



Introduction to Radio Interferometry

Anna Kapinska (NRAO)

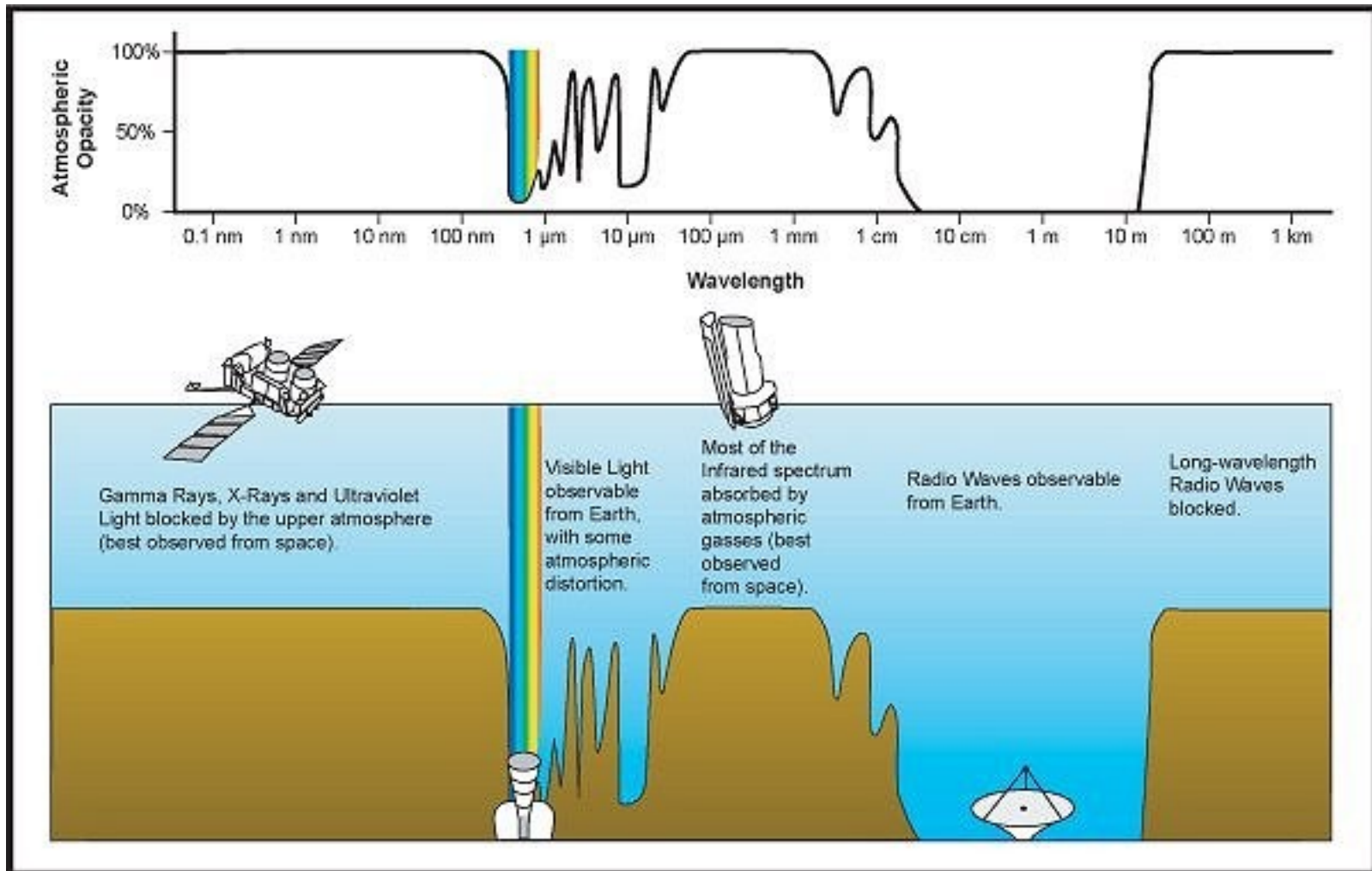
slides courtesy of Frank Schinzel (NRAO)



Radio Astronomy

ALMA VLA

VLBA

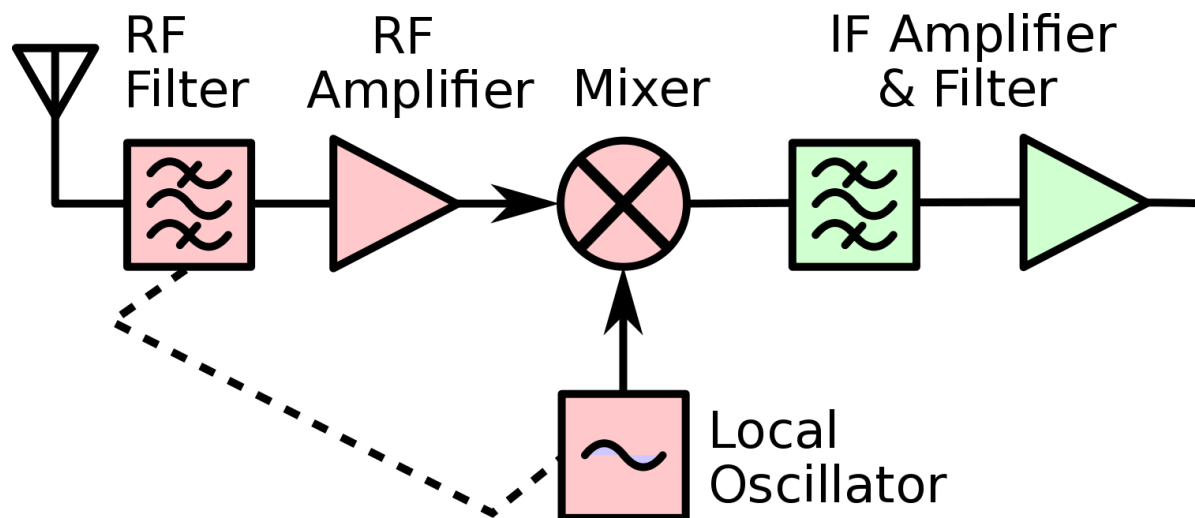


NASA/IPAC

Heterodyne Receiver (1901 -)

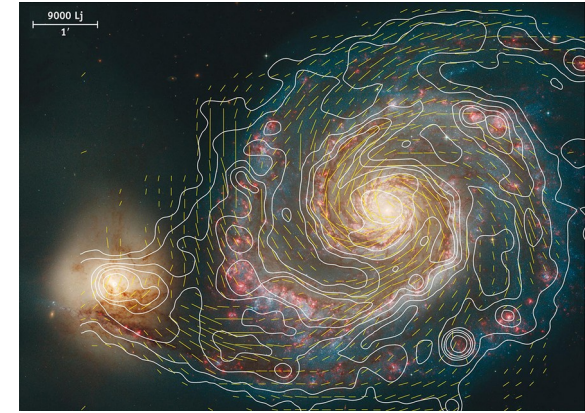
Observed sky frequencies are converted to lower frequency signals by mixing with a signal artificially created by a Local Oscillator.

The output can then be amplified and sampled easily while retaining original **phase and amplitude** information.



Mapping the Sky in Radio Astronomy

- In astronomy, we wish to know the angular distribution of electromagnetic emission.
- ‘Angular Distribution’ means we are interested in the **brightness** of the emission, not just the **flux density**.
- Measuring the brightness means making a map.
- Our targets are distance, the emission is extremely weak.
- Early radio surveys employed single dishes.
- **Nowadays, most (but not all!) radio telescopes are interferometers.**

