lecture overview

1) a bit of **HISTORY**: radio astronomy / interferometry

2) motivation - **why interferometry?**

3) basics: **interferometers** / **visibilities** / **uv-plane**

4) **imaging**

5) **deconvolution**

6) **power of interferometry via 2 cool examples**
For thousands of years human observation of the Universe was limited to the visible spectrum

Until.....
Karl Jansky’s serendipitous discovery

an engineer of Bell Laboratories, investigating static that interfered with short wave transatlantic voice transmissions. Using a large directional antenna, Jansky noticed that his analog pen-and-paper recording system kept recording a repeating signal of unknown origin. Since the signal peaked about every 24 hours, Jansky originally suspected the source of the interference was the Sun crossing the view of his directional antenna.
Wide-Field VLA Radio Image of the Galactic Center

(\( \lambda = 90 \text{ cm} \))
Motivation: why interferometry?

answer: all has to do with diffraction which is the limiting resolution of your telescope.

$$\theta_{\text{ang res}} \approx \frac{\lambda}{D}$$

largest fully steerable radio dish: GBT with 100m dish

to reach 1 arc sec resolution you need a 42 km aperture!!
studied radio signals emanating from the Sun

built the first multi-element astronomical radio interferometer in 1946.

production of a number of important radio source catalogues, including the Third Cambridge (3C) Catalogue, which helped lead to the discovery of the first Quasar.
Motivation: why interferometry?

there is a need to develop a better technique than just building larger and larger antennas..

for an interferometer, resolution is given by

\[ \theta_{\text{ang res}} \approx \frac{\lambda}{B} \]

\[
\theta = \frac{(21e-2/100e3) \times 206265}{B}
\]

\[
\theta = 0.4 \text{ arcsec}
\]

Aperture synthesis: methodology of synthesising a continuous aperture through summation of separated pairs of antennas.
The Essential Books

NRAO Synthesis Imaging Workshop in Socorro (VLA) every two years

**Astronomy and Astrophysics Library**

T.L. Wilson
K. Rohrfs
S. Hüttmeister

Tools of Radio Astronomy

Fifth Edition

Springer

Synthesis Imaging in Radio Astronomy II

A Collection of Lectures from the Sixth NRAO/NMMA Synthesis Imaging Summer School, Held in Socorro NM 1998 June 17–23

Edited by
G. B. Taylor, C. L. Carilli, and R. A. Perley
Interferometers: the basics

- Interferometry: a method to ‘synthesize’ a large aperture by combining signals collected by separated small apertures.
- An Interferometer measures the interference pattern produced by two apertures, which is related to the source brightness.
- The signals from all antennas are correlated, taking into account the distance (baseline) and time delay between pairs of antennas.

stolen from: Nuria Marcelino
North American ALMA Science Center
two-element interferometer

the **most basic interferometer** seeks a relation between the the product of the voltages from two separated antennas and the distribution of the brightness of the originating source on the sky.
2. Visibility data

\[ C_{12}(\nu) = \langle E_{\nu}(\vec{r}_1) E_{\nu}(\vec{r}_2) \rangle \]

Calibration

\[ V_{\nu}(\vec{u}) = \int \int \frac{dx \, dy}{\sqrt{1 - x^2 - y^2}} I_{\nu}(\vec{x}) A_{\nu}(\vec{x}) \exp \left[ -2\pi i (\vec{x} \cdot \vec{u}) \right] \]

\[ \vec{u} = \frac{\vec{B}_s^{12}}{\lambda} \]

Sky image

primary beam

from S. Casassus’ lecture
Visibilities

- each $V(u,v)$ contains information on $T(l,m)$ everywhere, not just at a given $(l,m)$ coordinate or within a particular subregion.

- each $V(u,v)$ is a complex quantity
  - expressed as $(\text{real, imaginary})$ or $(\text{amplitude, phase})$
Fourier transforms are at the heart of interferometry.

Jean Baptiste Joseph Fourier
<table>
<thead>
<tr>
<th>FT relationships</th>
<th>$f(x) \rightleftharpoons F(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>scaling</td>
<td>$f(\alpha x) = \alpha^{-1} F(s/\alpha)$</td>
</tr>
<tr>
<td>shifting</td>
<td>$f(x - x_0) = F(s) e^{i2\pi x_0 s}$</td>
</tr>
<tr>
<td>convolution/multiplication</td>
<td>$g(x) = f(x) \otimes h(x); \quad G(s) = F(s)H(s)$</td>
</tr>
</tbody>
</table>

Thompson, Moran & Swenson (2001)
Example 2D Fourier Transforms

\[ T(l,m) \quad \mathcal{F} \quad V(u,v) \text{ amplitude} \]

- \( \delta \text{ function} \)
- elliptical Gaussian

\[ \mathcal{F} \]

