


Radio Astronomy

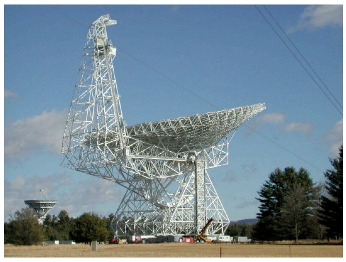
Lecture 1

The History of Radio Astronomy: Past to Present

Lecturer: Jason Hessels (j.w.t.hessels@uva.nl)

SP A1.20 - March 30, 2015



- Welcome to the course!

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.

- After this course you should be able to do a simple research project in the area of radio astronomy.

Resources

Course Wiki

https://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2015

Main resource for the course, and includes:

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

- All necessary background materials can be found on the course wiki.

Lecturers

Coordinator: Jason Hessels (j.w.t.hessels@uva.nl)
Joeri van Leeuwen (leeuwen@astron.nl)
Michael Wise (wise@astron.nl)

Teaching Assistants

Daniele Michilli (danielemichilli@gmail.com)

Amruta Jaodand (amruta.jaodand@gmail.com)

• The course has 3 (!) lecturers and 2 (!) TAs, so don't be shy about asking us questions. Each lecturer/TA brings a different perspective to the course material.

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

- There are 3 main components to the final grade.
- The mock observing proposal and practica make up the majority of the final grade.
- The final exam will test the other material covered in the lectures.

Lectures
(and other important sessions)

Lecture 1: March 30, 2015 - The History of Radio Astronomy: Past to Present - Jason

Lecture 2: April 1, 2015 - The Science of Radio Astronomy: Extragalactic - Michael

Lecture 3: April 8, 2015 - The Science of Radio Astronomy: Galactic and Solar System - Joeri

Lecture 4: April 13, 2015 - Emission Mechanisms in Radio Astronomy - Jason

Lecture 5: April 15, 2015 - The Radio Telescope - Joeri

Lecture 6: April 20, 2015 - The Techniques of Radio Interferometry I: The Basics - Jason

Lecture 7: April 22, 2015 - The Techniques of Radio Interferometry II: Calibration - Michael

Lecture 8: April 29, 2015 - The Techniques of Radio Interferometry III: Imaging - Michael

May 6, 2015 - Field Trip to LOFAR and Westerbork - Michael + Joeri + Jason + Dario

Lecture 9: May 11, 2015 - The Techniques of Time-Domain Radio Astronomy I: Single-dish techniques - Joeri

Lecture 10: May 13, 2015 - The Techniques of Time-Domain Radio Astronomy II: High time resolution with interferometers - Jason

Lecture 11: May 18, 2013 - The Future of Radio Astronomy - Michael

May 19???, 2015 - Observing proposal presentations - All (NAC: May 20-22)

May 27, 2015 - Final Exam - Jason + Daniele + Amruta

- There are 11 formal lectures as well as a full-day field trip to Westerbork and LOFAR.
- There will also be a half-day session to go through the student presentations for the mock observing proposals.

Practica

(follow lectures; work also required outside "lab" time)

Practicum 1: March 30, 2015 - Basic computer account setup etc. - Jason + Daniele + Amruta

Practicum 2: April 1, 2015 - Writing of mock observing proposal I - Michael + Jason? + Daniele + Amruta

Practicum 3: April 8, 2015 - Writing of mock observing proposal II - Joeri + Daniele + Amruta

Practicum 4: April 13, 2015 - Writing of mock observing proposal III - Jason + Daniele + Amruta

Practicum 5: April 15, 2015 - Simulate your own interferometer I - Joeri + Daniele + Amruta

Practicum 6: April 20, 2015 - Simulate your own interferometer II - Jason + Daniele + Amruta

Practicum 7: April 22, 2015 - Make a VLA interferometric image I - Michael + Daniele + Amruta

Practicum 8: April 29, 2015 - Make a VLA interferometric image II - Michael + Daniele + Amruta

Practicum 9: May 6, 2015 - Field Trip to Westerbork and LOFAR - All

Practicum10: May 11, 2015 - "Discover" and characterize a radio pulsar - Joeri + Daniele + Amruta

Practicum 11: May 13, 2015 - "Discover" and characterize a radio pulsar - Jason + Daniele + Amruta

Practicum 12: May 18, 2015 - Writing of mock observing proposal IV - Michael + Daniele + Amruta

Practicum 13: May 19???, 2015 - Observing proposal presentations - All (NAC: May 20-22)

• Practica sessions follow each of the formal lectures (hoorcolleges).
• These practica sessions in the computer lab are meant to get you started on the right foot with the practica assigments.
• The practica sessions are also a good opportunity to ask questions about in-progress assignments.
• The mock observing proposal and other practica will also require work outside of the practica sessions themselves.
• Expect to spend ~12hrs per week on "homework". The rough required time for each project is on the wiki, as are the input materials.
• After this lecture we will get everyone set up with their computer accounts for the practica.

Questions?

- Are there any questions about the course design or goals?

The History of Radio Astronomy: Past to Present

• To start the course, I'll put radio astronomy in the context of modern astronomy in general, by giving a brief summary of its history and the currently available instruments.

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

- Lecture outline.
- Moving from past to present.

Key figures in the pre-history of radio astronomy

• Let's start with a very brief history of the scientific milestones that lead to the birth 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 and the concept of traveling electromagnetic waves are the first critical piece of the puzzle.
• Radio waves could be used for artificially transmitting information, and similarly they could allow us to study natural sources at a distance.

Maxwell's Equations

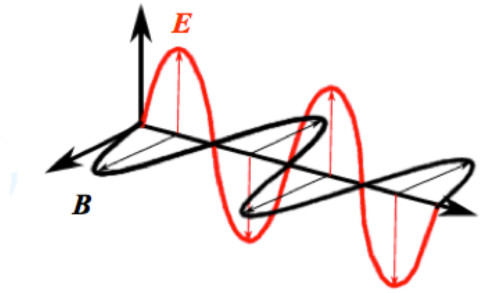
Gauss's Law	1. $\nabla \cdot \boldsymbol{E} = 4\pi\rho$
Faraday's Law of Induction	2. $\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$
Gauss's Law for Magnetism	3. $\nabla \cdot \boldsymbol{B} = 0$
Ampere's Circuital Law	4. $\nabla \times \boldsymbol{B} = \frac{4\pi \boldsymbol{J}}{c} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$

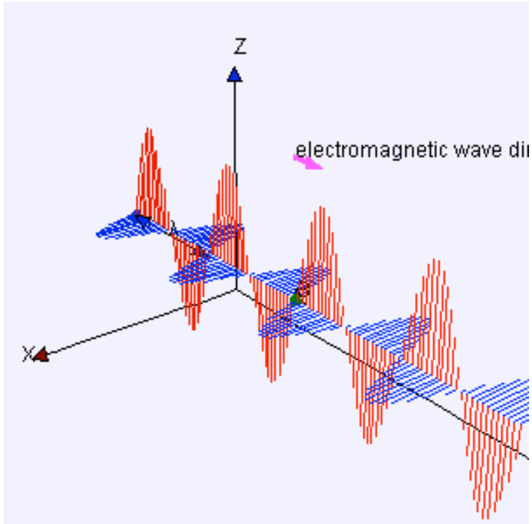
• These are simply the well know Maxwell equations.

Maxwell's Equations

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}_0 \sin(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)$$

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_0 \sin(\omega t - \boldsymbol{k}\cdot\boldsymbol{r} + \varphi_0)$$



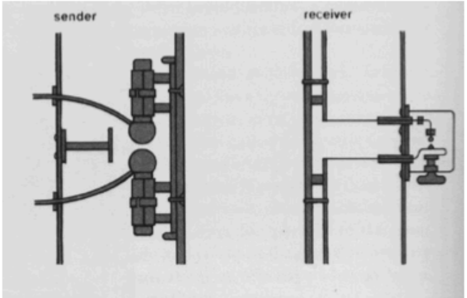


Solution is a wave

• The generic solution to these equations is a transverse wave of oscillating electric and magnetic field.

Heinrich Hertz

(1857-1894)



Once it was shown that the quantity that oscillates in a light wave is the electric field or the magnetic field, Heinrich Hertz artificially produced waves of different wave-length from those of visible light. Above are his oscillator, or sender, and his resonator, or receiver.

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

• Let's move from theory to observation.
• Hertz (of the "Hz") was the first to observe the EM-waves predicted by the Maxwell Equations.
• He was also the first to build a system for producing and receiving such waves, at a wavelength of 5m.

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

• We've seen theory and experiment. Now let's move to using this in practice.
• Marconi's transatlantic communications were a seminal step in the lead-up to the modern communications industry.
• e.g. think about how reliant we are on radio-based wireless internet!

Nobel Prize Physics 1909

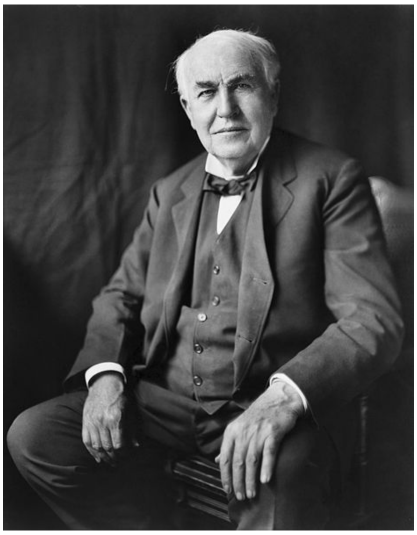
Guglielmo Marconi & Karl Ferdinand Braun

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

- In some (tangential) sense this was the first Nobel Prize for radio astronomy.