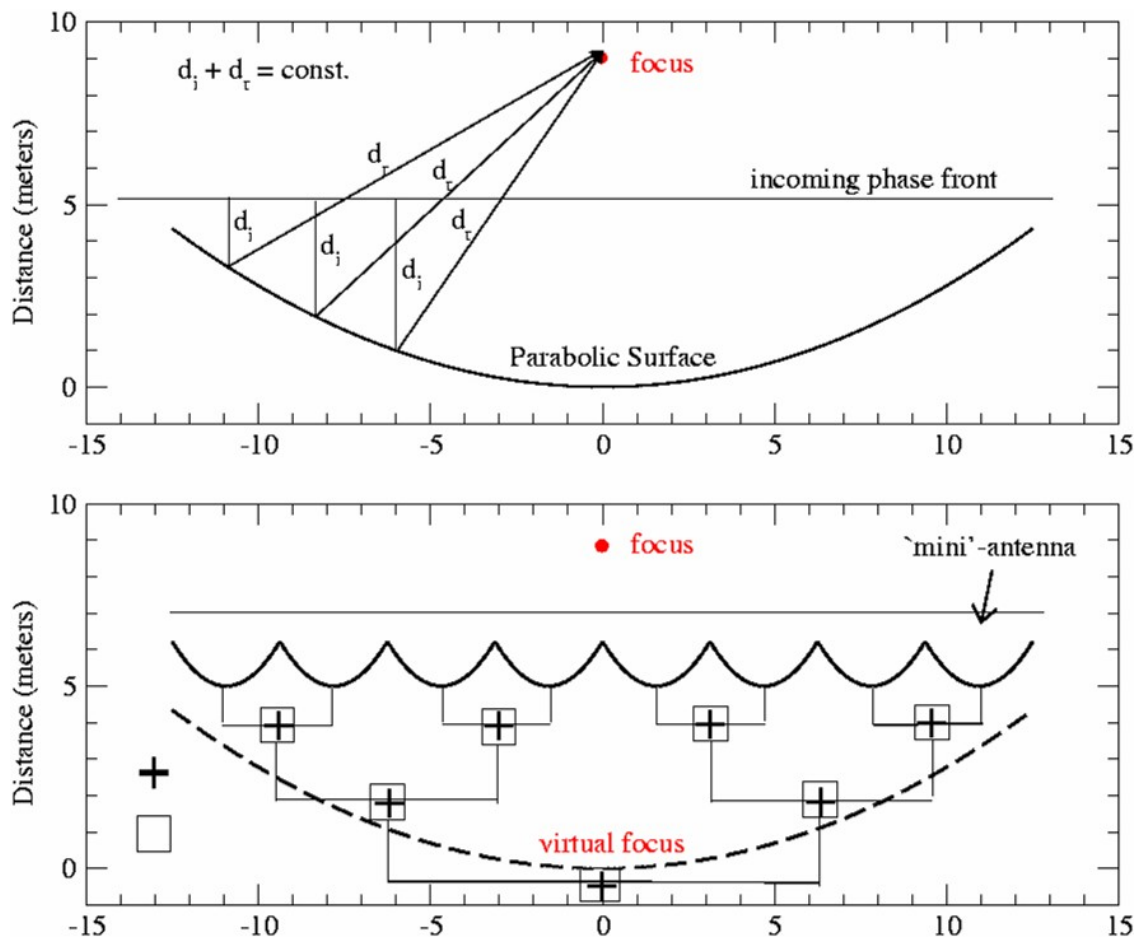


Why Interferometry?

- It's all about **Diffraction** – a consequence of the wave nature of light.
- Radio telescopes coherently sum electric fields (**E**) over an aperture of size D . Applying the diffraction theory the angular resolution of 1 arcsecond at a 21 cm wavelength requires an aperture of ~ 42 km!
- The largest single, fully-steerable aperture are the 100-m antennas in Effelsberg and Green Bank, and non-movable 300-m FAST telescope in China. Nowhere big enough.
- **Solution: Synthesize an aperture of that size with pairs of antennas!**

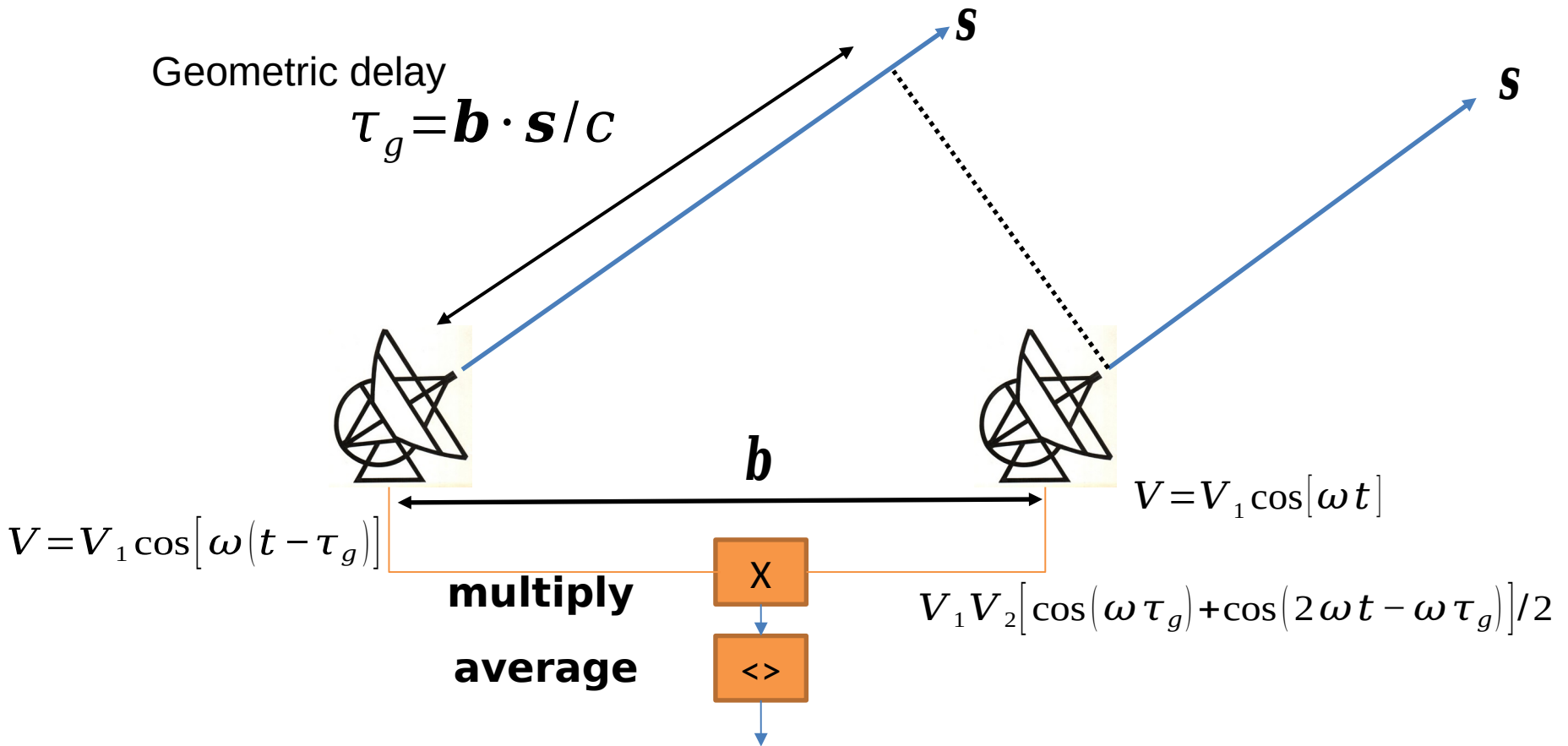
Interferometry - Basic Concept

- A parabolic dish coherently sums **EM** fields at its focus.
- The same result can be achieved by combining voltages of multiple smaller dishes in a network.
- This is the basic concept of interferometry. Aperture Synthesis is an extension of this concept.



Stationary, Monochromatic Interferometer

- A small (but finite) frequency width, and no motion.
- Consider radiation from a small solid angle, from direction \mathbf{s} .

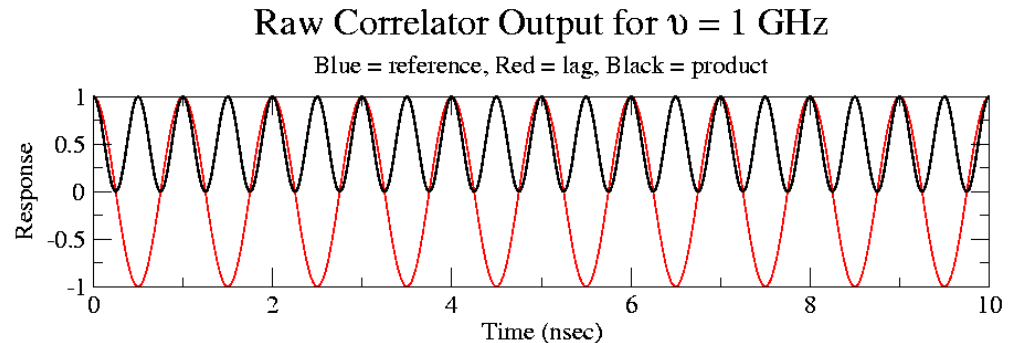


Examples of the Signal Multiplications

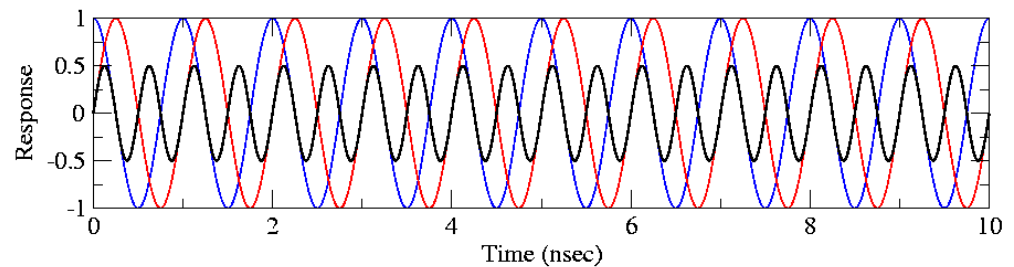
The two input signals are shown in **red** and **blue**.

