UFYS2010: Radio astronomy instrumentation and interferometry

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Some of the figures are from Wilson, Rohlfs, Hüttemeister: 'Tools of Radio astronomy'

Outline

Lectures, places, times

Lectures Tursdays 14:15 - 16 in Qh 314 and demos occasionally after the lecture.

There will be some exercises (demos), they will not be obligatory but points from these will be added to exam points (with a scale, corresponding about two exam problems).

Also an interferometry data reduction exercise is planned, more info later.

Webpage:
`http://tube.utu.fi/UFYS2010`
containing lectures and exercises. It works now...

Overview I

Goals:

- Basic knowledge of observational radio astronomy
    - Radiation mechanisms
    - Radiative transfer
    - Radio sources at different wavelengths
    - Observational methods (single dish)

- Basic knowledge of instrumentation
    - Basic design of radio receivers and radiometers
    - Sensitivity and noise temperature
    - Backends: spectrometers, recorders and radiometers
    - Current state-of-the-art

Overview II

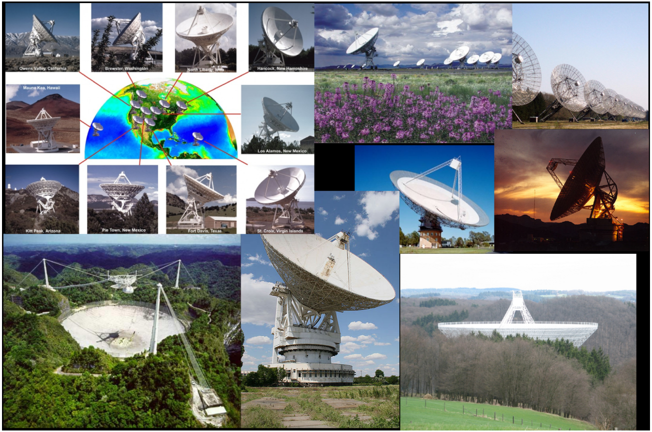
- Principles of interferometry
  - Basic concepts: UV-plane, sampling, deconvolution
  - History and development of interferometry
  - Optical interferometry
  - Current and future interferometric arrays
- Interferometry (VLBI) in practise
  - A-priori calibration
  - Delay and rate calibration
  - Deconvolution
  - Self calibration
  - Model fitting
  - Making an observing proposal

Literature

- Lecture slides (http://tube.utu.fi/UFYS2010 ..working on it..)
- Selected chapters of 'VLBA-book' aka Very Long Baseline
- Interferometry and the VLBA: Proceedings from the 1993 NRAO Summer School, NRAO Workshop No. 22 (http://www.cv.nrao.edu/vlbabook/)
- (Copies of) Rohlfs: Tools of radio astronomy
- (Copies of) Taylor, Carilli, Perley: Synthesis Imaging in Radio Astronomy II
- (Copies of) Thompson, Moran, Swenson: Interferometry and Synthesis in Radio Astronomy
- Copies of various scientific articles and journals

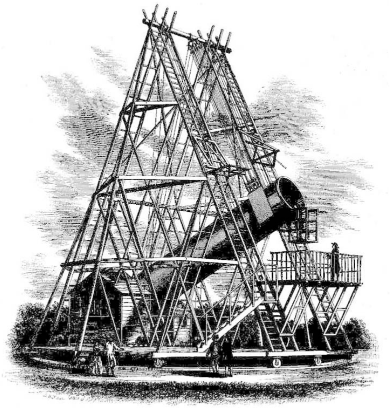
Radio receivers are sensitive!