Thomas Edison

(1847 - 1931)

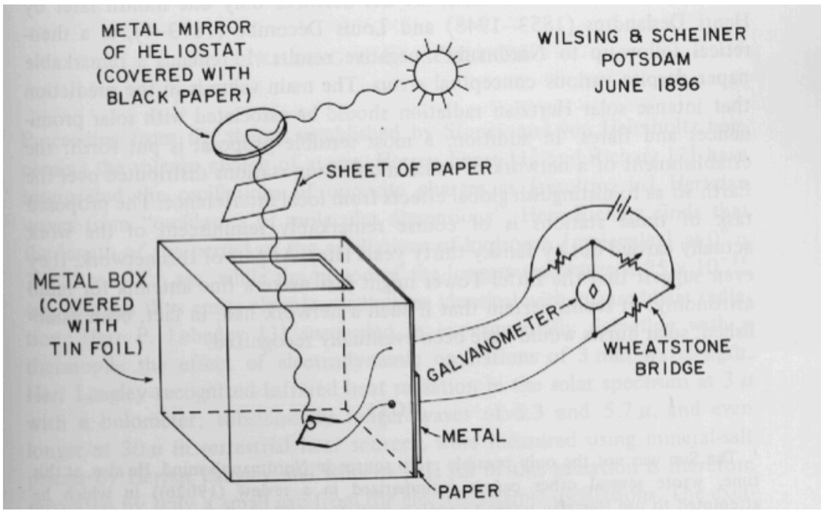


- First recorded suggestion of looking for astronomical sources of radio waves (1890).

• Edison was famous for many inventions, and also may be one of the first people to suggest looking for radio waves from astronomical sources.

Johannes Wilsing & Julius Scheiner

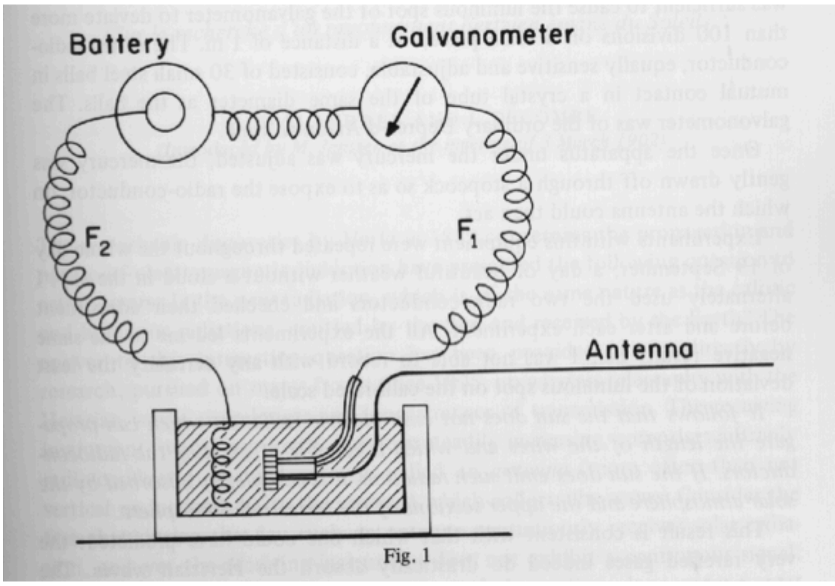
(1856 - 1943) (1858 - 1913)



- 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?

- The Sun was an obvious first source to go after.
- In the early days people were quite naive about what radio frequencies to look for (this will be a recurring theme).
- Early attempts probably didn't consider issues with atmospheric absorption/reflection.

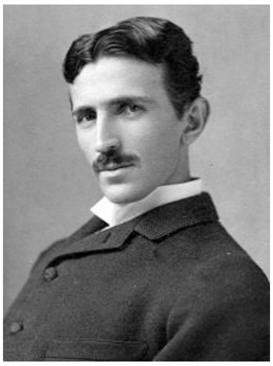
Charles Nordman

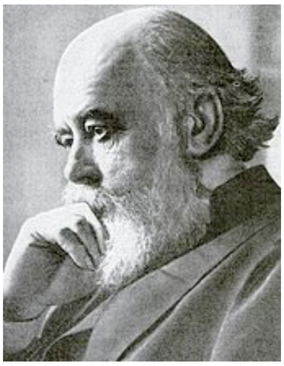


- French graduate student.
- Took experiment to top of Mont Blanc (avoid absorption).

• Another unsuccessful attempt. People are getting more inventive and going to greater lengths.

Still more attempts...





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

- Some big names also weight in.

Max Planck

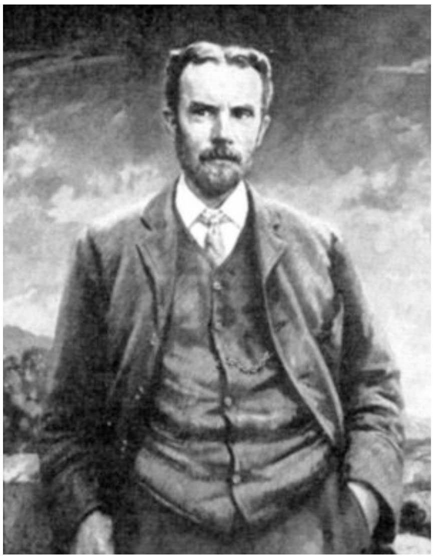
(1858 - 1947)

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

• The concept of EM-waves is only one piece of the puzzle, we also need to think carefully about the emission mechanism itself and its relation to the physical processes of the source.
• A critical point is that thermal radio emitters should have very, very low temperatures. So, detecting the Sun in this way seems fruitless.

Oliver Heaviside

(1850 - 1925)

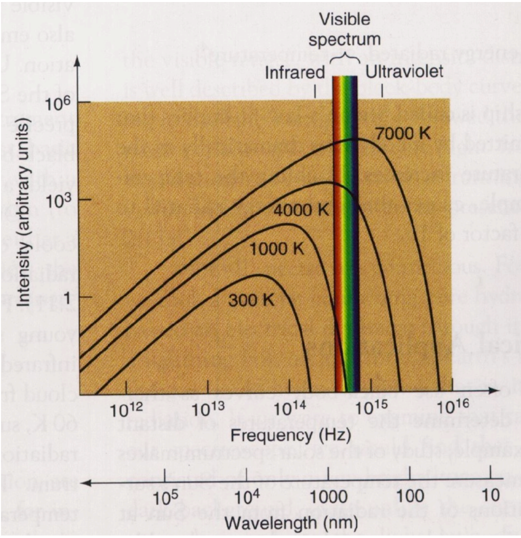


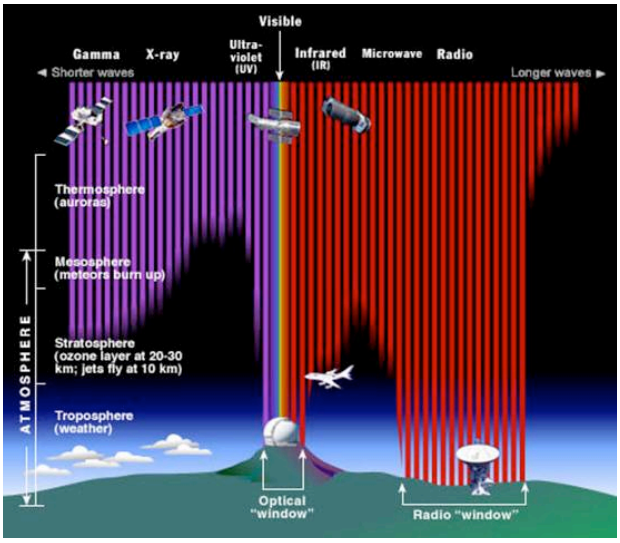
- British.
- Ionized ionospheric layer will reflect low-frequency radio waves (< 10-20MHz).
- Ionosphere predicted in 1902, observed in 1920.
- The "Kennelly-Heaviside" layer.

- Let's not forget that we have to look through the atmosphere.
- Most importantly, the ionosphere will prevent radio observations below 10-20MHz.
- At very high radio frequencies, atmospheric absorption becomes the limitation.

