

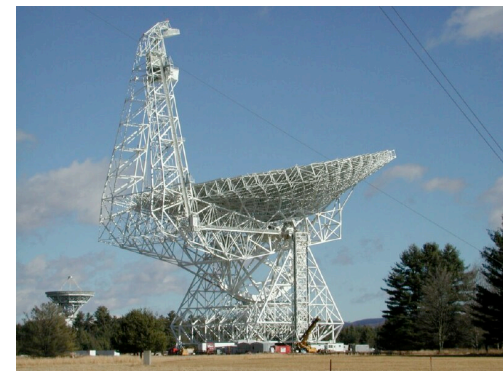
# Radio Astronomy

## Lecture I

### **The History of Radio Astronomy: Past to Present**

Lecturer: Joeri van Leeuwen ([leeuwen@astron.nl](mailto:leeuwen@astron.nl))

SP A1.20 - April 3, 2017



# Course Goals

Get you excited about radio astronomy!

Give a broad overview of the science, techniques and context of radio astronomy.

Enable the student to feel comfortable with using radio astronomical observations as part of their multi-wavelength science approach or set them on the path to being a radio astronomer.

# Resources

## Course Wiki

[https://www.astron.nl/astrowiki/doku.php?id=uva\\_msc\\_radioastronomy\\_2017](https://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2017)

Main resource for the course, and includes:

- Schedule
- Lecture slides
- Practicum materials
- Materials from other similar courses
- Recommended books

# Lecturers

Coordinator: Jason Hessels ([j.w.t.hessels@uva.nl](mailto:j.w.t.hessels@uva.nl))

Joeri van Leeuwen ([leeuwen@astron.nl](mailto:leeuwen@astron.nl))

Michael Wise ([wise@astron.nl](mailto:wise@astron.nl))

# Teaching Assistants

Daniele Michilli ([danielemichilli@gmail.com](mailto:danielemichilli@gmail.com))

# Marking Scheme

**35% - Observing proposal and presentation**

(written proposal: 20%, oral presentation 15%)

**35% - Other Practica**

(simulate interferometer: 10%, VLA imaging: 15%, pulsar search: 10%)

**30% - Final exam**

# Lectures

## (and other important sessions)

Lecture 1: Apr 3, 2017 - The History of Radio Astronomy: Past to Present - Joeri

Lecture 2: Apr 7, 2017 - The Science of Radio Astronomy: Extragalactic - Michael

Lecture 3: April 10, 2017 - The Science of Radio Astronomy: Galactic and Solar System - Joeri

Lecture 4: April 21, 2017 - Emission Mechanisms in Radio Astronomy - Jason

Lecture 5: April 24, 2017 - The Radio Telescope - Joeri

Lecture 6: May 1, 2017 - The Techniques of Radio Interferometry I: The Basics - Jason

Lecture 7: May 8, 2017 - The Techniques of Radio Interferometry II: Calibration - Michael

Lecture 8: May 12, 2017 - The Techniques of Radio Interferometry III: Imaging - Michael

Lecture 9: May 15, 2017 - The Techniques of Time-Domain Radio Astronomy I: Single-dish techniques - Joeri

May 18, 2017 - Field Trip to LOFAR and Westerbork - Michael + Joeri + Jason + Daniele

Lecture 10: May 19, 2017 - The Techniques of Time-Domain Radio Astronomy II: High time resolution with interferometers - Jason

Lecture 11: May 22???, 2017 - The Future of Radio Astronomy - Michael **(NAC: May 22-24)**

**May 24???, 2017 - Observing proposal presentations - All (NAC: May 22-24)**

**Jun 2, 2017 - Final Exam - Jason + Daniele**

# Practica

(follow lectures; work also required outside “lab” time)

Practicum 1 - Apr 3 - Joeri + Daniele - Short lecture on how to write an observing proposal (see slides below).

Practicum 2 - Apr 7 - Jason + Joeri + Michael + Daniele - Discuss observing proposal ideas in a group (outside if possible!).

Practicum 3 - Apr 10 - Arrange appt. w your advisor - Discuss observing proposal ideas one-on-one.

Practicum 4 - Apr 21 - Jason - Work on observing proposal yourself.

Practicum 5 - Apr 24 - Jason + Daniele - Setup computing environment.

Practicum 6 - May 1 - Jason - Simulate your own interferometer - session I.

Practicum 7 - May 8 - Michael - Simulate your own interferometer - session II.

Practicum 8 - May 12 - Michael - Calibrate and image VLA data - session I.

Practicum 9 - May 15 - Joeri - Calibrate and image VLA data - session II.

RA Field Trip - May 18 - All day

Practicum 10 - May 19 - Jason - Search and time pulsar in LOFAR data - session I.

Practicum 11 - May 22??? - Michael - **(NAC: May 22-24)** - Search and time pulsar in LOFAR data - session II.

Final Presentations - May 24??? - All - **(NAC: May 22-24)**

# Questions?



# The History of Radio Astronomy: Past to Present

# Lecture outline

- Key figures in the pre-history of radio astronomy
- Key figures in early radio astronomy
- Seminal discoveries and nobel prizes
- Key instruments
- The current landscape

# Key figures in the pre- history of radio astronomy

# James Clerk Maxwell

(1831-1879)



- Maxwell's equations encapsulated all that was known about electricity and magnetism.
- Unify electricity and magnetism as a single electromagnetic force.
- Maxwell's equations predict electromagnetic waves.
- Light is a form of electromagnetic radiation.

So do natural (astronomical) sources produce em-waves?

# Maxwell's Equations

Gauss's Law

$$1. \nabla \cdot \mathbf{E} = 4\pi\rho$$

Faraday's Law of Induction

$$2. \nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

Gauss's Law for Magnetism

$$3. \nabla \cdot \mathbf{B} = 0$$

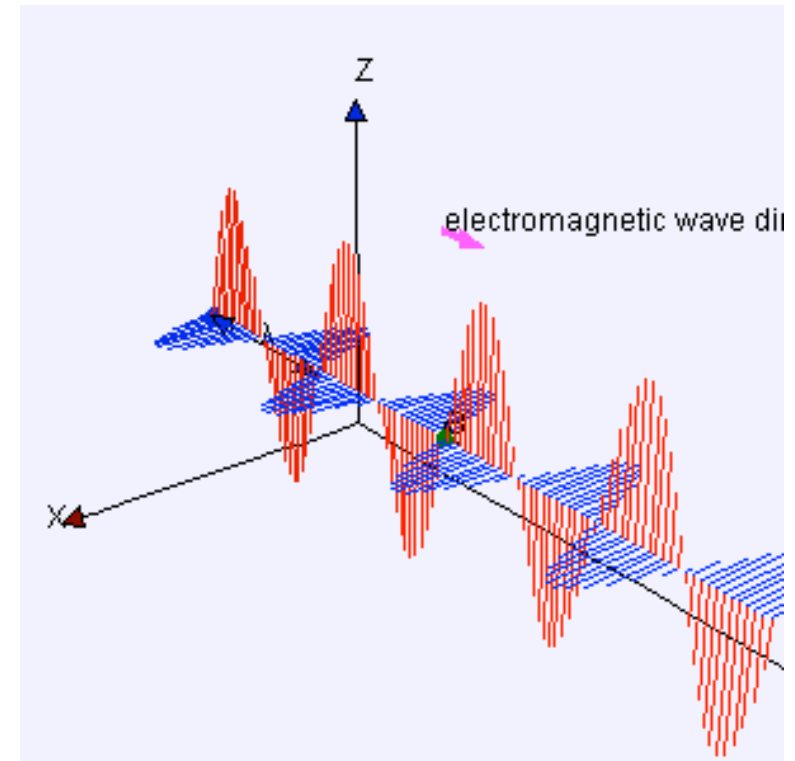
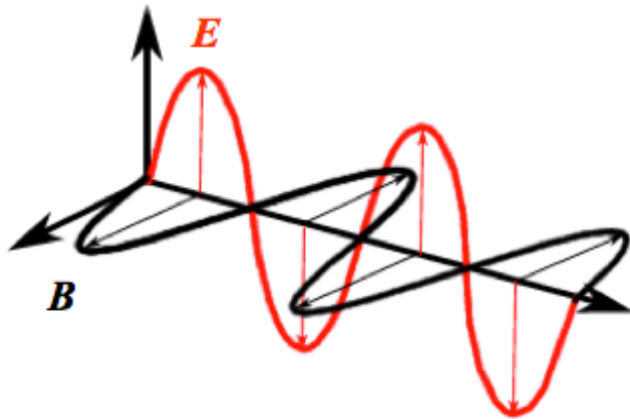
Ampere's Circuital Law

$$4. \nabla \times \mathbf{B} = \frac{4\pi\mathbf{J}}{c} + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}$$

# Maxwell's Equations

$$\mathbf{E}(\mathbf{r}, t) = E_0 \sin(\omega t - \mathbf{k} \cdot \mathbf{r} + \varphi_0)$$

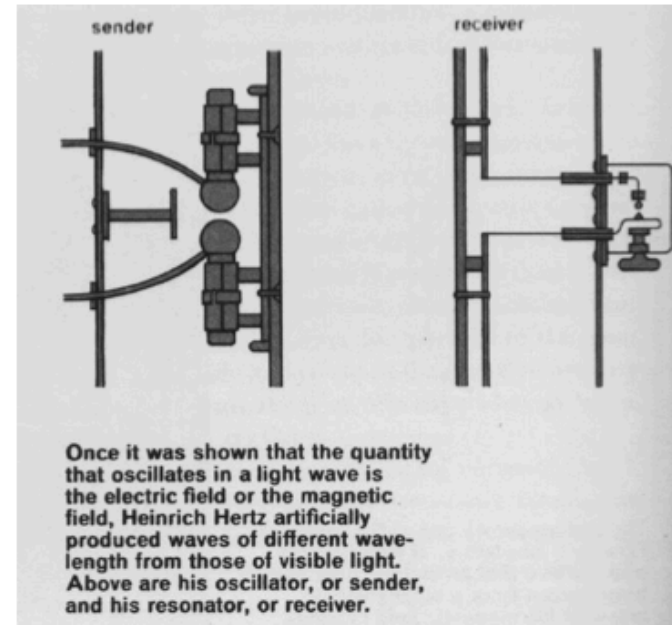
$$\mathbf{B}(\mathbf{r}, t) = B_0 \sin(\omega t - \mathbf{k} \cdot \mathbf{r} + \varphi_0)$$



Solution is a wave

# Heinrich Hertz

(1857-1894)



- First observation of electromagnetic waves (“Hertzian” or “aetheric” waves).
- In 1888 built a system for sending and receiving 5-m radio waves.

# Guglielmo Marconi

(1874 - 1937)



- Italian (also heir to Irish/Scots Whiskey distillery *Jameson & Sons*).
- Improved transmitter and receiver designs and made communication practically possible (Nobel Prize 1909).
- 1901: communication between Newfoundland, Canada and Cornwall, UK (though some skepticism about exact first detection).
- Father of long-distance radio communication.
- Mussolini was his best man at second wedding



# Nobel Prize Physics 1909



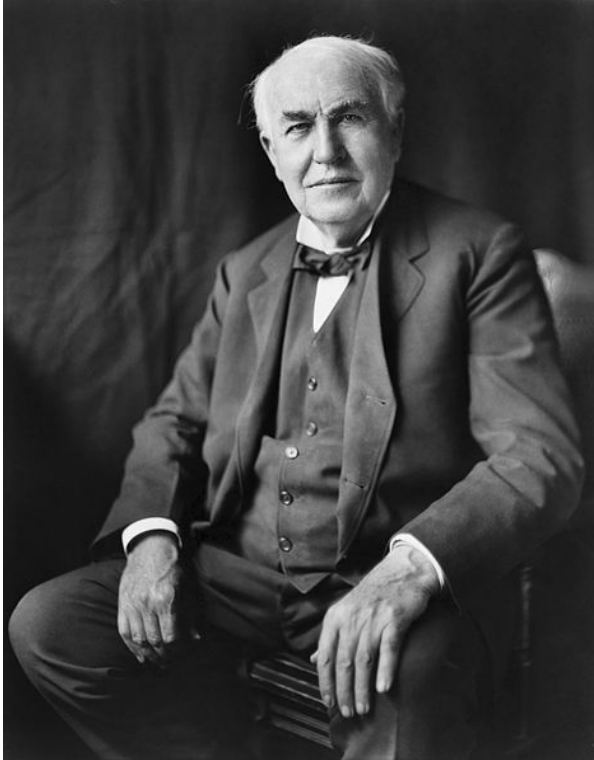
Guglielmo Marconi & Karl Ferdinand Braun

*"in recognition of their contributions to the development of wireless telegraphy"*



# Thomas Edison

(1847 - 1931)

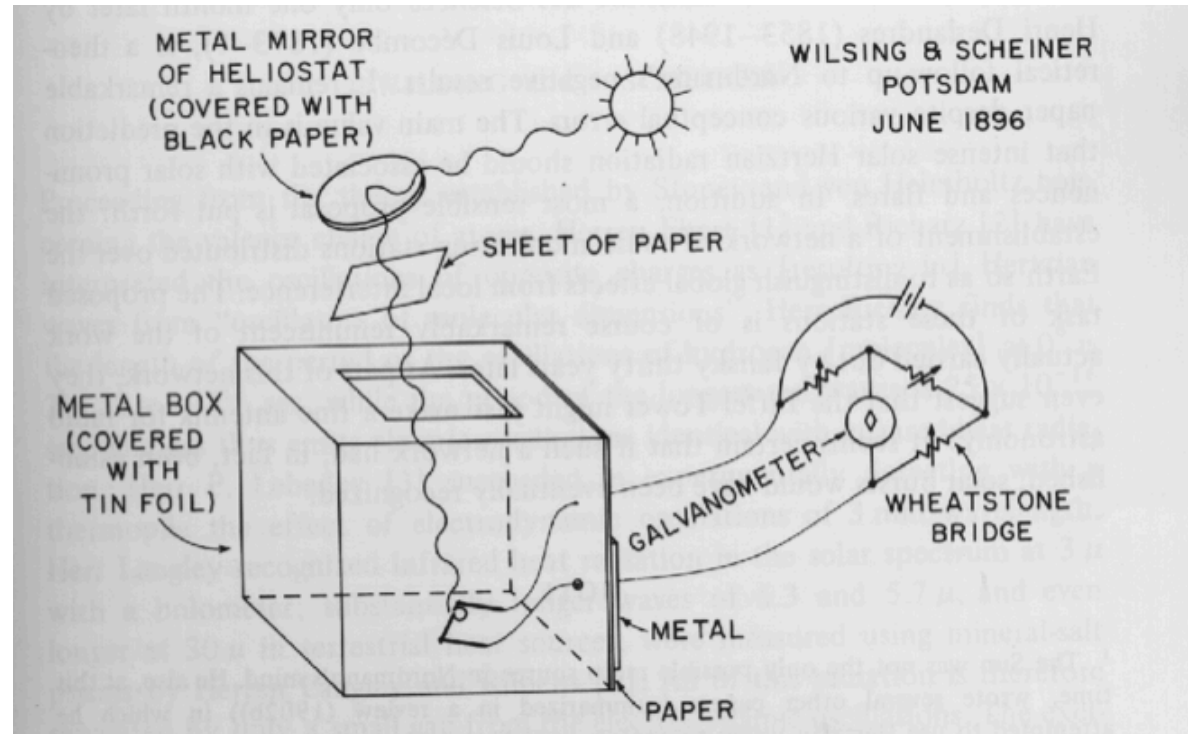


- First recorded suggestion of looking for astronomical sources of radio waves (1890).