The desired coherence is the average of the product (black).

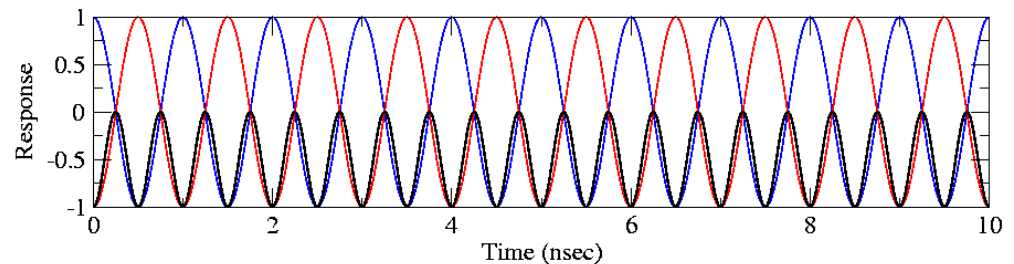
In Phase:



Quadrature Phase:



Anti-Phase:



Complex Visibility

“Visibility is a complex quantity, [...] an unnormalised measure of the coherence of the Electric field, modified to some extent by the characteristics of the interferometer.”

Lecture 2, White Book

- Combine the cosine and sine responses (two independent correlator outputs) to form the complex visibility:

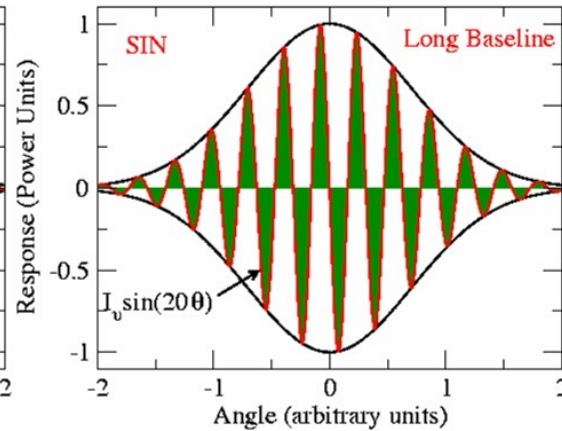
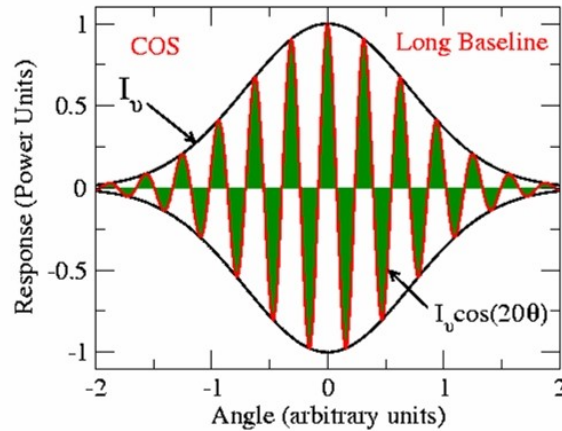
$$V = R_c - iR_s = Ae^{-i\phi}$$

- where the amplitude is: $A = \sqrt{R_c^2 + R_s^2}$
- where the phase is: $\phi = \tan^{-1}(R_s/R_c)$
- This also gives the relationship between the source brightness, and the response of an interferometer:

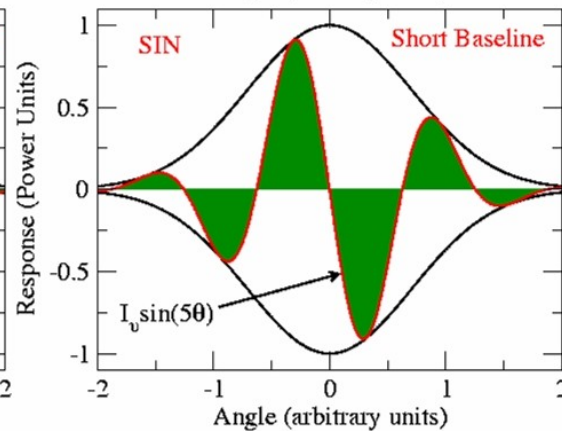
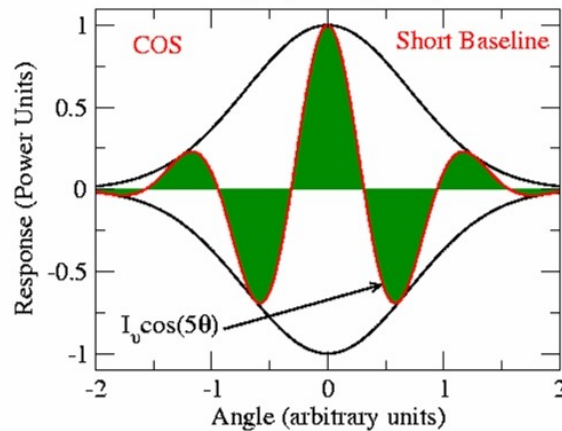
$$V(\mathbf{b}) = R_c - iR_s = \iint I_\nu(s) e^{-2\pi i \nu \mathbf{b} \cdot \mathbf{s} / c}$$

Visualizing the Visibility

The intensity (black), the 'fringes' → measured interference pattern (red).
The visibility is the net dark green area.



Long
Baseline



Short
Baseline

Fourier Transform

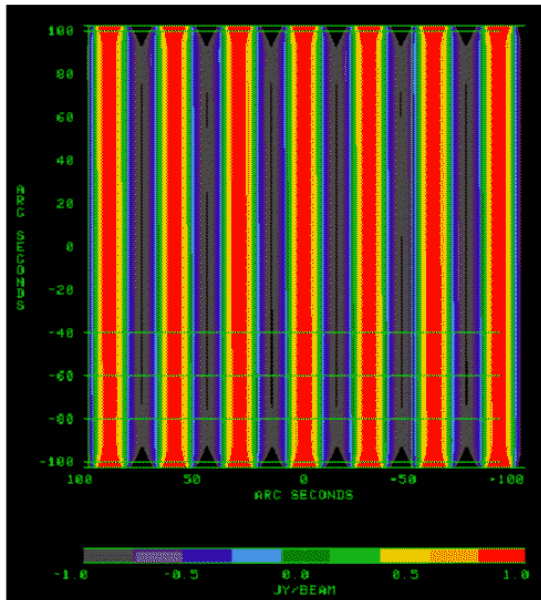
Relate measured interference pattern (fringes) to the radio intensity on the sky.

- A radio interferometer measures the **interference pattern** (fringes) produced by pairs of apertures.
- The **fringe pattern** is directly related to the source brightness, where for small field-of-view: the complex visibility, $V(u,v)$ is the 2D Fourier transform of the brightness on the sky.

