RADIO ASTRONOMY: The Very Large Array (VLA)

Radio telescope system situated on the plains of San Agustin near Socorro, New Mexico, U.S, the most powerful radio telescope in the world, operated by the National Radio Astronomy Observatory.

Patrizia Bussatori

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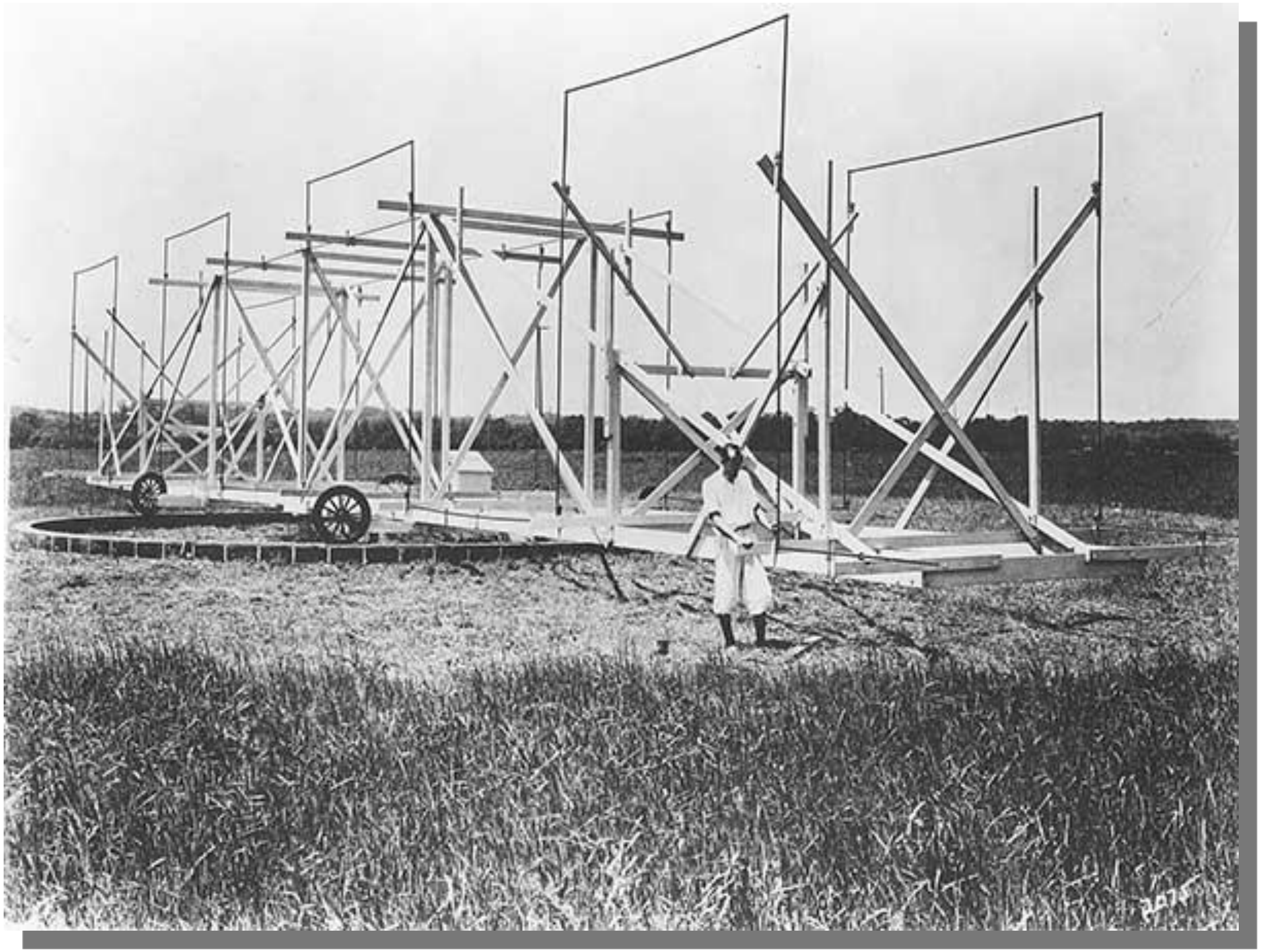
Dipartimento di Fisica e Astronomia "Galileo Galilei"

NRAO National Radio Astronomy Observatory

Brief history



Karl Jansky built an *antenna* that could be rotated on the wheels of a Model T so that he could track down sources of radio static, inventing radio astronomy in the process.

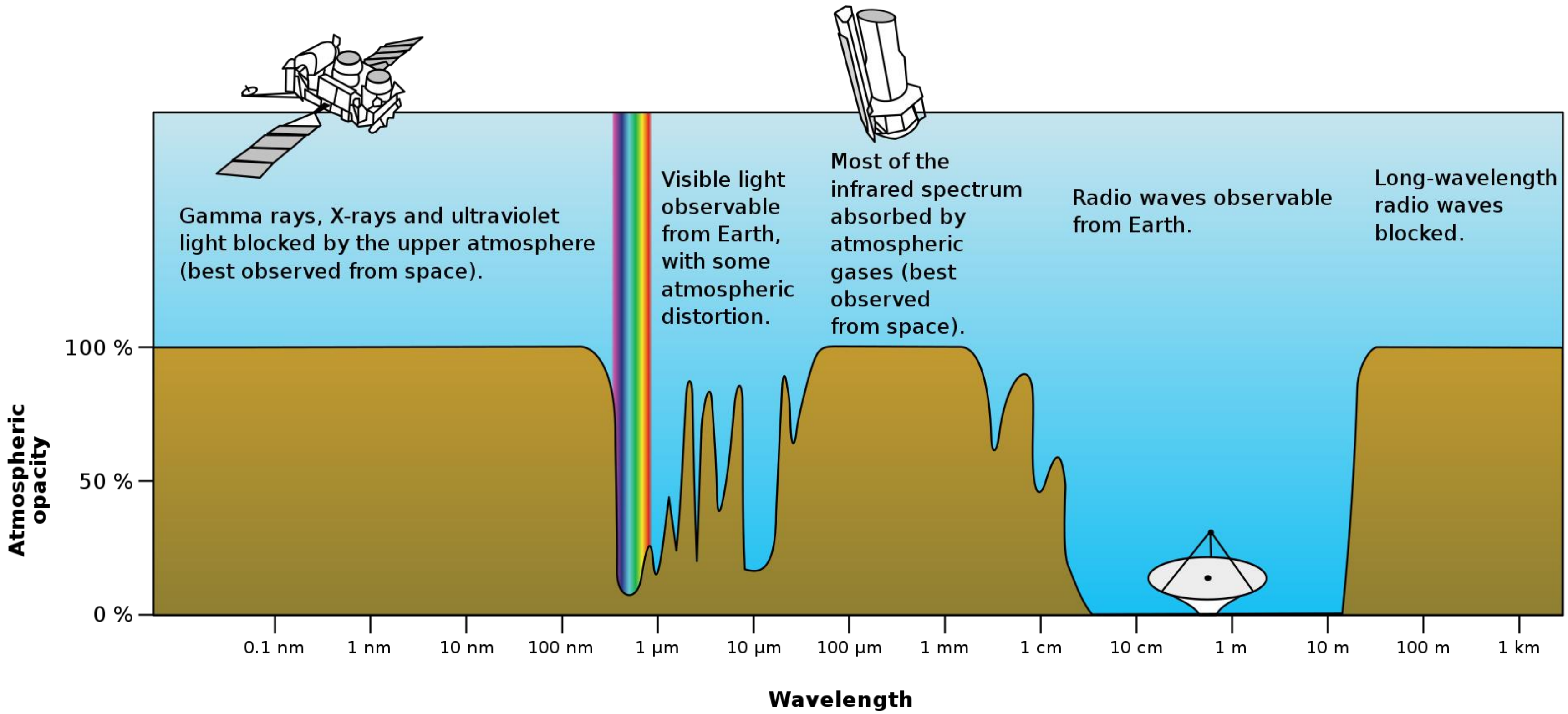
In 1933 he found a source with a cycle of 23 hours and 56 minutes.

