Why Single Dish Radio Astronomy?

Jay Frothingham (they/he)

Credit to Will Armentrout, Chris Salter and Darrel Emerson

GREEN BANK OBSERVATORY

GBO Single Dish Summer School, June 2024





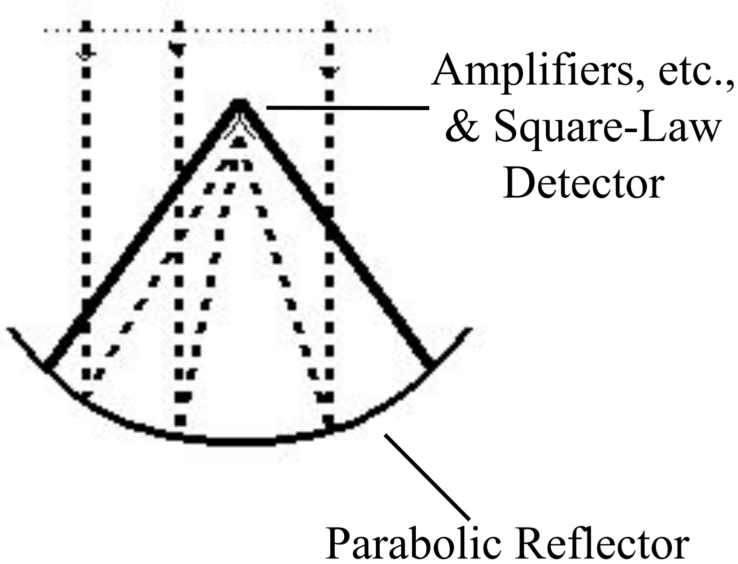



Why Single Dishes? *Outline*

- **What is a Single Dish?**
- **What is an Interferometer?**
- **Let’s Compare**
- **Single Dish Science Highlights**

Disclaimer: This is a “school”, and you’ll see more math than you normally would in conference talks. Slides are available online, and the staff is here to help!

What is a Single Dish?

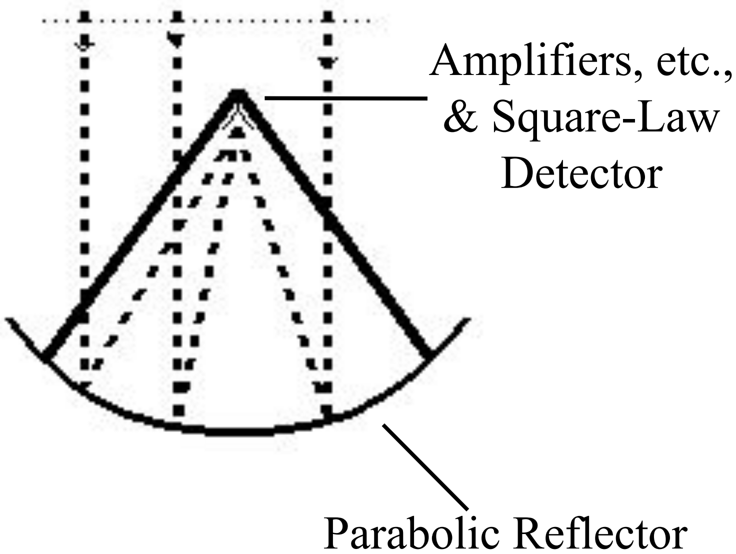


Single Dish

Free space propagation & reflection to bring all signals together in phase. The voltages are "square-law detected" as we are interested in signal power.

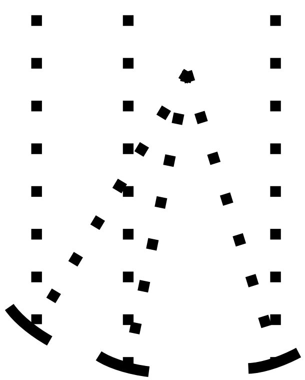
You don't need the full parabola. You can take just a cut out from the parabola (offset parabolic antenna) and get the same result. Signals from each part of the dish are ***added together.***

What is a Single Dish?



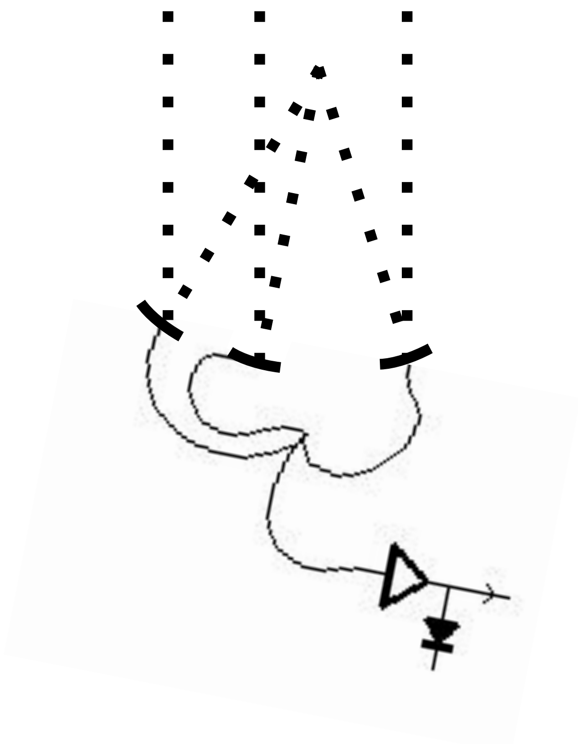
Single Dish

Free space propagation & reflection to bring all signals together in phase. The voltages are “square-law detected” as we are interested in signal power.



What if we cut out more pieces of the dish? *It still works the same, it’s just less sensitive (lower collecting area).*

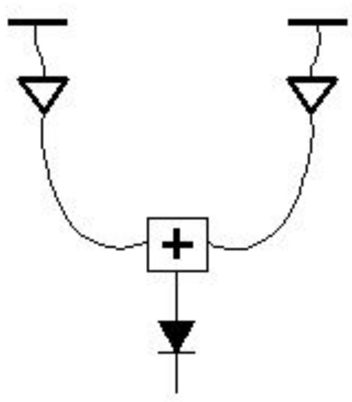
What is a Single Dish?



Or what if we collect the signal directly at each of these locations and add the signal together?

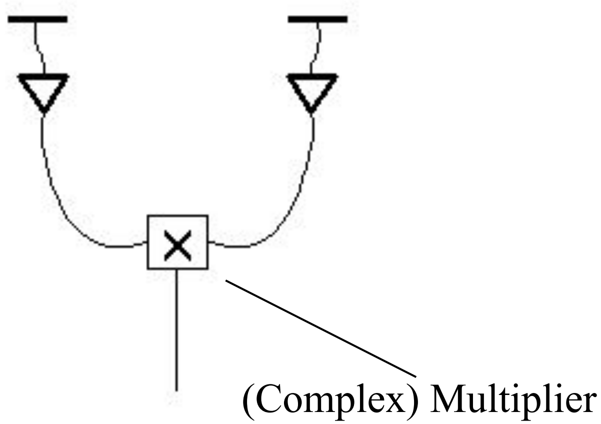
We've just designed a type of **interferometer** that functions like a **single dish**.

