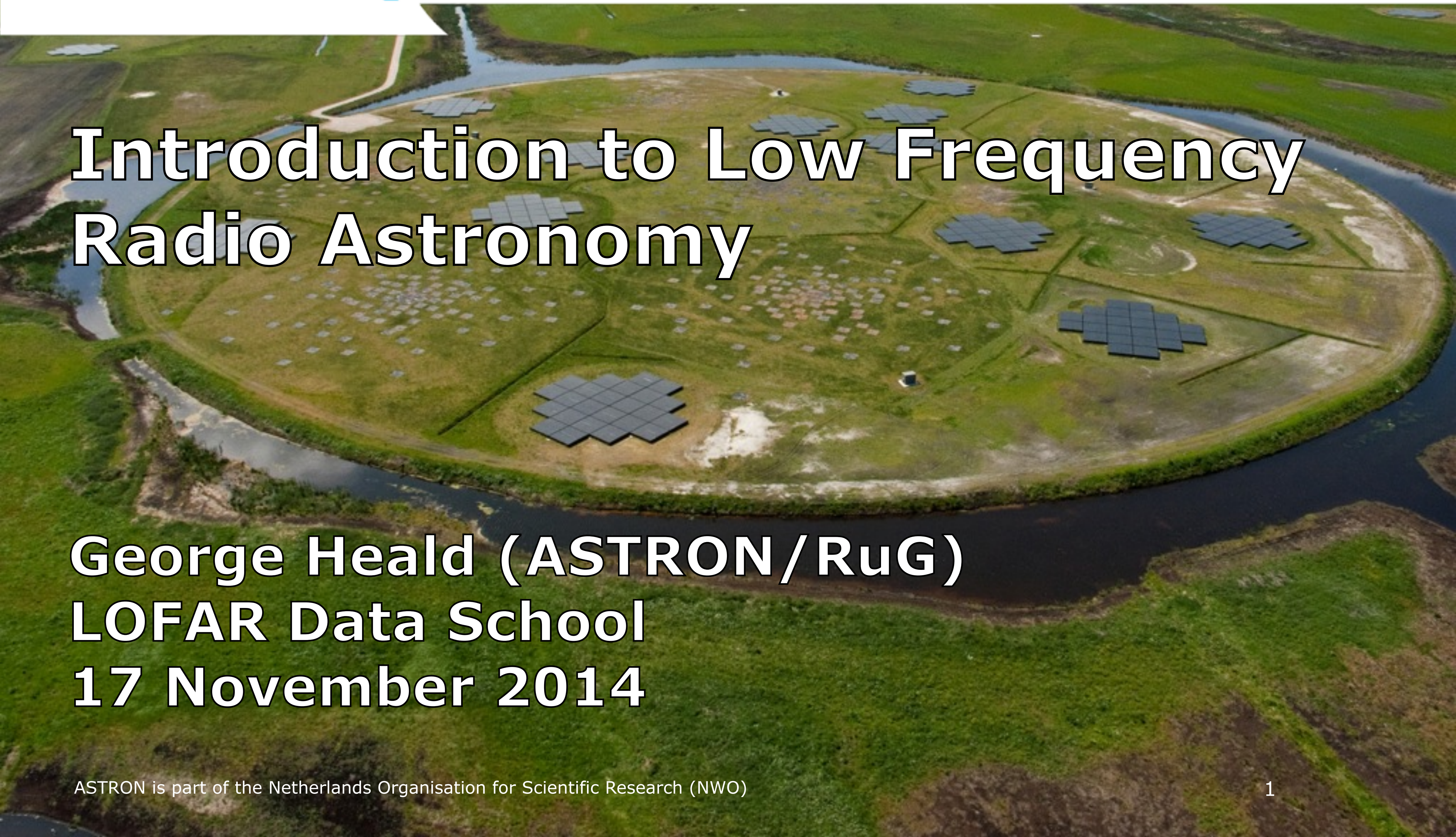
ASTRON

Netherlands Institute for Radio Astronomy



Introduction to Low Frequency Radio Astronomy

George Heald (ASTRON/RuG)

LOFAR Data School

17 November 2014

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

Introduction

- References
  - Sullivan, W.T. *The early years of Radio Astronomy* 1984, Cambridge University Press, Cambridge
  - Kraus, J.D. *Radio Astronomy* (2nd ed.) 1986, Cygnus-Quasar Books, Ohio
  - Thompson, Moran, & Swenson *Interferometry and Synthesis in Radio Astronomy* (2nd ed.) 2004, WILEY-VCH, Weinheim
  - Taylor, Carilli, & Perley *Synthesis Imaging in Radio Astronomy II* 1999, Astronomical Society of the Pacific, San Francisco

http://tinyurl.com/siraii

- Thanks!
  - Material from lecture slides courtesy of Jason Hessels, Marco de Vos, Mike Garrett, Tom Oosterloo

Topics

- Why observe in the radio?
- Radio waves & how to detect them
- History of (low frequency) radio astronomy
- Interferometry: quick review
- Survey of low frequency radio facilities
    - Current telescopes
    - Future telescopes
    - Key capabilities
- Current science topics in low frequency radio astronomy [Emphasis on LOFAR Key Science Projects]

What can we observe at radio wavelengths?

- Thermal (bremsstrahlung) radiation [ionized gas]
- (Polarized) Synchrotron radiation
  [Cosmic rays and magnetic fields, pulsars, galaxies, clusters, …]
- Cyclotron radiation [planetary magnetic fields]
- Spectral lines
  [Neutral hydrogen, radio recombination lines, molecules, masers]
- NB: no dust absorption

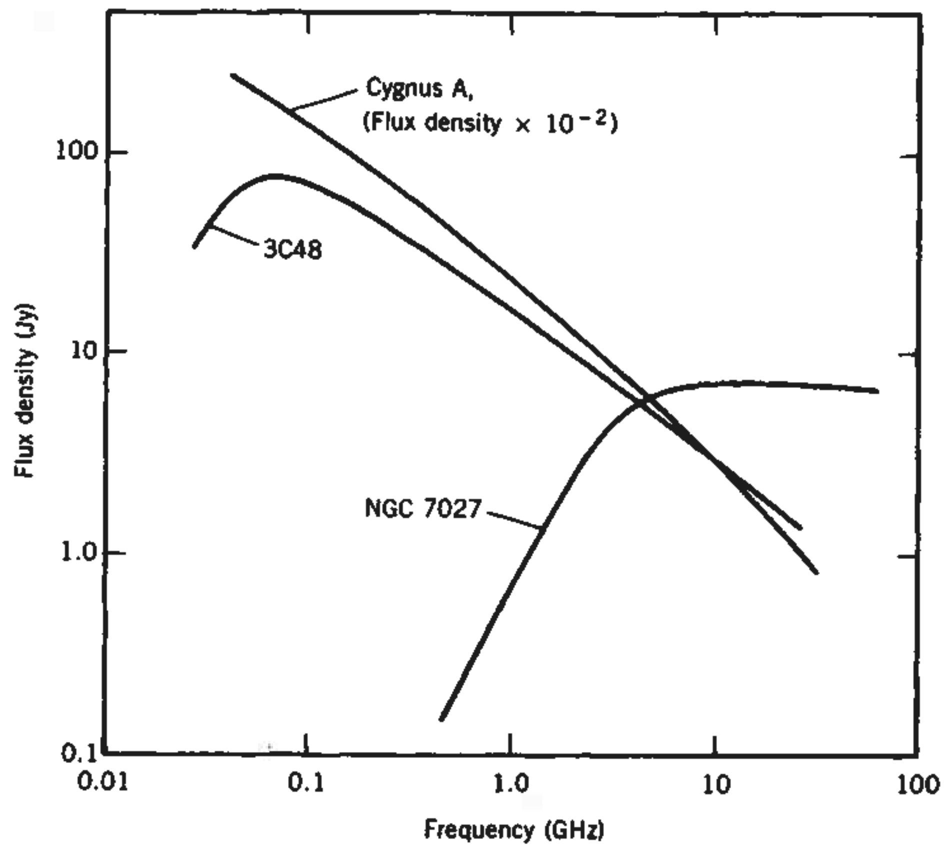
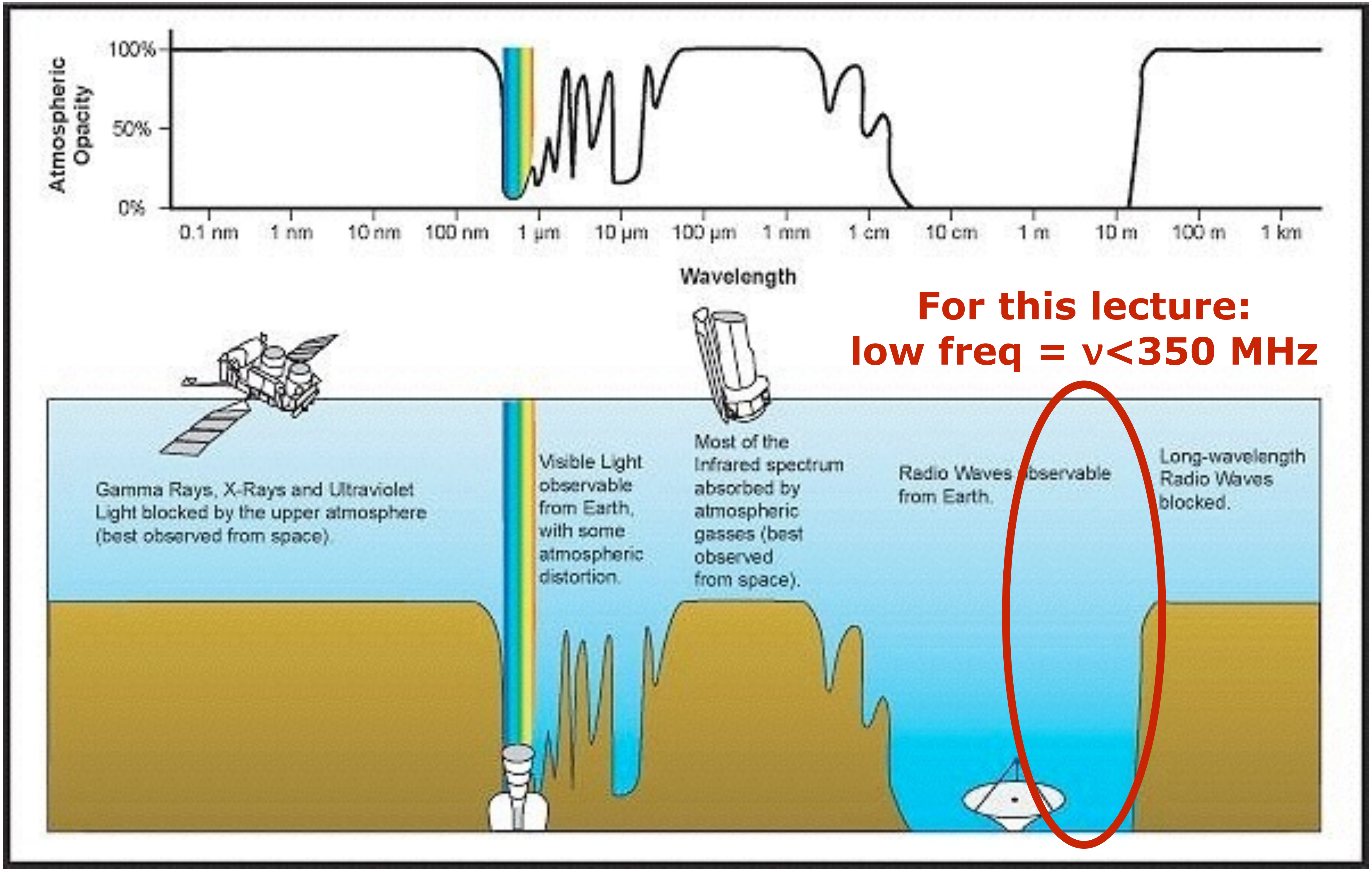


Figure 1.1 Continuum spectra of three discrete sources: Cygnus A, a radio galaxy; 3C48, a quasar; and NGC7027, an ionized nebula within our Galaxy. Data are from Conway, Kellermann, and Long (1963); Kellermann and Pauliny-Toth (1969); and Thompson (1974). [One jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1}.]

Context

- Radio waves (λ<30m ⇔ freq>10 MHz) can be observed from the ground

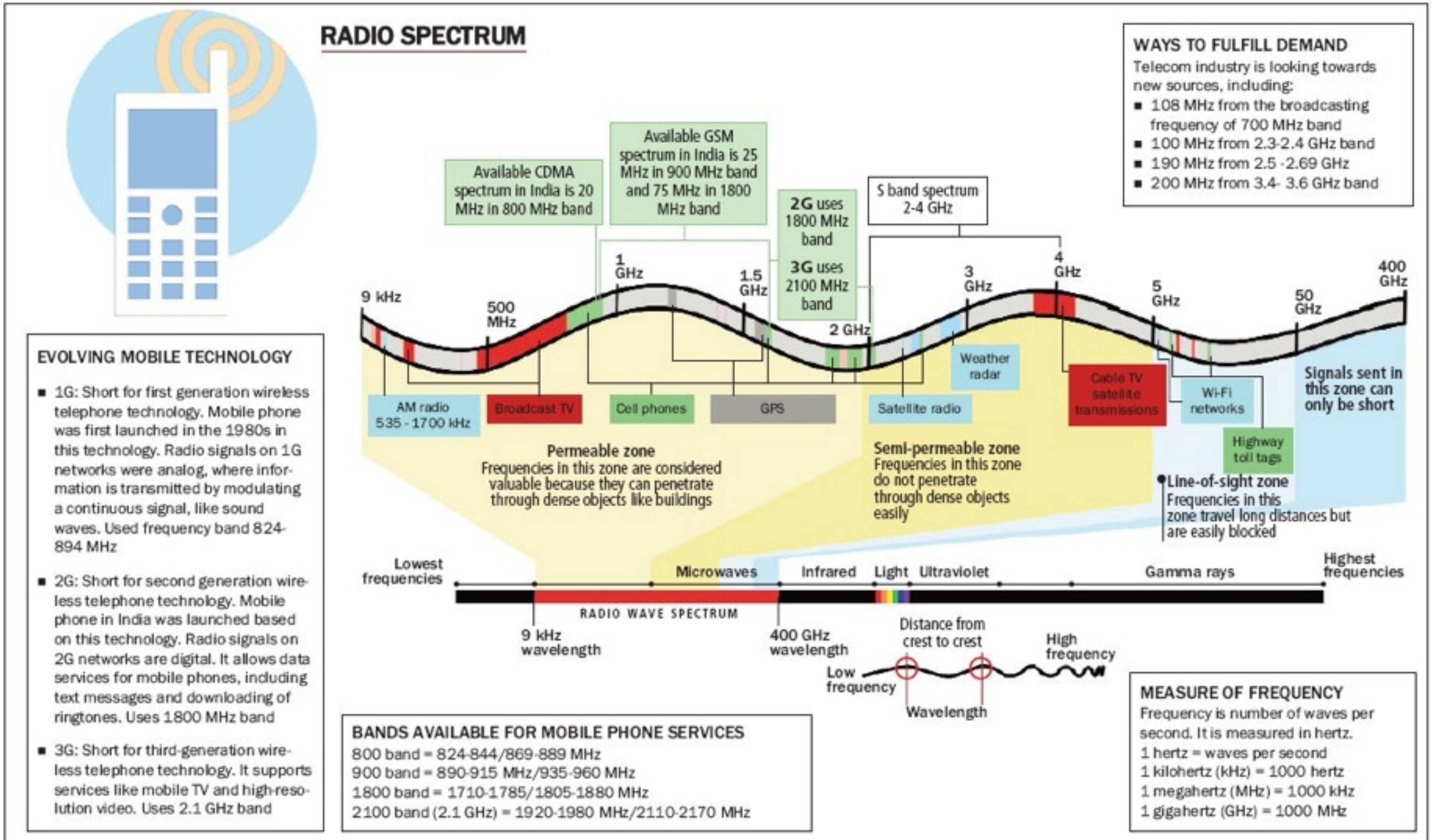


http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/irwindows.html

Context

- Radio waves (λ<30m ⇔ freq>10 MHz) can be observed from the ground

  … but are also useful for commercial applications like communications



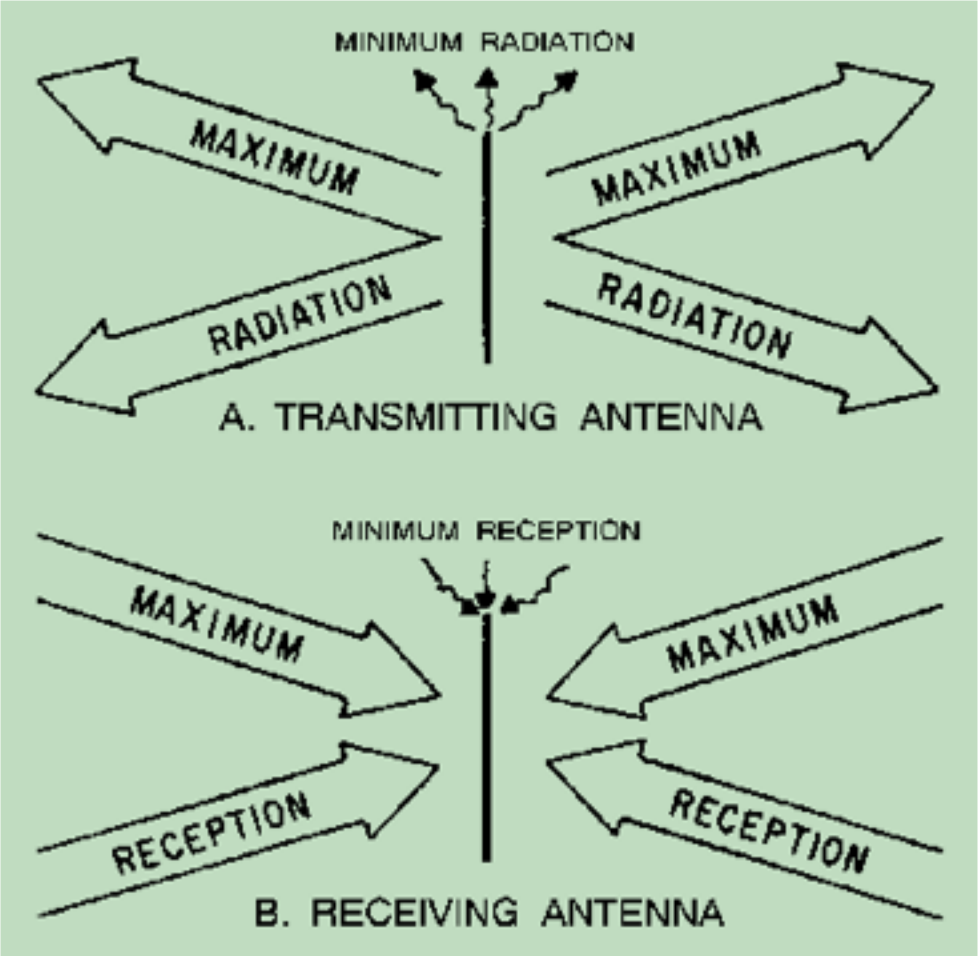
http://www.downtoearth.org.in/content/all-about-mobile-spectrum