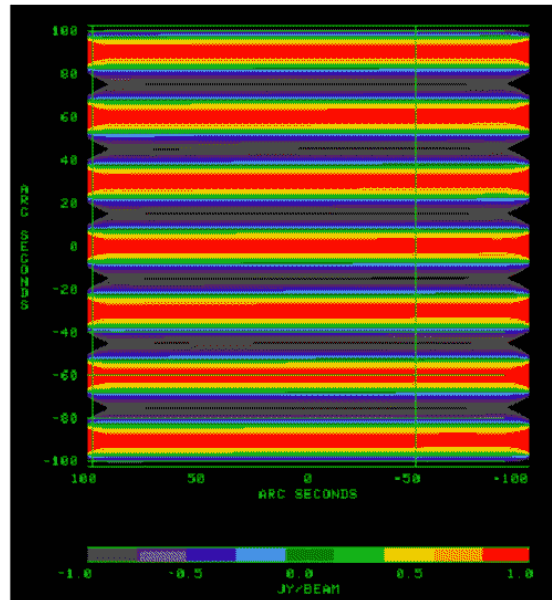
(Van Cittert-Zernike theorem)

Real Fringes

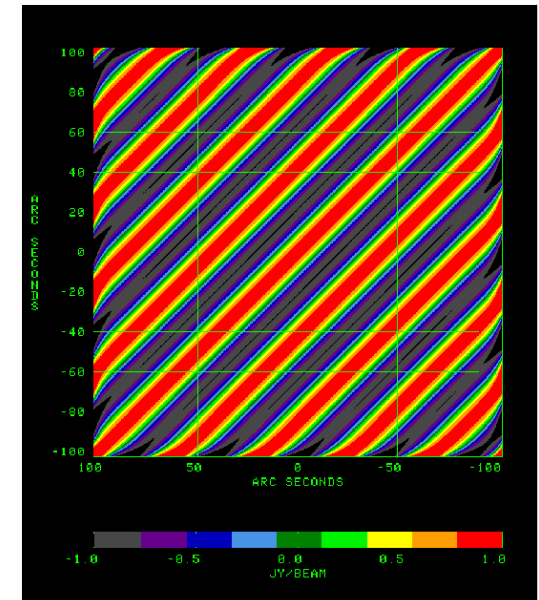
The fringe separation is given by baseline length in wavelengths
The orientation is given by the orientation of the baseline



East-West baseline
makes vertical fringes



North-South baseline
makes horizontal fringes



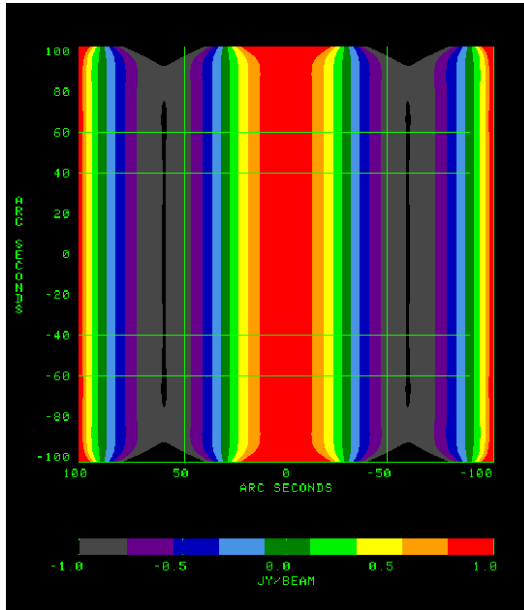
Rotated baseline
makes rotated fringes

Fringe angular spacing given by baseline length in wavelengths:

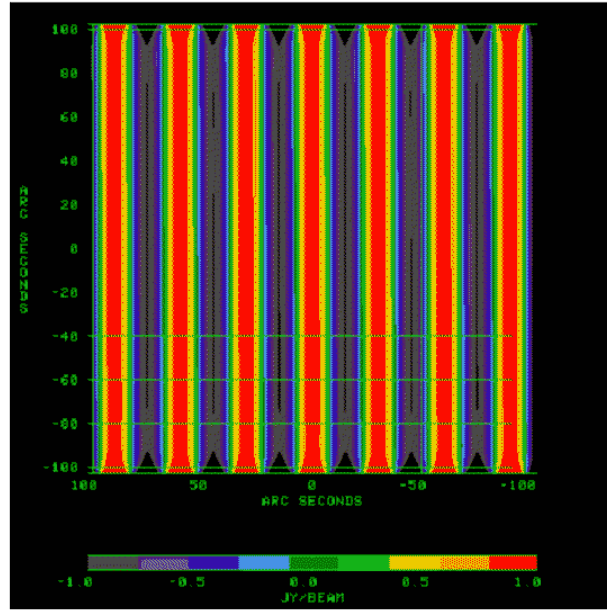
$$\Delta\theta = \lambda/b$$

Longer Baselines → Smaller Fringes

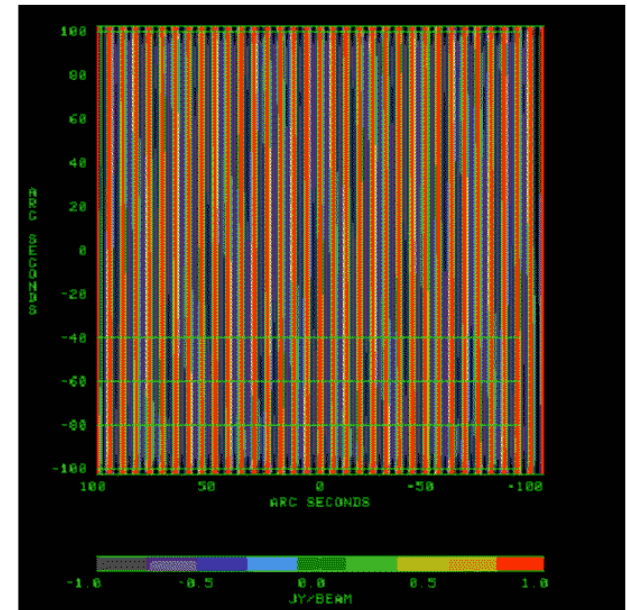
With longer baselines (**in wavelengths!**) come finer fringes:



250 meter baseline
120 arcsecond fringe



1000 meter baseline
30 arcsecond fringe

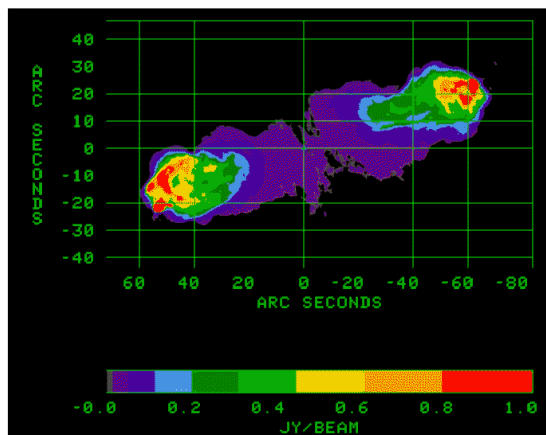


5000 meter baseline
6 arcsecond fringe

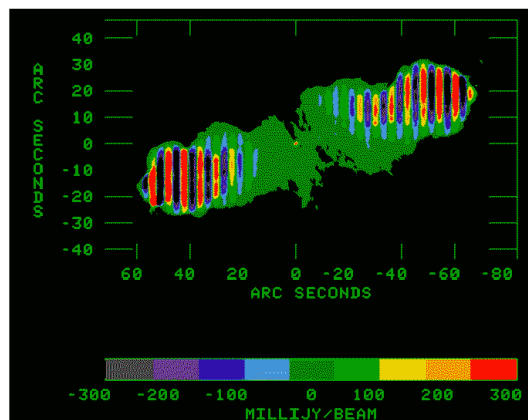
What the interferometer measures is the integral (sum) of the product of this pattern with the actual brightness.

Cyg A Fringe example

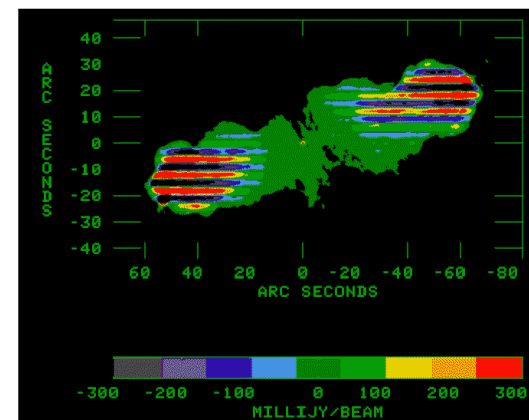
- Cygnus A is a powerful, nearby radio galaxy.
- The left panel shows the actual brightness.
- The other two panels show how the 5km-baseline interferometer 'sees' it



Zero-spacing
Image
Sum = 999 Jy



5 km EW spacing
Sum = 61 Jy



5 km NS spacing
Sum = -16 Jy

Visibility to Image Space

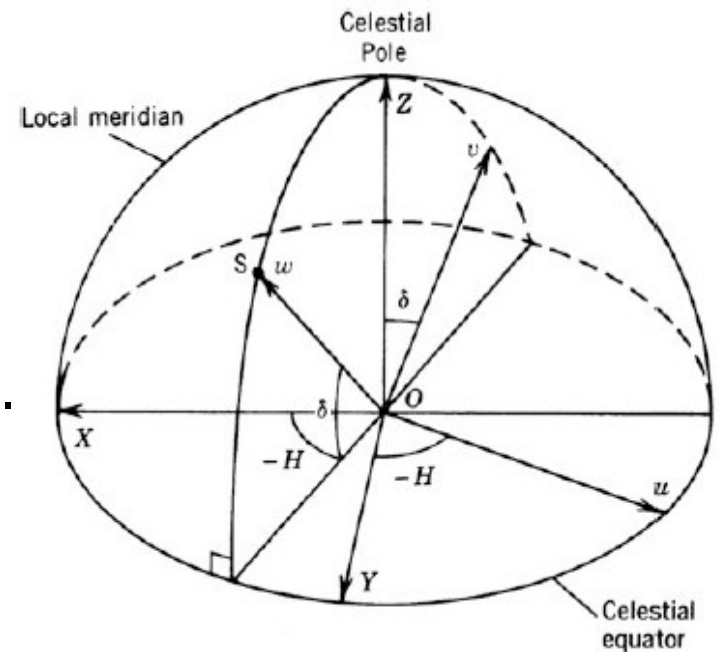
- Fourier Space (u,v,w) – right handed coordinate system:

$$\overset{\text{visibility}}{\nearrow} V(u,v,w) = \iiint I(x,y,z) \overset{\text{brightness}}{\nwarrow} e^{2\pi i(ux+vy+wz)} dx dy dz$$