Sagitarius A

Radio window

Radio window is a range of frequencies of electromagnetic radiation that penetrate the Earth's atmosphere

1 THz (λ ≈ 0.3 mm) – 15 MHz (λ ≈ 20 m)



Electromagnetic power huddled up in bandwidth $\delta\nu$ from solid angle $\delta\Omega$ intercepted by surface δA is:

$$\boldsymbol{\delta W = I_\nu \, \delta\Omega \, \delta A \, \delta\nu}$$

SURFACE BRIGHTNESS I_ν
$[W\, m^{-2}\, Hz^{-1}\, sr^{-1}]$

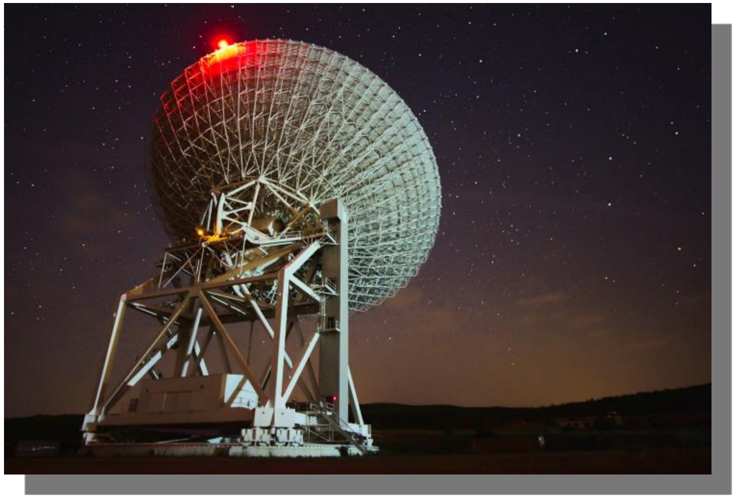
Distance independent

$$\boldsymbol{S_\nu = \int I_\nu \, d\Omega = \frac{L_\nu}{4\,\pi\, d^2}}$$

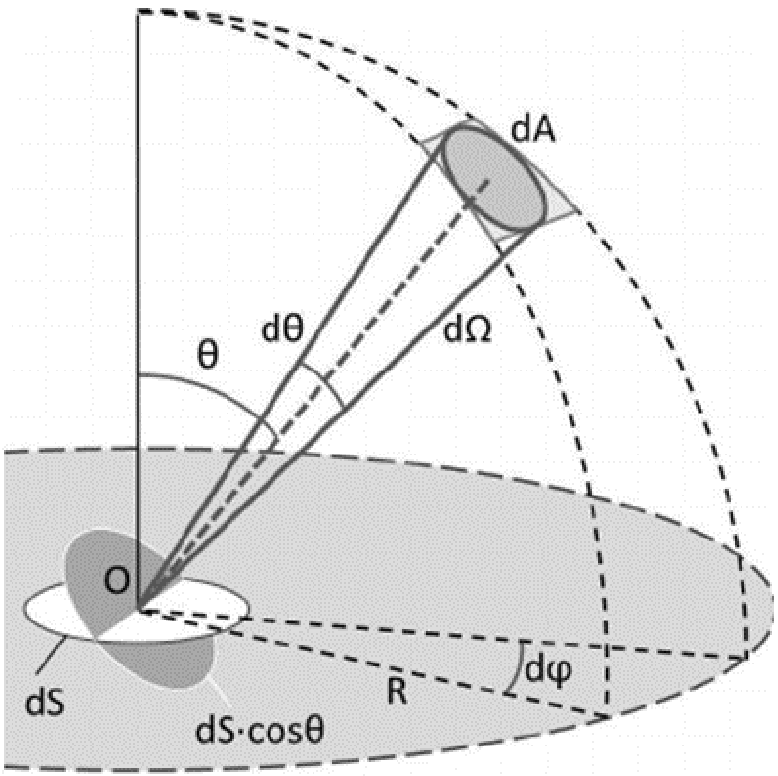
FLUX DENSITY
$[W\, m^{-2}\, Hz^{-1}]$

Distance dependent

$$\boldsymbol{1\, Jy = 10^{-26}\, W\, m^{-2}\, Hz^{-1} = 10^{-23}\, erg\, s^{-1}\, cm^{-2}\, Hz^{-1}}$$



On the contrary *surface brightness* is position dependent indeed, given the angles θ and φ, I_ν is given by:



$$I_\nu(\theta,\varphi) = \frac{2\,k\,\nu^2\,T(\theta,\varphi)}{c^2}$$

So, going back to the *flux density*, S_ν can be described as:

$$S_\nu = \int I_\nu(\theta,\varphi)\,d\Omega = \frac{2k\nu^2}{c^2}\int T(\theta,\varphi)\,d\Omega$$

In general, a radio telescope maps the **temperature distribution** of the sky so we can define the **brightness temperature**. The brightness temperature T_B of a source is defined as the temperature of a *blackbody with the same surface brightness at a given frequency*:

$$\boldsymbol{I_\nu = \frac{2k\nu^2 T_B}{c^2}} \quad \Rightarrow \quad \boldsymbol{S_\nu = \int I_\nu \, d\Omega = \frac{2k\nu^2}{c^2} \int T_B \, d\Omega}$$

Another useful quantity is the **spectral energy density per solid angle**:

$$\boldsymbol{u_\nu = \frac{1}{c} I_\nu} \quad \Rightarrow \quad \boldsymbol{u_\nu = \frac{1}{c} \int_{4\pi} I_\nu \, d\Omega}$$

INTEGRATING OVER THE SPHERE

Given the linear **absorption coefficient** k_ν (*independent* of the intensity I_ν) and the **emissivity coefficient** ϵ_ν (that can depend on I_ν according to the environment), we can define the **equation of transfer**:

$$\boxed{\frac{d\boldsymbol{I_\nu}}{d\boldsymbol{s}} = -\boldsymbol{k_\nu}\,\boldsymbol{I_\nu} + \boldsymbol{\epsilon_\nu}}$$

1) ***Emission only*** - $k_\nu = 0$

$$\boxed{I_\nu(s) = I_\nu(s_0) + \int_{s_0}^{s} \epsilon_\nu(s) ds}$$

2) ***Absorption only*** - $\epsilon_\nu = 0$

$$\boxed{I_\nu(s) = I_\nu(s_0)\, exp\,(\int_{s_0}^{s} k_\nu(s) ds\,)}$$

3) ***Thermodynamic equilibrium (TE)***

$$I_\nu(s) = B_\nu(T) = \frac{\epsilon_\nu}{k_\nu}$$

$$\boldsymbol{B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}}$$

PLANCK FUNCTION

4) ***Local thermodynamic equilibrium (LTE)***

$$\tau_\nu(s) = \int_{s_0}^{s} k_\nu(s)\,ds$$

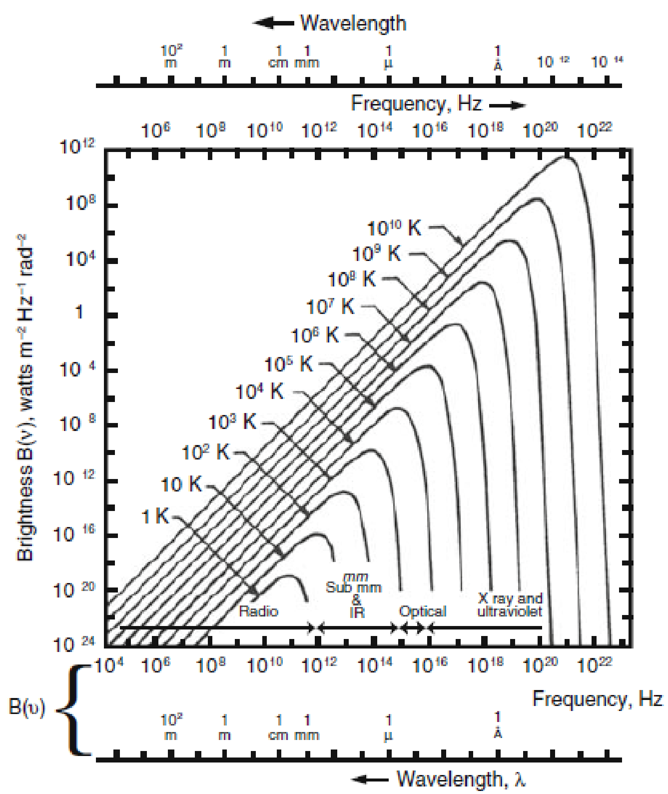
$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} B_\nu\big(T(\tau)\big)e^{-\tau}\,d\tau$$

$$\boldsymbol{I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T)\left(1 - e^{-\tau_\nu(s)}\right)}$$

The spectral distribution of the radiation of a black body in thermodynamic equilibrium is given by the **Planck law**:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\,\frac{1}{e^{h\nu/kT}-1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\,\frac{1}{e^{hc/kT\lambda}-1}$$