Two Types of Interferometers



Phased Array or
Adding Interferometer

A single dish with missing metal.

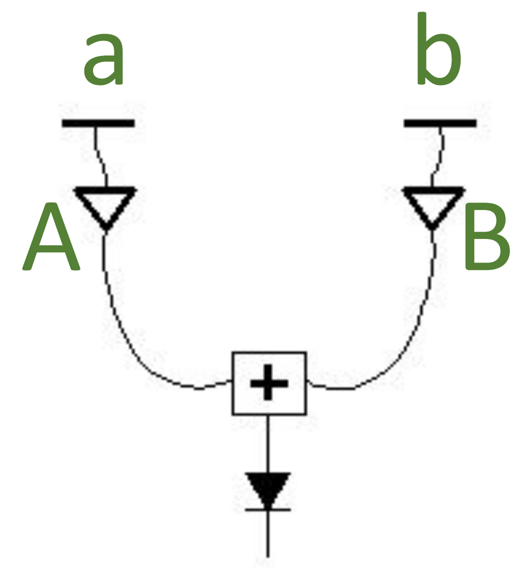


Correlation or
Multiplying interferometer

All aperture synthesis radio telescopes (VLA, SKA, ATCA, etc.) are made up of multiple correlation interferometers

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

2-Element Phased Array



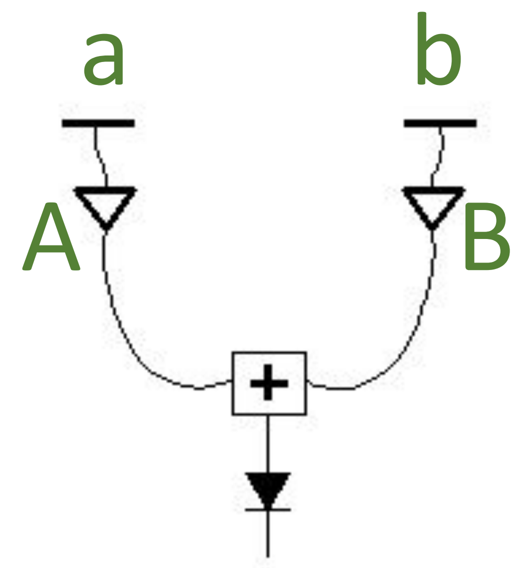
Signal voltage into each antenna element: a, b

Noise voltage of each antenna amplifier: A, B

Before detector: (A + a) + (B + b)

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

2-Element Phased Array



Signal voltage into each antenna element: a, b

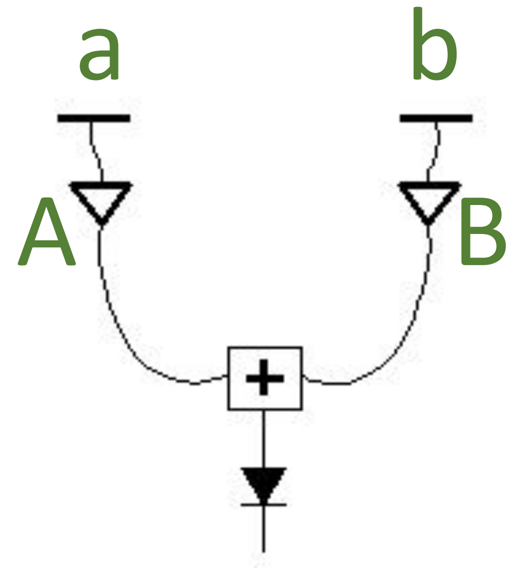
Noise voltage of each antenna amplifier: A, B

Before detector: (A + a) + (B + b)

After square-law detector: $[(A+a) + (B+b)]^2$

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

2-Element Phased Array



Signal voltage into each antenna element: a, b

Noise voltage of each antenna amplifier: A, B

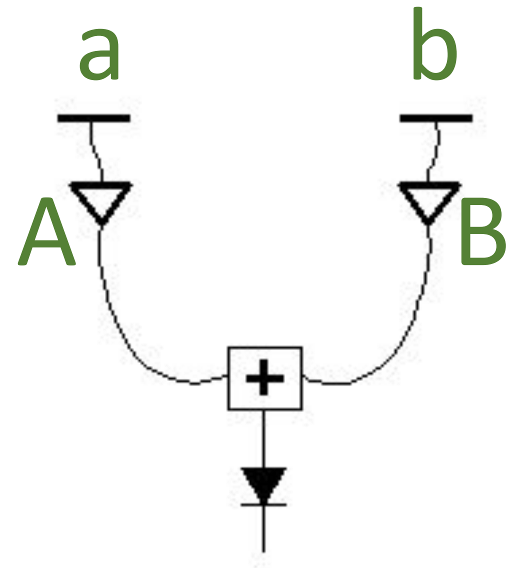
Before detector: $(A + a) + (B + b)$

After square-law detector: $[(A+a) + (B+b)]^2$

or $A^2 + B^2 + a^2 + b^2 + 2.(A.a + A.b + B.a + B.b + A.B + a.b)$

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

2-Element Phased Array



Signal voltage into each antenna element: a, b

Noise voltage of each antenna amplifier: A, B

Before detector: $(A + a) + (B + b)$

After square-law detector: $[(A+a) + (B+b)]^2$

or $A^2 + B^2 + a^2 + b^2 + 2.(\cancel{A}.a + \cancel{A}.b + \cancel{B}.a + \cancel{B}.b + A.\cancel{B} + a.b)$

Time-averaged products of uncorrelated quantities tend to zero, so this averages to just:

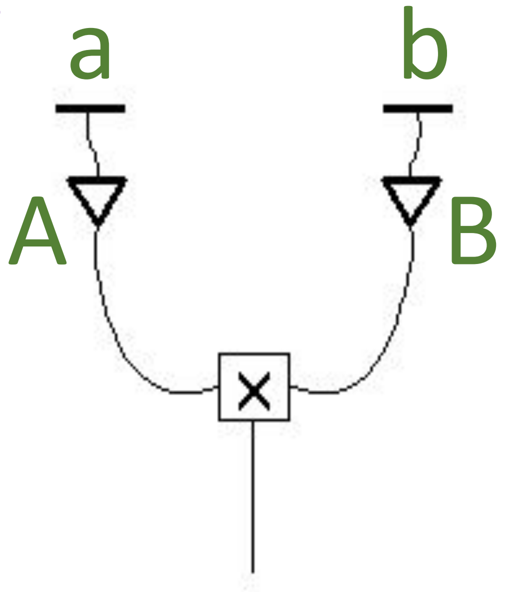
$$\boxed{A^2 + B^2 + a^2 + b^2 + 2.a.b}$$

