Fundamentals of Radio Astronomy: I

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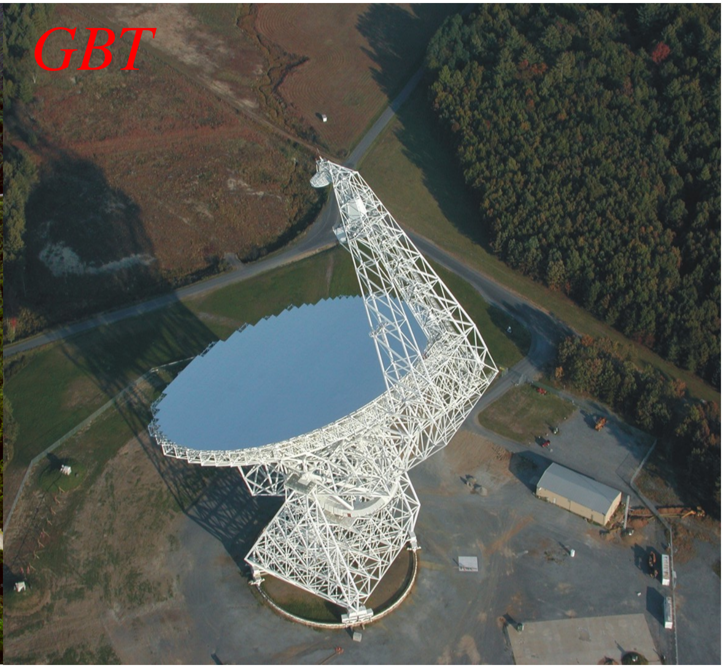
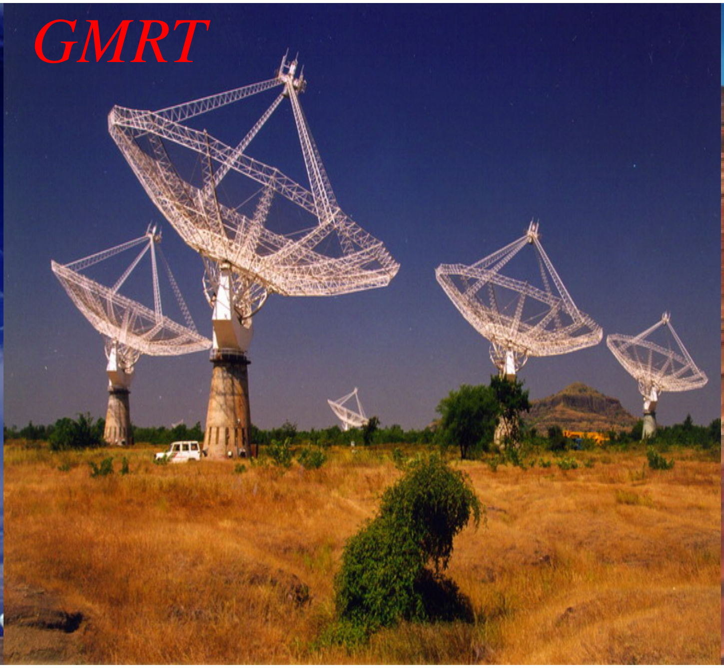
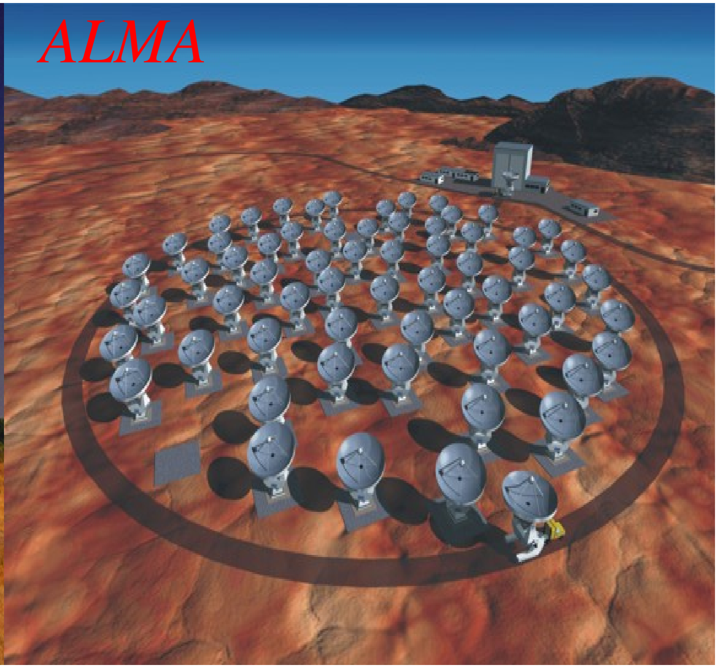






PLAN

- Introduction to Radio Astronomy.
- Science at radio frequencies.

References

- *Tools of Radio Astronomy* (Wilson, Rohlfs & Huchtmeier)
- *Radio Astronomy* (John Krauss)
- *Essential Radio Astronomy* (Jim Condon & Scott Ransom)

  http://www.cv.nrao.edu/course/astr534/ERA.shtml

Introduction to Radio Astronomy: Outline

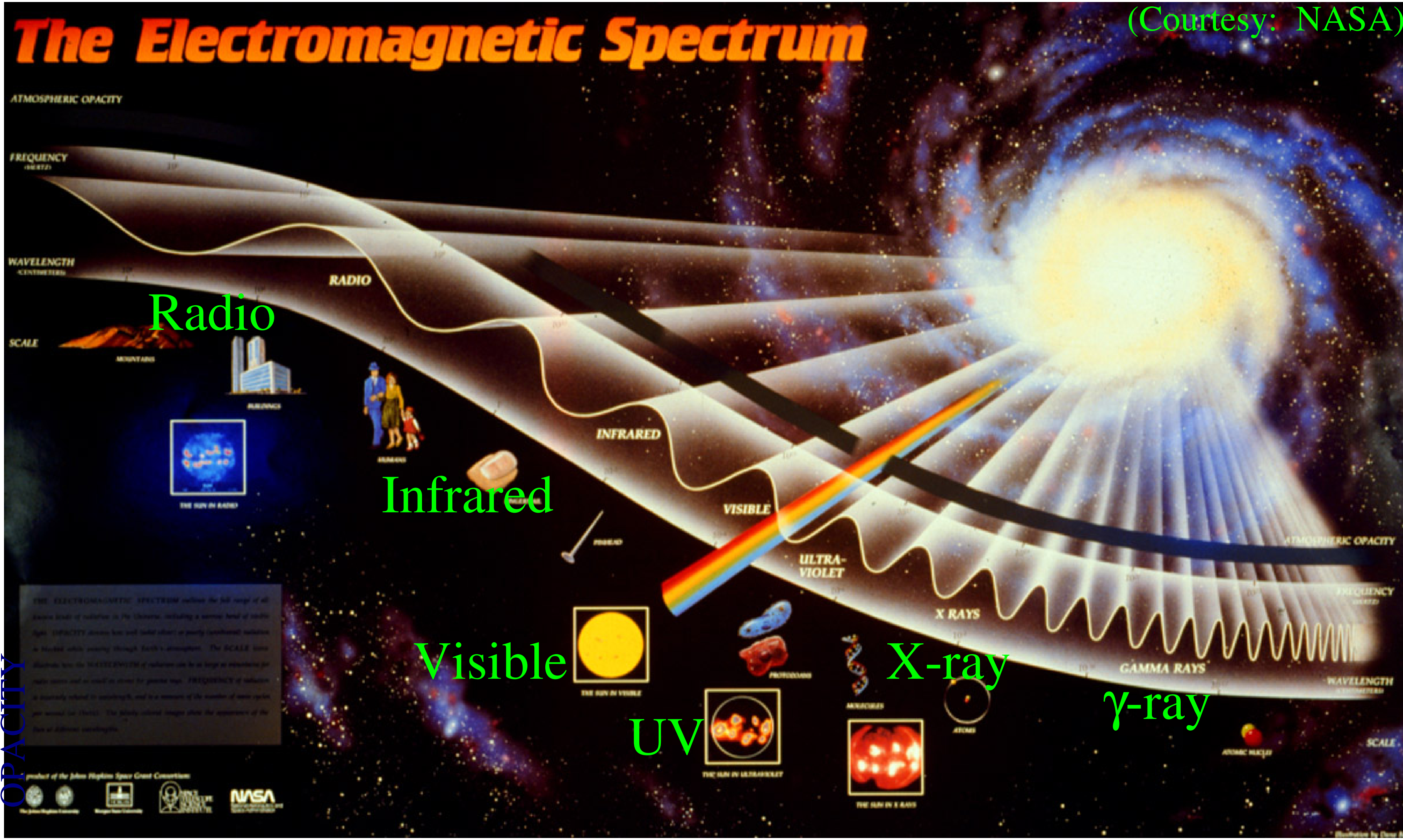
- The electromagnetic spectrum from terra firma.
- Radio astronomy: When and Why ?
- Astronomy at radio frequencies.
- The measurements.
- Resolution: Angular, Frequency, Time.
- Single dishes.
- Radio interferometers and radio interferometry.
- Specifications of a radio telescope.

