The Universe in my pocket

Radio telescopes

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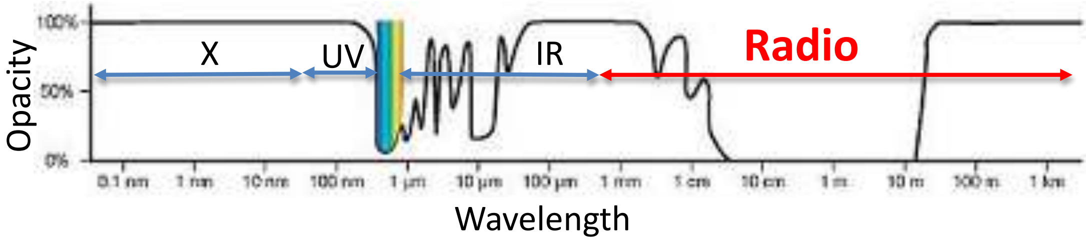
No 45
THE UNIVERSE IN MY POCKET

Laurent Pagani
CNRS & Observatoire de Paris-PSL



Transparency of the sky as a function of wavelength. Radio waves cover from about 1 mm to tens of km in wavelength. The sky is totally transparent from 3 cm to 20 m and partially transparent between 3 cm and 0.3mm. At short wavelengths it is advantageous to locate radio telescopes at high altitudes to improve the transmission partially blocked by water vapor which is mostly present at lower elevations.



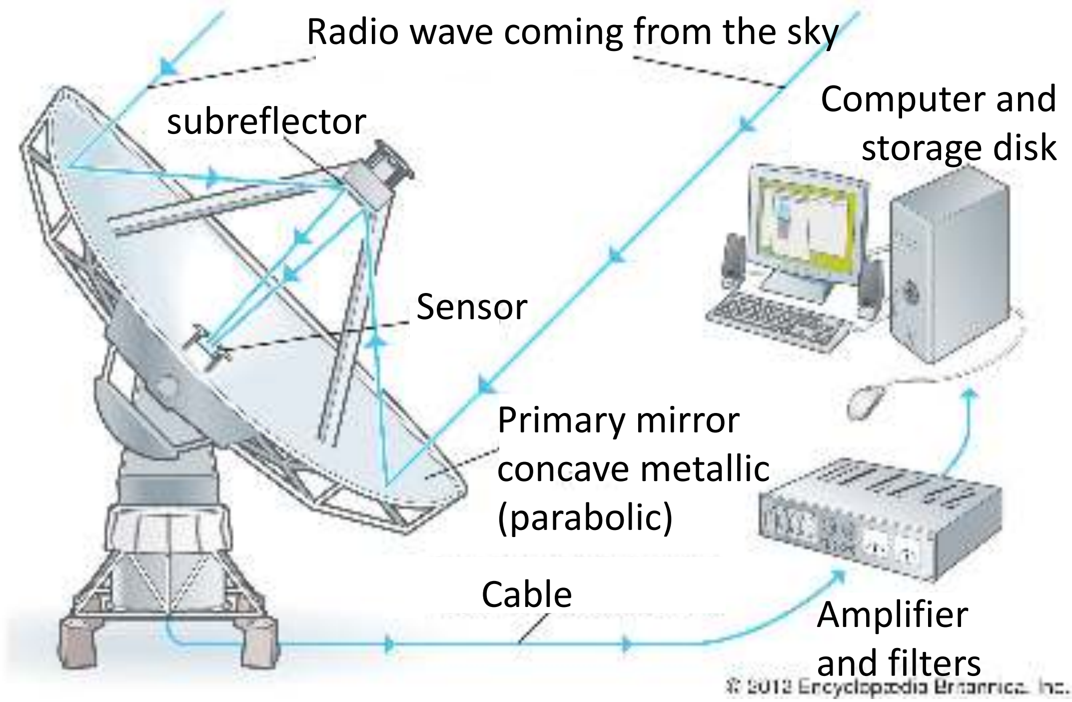


All these devices work on the same principle: they capture a radio wave which they amplify and demodulate to deliver as sound or an image.

Introduction

To observe the cosmos, we must capture the messages it sends us (see TUIMP 43). The best-known messenger is light, of which only a small part can be captured by the eye (the so-called 'visible' light, consisting of the colors of the rainbow). But there are many other types of light, one of which was discovered at the very end of the 19th century and has been widely used ever since: radio waves.

These waves have a length (λ) very long compared to visible light (from a thousand to billions of times longer) and therefore a very low frequency (ν) ($c = \lambda \times \nu$, where c is the speed of light). We have been able to build many devices to transmit and receive radio waves, such as radio or television sets, walkie-talkies, cellular phones and radars.



