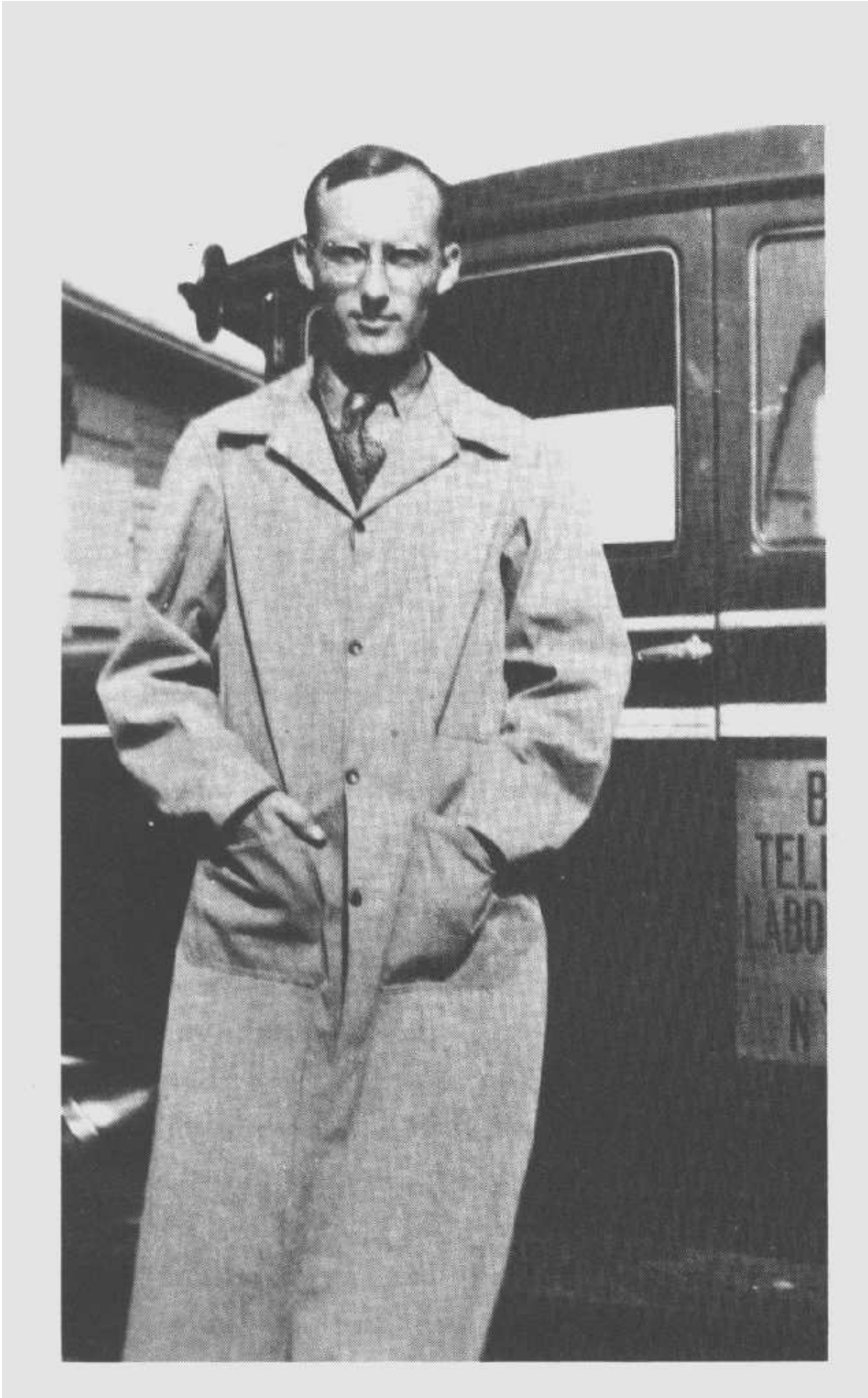

Figure 1: **Karl Jansky**

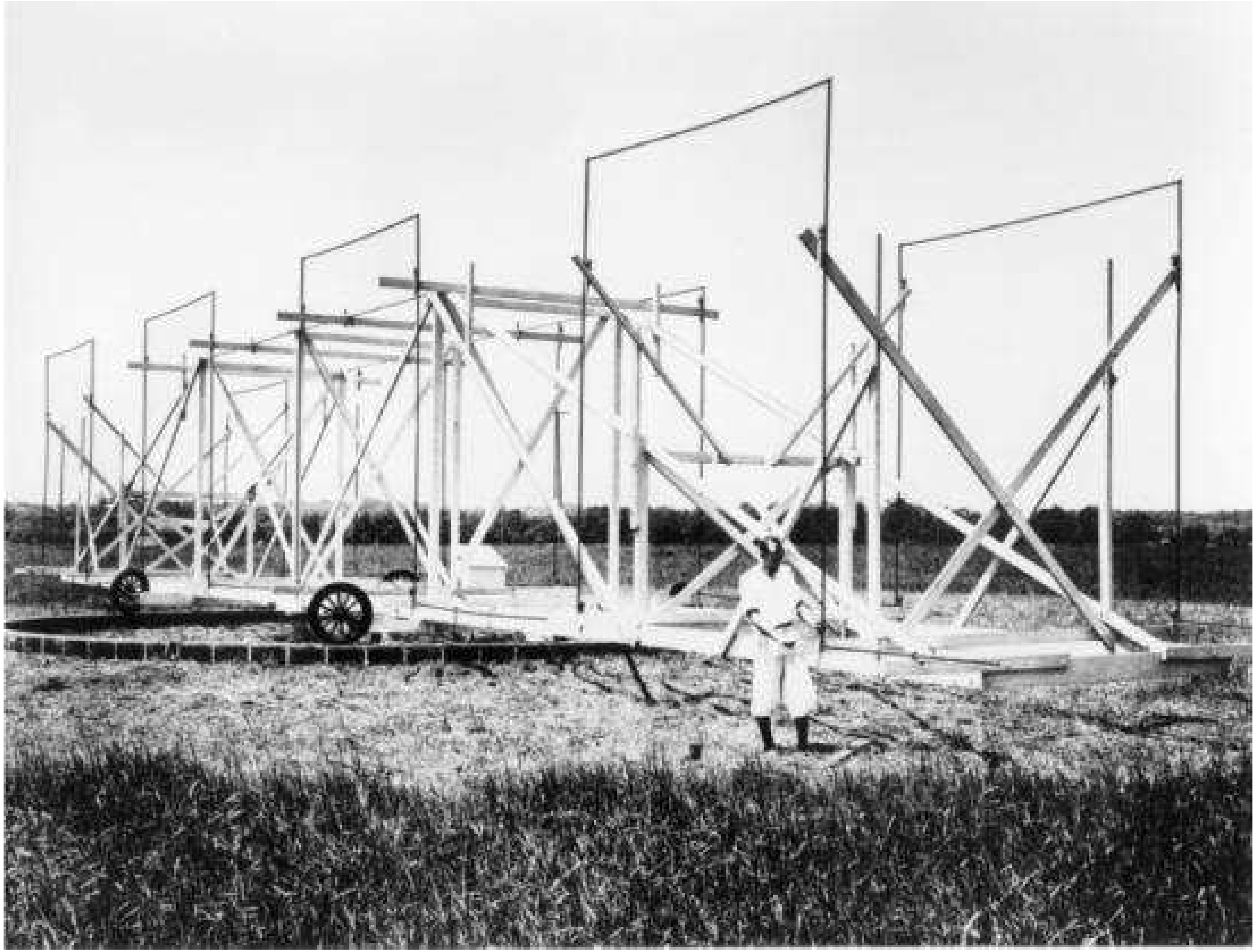

Figure 2: **Karl Jansky's Antenna**

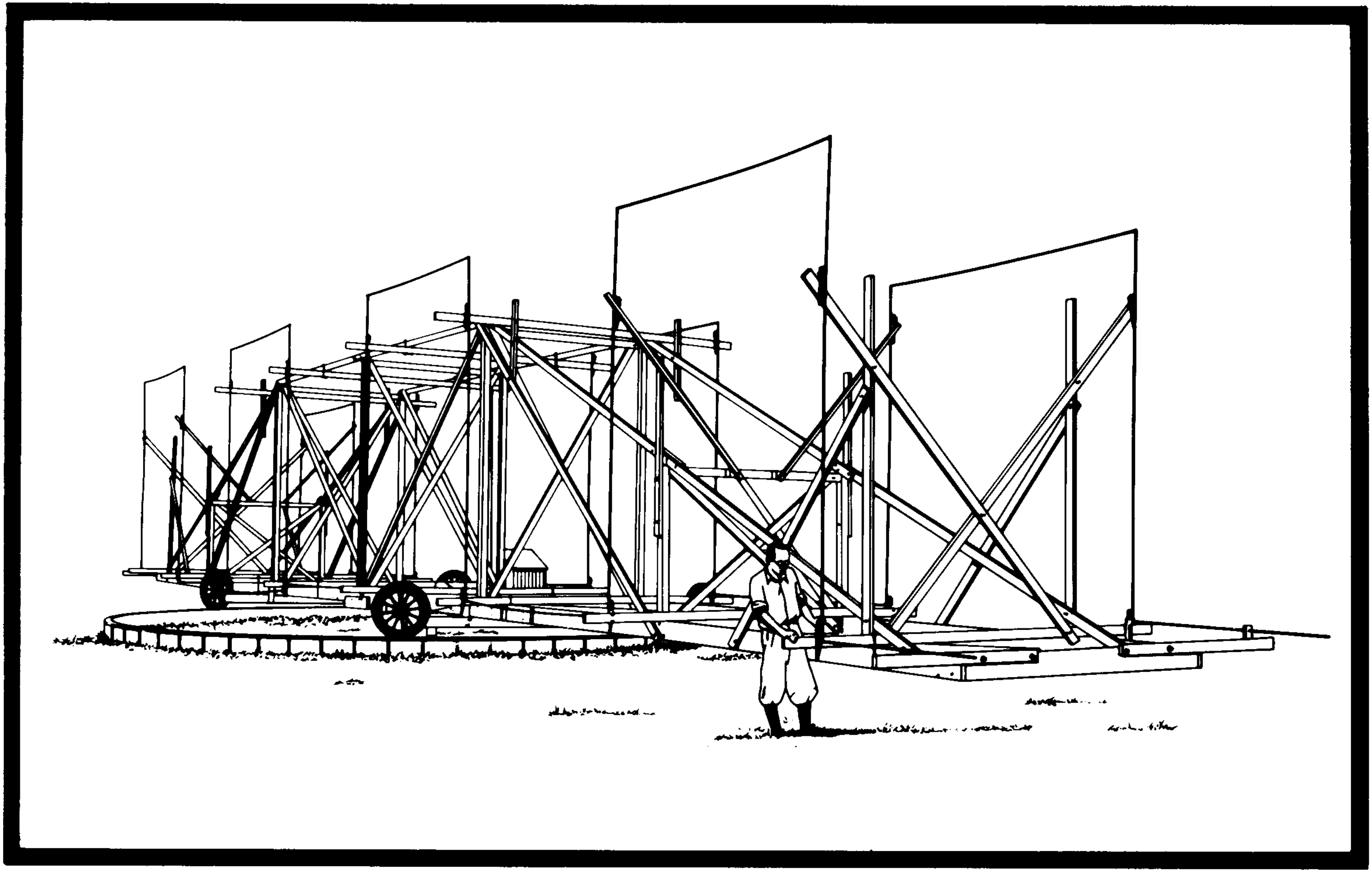

Figure 3: **Karl Jansky's Antenna**

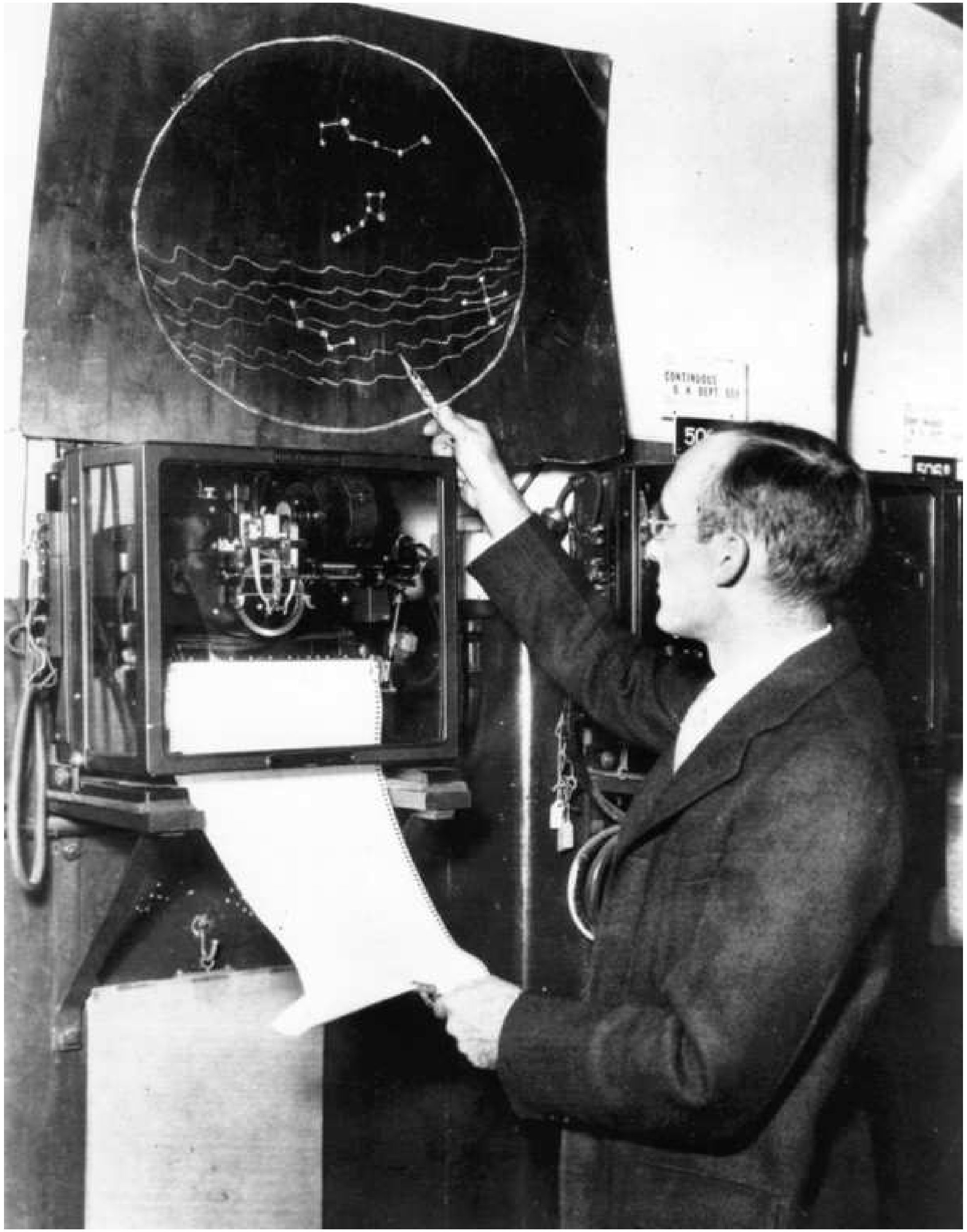

Figure 4: **Karl Jansky pointing at the Galactic emission**

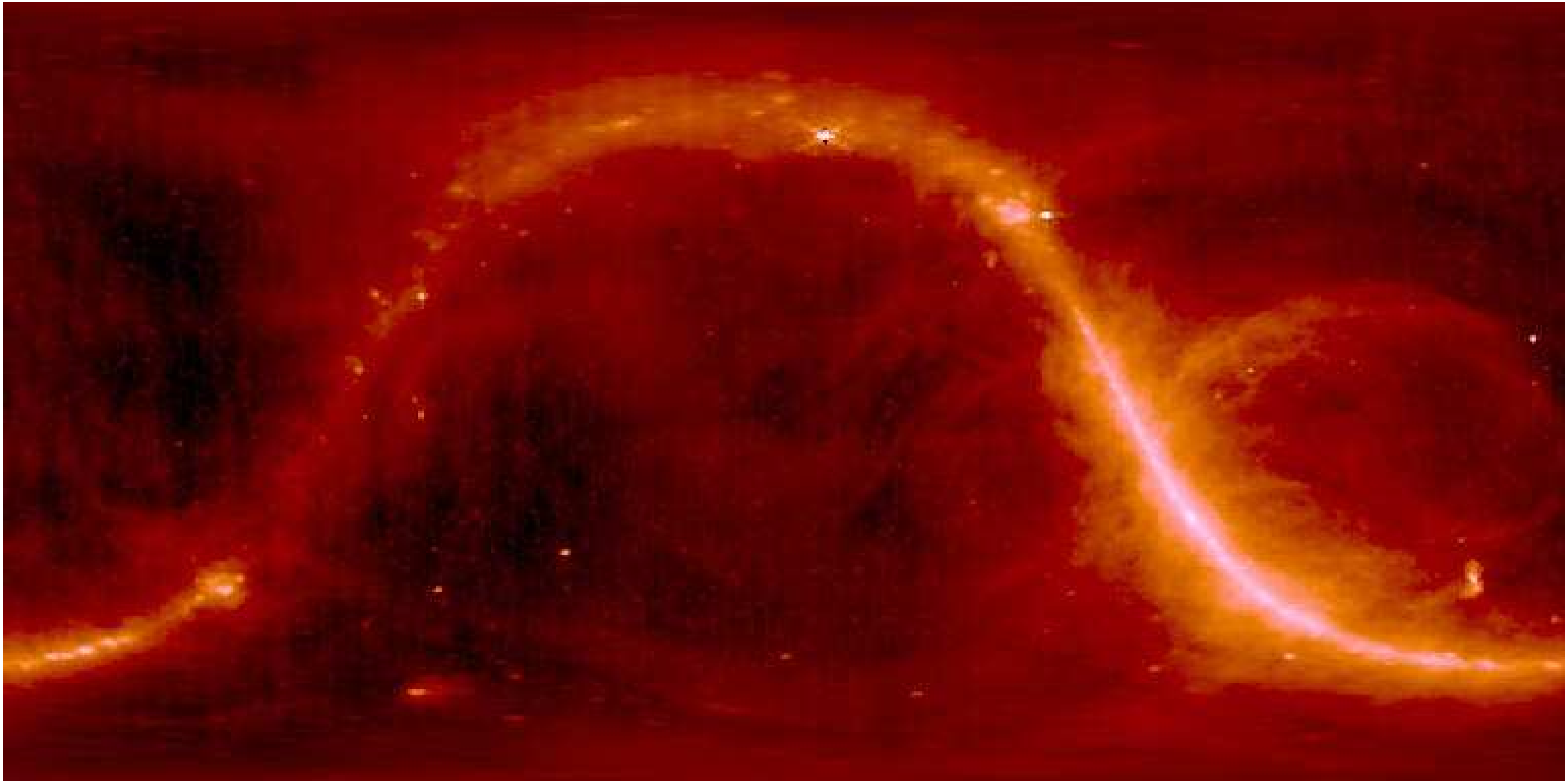