Detection of radio emission

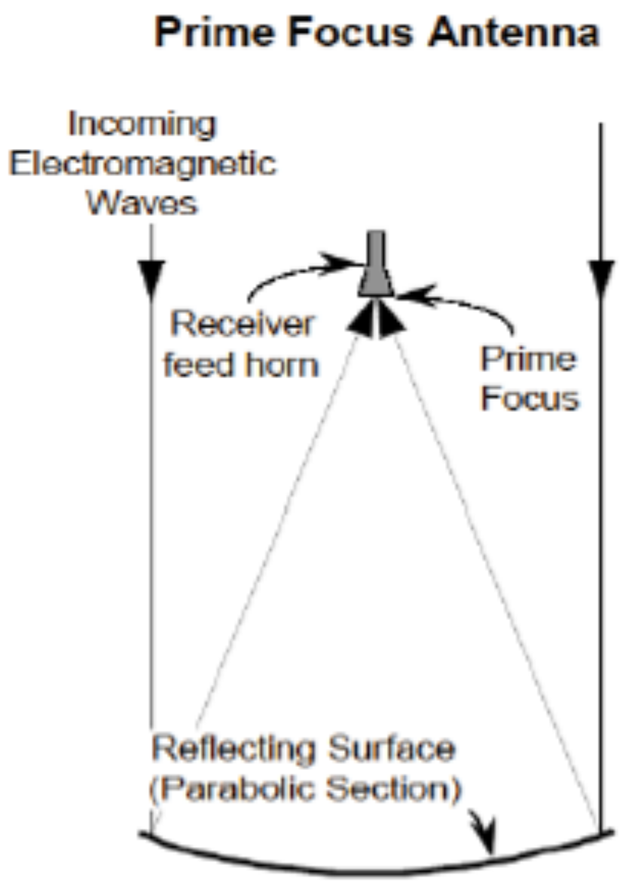
- Detection of induced current in conducting feeds, not liberated electrons
- Induced currents are very weak and must be amplified

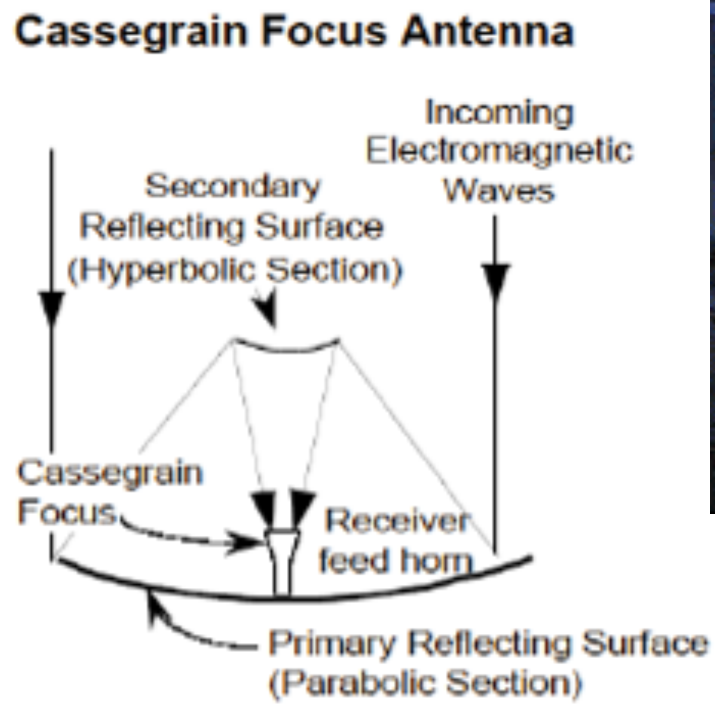
- Detectors respond to amplitude of electric field of incident EM waves
  - Dipole antenna
  - Dish + feed horn (+LNA)
  - full receiver chain up to A/D conversion

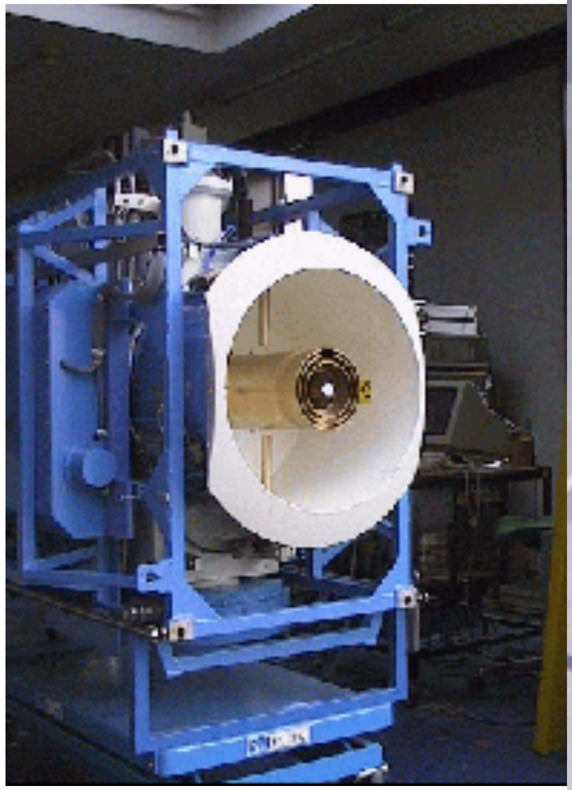
- Phase is preserved
- Separate polarizations
- Typically narrowband (< 1 octave)

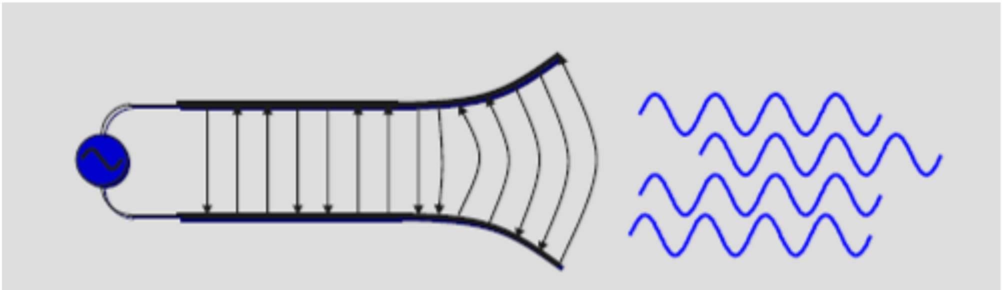


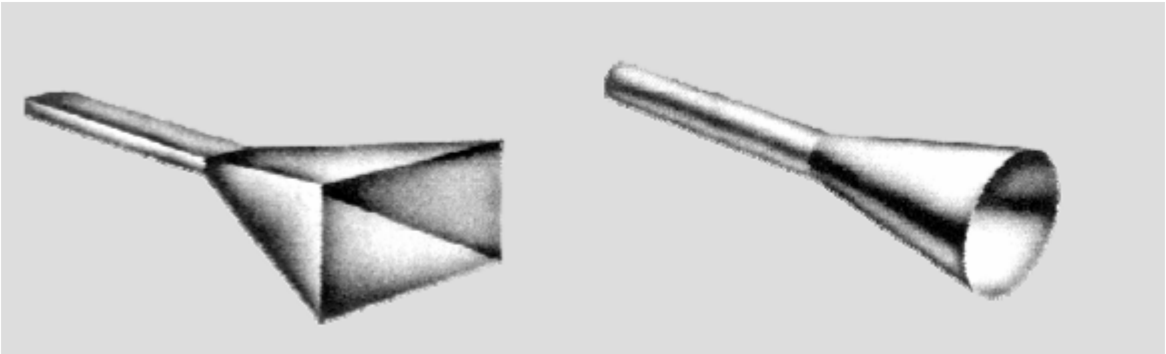
Horn antennas





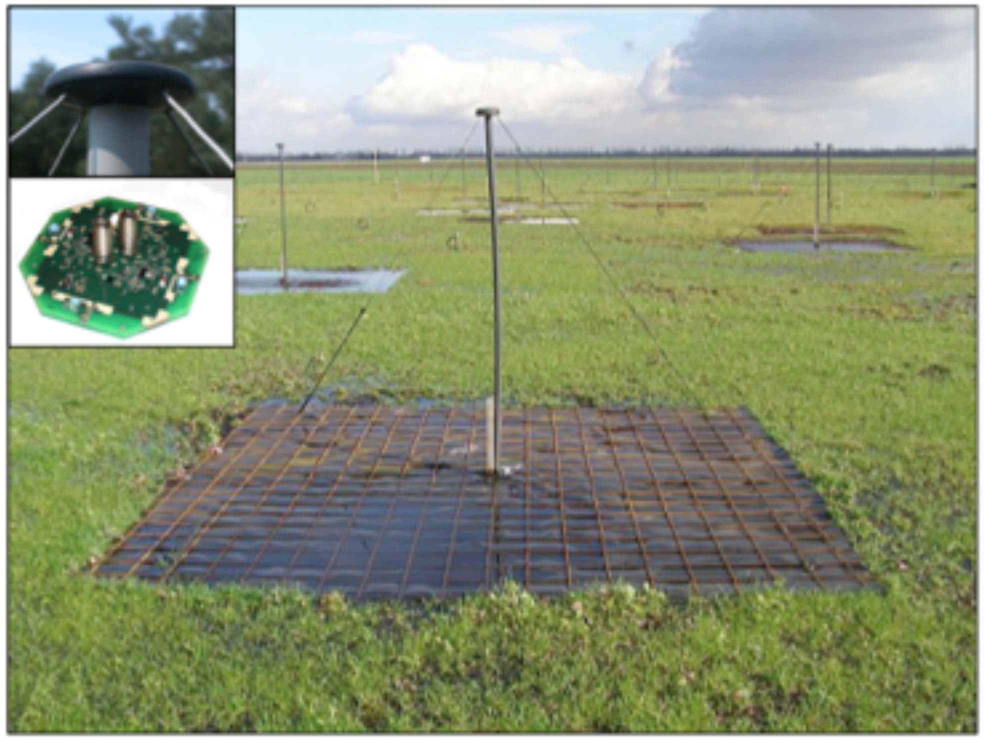


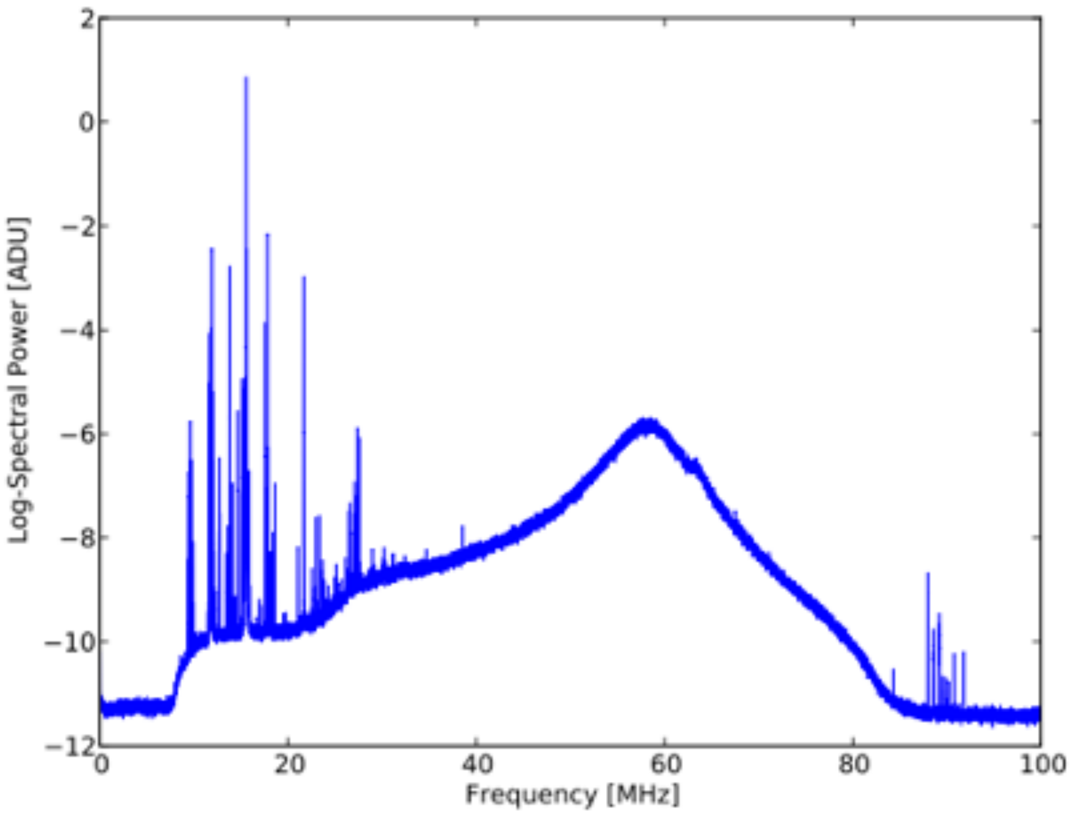


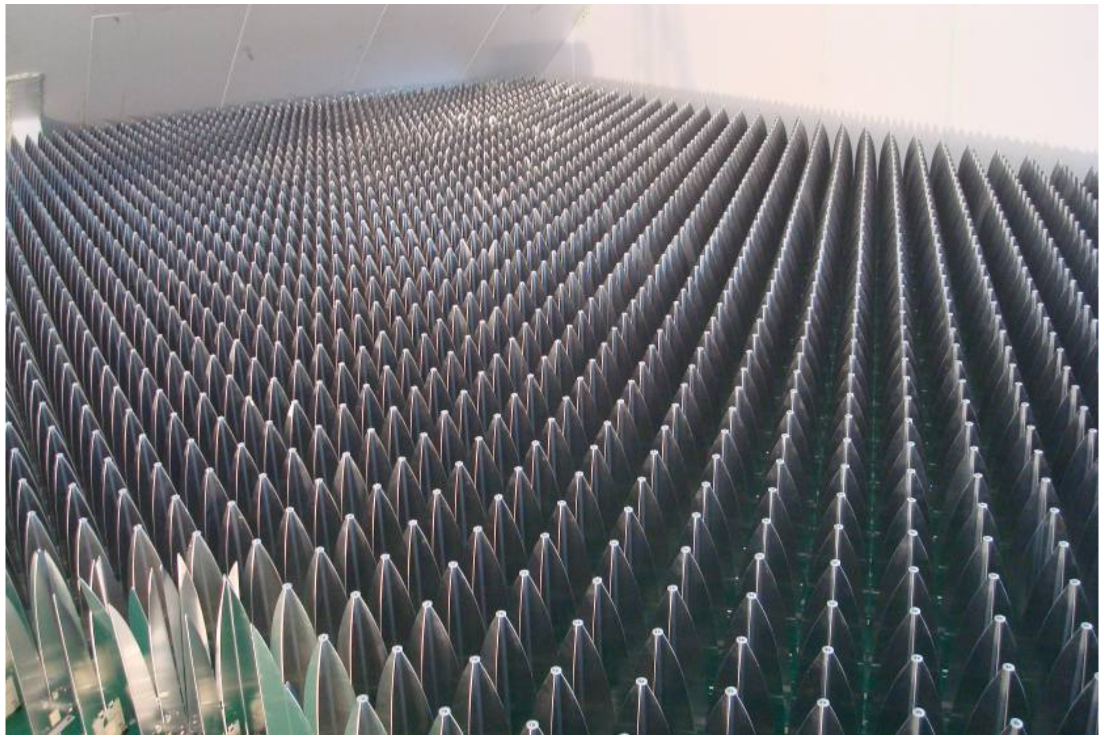


Wire, Vivaldi antennas

- Can provide wide frequency coverage with simple designs

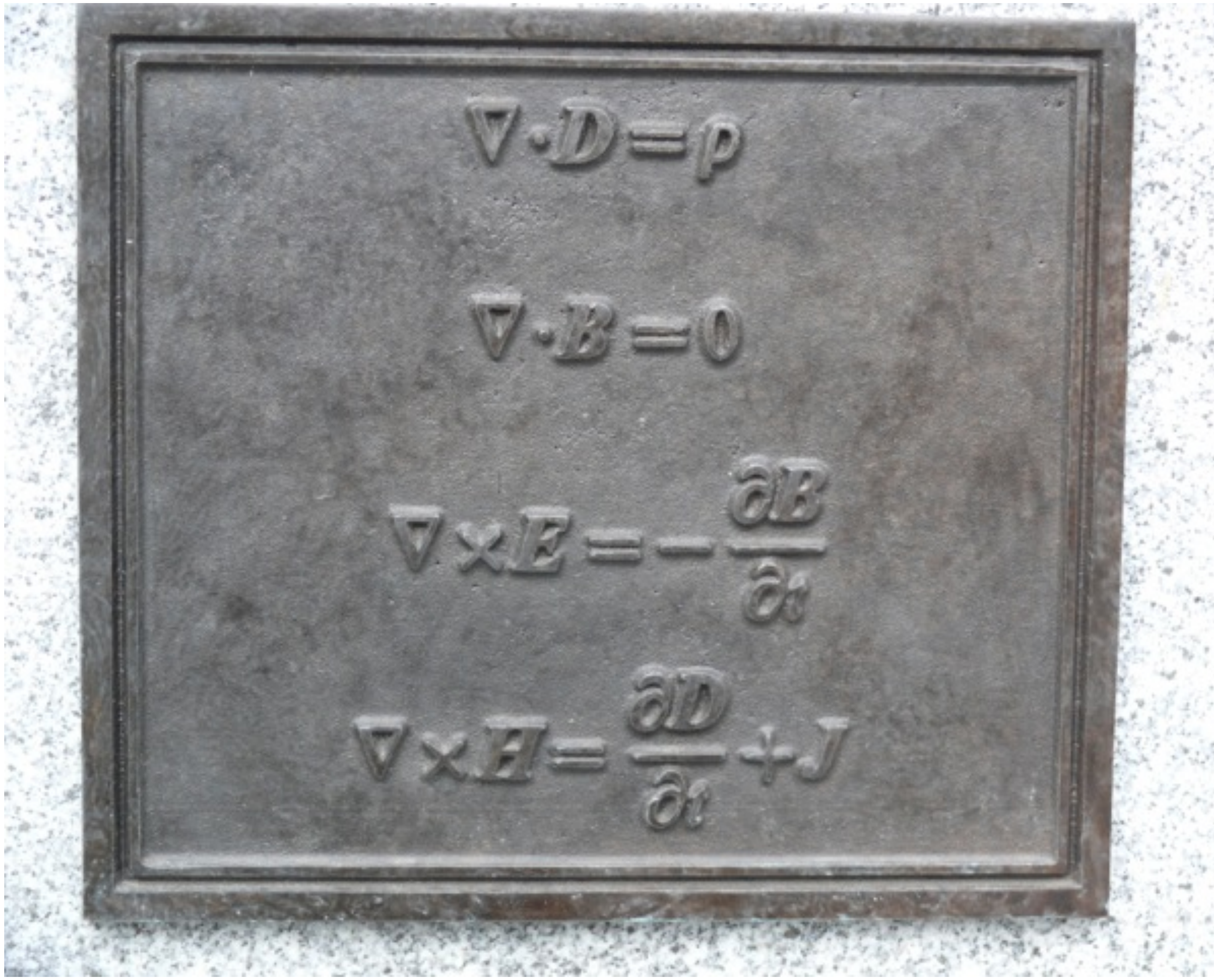






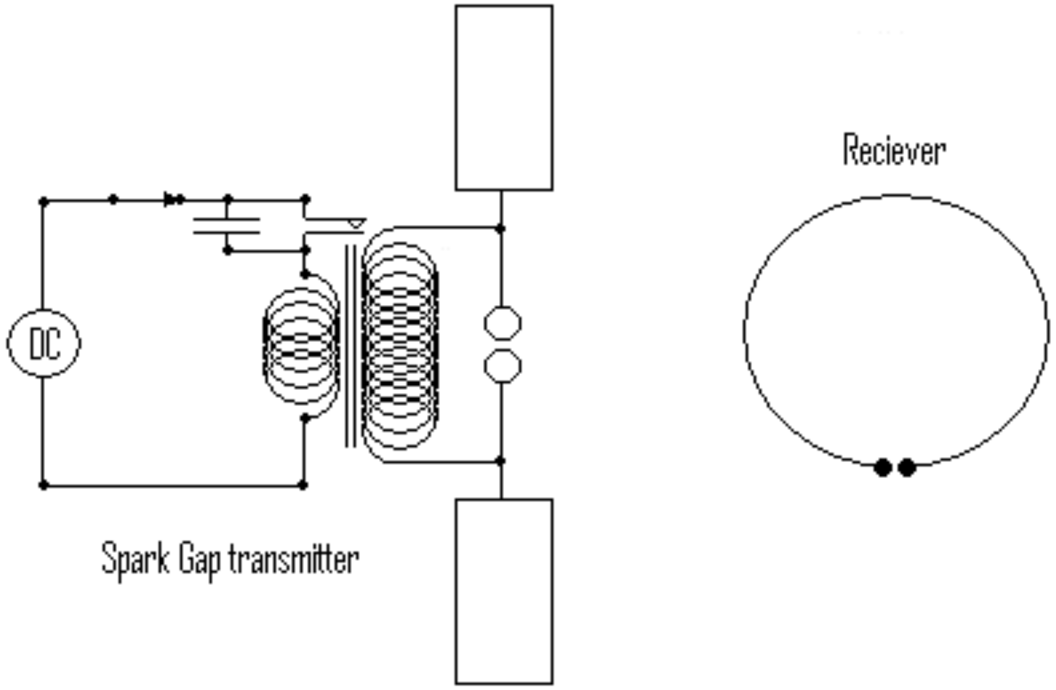
Pre-history of radio astronomy

- Context: development of radio communications following Maxwell's laws (published 1865)