Schematic of a radio telescope. The primary mirror, metallic and large, reflects the signal to a secondary mirror and then to a detector. The signal is then amplified and filtered in a frequency range
to be finally analyzed by a computer. If the frequency is too high to be amplified directly, the frequency is changed first, to a lower value, before being amplified. This is the so-called heterodyne technique.

Radio technique

Because of its low energy, the corpuscular nature of radio light (see TUIMP 43) does not generally manifest itself. Rather, it interacts as a wave, composed of an electrical part and a magnetic part. It is emitted or received with an antenna - generally a structure of conductive metal, sensitive to the electric field of the radio wave in reception, or creating this electric field in transmission.

Radio astronomy uses all the radio techniques associated with large antennas pointed towards the sky to capture the very weak signals that come to us from the Universe.

Note that radio telescopes can observe both day and night, because the sky does not emit in radio waves.

Antenna of a Würzburg radar

The Sun's emission was first detected in 1942 by the British physicist James Hey. This discovery remained secret because the Allies knew that their planes, if they had the sun behind them, would not be detected by German radars.

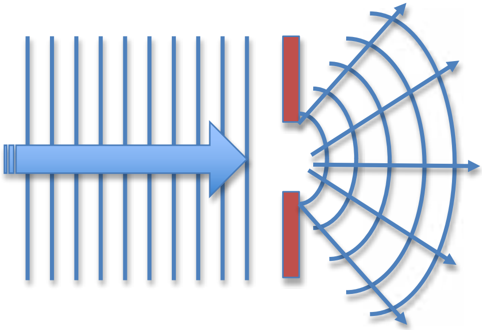
These German radars (called Würzburg) were reused after WWII to make the first steps in radio astronomy in Europe.

The beginnings

After initial unsuccessful attempts to detect radio waves from the Sun between 1896 and1901, it was Karl Jansky who made the first discovery of extraterrestrial radio waves, emitted by the center of the Milky Way, in 1932.

From then on, radio astronomy made rapid progress to become a rich science and very complementary to traditional optical astronomy (see TUIMP 46).

Radio astronomy can perform direct detection of light, as in optics (measuring the signal energy) or heterodyne detection (measuring the incident electric field), which allows amplifying the signal and filtering it with high precision thanks to radio frequency electronics.



Diffraction pattern: the wave that arrives on the obstacle disperses in various directions.

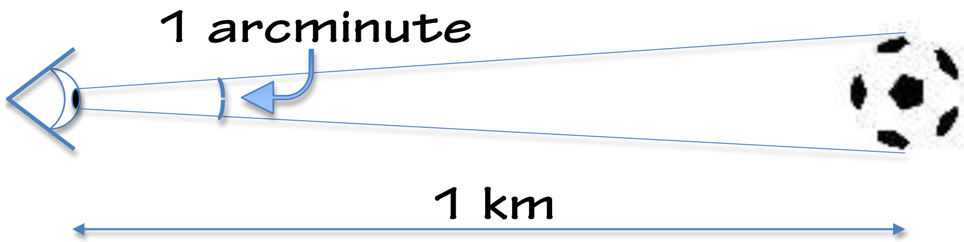
FAST, in China, 500 m in diameter, is the largest fixed radio telescope in the world.

The Green Bank Telescope, in the USA, with a diameter of approximately 100 m, is the largest mobile telescope in the world.

Size and resolution

For visible light, the resolution of telescopes is limited by atmospheric turbulence. This problem does not exist in radio and diffraction is perceptible (see figure on the opposite page). The angular resolution is $\theta \approx 1.2\ \lambda / D / 0.0003$; λ is the wavelength, D the diameter of the telescope, and θ is in arc minutes.

Because λ is large, diffraction is substantial, limiting the resolving power of radio telescopes. To mitigate this, radio astronomers use extremely large antennas that are very sensitive to electrical interference. They are located far from urban centers and factories that produce electrical interference. Certain radio frequencies are protected from anthropogenic emissions by the International Telecommunication Union (ITU).



Some examples of angular resolution:

The eye has a resolution of one arc minute, thus one could distinguish 2 footballs side-by-side at 1 km distance.

An optical telescope has a resolution of one arc second. This is 60 times better than the eye, so it can distinguish 2 balls up to 60 km away or 2 dice at 1 km.

FAST has even less resolution than the eye: three arc minutes. It can only separate the 2 balls at 300 m (less than the size of the antenna!).

Radio interferometers can see tiny details. Their resolution is measured in thousandths or even millionths of an arc second. At this extreme resolution, they could see a ping-pong ball on the Moon.