1902-1932

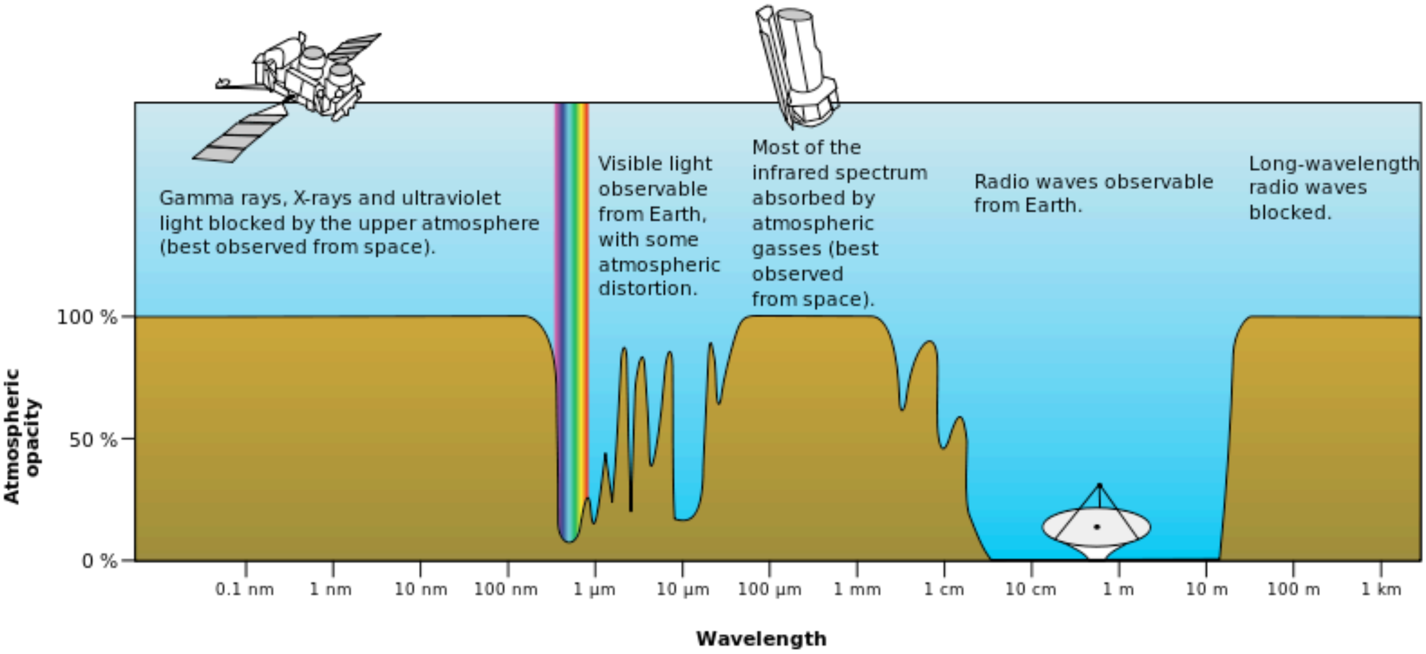
- People discouraged by Planck's prediction of low thermal brightnesses.
- Attempts also discouraged because of the ionosphere.





• For a time it seems like the cute idea of doing astronomy using radio waves won't work in practice because thermal radio sources will be too weak and the atmosphere too problematic.

EM Spectrum



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

• That said, there is a healthy range of radio wavelengths/frequencies in which radio waves pass basically unhindered through the atmosphere.

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.

• Enough with the false starts; let's have a seminal breakthrough!
• This is one of the most beautiful examples of a ground-breaking serendipitous discovery in science (we'll see several more in radio astronomy during this lecture).

Karl Guthe Jansky

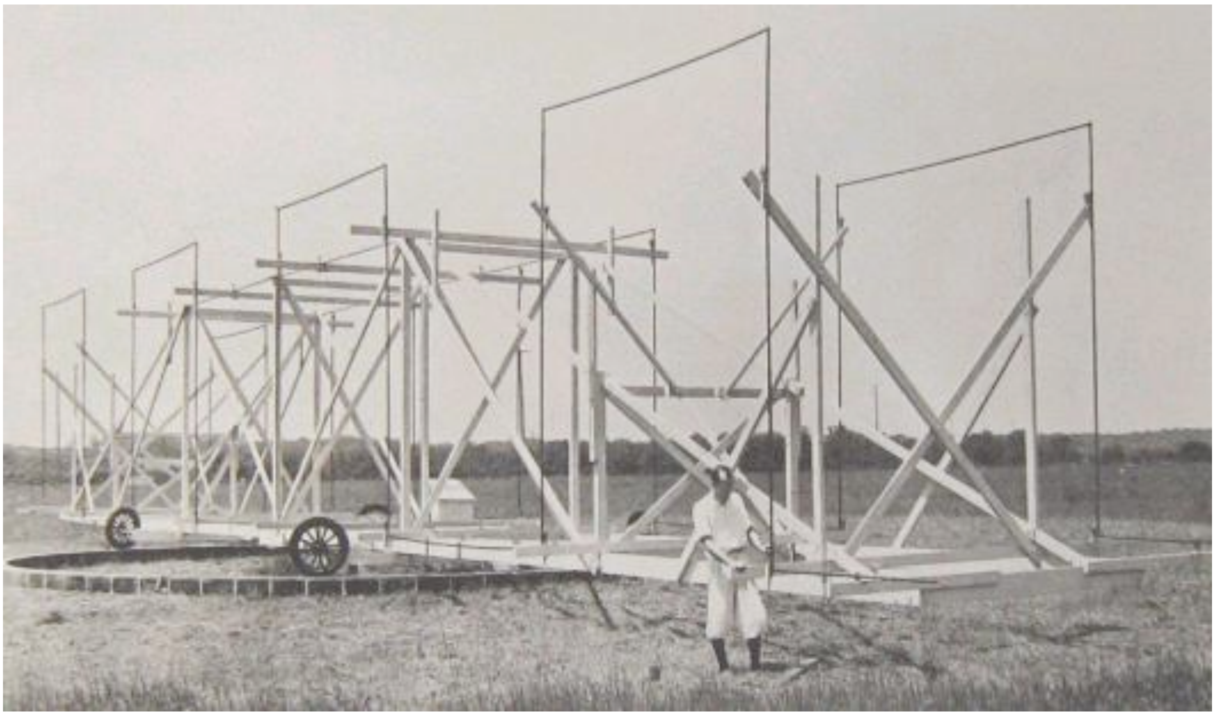
(1905-1950)

- 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" (1Jy = 10-26 W/m2/Hz).

No Nobel Prize because he died too young?

• Jansky made the first radio astronomical detections, but didn't become the first true radio astronomer (was reassigned by Bell Labs).
• Seems like a Nobel Prize worthy discovery, but he died quite young.

Jansky's telescope 1933



Discovery during the Great Depression bad timing?

Radio astronomy did not immediately take off...

• The timing of the discovery was poor. The economy was extremely weak, and World War II was looming on the horizon.

Jansky's telescope today

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

• If you visit Green Bank WV (site of the GBT and other NRAO telescopes), you can see a full-sized replica of Jansky's telescope.

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.

• Even though Jansky's discovery only made a short splash in the media, at least one person took up the torch.

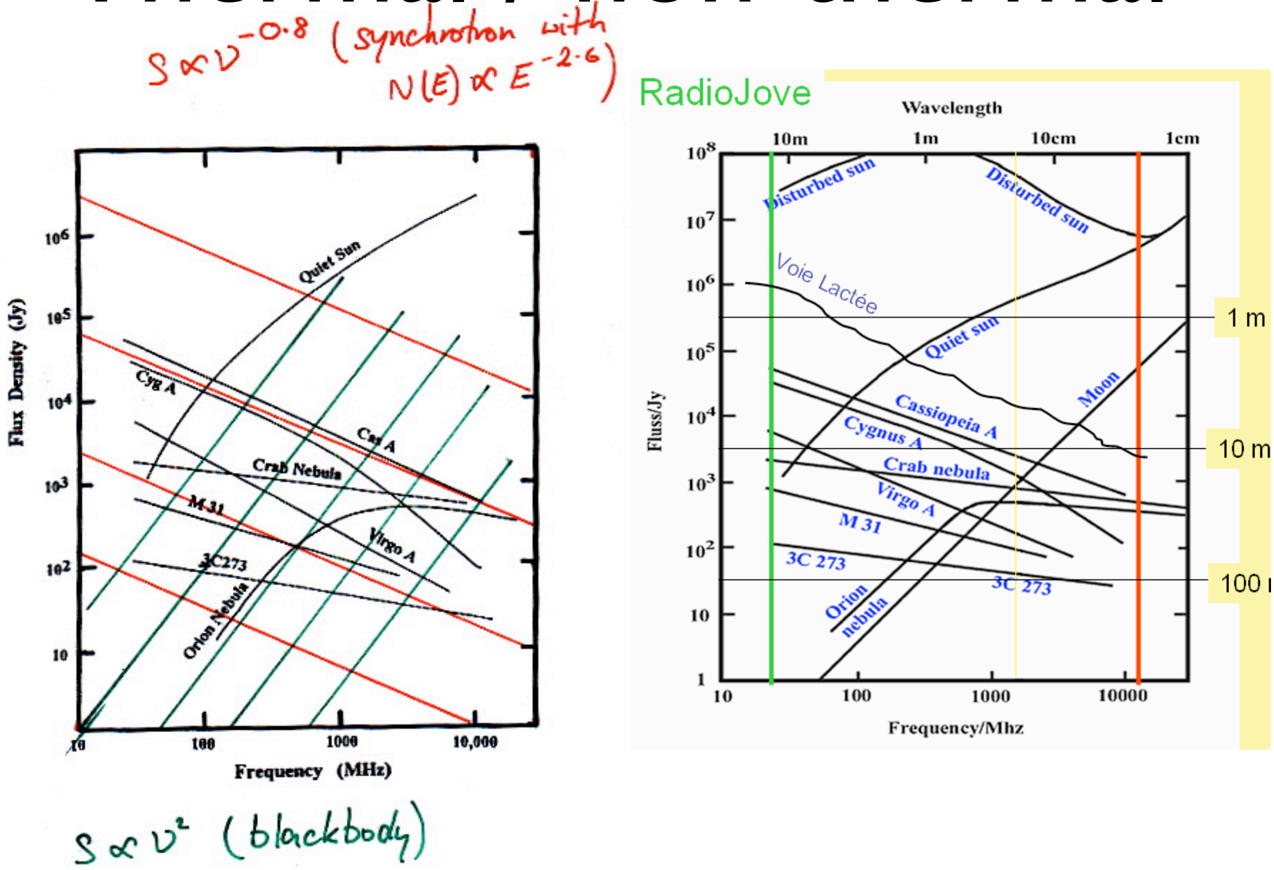
Grote Reber

(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.