Pre-history of radio astronomy

- Context: development of radio communications following Maxwell's laws
  Transmission & reception of radio pulses by Heinrich Hertz (ca. 1888)



- Completely misunderstood the impact of his work:

> It's of no use whatsoever[...] this is just an experiment that proves Maestro Maxwell was right—we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.
>
> -Hertz

Pre-history of radio astronomy

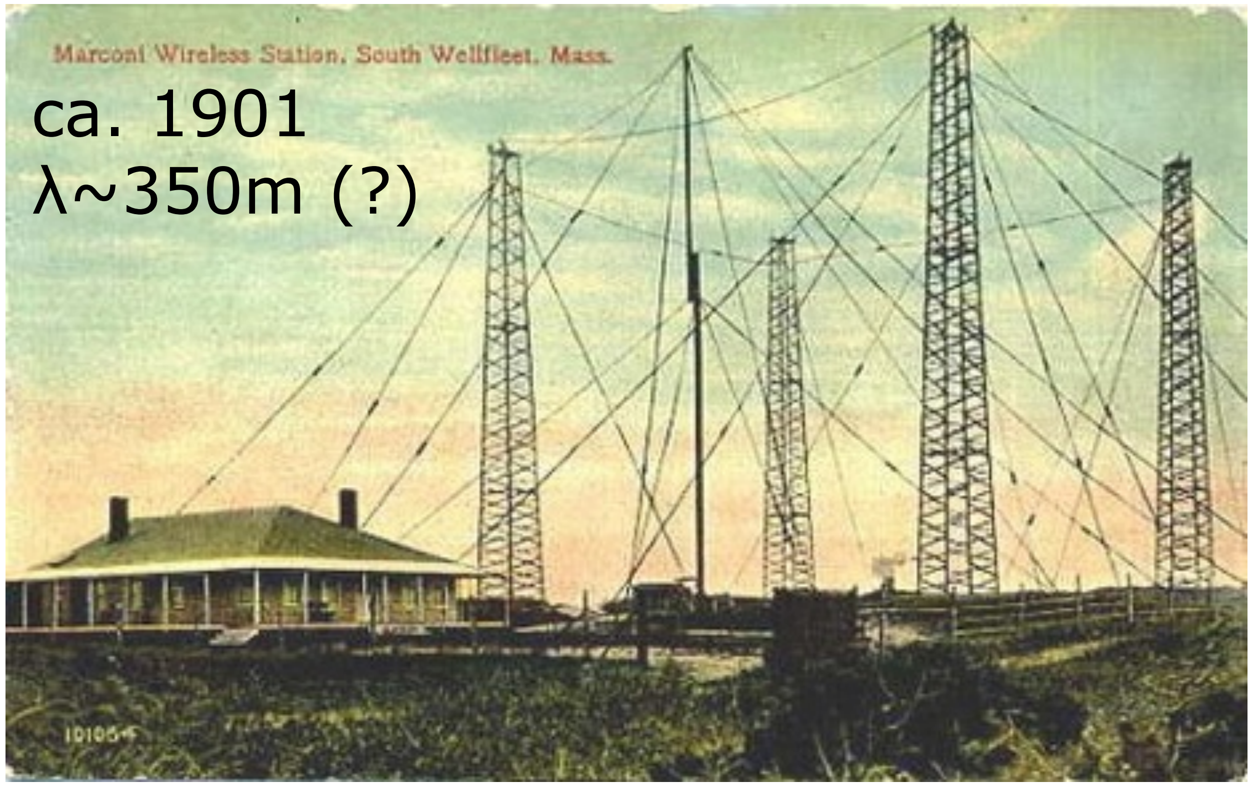
- Context: development of radio communications following Maxwell's laws
  Development of long-distance radio communication by Marconi & Braun

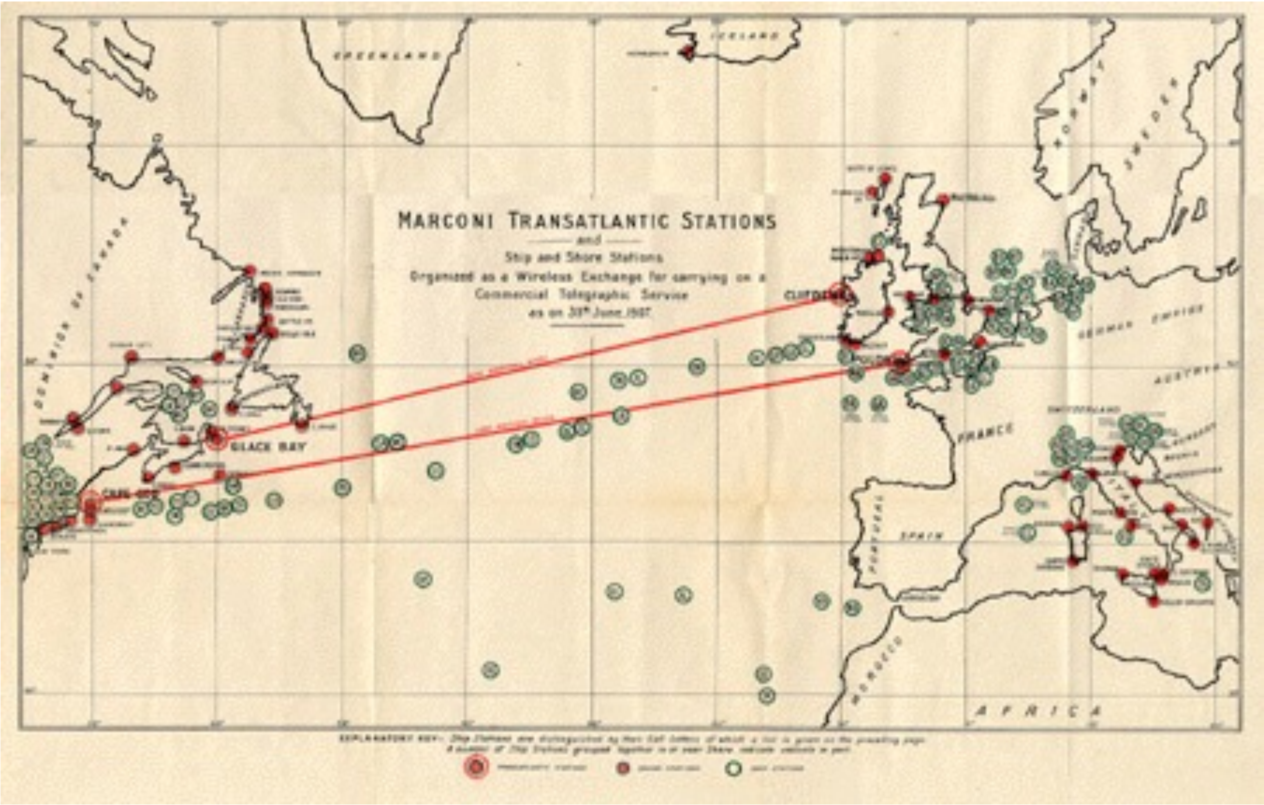
Nobel Prize (1909) winners

Guglielmo Marconi:
"father of radio"

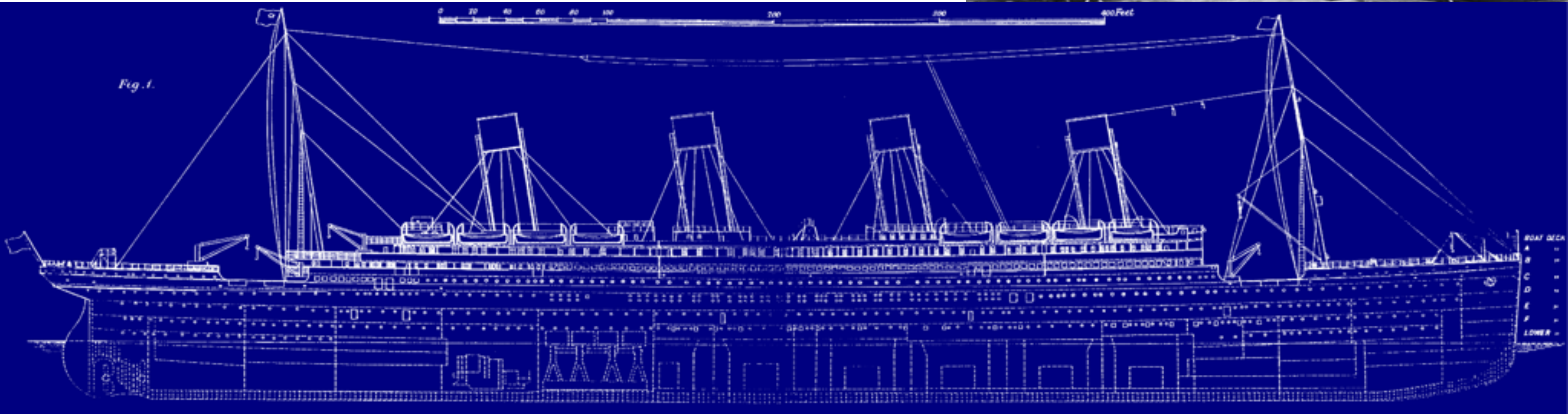
-and-

Karl Ferdinand Braun:
inventor of phased array antennas (ca 1905)





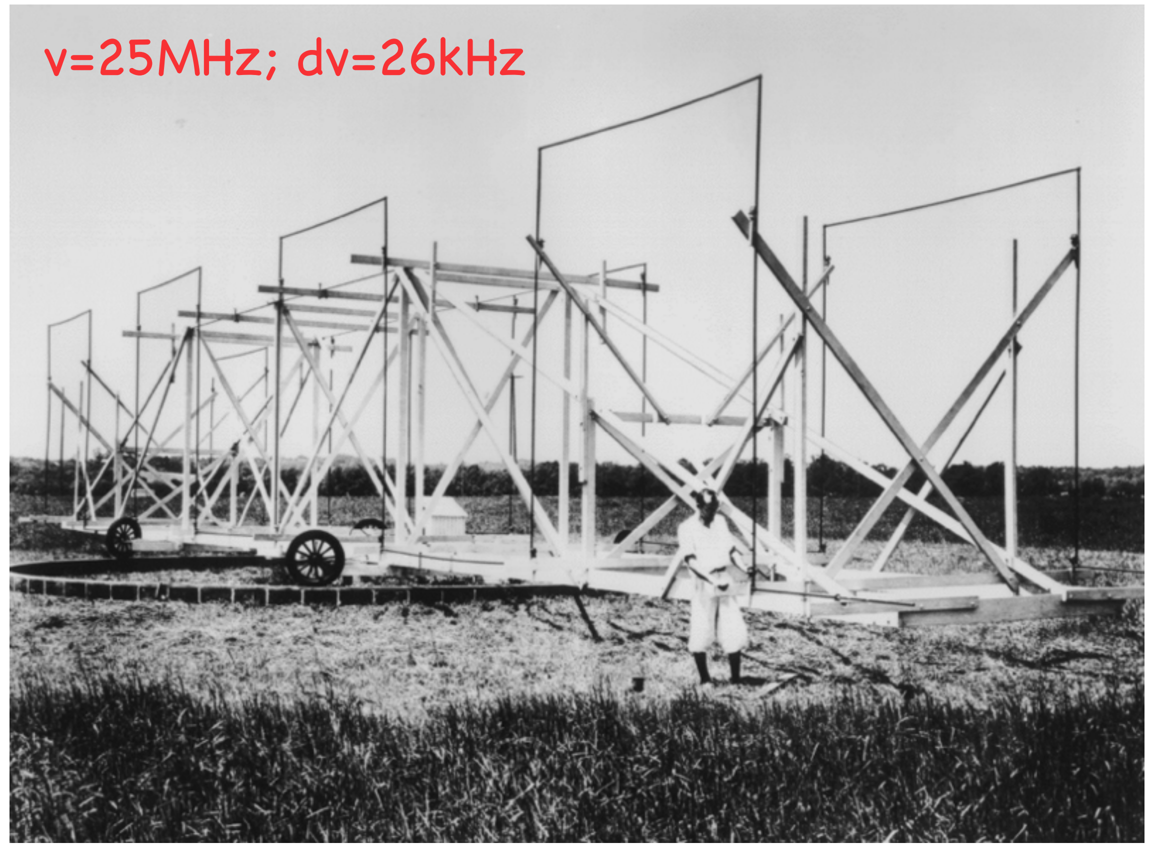
- Radio communications: evolution of frequency usage
  - pre-1920: $\nu \lesssim 100$ kHz
  - ca. 1920: shift to $\nu \sim 1.5$ MHz
  - post 1920: push to tens of MHz for increased number of voice channels and improved reliability (less sensitivity to ionosphere and thunderstorms)
  - Research labs sprung up in early 1900s …

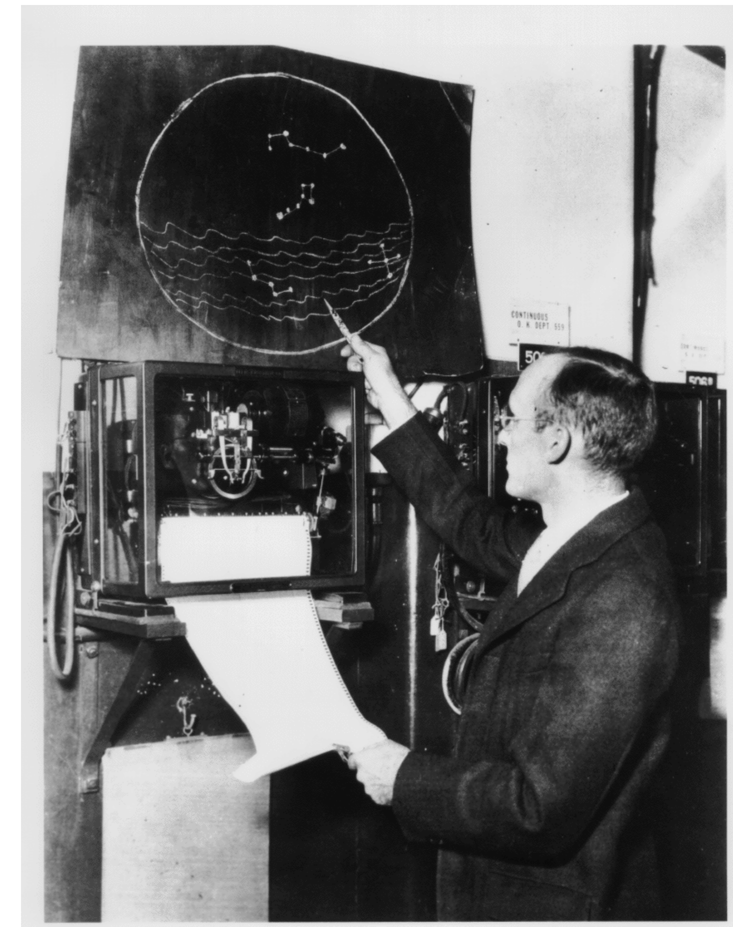


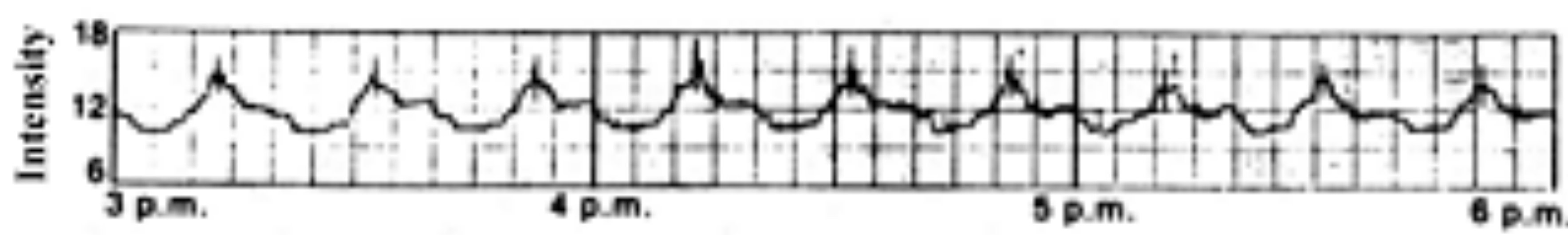
Early days of radio astronomy

- Discovery of cosmic radio waves - Karl Jansky, 1932

KJ in 1928 … working at Bell Labs for $33/week!





