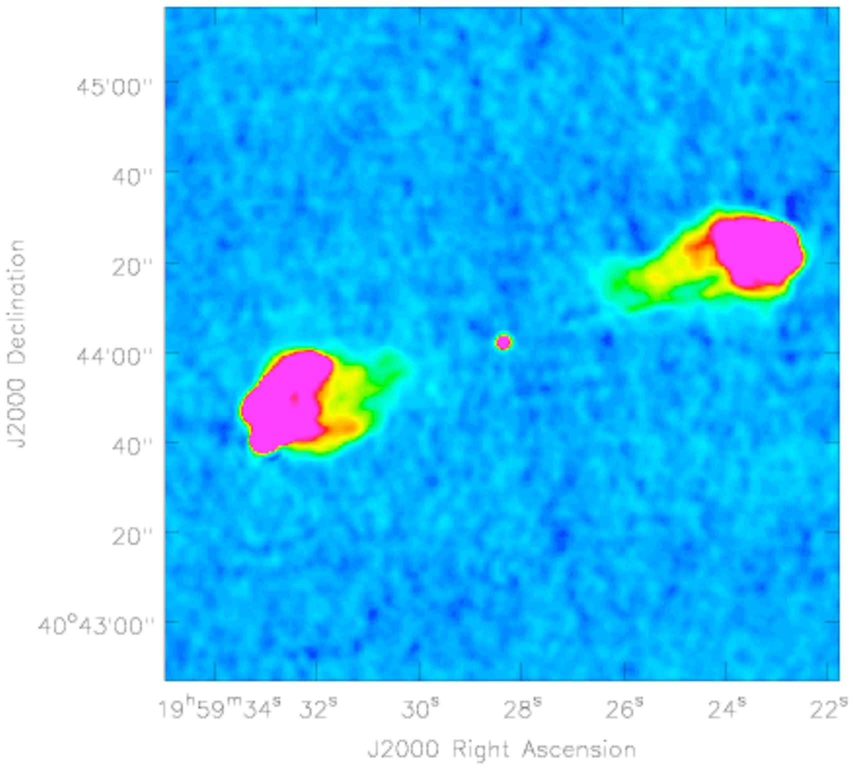
(Re)discovery of closure phase idea made maging on baselines >5km possible. Two approaches – closure phase, combine measurements to make quantity independent of atmosphere, or solve explicitly for antenna-based phase errors and correct – must be done at same time we deconvolve, needs iterative methods

Image without self-calibration

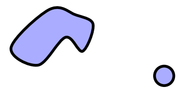
- Phase calibration using nearby source observed every 20 minutes
- Peak ~ 22Jy
- Display shows -0.05Jy to 0.5Jy

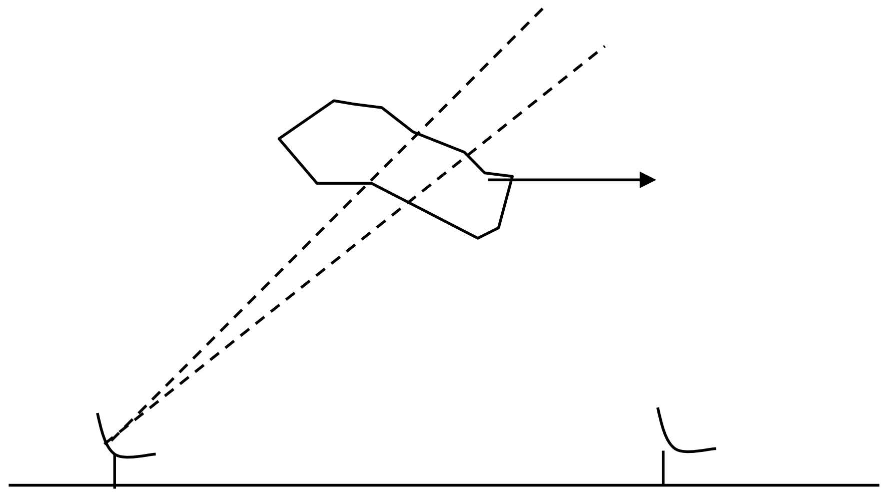


After 4 amplitude and phase calibrations



Phase Referencing/Fast Switching





To work need a bright target, if our target weak wwitch back an forth every few minutes between the target source and nearby (few degrees away) bright, compact calibrator.Use self-cal methods to estimate atmospheric phase/amplitude toward calibrator source (which is bright and often simple) – interpolate in time and apply these corrections to data for a target source (which is maybe weak and complicated).