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

Multiplying or Correlation Interferometer

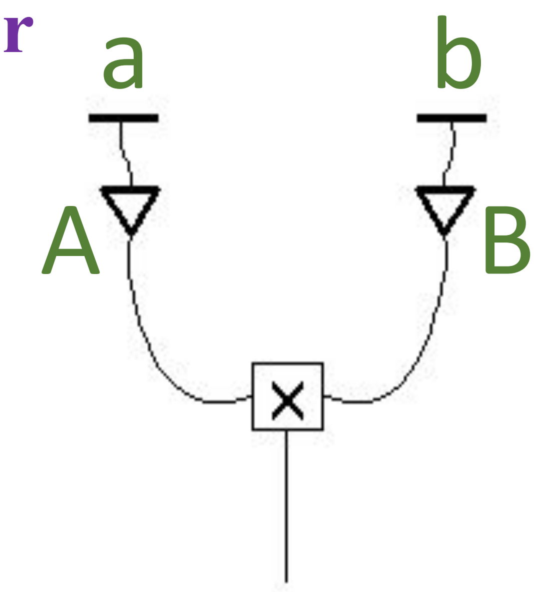
After multiplier: $(A + a).(B + b)$

or $A.B + A.b + a.B + a.b$



Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

Multiplying or Correlation Interferometer



After multiplier: $(A + a).(B + b)$

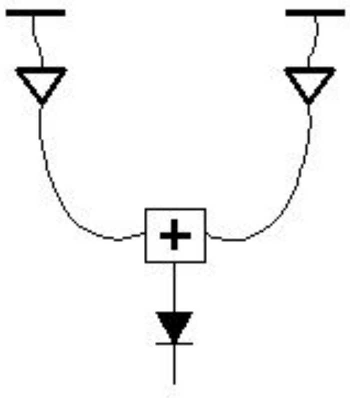
or $\cancel{A.B} + \cancel{A.b} + \cancel{a.B} + a.b$

After averaging, uncorrelated products tend to zero, so this becomes just:

$$\boxed{a.b}$$

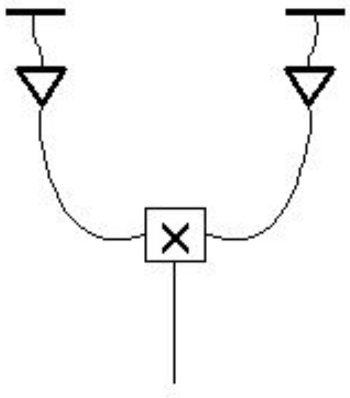
The averaged output no longer depends on A or B, the internally generated amplifier noise voltages.

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer



Phased Array or
Adding Interferometer

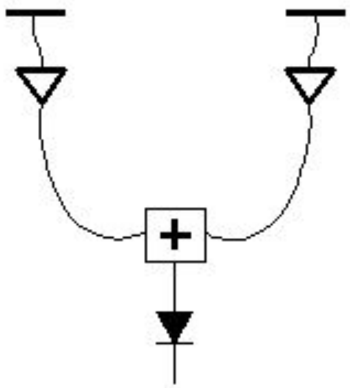
$$A^2 + B^2 + a^2 + b^2 + 2.a.b$$



Correlation or
Multiplying Interferometer

$$a.b$$

Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

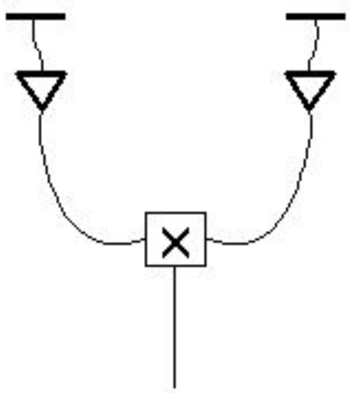


$A^2 + B^2 + a^2 + b^2 + 2.a.b$

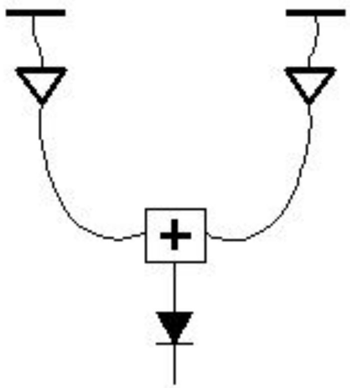
The **Phased Array (Adding Interferometer)** is the same as the **Single-dish telescope**, (just missing some metal & using more cable instead).

Single Dish/Phased Array are intrinsically ***very*** susceptible to changes/drifts in receiver gain, **and** noise temperature.

$a.b$



Phased Array (Adding) *vs.* Correlation (Multiplying) Interferometer

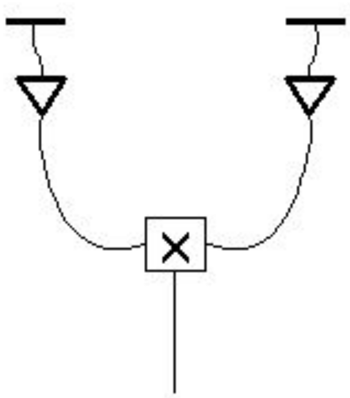


$A^2 + B^2 + a^2 + b^2 + 2.a.b$

The **Phased Array (Adding Interferometer)** is the same as the **Single-dish telescope**, (just missing some metal & using more cable instead).

Single Dish/Phased Array are intrinsically ***very*** susceptible to changes/drifts in receiver gain, **and** noise temperature.

$a.b$

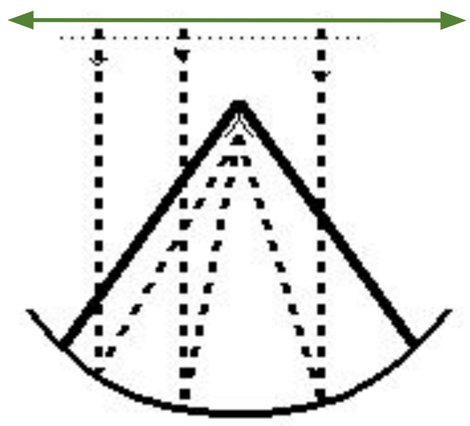


The **Correlation (Multiplying) Interferometer** is essentially immune to receiver gain and noise changes.

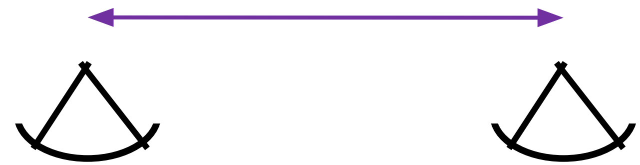
Some source distributions, or combination of sources may be ***invisible*** to the **Correlation Interferometer**. This includes angularly very extended distributions.