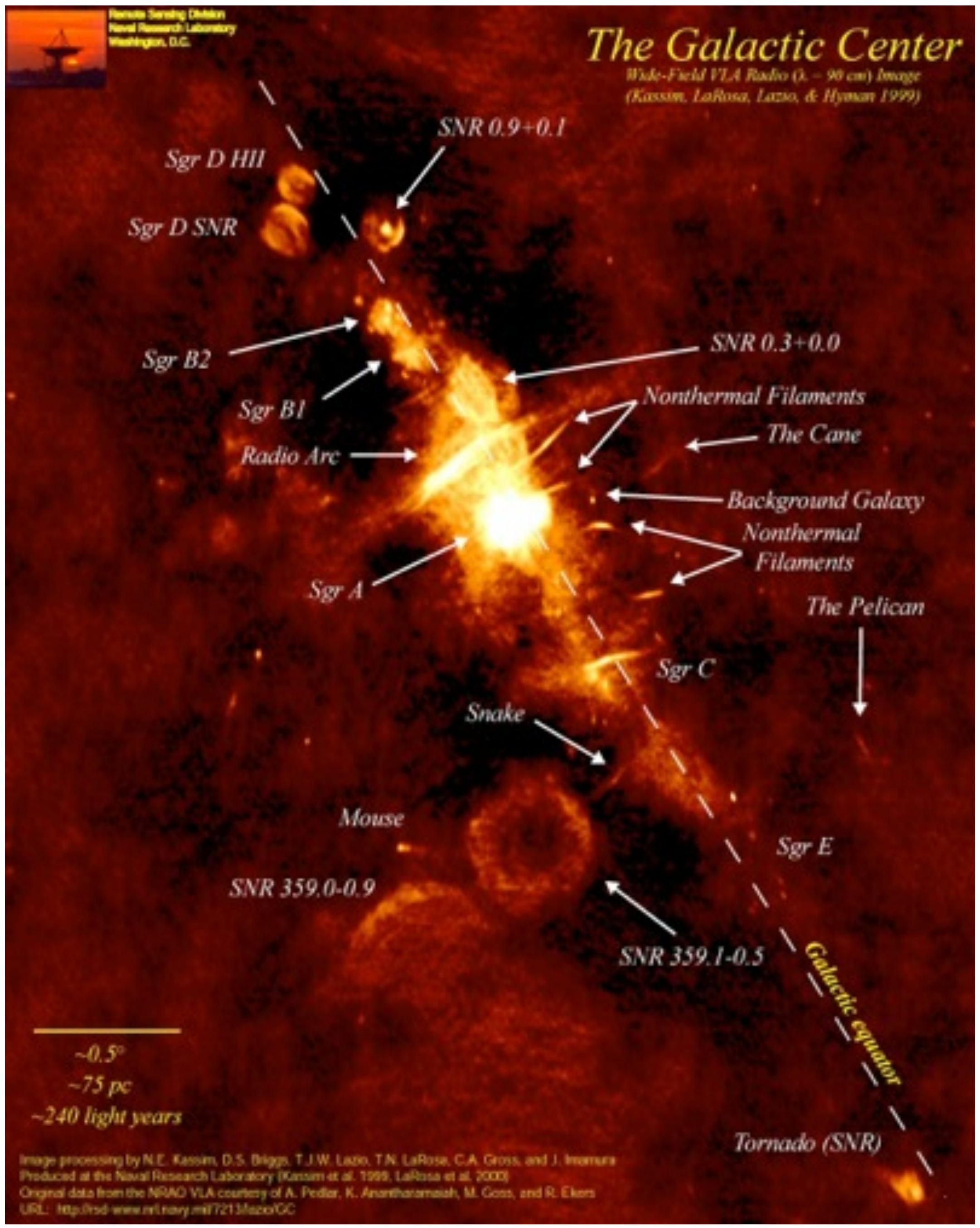


Sidereal rate determined in December 1932, along with (RA,dec)=(18h,-4d) (later shifting south)

Discovery of Galactic center

ASTRON

- “There is no indication of any kind [...] that these galactic radio waves constitute [...] some form of intelligence striving for intra-galactic communication.”



NY Times

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signalling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

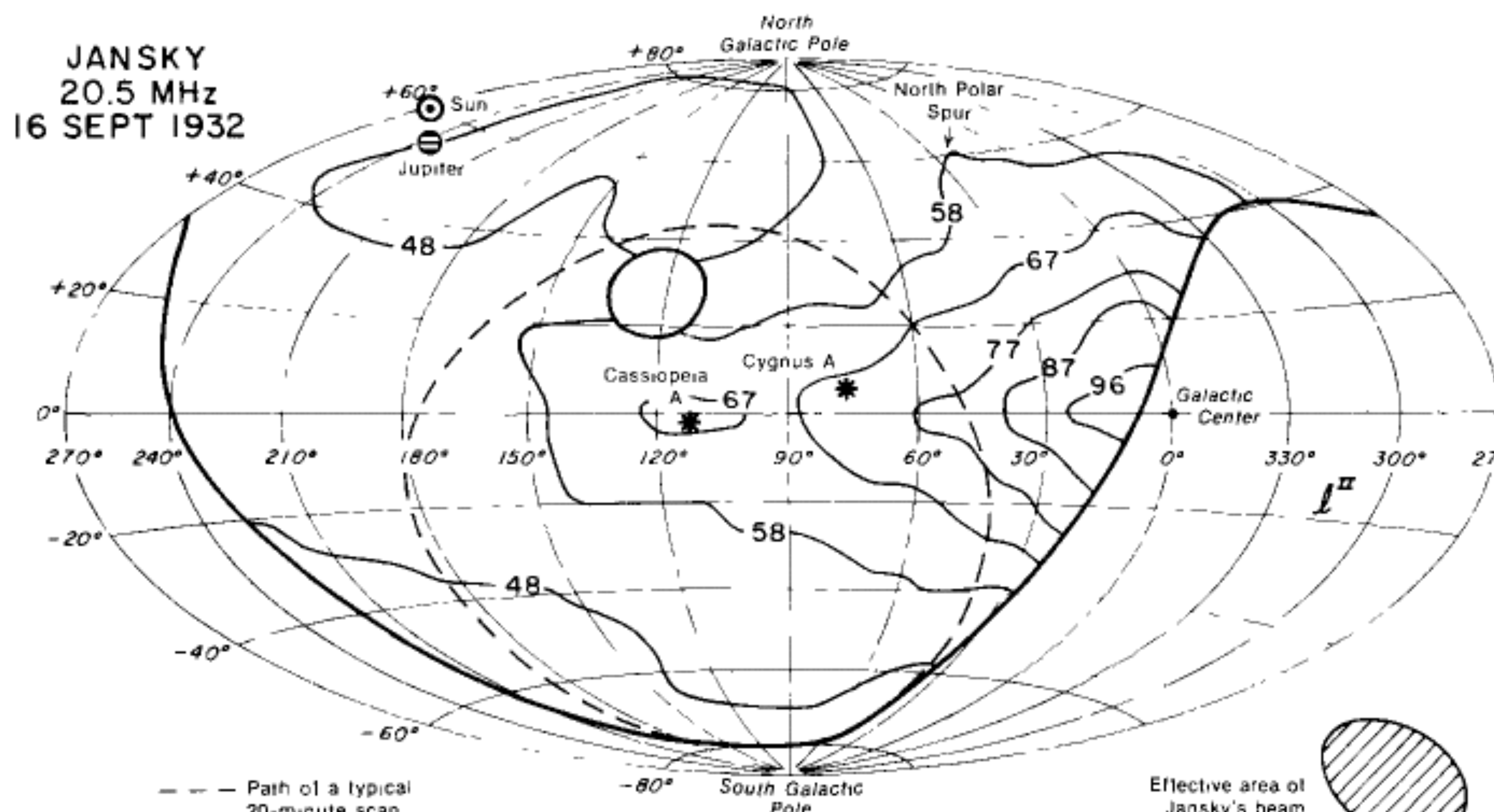
"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

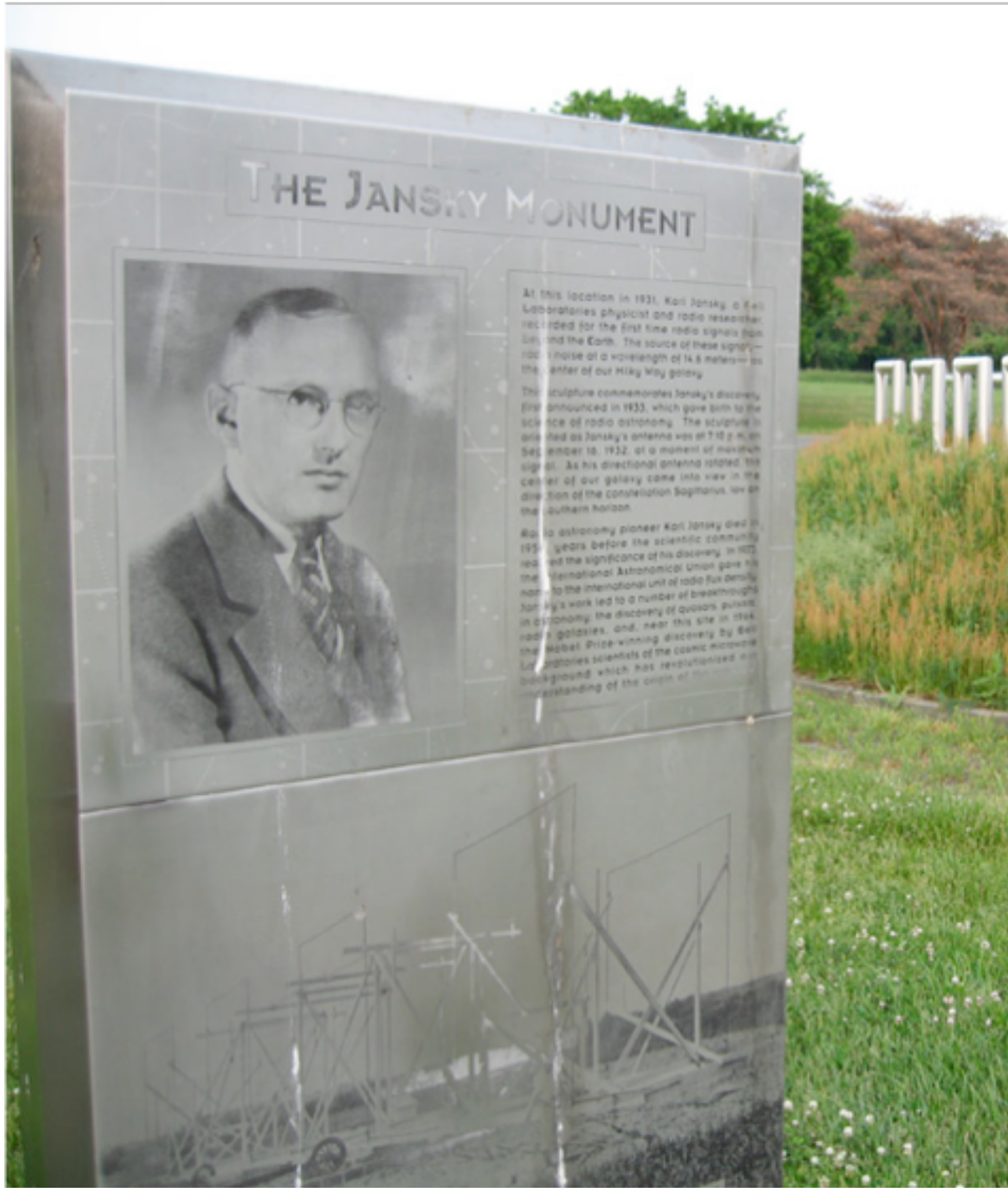
Radio Entertains the Children With Crime. Arthur Mann in May Scribner's.—Advt.

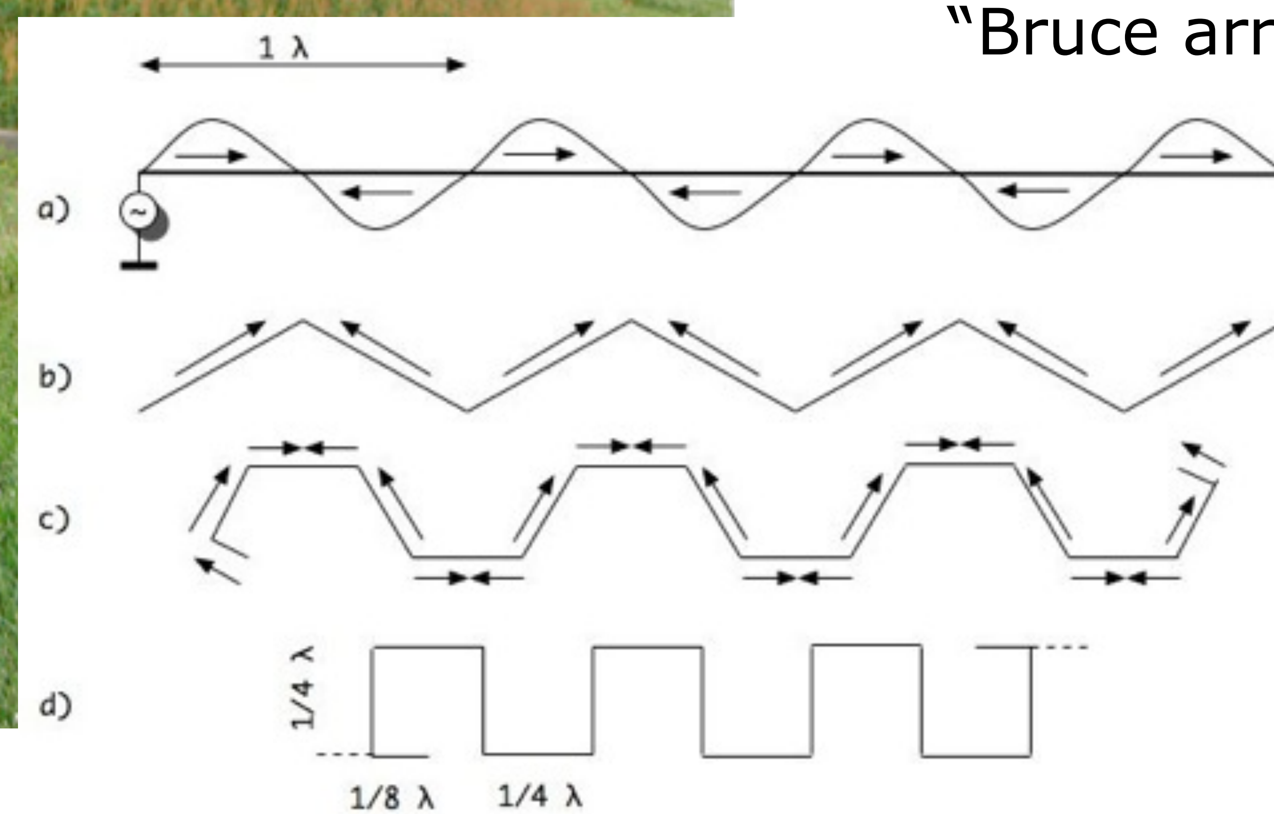
Figure 11. A modern reduction (Sullivan 1978) of Jansky's traces of 16 September 1932 (Fig. 4). The contour map is in galactic coordinates, in which 0° latitude corresponds to the plane of the Milky Way and 0° longitude is towards the galactic center. Contours are normalized to a peak value of 100, corresponding to ~100,000 K in brightness temperature at 20.5 MHz. The positions of the sun and Jupiter on that day, as well as several other radio sources discovered later, are indicated. This map is offset by about 5° because an incorrect value of 13 sec for the time constant of Jansky's receiver was used; the correct value is 30 sec.



Jansky monument in NJ

- Monument dedicated in 1998



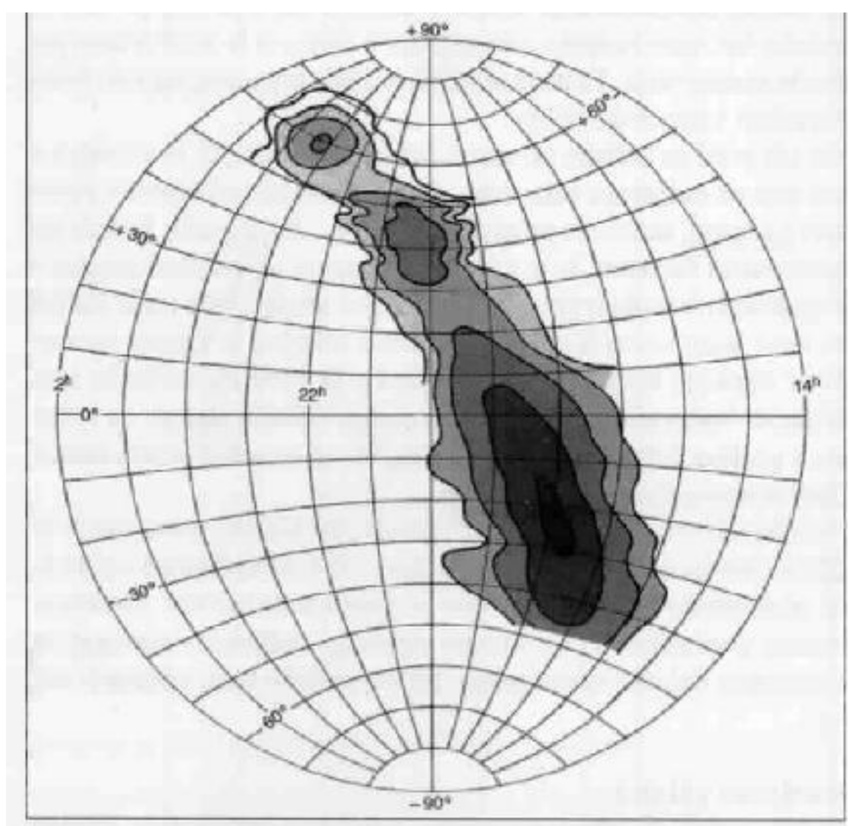


Jansky used a “Bruce array”

The first radio astronomer

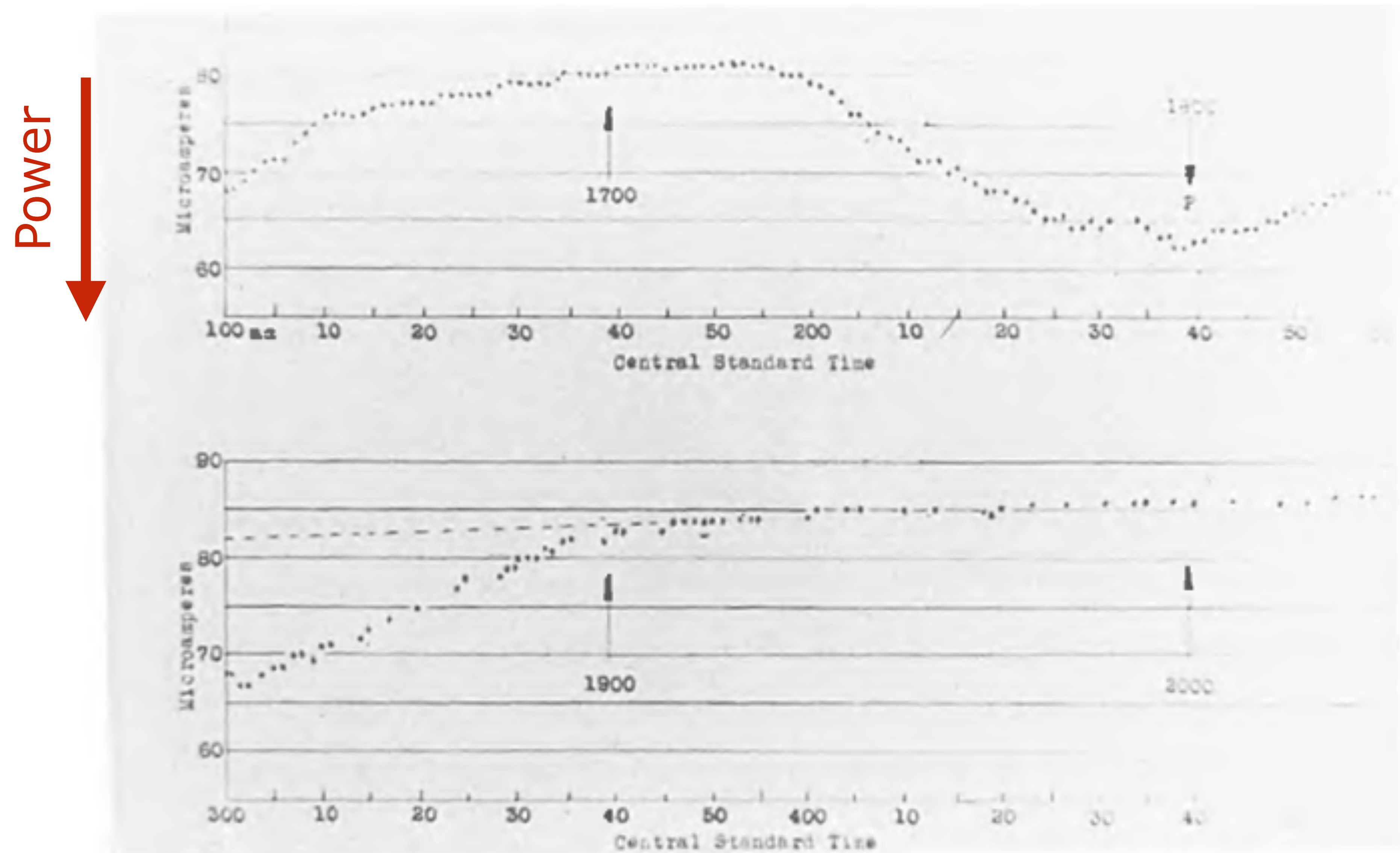
- Grote Reber (Wheaton, IL, USA)
    - built the first radio telescope
    - reasonable resolution (0.6° @ 10cm)
    - good sky visibility (transit mount)
    - detected MW, Sun, bright radio sources (1939-47)
    - published in journals: ApJ, Nature
    - 160 & 480 MHz


—Grote Reber, about 1937.