CAUTION: We do NOT listen to radio data!

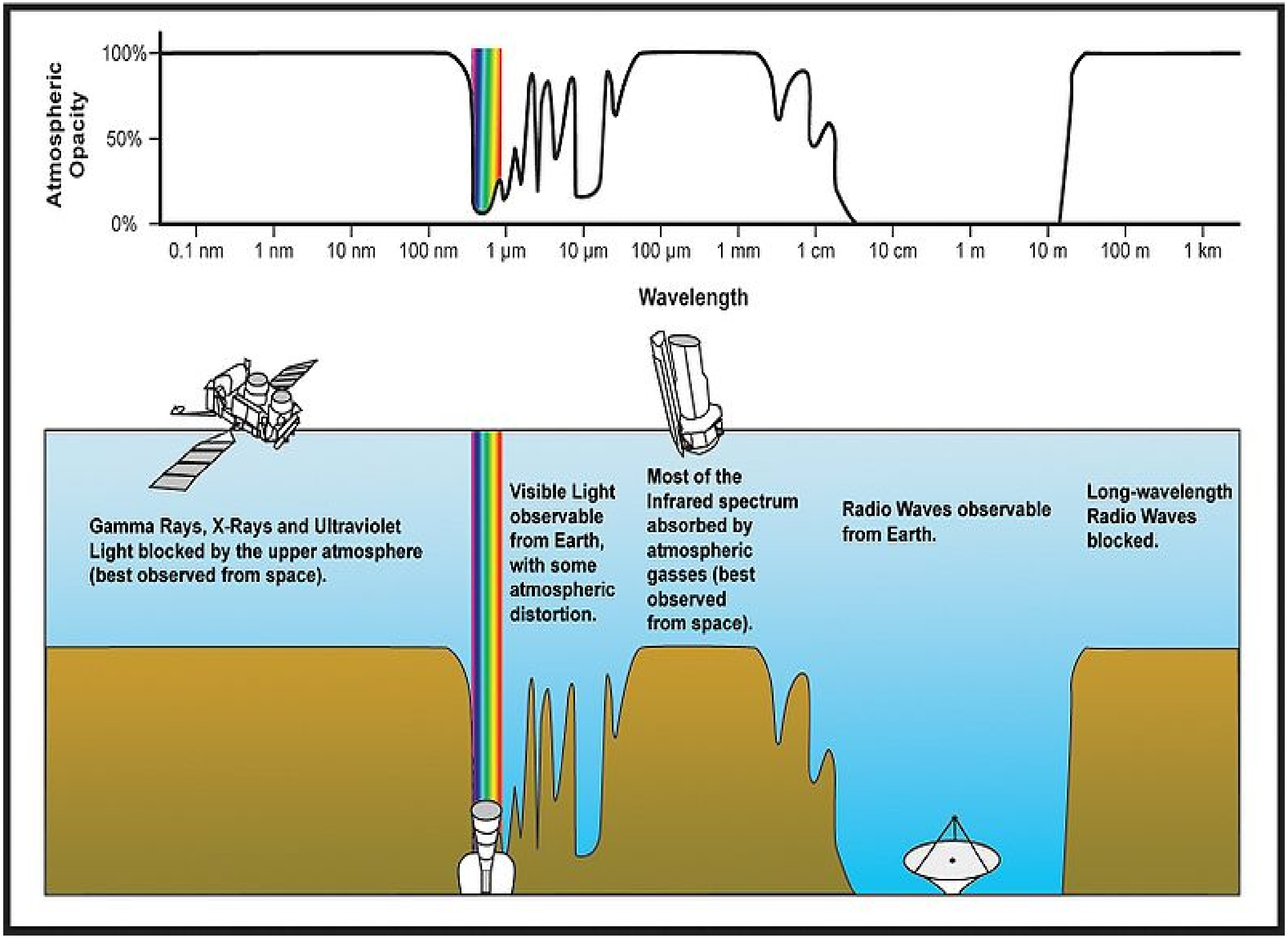
Note to budding Hollywood directors: Radio waves are electromagnetic waves, not sound waves.

More unfortunate caution: Jodie Foster doesn't hang out at the GMRT or the VLA.

The Electromagnetic Spectrum



The E-M Spectrum from Terra Firma



ATMOSPHERIC OPACITY

WAVELENGTH

(Courtesy: JPL)

The radio sky : ν ~ 10 MHz – 1 THz; λ ~ 30 m – 0.3 mm.

The optical sky: λ ~ 3,000 Å – 10,000 Å.

Radio Astronomy: When ?

- Astronomers are smart: it was obvious in the 1900's that stars can't be detected in the radio! Luckily, radio engineers are less "smart"!

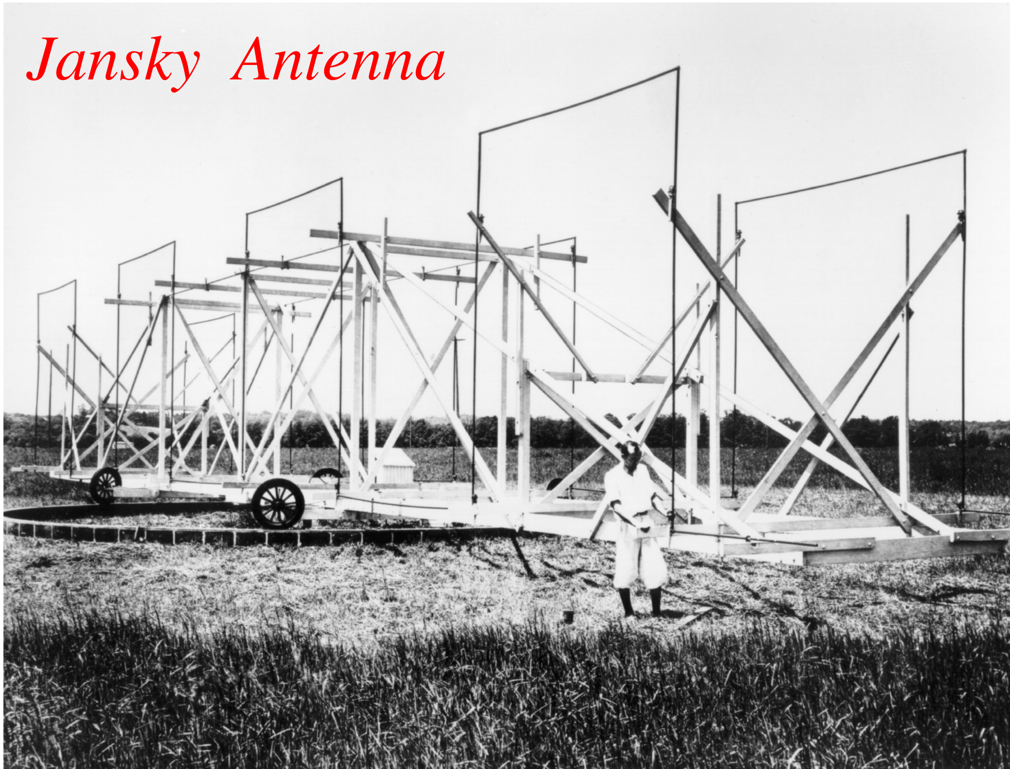
- 20.5 MHz antenna built to test trans-Atlantic transmission problems: Karl Jansky identified the centre of the Galaxy as a bright source! Most astronomers didn't take him seriously...