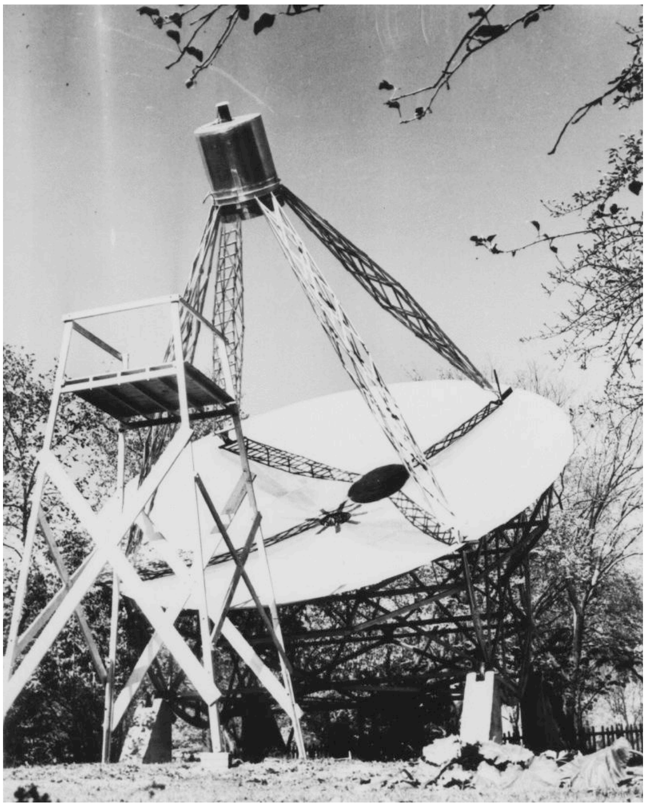
- Groet Reber was a true eccentric and non-conformist.
- He was without a doubt the first true radio astronomer.
- His early work set the stage for the explosion in radio astronomy that would happen after WWII.

Thermal / non-thermal



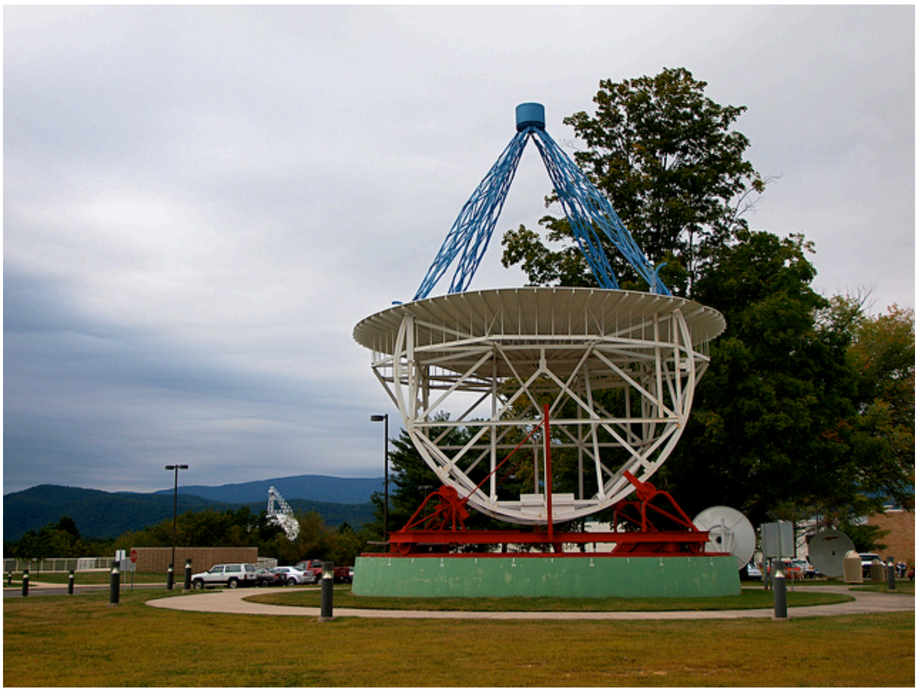
- This is critical and a transformational moment for astronomy in general: most well-observed radio astronomical sources show a non-Blackbody spectrum!
- Remember that until this point there was only optical astronomy, which studied astronomical sources based on their thermal properties.
- Radio astronomy opened a truly different window on the Universe by giving us a view of emission processes related to particle acceleration.

Reber's telescope 1937



- Built by hand in his own back yard.

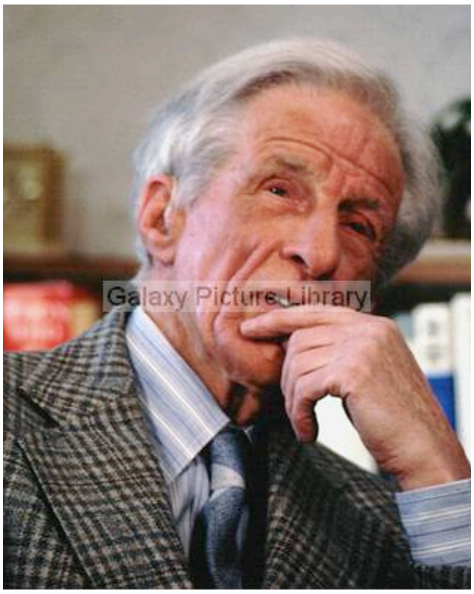
Reber's telescope today



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

• Another replica telescope you can visit in Green Bank. The 110-m GBT telescope is visible in the distance.

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.

• During WWII the rapid development of radar and radio communication served to both push the technology forward and to train a sizable group of people in the techniques that would be critical for performing radio astronomy.
• Many of the early radio astronomers converted their WWII know-how into promising scientific careers.
• The early style of radio astronomy was very technical/experimental/hands-on. This somewhat persists to this day. Unfortunately it also means that for a long time radio astronomy was seen as a very specialized and difficult area of astronomy, only accessible to true experts. This is changing, and radio astronomical data is becoming ever more accessible.

Joseph Pawsey

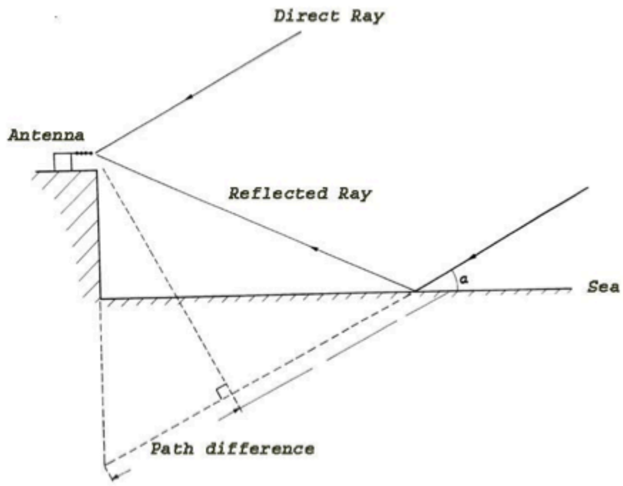
(1908 - 1962)

- 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.

• The introductions of interferometry (looking at the interference pattern of radio waves traveling along different paths) is critical to radio astronomy because it allows the type of angular resolution required to match (and surpass) the ~1 arsec used in optical astronomy.
• For a typical observing frequency of 1400MHz, a 57-km-wide dish would otherwise be needed to achieve ~1 arcsec resolution. Really have to move to synthesizing collecting areas from discrete antennas.

“Sea” interferometry

(mid 1940s)

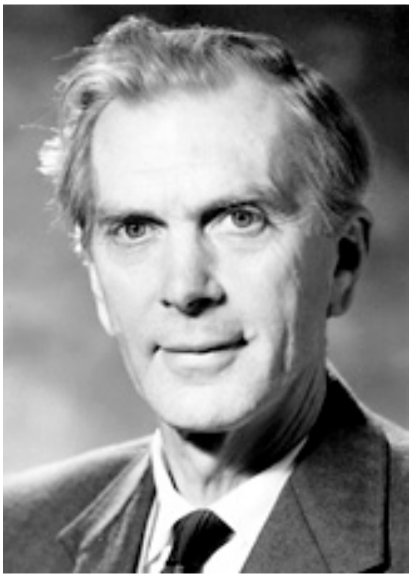


Dover Heights near Sydney

- This is one of the clever early techniques that was used. The sea acts as an extra mirror.

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.

• One of the most famous early radio astronomers. Lead the highly successful Cambridge group.
• One of the fathers of radio intererometry.
• Earth-rotation aperture synthesis is still used today in all radio interferometers. It helps to fill-in the "uv-plane" - i.e. to give a more complete view of the source structure.

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.