$$B(T) = \frac{2h}{c^2}\int_0^\infty \frac{\nu^3}{e^{h\nu/kT}-1} = \sigma\,T^4$$

$$\frac{\nu_{max}}{GHz} = 58{,}789\,\frac{T}{K}$$

$$\frac{\lambda_{max}}{cm}\frac{T}{K} = 0{,}28978$$

- $h\nu \ll kT$: **Rayleigh-Jeans Law**

$$e^{\frac{h\nu}{kT}} \sim 1 + \frac{h\nu}{kT} + \ \ldots$$

$$\boxed{B_{RJ}(\nu, T) = \frac{2\nu^2}{c^2} kT}$$

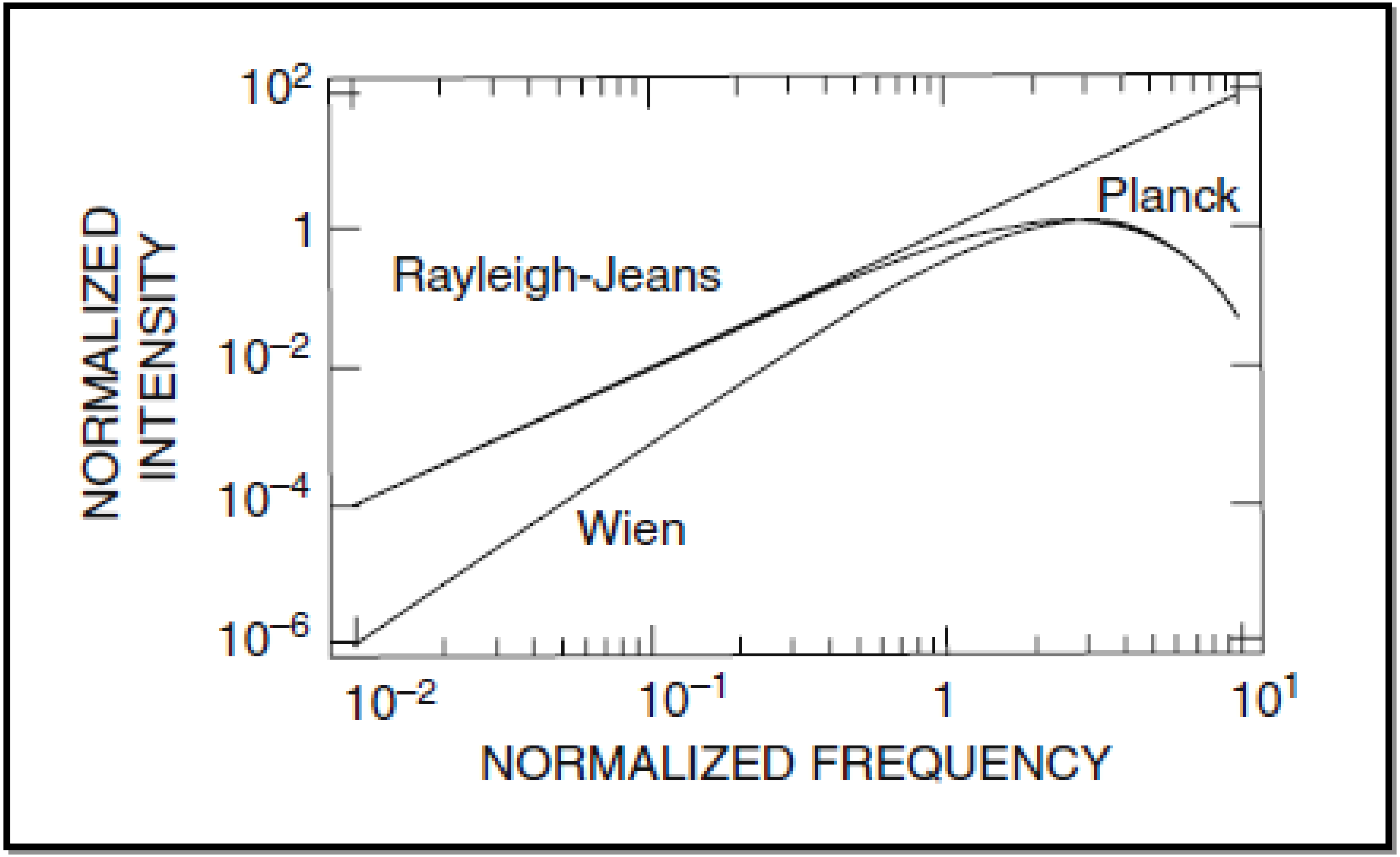
$$\boxed{\frac{\nu}{GHz} \ll 20{,}84 \frac{T}{K}}$$

- ~~$h\nu \gg kT$: **Wien's Law**~~

$$\cancel{e^{\frac{h\nu}{kT}} \gg 1}$$

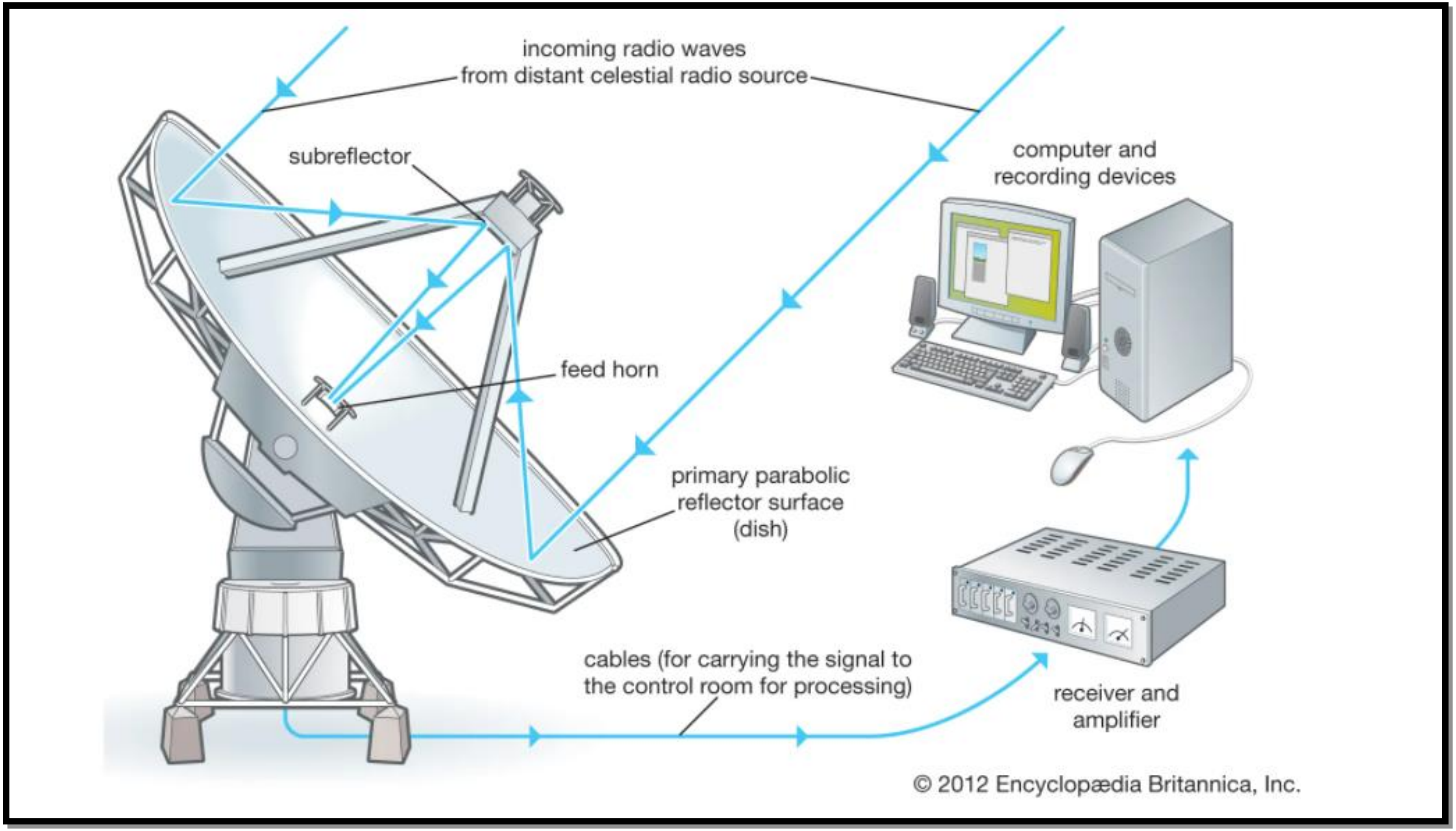
$$\cancel{\boxed{B_W(\nu, T) = \frac{2h\nu^3}{c^2} e^{h\nu/kT}}}$$

$$\boxed{T_b = \frac{c^2}{2k} \frac{1}{\nu^2} I_\nu = \frac{\lambda^2}{2k} I_\nu}$$


Planck
Rayleigh-Jeans
Wien
NORMALIZED INTENSITY
NORMALIZED FREQUENCY
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-2}
10^{-1}
1
10^1

How works a radio telescope

What does a radio telescope detect?



How works a radio telescope

What does a radio telescope detect?

Consider a radio telescope of *effective area* A_e. This telescope receives **power** P_{rec} per unit frequency from an *unpolarized source* (it is only sensitive to one mode of polarization):

$$\boxed{\boldsymbol{P_{rec} = \frac{1}{2} I_\nu A_e \delta\Omega}}$$

However, it is sensitive to radiation from more than one direction with relative sensitivity given by the **normalized antenna pattern** $P_N(\theta, \varphi)$. Then the power received is given by:

$$\boxed{\boldsymbol{P_{rec} = \frac{1}{2} A_e \int_{4\pi} I_\nu(\theta, \varphi)\, P_N(\theta, \varphi) d\Omega}}$$

How works a radio telescope

What does a radio telescope detect?