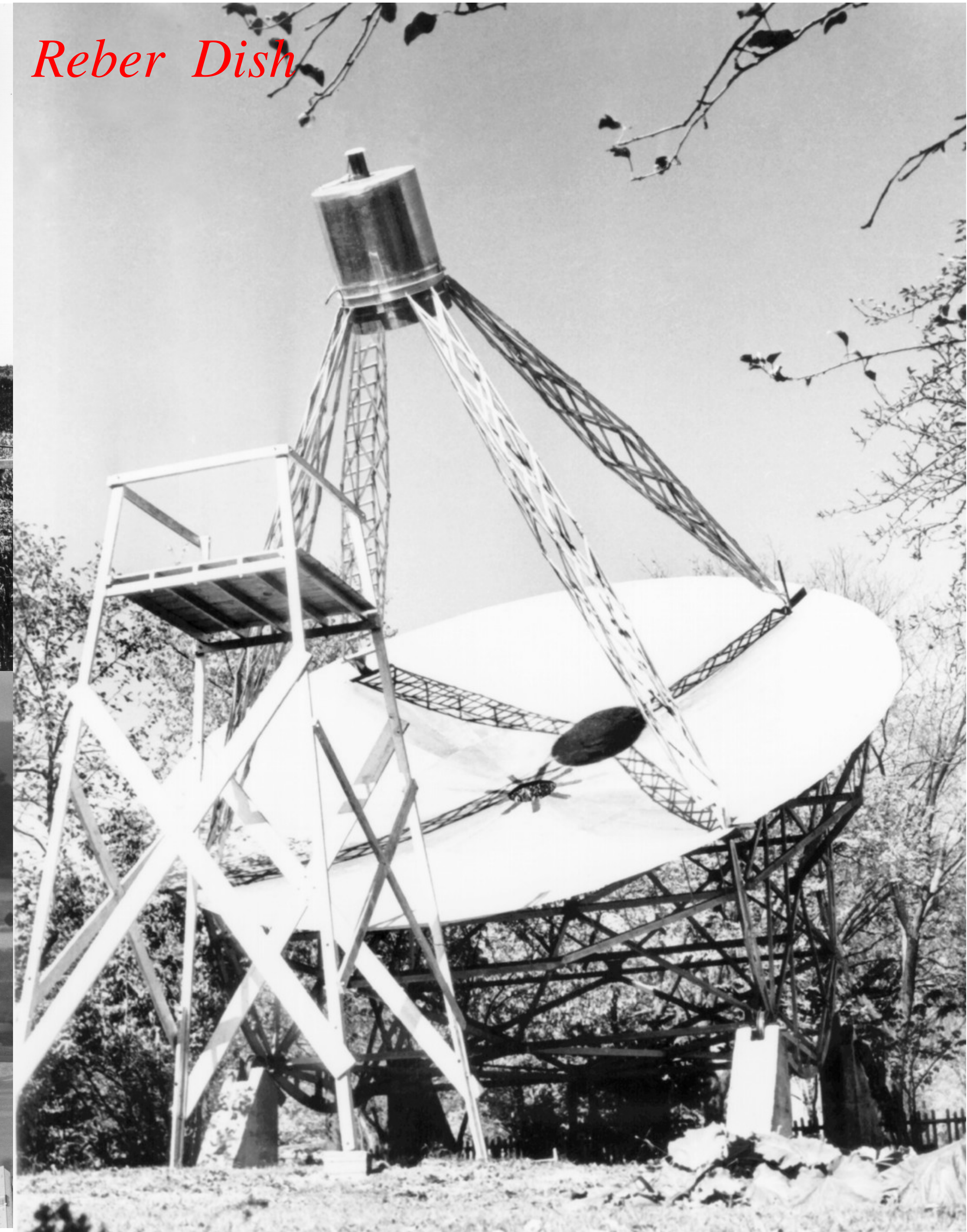
- First astronomy: Grote Reber built a dish, searched for Jansky's signals, re-detected them at 160 MHz, and mapped the Galaxy!
  "*The astronomers didn't know anything about radio and electronics and the radio engineers didn't know anything about astronomy. So I consulted with myself and decided to build a dish.*"

- First evidence for non-thermal emission processes in astronomy!

- Rapid progress due to radio and radar work during World War II. HI-21cm emission in 1951; radio interferometry over 1947 – 1955.

The Jansky and Reber Antennas





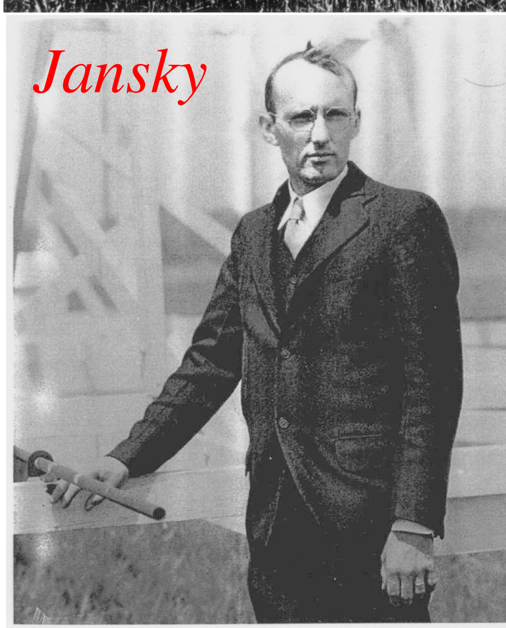
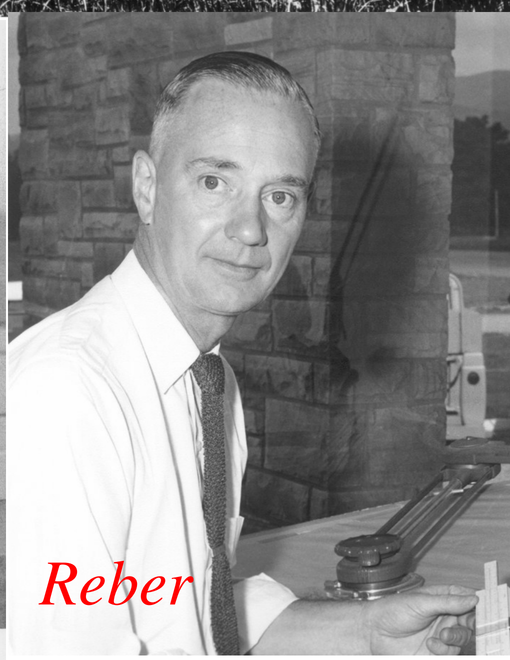


Fig. 1—Karl Guthe Jansky, about 1933.



Radio Astronomy: Why ?

- Some physical processes have signatures *only* (or primarily) at radio wavelengths, *e.g.* pulsars, jets and lobes of active galactic nuclei, the cosmic microwave background, etc.

- Critical spectral lines of the interstellar medium (e.g. the HI-21cm line of neutral hydrogen, molecular rotational lines, the CII-158μm line of ionized carbon, etc) all lie at radio wavelengths.

- Detailed maps of the velocity structure of galaxies and their dark matter content, out to high redshifts!

- Spectacular (sub-milliarcsecond) angular resolution with VLBI!

- Radio waves unaffected by dust obscuration!

- Main probe of magnetic fields in astronomy!

- ...

Astronomy at Radio Frequencies

- Basic aim: measure the *intensity* at radio frequencies coming from some part of the sky, possibly as a function of space, time and/or frequency.

- Angular resolution, frequency resolution, time resolution.

- Three categories of radio astronomy (telescopes):

  "Single-dish", "Interferometer", and "VLBI" studies.

- Three categories of radio astronomy (science):

  "Continuum", "Spectral-line", and "Pulsar" studies.

THE MEASUREMENTS

- The infinitesimal power dP intercepted by an infinitesimal surface $d\sigma$ is proportional to the bandwidth $d\nu$, the solid angle $d\Omega$ from which radiation is being received, and the surface area $d\sigma . \mathrm{Cos}\theta$ normal to the direction of incidence:

$$dP = I_\nu . \mathrm{Cos}\theta . d\sigma . d\Omega . d\nu$$

- I_ν is the "specific intensity" or "brightness". Units: $W\ m^{-2}\ Hz^{-1}\ sr^{-1}$.

- The "flux density" S_ν is the integral of I_ν over the solid angle subtended by the source:

$$S_\nu = {}_\Omega\int I_\nu(\theta,\phi)\ \mathrm{Cos}\theta\ d\Omega$$

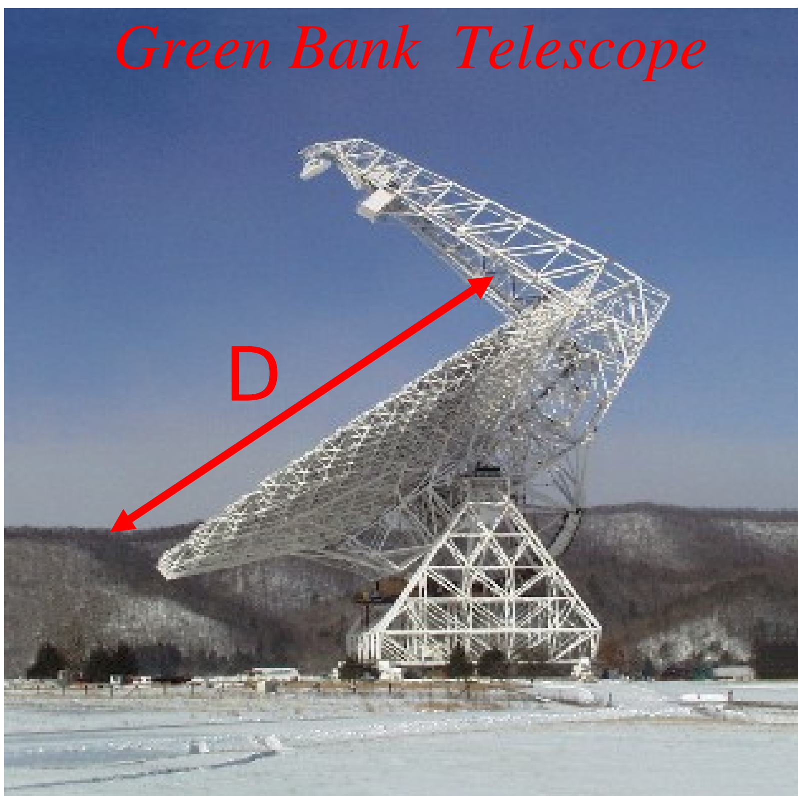
- The flux density S_ν is measured in Jansky: $1\ Jy = 10^{-26}\ W\ m^{-2}\ Hz^{-1}$.

- Dishes have a direction-dependent power pattern, the primary beam.

ANGULAR RESOLUTION

- Angular resolution: the smallest separation that you can measure.
  Resolution ~ (λ/D).
  D $\equiv$ Diameter for a single dish; longest baseline for an array.
  Interferometric arrays have much better angular resolution!

- Better angular resolution at higher frequencies!