• Under Ryle's supervision, the Cambridge group produced many of the important first radio catalogs.
• Many of these source names persist to this day (e.g. the LOFAR EOR team regularly observes the 3C196 field).

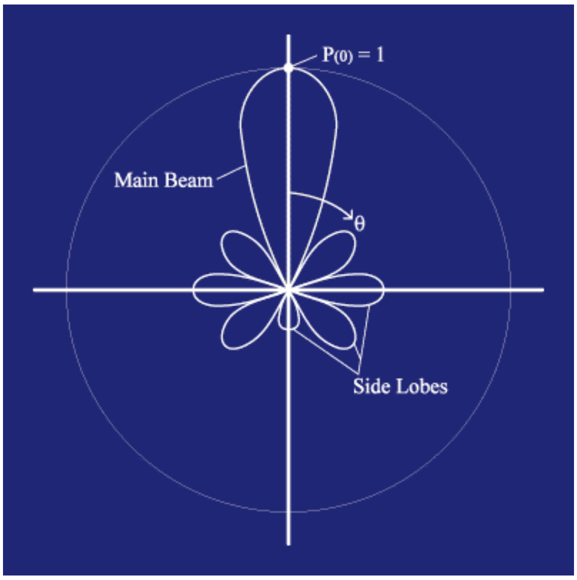
Bernard Lovell

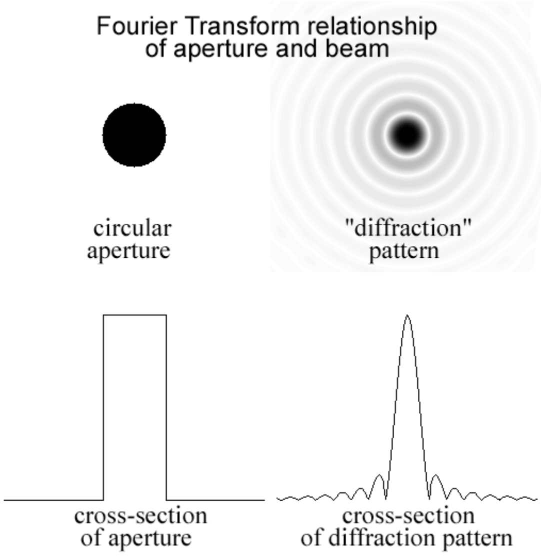
(1913 - 2012)

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

• A contemporary of Ryle, Lovell lead the other famous radio astronomy group in Britain: the Manchester/Jodrell Bank group.
• Put his efforts more into single-dish radio astronomy science.

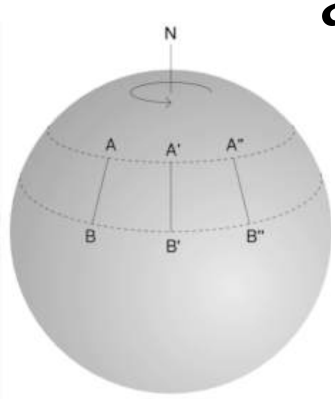
Radio telescope FoV

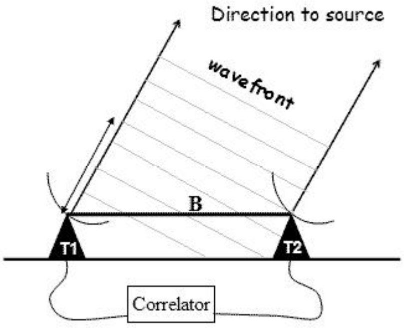


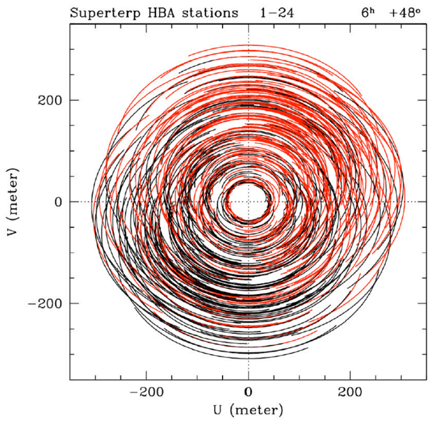


• The field-of-view (or "beam") of a radio telescope is a diffraction pattern. The main beam/lobe is normally what we simply call the field-of-view, but there are also contributions from the side-lobes.
• Bright sources in the side-lobes can still have a strong influence on the observations.
• We will discuss this in a lot more detail in various lectures and investigate this during the practica.

Development of interferometry and aperture synthesis



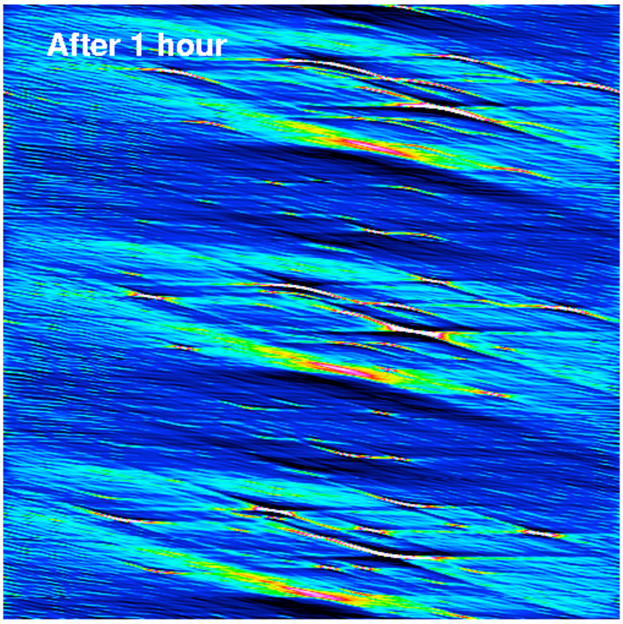




- Need for resolution.
- Earth rotation fills in the image.
- Sky brightness is the 2D Fourier transform of the spatial frequencies.

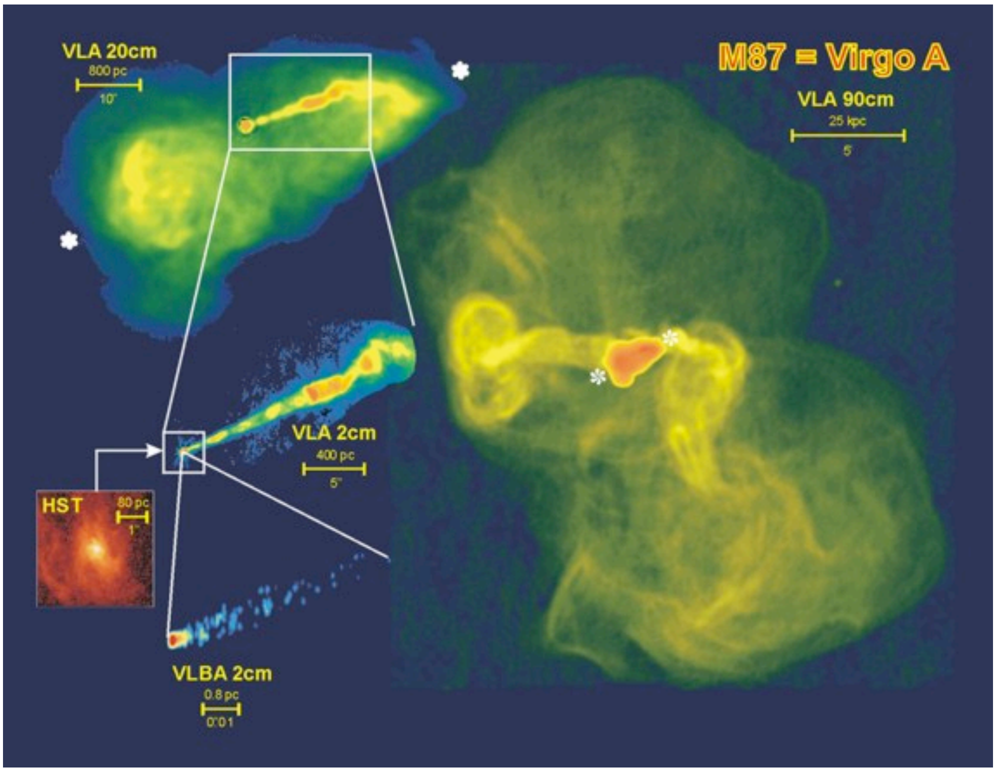
• For imaging, single dishes normally don't cut it because they provide very poor angular resolution (typically ~10 arcmin).
• Interferometry is needed, and the process of radio interferometry/imaging/calibration is both a beautiful and challenging technique (NB: Ryle shared the Nobel Prize for developing "aperture synthesis").
• We will discuss this in a lot more detail in various lectures and investigate this during the practica.

Development of interferometry and aperture synthesis



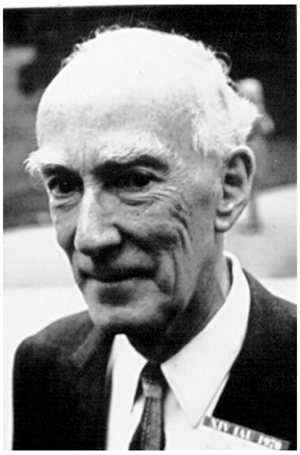
- Westerbork is a linear array of 14 dishes spanning a total length of 3km.
- The long baseline of the array offers ~10 arcsec resolution at 1400MHz/21cm.
- Despite offering angular resolution in only 1 dimension, it is still possible to make 2-D maps by allowing the Earth to rotate the array with respect to the sky!