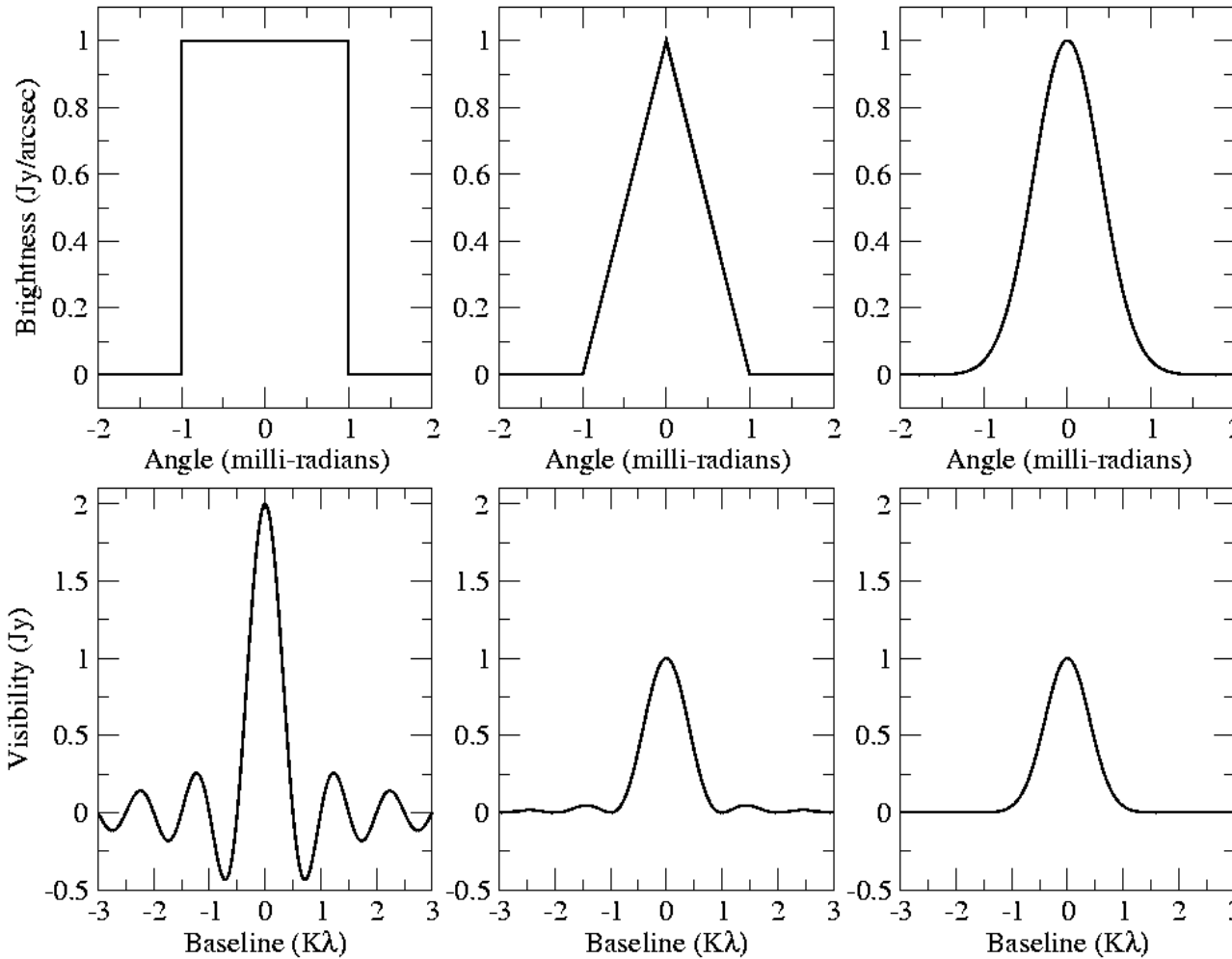
- Image Space (x,y,z)

Can simplify and drop w(z) term
(when coplanar, can't do for wide fields).

*(a lot more information can be found in
e.g. Thompson, Moran & Swenson)*



Visibility and Brightness in 1D

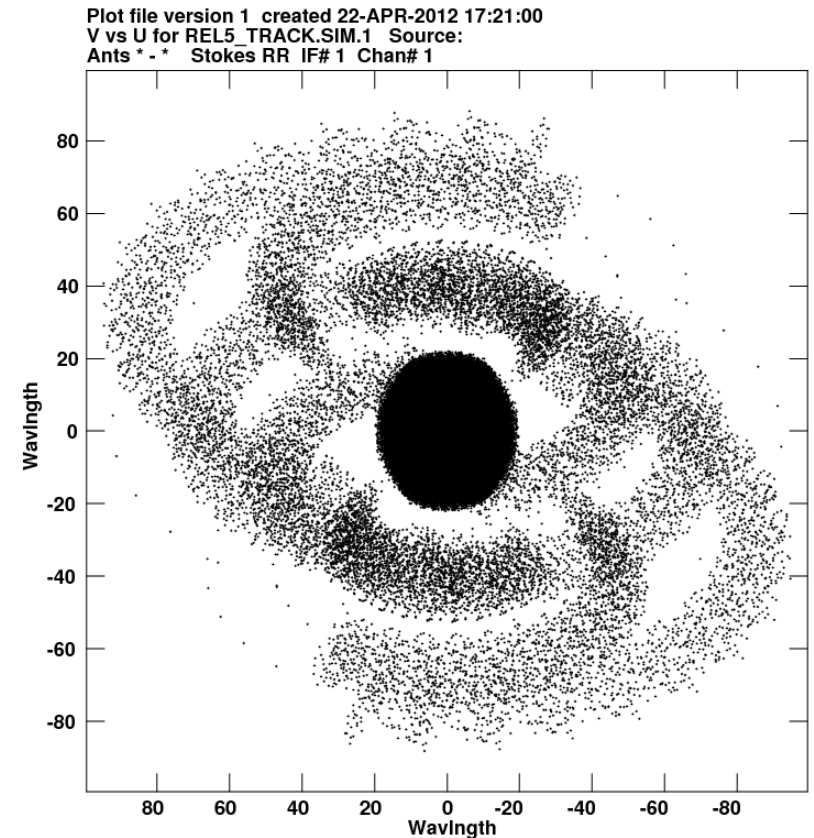
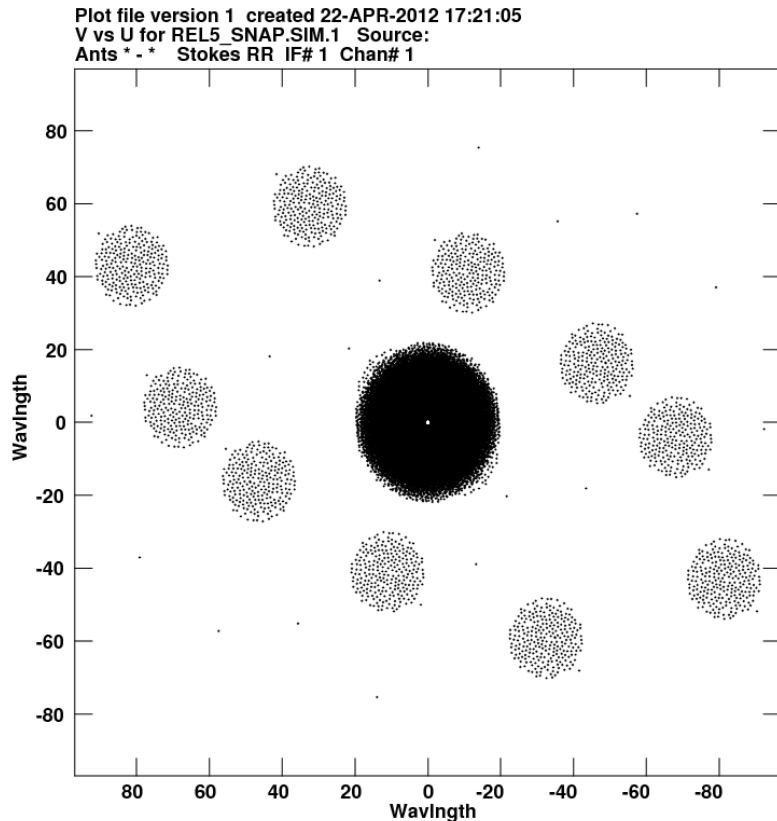


Input:
Even brightness
distributions.