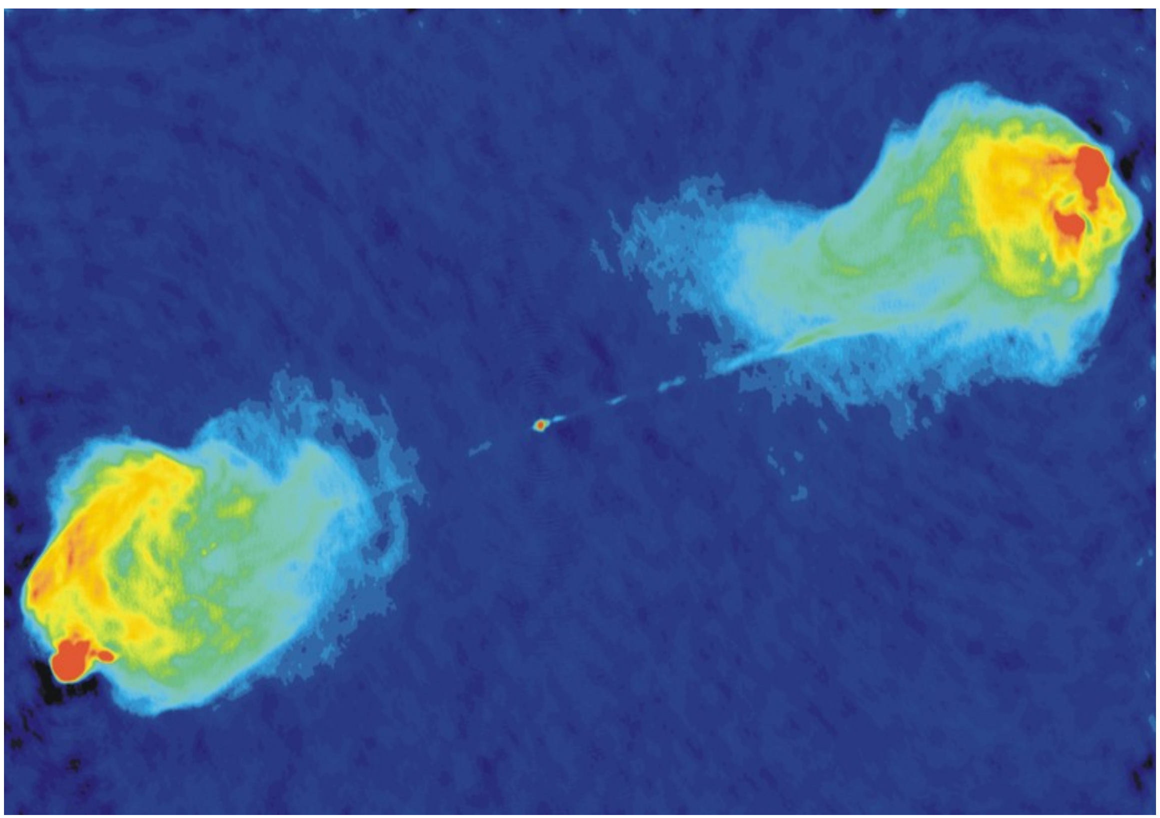
Single dish

Interferometer

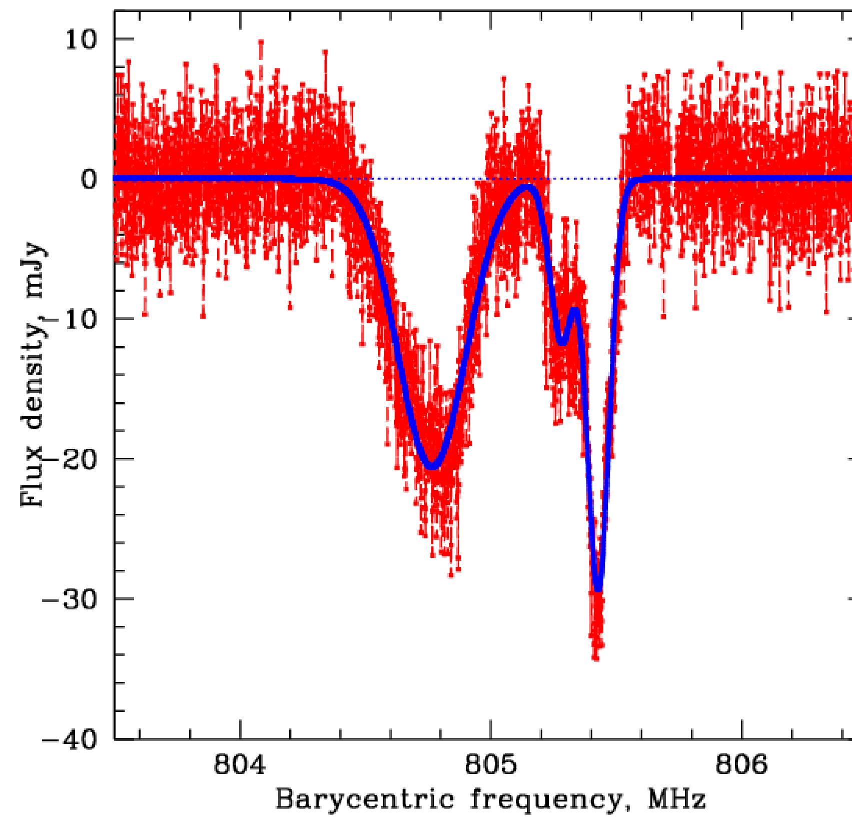
Frequency Resolution

- Accelerated charged particles: Broad-band radiation
  ⇨ "Continuum imaging", best done with wide bandwidths!

- Quantum transitions in atoms/molecules: "Spectral lines" at specific frequencies. Inherently narrow-band phenomenon!
  ⇨ Need high frequency resolution to detect spectral lines!



(Carilli et al. 1991, ApJ)



(Kanekar et al. 2005, PRL)

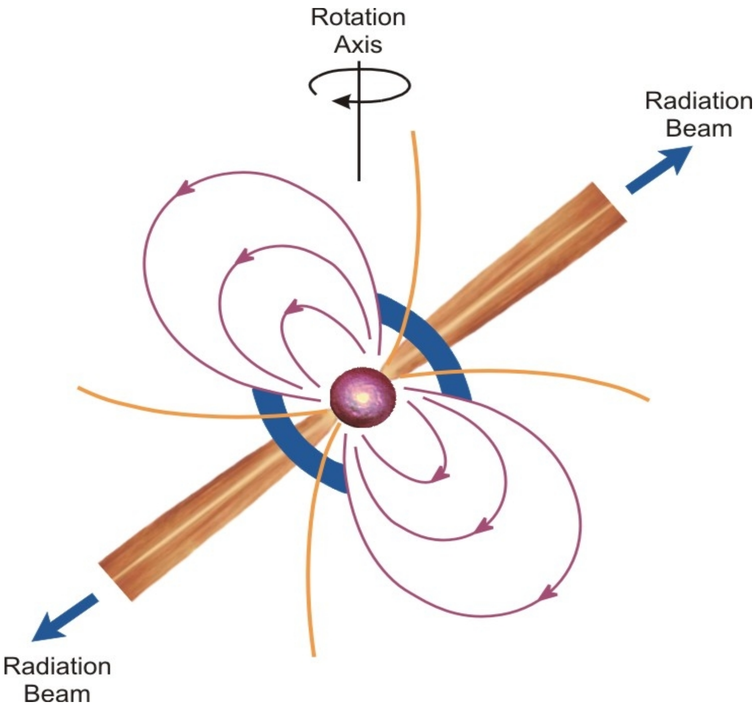
Time Resolution

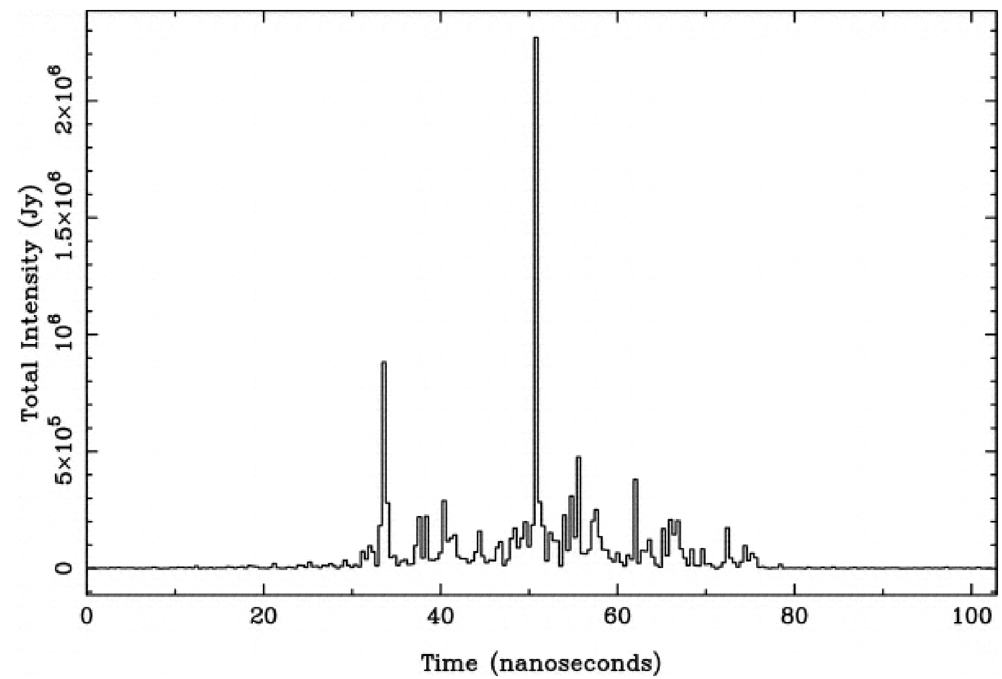
- High time resolution critical for observations of *transient* phenomena: e.g. pulsars, solar flares, etc.