# Johannes Wilsing & Julius Scheiner

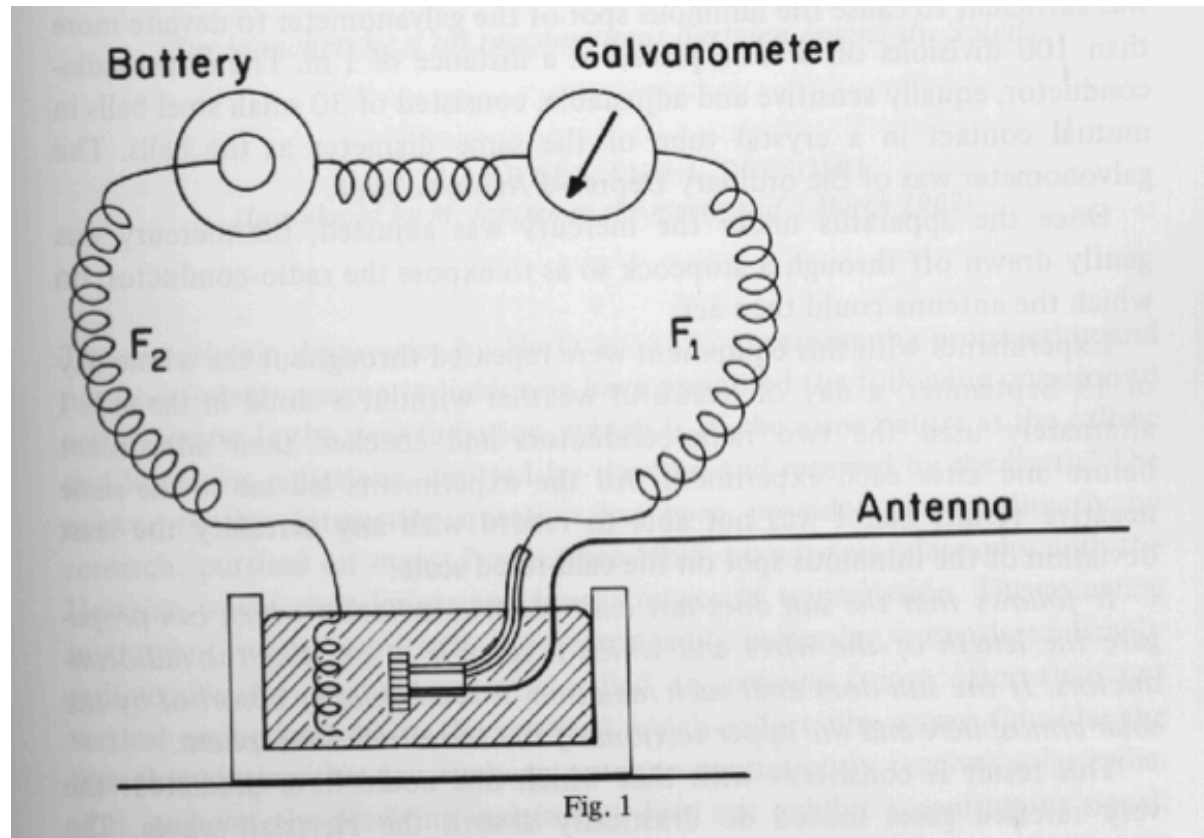
(1856 - 1943)

(1858 - 1913)



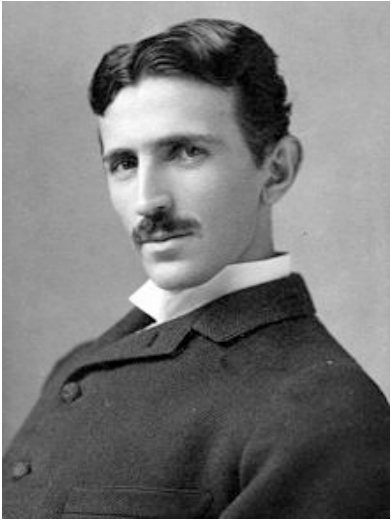
- Astrophysicists.
- First to properly publish their attempt to detect the Sun in radio (Ann. Phys. Chem. 59, 782, 1896; in German).
- Atmospheric absorption to blame?

# Charles Nordman



- French graduate student.
- Took experiment to top of Mont Blanc (avoid absorption).

# Still more attempts...



- Nikola Tesla & Oliver Lodge also tried to detect Sun, unsuccessfully.



# Max Planck

(1858 - 1947)



- Explanation of black-body spectrum using “quanta” of energy.
- Prediction for the Sun shows very little thermal radio emission.

# Oliver Heaviside

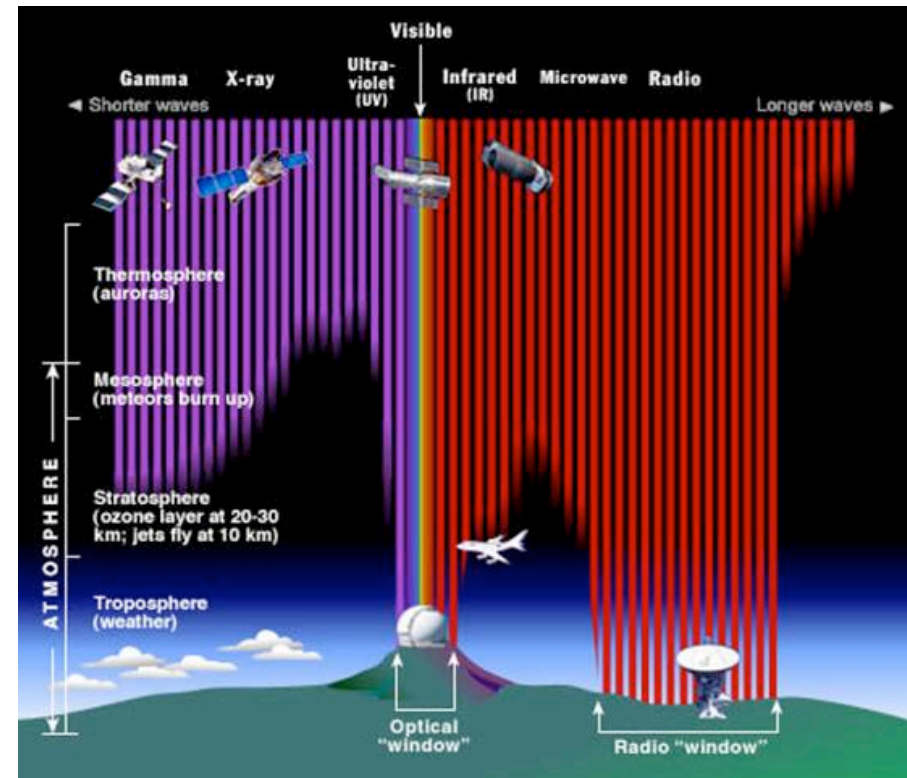
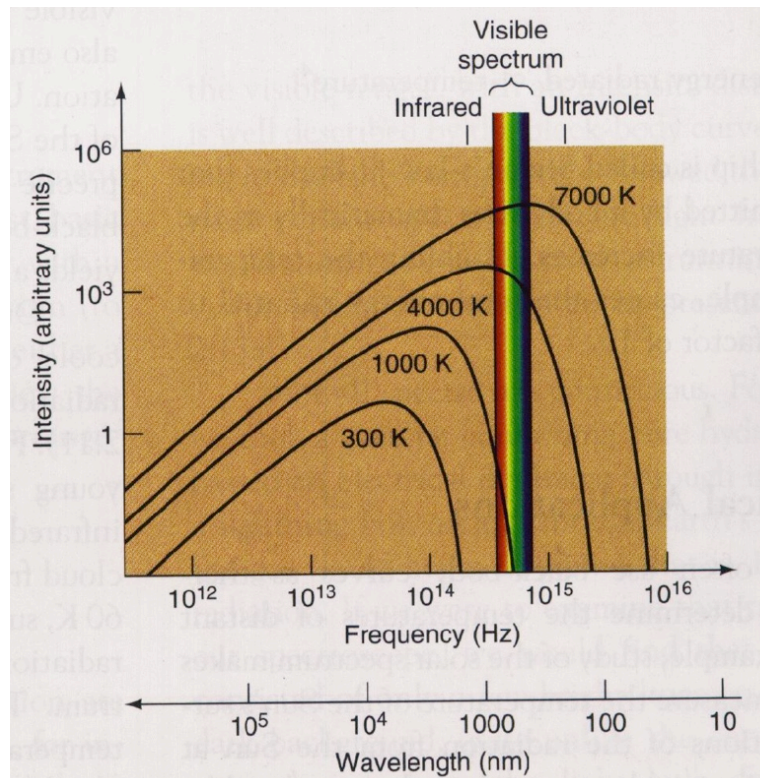
(1850 - 1925)



- British.
- Ionized ionospheric layer will reflect low-frequency radio waves ( $< 10\text{-}20\text{MHz}$ ).
- Ionosphere predicted in 1902, observed in 1920.
- The “Kennelly-Heaviside” layer.

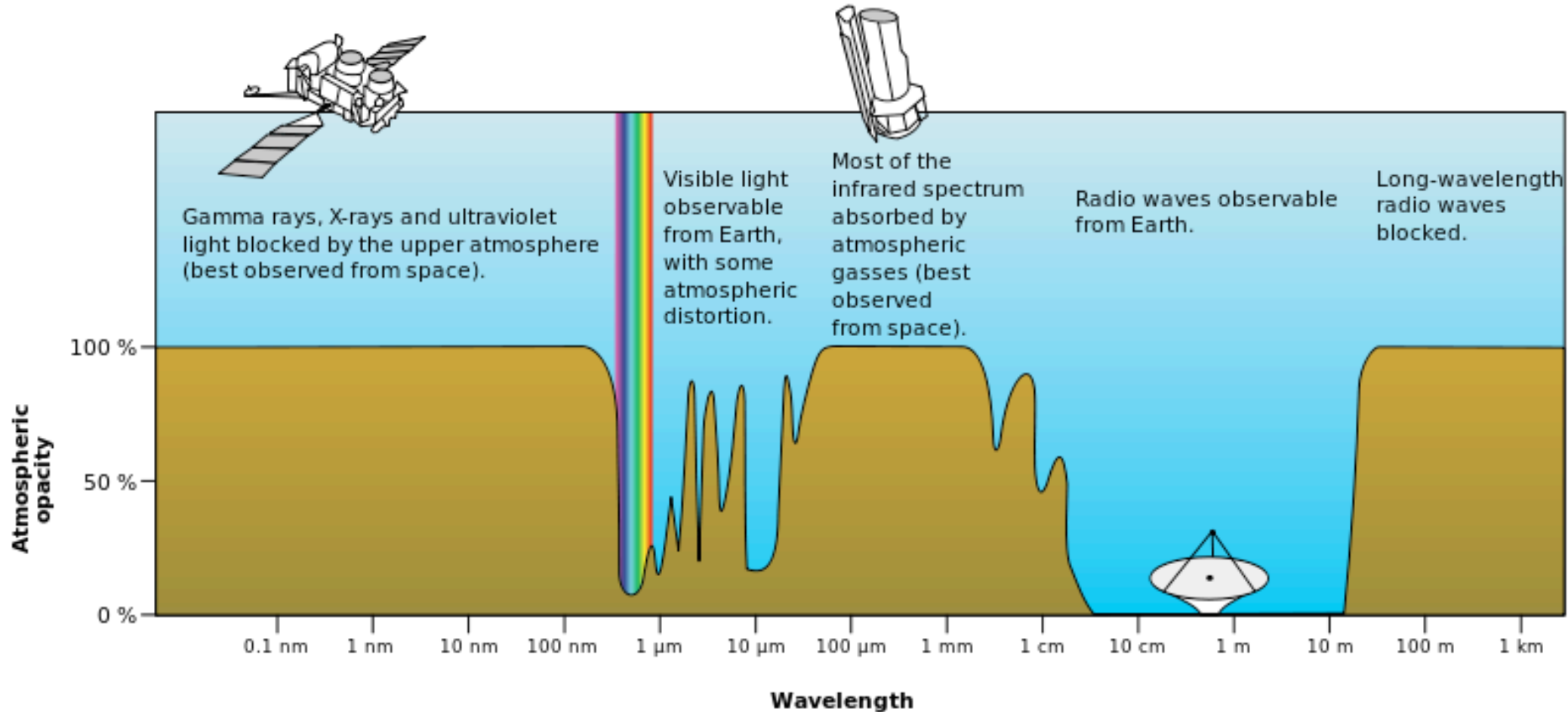
# 1902-1932

- People discouraged by Planck's prediction of low thermal brightnesses.
- Attempts also discouraged because of the ionosphere.





# EM Spectrum



- Only optical/IR and radio pass through the atmosphere.
- Radio window: 1 cm - 30m / 10MHz - 30 GHz (or more)

# Key figures in early radio astronomy

# Karl Guthe Jansky

(1905-1950)



- American
- Engineer at Bell Telephone Laboratories.
- Investigating interfering static in wireless communication.
- Directional antenna (at 20MHz).
- Repeating signal at the 23h56m siderial rate.