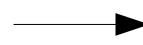
Output:
Real, even
visibility functions.

Filling the Fourier Plane in 2D

Earth Rotation Synthesis



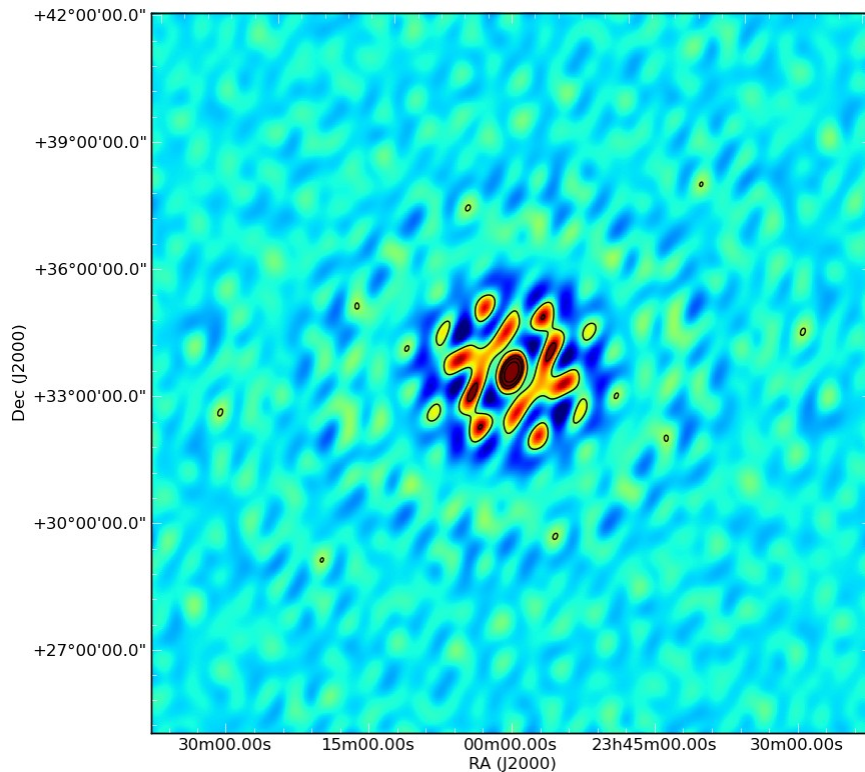
Snapshot (u,v)-coverage



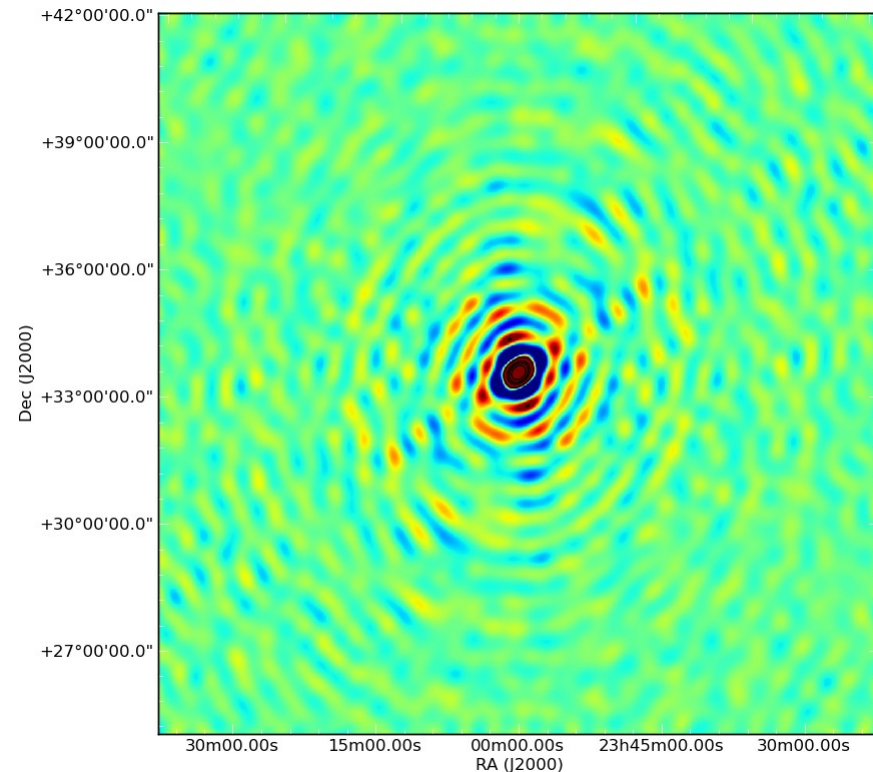
12 hour track (u,v)-coverage

Making Images (FT)

sky + interferometer response



Snapshot dirty image



12 hour track dirty image

Uniform weighting scheme of intensities.

Making Images - Deconvolution

Limited sampling of the (u,v) plane causes defects in the FT images.

“The ‘CLEAN’ algorithm is most commonly used in radio interferometry to solve the convolution equation by representing a radio source by a number of point sources in an otherwise empty field of view. The final ‘deconvolved’ image, usually referred to as ‘CLEAN’ image, is the sum of these point components convolved with a ‘CLEAN’, usually Gaussian, beam to de-emphasize the higher spatial frequencies.” (Cornwell & Braun 1989)

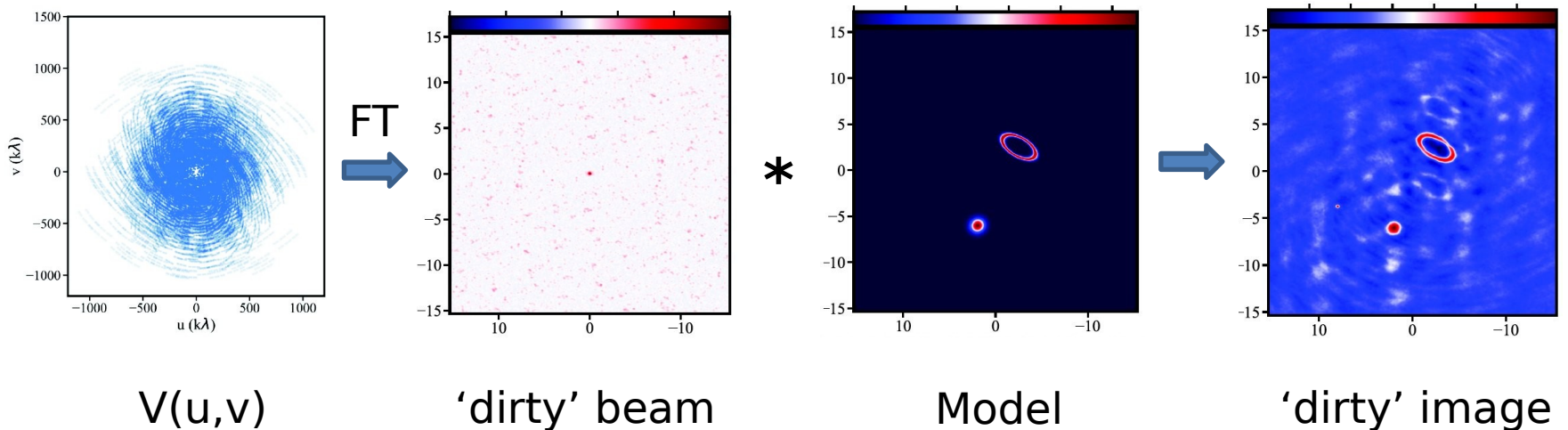


Image Credit: D. Wilner (SIW 2018)

Visibility Weighting Schemes

	Robust/Uniform	Natural	Taper
resolution	higher	medium	lower
sidelobes	lower	higher	Depends on # of baselines
Point source sensitivity	lower	maximum	lower
Extended source sensitivity	lower	medium	higher