First astrophysics

- Reber’s early tests were at 9cm wavelength - no obvious detection
  Immediately counter to the idea that Jansky’s noise was thermal radiation!
- Next 33cm … again no detection.
- Then 187cm - LOFAR frequency range!
  Immediately hampered by RFI from automobiles, but once the MW was rising at night time it was detected!



First astrophysics

- Reber's early tests were at 9cm wavelength - no obvious detection
  Immediately counter to the idea that Jansky's noise was thermal radiation!
- Next 33cm … again no detection.
- Then 187cm - LOFAR frequency range!
  Surveys at 160 MHz and 480 MHz (Reber 1944) confirm nonthermal radiation

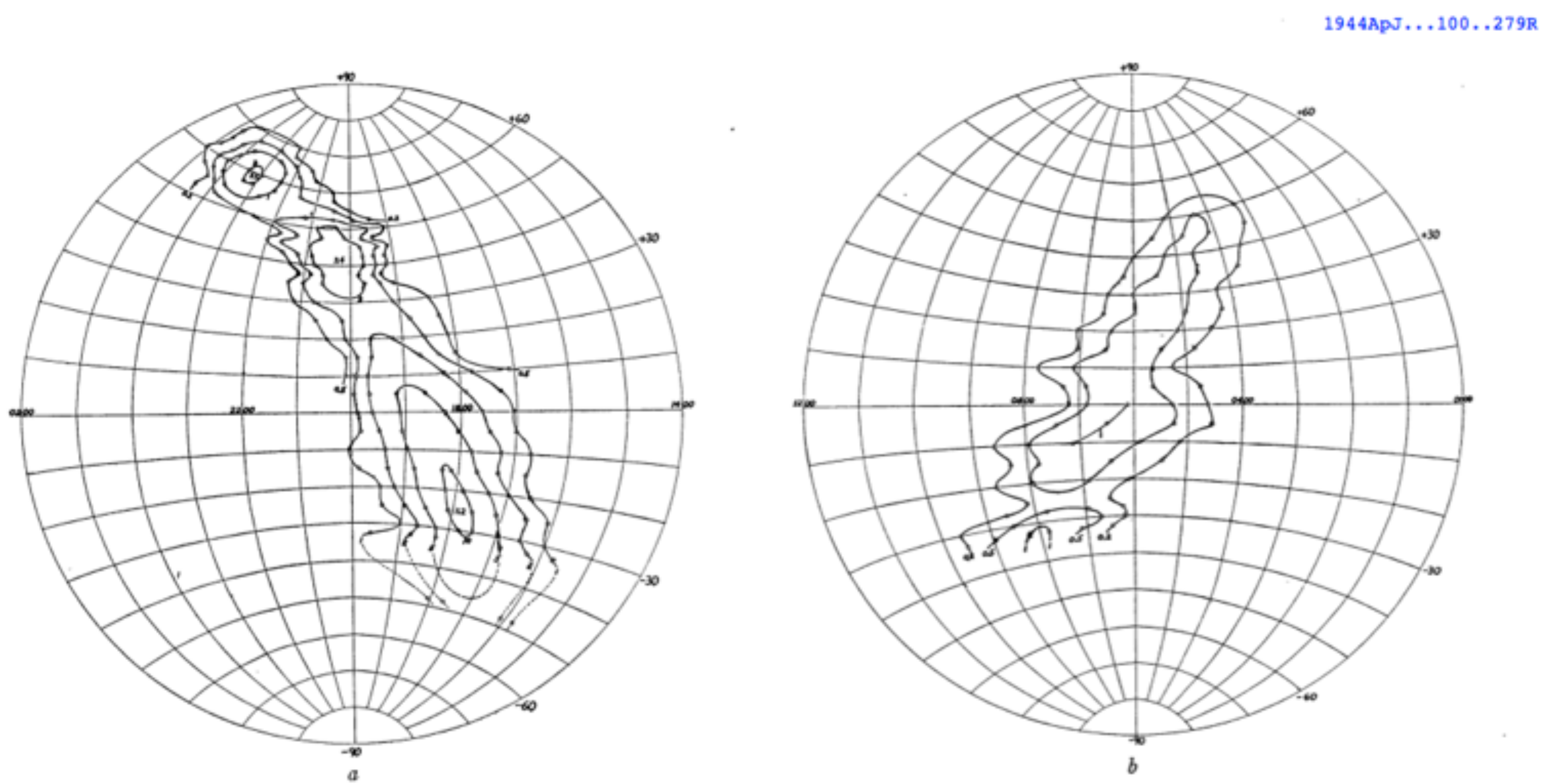


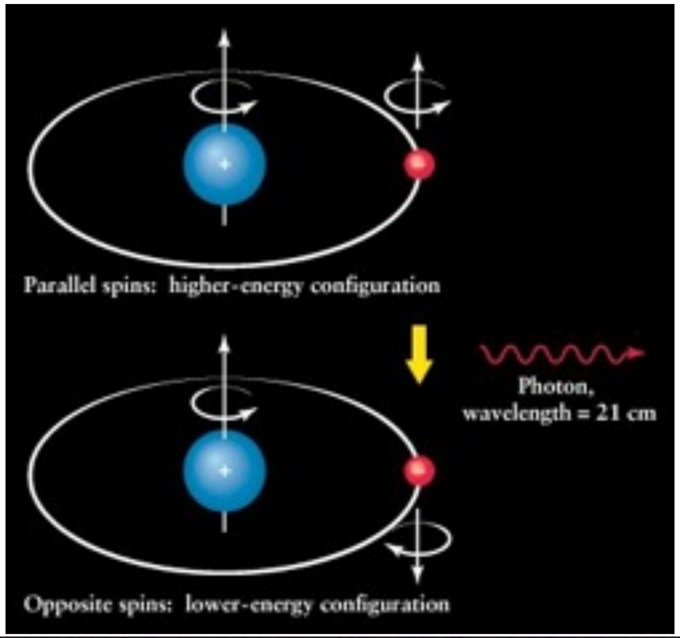
FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

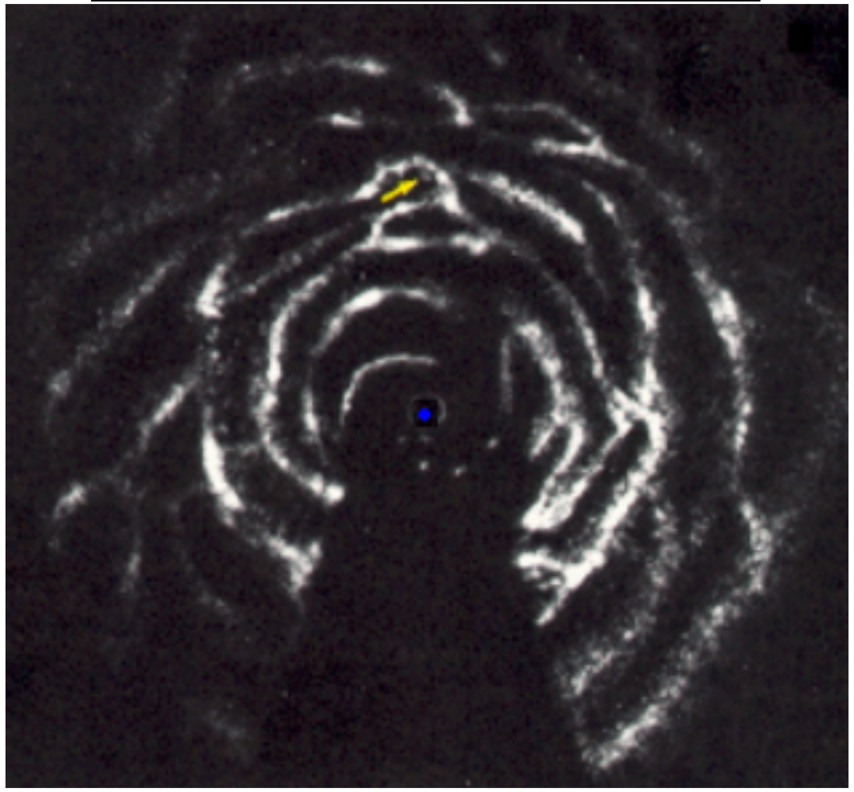
The first SKA....

- SKA @ 2 MHz in Tasmania...!

Prediction & detection of HI

- HI - neutral hydrogen hyperfine line - was predicted by van de Hulst (1944)
- Detected at 21 cm by Ewen & Purcell in 1951, and shortly thereafter by Oort & Muller (at Kootwijk)





Wurzburg "Riese" Radar Antenna, 7.5 m diameter

Largest radio telescope ....

- Dwingeloo 25-m telescope ... largest in the world for a while....

Grote Reber's ashes interred in telescope foundation

Largest radio telescope ….

- until the Jodrell Bank 76-m telescope (completed 1957)

Largest radio telescope ....

- Parkes radio telescope (64m, established 1961)

Largest radio telescope ....

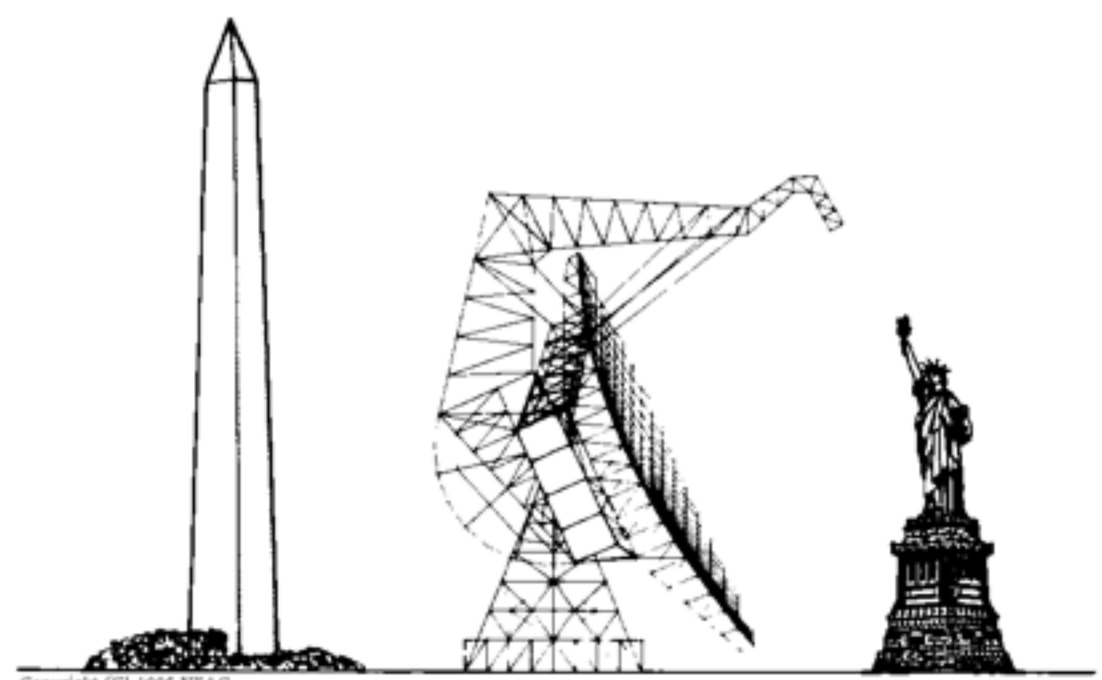
- Arecibo 305-m dish (1963)

Soon to be largest radio telescope ....

- FAST 500-m dish (under construction)

Largest steerable single dishes

- Effelsberg (left) and Green Bank Telescope (GBT; right)



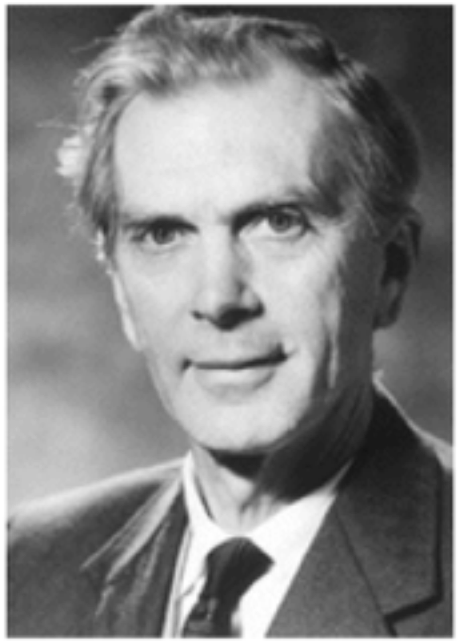
300 ft transit telescope

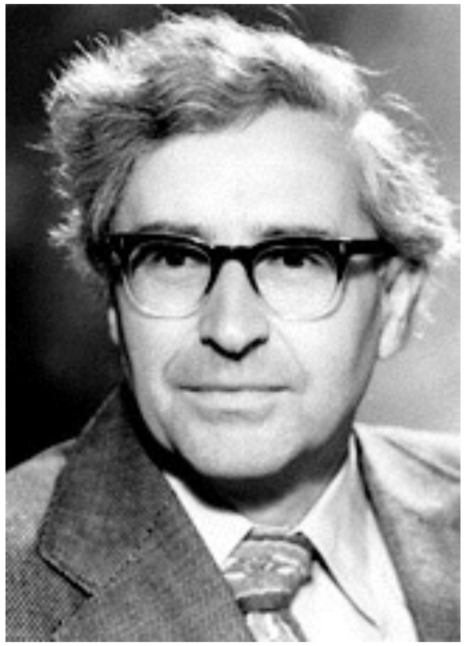
1962-1988

http://www.cv.nrao.edu/course/astr534/RadioTelescopes.html

Largest radio telescope ....

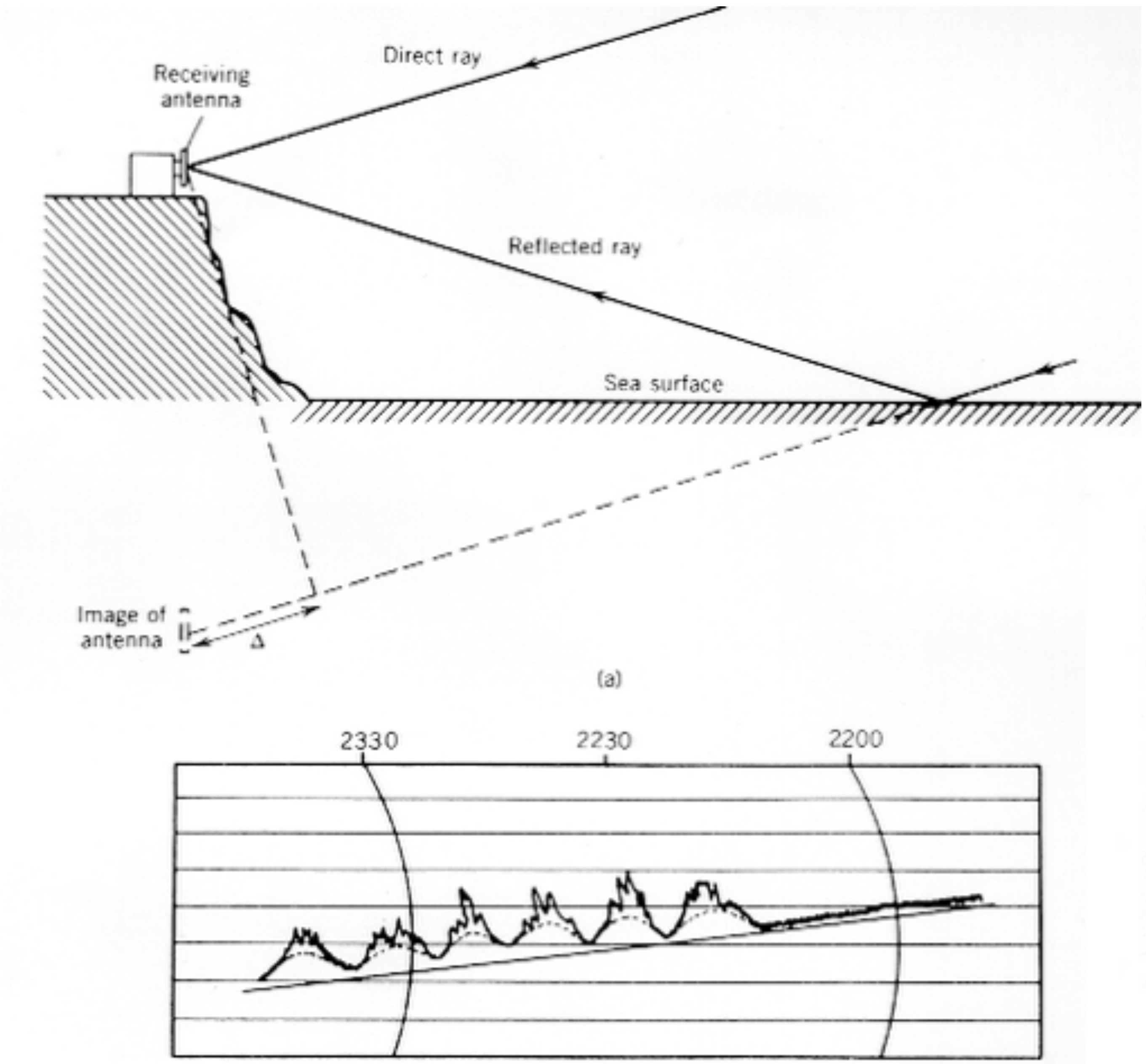
- How to build a bigger radio telescope? Interferometry .....