# Karl Guthe Jansky

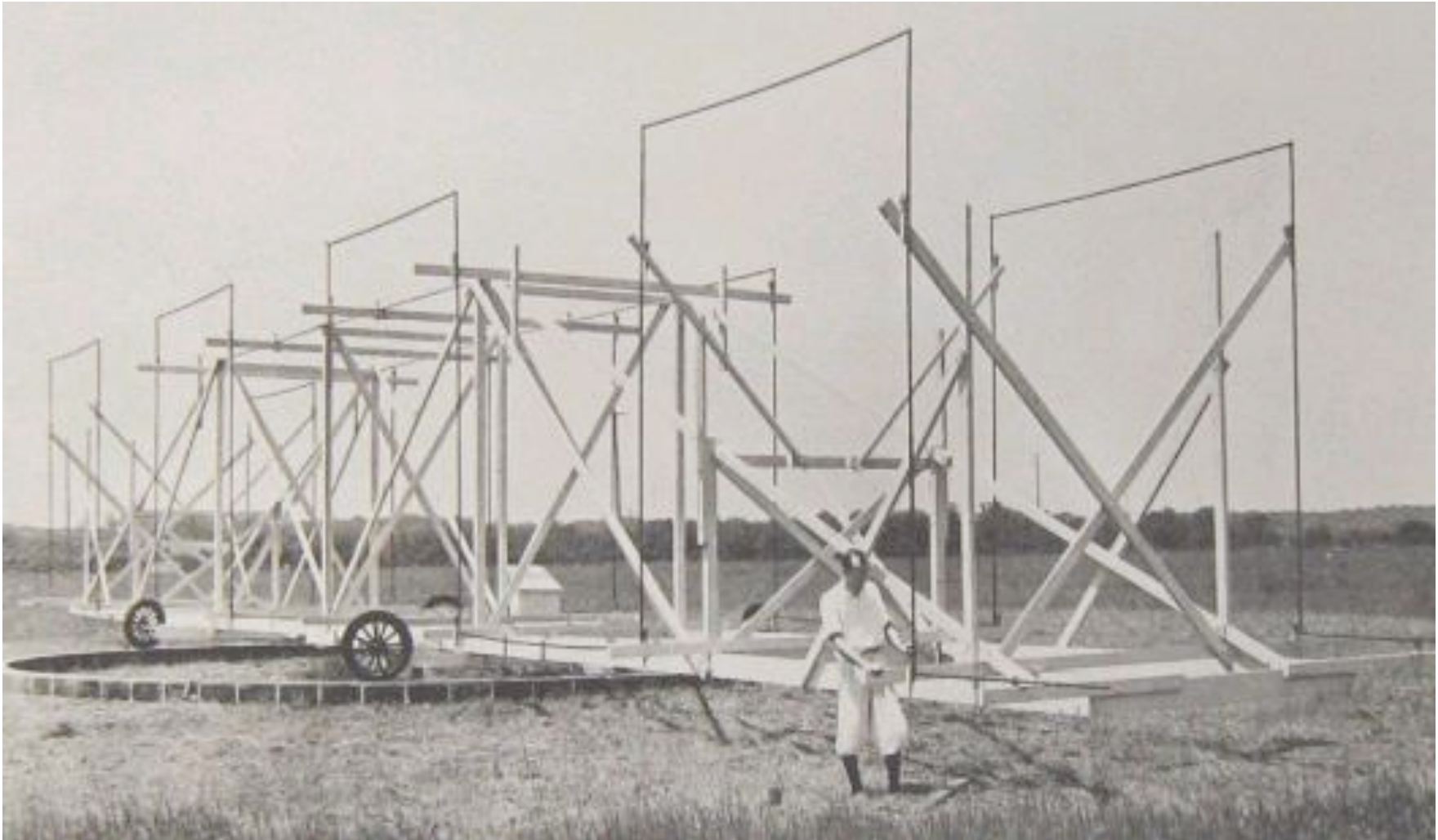
(1905-1950)



- Direction of Sagittarius.
- First detection of radio waves from an astronomical source (the Milky Way) announced in 1933.
- Proposed a 30-m dish, but...
- Re-assigned to another project by Bell Labs.
- Namesake of the flux density unit the “Jansky” ( $1\text{ Jy} = 10^{-26}\text{ W/m}^2/\text{Hz}$ ).

No Nobel Prize because he died too young?

# Jansky's telescope 1933



Discovery during the Great Depression bad timing?  
Radio astronomy did not immediately take off...

# Jansky's telescope today



One of the three historic radio telescopes in Green Bank, West Virginia (replica).

# Grote Reber

(1911 - 2002)



- American.
- Amateur inspired by Jansky's pioneering work.
- Couldn't get a job at Bell Labs (height of Great Depression).
- Built a 9-m parabolic reflector in 1937 (in his own backyard!).
- Only successful on third attempt (3300MHz, 900MHz, 160MHz).
- Conducted first sky survey at radio frequencies.

# Grote Reber

(1911-2002)

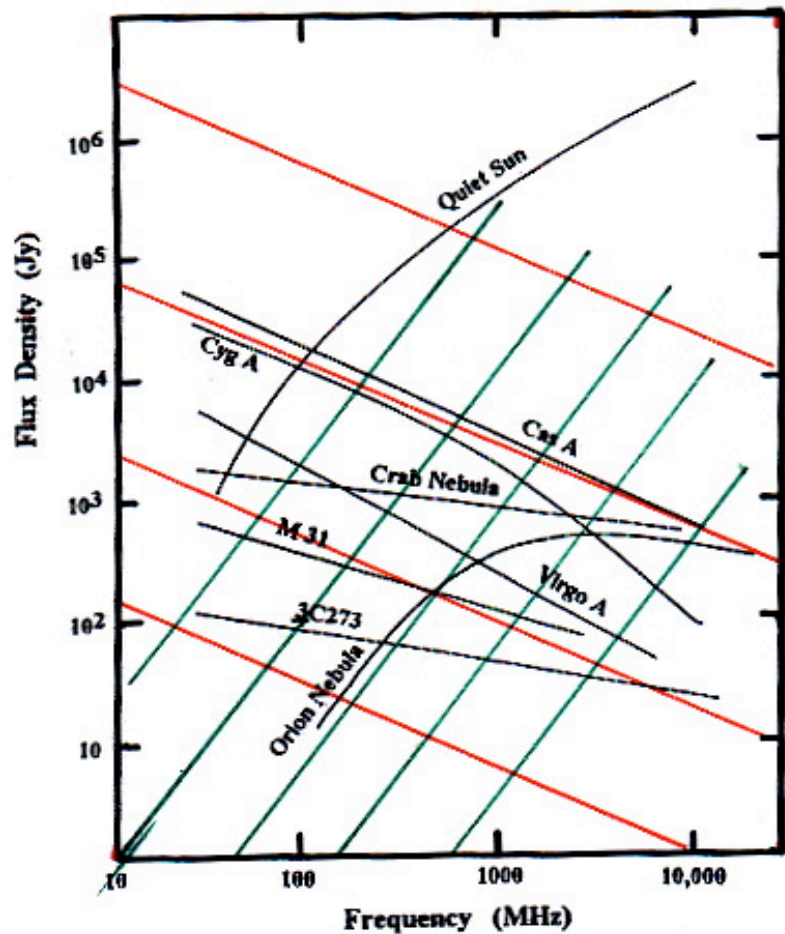


- First true radio astronomer.
- Sole radio astronomer for nearly a decade.
- Mystery of low-energy (non-thermal, synchrotron) emission.
- Set the stage for the explosion in radio astronomy that followed WWII.
- Some of his ashes at ASTRON and at other major radio institutes.

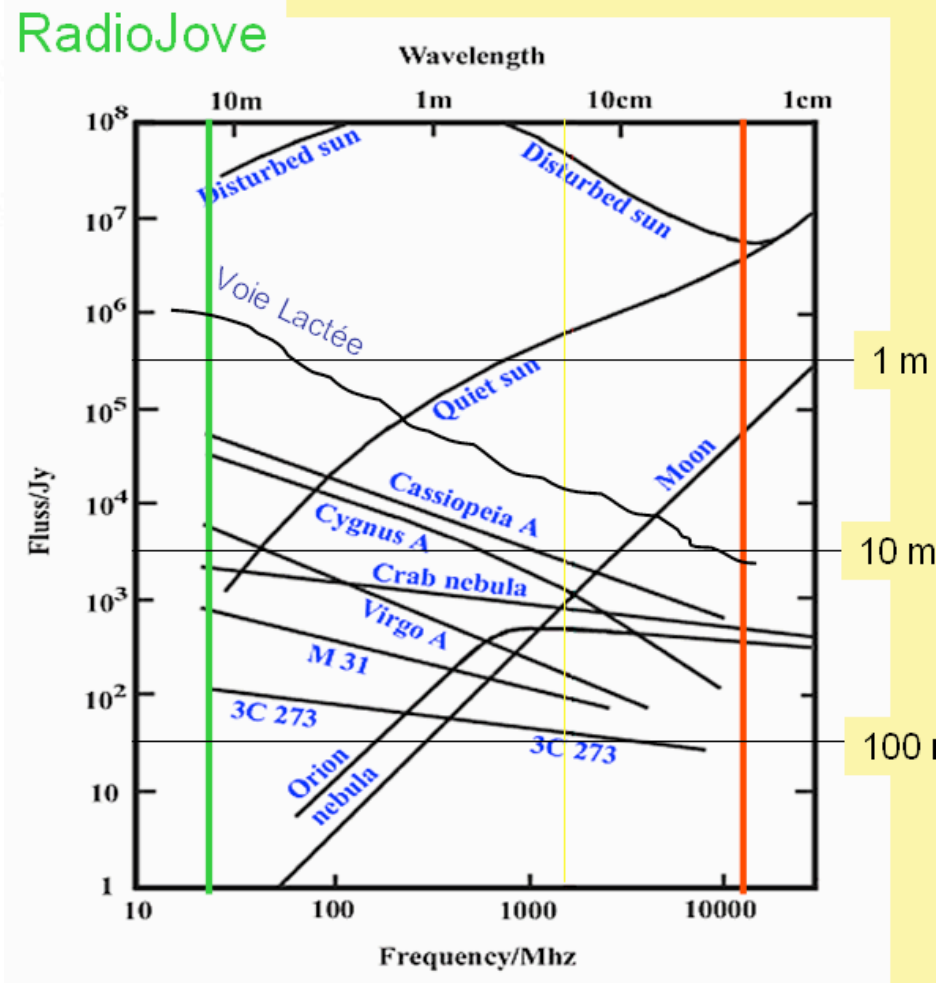


# Thermal / non-thermal

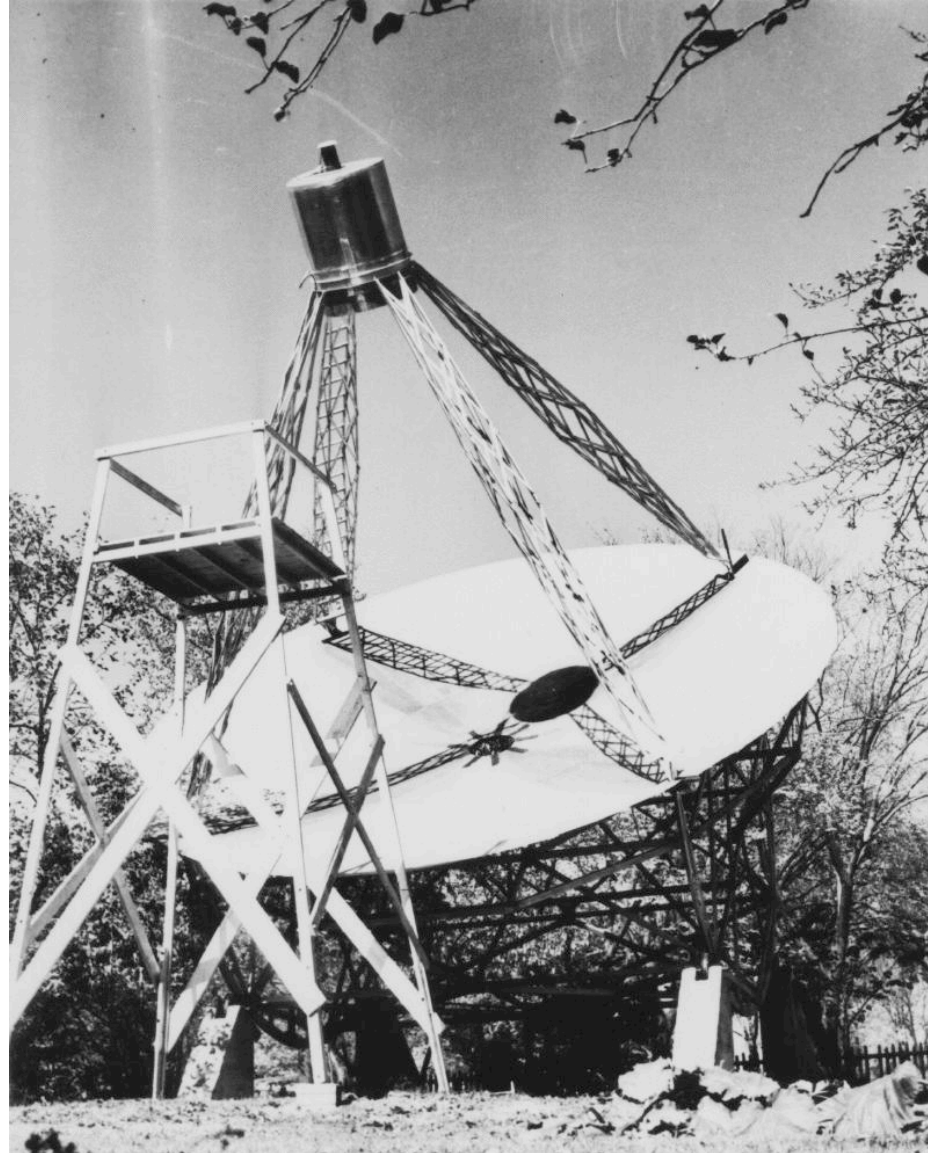
$S \propto \nu^{-0.8}$  (synchrotron with  $N(E) \propto E^{-2.6}$ )



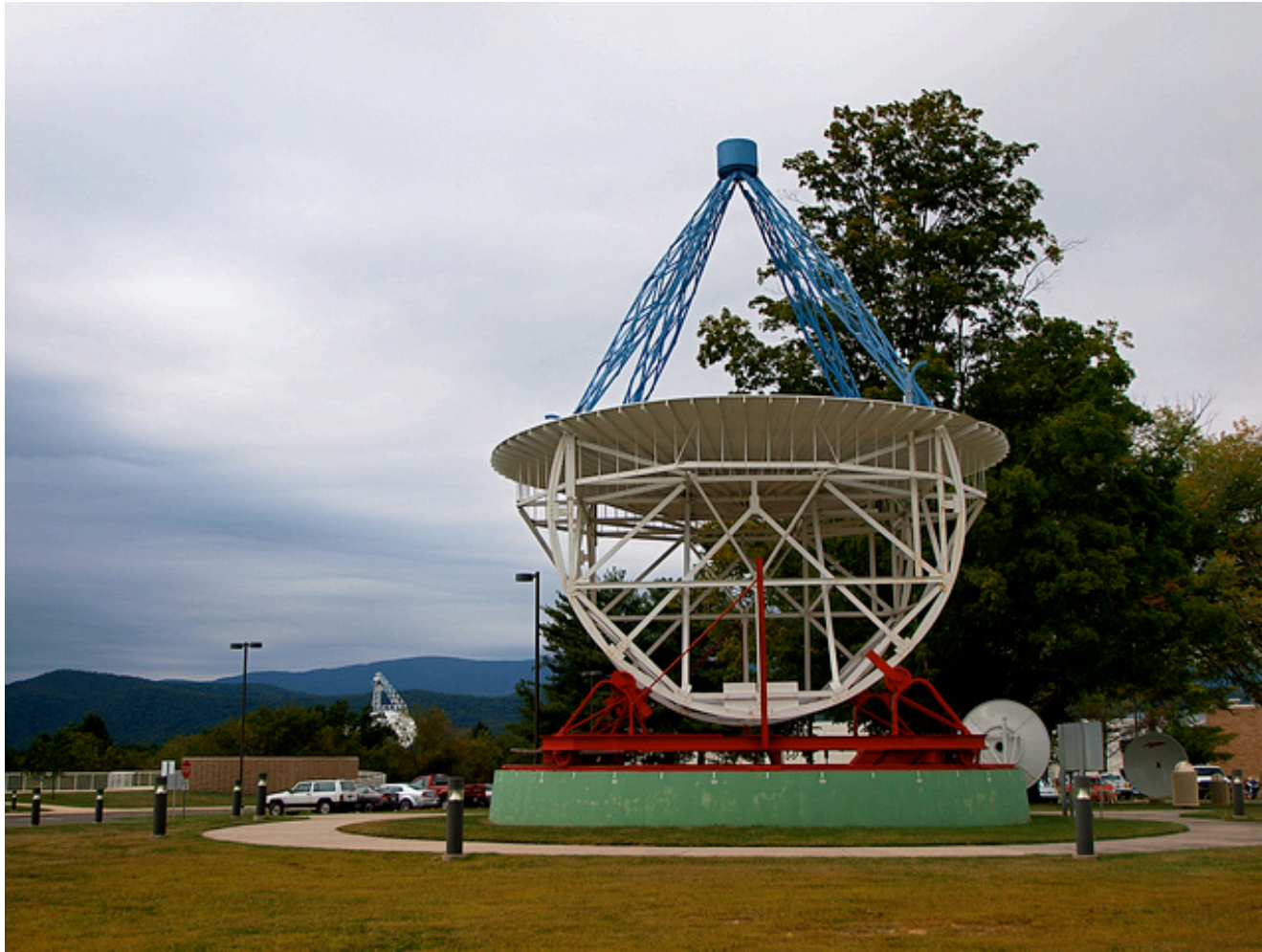
$S \propto \nu^2$  (blackbody)