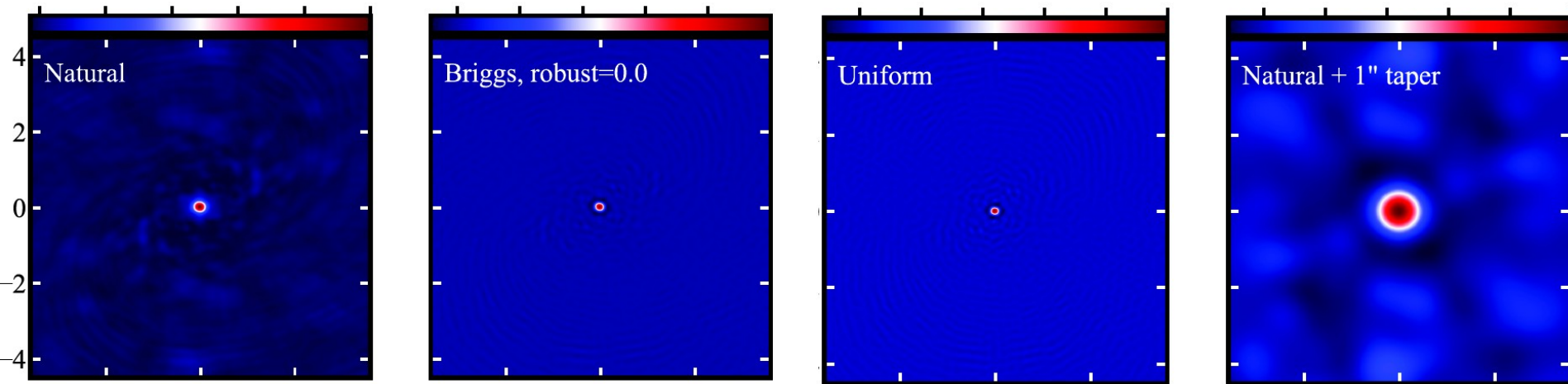


Image Credit: D. Wilner (SIW 2018)

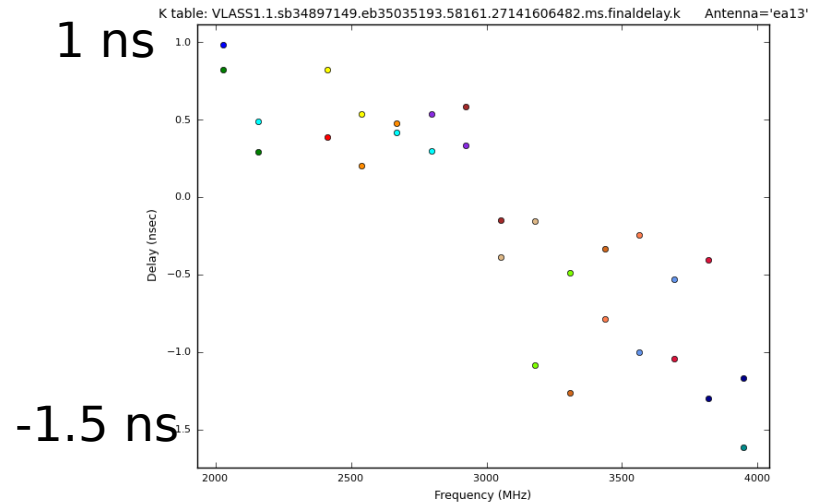
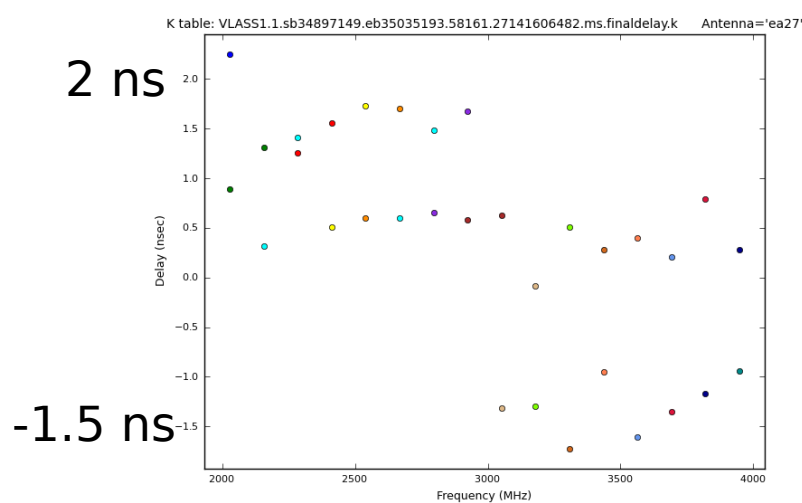
Interferometry Basic Parameters

- **Sensitivity:** Is given by the number of antennas times their effective collecting area.
- **Resolution:** Is given by the largest distance between antennas (longest baseline length). This determines the smallest scale of the synthesized beam.
- **Largest Angular Scale:** This is determined by the shortest distance between antennas.
- **Field of View:** Is given by the size of the beam of a single antenna (corresponding to the resolution of a single dish)

General Observing/Calibration Concepts

Delay

For example VLA digital data transport system (DTS) introduces small delay offsets between antennas that are not accounted for during correlation. These are small and we can determine those by searching for the maximum fringe amplitude on a bright astronomical target applying a range of delay offsets.

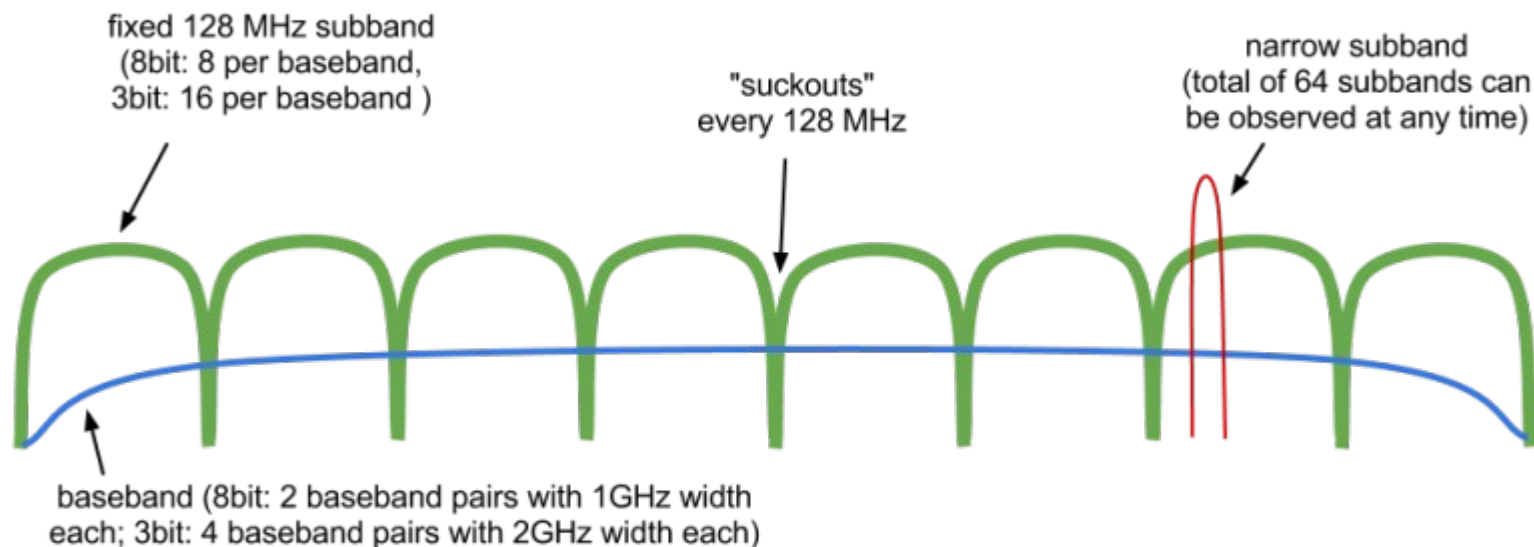


General Observing/Calibration Concepts

Bandpass

Observe a bright calibrator (S/N per channel of 5-10) to obtain per antenna bandpass shapes.