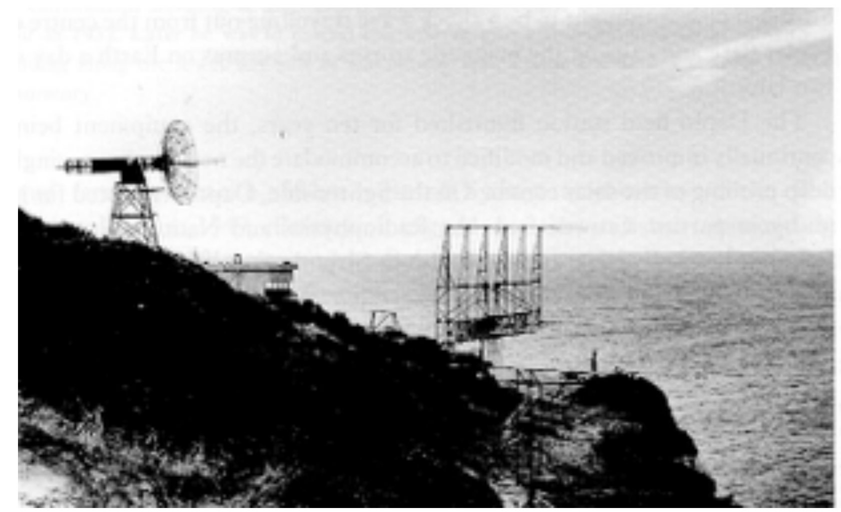


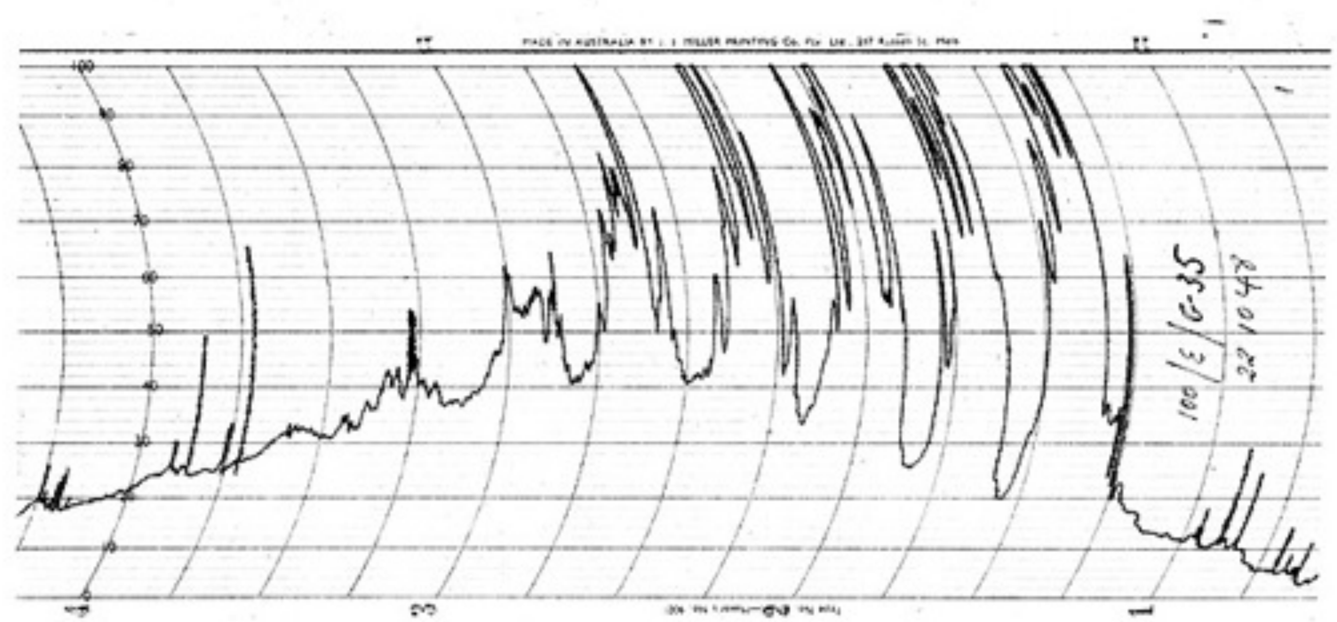


One-element interferometry

- Dover Heights (near Sydney, Australia)
  First identification of a radio source with an extragalactic object
  (Virgo A; Cygnus A; Centaurus A) in 1947/48 by Bolton, Slee, & Gordon



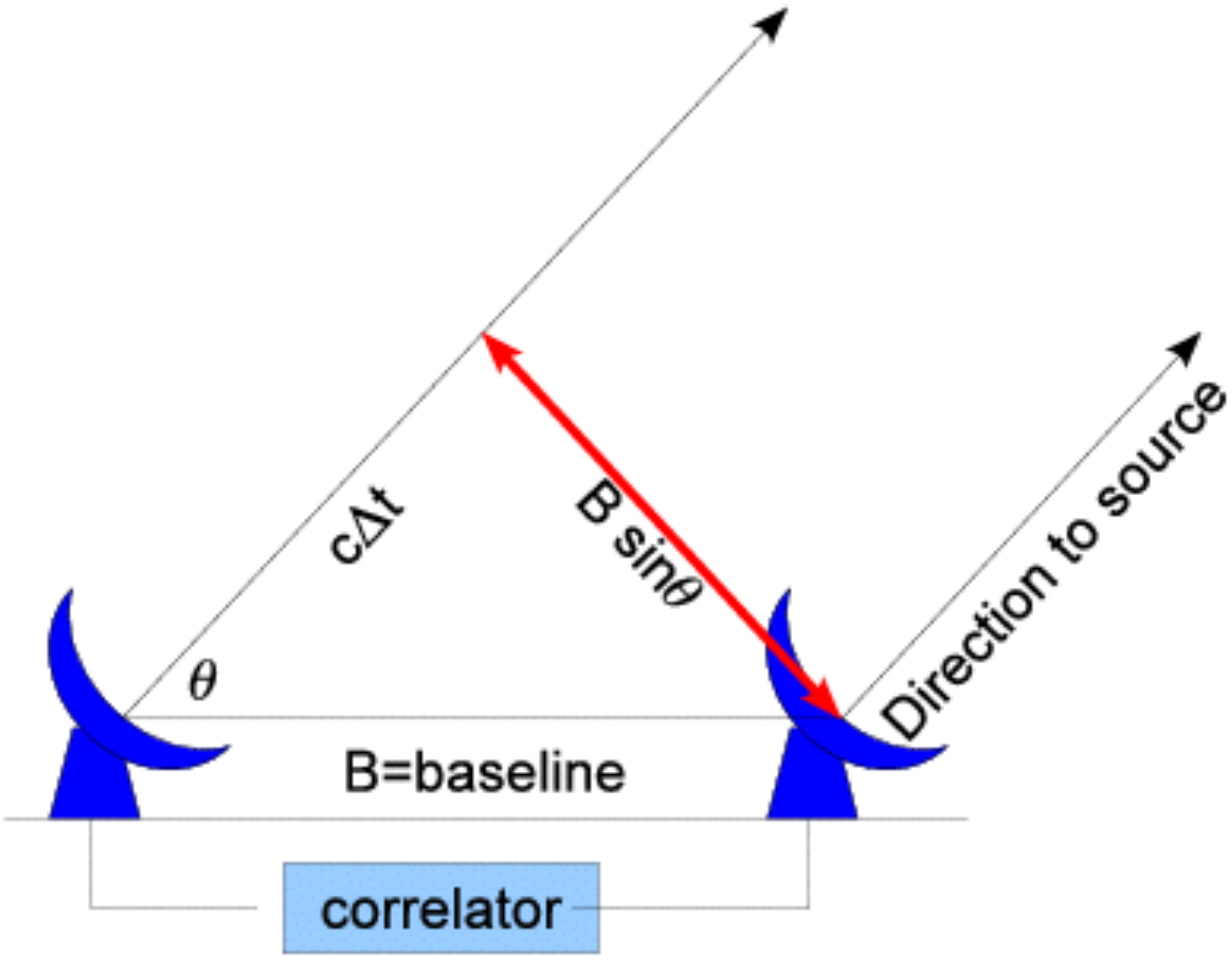




Sea interferometer strip chart of Cygnus A

Radio interferometry

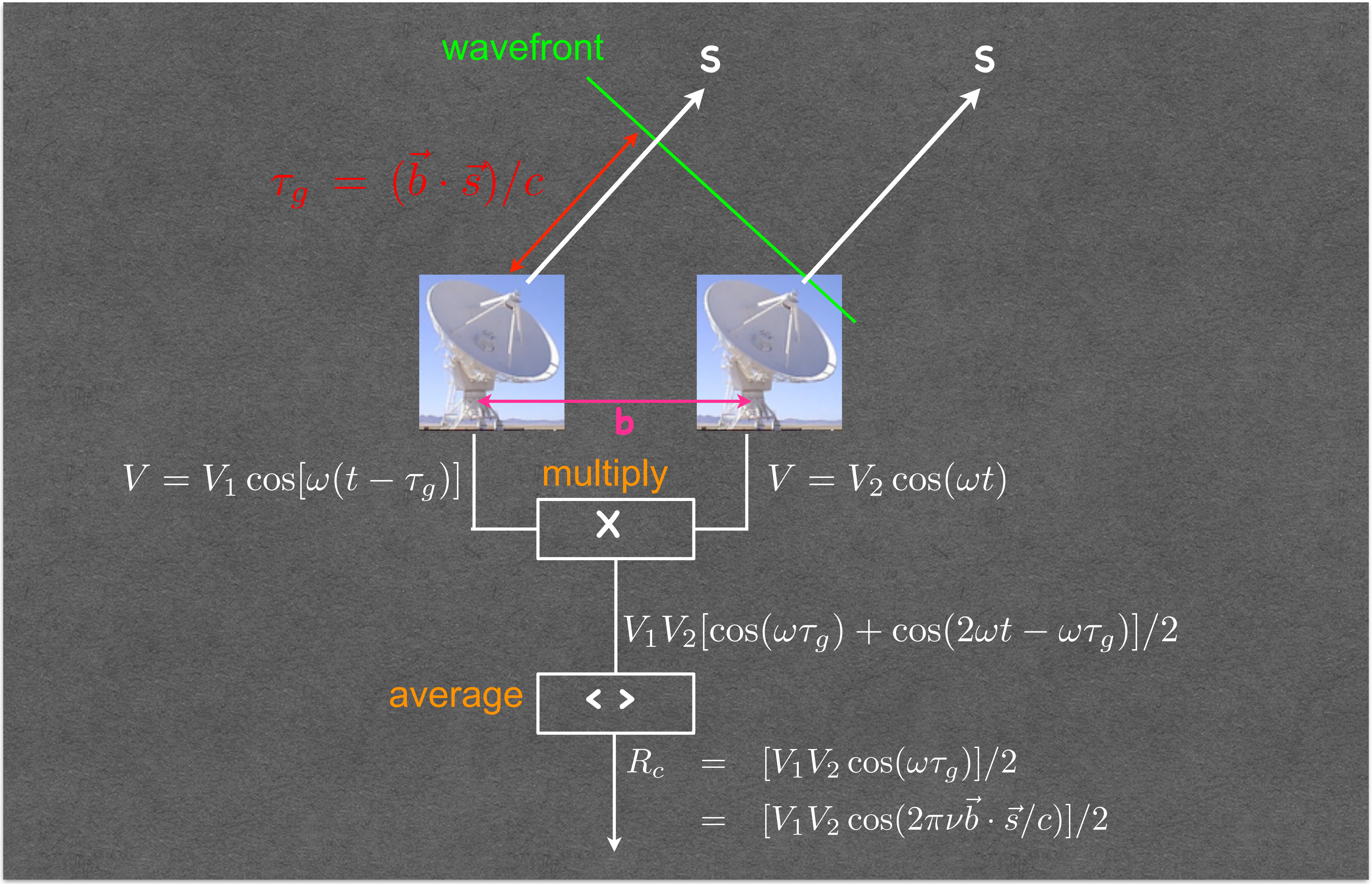
- Interferometric techniques essential for competitive low frequency radio astronomical observations



$$\text{Angular resolution } \Theta \approx \frac{\lambda}{B_{\max}}$$

Monochromatic interferometer

- Assume small frequency width (Δv) and no motion of the source. Now consider radiation from a small solid angle dΩ from direction S



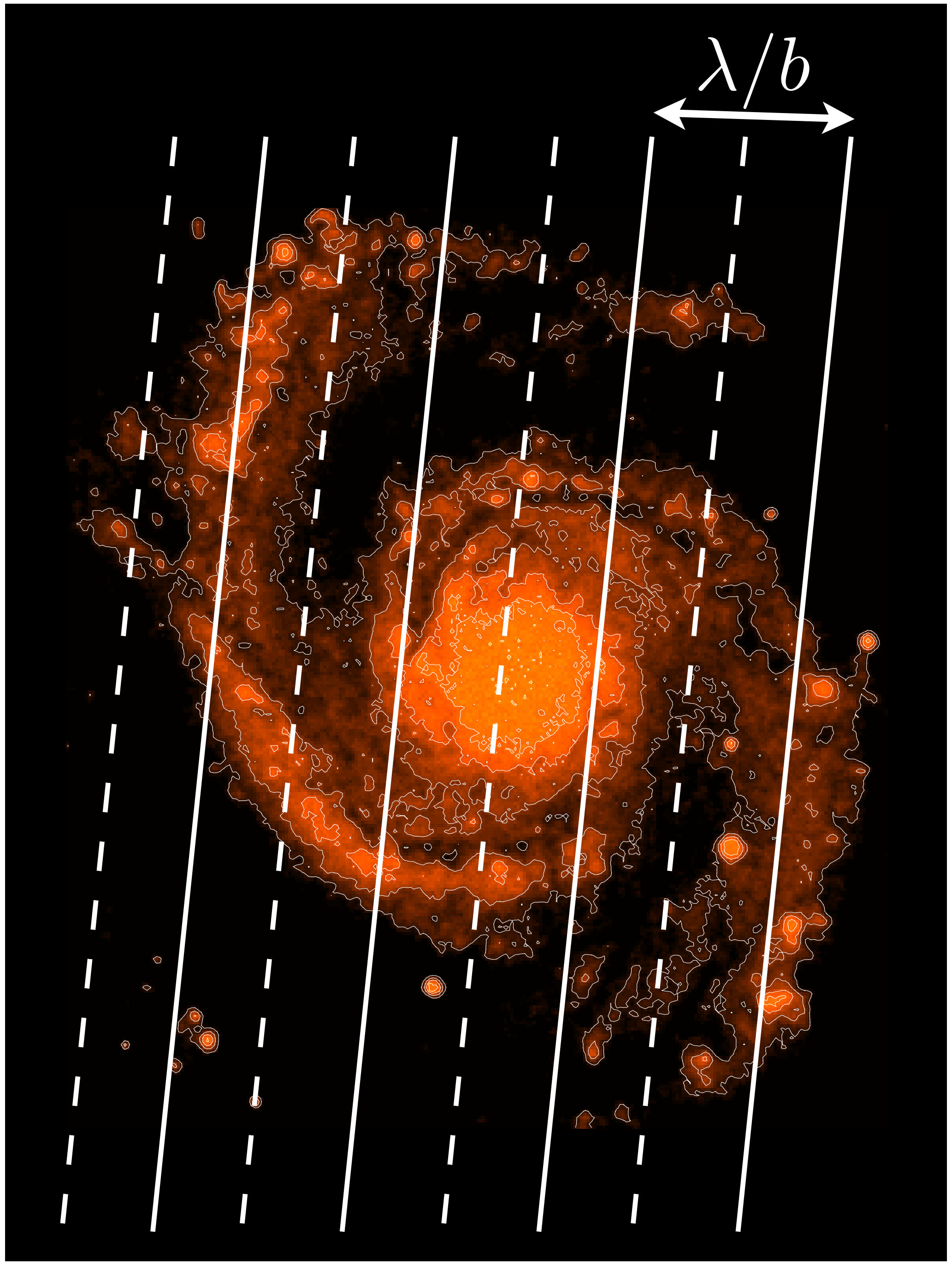
Schematic

- The cosine correlator can be thought of as casting a sinusoidal fringe pattern on the sky (of angular scale λ/b). The correlator multiplies the source intensity distribution by this fringe, and integrates the product over the sky.

$$R_c = \int\int I_\nu(\vec{s}) \cos(2\pi\nu\vec{b}\cdot\vec{s}/c)\,\mathrm{d}\Omega$$

source brightness

fringe pattern



- The orientation of the fringe is set by the baseline geometry

  The fringe separation is set by baseline length, and the observing wavelength

Complex visibilities

- We define a complex visibility to be

$$V = R_c - iR_s = Ae^{-i\phi}$$

where

$$A = \sqrt{R_c^2 + R_s^2}$$

$$\phi = \tan^{-1}\left(\frac{R_s}{R_c}\right)$$

and now we have

$$V(\vec{b}) = R_c - iR_s = \int\int I_\nu(\vec{s})e^{-2\pi i\nu\vec{b}\cdot\vec{s}/c}\,\mathrm{d}\Omega$$

- So now we have a beautiful and useful relationship between the source brightness and the response of the interferometer!
- This can be inverted to get I(s) from V(b).

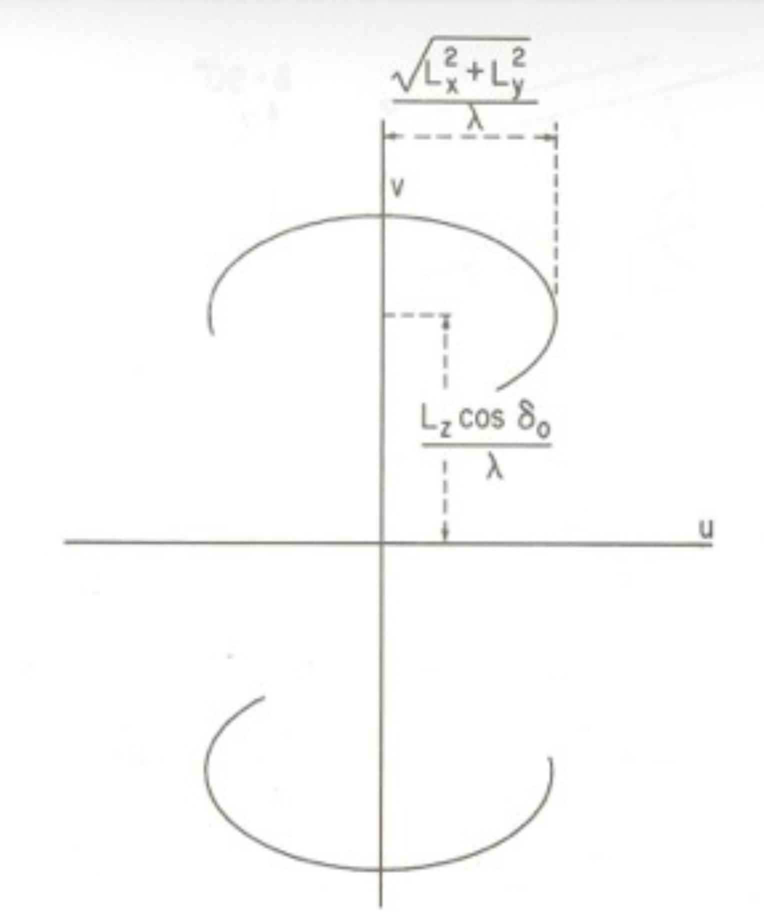
Earth rotation synthesis

- u,v,w coordinates:
  X pointing to ha=0h, dec=0°
  Y pointing to ha=-6h, dec=0°
  Z pointing to dec=90°
- Lx, Ly, and Lz represent a single baseline, h is hour angle, δ is dec

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \frac{1}{\lambda} \times \begin{pmatrix} \sin h & \cos h & 0 \\ -\sin\delta\cos h & \sin\delta\sin h & \cos\delta \\ \cos\delta\cos h & -\cos\delta\sin h & \sin\delta \end{pmatrix} \begin{pmatrix} L_x \\ L_y \\ L_z \end{pmatrix}$$

so that

$$u^2 + \left(\frac{v - (L_z/\lambda)\cos\delta}{\sin\delta}\right)^2 = \frac{L_x^2 + L_y^2}{\lambda^2}$$



As Earth rotates, baselines describe an ellipse
For EW baselines, Lz=Lx=0
⇒ concentric, coplanar ellipses