- Pulsar periods range from ~ 1 milli-second to ~ few seconds;
  ⇨ Time resolutions of ~ 100 μ-seconds for pulsar studies!

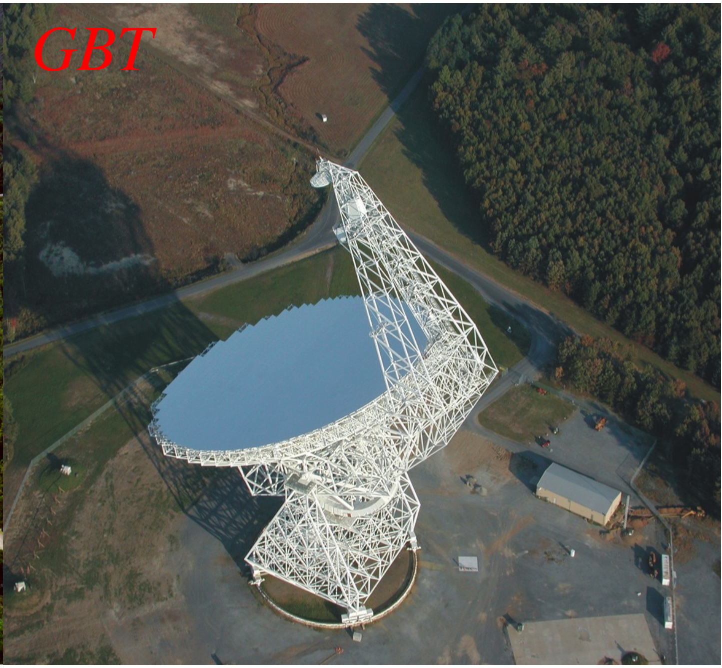
- Note: Structure also seen on time-scales of nanoseconds in individual giant pulses!

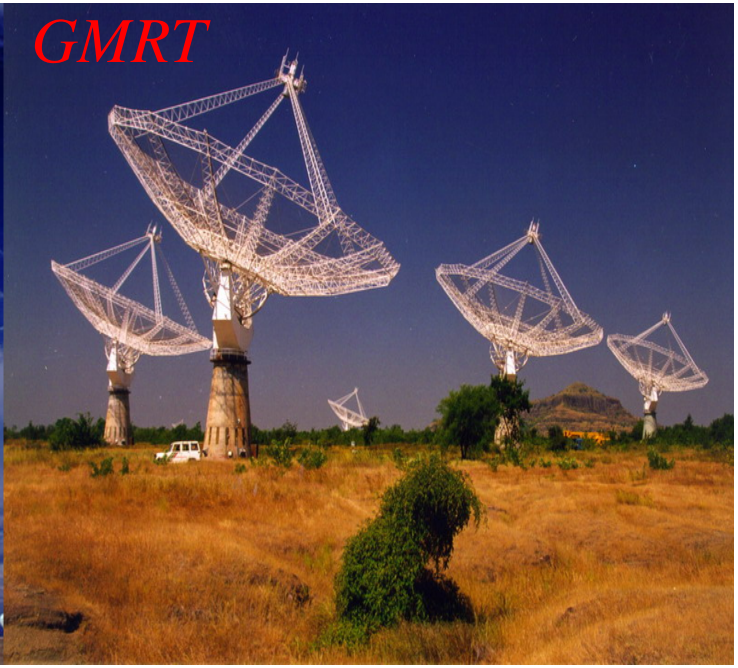
(Hankins et al. 2003, Nature)





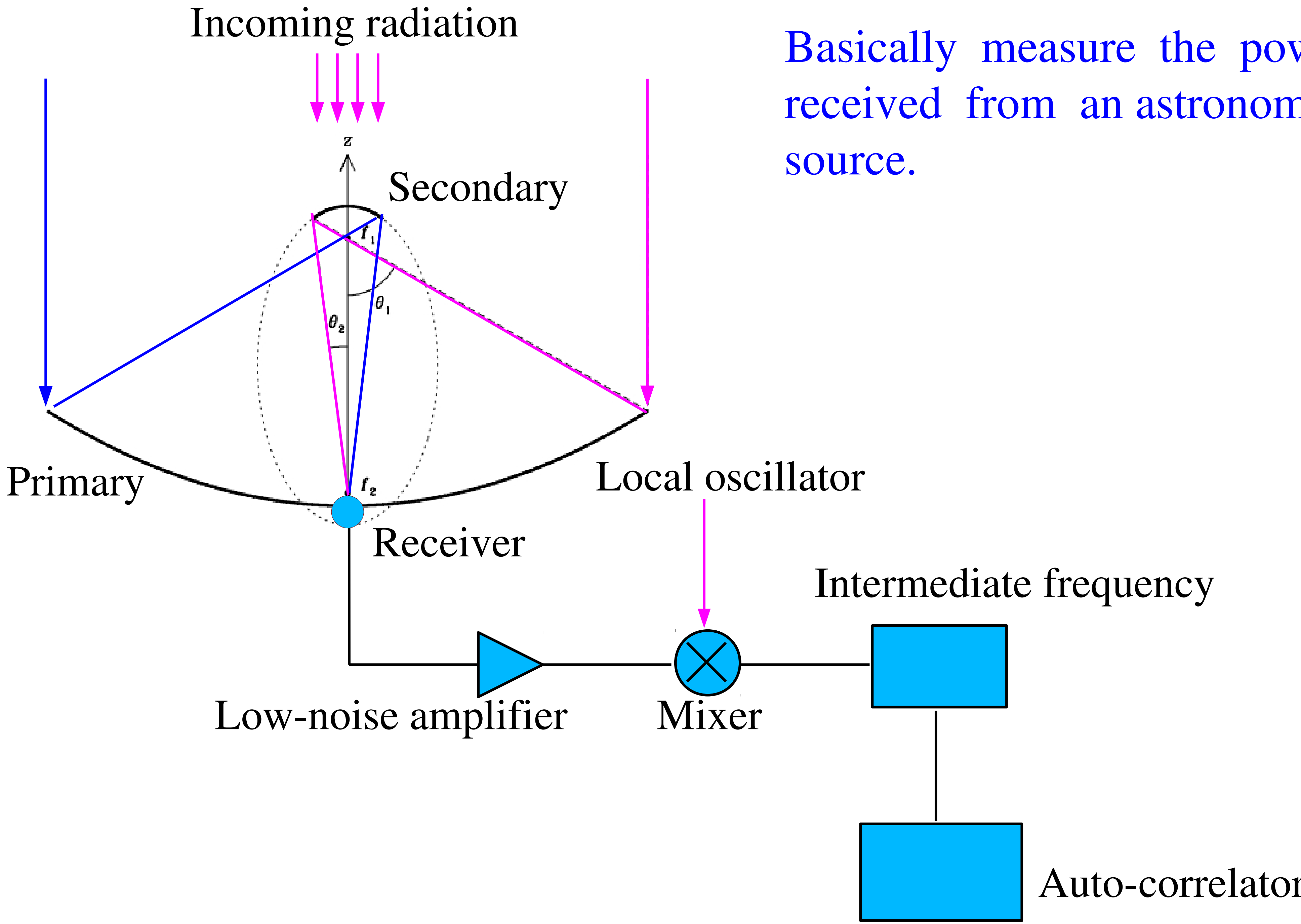
SINGLE DISHES AND INTERFEROMETERS





SINGLE-DISH RADIO TELESCOPES

Basically measure the power received from an astronomical source.



Single-Dish Radio Astronomy

- Sensitivity $\propto$ Collecting area $\propto D^2$; ($D \equiv$ Dish diameter).

- Angular resolution ~ λ/D: Larger dish $\Rightarrow$ better resolution.
  Biggest moving dishes (GBT, Effelsberg) ~ 100 metres.
  At a wavelength of 21 cm, ⇨ Angular resolution ~ 8'.