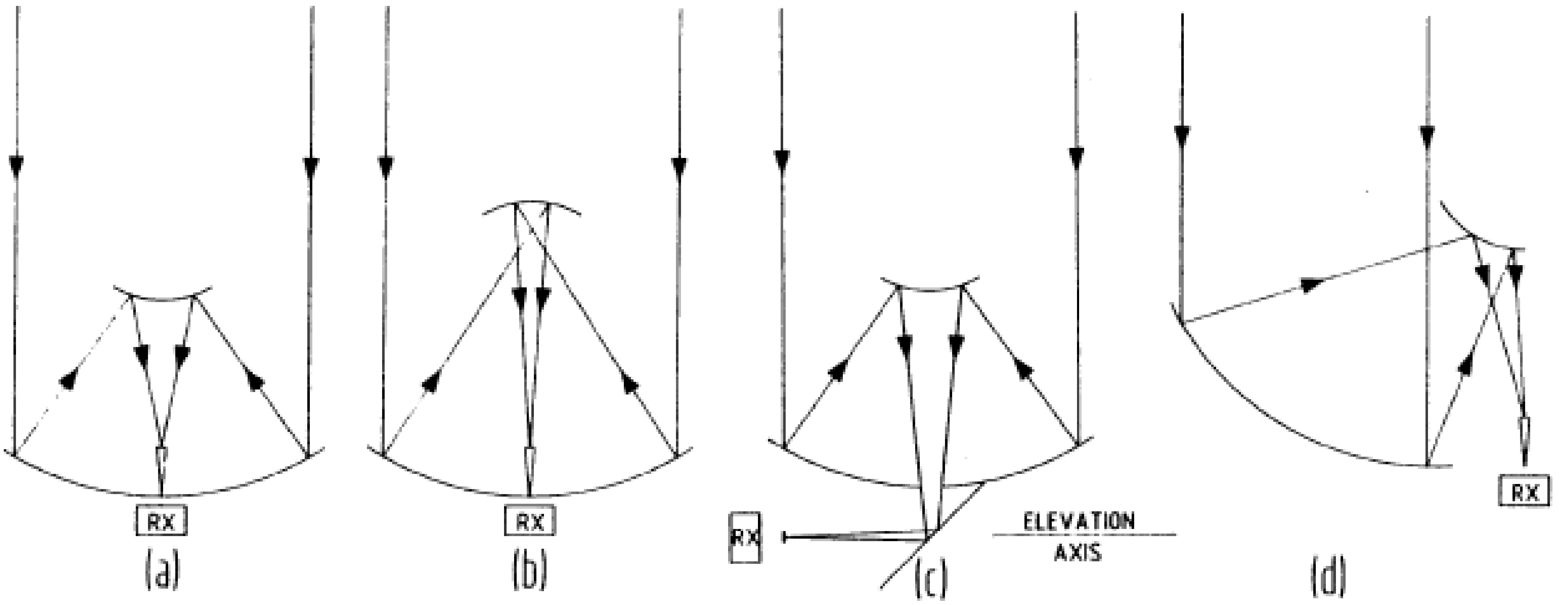


Fig. 7.6 The geometry of (a) Cassegrain, (b) Gregory, (c) Nasmyth and (d) offset Cassegrain systems

- **Normalized power pattern**:

$$P_n(\theta,\varphi) = \frac{1}{P_{max}} P(\theta,\varphi)$$

- **Directive gain**:

$$G(\theta,\varphi) = \frac{4\pi P(\theta,\varphi)}{\iint P(\theta,\varphi) d\Omega}$$

- **Beam solid angle**:

$$\Omega_A = \iint_{4\pi} P_n(\theta,\varphi) d\Omega$$

- **Main beam solid angle**:

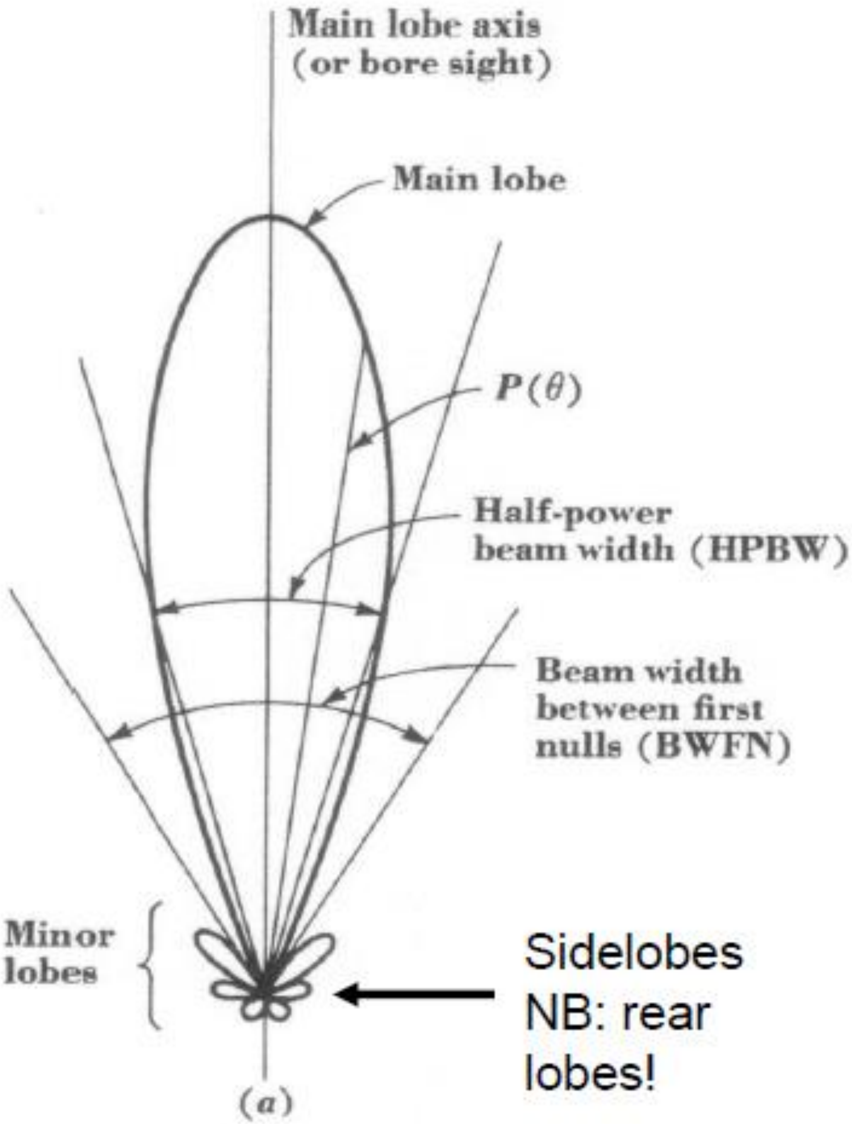
$$\Omega_{MB} = \iint_{main\ beam} P_n(\theta, \varphi)\, d\Omega$$

- **Main beam efficiency**:

$$\eta_B = \frac{\Omega_{MB}}{\Omega_A}$$

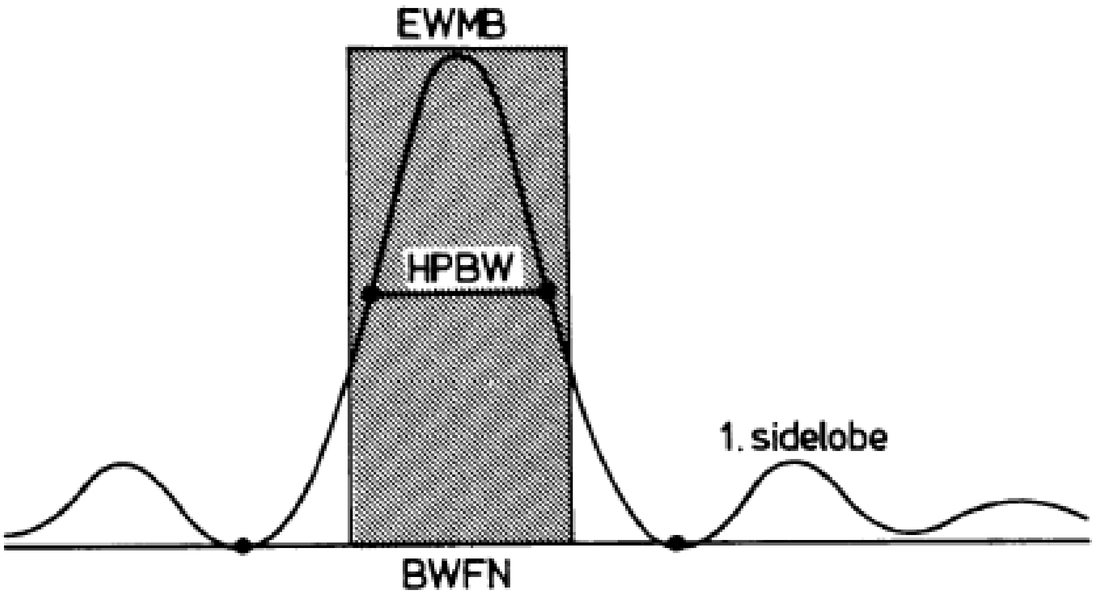
- **Maximum directive gain**:

$$D = G_{max} = \frac{4\pi}{\Omega_A}$$



Sidelobes
NB: rear
lobes!