\( \delta \text{ function} \) transforms into a constant, and elliptical Gaussian transforms into another elliptical Gaussian. Narrow features transform into wide features (and vice-versa).

stolen from: David Wilner
Example 2D Fourier Transforms

sharp edges result in many high spatial frequencies

uniform disk

$T(l,m)$

$V(u,v) \text{ amplitude}$

Bessel function

stolen from: David Wilner
Amplitude and Phase

- amplitude tells “how much” of a certain spatial frequency
- phase tells “where” this spatial frequency component is located

\[ T(l,m) \]  \[ V(u,v) \text{ amplitude} \]  \[ V(u,v) \text{ phase} \]
The Visibility Concept

\[ V(u, v) = \int \int T(l, m) e^{-i2\pi(ul+vm)} dldm \]

- visibility as a function of baseline coordinates \((u,v)\) is the Fourier transform of the sky brightness distribution as a function of the sky coordinates \((l,m)\)

- \(V(u=0,v=0)\) is the integral of \(T(l,m)dldm\) = total flux density

- since \(T(l,m)\) is real, \(V(-u,-v) = V^*(u,v)\)
  - \(V(u,v)\) is Hermitian
  - get two visibilities for one measurement

stolen from: David Wilner
The Visibility Concept

\[ V(u, v) = \int \int T(l, m) e^{-i2\pi(u l + v m)} \, dl \, dm \]
The Visibility Concept

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stolen from: David Wilner
The Visibility Concept

\[ V(u, v) = \int \int T(l, m) e^{-i2\pi(ul + vm)} \,dl \,dm \]
Inner and Outer \((u,v)\) Boundaries

\[ V(u,v) \text{ amplitude} \quad V(u,v) \text{ phase} \quad T(l,m) \]

\[ \mathcal{F} \rightarrow \]

\[ V(u,v) \text{ amplitude} \quad V(u,v) \text{ phase} \quad T(l,m) \]

\[ \mathcal{F} \rightarrow \]
2. Visibility data

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\[ \vec{u} = \frac{\vec{B}_{12}^s}{\lambda} \]

Sky image

primary beam

from S. Casassus’ lecture
Aperture Synthesis Basics

• idea: sample $V(u,v)$ at enough $(u,v)$ points using distributed small aperture antennas to synthesize a large aperture antenna of size $(u_{\text{max}}, v_{\text{max}})$

• one pair of antennas = one baseline
  = two $(u,v)$ samples at a time

• $N$ antennas = $N(N-1)$ samples at a time

• use Earth rotation to fill in $(u,v)$ plane over time
  (Sir Martin Ryle, 1974 Nobel Prize in Physics)

• reconfigure physical layout of $N$ antennas for more samples

• observe at multiple wavelengths for $(u,v)$ plane coverage, for source spectra amenable to simple characterization (“multi-frequency synthesis”)

• if source is variable, then be careful

stolen from: David Wilner
Two ingredients to get an interferometric image

You need two things...

1. Fourier Transform

2. Deconvolution

(actually, there's a bit more to it than this, but time is short and so are attention spans)

stolen from: Katherine Blundell
Synthesis imaging in a nutshell

\[ I^D(x,y) \iff S(u,v) \times I(u,v) \]

The recovered ‘dirty’ image

The \( uv \)-plane sampling function

The Fourier Transform of the true sky brightness distribution

Image plane

A Fourier transform

Fourier plane

stolen from: Katherine Blundell
Synthesis imaging in a nutshell

The recovered ‘dirty’ image
FT of the $uv$-plane sampling function
The true sky brightness distribution (what we want!)

$$I^D(x,y) = Beam \otimes I(x,y)$$

Image plane

What we need to deconvolve

stolen from: Katherine Blundell
Examples of Aperture Synthesis Telescopes (for Millimeter Wavelengths)

- Jansky VLA
- ALMA
- SMA
- ATCA
- IRAM PdBI
- CARMA
The separation of the VLA antennas is altered every ~4 months.

Most extended: A    Most compact: D

stolen from: Katherine Blundell
Dirty Beam Shape and N Antennas

2 Antennas

stolen from: Katherine Blundell
Dirty Beam Shape and N Antennas

3 Antennas

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Dirty Beam Shape and N Antennas

4 Antennas

stolen from: Katherine Blundell
Dirty Beam Shape and N Antennas

5 Antennas

stolen from: Katherine Blundell
Dirty Beam Shape and N Antennas

6 Antennas

stolen from: Katherine Blundell
Dirty Beam Shape and N Antennas

7 Antennas

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Dirty Beam Shape and N Antennas

8 Antennas

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Dirty Beam Shape and Super Synthesis

8 Antennas x 2 samples

stolen from: Katherine Blundell
Dirty Beam Shape and Super Synthesis

8 Antennas x 6 samples

stolen from: Katherine Blundell
Dirty Beam Shape and Super Synthesis

8 Antennas x 30 samples

stolen from: Katherine Blundell
Dirty Beam Shape and Super Synthesis

8 Antennas x 107 samples

stolen from: Katherine Blundell
Deconvolution Algorithms

• an active research area, e.g. compressive sensing methods

• **clean**: dominant deconvolution algorithm in radio astronomy
  – *a priori* assumption: $T(l,m)$ is a collection of point sources
  – fit and subtract the synthesized beam iteratively
  – original version by Högbom (1974) purely image based
  – variants developed for higher computational efficiency, model visibility subtraction, to deal better with extended emission structure, etc.