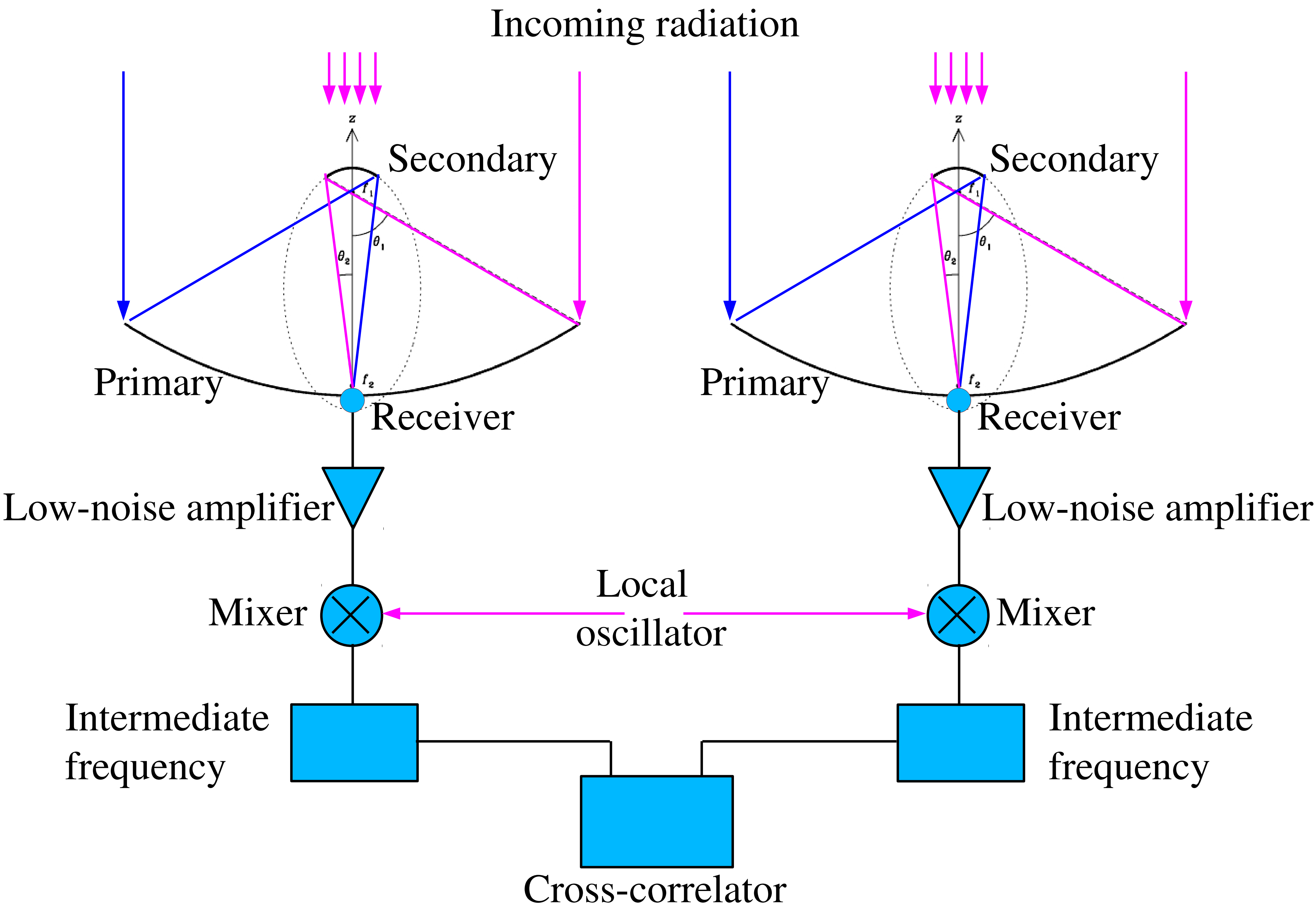
- Signals must be detected in the presence of noise from the receiver, as well as extra radiation from the ground, the atmosphere, the sidelobes, the feed legs, etc. This noise is quantified by the "system temperature", T_{sys}.

- RMS noise $\sigma_S \approx (T_{sys} / G) \times 1/[\Delta\nu.\Delta t]^{1/2}$, where G is the antenna "gain", $G = \eta.A/2k_B$; A is the collecting area of the dish, and η is its aperture efficiency.

Radio Interferometry

- Radio interferometer: A set of radio antennas that observe simultaneously to effectively yield a telescope of much larger size, but with an *incompletely filled* aperture.
- The effective telescope size is roughly the largest antenna spacing.
- The antenna locations are where the effective telescope samples radiation from sources in the sky. These locations are shifted around by the rotation of the Earth, giving better sampling.
- Connected-element interferometry: Typically, baselines < 50 km. E.g. the Very Large Array (27 dishes, 35 km, 1 – 50 GHz), the Giant Metrewave Radio Telescope (30 dishes, 25 km, 0.14 – 1.4 GHz), the Atacama Large Millimeter Array (50 dishes, 16 km, 30 – 900 GHz).
- Very Long Baseline Interferometry (VLBI): Baselines ~ 10,000 km. The Very Long Baseline Array (0.3 – 100 GHz, 10 dishes, 8600 km).

Radio Interferometers



RADIO INTERFEROMETRY

- Based on the van Cittert – Zernike theorem:
  The spatial correlation function $V(\mathbf{r}_1, \mathbf{r}_2) \equiv \langle E(\mathbf{r}_1).E^*(\mathbf{r}_2)\rangle$ of the signals measured by antennas at $\mathbf{r}_1$ and $\mathbf{r}_2$ depends only on $(\mathbf{r}_1\text{-}\mathbf{r}_2)$ and is the 2-D Fourier transform of the sky intensity distribution.

$$I_\nu(l,m) \approx \iint V_\nu(u,v) \,.\, \exp[-2\pi i(u.l + v.m)].\, du.dv$$

(u,v) are components of $(\mathbf{r}_1\text{-}\mathbf{r}_2)$; (l,m) are direction cosines in the sky

- Measure *cross-correlations* of the voltages obtained at different antennas, as a function of their separation. Then carry out a 2-D Fourier transform to infer the sky intensity distribution!

- As the Earth rotates, the separation of a pair of antennas relative to a given direction will change! So, each antenna pair measures $V(\mathbf{r}_1\text{-}\mathbf{r}_2)$ at a *changing* $(\mathbf{r}_1\text{-}\mathbf{r}_2)$, i.e. at a different (u,v) point, as the Earth rotates; this gives a better sampling of the Fourier plane!

⇨ Earth-rotation Aperture Synthesis

RADIO INTERFEROMETRY

- Sensitivity $\propto$ Collecting area $\propto$ $N \times D^2$ (N = no. of antennas).

- RMS noise, $\sigma_S \approx (T_{sys} / G) \times 1/[N(N-1) \times \Delta\nu \times \Delta t]^{1/2}$.

- Angular resolution ~ λ/L (where L is the longest baseline).
  For GMRT, L ~ 25 km ⇨ 21cm angular resolution ~ 2".
  For VLBA, L ~ 8,600 km ⇨ 21cm angular resolution ~ 5 mas!

- If L_1 and L_2 are the longest and shortest baselines ⇨ Information on the radio emission on angular scales between (λ/L_1) & (λ/L_2).

- The image of the sky is obtained via a 2-D Fourier transform of the cross-correlations measured on the ground ⇨ Requires that the antenna baselines cover the ground as uniformly as possible!

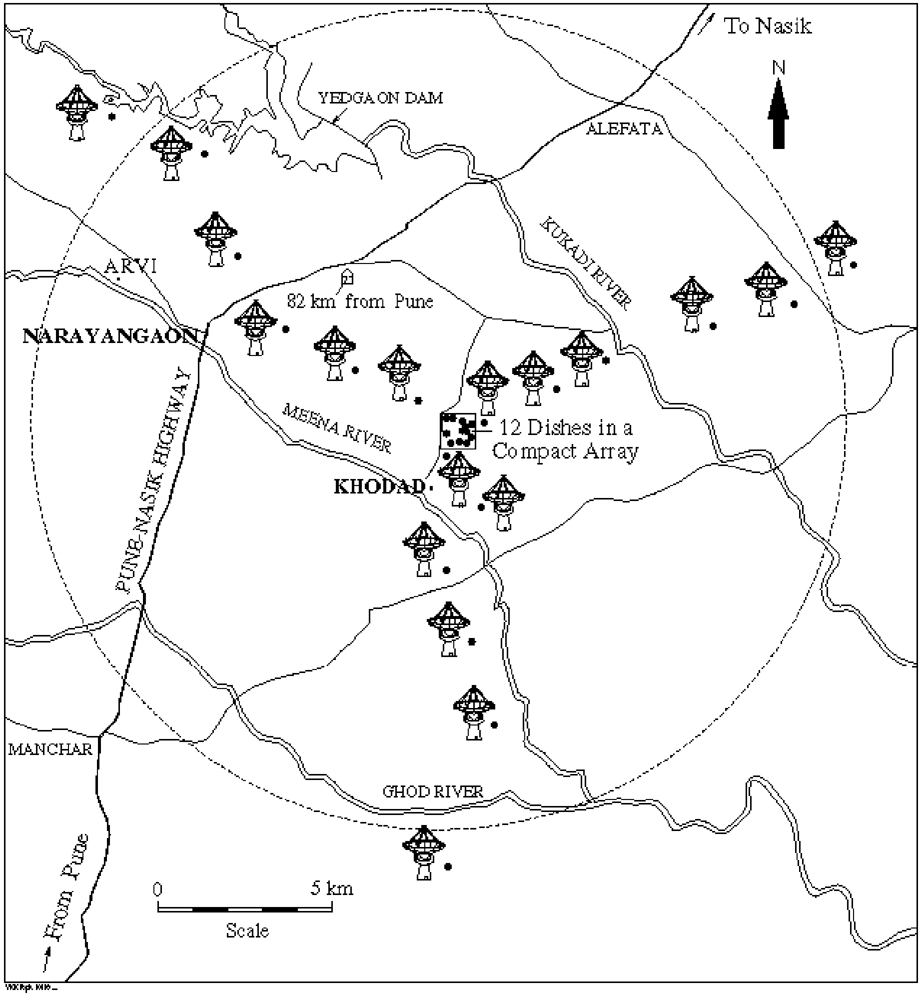
- Distribute the N antennas so as to obtain the best (most uniform) coverage of the 2-D Fourier plane, for *all* directions.