Single Dish vs. Interferometer Resolution

Dish Diameter **D**



Interferometer separation **d**



Dish diameters **D**

d - D

d + D

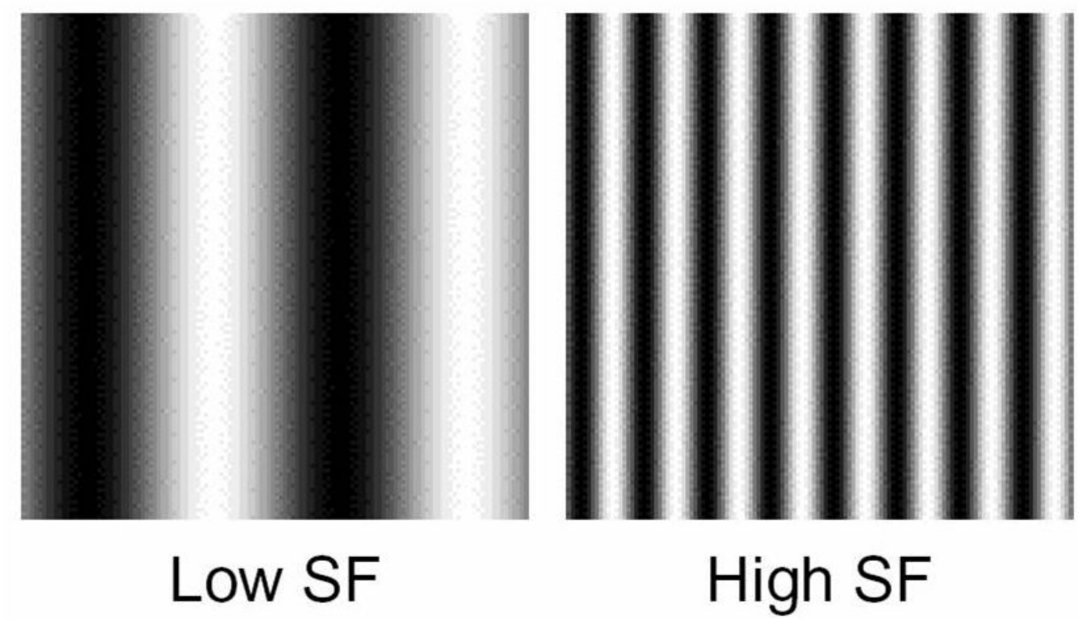
A single dish of diameter **D** includes all baselines from **0** to **D**

A correlation interferometer of separation **d**, using dishes of diameter **D**, includes all baselines from **d – D** to **d + D**

Shorter Baselines (down to 0)

Longer Baselines

Celestial Spatial Frequencies

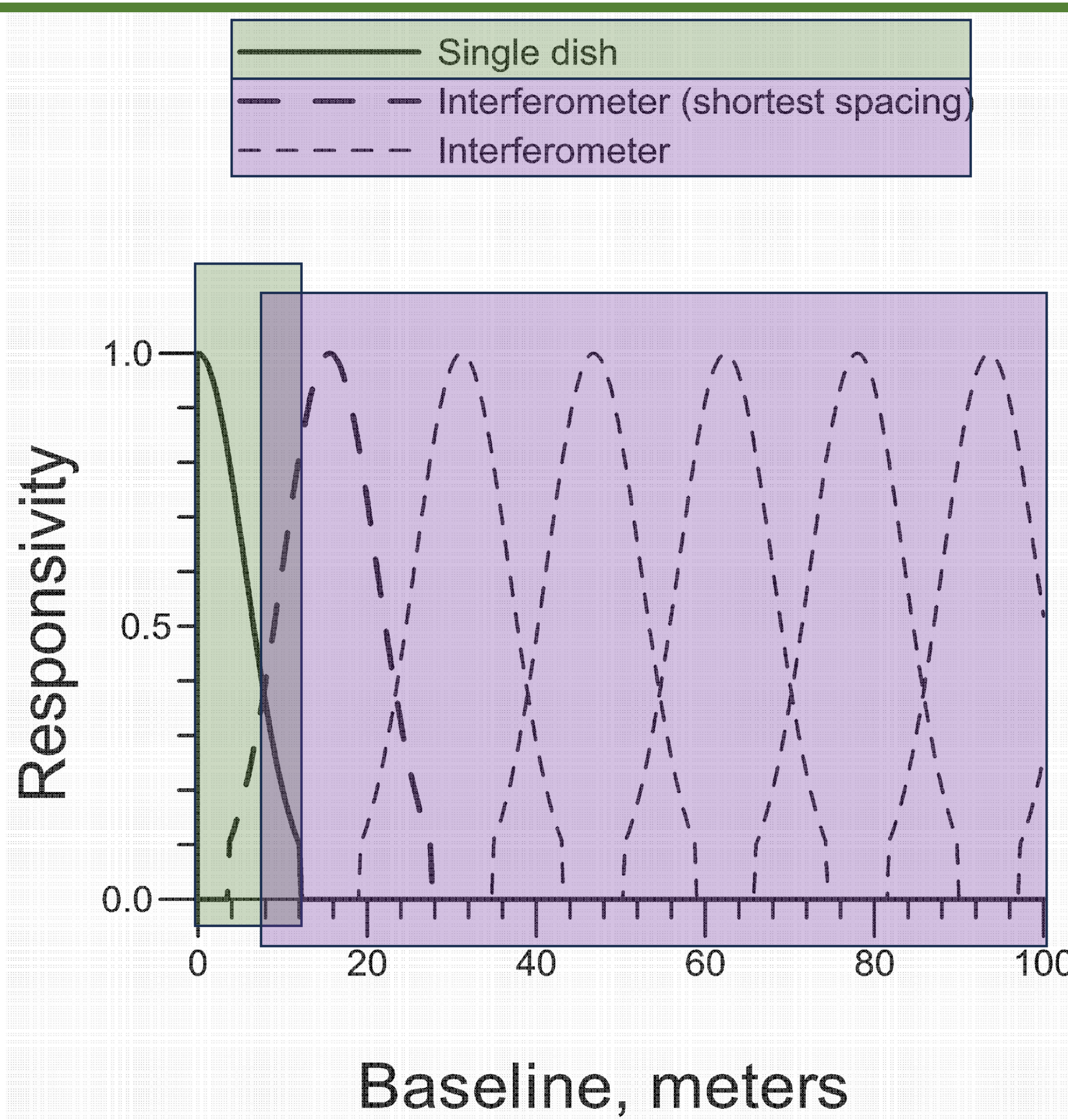


The Fourier Transform of a celestial brightness distribution yields spatial frequencies in cycles per radian.