The quest for resolution



Jan Oort

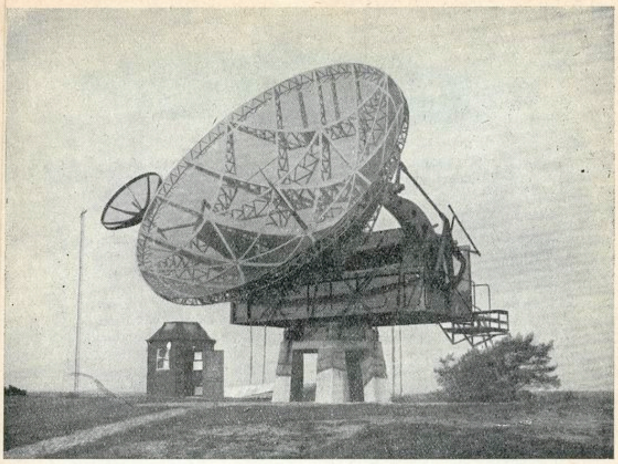
(1900-1992)



- 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."

• Father of Dutch radio astronomy, he set the Netherlands on the path to becoming a major player on the world stage.
• Took a great interest in radio astronomy because of the possibilities it offered for studying the structure and dynamics of the Milky Way.

Beginnings of Dutch radio astronomy



De radio-telescoop te Kootwijk (zie ook de voorplaat). De middellijn van de spiegel is 7½ 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.

- The Würzburg antennas left by the Germans were the first Dutch radio telescopes.
- Two Würzburg dishes were used for several decades at ASTRON, but are now in museums.
- There was quickly the drive to build a much larger, dedicated Dutch radio telescope.

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.

- A critical early step in the development of radio astronomy was the prediction and later discovery of the "21-cm line" of hydrogen.
- This spectral line provides a beautiful diagnostic tool for probing gas properties and kinematics.
- It has proven essential for mapping the kinematics of our and other Galaxies (among many applications).

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).

• A discovery so important that they reconstructed the original meeting in which it was first presented.
• Made for quite the nice PhD thesis!

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)

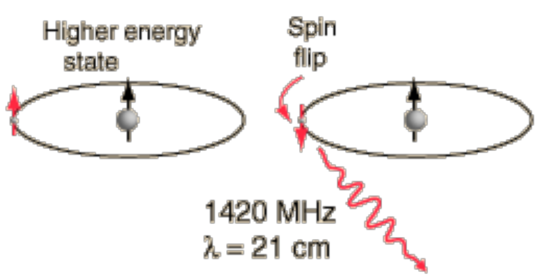
- Oort asked van de Hulst to investigate what lines there might be.
- van de Hulst discovered that a 21-cm line would result from an electron flipping its spin in the ground state of hydrogen.
- Published in Dutch in the Ned. Tijdschrift voor Natuurkunde.

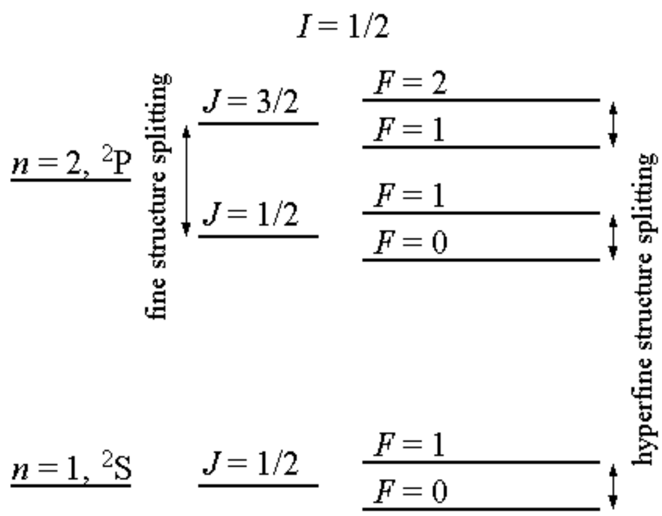
• Amazing that such a seminal discovery would be published in Dutch in the NTvN!

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.





• Quite fortuitously, neutral hydrogen, which is extremely abundant in the Universe, produces a transition that creates 1400MHz/21cm emission, which itself easily travels across intergalactic space and is easily detectable from the Earth's surface.

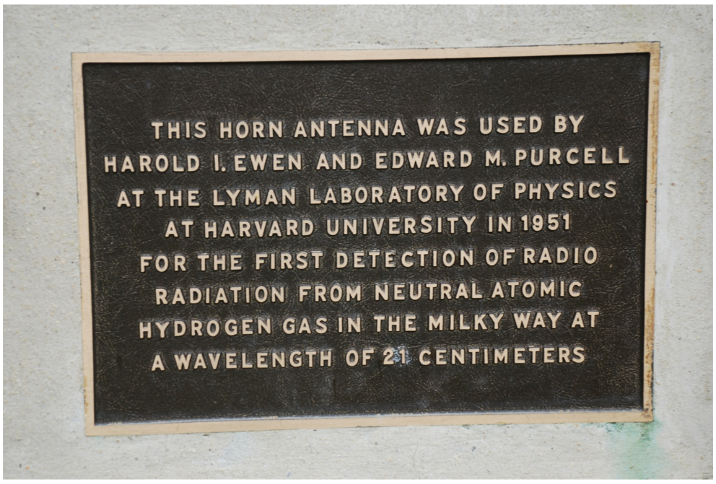
Detection of the 21-cm Line

(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

• Great, prediction, but can we detect the 21-cm line and start using it to do astrophysics?
• The receiver horn was literally hanging out the window of the lab on the 2nd (or 3rd?) floor of the building.
• A carefully built, low-noise receiver was the key ingredient - as opposed to a very large collector.

Ewen & Purcell Feed Horn Today

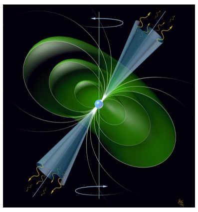


One of the three historic radio telescopes in Green Bank, West Virginia (original).

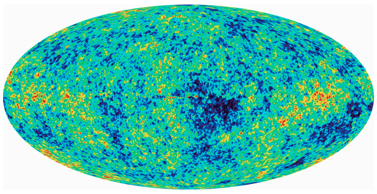
• This telescope at Green Bank is the original!

Seminal discoveries and Nobel prizes

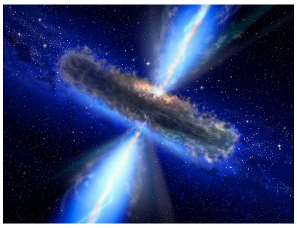
Seminal Discoveries



Pulsar - Jocelyn Bell & Antony Hewish (1967)



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

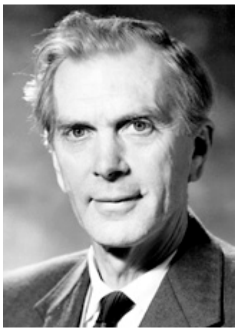


Quasars - Martin Ryles et al. (late 1950s)

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

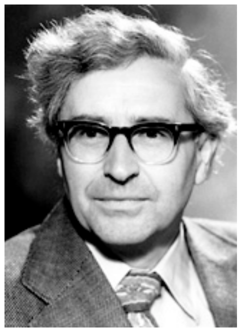
• A flurry of surprising astronomical discoveries starting pouring in in the 40s, 50s, 60s.
• These still form major cornerstones of radio astronomical research since we still don't understand these sources entirely.

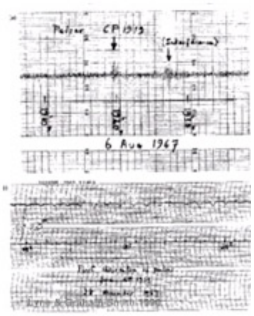
Nobel Prize Physics 1974



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"

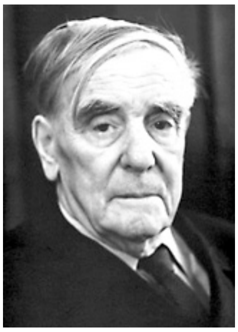




Jocelyn Bell-Burnell

- Discovery of pulsars will be discussed in more detail in a later lecture.
- Another beautiful example of serendipity, the telescope that discovered pulsars was built to study interplanetary scintillation.
- The short time constant (high time resolution) of the data recording was the key ingredient. Opening a new observing parameter space sometimes leads to such surprising discoveries.
- Data was still recorded on chart paper at that time!