# Reber's telescope 1937

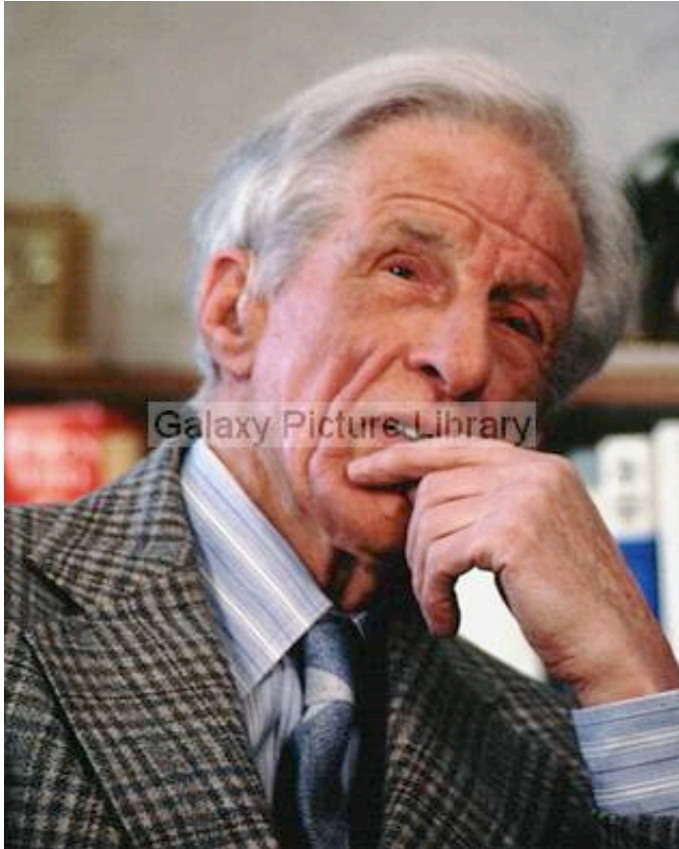


# Reber's telescope today



One of the three historic radio telescopes in Green Bank, West Virginia (reconstructed).

# J.S. Hey



- British Army research officer (radar WWII).
- First detection of radio waves from the Sun in 1942.
- First localized an extra-galactic radio source in Cygnus.
- Set stage for explosion of radio astronomy research in UK after WWII.

# Joseph Pawsey

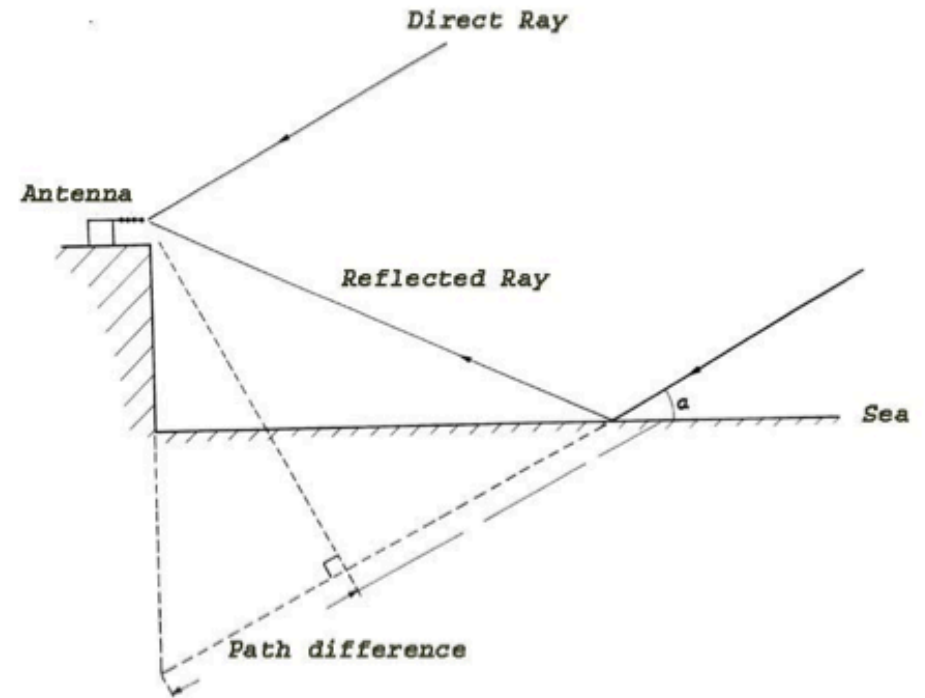
(1908 - 1962)



- Australian.
- Early studies of irregularities in the ionosphere.
- Developed microwave technology for the Australian Navy during WWII.
- Introduced interferometry to radio astronomy.
- Used “sea interferometry” at Dover Heights to resolve sunspots.
- Father of radio astronomy in Australia.

# “Sea” interferometry

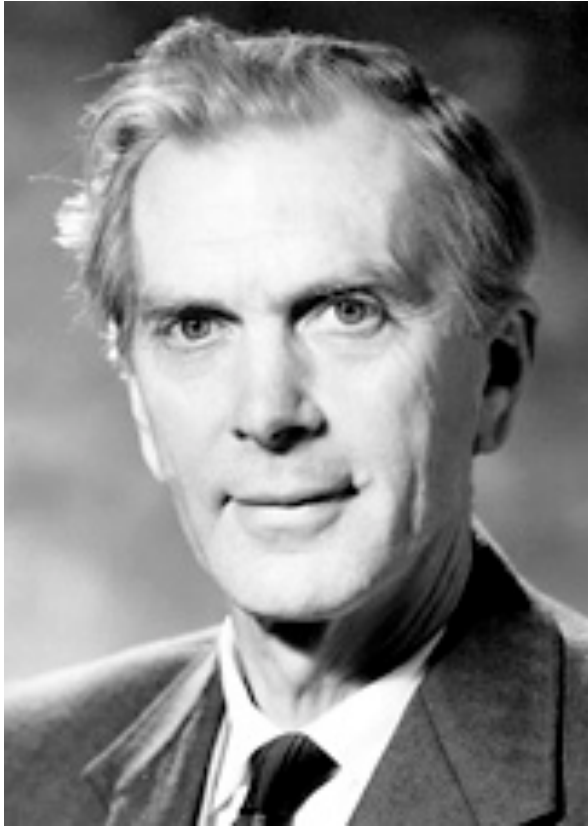
(mid 1940s)



Dover Heights near Sydney

# Martin Ryle

(1918 - 1984)



- British
- Worked on airborne radar antennas during WWII.
- First *published* interferometric observations (see Pawsey).
- Introduced (Earth-rotation) aperture synthesis to radio astronomy (1974 Nobel Prize).
- Built first multi-element interferometer in 1946.
- Led 3C catalog in 1959.

# Cambridge radio catalogs

e.g. famous “3C” catalog

- Various Cambridge interferometers at 80 - 200MHz.
- 1C, 2C First sample of quasars.
- 3C published in 1959.
- Many of the brightest, most famous sources are “3C” sources.



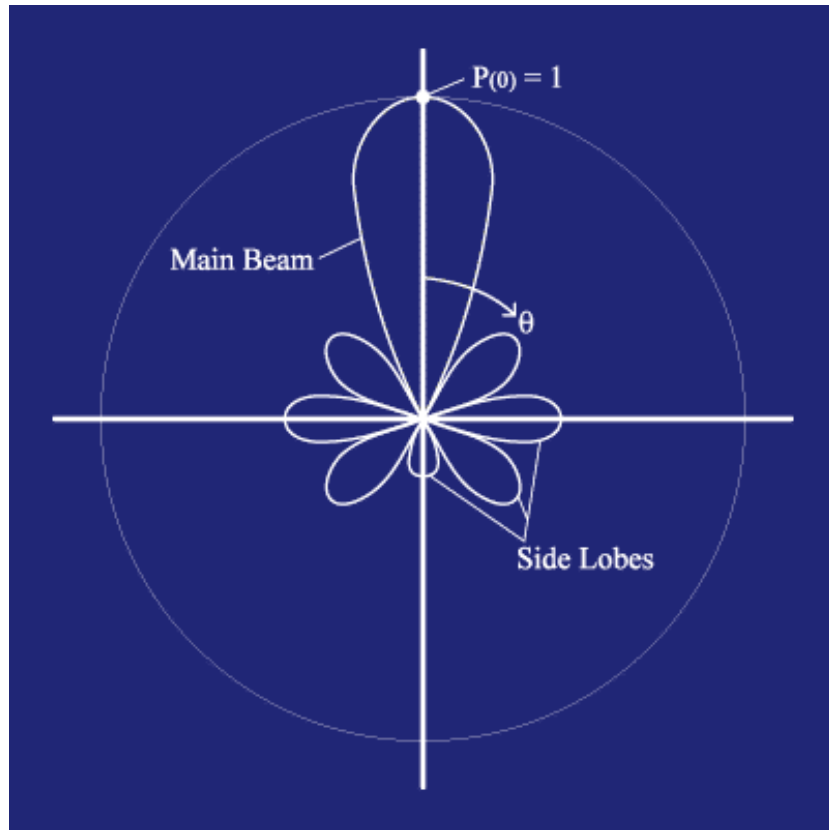
# Bernard Lovell

(1913 - 2012)



- British
- Director Jodrell Bank Observatory 1945 - 1980.
- Worked on airborne radar systems during WWII.
- Led construction of the 76-m Lovell Telescope.

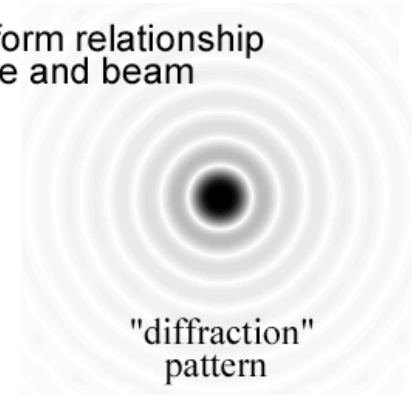
# Radio telescope FoV



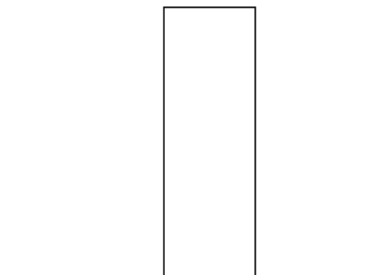
Fourier Transform relationship  
of aperture and beam



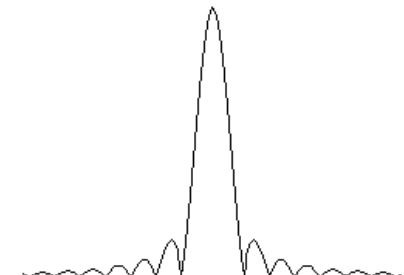
circular  
aperture



"diffraction"  
pattern

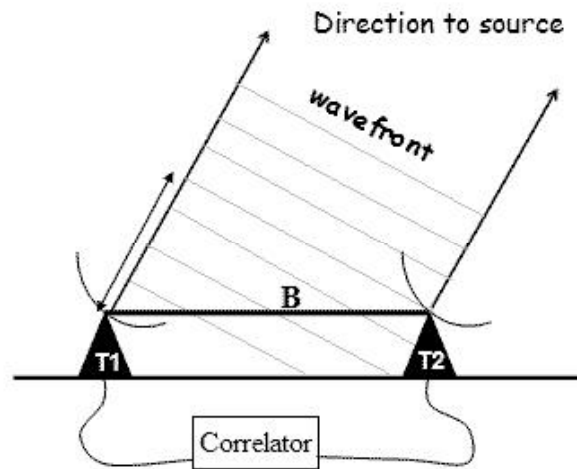
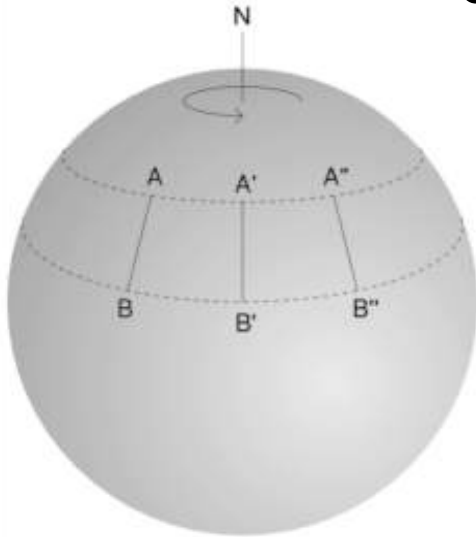