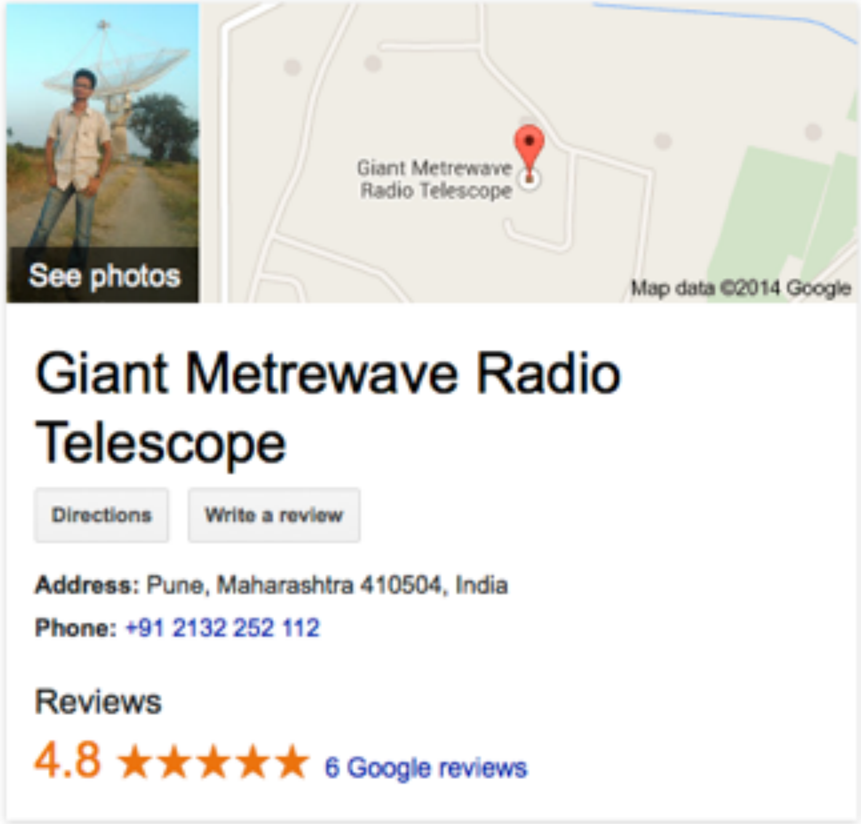
Current low frequency radio facilities

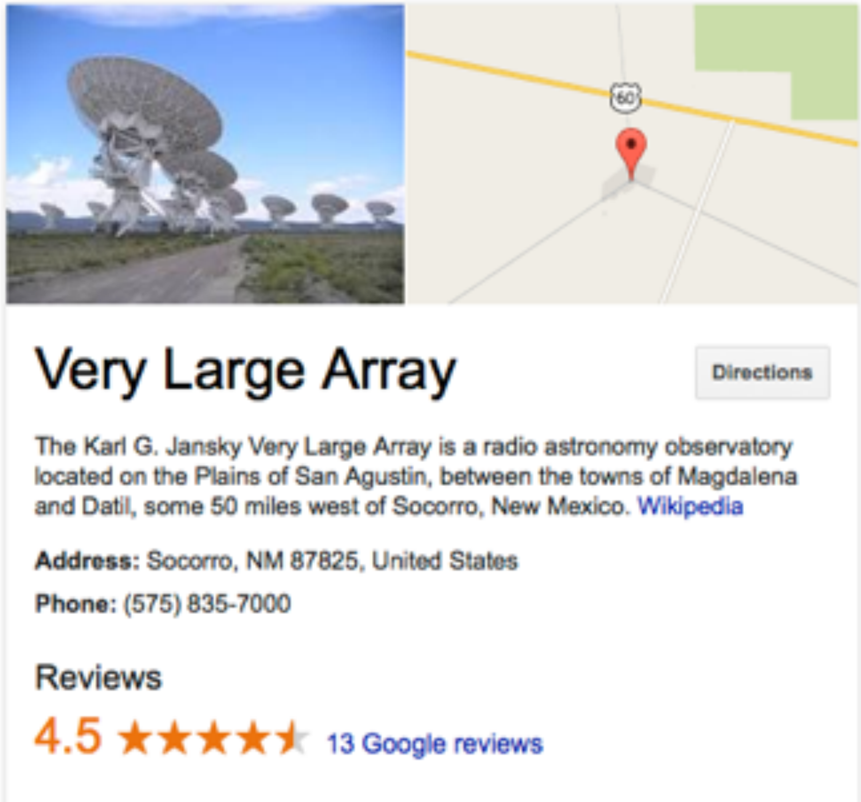
- List of currently active low frequency radio telescopes

  - GMRT (India)
    Giant Metrewave Radio Telescope
  - LWA (USA)
    Long Wavelength Array
  - MWA (Australia)
    Murchison Widefield Array
  - VLA (USA)
    Karl G. Jansky Very Large Array
  - WSRT (Netherlands)
    Westerbork Synthesis Radio Telescope

    and

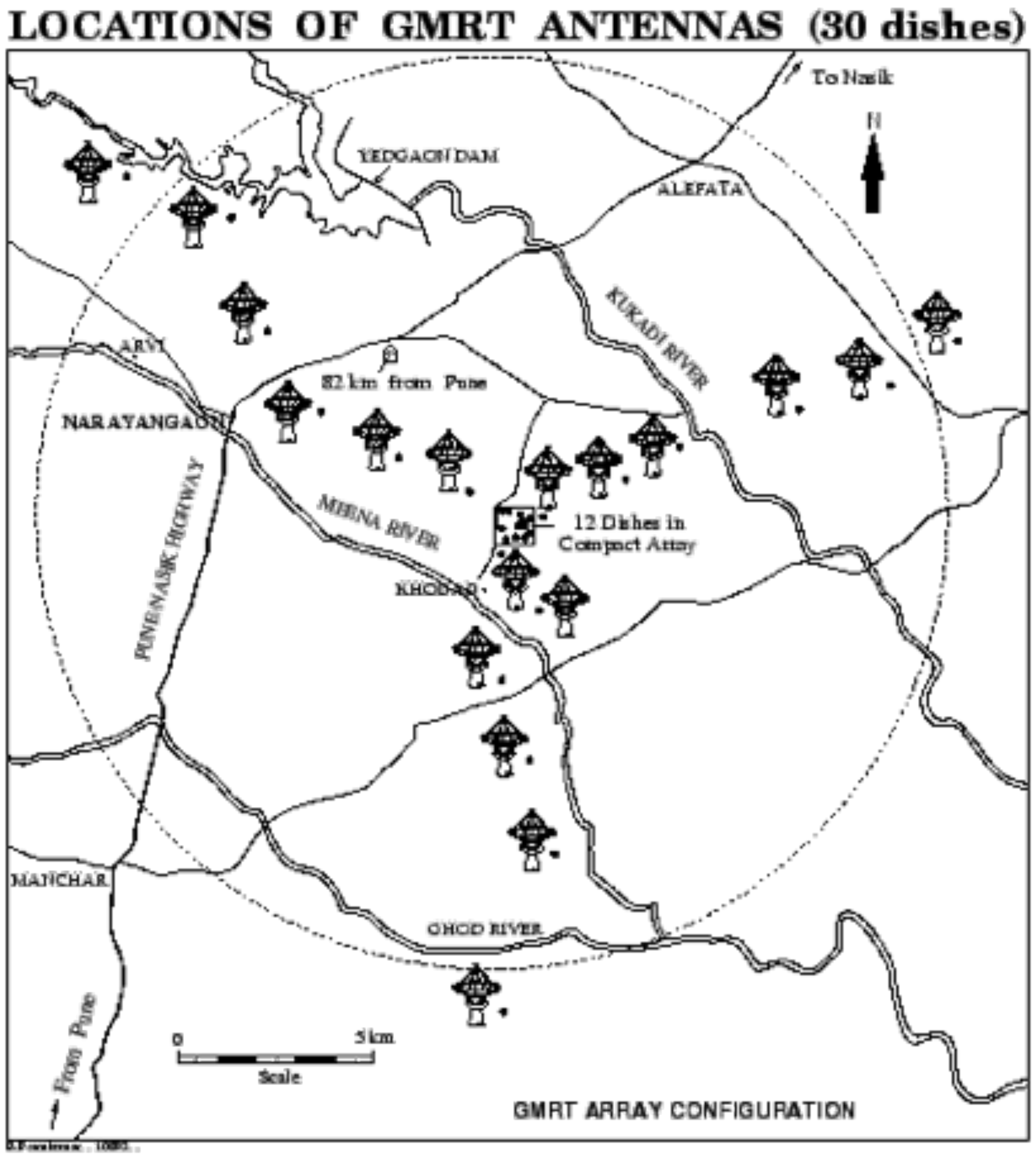
  - LOFAR (Netherlands)
    Low Frequency Array





Current low frequency radio facilities

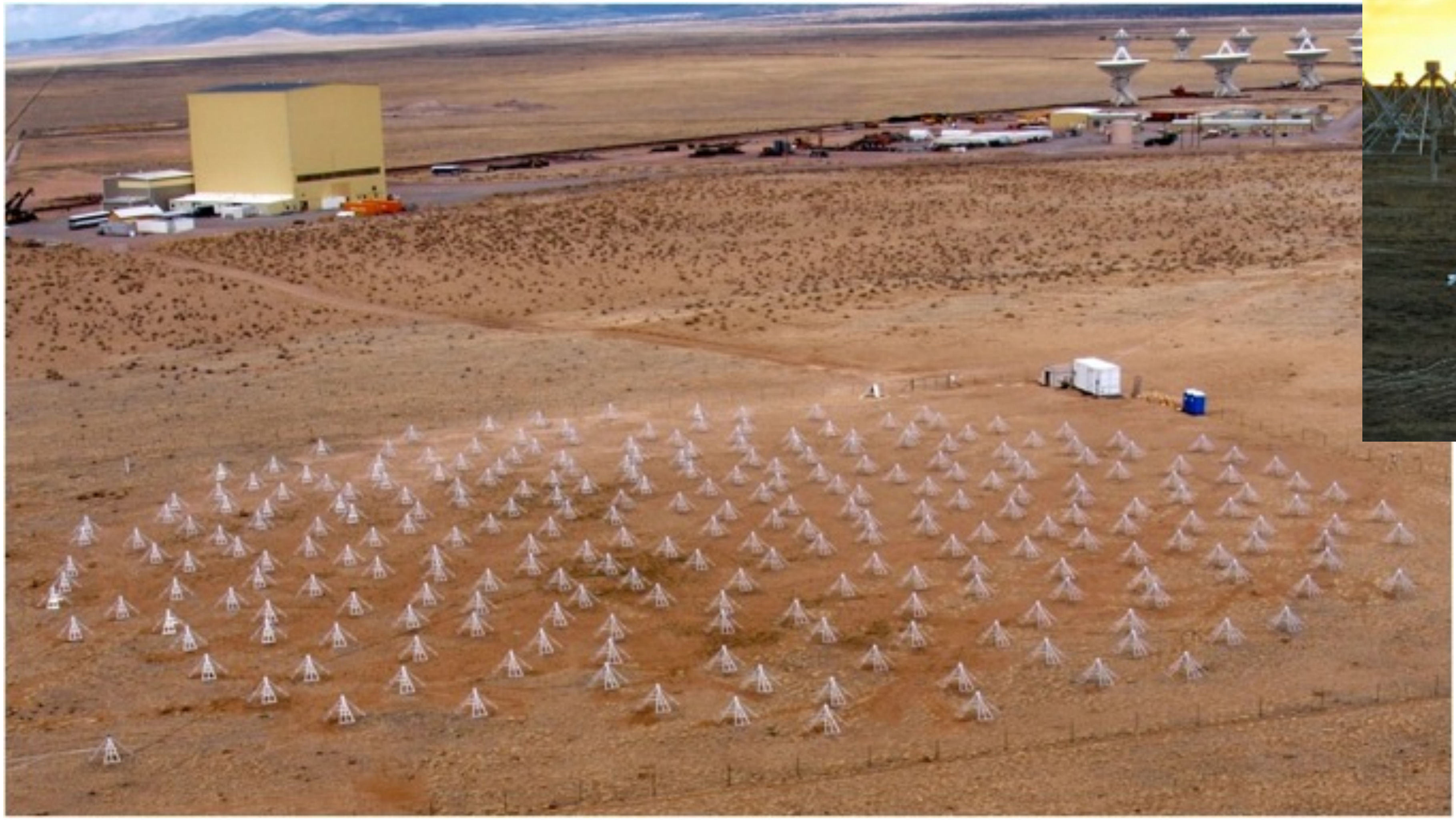
- GMRT (India)
  Giant Metrewave Radio Telescope



- Low frequency bands at 150, 235, 327 MHz (32 MHz bandwidth)
- 30 45m antennas
- baselines of up to 25 km
- Upgrade underway, providing contiguous 30-1500 MHz with 400 MHz BW

Current low frequency radio facilities

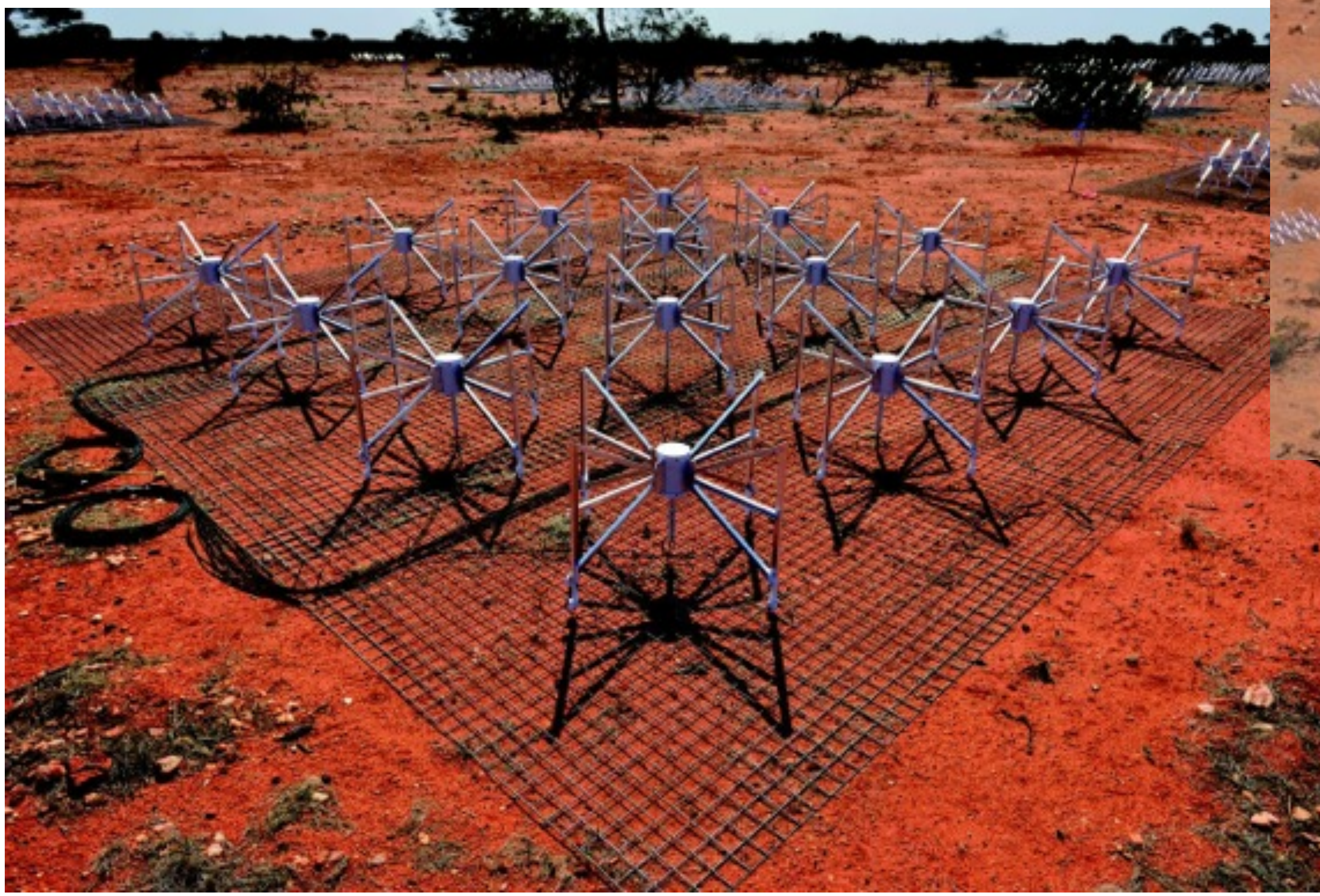
- LWA (USA)
  Long Wavelength Array



- 10-88 MHz; 4 simultaneous beams
- LWA1 = 257 (256+1) dual-pol dipoles (100x110m station)
- Full array: ambitions to have baselines up to 400 km (~50 stations in NM)
- LWA2 currently under construction (will provide a 19km baseline to LWA1)

Current low frequency radio facilities

- MWA (Australia)
  Murchison Widefield Array



- 80-300 MHz; ~32 MHz instantaneous bandwidth; 40 kHz spectral resolution
- 128 tiles (8128 BL!), each of 4x4 dual-pol dipoles (very like LOFAR HBA tiles)
- Baselines of up to ~3 km; most tiles (112) within 1.5 km core area
- Expansion to at least 256 tiles being planned

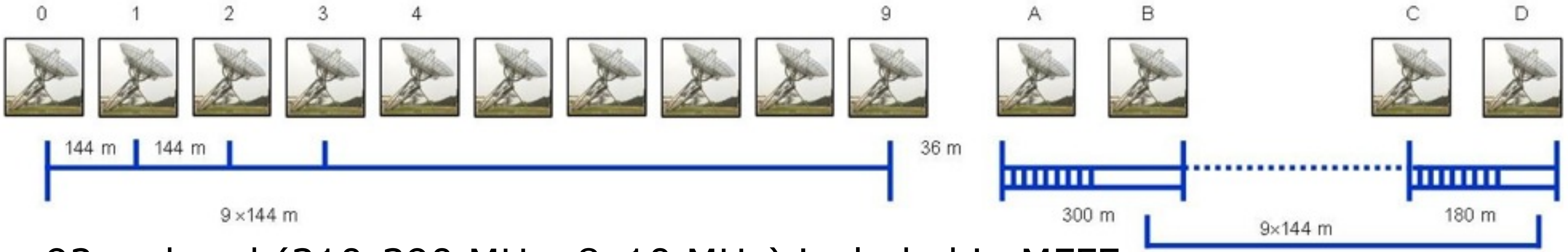
Current low frequency radio facilities

- VLA (USA)
  Karl G. Jansky Very Large Array

- With upgraded VLA, Pband (230-470 MHz) feeds available in Shared Risk
- Receivers in place to sample down to 50 MHz
- 27 antennas with maximum baselines up to 36 km in 4 configurations (A-D)
- Plans for LOBO and VLITE … later, aspiration to greatly expand the array

Current low frequency radio facilities

- WSRT (Netherlands)
  Westerbork Synthesis Radio Telescope



- 92cm band (310-390 MHz, 8x10 MHz) included in MFFE
- 14 antennas with baselines up to 2.7 km
- Due to APERTIF upgrade, only up to ~8 antennas now available

Current low frequency radio facilities

- LOFAR (Netherlands)
  Low Frequency Array

- Low Band Array (LBA) 10-90 MHz, with filter 30-80 MHz effective
- 38 Dutch stations (~120 km) + 9 (12) EU stations (~1500 km)
- Each station has 2x48 dual-pol dipoles (all 96 used for international stations)
- Up to 488 200 kHz beamlets can be formed in “8-bit mode”

Current low frequency radio facilities

- LOFAR (Netherlands)
  Low Frequency Array

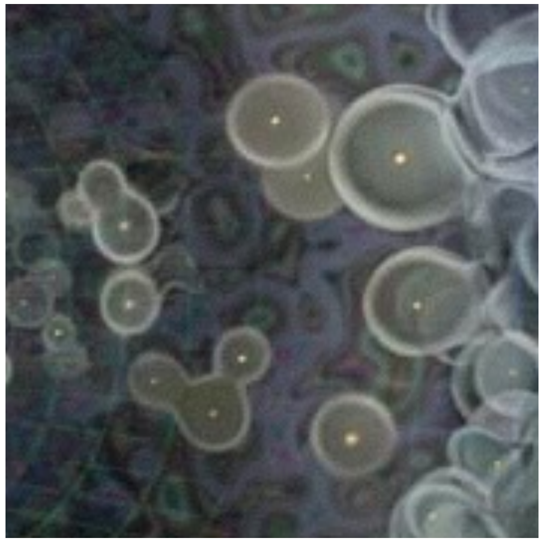
- High Band Array (HBA) 110-250 MHz, 3 ranges (110-190,170-230,210-250)
- 62 Dutch fields (2x24+14) (~120 km) + 9 (12) EU stations (~1500 km)
- Core fields have 24x16 dual-pol dipoles (48 for remote, 96 for international)
- Up to 488 200 kHz beamlets can be formed in "8-bit mode"
  Limitation of effective field of view by analog tile beam (~30° at 150 MHz)

Computing, computing, computing

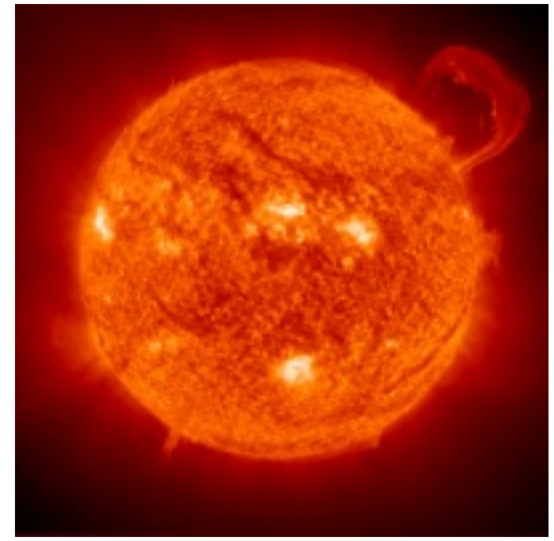
- Computing needed not just for beamforming and correlation, but also calibration and imaging (other lectures throughout this week)

Radio science at low frequencies

- Here, summarizing the 6 LOFAR Key Science Projects (KSPs) for simplicity



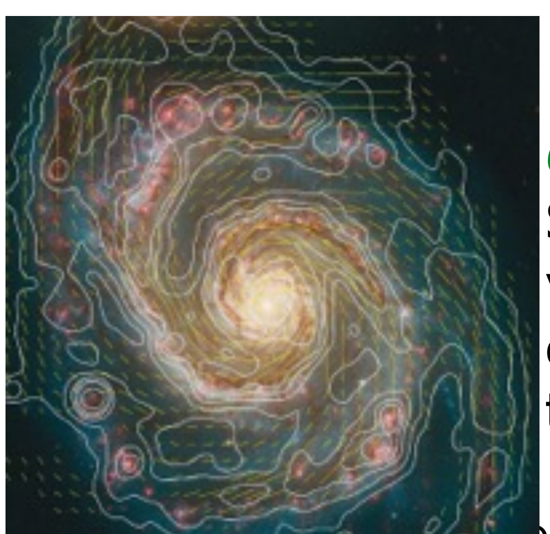
Epoch of Reionization (EoR)
Detection and statistical characterization of the reionization of the IGM by the first stars & galaxies.