- If we could collect all energy in the form of radio emission that falls to the Earth's are, we could melt 2 mg water each second
- The energy that is capured by all existing telescopes at all times corresponds to the kinetic energy of a falling snowflake



History

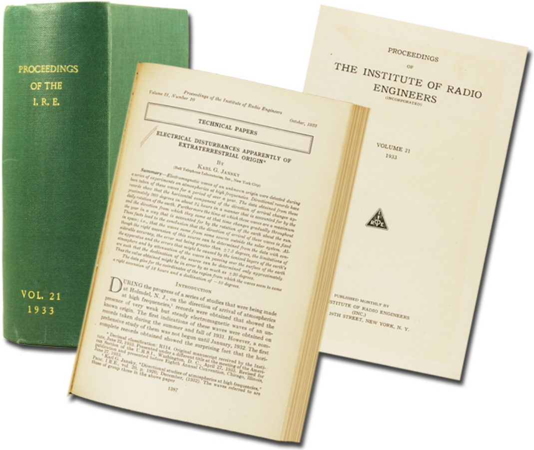
For thousands of years, astronomical observations were limited to the wavelengths in the visible spectrum.
Until 1930's, the observations were limited from near-ultraviolet to near-infrared ($0.35\mu m \leq \lambda \leq 1\mu m$) using photoelectric detectors and photographic plates.



Karl Jansky

(Wikimedia Commons)

1931 Karl Jansky got a project to investigate the sources of interference to radio communications (telephone service). He noticed that some interference sources followed the diurnal cycle but not exactly and followed the sidereal period. The natural conclusion was that the radio noise-like interference was coming from space.


PROCEEDINGS
OF THE
I. R. E.
VOL. 21
1933
Proceedings of the Institute of Radio Engineers
Volume 21, Number 10
October, 1933
TECHNICAL PAPERS
ELECTRICAL DISTURBANCES APPARENTLY OF EXTRATERRESTRIAL ORIGIN*
By
Karl G. Jansky
Introduction
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PROCEEDINGS
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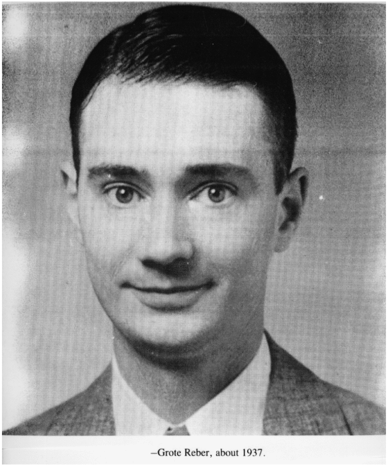
(INCORPORATED)
VOLUME 21
1933

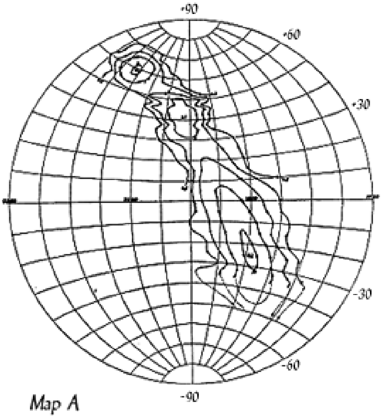
Grote Reber

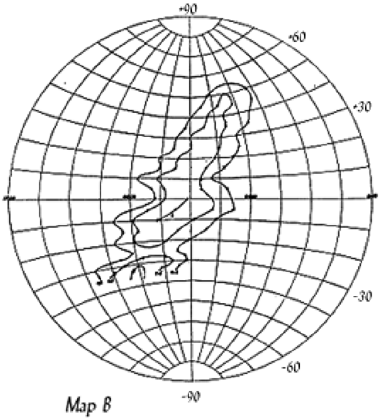


(NRAO)