cross-section  
of aperture

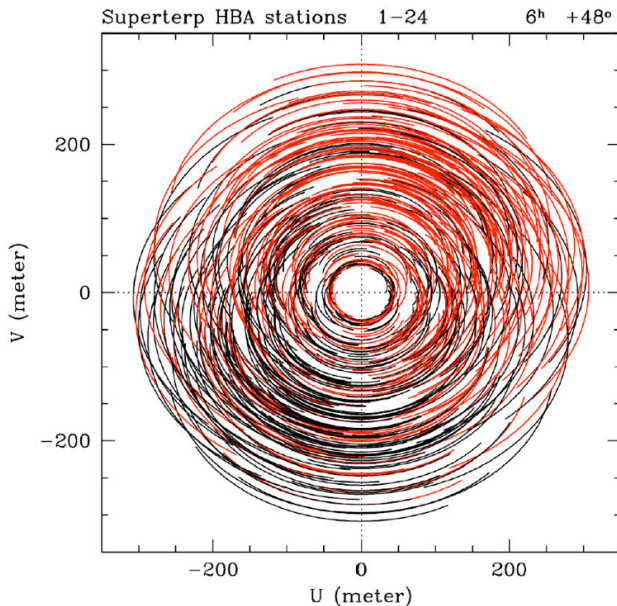


cross-section  
of diffraction pattern

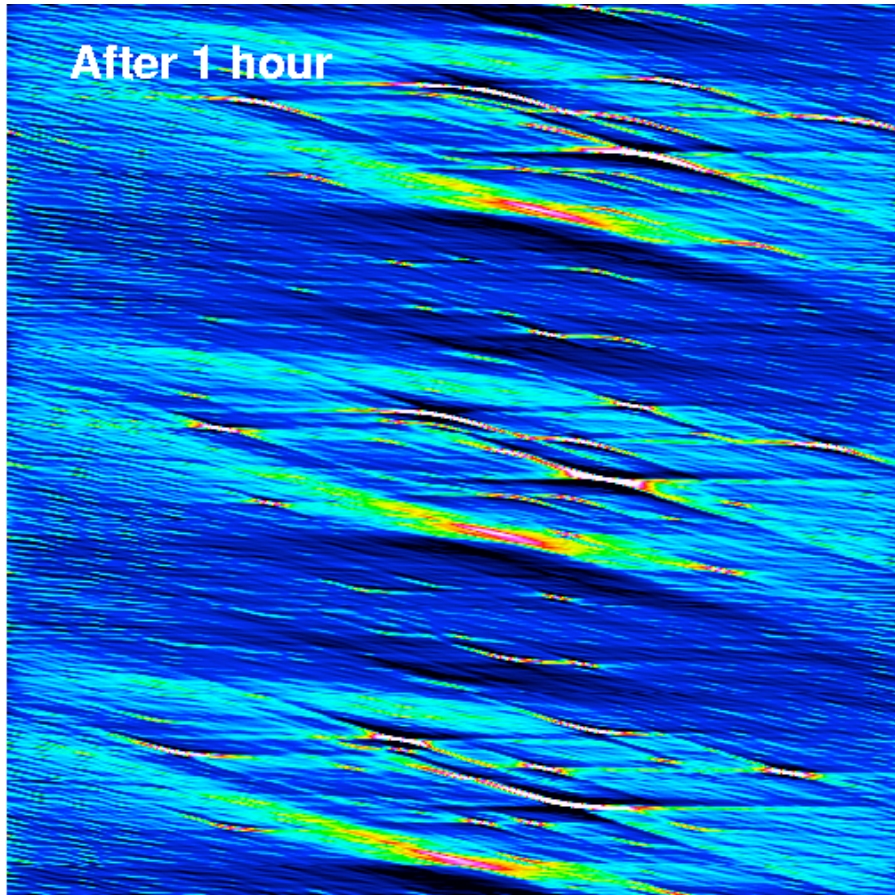
# Development of interferometry and aperture synthesis



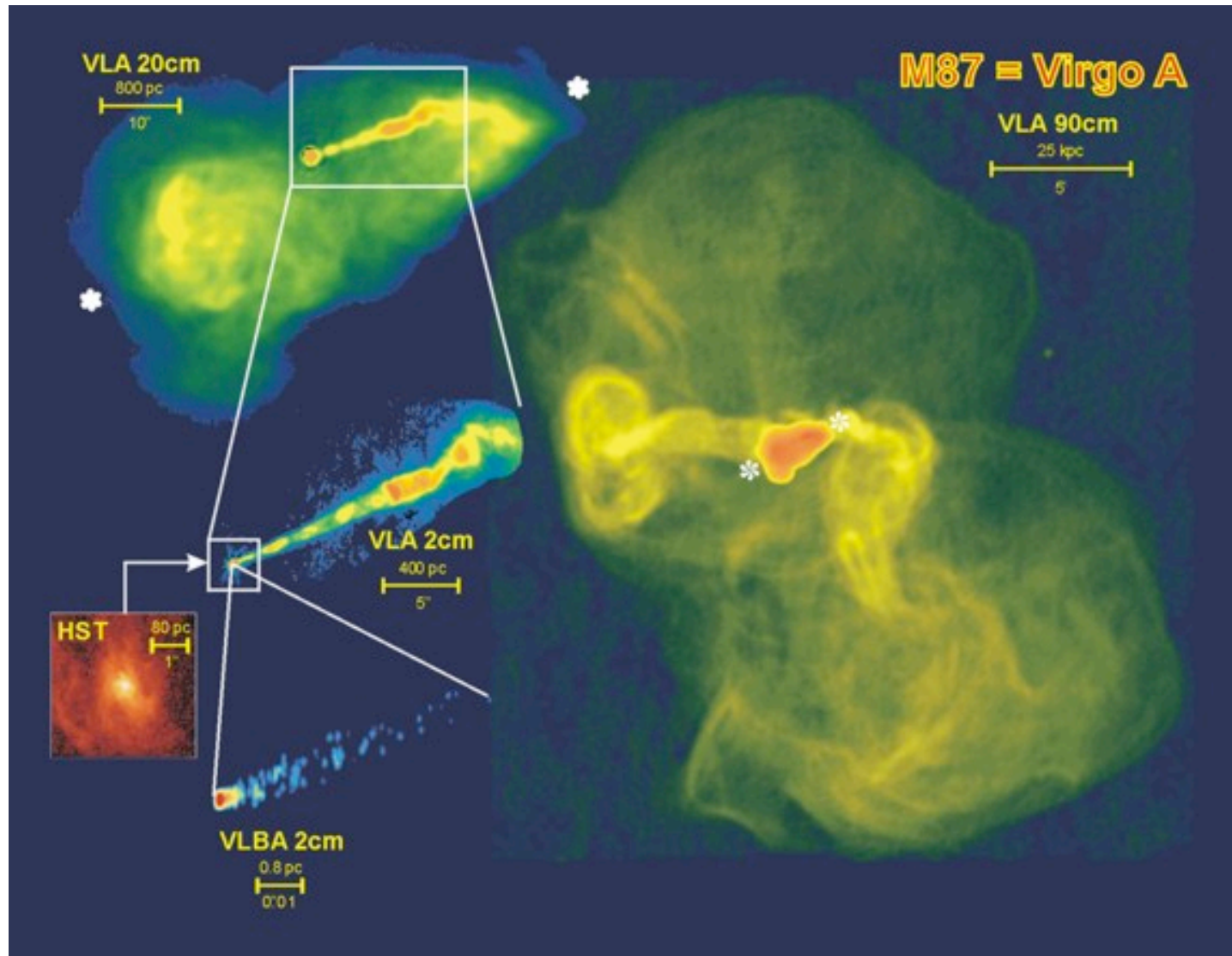
- Need for resolution.
- Earth rotation fills in the image.
- Sky brightness is the 2D Fourier transform of the spatial frequencies.



# Development of interferometry and aperture synthesis

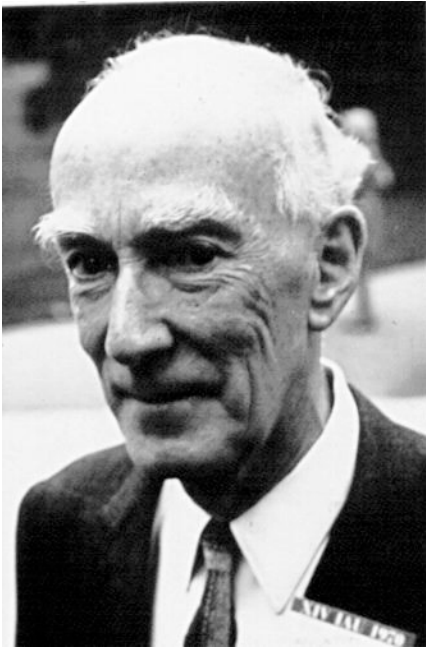


# The quest for resolution



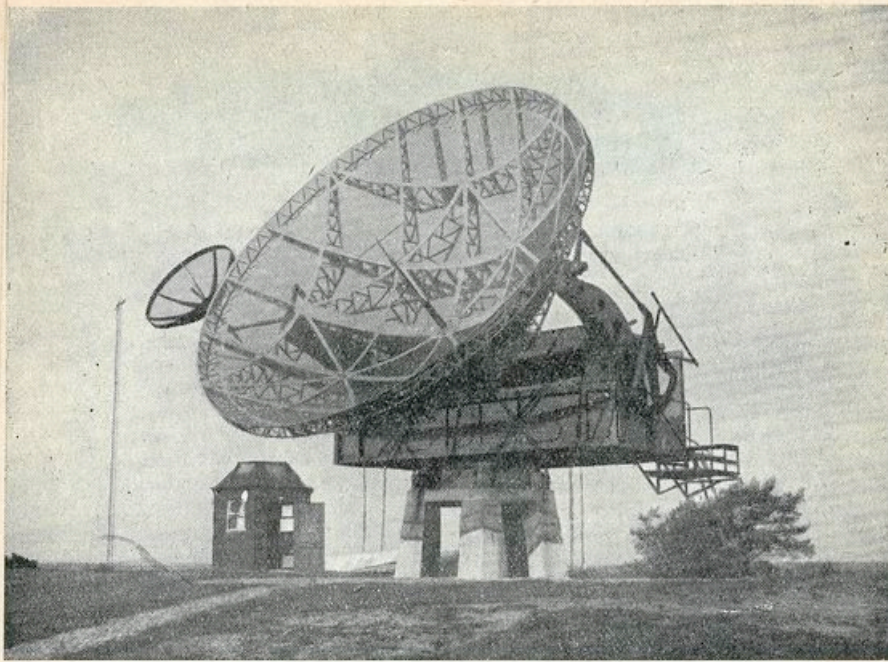
# Jan Oort

(1900-1992)



- Professor in Leiden and father of Dutch radio astronomy.
- Expert on Milky Way structure.
- Kootwijk radar dish used after WWII (start of Dutch radio astronomy).
- Built Dwingeloo telescope and later Westerbork.
- Upon his death, Nobel Prize winning astrophysicist Subrahmanyan Chandrasekhar remarked, "The great oak of Astronomy has been felled, and we are lost without its shadow."

# Beginnings of Dutch radio astronomy



De radio-telescoop te Kootwijk (zie ook de voorplaat). De middellijn van de spiegel is  $7\frac{1}{2}$  m. Het gevaarte kan op zijn voetstuk draaien. De spiegel zelf kan omhoog en omlaag gericht worden.



De parabolische zandkuil van de radio-sterrenwacht te Kootwijk. (De middellijn bedraagt 30 meter). In het middelpunt is de antenne duidelijk te zien.

- Presided over by Jan Oort.
- Kootwijk radar antenna leftover from WWII by Germans.
- First (Dutch) detection of 21-cm line.

# Hendrik van de Hulst

(1918-2000)



- Student of Oort
- In 1944 first predicted the 21-cm hyperfine line of neutral interstellar hydrogen.
- First reveal spiral structure of Milky Way.



# Prediction of the 21-cm Line

(1944)



Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting).  
(By courtesy of H. C. van de Hulst, Leiden)

(re-enactment)

- Astronomers still meeting in the Netherlands during WWII.
- ApJ still reaching Leiden Observatory.
- Excited by Reber's findings, Oort realized that a radio spectral line could be used to map the Milky Way's structure (optical is absorbed).

# Prediction of the 21-cm Line

(1944)



Plate 1.6 Van de Hulst reading his paper on the 21 cm hydrogen line. (This photograph taken in 1955 is a reconstruction of the 1944 meeting).  
(By courtesy of H. C. van de Hulst, Leiden)

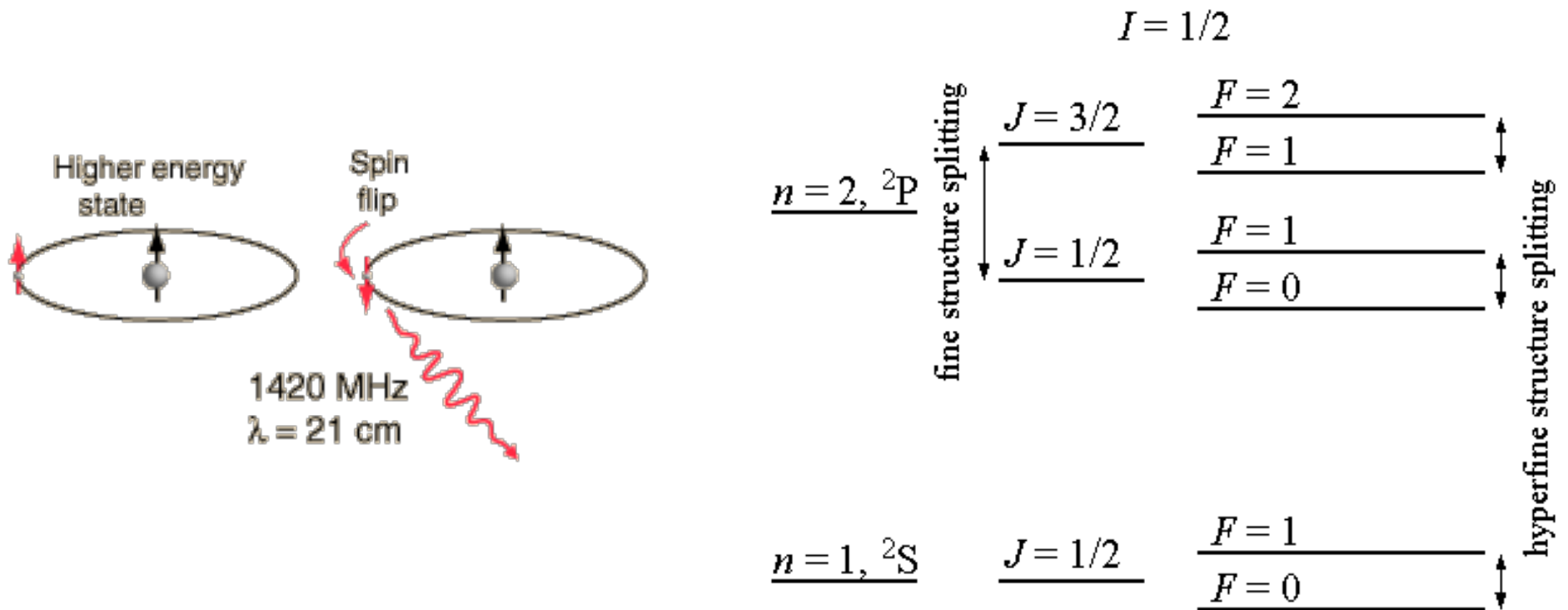
(re-enactment)

- Oort asked van de Hulst to investigate what lines there might be.
- van de Hulst discovered that a 21-cm line would result from an electron flipping its spin in the ground state of hydrogen.
- Published in Dutch in the *Ned. Tijdschrift voor Natuurkunde*.

# Prediction of the 21-cm Line

(1944)

Frequency of 1420.40575177 MHz, which is equivalent to the vacuum wavelength of 21.10611405413 cm in free space.