Solar & Space Weather
Characterization of the Sun at low radio frequency, detection and study of CMEs and solar wind.

Surveys (SKSP)
Detection of high-z RGs, deep surveys of the radio sky at low frequency.
Synergy with high frequency!

Ultra high energy cosmicrays
Detection of cosmic ray showers, characterization of particle mass and origin.
Also particle detection.



Cosmic magnetism (MKSP)
Study of magnetic fields in various astrophysical objects, e.g. galaxies, and possibly the IGM.

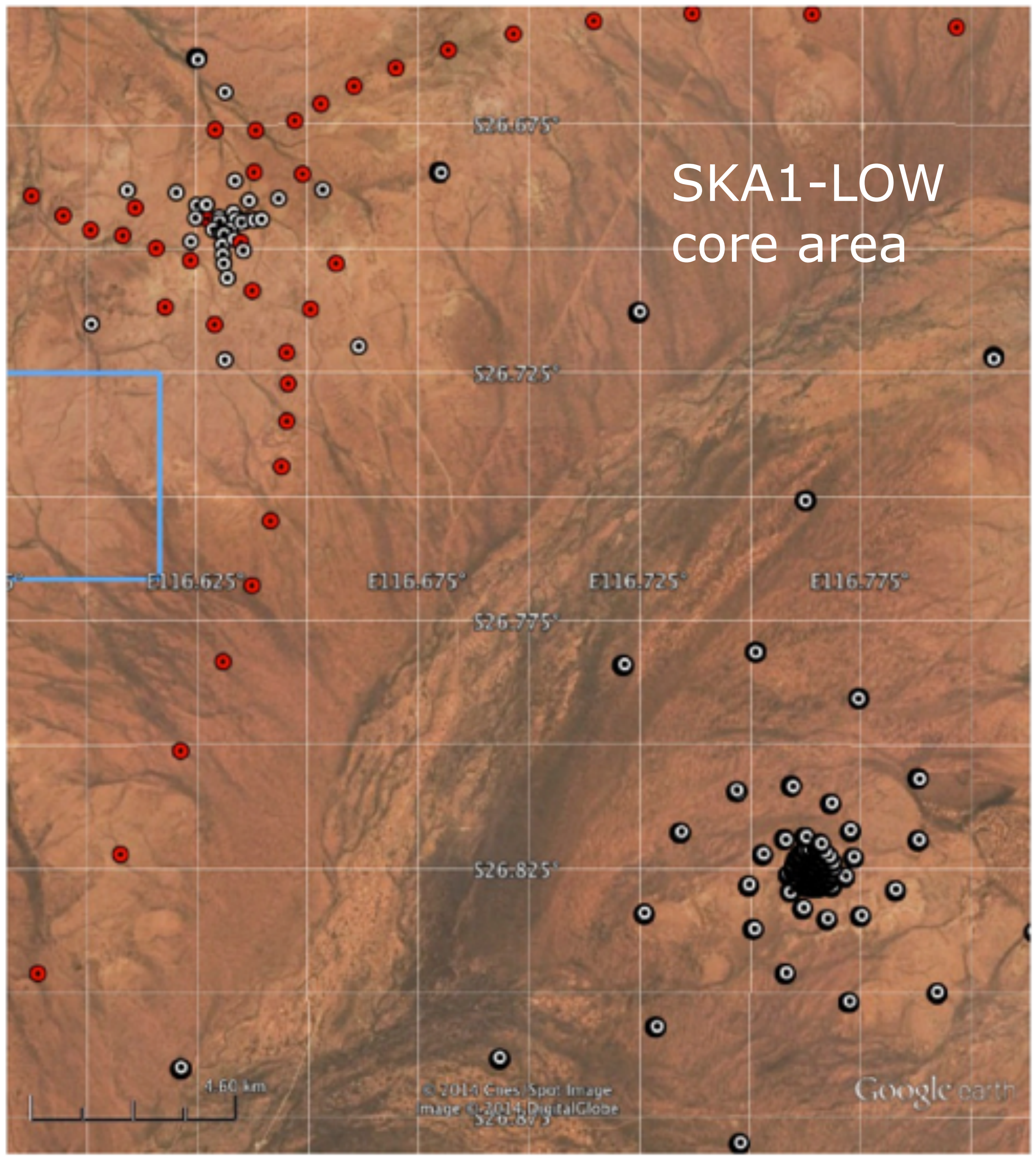
Transients (TKP)
Search for fast transients (e.g. Lorimer bursts, pulsars) and slow transients (e.g. supernovae).

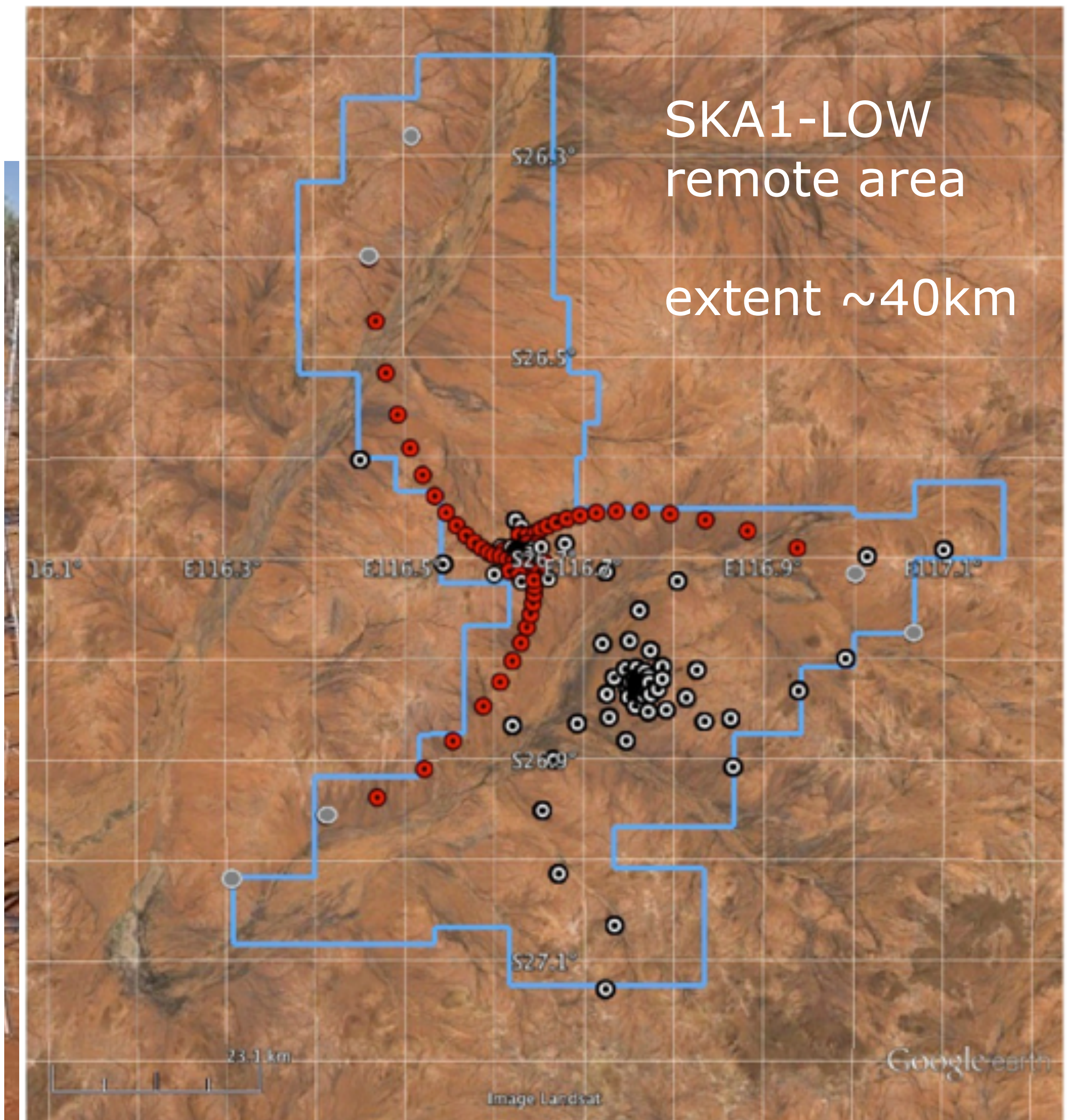
The future of low frequency radio astronomy

- The Square Kilometre Array (SKA) will have a low frequency component (SKA1-Low is the first stage, to be located in Western Australia)

The future of low frequency radio astronomy

- The Square Kilometre Array (SKA) will have a low frequency component (SKA1-Low is the first stage, to be located in Western Australia)

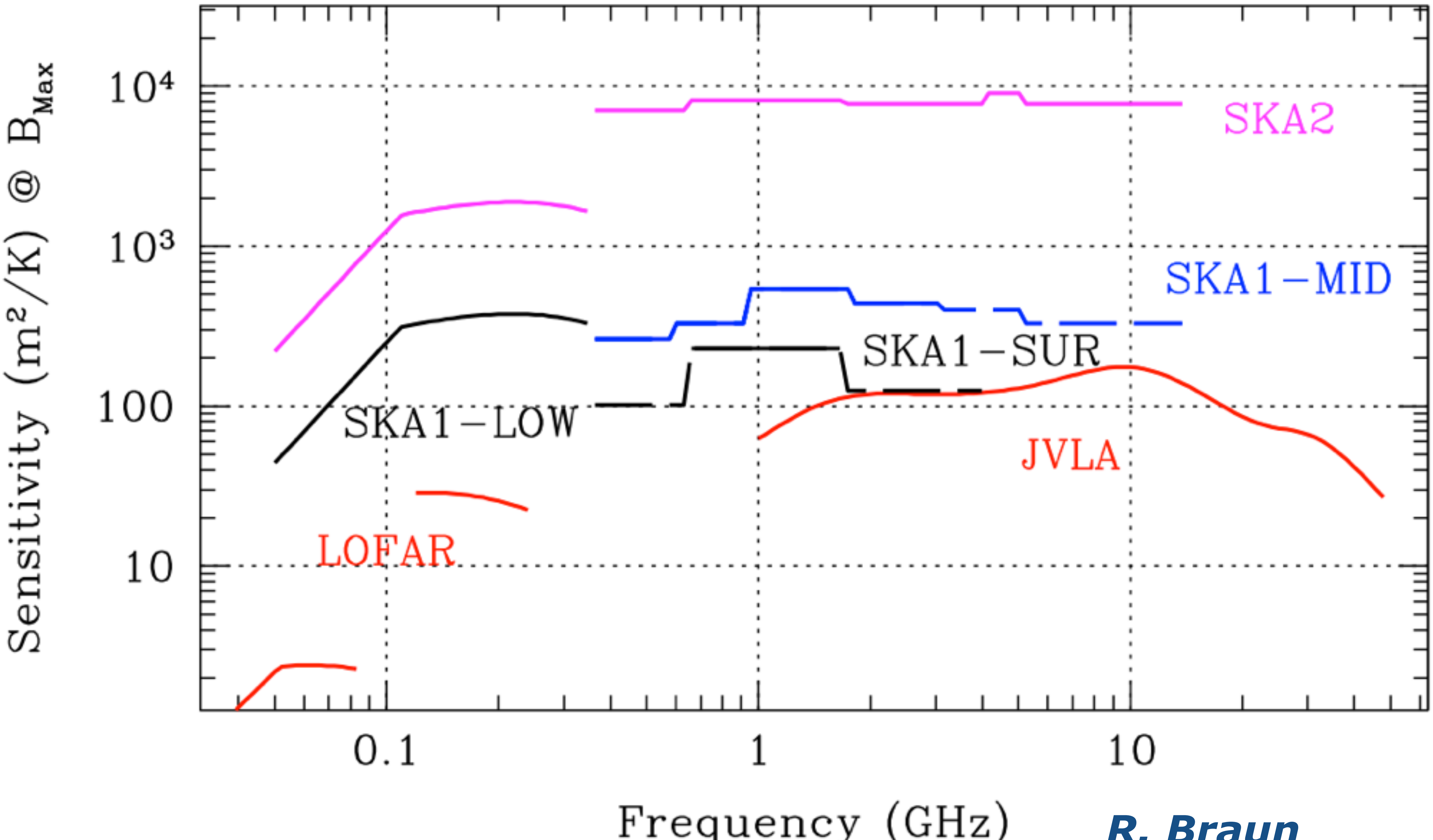




The future of low frequency radio astronomy

ASTRON

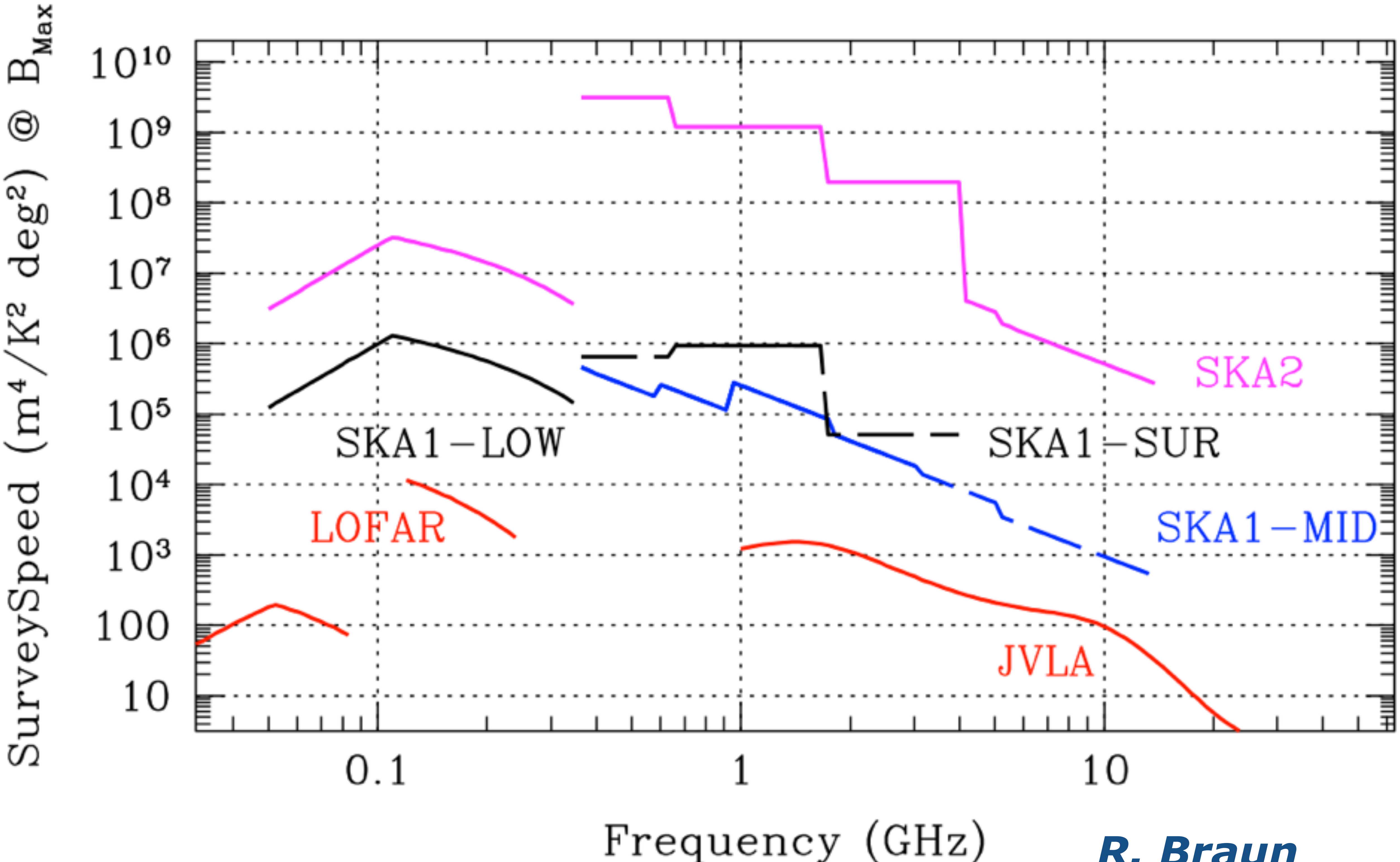
- The Square Kilometre Array (SKA) will have a low frequency component (SKA1-Low is the first stage, to be located in Western Australia)



R. Braun

The future of low frequency radio astronomy

- The Square Kilometre Array (SKA) will have a low frequency component (SKA1-Low is the first stage, to be located in Western Australia)



R. Braun

Summary

- Radio astronomy had its origins at low frequencies, and after a successful diversion to higher frequencies, attention is returning to $\nu<350$ MHz
  - Modern dipoles still quite simple (though designed with the aid of sophisticated modeling)
  - Key to modern radio astronomy is computational power!
- Interferometry is essential for competitive low frequency science
  - Basics of interferometry reviewed here; see also SIRA II (VLA white book)
  - Stay tuned for additional lectures on calibration, imaging, etc
- Several important low frequency radio telescope facilities currently available
  - LOFAR plays a key role, and together with several other complementary telescopes makes for an active worldwide community
  - Interesting to note that most telescopes currently looking at upgrades…
  - SKA will have low frequency component in Western Australia
    - Huge sensitivity, though note max baselines shorter than LOFAR's
- Key low radio frequency science spans range of astrophysical topics
  - MW and pulsars, through galaxies, AGN, etc - to cosmology (EoR, IGM B)