- **HPBW**: half power beam width;
- **FWHP**: full width to half power;
- **BWFN**: beam width between first nulls;
- **EWMB**: equivalent width of the main beam:



$$EWMB = \sqrt{\frac{12}{\pi}\,\Omega_{MB}}$$

- **Effective aperture**:

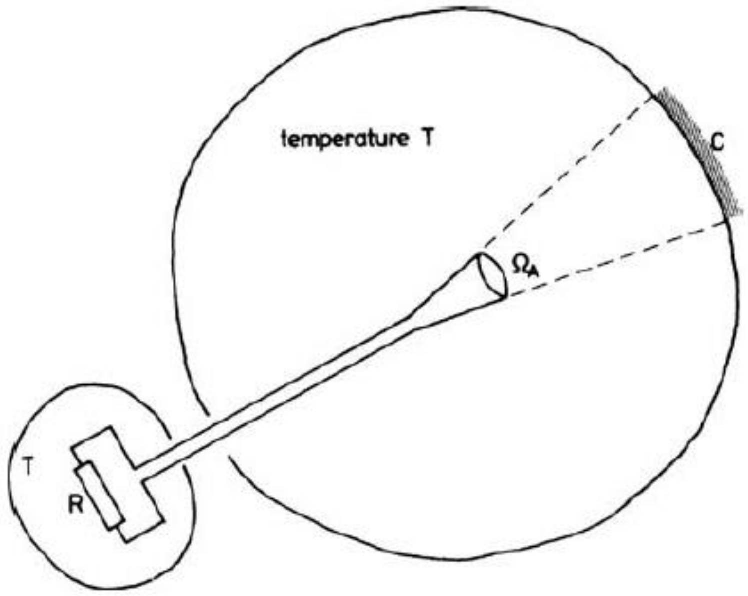
$$A_e = \frac{P_e}{|S|} = \eta_A A_g$$

$$D = G_{max} = \frac{4\pi A_e}{\lambda^2}$$

$$A_e\,\Omega_A = \lambda^2$$

According to the *Rayleigh-Jeans relation*, the surface C radiates with the **intensity** $[W\ m^{-2}\ Hz^{-1}]$:

$$I_\nu = \frac{2kT}{\lambda^2}\,\Delta\nu$$



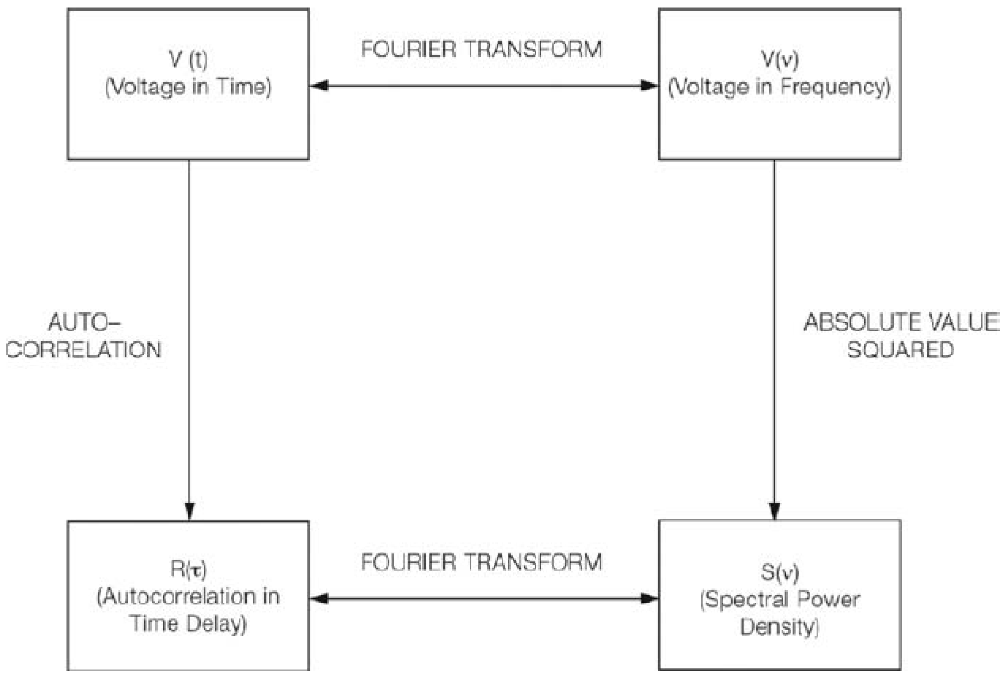
Given a normalized power pattern $P_n(\theta,\varphi)$ and a brightness distribution $B_\nu(\theta,\varphi)$. Then at the output terminals of the antenna, the total power per unit bandwidth is:

$$P_\nu = \frac{1}{2} A_e \iint B_\nu(\theta,\varphi) P_n(\theta,\varphi) d\Omega$$

BUT

$$P_\nu = k\, T_A$$

$$T_A(\theta_0,\varphi_0) = \frac{\int T_b(\theta,\varphi) P_n(\theta-\theta_0,\varphi-\varphi_0)\, sin\theta\; d\theta\; d\varphi}{\int P_n(\theta,\varphi)\; d\Omega}$$



The output power detected is the sum of the *power of antenna* and the *power* introduced by the *system* itself:

$$\boldsymbol{P_{out} = P_A + P_{sys}}$$

Since the power is *proportional to the temperature*, the previous relation can be expressed also as:

$$\boldsymbol{T_{out} = T_A + T_{sys}}$$

$$T_{sys} = T_{bg} + T_{sky} + T_{spill} + T_{loss} + T_{cal} + T_{rx}$$

VLA Construction Timeline

1972 August – VLA approved by Congress
1973 April – Construction begins on VLA
1975 September 22 – First antenna put in place
1976 February 18 – First interferometric observation
1980 – Formal dedication of the VLA

FIG. 3

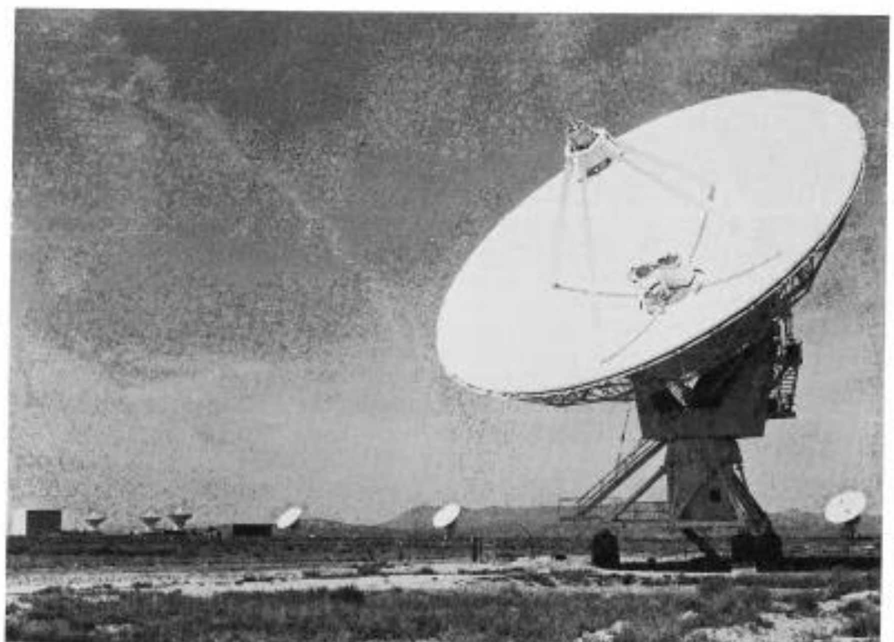


FIG. 5

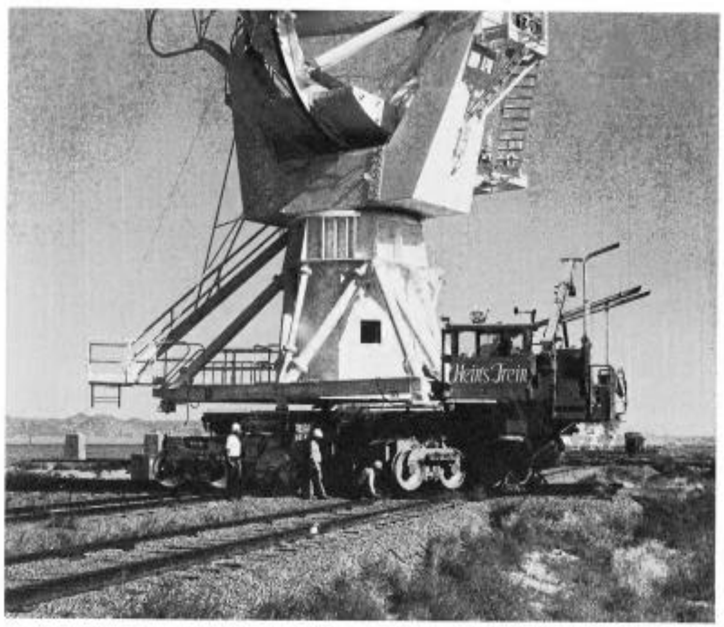


FIG. 3.—View to the west from the vicinity of E12. The Control Building can be seen to the left of center and the Antenna Assembly Building at the extreme left.