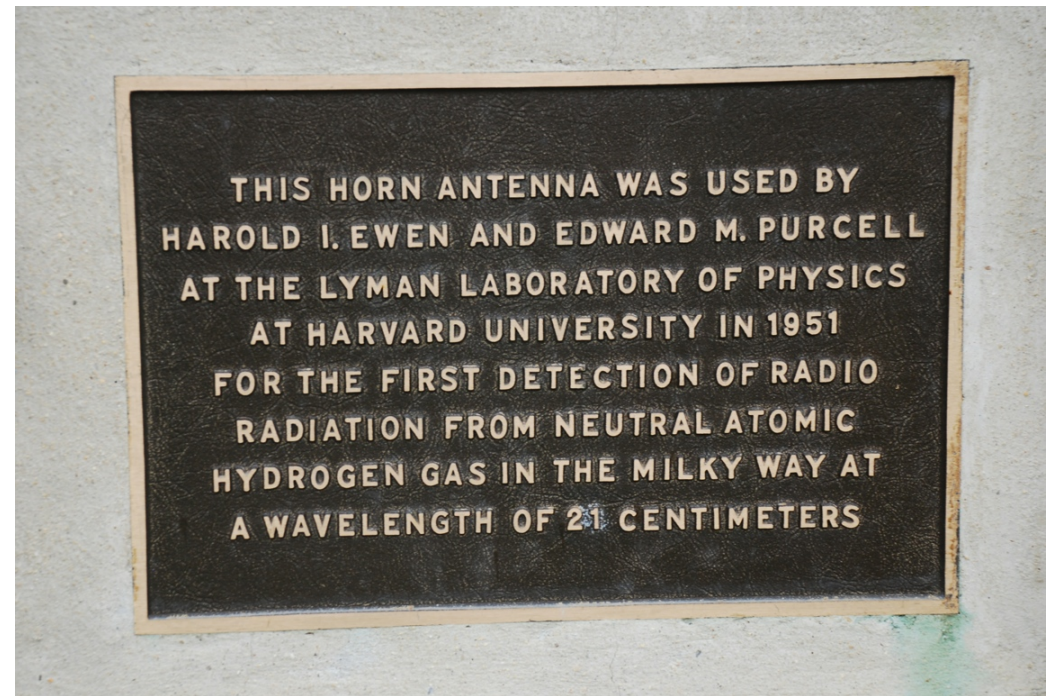
# Detection of the 21-cm Line

(1951)



- Building a sensitive receiver proved challenging.
- Reber started work but moved on.
- Ewen & Purcell at Harvard made first detection on March 25th, 1951.
- van de Hulst visiting Harvard at that time.
- Talked to Oort on phone for an hour.
- American and Dutch results were published in the same issue of Nature

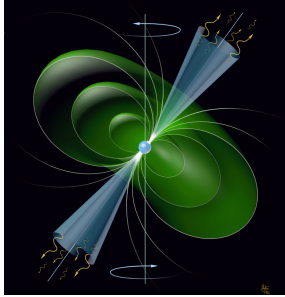
# Ewen & Purcell Feed Horn Today



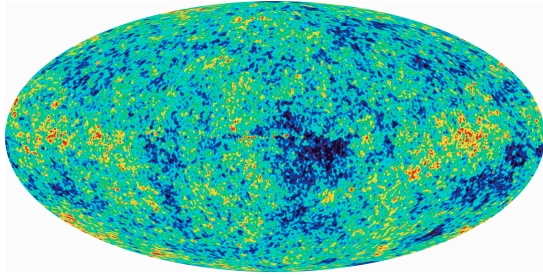
One of the three historic radio telescopes in Green Bank, West Virginia (original).

# Seminal discoveries and Nobel prizes

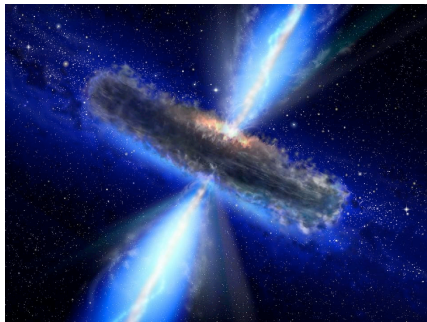
# Seminal Discoveries



Pulsar - Jocelyn Bell & Antony Hewish (1967)



Cosmic Microwave Background - Arno Penzias & Robert Wilson (1965)

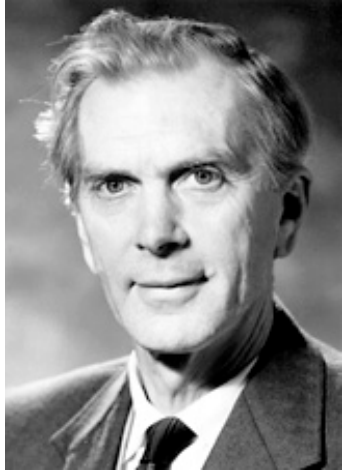


Quasars - Martin Ryles et al. (late 1950s)



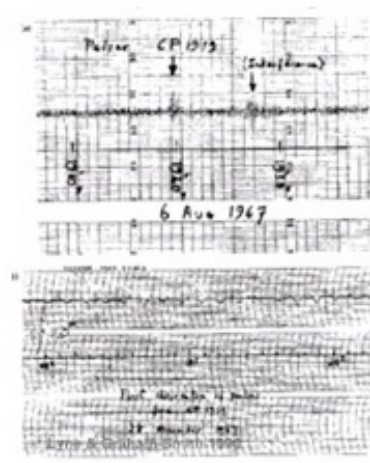
Radio Galaxies - Grote Reber, Bolton, Stanley, et al. (1940 - 1950s)

# Nobel Prize Physics 1974



Martin Ryle & Antony Hewish

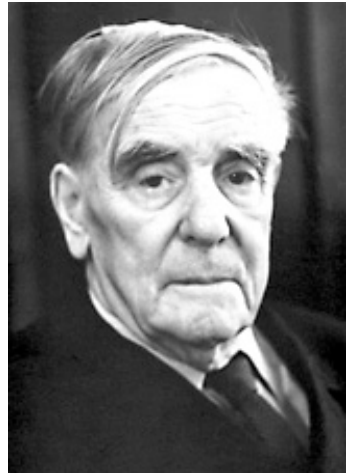
*"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"*



Jocelyn Bell-Burnell



# Nobel Prize Physics 1978

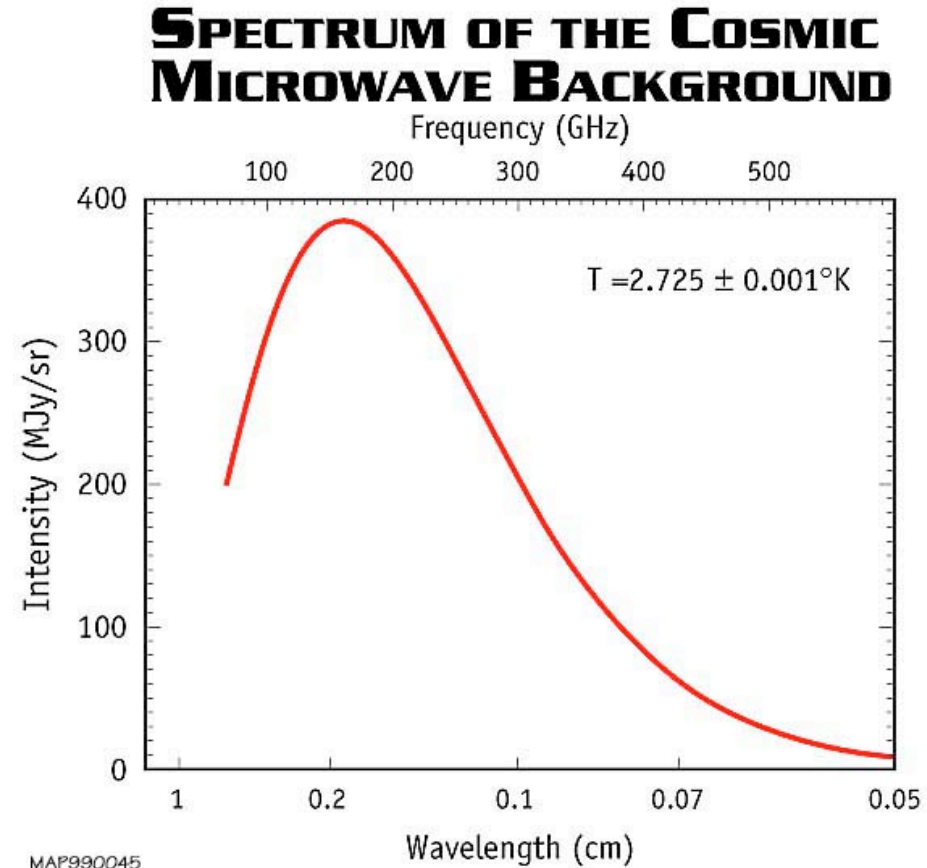
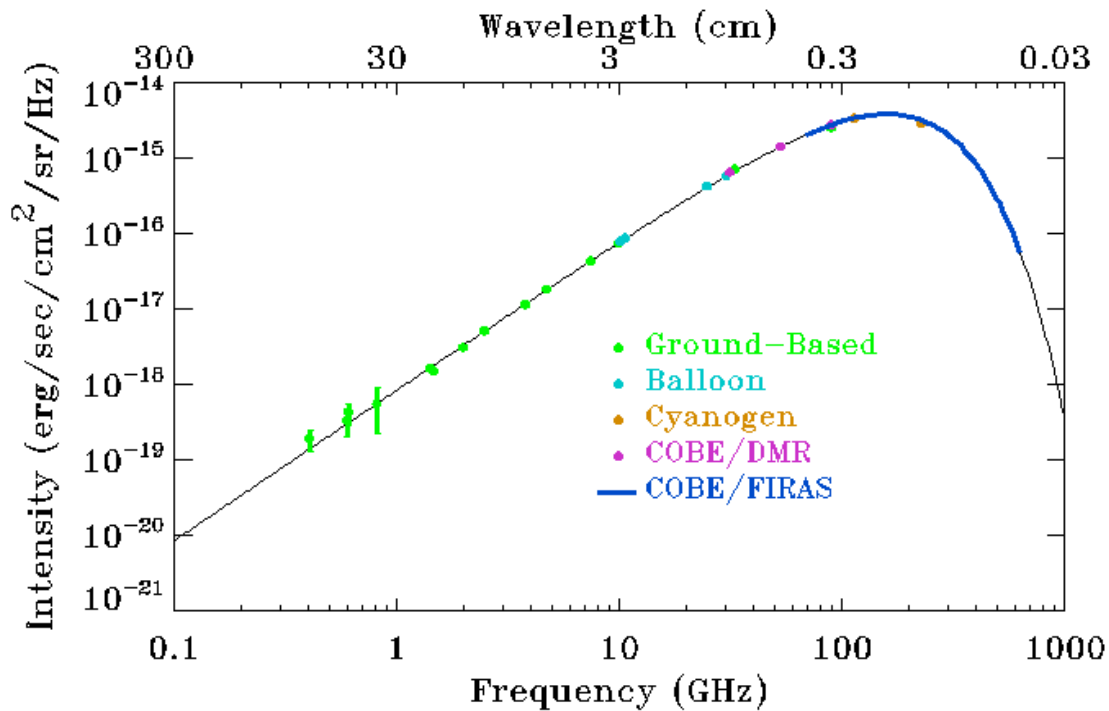


Pyotr Kapitsa, Arno Penzias & Robert Wilson

*"for their discovery of cosmic microwave background radiation"*



# Universe's temperature

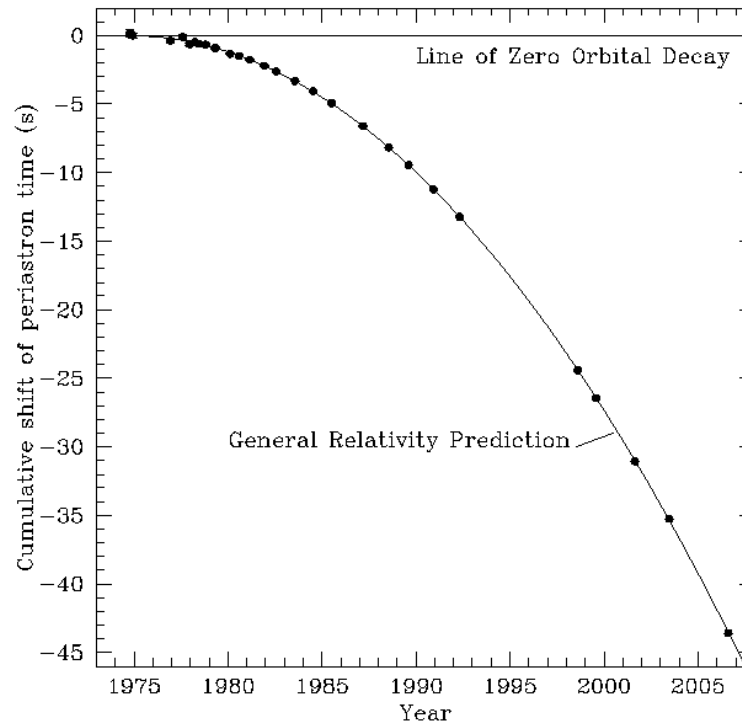


# Nobel Prize Physics 1993



Russell Hulse & Joseph Taylor

*"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"*

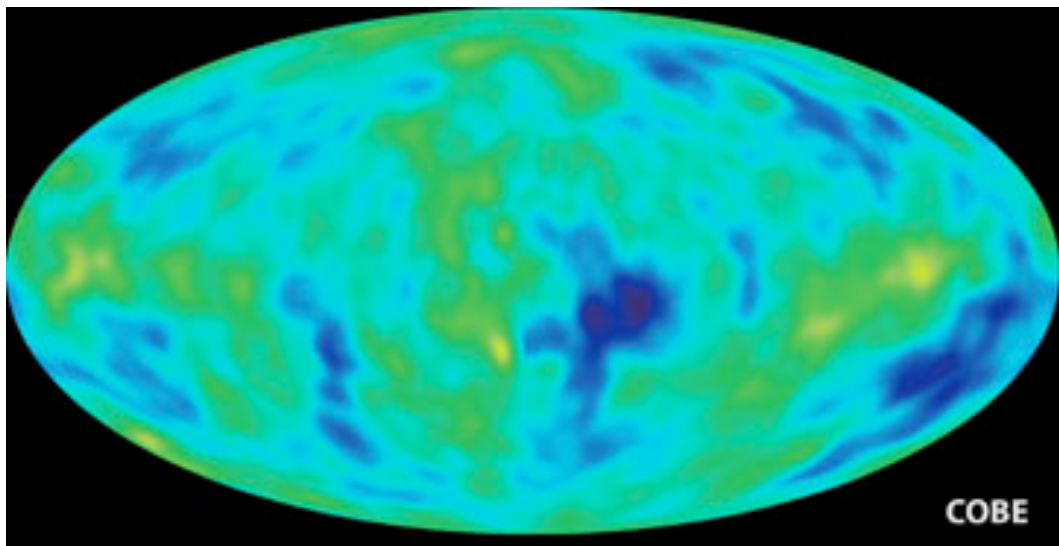


# Nobel Prize Physics 2006

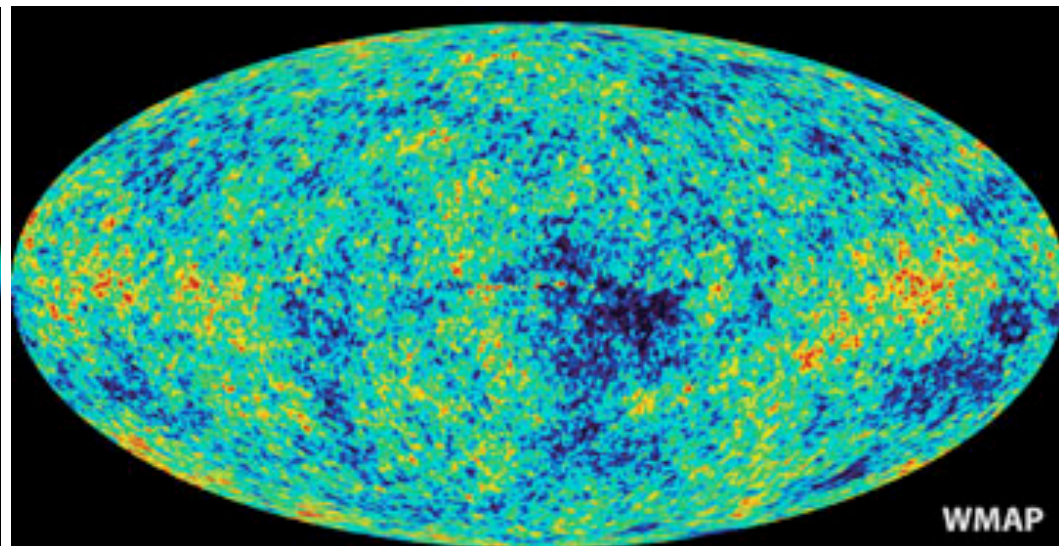


John Mather & George Smoot

*"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*



COBE



WMAP

# Key instruments

# Historic Radio Telescopes

[http://en.wikipedia.org/wiki/Timeline\\_of\\_telescopes,\\_observatories,\\_and\\_observing\\_technology](http://en.wikipedia.org/wiki/Timeline_of_telescopes,_observatories,_and_observing_technology)