For a 2-element interferometer: Angle on sky = (λ/Baseline) radians

Spatial frequency sensitivity is proportional to baseline (short baseline, low SF, large angle on sky)

Single Dish vs. Interferometer Resolution



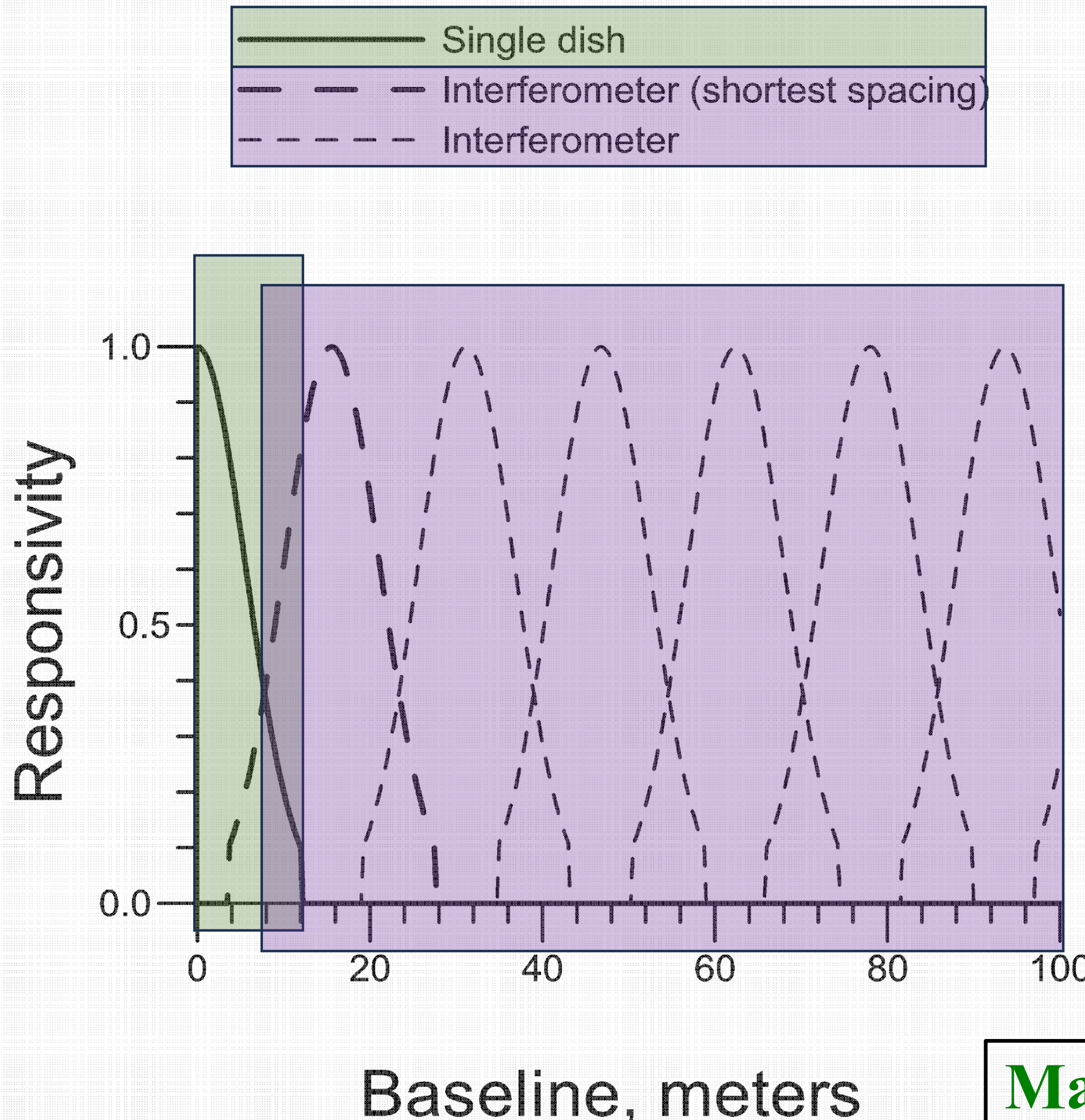
Short baselines let you see more large scale emission

Long baselines let you see more small scale emission

Resolution = 1.22 λ/D

If you want better resolution, Increase Your Baseline!

Single Dish vs. Interferometer Resolution

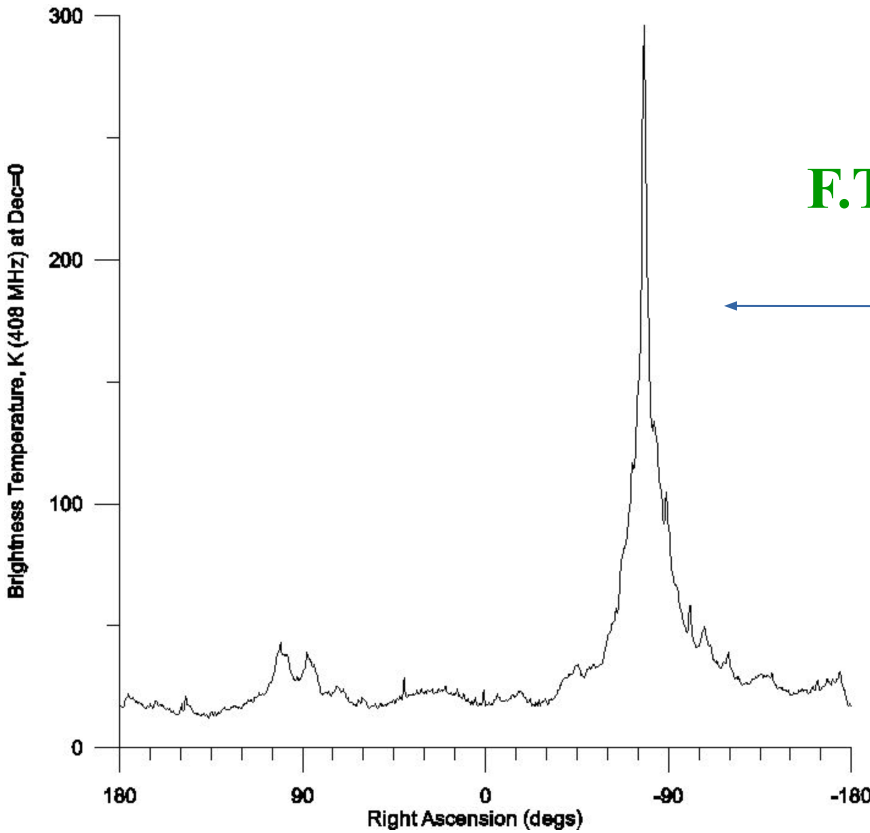


To get an accurate picture of (1) the large scale structure and total flux density in a field, AND (2) the fine scale detail in a source, ***you require a combination of both single-dish and interferometric observations.***

