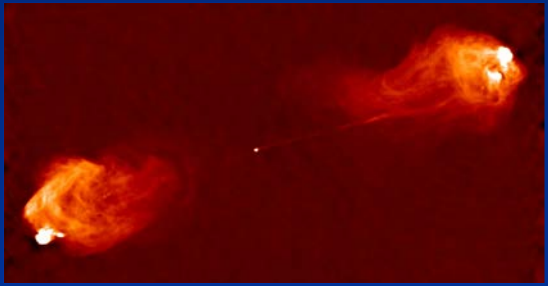
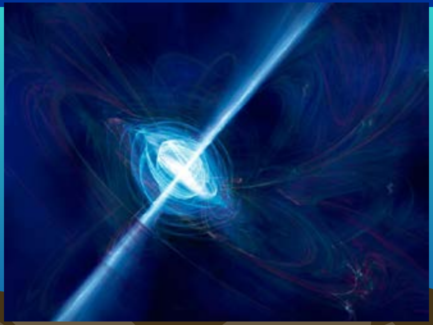
Radio Astronomy

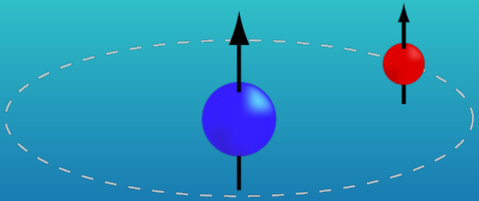
PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg







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Tentative Schedule:
16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
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20.11. Instruments – line detection (HB)
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04.12. Line radiation (HB)
11.12. Radiation transfer (HL)
18.12. Buffer ...
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

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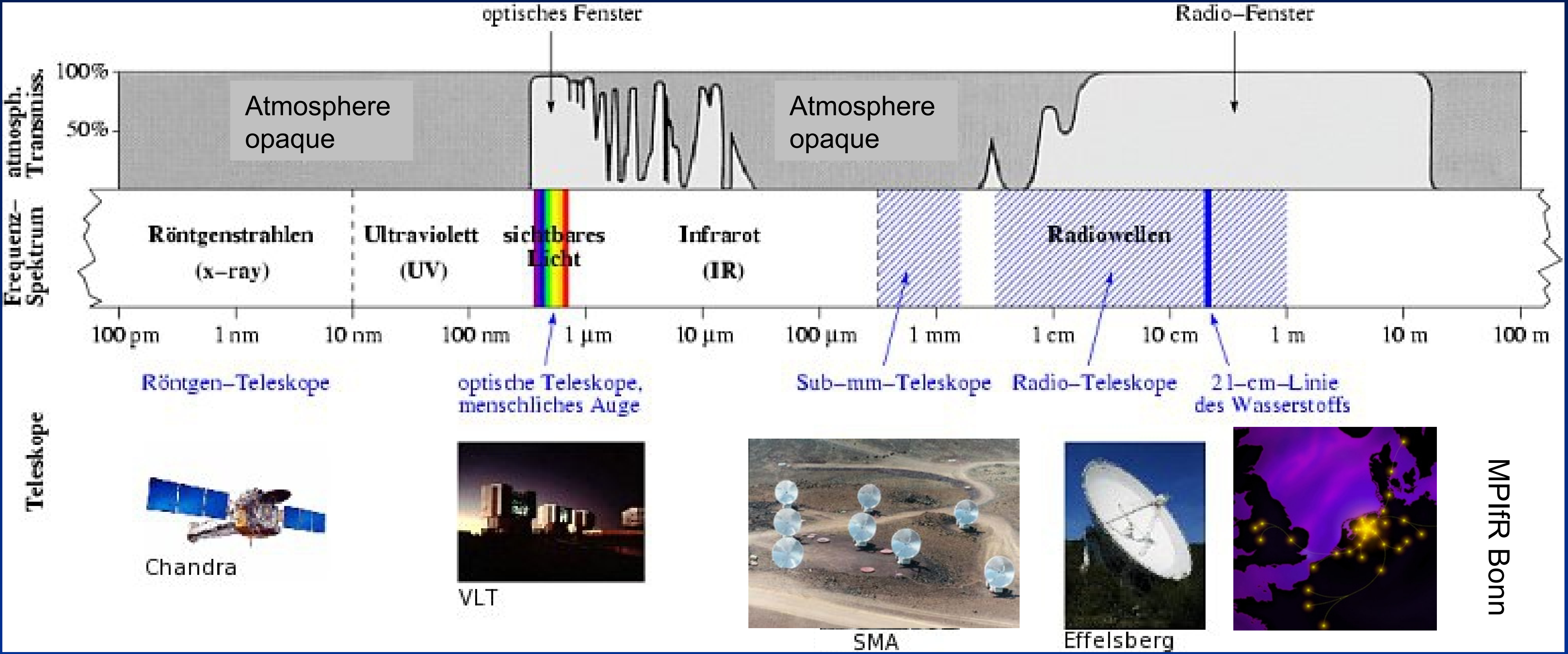
Topics for today:

- telescope sites / atmospheric conditions

- spatial resolution and telescope beam

- telescope designs and examples

Radio signals and the Earth atmosphere



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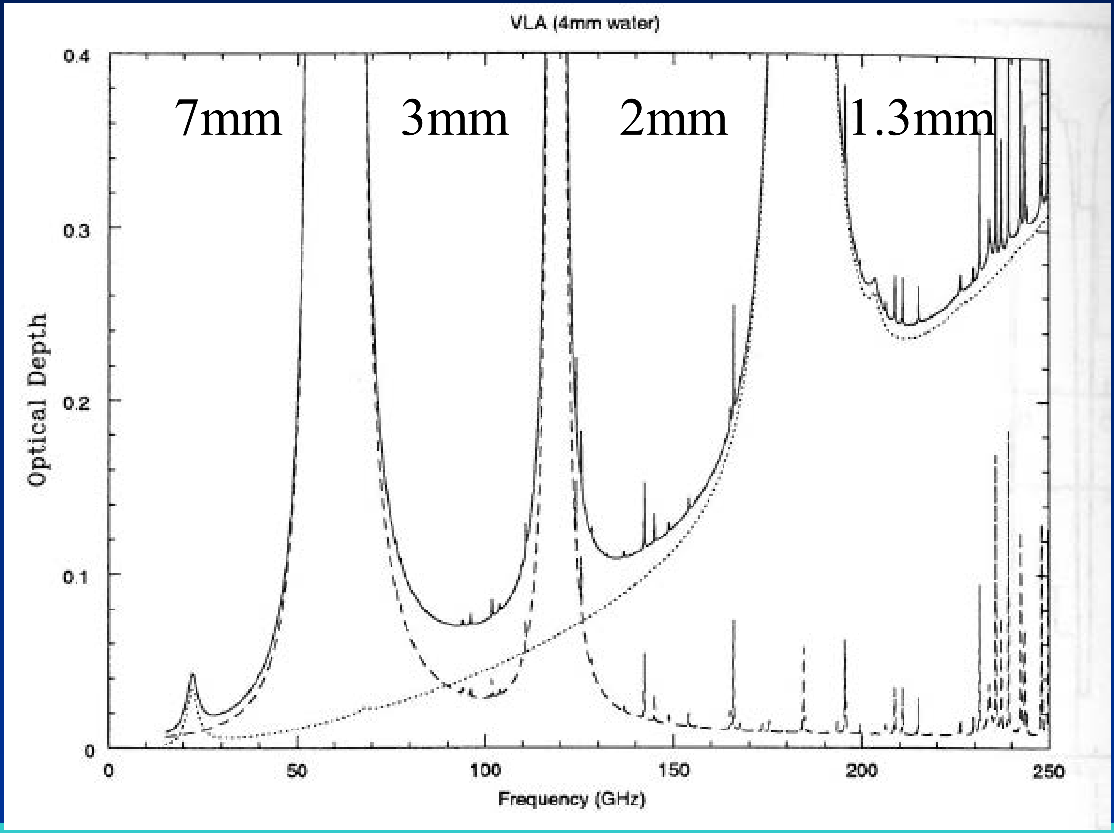
Radio signals and the Earth atmosphere



Optical depth $\tau : I = I_0 \cdot e^{-\tau}$

Two principle components in the lower atmosphere that cause transmission losses:

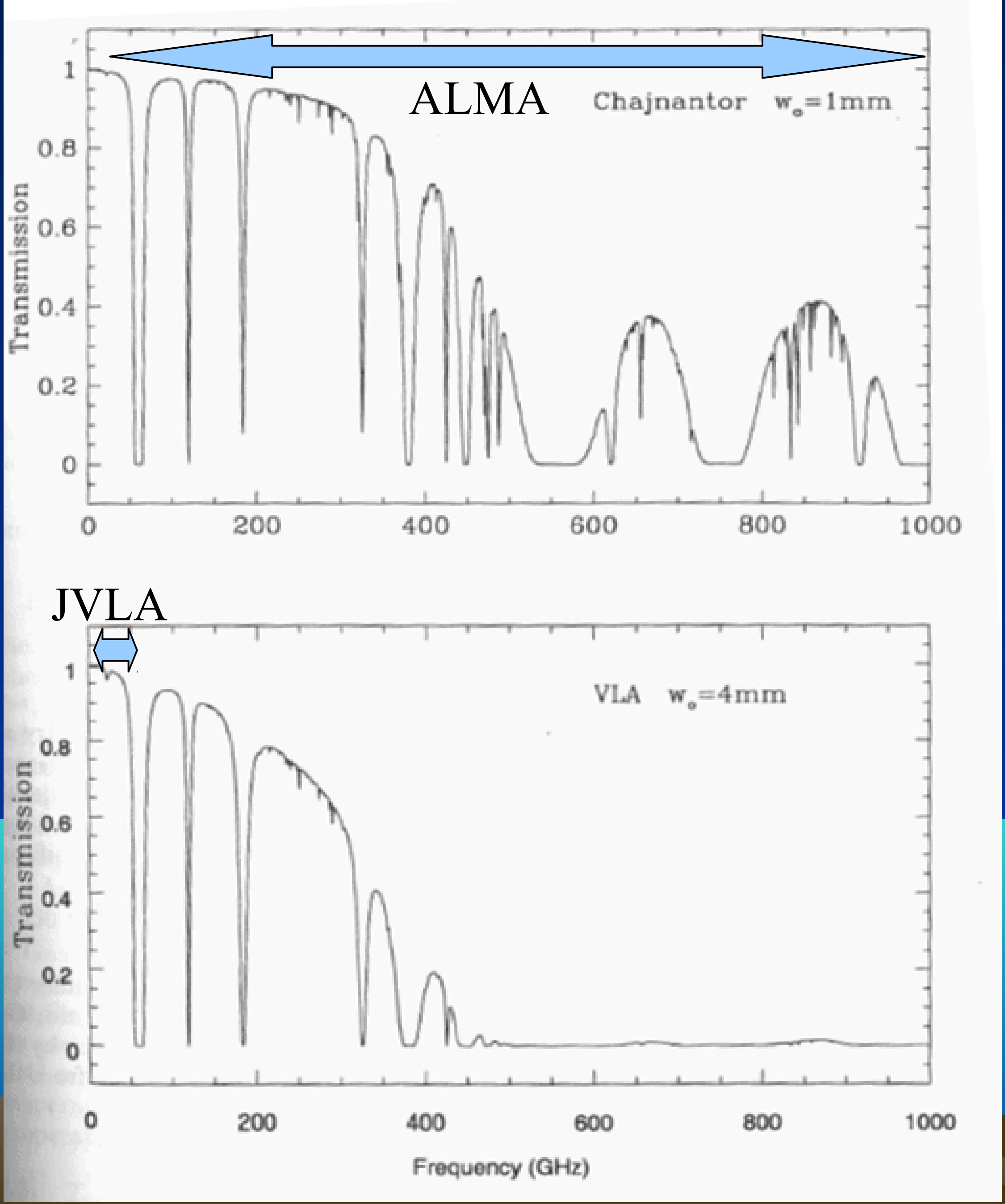
“dry” component: partly CO$_2$, but mainly O$_2$ (dashed curve)

“wet” component: water vapor (dotted curve)

Solid curve as combination of the two components

Strong atmospheric features as the historic demarcations between many radio and millimeter bands/windows

Radio signals and the Earth atmosphere



Atmospheric transmission at high radio frequencies – a good site is important! High water vapor content is a show stopper …

pwv = precipitable water vapor

(1mm: very good, 4 mm still fine,

Germany: 7-10 mm and more ...)

←

Atmospheric transmission for the

ALMA interferometer site: high

plain of Chajnantor in the

Atacama desert in Chile, 5100 m

←

Atmospheric transmission for the

JVLA interferometer site:

San Augustin high plain in New

Mexico, USA, 2100 m

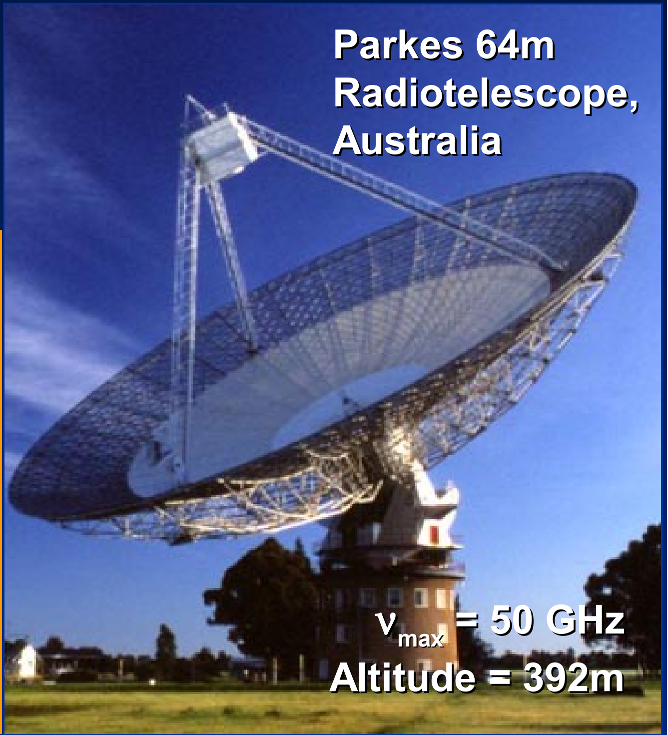
Single-dish radio telescopes in operation