Nobel Prize Physics 1978

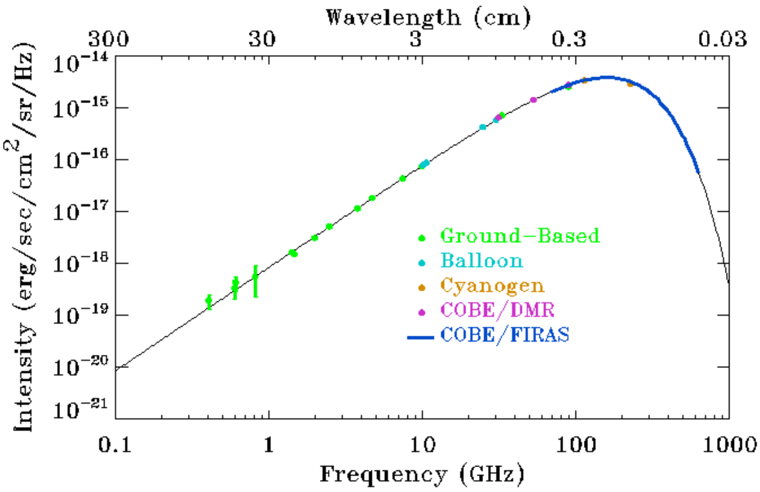


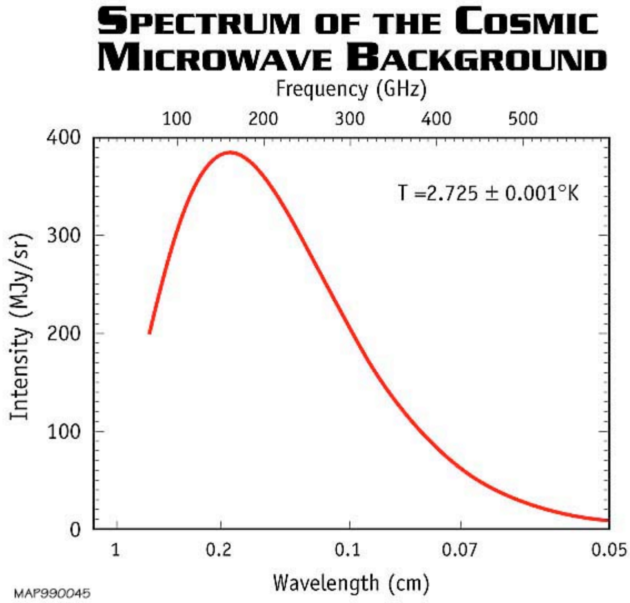
Pyotr Kapitsa, Arno Penzias & Robert Wilson

"for their discovery of cosmic microwave background radiation"

• Yet another serendipitous discovery, a key factor in their success was that they meticulously calibrated the instrument and noticed an extra "noise source" (an extra 2.7 Kelvin of system temperature) which proved to be spectacularly interesting. (famously, this extra noise did not come from bird droppings, as they had originally hypothesized)

Universe’s temperature



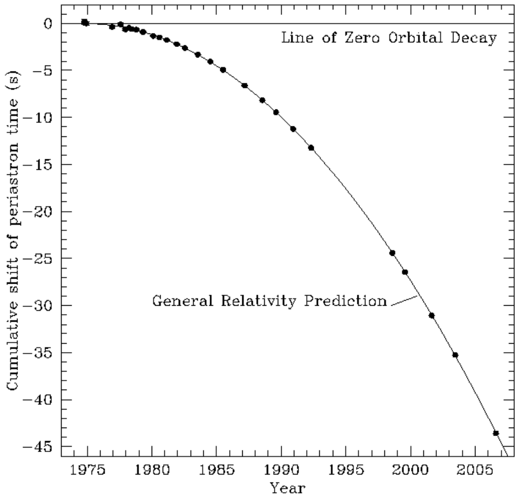


• CMB is an example where radio astronomy can make a unique contribution to studying a thermal process.
• Getting the peak of the CMB blackbody curve means going above the Earth’s atmosphere (e.g. balloon, COBE, WMAP, Planck).

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"

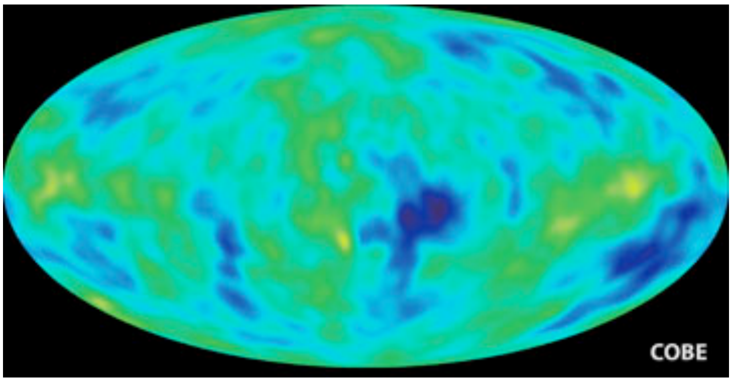


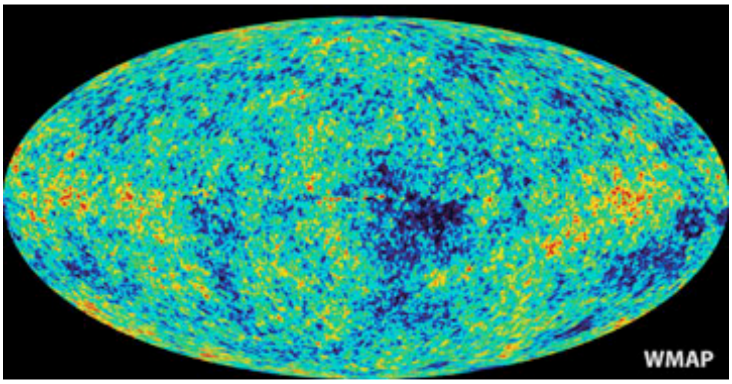
- 2nd of two Nobel Prizes for pulsars.
- 3rd (or 4th if you count Marconi) Nobel Prize for radio astronomy.

Nobel Prize Physics 2006

John Mather & George Smoot

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





- 2nd CMB Nobel Prize.
- Detailed characterization of the CMB lead to the 4th Nobel Prize for radio astronomy.
- Spectrum of fluctuations provide precision cosmological parameters.
- Planck is pushing this even further by providing a detailed polarimetric view.
- Modeling foregrounds is crucial for getting at the intrinsic cosmological signal.

Key instruments

Historic Radio Telescopes

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

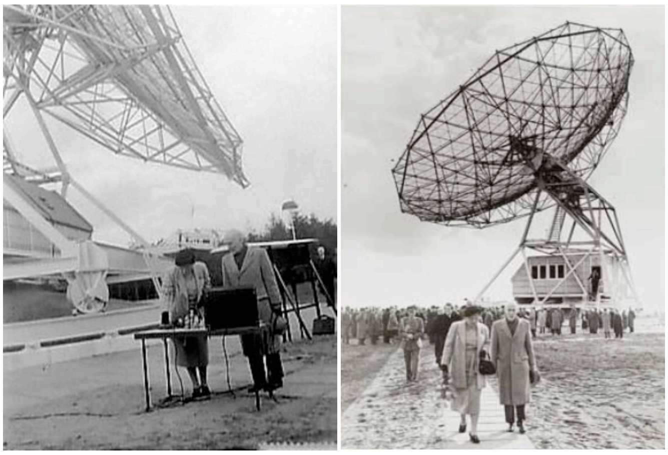
- Nowadays there are more radio telescopes than we could possibly discuss in this lecture.
- I'll briefly discuss some of the major existing facilities.
- You'll be choosing one (or more?) of these facilities to be the instrument you propose for in your mock observing proposal.

Dwingeloo

• Near Dwingeloo, the Netherlands.
• Opened in 1956.
• 25-m dish (briefly the largest in the world).
• Mapped 21cm 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 ~0.5 arcsec at 1.4GHz.
- Being upgraded with "APERTIF".

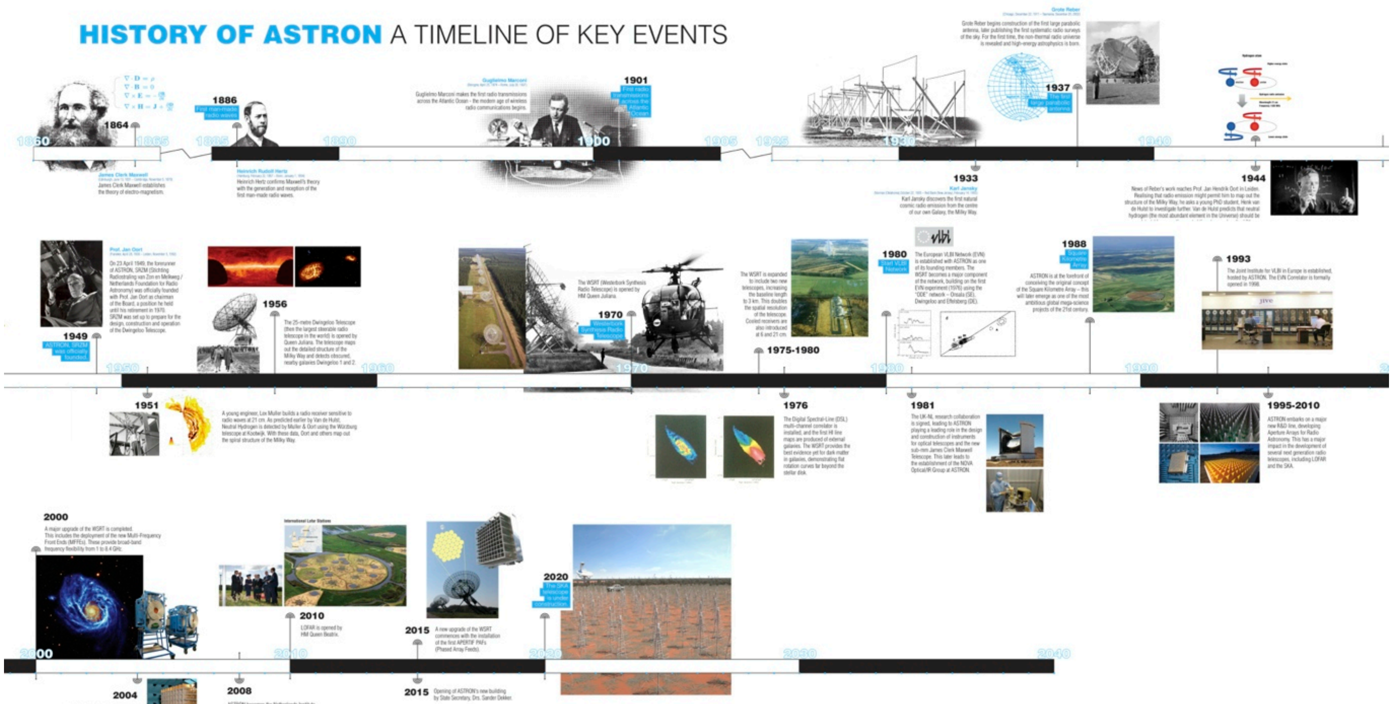
Low-Frequency Array

• 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.