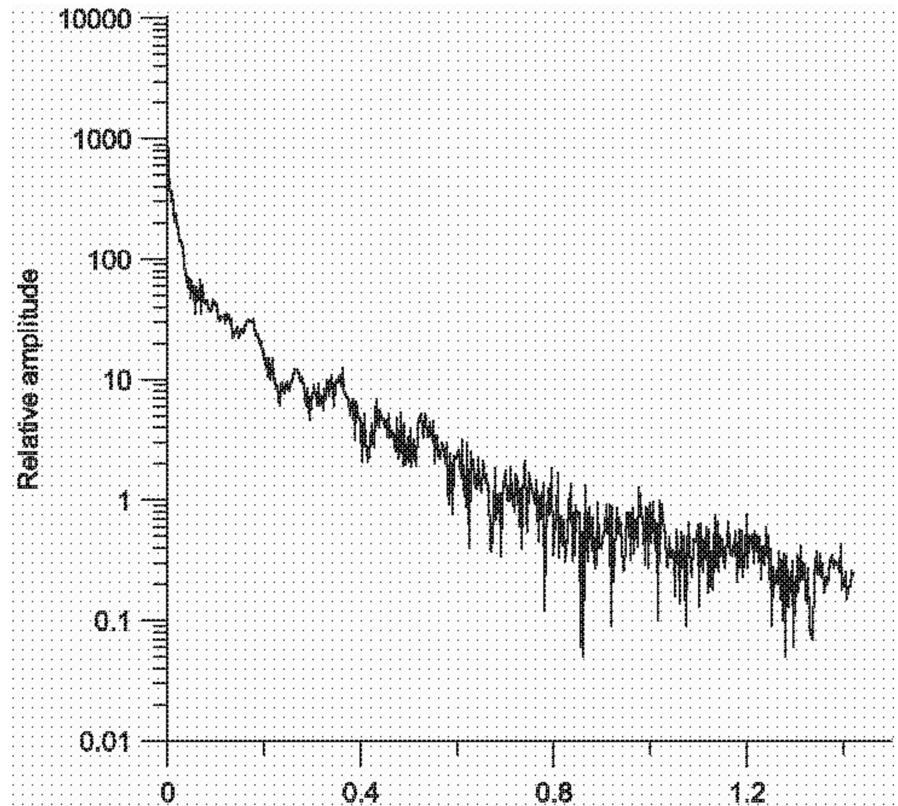
Make sure that you attend Adele Plunkett's talk!

A cross-section through the 408-MHz All-Sky Image at Dec~0°

Spatial frequency distribution of the all-sky 408 MHz distribution



F.T.



Spatial frequency (1/degrees)

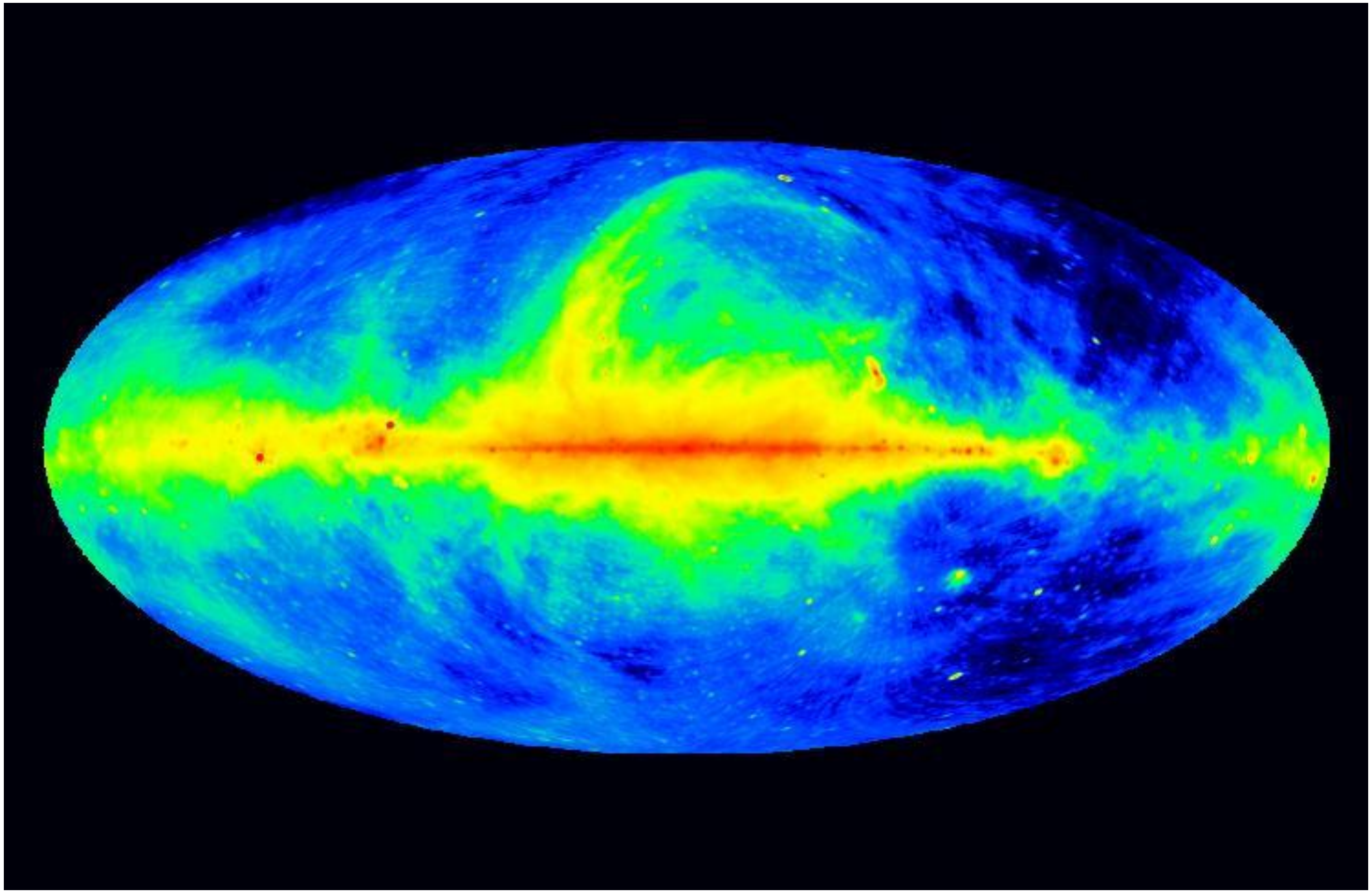
Single Dish vs. Interferometer Resolution

A Single Dish has its resolution set by its diameter, ***while*** an Interferometer Array has its resolution set by its longest baseline. ***(Interferometers can see smaller things)***

A Single Dish has baselines of zero to D ***while*** an Interferometer Array has baselines set by minimum/maximum antenna separation. ***(Single dishes can see bigger things)***

