Lecture 4: Microwave & Radio Astronomy

Erin Healy & Christoph Welling
What are microwaves and radio waves?

Microwaves and radio waves are common in everyday life:

- Radio waves are big and pass through media (trees, buildings, etc.) = good for communication
- Microwaves excite (heat up) water = good for cooking!
- Medical imaging = able to safely probe internal structures

Marconi telegraph equipment (1987)  Modern cell tower
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To astronomers, microwave and radio are just longer waves on the same spectrum as visible. Longer wavelength means lower energy and frequency.
Microwave vs. visible light telescopes

Imagine you have two telescopes with 0.5m apertures, one is a \textit{microwave} telescope, the other is an \textit{optical} telescope:

Which telescope will see the moon with better resolution?
Microwave telescopes

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What size features on the moon can an optical vs. microwave telescope resolve?
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A 2m telescope in optical can resolve a ~500m crater on the moon

A 2m telescope in the microwave can resolve the moon
Microwave telescopes

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A 2m telescope in the microwave can resolve the moon
When Bell Labs radio astronomers Penzias and Wilson turned their telescope in any direction, they detected a pesky 3K signal that looked like a noise source…
Evidence was suggesting a hotter, denser early universe which would have been radiation dominated → the Big Bang
Einstein’s theory of relativity enabled physicists to relate the energy contents of the universe to the geometry of its spacetime.

Einstein’s field equation:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Spacetime geometry

Energy contents of the universe

Evidence of an expanding universe from Hubble

Princeton cosmologists were on the hunt for this cosmic signal when they got the call from the mystified astronomers up the road.

A new theory of the universe

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Spacetime geometry

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Hubble diagram

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“Well boys, we’ve been scooped.”
Bob Dicke (1965)
If the universe was a uniform blackbody 13.8 billion years ago, what are the seeds of structure in the universe?

As the universe expanded, the wavelength of the early universe radiation was also stretched out.
Cosmic Microwave Background

1965
Penzias & Wilson

1992
COBE

2003
WMAP

2013
Planck
Cosmic Microwave Background

1965
1992
2003
2013

Penzias & Wilson
COBE
WMAP
Planck
Observing conditions

Where to build my observatory?

- Satellites and ballooning telescopes can observe past the atmosphere, but must be smaller and use less power
- Ground-based telescopes have an advantage of power budget and size
  - For microwave observation, need “high and dry” so there is less atmosphere to absorb microwaves

Source: NASA

Atacama Cosmology Telescope
5200m elevation (17,000 ft)
Improved ground-based maps

2m telescope

+6m telescope

Galaxy clusters
Modern microwave detection

In order to achieve unprecedented sensitivities for microwave detection, using superconducting detectors, which are photon-noise limited (i.e., photons are the “loudest” signal the detectors see)
“Radio Stars”

Parkes Radio Observatory

\[ \theta \approx 1.22 \frac{\lambda}{D} \]

\[ D = 64 \text{m} \quad \lambda \approx 5 \text{mm} \quad \Rightarrow \theta \approx 0.05^\circ \]

About 1/10th the size of the moon
The Curious Case of 3C 273

Cyril Hazard
The Curious Case of 3C 273

Marteen Schmidt
The Curious Case of 3C 273

Spectrum of 3C 273

Marteen Schmidt
Quasistellar Objects

Spectrum of 3C 273

Variability of 3C 273
Distances of “Qasars”

Martin Ryle
Qasar Evolution
Okay, but what are these “Quasars” actually?
Fourier Transformations
Fourier Transformations
Fourier Transformations

Joseph Fourier
Fourier Transformations
Fourier Transformations
Fourier Transformations
Fourier Transformations
Fourier Transformations
Fourier Transformations in 2D
Joint Photography Expert Group (JPEG)
Joint Photography Expert Group (JPEG)
Fourier Transformation

Recap:

• We can reproduce data by adding up sine waves
• We determine each wave’s contribution by multiplying it with the data and taking the average
• We can also do this with 2D data (images)
• Missing some information is fine, as long as you get the important parts
Radio Interferometry

Very Large Array
Radio Interferometry
Radio Interferometry

\[
\begin{align*}
\text{Physical delay} & \quad \text{Radio signal} \\
\text{Antenna} & \quad \text{Antenna} \\
\text{Amplifier} & \quad \text{Amplifier} \\
\text{Detect & integrate} & \quad \\
\end{align*}
\]
Radio Interferometry

[Diagram showing radio interferometry process]

[Graphs illustrating signal detection and processing]
Radio Interferometry

\[ \Delta t = \frac{D}{c \sin(\Delta \theta)} \]
Radio Interferometry

Very Large Array
Radio Interferometry

- Image of radio telescope
- Map showing Antenna B configuration and US Hwy 60
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Event Horizon Telescope
Back to Quasars

GMVA+ALMA $\lambda 3\text{mm}$

HSA $\lambda 2\text{cm}$

HST optical

2 light years
220 microarcseconds

40 light years
4.5 milliarcseconds

86,000 light years
9.7 arcseconds

3C 273
Active Galactic Nuclei

Cygnus A (3C 405)