• maximum entropy: a rarely used alternative
  – *a priori* assumption: $T(l,m)$ is smooth and positive
  – define “smoothness” via a mathematical expression for entropy, e.g. Gull and Skilling (1983), find smoothest image consistent with data
  – vast literature about the deep meaning of entropy as information content
Aperture synthesis or synthesis imaging is a type of Interferometry that mixes signals from a collection of telescopes to produce images having the same angular resolution as an instrument the size of the entire collection.

Observations from the Earth's surface are limited to wavelengths that can pass through the atmosphere. At low frequencies, limited by the ionosphere, which reflects waves with frequencies less than its characteristic plasma frequency. Higher frequencies (e.g. sub-mm), water vapor is the limiting factor.
A whole spectrum of radiation!
Curves showing the transparency of the atmosphere above the ALMA site as a function of frequency.
ALMA - FACT / Chajnantor at 5100 mts
ALMA - Chajnantor at 5100 mts
ALMA - Chajnantor at 5100 mts

16 km! telescope
ALMA - Chajnantor at 5100 mts
The Correlator, ALMA’s central computer, is located in ALMA’s Operations Center on the Chajnantor Plateau. It receives, processes and stores the information sent by the back end.

The Correlator is ALMA’s brain. Here, the data collected by the antennas is processed at a rate of thousands of millions of times per second.

You would need over 3 million laptop computers to carry out the same number of operations per second.

This colossal machine is the world’s most powerful calculator and has been designed especially for ALMA.
2 cool examples:

**HD 142527** - Protoplanetary Disk

**SS 433** - Stellar Mass Black Hole (famous)
ALMA's view / HD142527

We applied a circular intensity shaped outer disk. The star is at the origin of the coordinates. North is up and east is to the left.

Angular position north (arcsec): same as in Supplementary Fig. 1 for an overlay with the continuum.

Continuum: deconvolved models (Supplementary Information) of the continuum at 345 GHz, with specific intensity units in 0.5 mJy per beam. Inset to Figure 1.

Continuum: overlaid on a red–green–blue image also shows CO(3–2) line intensity, but integrated in emission in HCO\textsubscript{3}+.

A blueshifted high-velocity component can also be seen at the base of this zoomed-in region of Supplementary Fig. 8, taking into account the beam. A blueshifted high-velocity component is shown near the star (at channel at 3.4 km s\textsuperscript{−1} to 3.5 km s\textsuperscript{−1}).

The near-infrared emission abuts the inner rim of the horseshoe-shaped outer disk. The gap-crossing filaments are seen to grow from the eastern and western sides of the horseshoe. Contours are at 0.0015 and 0.005 Janskys per beam. Inset to Figure 1.

Intensity maps for the blue and red velocity levels at 0.5 and 0.95 times the peak values. These red and blue contours are an alternative way to present the intensity field shown in Figure 1.

CO 4.67-μm emission (green) at velocities where the gap-crossing filaments are seen, with a narrow exponential scale highlighting the ease of visualization.

Indeed, the CO 4.67-μm emission, with non-Keplerian flows near the star (comparison to Keplerian rotation in azimuth, but having radial velocity components when applied to planet-formation feedback in HD 142527 (ref. 7).

For the dynamical clearing of the large gap in HD 142527, they are not purely Keplerian, it does not bear the signature of the disk winds seen for the dynamical clearing of the large gap in HD 142527. They are excluded on the basis of the high collimation shown by the HCO\textsubscript{3}+ filamentary grounds (Supplementary Information, section 3).
SS433

X-ray binary / Microquasar

Companion star: unknown

Compact object: most likely a Black Hole

Accretion disc

Relativistic jets

3 main periodicities:

\[ P_{\text{orb}} = 13.1 \text{ days} \]
\[ P_{\text{prec}} = 162 \text{ days} \]
\[ P_{\text{nut}} = 6 \text{ days} \]

Carroll & Ostlie (2007)
An optical view of a microquasar in the Milky Way.
Why is SS 433 special?

Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor
fraction of a milli-arcsecond resolution!
(0.12 mas at 0.3 cm)
graphical tool for demonstrating the techniques of radio interferometry: 

**Pynterferometer**

(python based)

written by A. Avison from ALMA UK arc