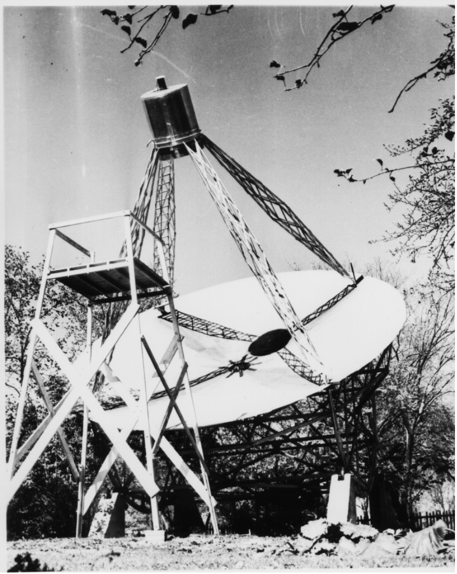
Jansky's discovery was considered first just as a curiosity among astronomers and no attempts to even confirm the findings were taken for several years. In 1937, a radio hobbyist Grote Reber decided to map the radio emission from the sky using a radio telescope he built to his backyard at his own expense. These first real all-sky maps made at 160 MHz are considered as the beginning of observational radio astronomy.

First radio map of the sky





The first almost all-sky radio map of the sky. Cygnus A is seen in the left map at about 40 degree declination. (G. Reber, The Astrophysical Journal)

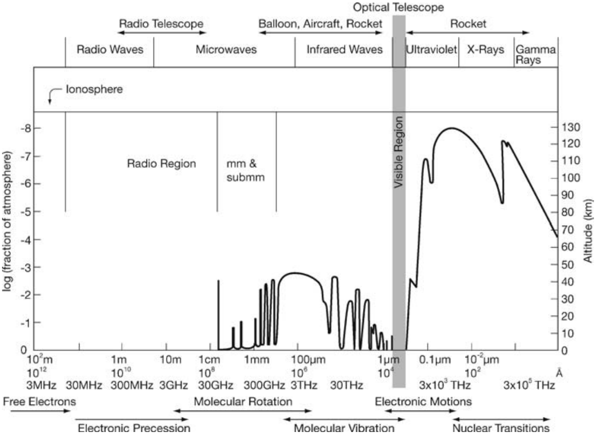


(NRAO)

Radio observations in astronomy

- Different emission mechanisms and physical phenomena: unique information.
- Radio emission is extremely penetrating, it is the only way to see into e.g. the cores of galaxies embedded in dust and plasma.
- Many emission and absorption lines of important molecules are in radio wavelengths (e.g. CO, SiO, H_2O, etc.).
- The whole information content (amplitude and phase) of the incoming radiation can only be recorded at radio frequencies and processed either real time or after observation (interferometry and FT spectroscopy).
- It is possible to make radio detectors (receivers) that their sensitivity is close to the theoretical limit (quantum noise). E.g. the power received from a (rather strong) 1 Jy radio source over a 100 m radio telescope is only 0.000000000000001 (10^{-15}) Watts but still it is very easy to detect.

Atmospheric radio window



Atmosphere is reasonably transparent from about 15 MHz to 1.5 THz. The graph shows the altitude where the radiation is attenuated by half.

Atmospheric attenuation

The ionospheric plasma attenuates radio radiation below the *plasma frequency*

$$\frac{\nu_{\rm p}}{\rm kHz} = 8.97\sqrt{\frac{N_{\rm e}}{\rm cm^{-3}}}. \qquad (1)$$

Because the attenuation varies as a function of time of the day and solar activity, it is not marked to the previous figure.
At higher frequencies water vapour (22 GHz, 183 GHz) and oxygen (60, 119 GHz) resonances are mainly reponsible for attenuation.

Brightness and total flux density

The infinitesimal power $\mathrm{d}P$ intercepted by an infinitesimal surface $\mathrm{d}\sigma$ from a source which has a *specific intensity* of I_ν (W m^{-2} Hz^{-1} sr^{-1}) in a frequency bandwidth of $\mathrm{d}\nu$ is

$$\mathrm{d}P = I_\nu \cos\theta \; \mathrm{d}\Omega \; \mathrm{d}\sigma \; \mathrm{d}\nu \tag{2}$$