• Such a telescope is basically a "sensor network" and relies heavily on fiber networks, hierarchical beam-forming, and lots of computing power.
• In many ways, LOFAR is a "software telescope".

History of ASTRON

(ASTRON is the "Netherlands Institute for Radio Astronomy")



HISTORY OF ASTRON A TIMELINE OF KEY EVENTS

Courtesy M. Garrett

• We will also visit ASTRON during the May 6th Field Trip to Westerbork and LOFAR.

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

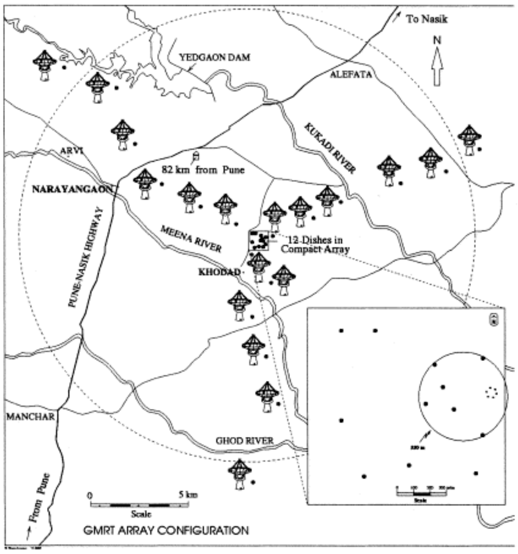
- Near Narrabri, Australia.
- Opened ???.
- Operated by ATNF.
- 6 dishes of 22-m diameter.
- 5 of the dishes can be moved along a 3-km track.
- Premier radio interferometer in the far south.

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).

- The dishes have quite high-precision surfaces, enabling observations up to ~50GHz (depends also a lot on weather at the high frequencies).

Giant Meterwave Radio Telescope

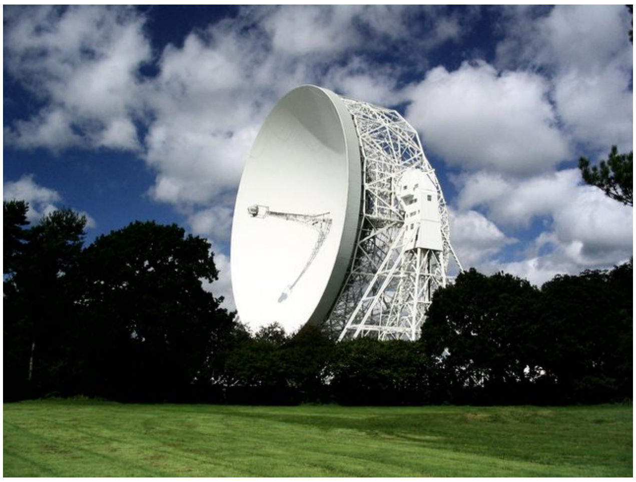


- Near Pune, India.
- First light 1995.
- Operated by NCRA.
- Aperture synthesis interferometer.
- 30 dishes of 45-m diameter.
- Max baseline ~30km.
- Covers 50 - 1500MHz range.
- Can reach 1 arsec resolution at 1.4GHz.
- A very powerful low-frequency radio interferometer.

- Notice the “floppy” dish design. The reflectors have a very sparse netting, which means that observations are only possible up to ~1400MHz. At higher frequencies the radio waves will pass through.

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.

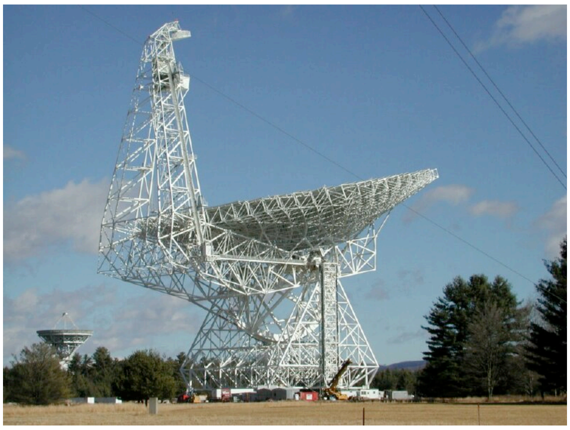
• The Lovell telescope has been timing radio pulsars for over 4 decades and has amassed an unparalleled record of their timing properties.

Parkes

- Near Parkes, Australia.
- Opened 1961.
- Operated by ATNF.
- Second largest dish in Sourth.
- 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.

- Has discovered more pulsars than any other radio telescope on Earth!

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 ~3/4 of the sky (down to Dec = -40 deg).

- This telescope discovered the fastest-spinning neutron star known.

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 deg < Dec < +38deg.
- Resolution of 3 arcmin at 1.4GHz.

- This is the telescope that discovered the Hulse-Taylor binary pulsar, and used it to indirectly detect gravitational waves.

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.

- Large European radio telescopes like these are also used in the European Very-Long-Baseline Interferometry Network (EVN).

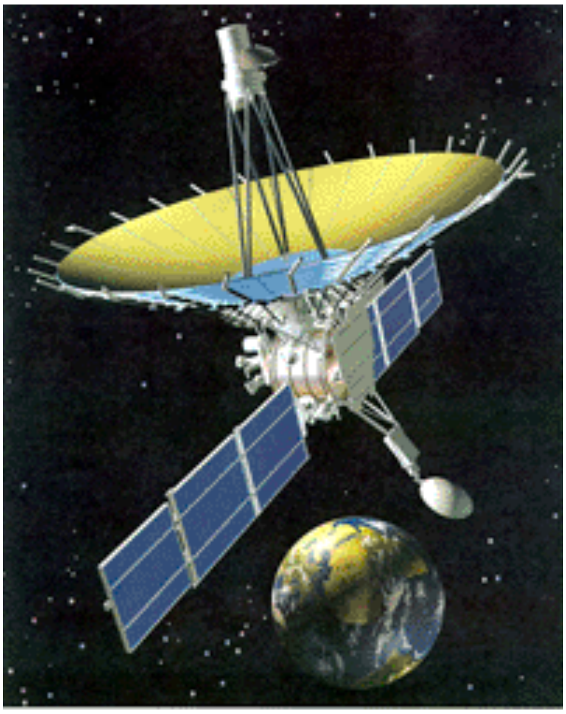
European VLBI Network

(EVN)

• A collection of Europe's distributed radio telescopes.
• The signals are brought together in Dwingeloo and cross-correlated by JIVE (the Joint Institute for VLBI in Europe).
• Provides the highest angular resolution (with the exception of using a space-based radio telescope baseline like RadioAstron).

RadioAstron

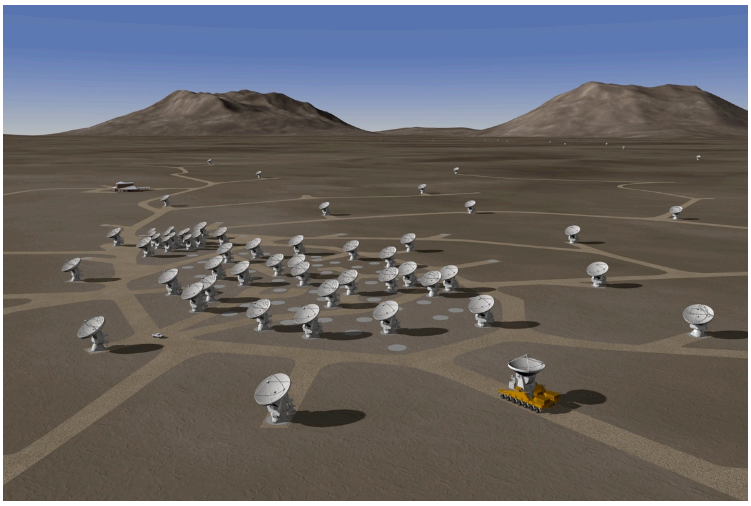
(Space based)



- 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.

- Provides even longer baselines than achievable from Earth's surface.
- uv-coverage is very, very poor so imaging is very tricky (or impossible on the longest baselines).

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.

- Still coming online.
- Major step forward for millimeter/sub-millimeter interferometry

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

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

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2013

Questions?