Interferometers

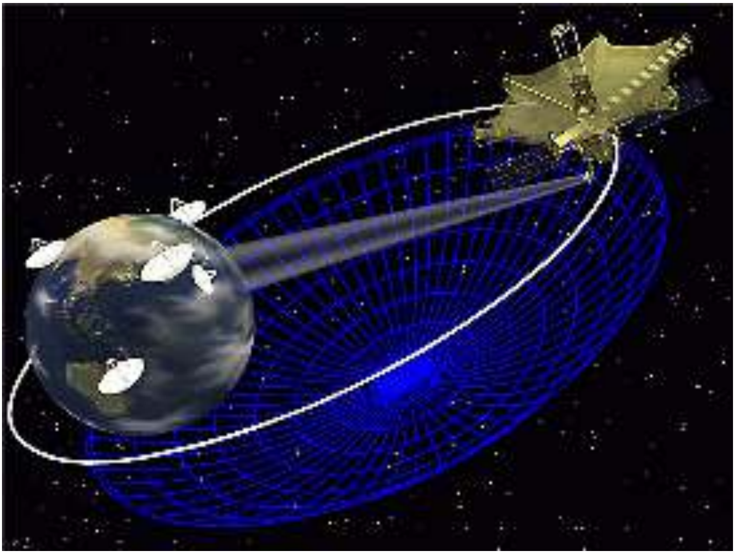
Radio telescopes can also be made by putting several antennas into service and combining their signals simultaneously. This is called 'radio interferometry' because the signals coming from all the antennas are mixed or 'interfered' with each other. The distances between the antennas can be enormous, up to the size of the Earth, or even more if one of the antennas is placed in orbit, as is the 10 m Russian RadioAstron telescope.

The resolution of an interferometer is similar to that of a single-dish telescope with a diameter equal to the separation between the two most-distant antennas. Such a large single-dish telescope would be impossible to build.

See the illustrations on page 12.

(IRAM - J. Boissier)

NOEMA, the Plateau de Bure interferometer (IRAM). 12 antennas of 15 m diameter each observe the same astronomical source simultaneously.



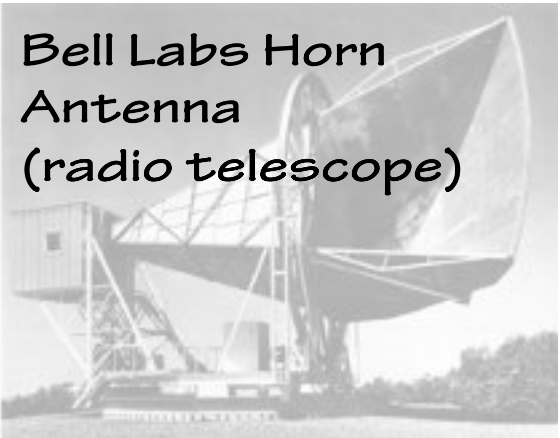
The 10 m Russian radio telescope RadioAstron in orbit around the Earth observes an astronomical source at the same time as the telescopes on the ground. The resolution is that of an equivalent radio telescope larger than the Earth (represented in blue in the figure) but the collecting surface remains very small, so only very bright objects can be observed.

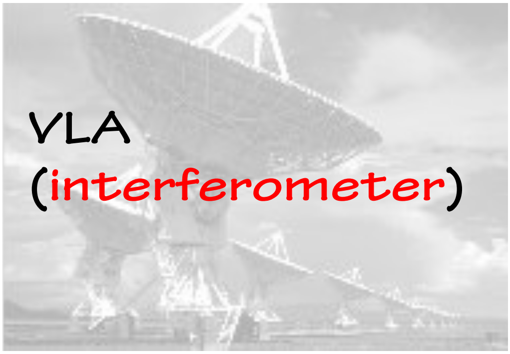
Single-dish radio telescopes often observe only one point in the sky at a time (called a 'pixel') because their receiver has only one sensor. To obtain an image, the telescope must scan the entire surface point by point. These points are then assembled to obtain an image or 'map'. On the other hand, their receivers can detect a wide range of frequencies at the same time with a very high 'spectral resolution'. This makes it possible to measure very small movements in the clouds where stars are formed and to identify hundreds of different interstellar molecules.
Some radio telescopes have receivers with hundreds to thousands of pixels, like a camera, but without spectral resolution. These receivers are called 'bolometers'; they are useful for observing cold interstellar dust that emits high-frequency radio waves.

Quiz

Which images show interferometers?

Answer on overleaf





Answer

Interferometers are always composed of several antennas.

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This booklet was written in 2025 by Laurent Pagani of the Observatoire de Paris and the CNRS and reviewed by Grażyna Stasińska of the Observatoire de Paris and Stan Kurtz from IRyA (Morelia, Mexico)

<u>Cover image:</u> one of the latest radio telescopes: MEERKAT
(Unless otherwise specified, general credits: Wikipedia)

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Translation: Stan Kurtz