FIG. 5.—Transporter with an antenna making a turn from the spur track at N4 to the main track. This operation involves lowering stabilizing jacks and, for one truck at at time, raising the wheels and turning the truck into alignment with the perpendicular track. The locomotive in the distance at the right is used to haul ballast for track construction.

Thompson, A. R. ; Clark, B. G. ; Wade, C. M. ; Napier, P. - 1980

Very Large Array (VLA)

Basics

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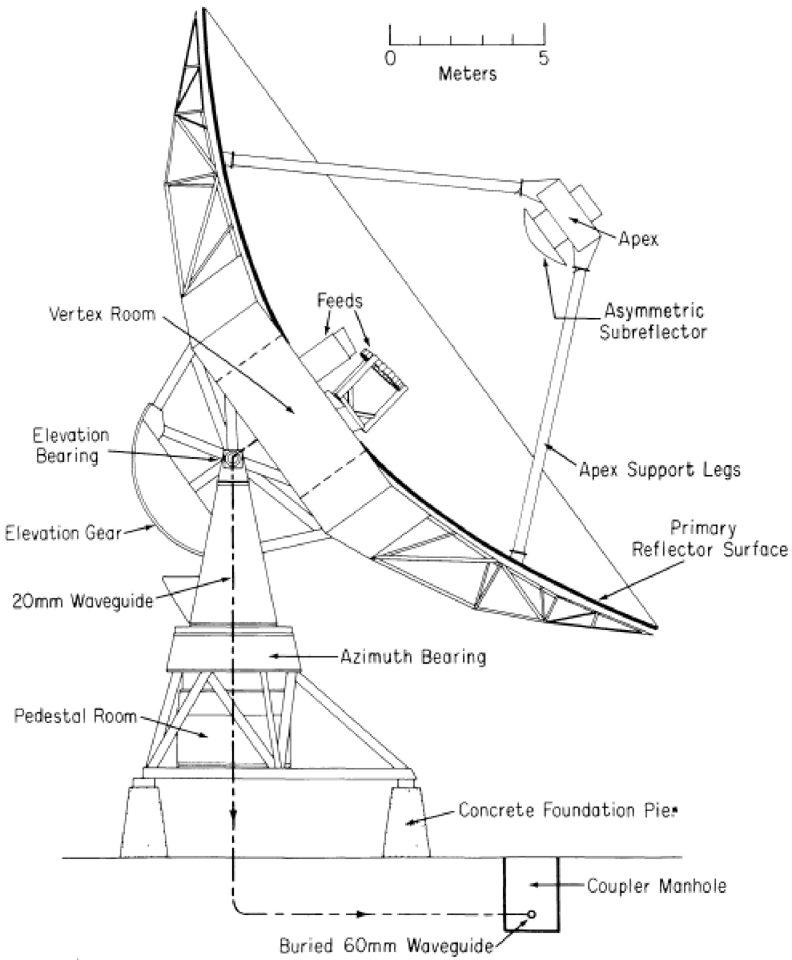

FIG. 6.—Principal structural features of an antenna. The lower feed is for the 18–21 cm band and the rectangular structure above it contains the other three feeds.

VLA OBSERVING BANDS

VLA Band	Wavelength	Primary[a] Radio-Astronomy Allocation	Atomic and Molecular Lines Within VLA Band[b]
1340–1730 MHz (L)[c]	18–21 cm	1400–1427 MHz	CH_2CHCN, vinyl cyanide, 1372MHz; H, neutral hydrogen, 1420.4 MHz; NH_2CHO, formamide, 1538–1541 MHz; $HCOOCH_3$, methyl formate, 1610 MHz; OH, hydroxyl radical, 1612, 1665, 1667, 1720 MHz; HCOOH, formic acid, 1639 MHz
4500–5000 MHz (C)	6 cm	4990–5000 MHz	H_2CO, formaldehyde, 4.592–4.593, 4.829 GHz; NH_2CHO formamide, 4.617–4.620 GHz; OH, hydroxyl radical, 4.660–4.766 GHz; HCOOH, formic acid, 4.916 GHz
14.4–15.4 GHz (U)	2 cm	15.35–15.40 GHz	H_2CO, formaldehyde, 14.488 GHz; HC_9N, cyanooctatetrayne, 14.526 GHz; HC_7N, cyanohexatriyne, 14.664 GHz
22.0–24.0 GHz (K)	1.3 cm	23.6–24.0 GHz	H_2O, water, 22.235 GHz; NH_3, ammonia, 22.653–23.872 GHz; HC_7N, cyanohexatriyene 23.688 GHz; OH, hydroxyl radical, 23.818, 23.827 GHz; HC_5N, cyanobutadiyne, 23.964 GHz

[a] Other bands allocated to radio astronomy on a secondary basis, or with footnote protection, also occur within the VLA bands.
[b] From Lovas, Snyder, and Johnson 1979.
[c] Band designation letter used in the VLA.

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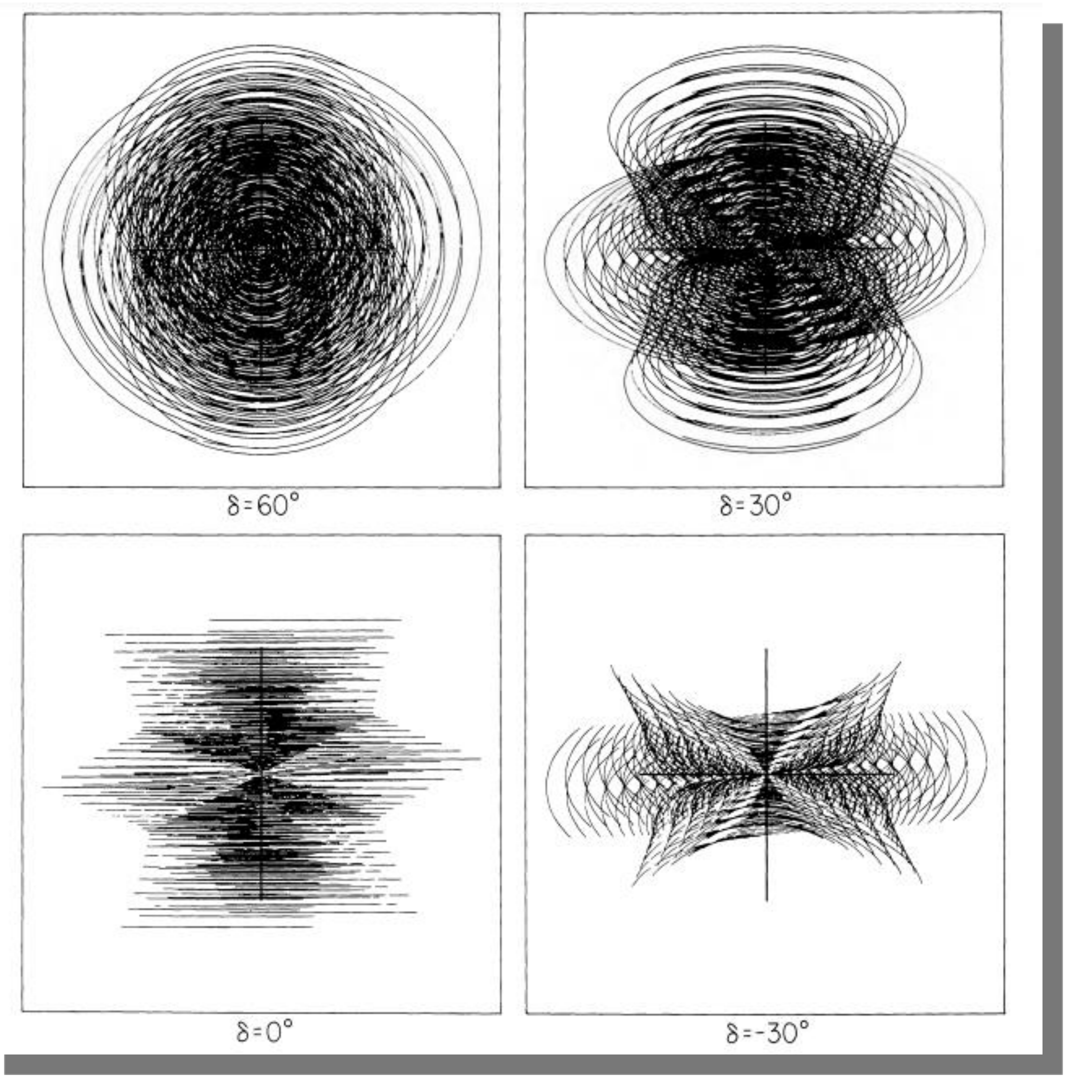
Very Large Array (VLA)

Basics



Examples of the *transfer function* of the array for four declinations. Except for minor details these apply to all four antenna configurations. The hour-angle coverage corresponds to the full range of the source above *29° elevation* (±6h) for *60° declination* and above 20° elevation for the other three cases. Observations can be made down to 8° elevation. In the usual terminology the abscissa in these diagrams is the *u-axis* and the ordinate the *v-axis* (measured in wavelengths).