Figure 5: **The Sky at 408 MHz (Haslam et al)**

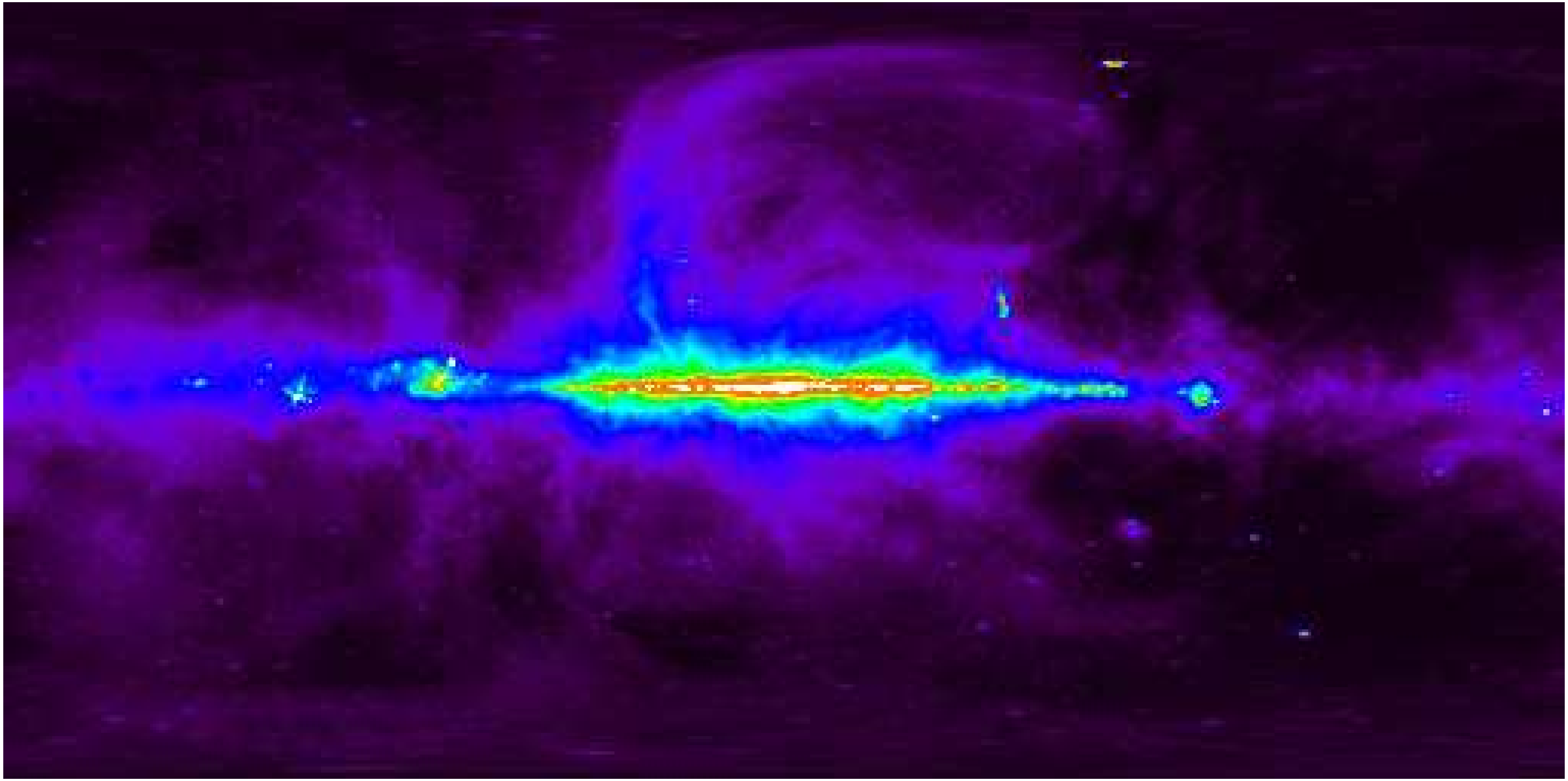

Figure 6: **The Sky at 408 MHz (Haslam et al)**

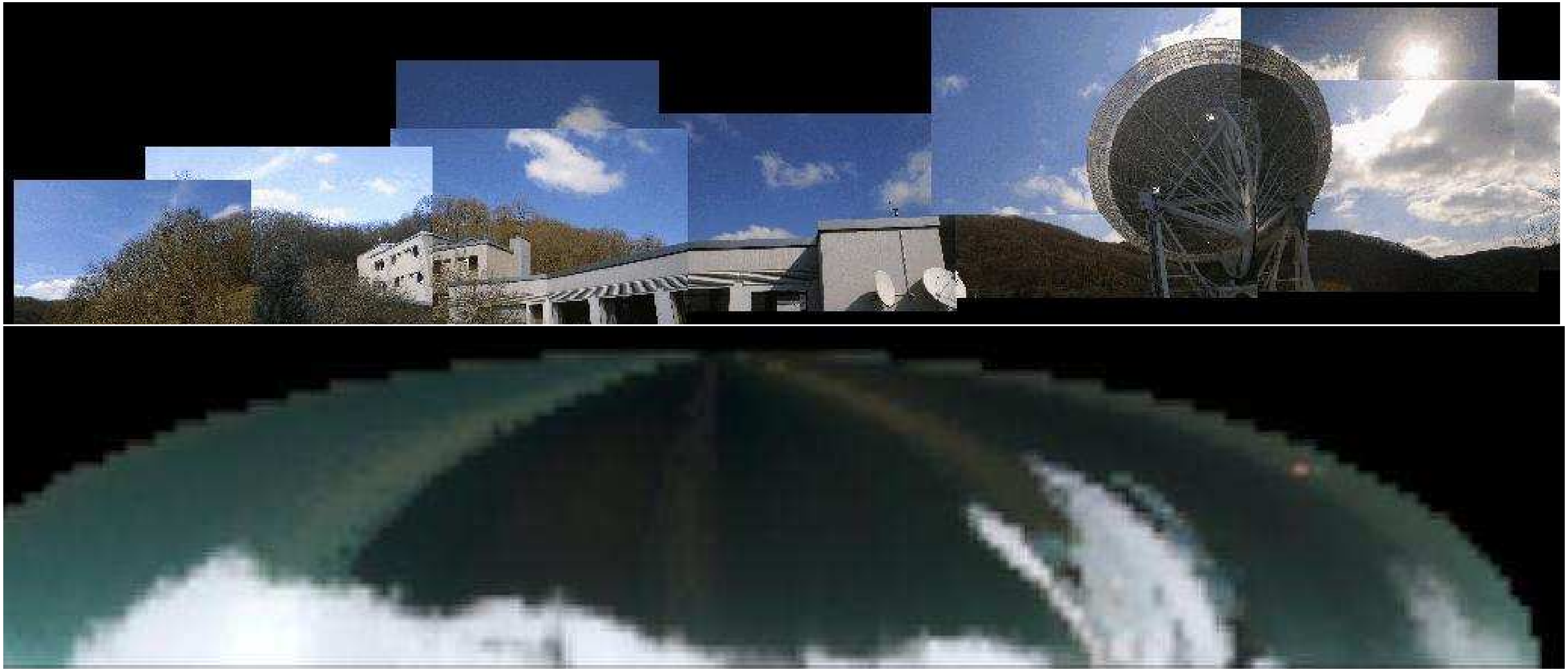

Figure 7: **Effelsberg Night Sky at 22GHz (A.Roy)**

Figure 8: **HRH, Sir Bernard, Andrew Lyne**

Figure 9: **Radio Night Sky at 5 GHz (NRAO 300ft Survey)**

Introduction to Radio Astronomy

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1 Contents

- **Radio Waves**
- **Radio Emission Processes**
- **Radio “Noise”**
- **Radio source names and catalogues**
- **Radio telescopes**
- **Radio receivers - the feed**
- **Description of noise**
- **Receivers: amplification**
- **Receivers: mixing and detection**
- **Signals for Interferometry**
- **Radio disturbances**

2 Radio Waves

- **EM-waves in frequency range 30 MHz to 800 GHz**
- **wavelengths 10 m – 0.4 mm; a factor 30,000**
- **The new interferometer arrays LOFAR and ALMA will explore these two extremes**

- Radio frequency band designations

  L band 1 to 2 GHz

  S band 2 to 4 GHz

  C band 4 to 8 GHz

  X band 8 to 12 GHz

  Ku band 12 to 18 GHz

  K band 18 to 26 GHz

  Ka band 26 to 40 GHz

  Q band 30 to 50 GHz

  U band 40 to 60 GHz

  V band 50 to 75 GHz

  E band 60 to 90 GHz

  W band 75 to 110 GHz

  F band 90 to 140 GHz

  D band 110 to 170 GHz

  The term P band is sometimes used for UHF frequencies below L-band.