ARRAY CONFIGURATIONS

- Y-shaped array optimal for ~ 20 – 40 antennas (VLA, GMRT). Random or spiral array for more than ~ 50 antennas.

- VLA: 27 antennas on rails. Moved every 4 months to optimize the coverage (1, 3.3, 11, 35 km).

LOCATIONS OF GMRT ANTENNAS (30 dishes)

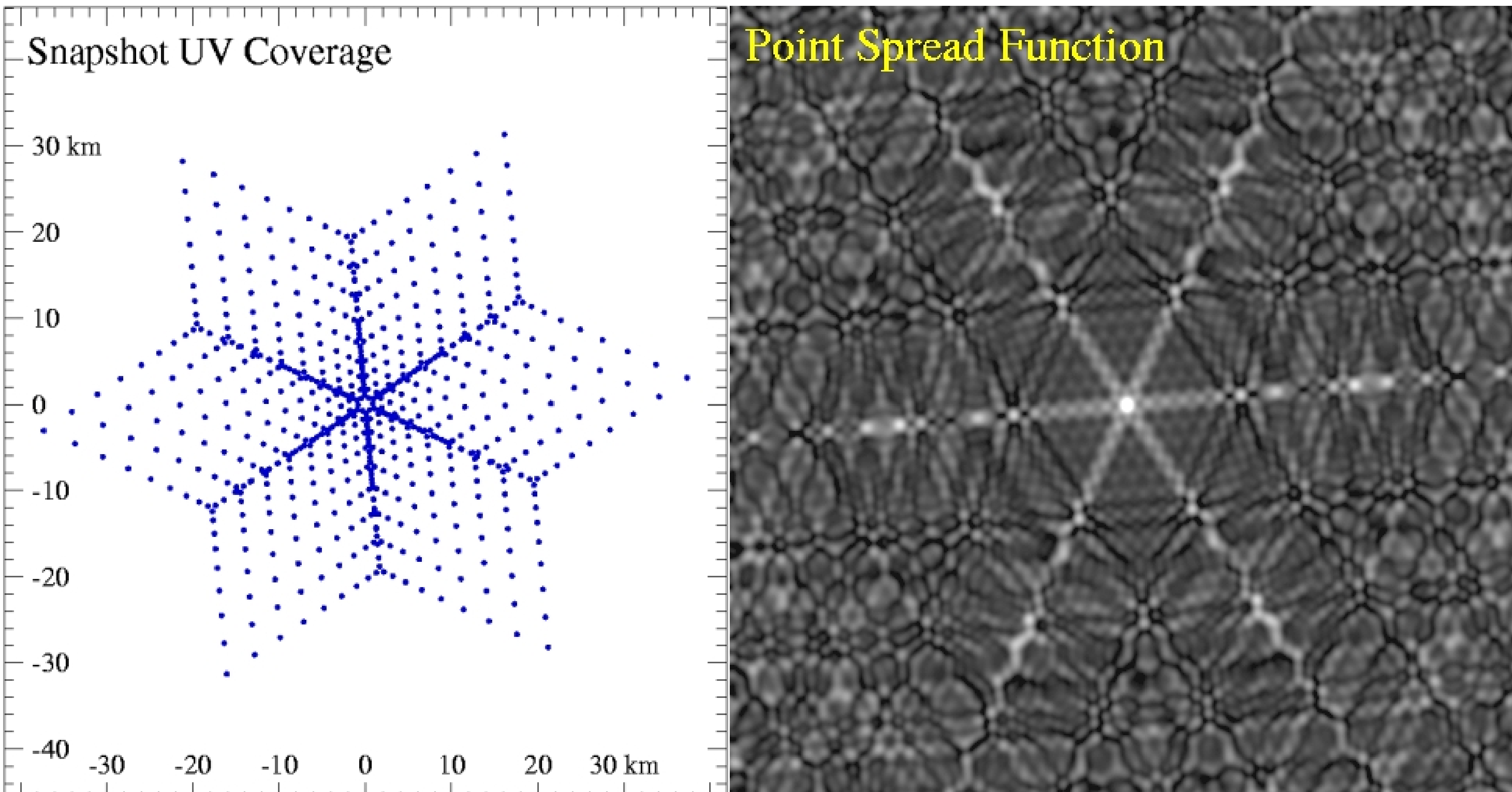


- GMRT: 30 fixed antennas, in an optimal distribution (25 km).

ARRAY U-V COVERAGE

- The U-V coverage is the set of all baseline vectors during the observations. Its 2-D Fourier transform is the point spread function (PSF) or the array "synthesized beam".

5-minute "snapshot" observation

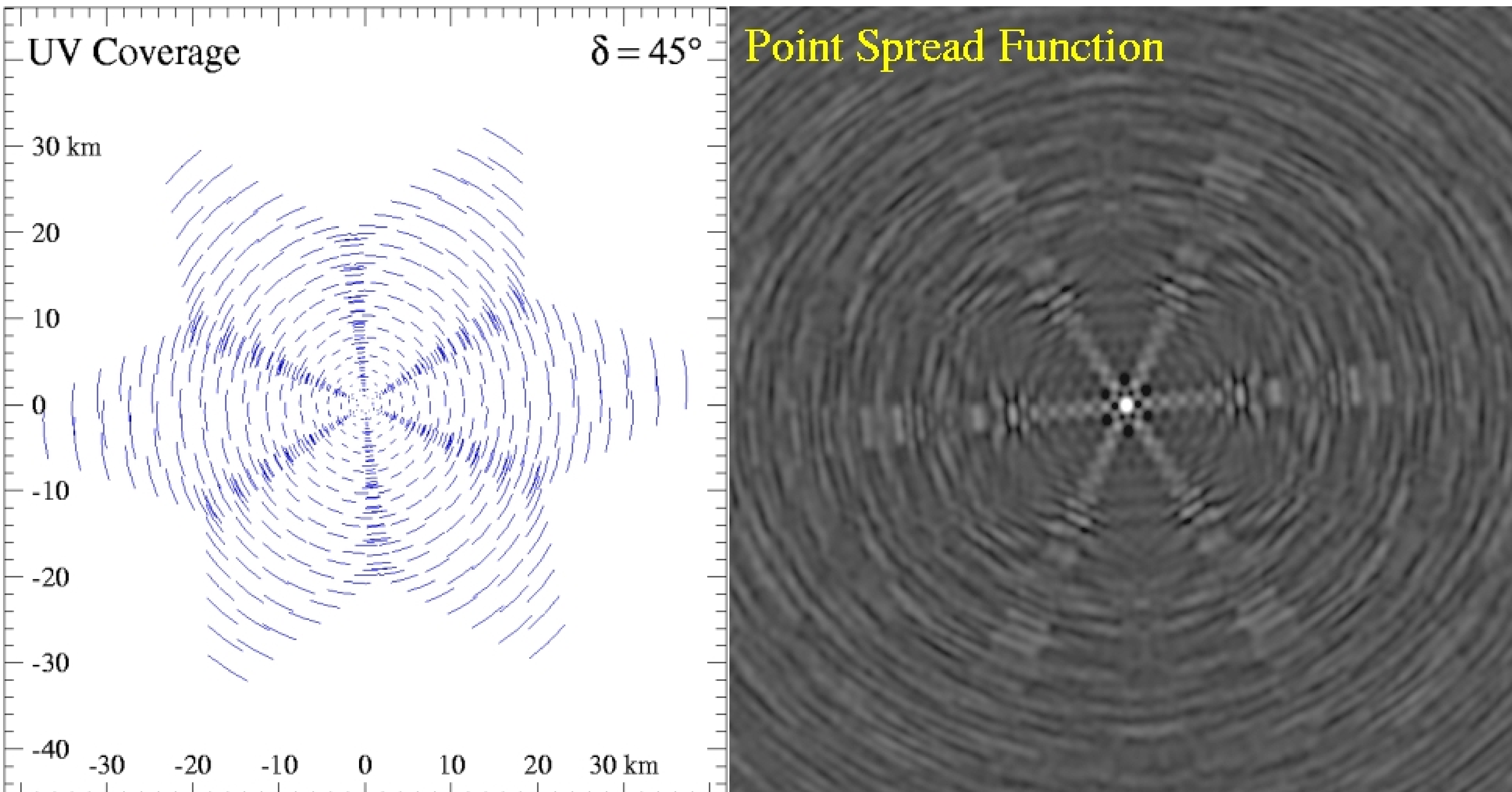


(Image courtesy of Craig Walker and NRAO/AUI)

ARRAY U-V COVERAGE: SHORT TRACK

- For longer tracks, Earth rotation causes a baseline between two antennas to move in the U-V plane. Observing a source for even a few hours hence gives a much better U-V coverage.