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Very Large Array (VLA)

Basics

MAIN PARAMETERS	
Number of antennas	28
Dish size	25 meters
Latitude	34°04'43.497" North
Longitude	107°37'03.819" West
Dish surface	Aluminum panels accurate up to 5 mm
Frequencies	From 1.0 GHz to 50 GHz
Resolution	0.2 arcseconds to 0.04 arcseconds
Reconfigurable array	North arm is 17,7 km long, two other arms are 20,9 km long
A configuration size	36,4 km across
B configuration size	11,4 km across
C configuration size	3,4 km across
D configuration size	1 km across

Web-site:

https://public.nrao.edu/telescopes/vla/

Web-cam:

https://public.nrao.edu/vla-webcam/

Cosmic radio waves are billions of a billion times fainter than radio waves used on Earth! So, radio telescopes must be located where these faint sources can be observed!

PROBLEM! Water molecules *distort* the radio waves passing through them and also give off their own radio waves that *interfere* with observations at certain frequencies

SOLUTION! We create radio telescopes in *deserts*!

Plains of San Augustin in New Mexico

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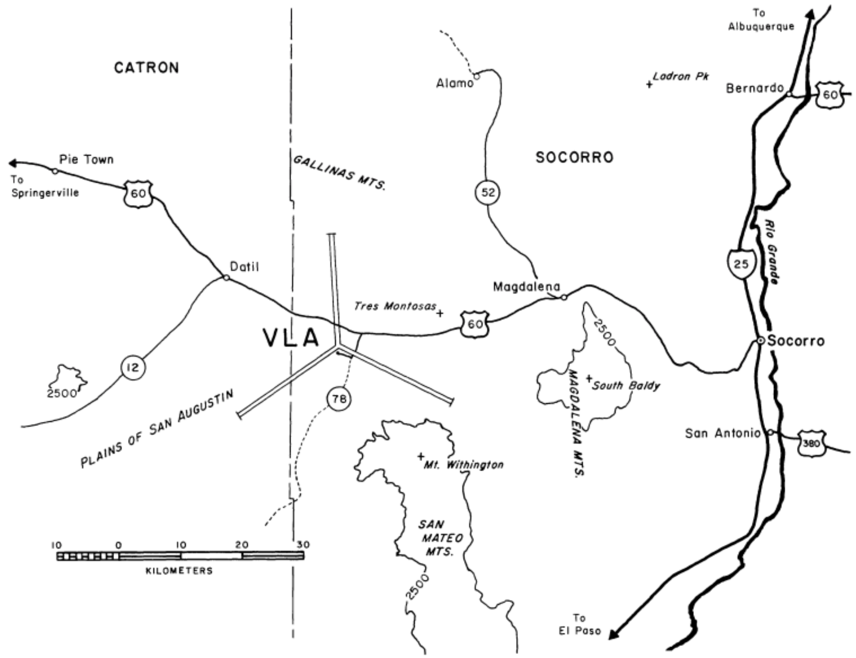

FIG. 2.—Geographical features in the vicinity of the VLA Site. The 2500 m elevation contour is shown, and north is toward the top.

Each antenna:
- **25-meter** dish
- **8 receivers** tucked inside
- **altitude-azimuth** mount

They are positioned in «**Y**» **schape**. VLA's unique shape gives *three long arms* of *nine* telescopes each. It also gives us the flexibility of stretching the arms when we need to *zoom* in for more *detail*.

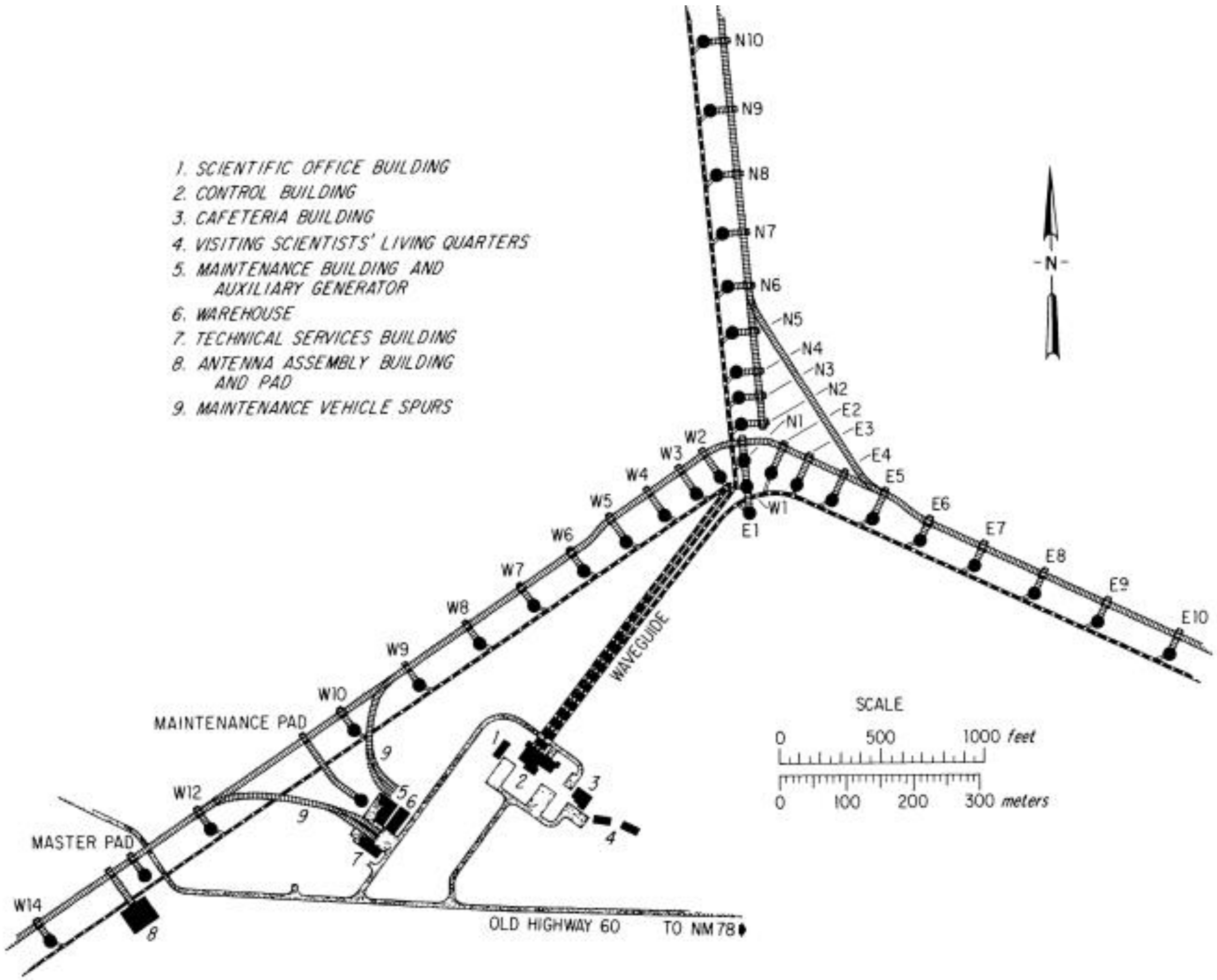

FIG. 4.—Rail track, antenna stations, buildings, and roads near the center of the array. The central electronics and the computers are located in the Control Building.