3 Radio Emission Processes

- **Thermal emission; black-body spectrum**
  Example: the Moon
- **Free-free emission (Bremsstrahlung) from ionized gas**
  Example: HII regions
- **Synchrotron emission from charged relativistic particles in magnetic field**
  Example: AGN jets
- **Spectral line emission from atoms, radicals, molecules**
  Example: Neutral hydrogen (HI); 1421 MHz (21 cm)
- **Also: spectral line absorption against background continuum emission**
- **Pulsar emission (probably curvature radiation)**

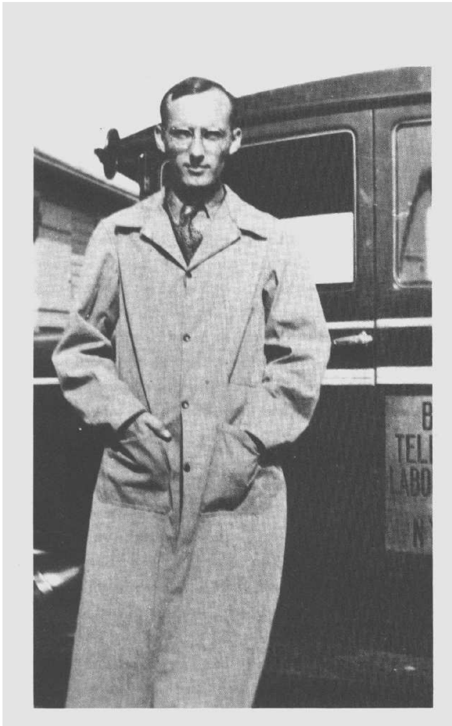


Figure 1: Karl Jansky

4 Radio “Noise”

- **Cosmic objects producing radio waves are called radio sources**
- **Radio emission often referred to as radio noise**
- **First detection of radio source by Karl Jansky in 1932-33**
- **Measure of radio source strength is its flux density, S (sometimes incorrectly termed “flux”)**
- **Unit of flux density = jansky (Jy) = 10^{-26} WHz^{-1}m^{-2}**
- **Flux density calibration sources at different frequencies**
- **Spectral index, α for continuum sources: S α $\nu^{+\alpha}$**
  steep spectrum: $\alpha < -0.5$ **(opt. thin synchrotron)**
  inverted spectrum: $\alpha > 0.0$
  flat spectrum: $0.0 > \alpha > -0.5$

- **Surface brightness of an extended source is the flux density per unit surface area. Units often used in maps or images of a radio source are mJy/beam (where beam is the area of the point source response in the map).**

- **Physical unit is brightness temperature, T_b : the temperature at which a black body would give the same radio emission per unit area**

  $\mathbf{T}_b = \mathbf{S}\lambda^2/\mathbf{2}k\Omega$

  where S is the source flux density, λ is the observing wave-length, k is Boltzmann's constant and Ω is the observed solid angle of the emission.

5 Radio source names and catalogues

- **Radio sky dominated by very different population from optical sky**
- **Radio sky looks different at different frequencies because of the wide range of frequencies (over 4 decades) and the range of different spectral indices. At low frequencies the sky is domininated by steep spectrum sources, mostly synchroton emitters. At high frequencies there are more flat and inverted spectrum sources.**
- **Source names often from catalogues derived from flux density-limited surveys of the radio sky at particular frequencies, especially if they are more prominent in the radio sky**

- **Some well-known examples:**

  CYGNUS A - the strongest source in Cygnus

  VIRGO A - but also M87

  3C 273 - strong quasar from the 3rd Cambridge Catalogue (178 MHz)

  3C 84 - but also N-galaxy NGC 1275

  PKS B 1413+135 - from the Parkes Catalogue (hhmm+dd.d)

6 Radio telescopes

- **They come in many shapes and sizes !**

  A single radio telescope is usually called an antenna

  A collection of antennas may be operated together to form an array (e.g. MERLIN, VLA, EVN, VLBA, ALMA....)

  The most common type of antenna is the steerable parabolic dish

  (but not used for LOFAR !)