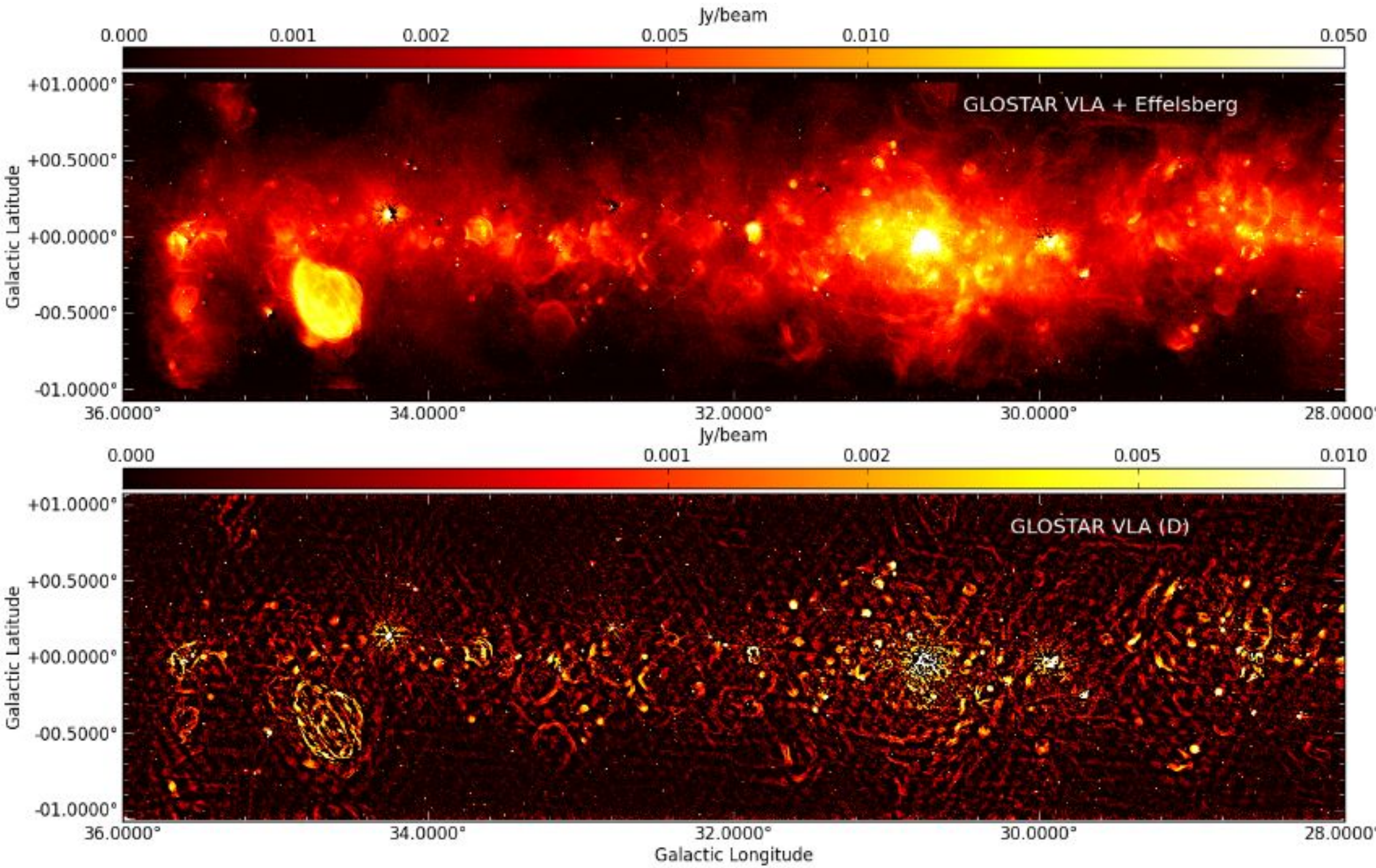
- For cases where we DO want large-scale structure, we may HAVE TO USE a Single Dish, (sometimes in combination with an Interferometer.)

The Whole Radio Sky (408 MHz -- λ73 cm)



Made with 4 large single-dish telescopes. Contains all the flux in the sky (including the 3 K Cosmic Microwave Background!) Could only have been made with single dishes. (Haslam et al. 1982)

"Give Me Back My Short Spacings!"



C-Band

(Brunthaler et al, 2021)

Practical Disadvantages of Single-Dish Observing

- Not able to resolve fine details.
- Mechanical structural complexity often replaces electronic complexity.
- Susceptible to instrumental drifts in gain and noise – don't have the correlation advantage of interferometers.
- Interferometers can *in principle* give high sensitivity and LARGE TOTAL collecting area (e.g. VLA, SKA).
- Aperture synthesis imaging is a form of multi-beaming - arguably obtaining more information from the radiation falling on a telescope than is possible with a single dish.

Practical Advantages of Single-Dish Observing:

- **Low Spatial Frequency Response (view large-scale structure!)**

- **Sensitivity:**
  - Point sources: Sensitivity in **Jy** depends critically on **collecting area**, SD or Interferometer.
  - Extended emission: Sensitivity in brightness temperature **K** gets WORSE as (Max. Baseline, d) squared, for the same collecting area – i.e. roughly as $\mathbf{(D/d)^2}$.
- Ability to map very extended areas quickly (e.g. ALFALFA, GALFACTS, GALFA).
- May provide large collecting area with manageable electronic complexity.

- **Simplicity**: Can be one receiver chain, not N receivers with N.(N-1)/2 correlations.
- It is *relatively* easy to implement large focal-plane arrays, including bolometers, which can increase mapping speeds by orders of magnitude.
- Multi-frequency receivers are a relatively straightforward investment.

- **Flexibility**: Relative ease of upgrading or customizing hardware to an experiment.
- Relative ease of implementing radar transmitter systems.
- A large single dish can add significant sensitivity to VLBI arrays.
- Software is possibly simpler: "Conceptually" easier to understand for novices.
- Use as test-bed for new receiver systems.
- User-developed equipment easily deployed for particular experiments.

- **Commensality:** Employed with the GBT and CHIME. (harder on interferometers)

Practical Advantages of Single-Dish Observing

View large-scale structure!

Sensitivity:

- – Point sources: Sensitivity depends critically on **collecting area**, SD or Interferometer.
- – Extended emission: Sensitivity gets **WORSE** as (Max Baseline, d) squared, for the same collecting area – i.e. roughly as $\mathbf{(D/d)^2}$**.**

- Ability to map very extended areas quickly.

Practical Advantages of Single-Dish Observing

View large-scale structure!

Sensitivity:

- Point sources: Sensitivity depends critically on **collecting area**, SD or Interferometer.
- Extended emission: Sensitivity gets **WORSE** as (Max Baseline, d) squared, for the same collecting area – i.e. roughly as $\mathbf{(D/d)^2}$.

- Ability to map very extended areas quickly.

Simplicity:

- May provide large collecting area with manageable electronic complexity.
- It is *relatively* easy to implement large focal-plane arrays, including bolometers, which can increase mapping speeds by orders of magnitude.
- Multi-frequency receivers are a relatively straightforward investment. *(ahem, astrochemists)*

Practical Advantages of Single-Dish Observing

View large-scale structure!