A differentially rotating disc in a high-mass protostellar system

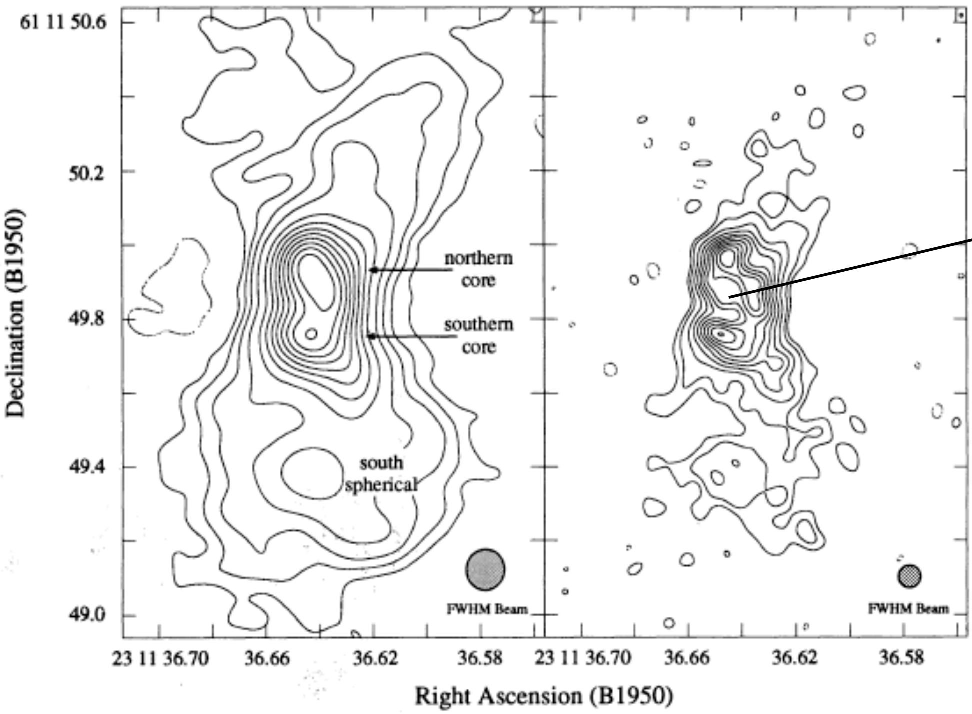
M.R. Pestalozzi[1], M. Elitzur[2], and J.E. Conway[3]

[1] Dept of Physics, University of Gothenburg, S-412 96, Göteborg, Sweden
e-mail: michele.pestalozzi@physics.gu.se
[2] Dept of Physics and Astronomy, Univ. of Kentucky, Lexington, KY 40506-0055, USA
e-mail: moshe@pa.uky.edu
[3] Onsala Space Observatory, S-439 92 Onsala, Sweden
e-mail: john.conway@chalmers.se

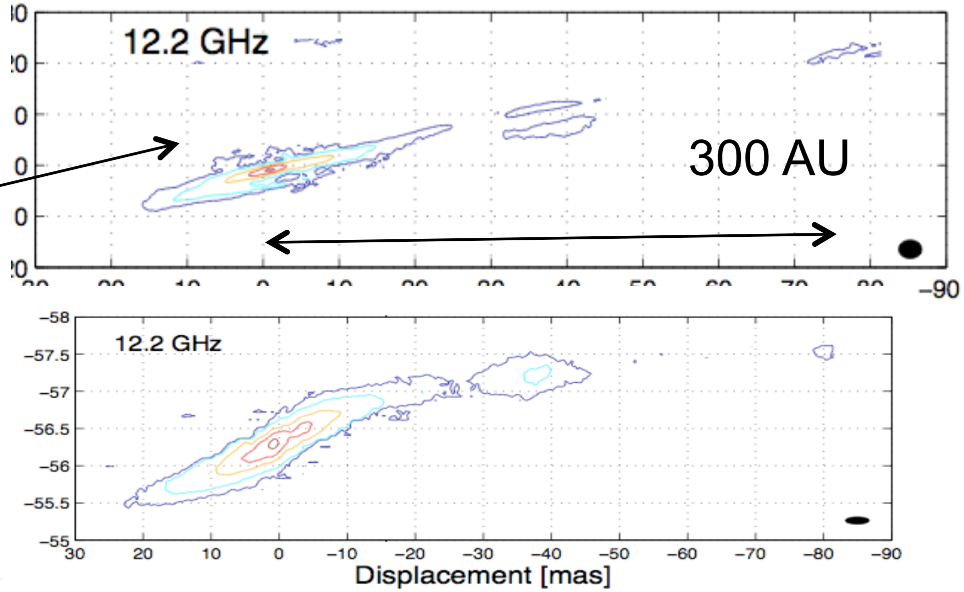
Preprint online version: March 25, 2009

Pestalozzi, Elitzur, Conway, 2009 arXiv:0904.3722

Model linear methanol feature as Keplerian rotating disk around a 30Msol protostar- Massive stars form in same was as low mass stars by accretion disks.



NGC7538-IRS1N VLA obs



VLBI methanol maser observations ¨1mas resolution