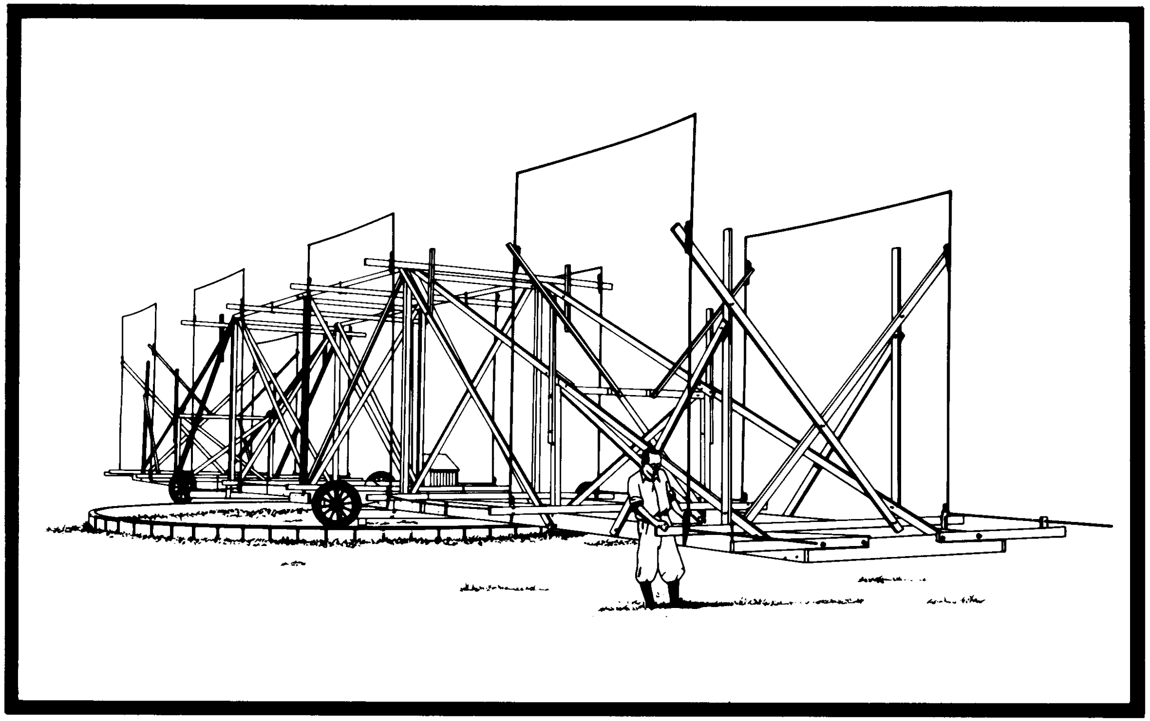
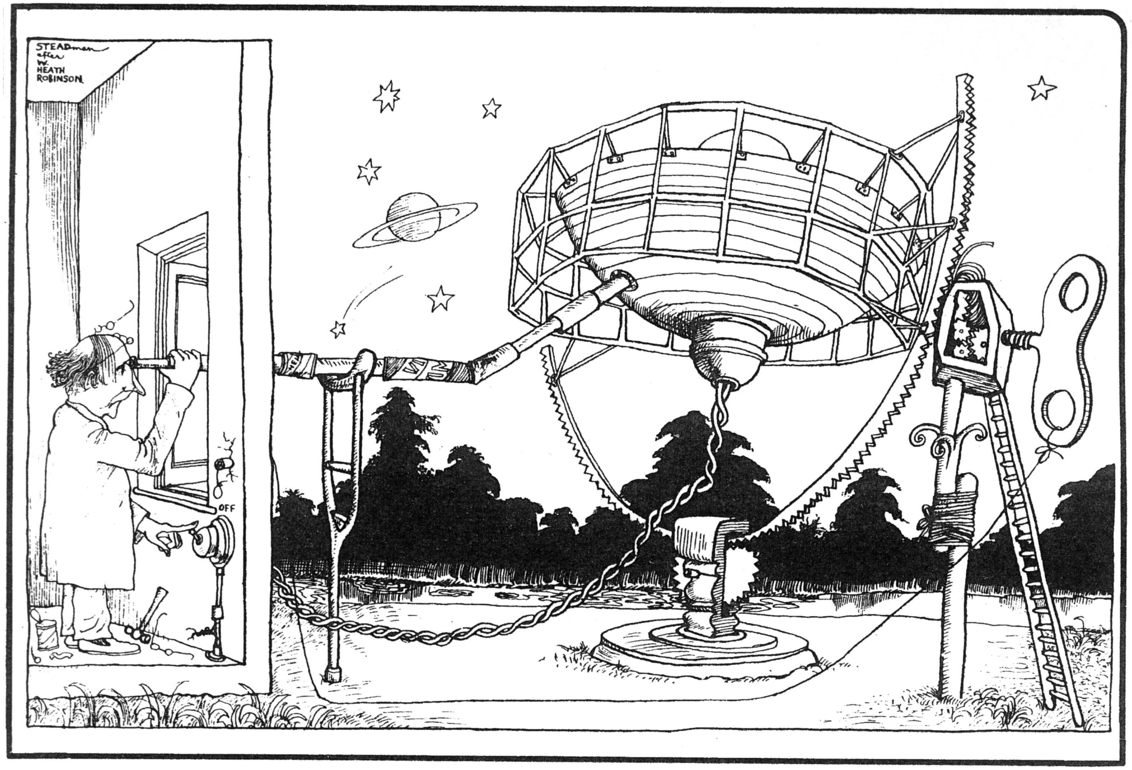


Figure 2: Karl Jansky's Antenna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- **A parabolic dish antenna focuses incoming radiation at the focus**

  It is pointed at the source by steering on orthogonal axes, on either an azimuth/elevation or polar (HA, DEC) mount.

  The size of the dish (diameter, D) determines both the resolution and the sensitivity

- **Resolution is given by the diffraction limit: $\theta \sim \lambda/D$**

  so radio telescopes must be big !

  Point-source response is known as the beam - its size is the beamwidth

- **Sensitivity determined by the collecting area: $\sim$ physical area but must have sufficient surface accuracy: $\sim \lambda/20$**
- **Figure of merit is the telescope gain, g which quantifies the amount of radio noise power received from a source of unit flux density: units K/Jy. (see next section.....)**
- **The gain is often a function of elevation, since there may be elevation-dependent gravitational deformations of the parabolic surface.**
- **Example: Effelsberg 100m diameter radio telescope**

	wavelength		
	50cm	6cm	3mm
beam FWHM	25'	2.5'	10"
gain K/Jy	1.5	1.5	0.1

7 Radio receivers - the feed

- **Radio photons of energy hν are too weak to do anything useful !**

- **EM-wave electric field oscillations can induce voltage oscillations in a conductor**

- **In a radio telescope this process happens at the antenna focus in a device called the feed. The simplest sort of feed is a linear dipole, which responds to E-field oscillations in a single plane. Other feeds may respond to a circular polarization mode.**

- **The output of a feed is a noise voltage, representing noise power from the radio source. By comparison with the Johnson noise from a resistor of temperature T (power = kT per unit bandwidth), the noise power s measured in kelvins, K, and is referred to as the antenna temperature, T_a**