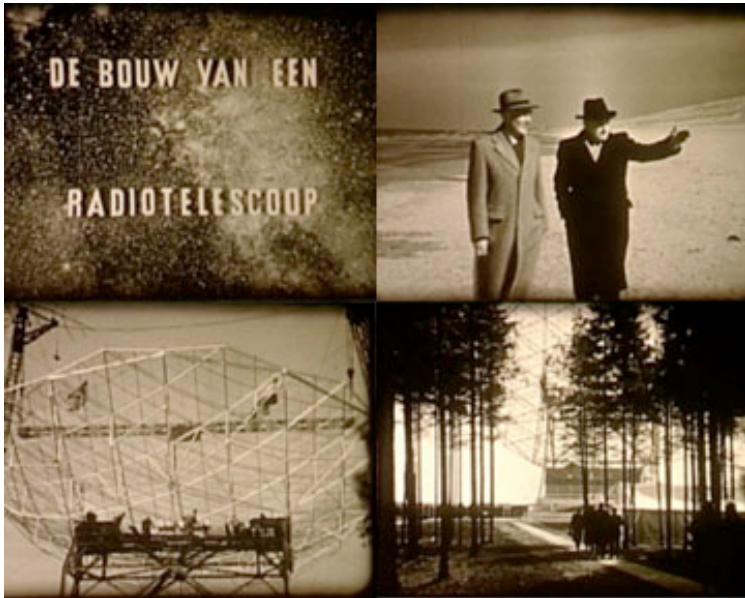
- 1930 - [Karl Jansky](#) builds a 30-meter long rotating aerial [radio telescope](#) This was the first radio telescope.
- 1937 - [Grote Reber](#) builds a 31-foot (9.4 m) radio telescope
- 1946 - [Martin Ryle](#) and his group perform the first astronomical observations with a radio interferometer
- 1947 - [Bernard Lovell](#) and his group complete the [Jodrell Bank](#) 218-foot (66 m) non-steerable radio telescope
- 1954 - Earth rotation [aperture synthesis](#) suggested (see e.g. Christiansen and Warburton (1955))
- 1956 - [Dwingeloo Radio Observatory](#) 25 m telescope completed, [Dwingeloo, Netherlands](#)
- 1957 - [Bernard Lovell](#) and his group complete the [Jodrell Bank](#) 250-foot (75 m) steerable radio telescope (the [Lovell Telescope](#))
- 1959 - The [3C](#) catalogue of radio sources is published (revised in 1962)
- 1960 - [Owens Valley](#) 27-meter radio telescopes begin operation, located in [Big Pine, California](#)
- 1961 - [Parkes 64-metre radio telescope](#) begins operation, located near [Parkes, Australia](#)
- 1962 - [Green Bank, West Virginia](#) 90m radio telescope
- 1963 - [Arecibo 300-meter radio telescope](#) begins operation, located in [Arecibo, Puerto Rico](#)
- 1964 - [Martin Ryle's](#) 1-mile (1.6 km) radio [interferometer](#) begins operation, located in [Cambridge, England](#)
- 1965 - Owens Valley 40-meter radio telescope begins operation, located in [Big Pine, California](#)
- 1967 - First [VLBI](#) images, with 183 km [baseline](#)
- 1970 - [Westerbork Synthesis Radio Telescope](#) completed, near [Westerbork, Netherlands](#)
- 1972 - 100 m [Effelsberg](#) radio telescope inaugurated ([Germany](#))
- 1980 - Completion of construction of the [VLA](#), located in [Socorro, New Mexico](#)
- 1984 - [IRAM 30-m](#) telescope at [Pico Veleta](#) near [Granada, Spain](#) completed
- 1987 - 15-m [James Clerk Maxwell Telescope](#) UK submillimetre telescope installed at [Mauna Kea Observatory](#)
- 1987 - 5-m Swedish-ESO Submillimetre Telescope (SEST) installed at the ESO [La Silla Observatory](#)
- 1988 - [Australia Telescope Compact Array](#) aperture synthesis radio telescope begins operation, located near [Narrabri, Australia](#)
- 1989 - [Cosmic Background Explorer](#) (COBE) satellite
- 1993 - [Very Long Baseline Array](#) of 10 dishes
- 1995 - [Giant Metrewave Radio Telescope](#) of thirty 45 m dishes at Pune
- 2000 - Green Bank Telescope 100x110m dish completed in West Virginia
- 2011 - Low-Frequency Array (LOFAR) opens in the Netherlands
- 2012 - Jansky VLA (upgraded array) opens in New Mexico
- 2012 - Long-Wavelength Array (LWA) opens in New Mexico
- 2012 - Australia Square Kilometer Array Pathfinder (ASKAP) opens in Australia
- 2013 - Murchison Widefield Array (MWA) opens in Australia

# Dwingeloo

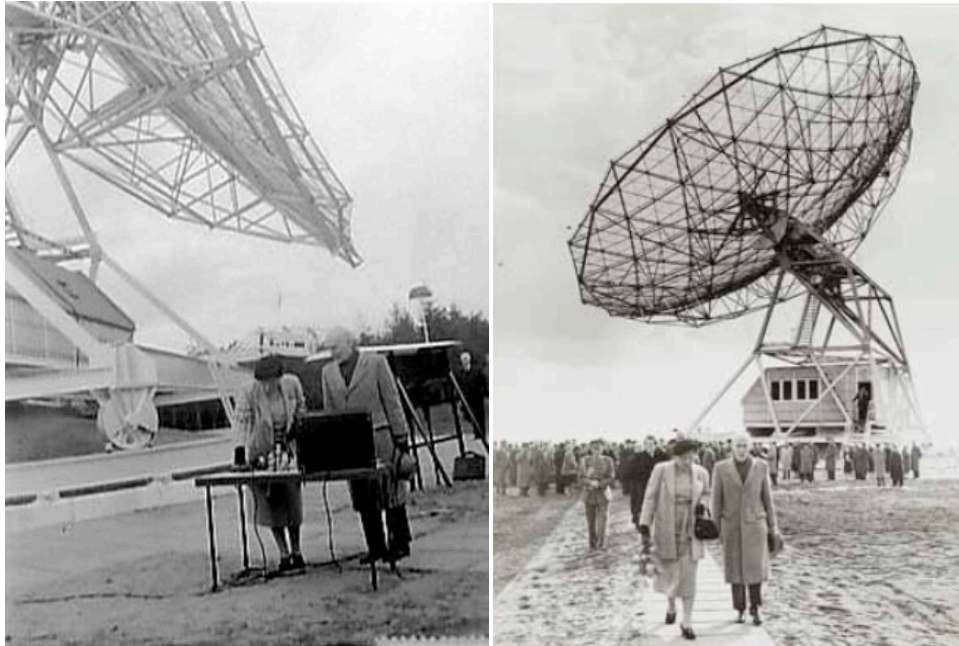


- Near Dwingeloo, the Netherlands.
- Opened in 1956.
- 25-m dish (briefly the largest in the world).
- Mapped 21 cm line emission in the Milky Way.
- Largest amateur radio telescope in the world (see “CAMRAS”).
- Recently renovated.

# Construction of Dwingeloo Telescope



<http://www.astron.nl/about-astron/history/footage/historic-footage>



- Built by Nederlandse Spoorweg.
- Inaugurated by Koningin Juliana.



# Westerbork



- Near Westerbork, the Netherlands.
- Opened in 1970.
- Premiere interferometer of its time.
- Operated by ASTRON.
- 14 dishes of 25-m diameter (two movable).
- Equatorially mounted.
- Maximum baseline 2.7km.
- East-West array (12hr for full synthesis).
- Covers 300MHz - 8GHz range.
- Resolution of  $\sim 0.5$  arcsec at 1.4GHz.
- Being upgraded with “APERTIF”.



# Low-Frequency Array

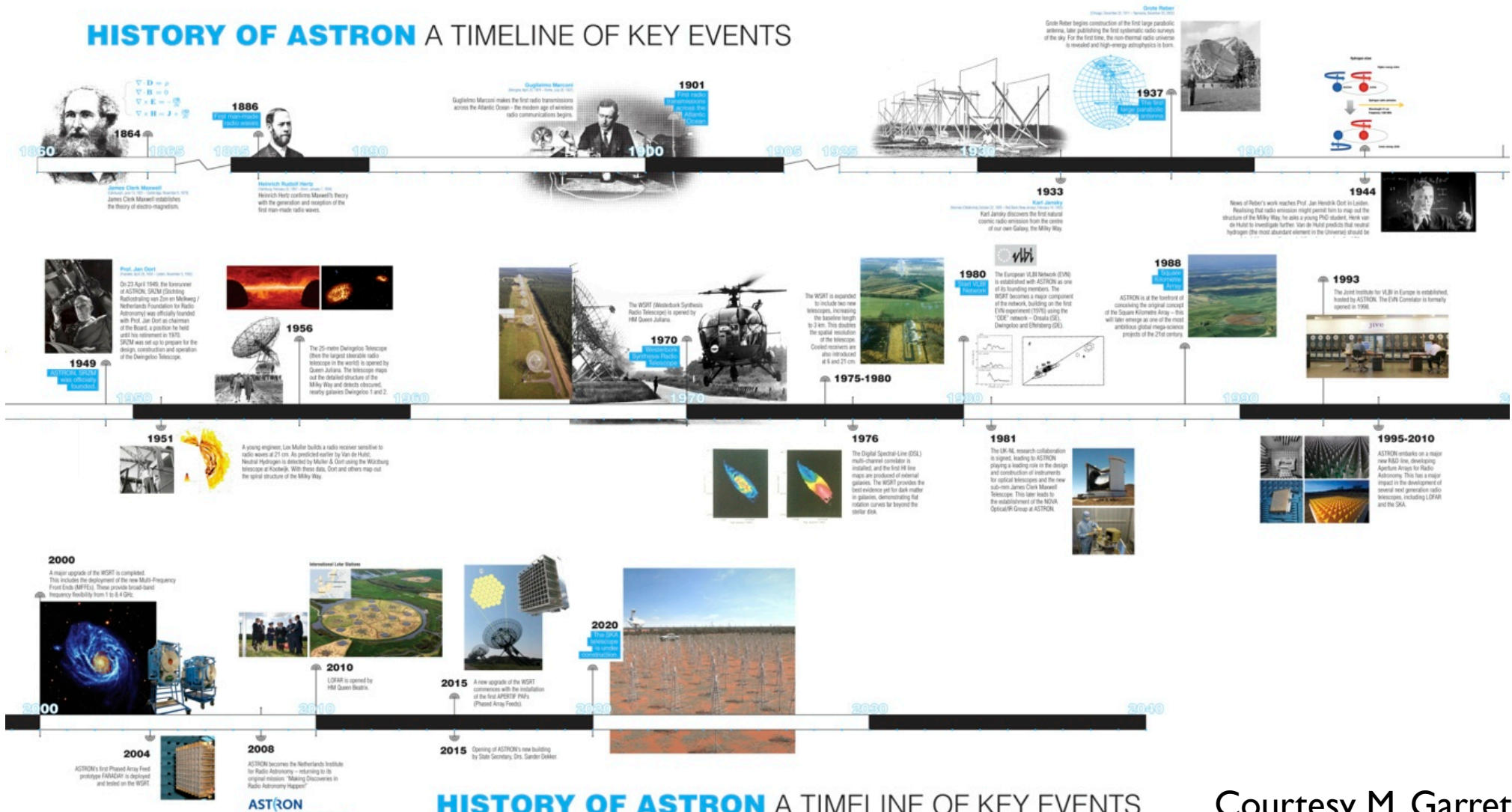


- Near Exloo, the Netherlands and spread across Europe.
- Opened 2011.
- Operated by ASTRON.
- Sparse digital “aperture array”.
- Two types of antennas.
- Pointing achieved by delays in software.
- Covers 10-240MHz range.
- Up to 1 arcsec resolution.
- World’s premier low-frequency radio telescope.

# History of ASTRON

(ASTRON is the “Netherlands Institute for Radio Astronomy”)

## HISTORY OF ASTRON A TIMELINE OF KEY EVENTS



## HISTORY OF ASTRON A TIMELINE OF KEY EVENTS

Courtesy M. Garrett

# Ryle Telescope

(at Mullard Radio Astronomy Observatory,  
formerly the “5-km Array”)



- Near Cambridge, UK.
- Opened in 1957
- 8 dishes of 13-m diameter.
- East-West array.
- Adjustable baselines, between 18m and 4.8km.
- Covers the 15GHz (2cm) range.
- Now morphed into the Arcminute Microkelvin Imager (AMI) Large Array.

# One-Mile Telescope

(at Mullard Radio Astronomy Observatory)



- Near Cambridge, UK.
- Opened in 1964.
- Operated by Cambridge Radio Astronomy group.
- 3 dishes of 18-m diameter (one movable).
- East-West array.
- First Earth-rotation aperture synthesis interferometer.
- Covered 400 and 1400MHz ranges.
- Resolution of 20 arcsec at 1.4GHz (3x better than unaided eye).
- Led to 1974 Nobel Prize for Martin Ryle.