Sensitivity:

- Point sources: Sensitivity depends critically on **collecting area**, SD or Interferometer.
- Extended emission: Sensitivity gets **WORSE** as (Max Baseline, d) squared, for the same collecting area – i.e. roughly as **$(D/d)^2$.**

- Ability to map very extended areas quickly.

Simplicity:

- May provide large collecting area with manageable electronic complexity.
- It is *relatively* easy to implement large focal-plane arrays, including bolometers, which can increase mapping speeds by orders of magnitude.
- Multi-frequency receivers are a relatively straightforward investment. *(ahem, astrochemists)*

Flexibility:

- Use as test-bed for new receiver systems.
- A large single dish can add significant sensitivity to VLBI arrays.
- Software is possibly simpler: "Conceptually" easier to understand for novices.

Practical Advantages of Single-Dish Observing

View large-scale structure!

Sensitivity:

- Point sources: Sensitivity depends critically on **collecting area**, SD or Interferometer.
- Extended emission: Sensitivity gets **WORSE** as (Max Baseline, d) squared, for the same collecting area – i.e. roughly as $\mathbf{(D/d)^2}$.

- Ability to map very extended areas quickly.

Simplicity:

- May provide large collecting area with manageable electronic complexity.
- It is *relatively* easy to implement large focal-plane arrays, including bolometers, which can increase mapping speeds by orders of magnitude.
- Multi-frequency receivers are a relatively straightforward investment. *(ahem, astrochemists)*

Flexibility:

- Use as test-bed for new receiver systems.
- A large single dish can add significant sensitivity to VLBI arrays.
- Software is possibly simpler: "Conceptually" easier to understand for novices.

Commensality: Employed with the GBT and CHIME. (harder on interferometers)

Single Dish Science Highlights

Pulsars, FRBs & Other Transients:

Search: ~3200 known radio PSRs; the vast majority found with single dishes.

NanoHz Gravitational-Wave Studies: AO & GBT have been major players in the NANOGrav project for many years.

FRB Science: FRB searches with single-dish PAFs/FPAs. Polarization and other pulse-structure studies of repeating FRBs.

GRB Afterglows: Detection and study of γ-Ray Burst afterglows.

Continuum Emission:

Surveys: Wide-area, full-Stokes, "background/source" surveys.

Source Imaging: Including providing high-sensitivity, full-Stokes data to complement high-resolution interferometer data.

Red-Dwarf Stars: Full-Stokes continuum emission studies.

Single Dish Science Highlights

Spectral Lines:

Prebiotic Molecule Search: Both in the Galaxy and in LIRGs.

Wide-Area Molecular Line Surveys: Galactic and extragalactic.

High-z Extragalactic Molecules: The detection of strong, redshifted maser lines (e.g. H_2O) in the nuclear regions of galaxies, and perhaps other highly abundant species in highly-redshifted galaxies.

Deep HI Galaxy Blind Searches: Such as the highly successful ALFA HI searches.

HI Intensity Mapping: Probing dark energy via HI emission at intermediate redshifts.

HI Absorption Studies: Against the continuum emission of the radio nuclei of galaxies to study the dynamics of neutral gas in active galaxies.

Very Long Baseline Interferometry (VLBI):

Studies of Galactic Nuclei

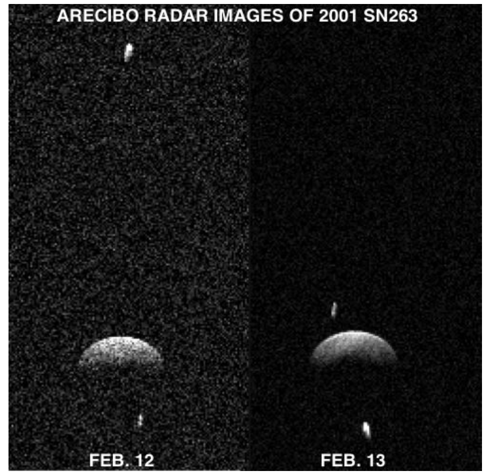
HI Absorption: HI absorption against AGN to study the neutral component in the host galaxy.

Localization of Repeating FRBs

Orbital VLBI: Collaboration with small orbital VLBI dishes, (e.g. GBT collaborations with RadioAstron.)

Single Dish Science Highlights

Solar System Radar



SETI Searches

N.B. Single-Dishes do seem to win Nobel Prizes!

1974 – Ryle + Hewish, pulsars

1978 – Penzias + Wilson, CMB

1993 – Hulse + Taylor, binary pulsar

2006 – Mather + Smoot, anisotropy of CMB

Single-Dishes: New or Under Construction

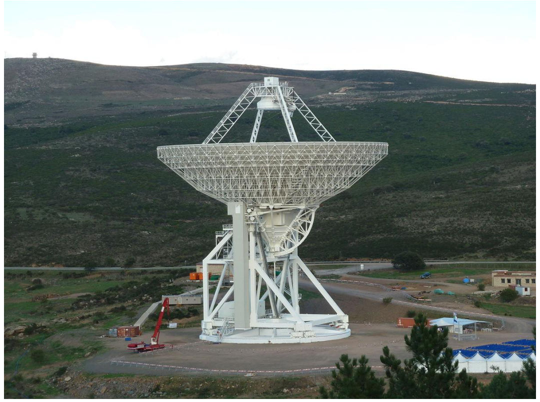
- The Large Millimeter Telescope (**LMT/GTM**) of 50-m diameter in Mexico of INAOE & Umass. In service since 2013.

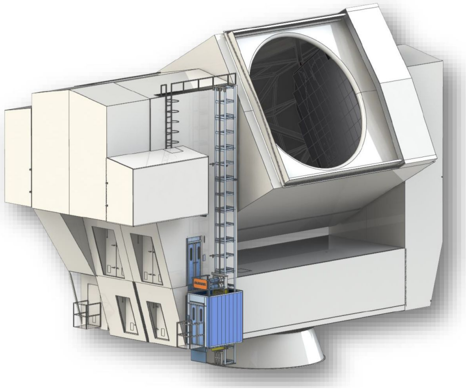
- Sardinia Radio Telescope (**SRT**) of 64-m diameter working to 115 GHz. In service from 2011.

- The Five hundred meter Aperture Spherical Telescope (**FAST**) of 500-m diameter built in China for frequencies to ~3 GHz. First light 2016.

- The 6-m sub-mm **CCAT-P** (Cerro Chajnantor Atacama Telescope)/FYST. First light planned for 2025.

- **CHIME** (Canadian Hydrogen Intensity Mapping Experiment) – Newly an interferometer, with one element on site in Green Bank. First light, 2017.



GREEN BANK
OBSERVATORY

greenbankobservatory.org

The Green Bank Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

GREEN
OBSERV