1-hour “short” track

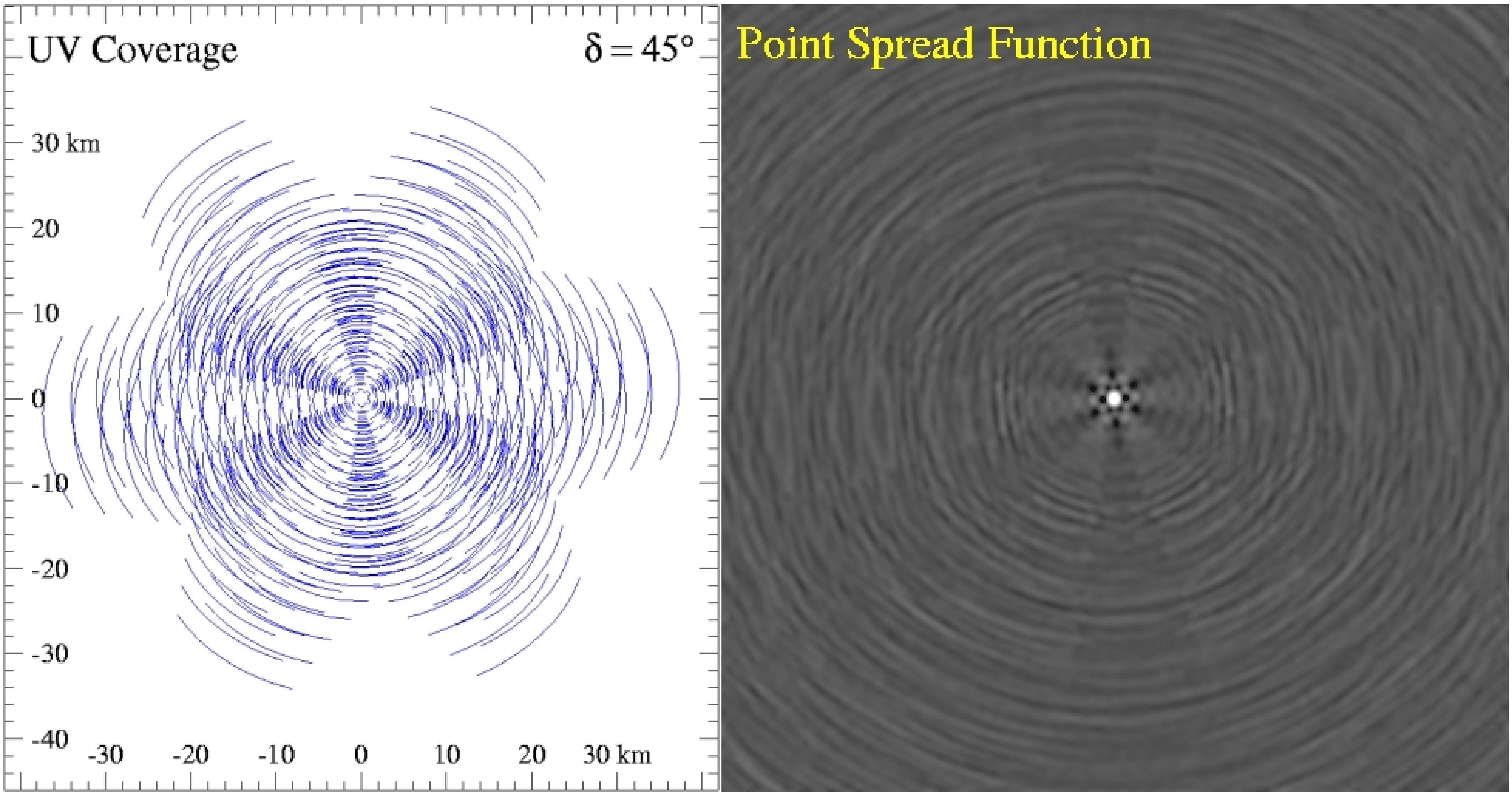


(Image courtesy of Craig Walker and NRAO/AUI)

Array U-V Coverage: Medium Track

- Note: The improved U-V coverage implies a significantly "cleaner" array synthesized beam (e.g. less structure in the PSF) !

3-hour "medium" track

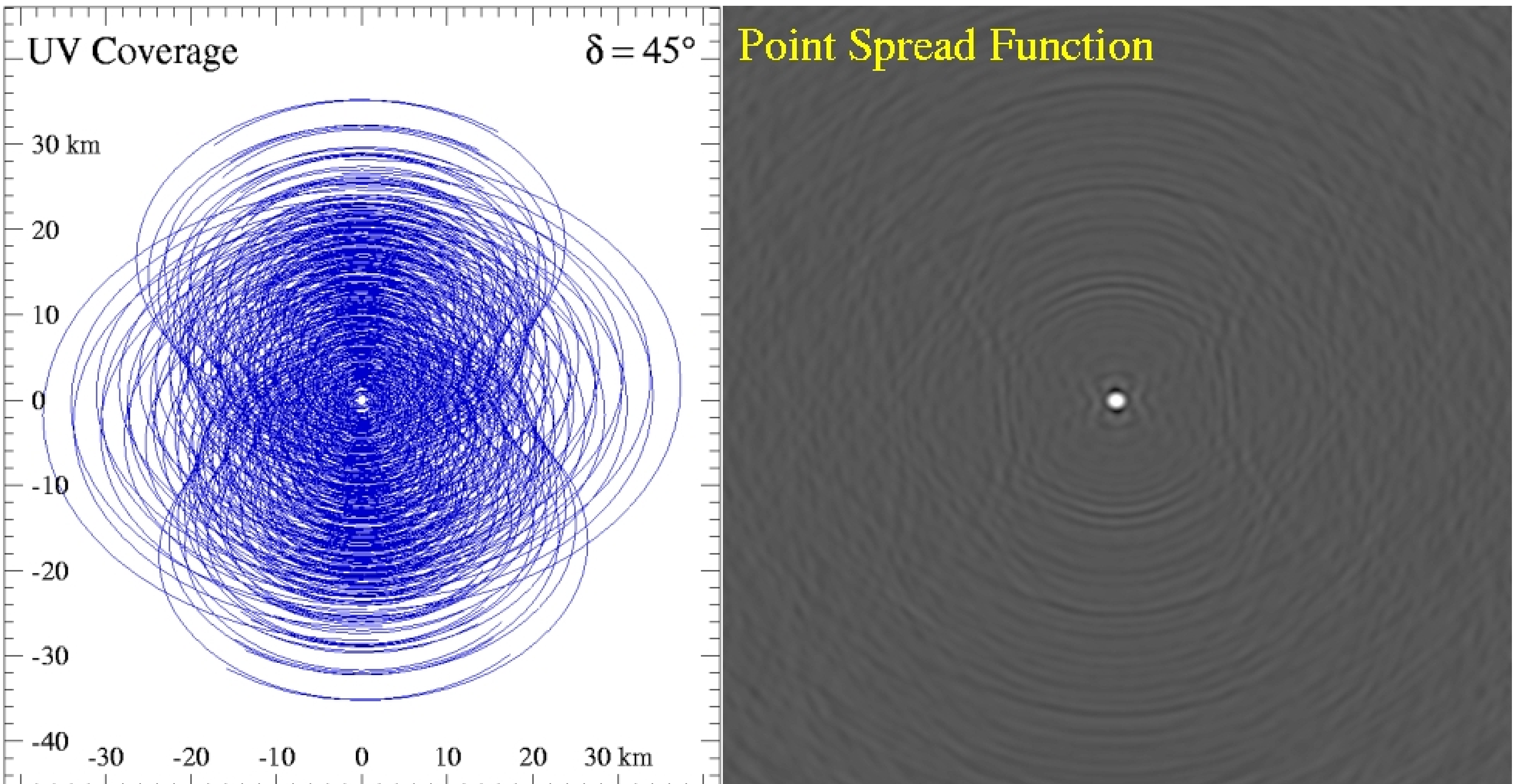


(Image courtesy of Craig Walker and NRAO/AUI)

Array U-V Coverage: Full Synthesis

- The maximum shift in the baseline between 2 antennas in the U-V plane occurs when one tracks a source from rise to set. This gives the best U-V coverage and the cleanest synthesized beam.

12-hour "full synthesis"



(Image courtesy of Craig Walker and NRAO/AUI)

A Radio Telescope

- Single dish (GBT, Arecibo), Interferometer (VLA, GMRT) or VLBI.
- Observing frequencies, collecting area, system temperature.
- For interferometers, number of dishes and U-V coverage.
- Correlator capacity: Bandwidth and number of channels.
- Sky coverage: e.g. Arecibo can only observe declinations $\sim 0^\circ - 40^\circ$.
- Time resolution and angular resolution.
- Prime focus or secondary focus receivers ?
  On-axis (most) or off-axis (GBT) receivers ?
  Equatorial (WSRT) or Alt-azimuth (most) mounts ?
- How bad is the radio frequency interference environment ?