- **For the Effelsberg telescope at 5 GHz (6cm) the antenna temperature from a 1 Jy source is 1.5 K. For a VLBA (25m) antenna it is 0.14 K.**

- **Since the E-field is a (2D) vector, and the induced voltage is a scalar, clearly 2 feed channels are needed to completely sample the field. This is then a dual-polarization feed.**

- **Note that a feed responds to the radiation at a single point in the focal plane - we are measuring the signal for a single pixel ! Focal plane feed arrays exist, but are rare.**

- **For azimuth/elevation ("alt/az") mounted telescopes the angle of the feed with respect to the radio source changes with HA by the parallactic angle.**

8 Description of noise

- **The induced voltage has characteristics which mimic the properties of (one component of) the E-field. We can describe the noise signal voltage as the sum of sinusoidal oscillations at all frequencies within the observing band, each with arbitrary relative phase. We characterise this by the centre frequency, the radio frequency or RF and the bandwidth, b. For a time shorter than $1/b$ the voltage behaves like a pure single frequency at RF. After a time longer than $1/b$ the signal phase has changed arbitrarily (due to relative rotation across the band of the individual component frequencies).**

- **The antenna noise power, $\mathbf{T}_a$, averaged for a time t has noise fluctuations $\sim\mathbf{T}_a/\sqrt{(}tb)$**

- **Note that this is a fundamental limit to the achievable signal-to-noise ratio. It is equivalent to (but not the same as) photon counting noise in other domains.**

- **A typical bandwidth may be $\sim$ 100 MHz; note that at 5 GHz this is only $\sim$ 2 percent of the band.**

9 Receivers: amplification

- **The induced voltage is in general too faint to detect directly.**
- **The voltage is amplified to achieve a detectable level. Note that the noise power fluctuations are also amplified by the same amount.**
- **The amplifier adds its own noise ! This is usually much greater than the signal noise we are trying to detect. Radio astronomers therefore need low noise amplifiers.**

- **For the Effelsberg telescope at 5 GHz the voltage noise after amplification (and after other spurious sources of noise have crept in) is equivalent to adding a further 30 K before amplification !**

  The average noise power is now α (T_a + 30) K

  The fluctuations are now α (T_a + 30)/$\sqrt(tb)$ K

  The signal-to-noise ratio is degraded by a factor T_a/(T_a + 30)

- **Further electronic stages generally do not add significantly to the (already amplified) noise. The sum total of all the noise contributions is referred to as the system temperature, T_{sys}.**

- **The quantity T_{sys}/g is a measure of the combined sensitivity performance of the antenna and the receiving system and is called the system equivalent flux density or SEFD.**

- **For most observing frequencies, further electronic manipulation is more conveniently performed at lower frequencies. We use heterodyne systems in which the RF signal is mixed with a pure frequency tone, the local oscillator, LO.**

  The output difference frequency is called the intermediate frequency or IF, typically centred around $\sim$ 150 MHz or $\sim$ 500 MHz.

- **The noise characteristics of the IF signal preserve those of the input RF signal, but contain a phase-shift due to the phase of the LO signal.**

- **The IF voltage signals can be transmitted over long distances via low-loss cables, e.g. from the focus cabin to the observing room on the ground. From here on the processing depends strongly on the type of observation being made.**

- **For single dish observations one may simply wish to measure the source average noise power. This is performed by passing the IF signal into a square-law detector.**

  The output measures the mean total noise power with fluctuations producing a "thermal noise error"(in Jy) given by:

  $\sim \mathbf{SEFD}/\sqrt{(tb)}$

  As the output is the sum of source and other contributions, however, it is necessary to compare an on-source measurement with an off-source measurement.

  But this is not the subject of this school !

11 Signals for Interferometry

- **Leading into the next lecture....**
- **For interferometry one wishes to cause interference between the IF voltage signals from 2 or more antennas. This mimics in electronics the results one would have by causing interference between the radio waves arriving at those antennas.**

  The IF signals from different antennas are transported to a correlator, using cables, waveguides (VLA), radio-links (MERLIN) or optical fibres.
- **Note that signals from a common noise source can only produce interference provided that their path difference is less than 1/b**

- **For very robust transmission it is necessary to digitize the signal using samplers. These sample the signal at the Nyquist rate ($1/2b$) and represent it at various levels of crudity: 1-bit, 2-bit,.....**

  For very long distances between the antennas (VLBI) one can then record the signals at each antenna on magnetic tape or disk, together with a time stamp to identify each bit. This permits off-line replay of the signals from the various antennas after they have been transported to the correlator. (This can be by air, sea, truck or internet !)

  Do not ask where the photons are.....

- **Note that for dual-polarization observations the whole amplification, mixing and digitization chain will be duplicated, resulting in 2 signals (e.g LHC and RHC polarization) which need to be correlated with their counterparts from other antennas.**

  Sometimes the IF signal band is divided into further sub-bands for separate digitization and correlation. These are loosely referred to as separate "IFs" in the AIPS world.

12 Radio disturbances

- **radio interference:** Radio source signals are extraordinarily weak compared with most man-made signals, and cannot normally be detected when the latter are present in the band. Radio astronomers are constrained to observe in narrow bands more-or-less reserved for them by international agreement.

- the troposphere causes:

  absorption of the radio signal, increasing at higher frequencies.

  corresponding thermal emission creating an unwanted addition to T_a

  an extra path delay of $\sim$ 2 m at the zenith with spatial and temporal variations

- the ionosphere produces:

  an extra (highly unpredictable) path delay proportional to λ^2

  a barrier for radio waves at frequencies below $\sim$ 10 MHz

  Faraday rotation for frequencies below $\sim$ 1 GHz