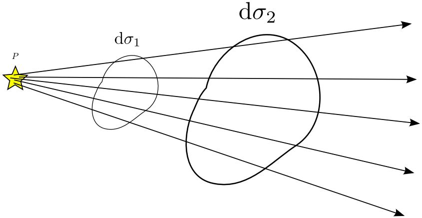
By integrating the previous equation over the full solid angle Ω_s we get the *total flux density* S_ν:

$$S_\nu = \int_{\Omega_\mathrm{s}} I_\nu(\theta, \phi) \cos\theta \; \mathrm{d}\Omega \tag{3}$$

The unit of S_ν is $\mathrm{W\,m^{-2}\,Hz^{-1}}$ but a more convenient unit Jansky (Jy, after Karl Jansky) is commonly used in radio astronomy:

$$1\mathrm{Jy} = 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}} \tag{4}$$

Brightness of an extended (non-pointlike) source (1)



An object emits a bundle of rays that contain the power dP. Naturally as long as all the rays go through the surface elements dσ_i the total power through these elements will be preserved:

$$\mathrm{d}P_1 = \mathrm{d}P_2. \tag{5}$$

From the previous equations (power vs. intensity) we get (for a perpendicular element):

$$\mathrm{d}P_1 = I_{\nu 1}\ \mathrm{d}\Omega_1\ \mathrm{d}\sigma_1\ \mathrm{d}\nu \tag{6}$$

$$\mathrm{d}P_2 = I_{\nu 2}\ \mathrm{d}\Omega_2\ \mathrm{d}\sigma_2\ \mathrm{d}\nu. \tag{7}$$

Brightness of an extended (non-pointlike) source (2)

If the distance between the surface elements is R, then the solid angles are $\mathrm{d}\Omega_2 = \mathrm{d}\sigma_1/R^2$ ja $\mathrm{d}\Omega_1 = \mathrm{d}\sigma_2/R^2$, therefore:

$$\mathrm{d}P_1 = I_{\nu 1}\,\mathrm{d}\sigma_1 \frac{\mathrm{d}\sigma_2}{R^2}\,\mathrm{d}\nu \tag{8}$$

$$\mathrm{d}P_2 = I_{\nu 2}\,\mathrm{d}\sigma_2 \frac{\mathrm{d}\sigma_1}{R^2}\,\mathrm{d}\nu. \tag{9}$$

Because $\mathrm{d}P_1 = \mathrm{d}P_2$

$$I_{\nu 1} = I_{\nu 2}, \tag{10}$$

i.e. brightness is independent of distance (in vacuum).

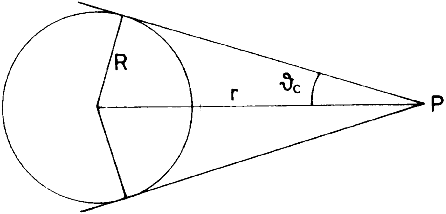
Total flux density and distance (1)

The total flux received from an uniformly bright sphere at a distance of r is

$$S_\nu = \int_{\Omega_s} I_\nu \cos\theta \, \mathrm{d}\Omega = I_\nu \int_0^{2\pi} \left(\int_0^{\theta_c} \sin\theta \, \cos\theta \, \mathrm{d}\theta \right) \mathrm{d}\varphi. \qquad (11)$$

$$\sin\theta_c = \frac{R}{r} \qquad (12)$$

defines the angle θ_c that corresponds the radius of the sphere at a distance of r.



Total flux density and distance (2)

$$\sin\theta_c = \frac{R}{r} \tag{13}$$

defines the angle θ_c that corresponds the radius of the sphere at a distance of r.

After integrating, we get

$$S_\nu = \pi\, I_\nu \sin^2\, \theta_c \tag{14}$$

or

$$S_\nu = I_\nu \frac{\pi\, R^2}{r^2} = I_\nu\, \Delta\Omega, \tag{15}$$

where $\Delta\Omega$ is defined as the solid angle that corresponds the object at a distance of r, so the total flux density is decreasing as a function of the distance $(1/r^2)$.