VLA example:

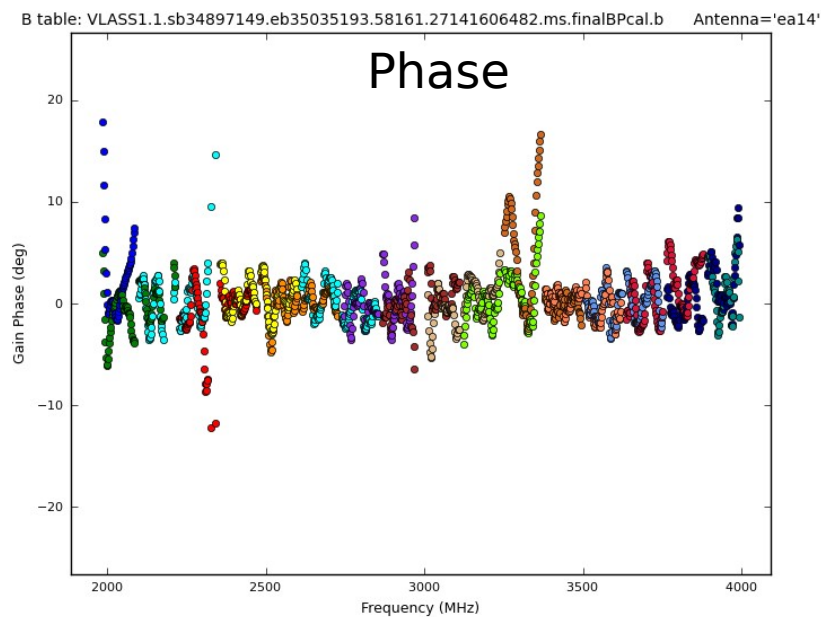
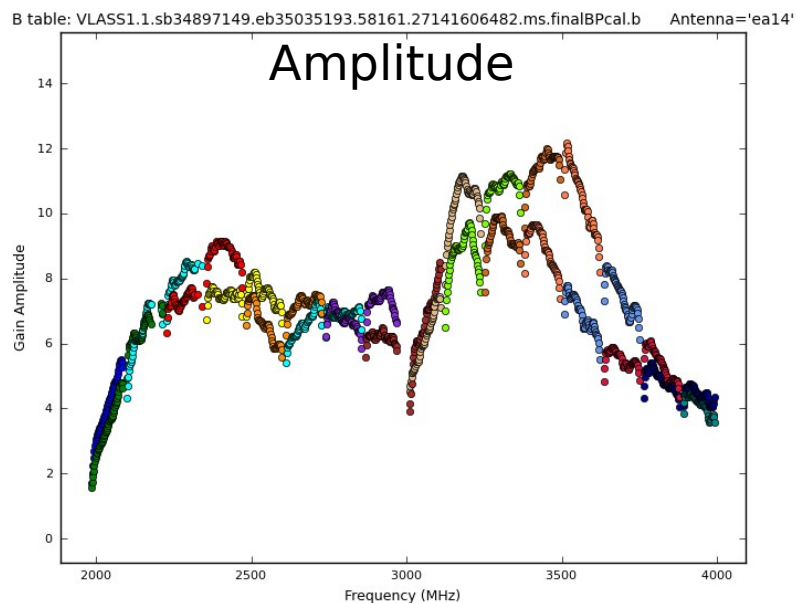


General Observing/Calibration Concepts

Bandpass/Flux Density Scale

Observe a bright calibrator (S/N per channel of 5-10) to obtain per antenna bandpass shapes. And scale gains to known flux density.

VLA example:

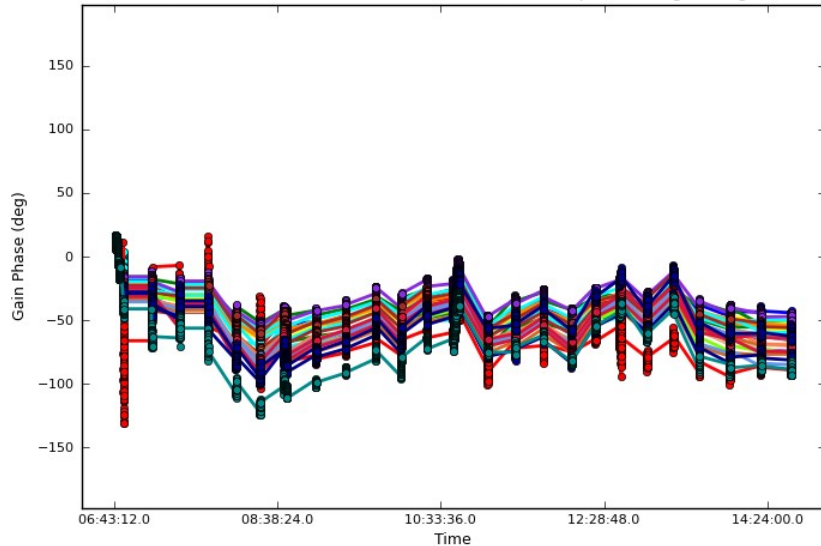


General Observing/Calibration Concepts

Complex Gain Calibration

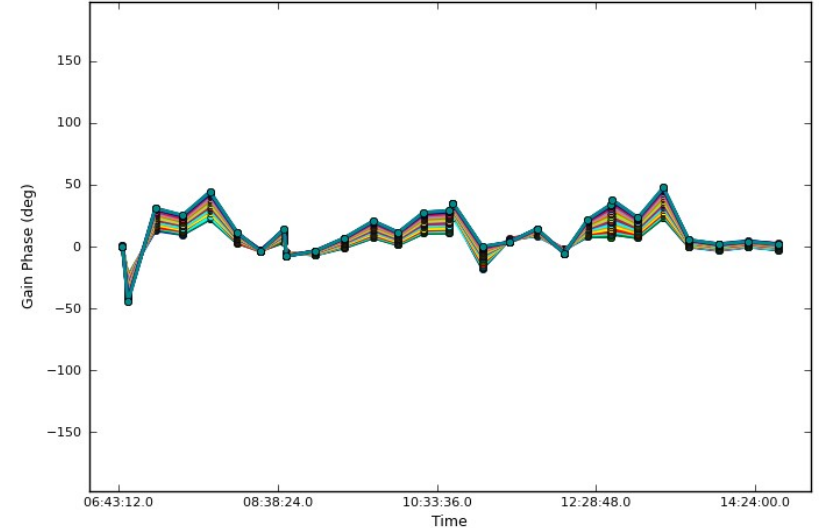
Tracking time variable changes, like atmosphere or changing gain in the instrument.

G table: VLASS1.1.sb34897149.eb35035193.58161.27141606482.ms.phaseshortgaincal.g Antenna='e'



Short time solution

G table: VLASS1.1.sb34897149.eb35035193.58161.27141606482.ms.finalphasegaincal.g Antenna='ea03'



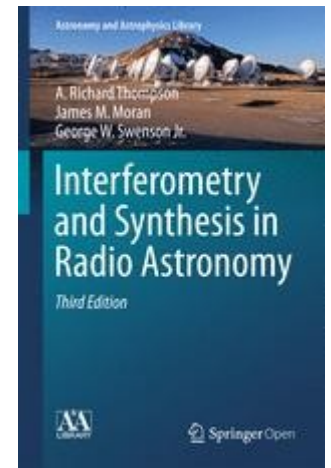
Long time solution

In Conclusion

- Interferometry samples Fourier components of sky brightness.
- Fourier transform can reconstruct the sky brightness distribution.
- Deconvolution attempts to reconstruct the sky brightness given imperfect sampling.
- Some care has to be taken when setting up observations in order to be able to calibrate and achieve the set science goals.
- Radio Interferometry is challenging. However instrumentation is reasonably well understood to make the lives of astronomers easier.

Further Reading

- Thompson, A.R., Moran, J.M., Swensen, G.W.
“Interferometry and Synthesis in Radio Astronomy”
Springer, 3rd edition 2017
Freely available as ebook:
<https://link.springer.com/book/10.1007/978-3-319-44431-4>
- Taylor, G.B., Carilli C.L., Perley, R.A., eds.
“Synthesis Imaging in Radio Astronomy”
ASP Conf. Series 180, 1999
<https://ui.adsabs.harvard.edu/abs/1999ASPC..180.....T/toc>
- ... there are many more references on radio interferometry with each focusing on different aspects ...



Synthesis Imaging Summer School

<https://go.nrao.edu/siw>

[Overview](#) [Program](#) [Venue/Lodging](#) [Registration](#) [Charlottesville, VA](#)

19th Synthesis Imaging Workshop

DoubleTree by Hilton Hotel

Charlottesville, Virginia

June 13, 2023 – June 21, 2023

🕒 Viewing in Eastern Time

Event Overview

The 19th NRAO Synthesis Imaging Workshop will be held from June 13 - 21, 2023 in Charlottesville, Virginia. The workshop will consist of lectures on aperture synthesis theory and techniques at a level appropriate for graduate students in astrophysics. The program will include discussion groups, and tutorials demonstrating data collection, calibration, and imaging of various types of observations, including new data from the Very Large Array (VLA), Very Long Baseline Array (VLBA), and Atacama Large Millimeter/submillimeter Array (ALMA).



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