# Australia Telescope Compact Array



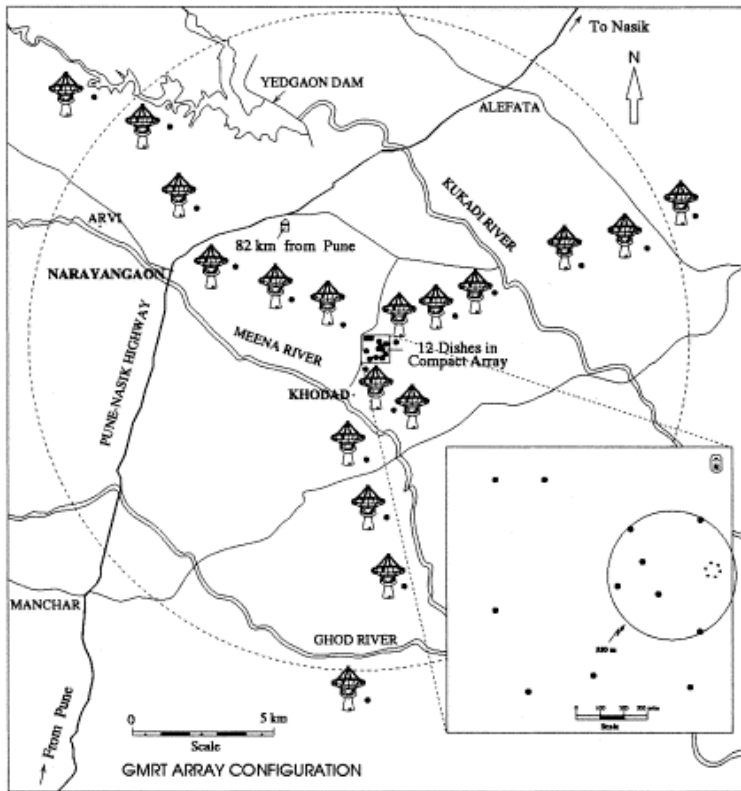
- Near Narrabri, Australia.
- Opened ???.
- Operated by ATNF.
- 6 dishes of 22-m diameter.
- 5 of the dishes can be moved along a 3-km track.
- Premier radio interferometer in the far south.

# Jansky Very Large Array



- Near Socorro, New Mexico.
- Opened ~1980 (and recently greatly refurbished).
- Operated by NRAO.
- 27 dishes of 25-m diameter.
- Maximum baseline of 36km.
- Covers 74MHz to 50GHz range.
- Dishes transported along rails.
- Can reach 0.05 arcsec resolution at 7mm (~42GHz).
- The best interferometer on Earth (in many ways).

# Giant Meterwave Radio Telescope

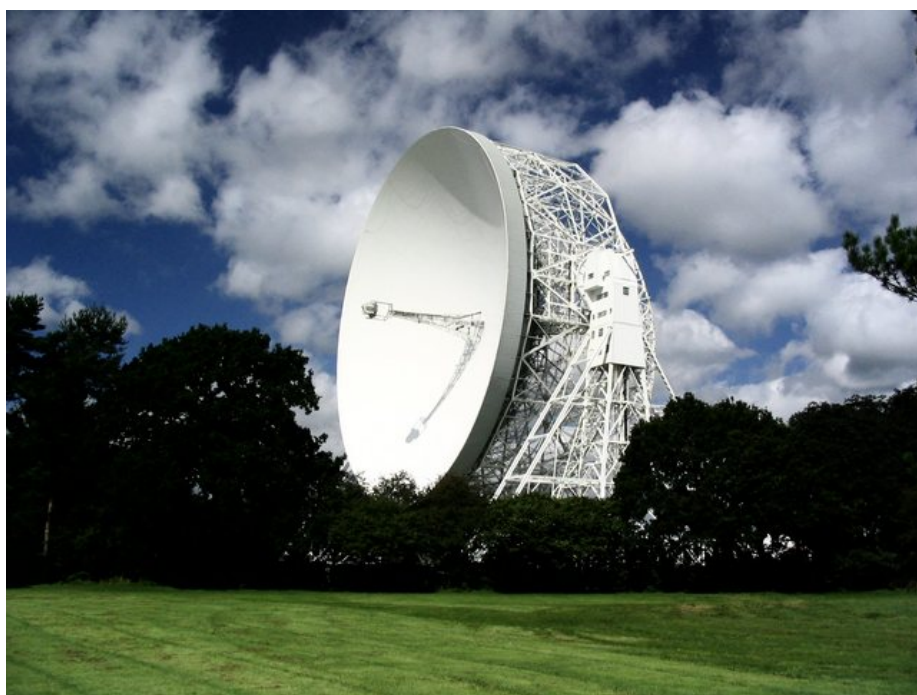


- Near Pune, India.
- First light 1995.
- Operated by NCRA.
- Aperture synthesis interferometer.
- 30 dishes of 45-m diameter.
- Max baseline  $\sim 30$ km.
- Covers 50 - 1500MHz range.
- Can reach 1 arsec resolution at 1.4GHz.
- A very powerful low-frequency radio interferometer.



# Lovell

(at Jodrell Bank Observatory)



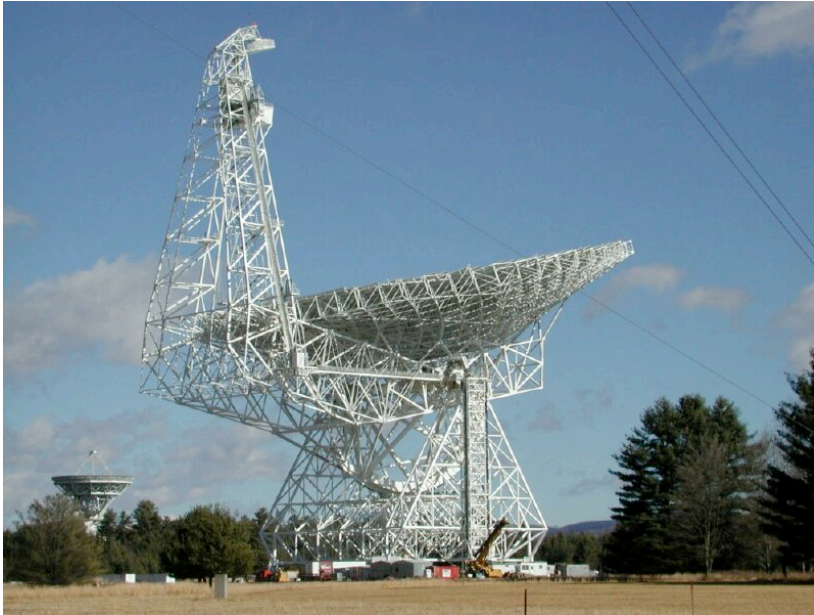
- Near Manchester, UK.
- Opened 1957.
- Operated by University of Manchester.
- 76-m dish.
- Formerly the largest dish in the world.
- Covers mostly 1.3 - 1.6GHz range.
- Includes two 15-in bearings from WWII battleships.
- Resolution of 12 arcmin at 1.4GHz.

# Parkes



- Near Parkes, Australia.
- Opened 1961.
- Operated by ATNF.
- Second largest dish in South.
- 13-beam multibeam receiver at 1.4GHz.
- Discovered ~half the known pulsars.
- Small master equatorial in center of telescope.
- Covers primarily 0.6 - 3GHz range.
- Resolution of 15 arcmin at 1.4GHz.

# Green Bank



- Near Green Bank, West Virginia.
- First light 2000.
- Operated by NRAO.
- 100x110m dish.
- Offset feed cabinet.
- Largest steerable dish (and largest man-made movable object on land).
- “Active surface”.
- Covers 300MHz - 80GHz range.
- Can see  $\sim 3/4$  of the sky (down to Dec = -40 deg).

# Arecibo

## “William E. Gordon Telescope”



- Near Arecibo, Puerto Rico.
- Opened in 1963.
- Operated by NAIC.
- 305-m dish.
- Largest non-movable dish in the world.
- Built in a natural karst depression.
- Observe  $-2 \text{ deg} < \text{Dec} < +38 \text{ deg}$ .
- Resolution of 3 arcmin at 1.4GHz.

# Effelsberg



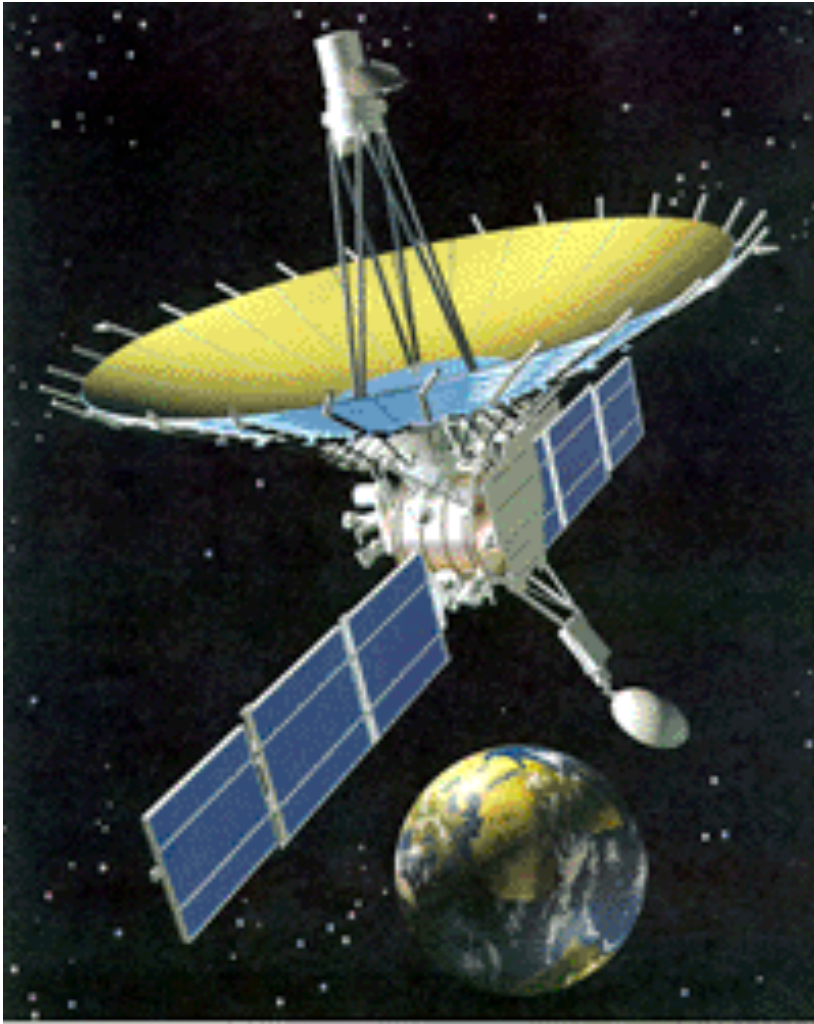
- Near Effelsberg, Germany.
- Opened 1972.
- Operated by MPIfR.
- 100-m dish.
- Largest in world for 29 years.
- Paraboloid deforms in different positions.
- Angular resolution is 10 arcmin at 1.4GHz.

# European VLBI Network (EVN)



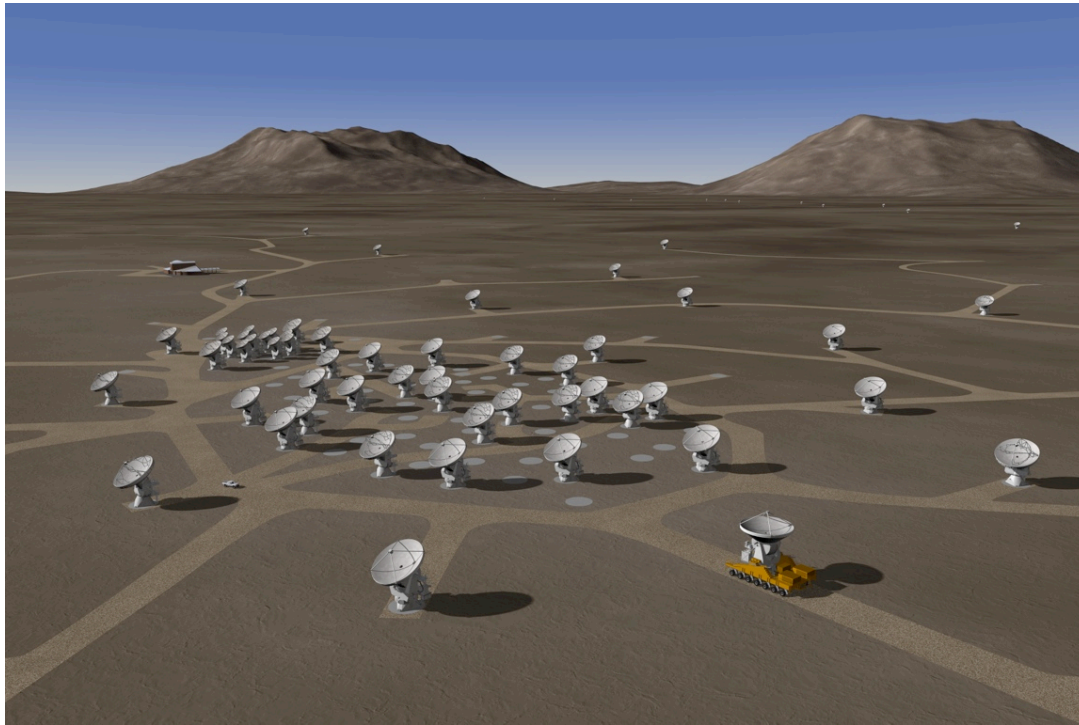
# RadioAstron

(Space based)



- Russian built.
- Correlated with radio telescopes on Earth.
- Provides baselines of many Earth diameters.
- Imaging is in some cases impossible because of poor uv-coverage.
- Knowing the space-craft position is critical in the correlation process.

# Atacama Large Millimeter Array (ALMA)



- Still coming online.
- Major step forward for (sub)millimeter interferometry.
- On the Atacama plateau in order to greatly reduce atmospheric absorption.
- Observing frequencies of 100s GHz up to THz.



# The current landscape

# The Culture of Radio Astronomy

- “Do it yourself” attitude still very present (both good and bad).
- Less “accessible” compared with other wavebands?
- Moving from more and more from small experiments to major facilities.
- The Square Kilometer Array will change both the science and the culture of radio astronomy.

# Major Institutes



- NRAO: National Radio Astronomy Observatory
- ATNF:
- ASTRON: Netherlands Institute for Radio Astronomy
- MPIfR: Max Planck Institute for Radio Astronomy
- NCRA: National Center for Radio Astronomy

# URSI

Union Radio-Scientifique Internationale /  
International Union of Radio Science



- Commission J is “Radio Astronomy.”
- Activities to protect radio-astronomical observations from interference.

# Sources

**NRAO:** <http://www.nrao.edu/index.php/learn/radioastronomy/radioastronomyhistory>

**Wikipedia:** [http://en.wikipedia.org/wiki/Radio\\_astronomy](http://en.wikipedia.org/wiki/Radio_astronomy)

Other course slides (see links on  
course wiki page):

[http://www.astron.nl/astrowiki/doku.php?id=uva\\_msc\\_radioastronomy\\_2017](http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2017)

# Questions?