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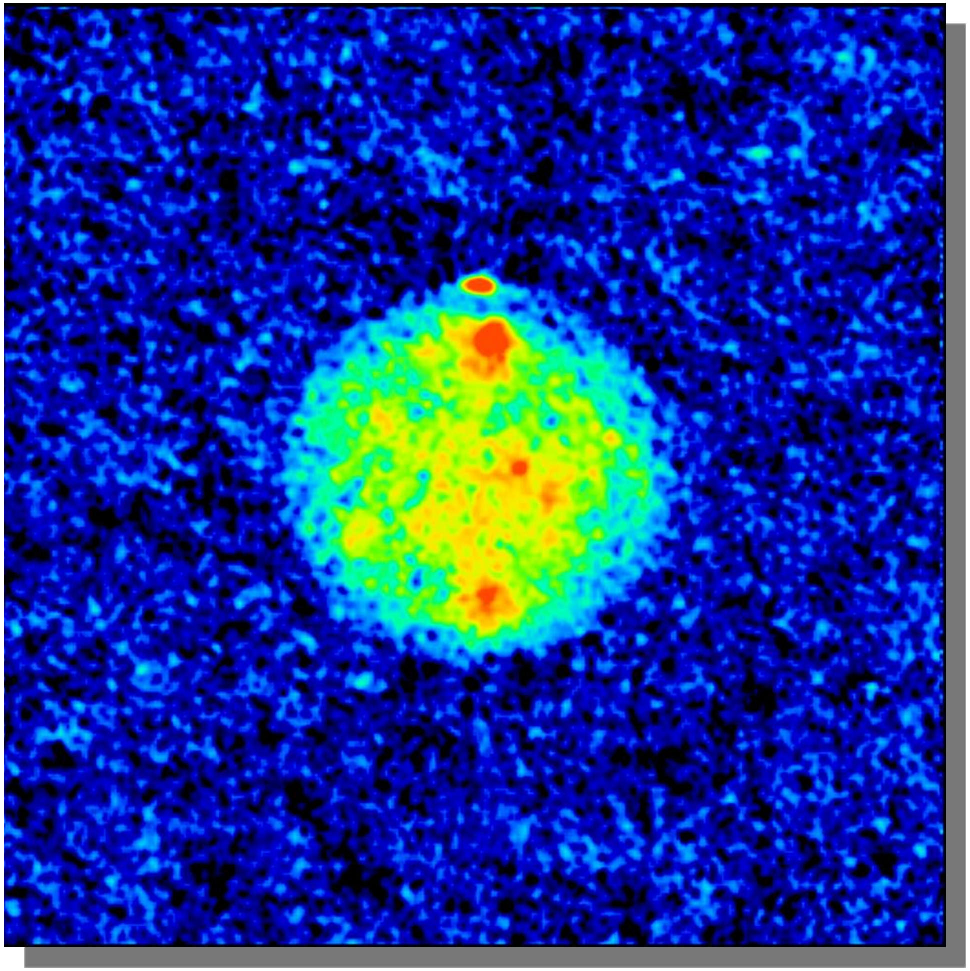
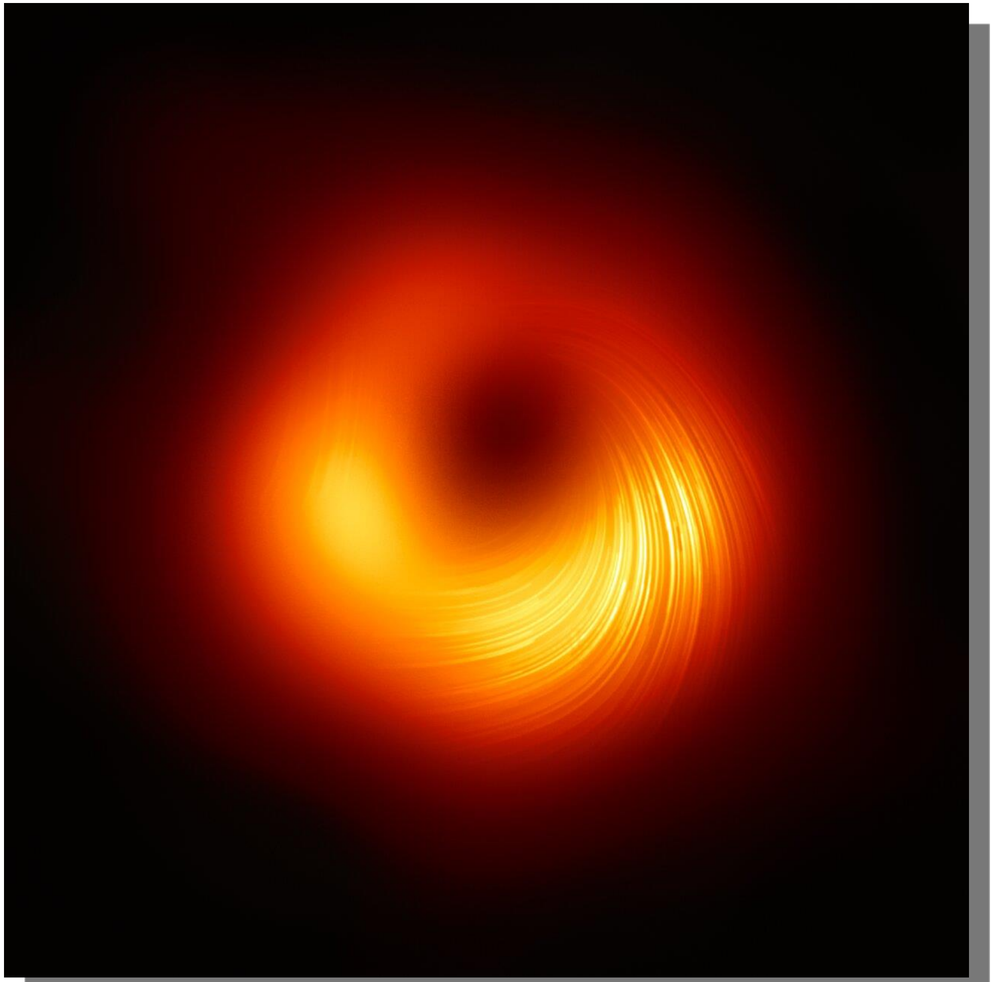
Ice on Mercury



This image of Mercury was the result of a *radar experiment* using the NASA JPL/DSN 70-m antenna in Goldstone, CA, as the transmitter, and the Very Large Array (VLA) as the receiver. *Red areas are areas of high radar reflectivity*, which can either be a result of surface and near-surface composition, or surface roughness. The *north pole is the brightest region*, an indication of the presence of *significant amounts of water ice*. A similar region has been detected at the south polar regions.

Supermassive Black Hole



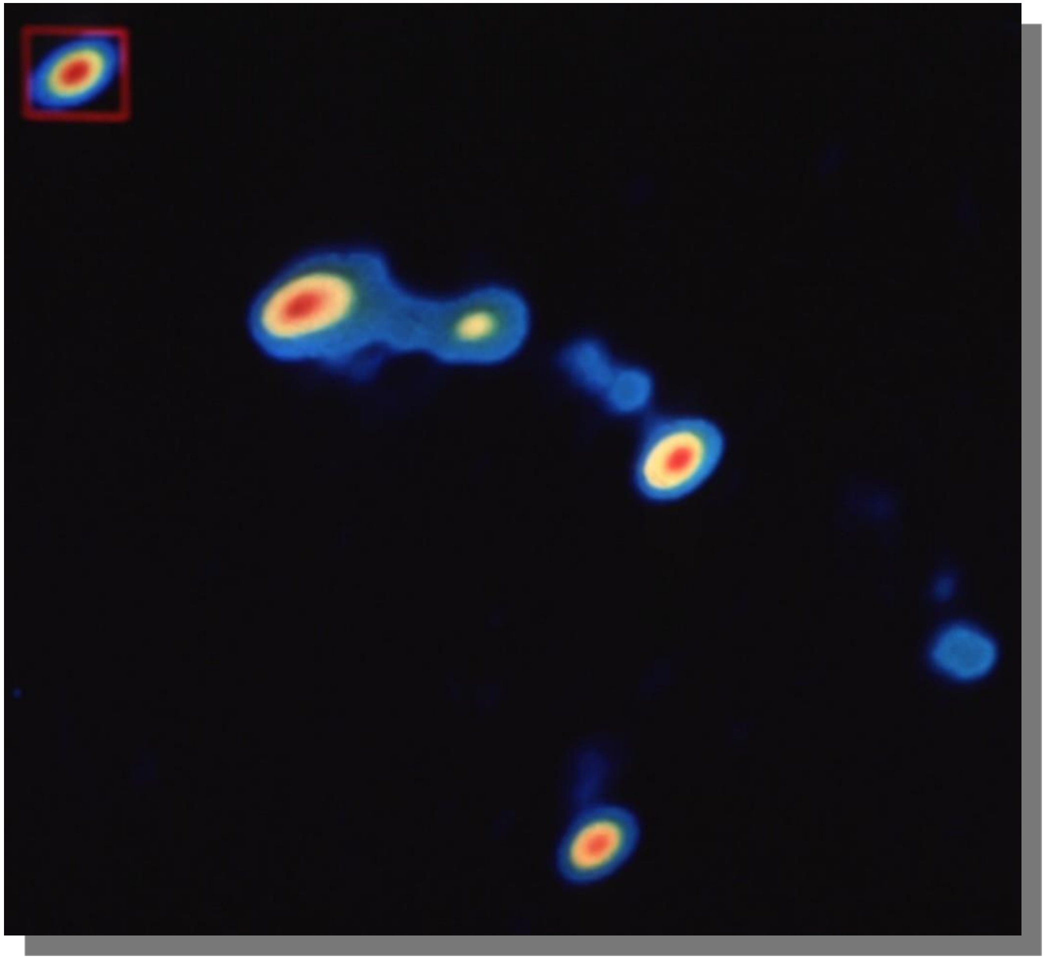
The story of how supermassive black holes were found began with the investigation by Maarten Schmidt of the *radio source 3C 273* in 1963. Initially this was thought to be a star, but the spectrum proved puzzling.

In 2019, the *Event Horizon Telescope (EHT)* collaboration produced the first-ever image of a black hole, which lies at the center of the M87. It has been obtained by *planet-scale array of ground-based* radio telescopes.

Center of our Galaxy

The center of our Milky Way Galaxy is anchored by a *black hole* that is nearly 5 million times the mass of our Sun. Surrounding it is a chaotic city of stars, gas, and dust that we call *Sagittarius A*. It has been the first radio source discovered at the beginning of 1933.

Einstein Rings



The first gravitational lens was discovered in *1979*, when two quasars were discovered very close to each other in the sky and with *similar distances and spectra*. The two quasars were actually the same object whose light had been split into two paths by the *gravitational influence of an intervening galaxy*. Optical observers discovered it but the VLA quickly was used to confirm the discovery.

Thanks for your attention!