Green Bank
Telescope
110m
NRAO
USA

ν_{max} = 100 GHz
Altitude = 807m

305m, Arecibo, Puerto Rico

ν_{max} = 10 GHz
Altitude = 496m

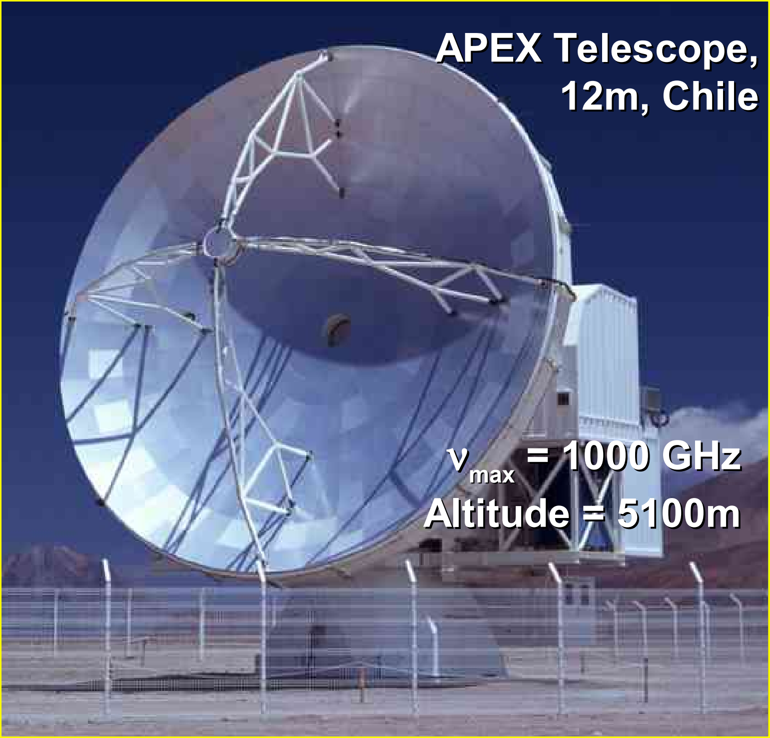


Parkes 64m
Radiotelescope,
Australia

ν_{max} = 50 GHz
Altitude = 392m

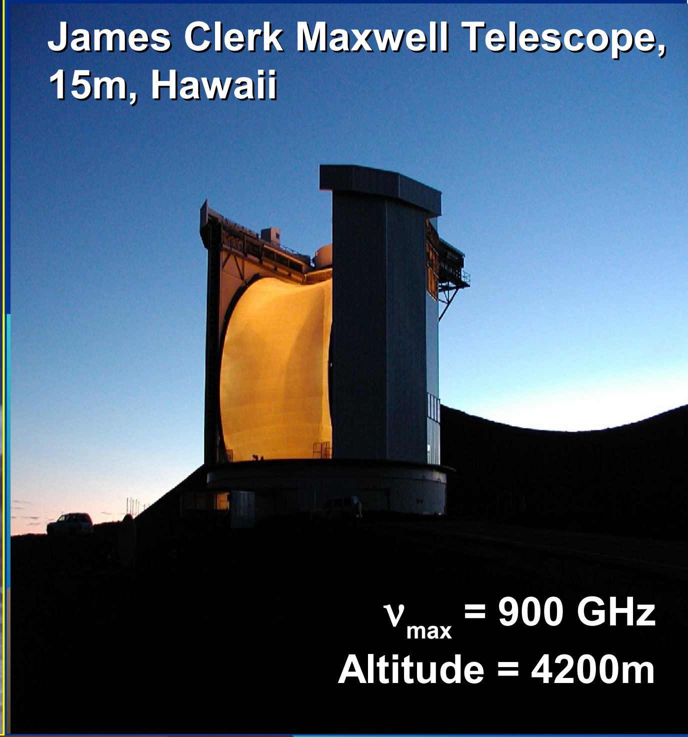
IRAM 30m, Spain

ν_{max} = 360 GHz
Altitude = 2950m



APEX Telescope,
12m, Chile

ν_{max} = 1000 GHz
Altitude = 5100m



James Clerk Maxwell Telescope,
15m, Hawaii

ν_{max} = 900 GHz
Altitude = 4200m

Radio Astronomy … what we will cover:

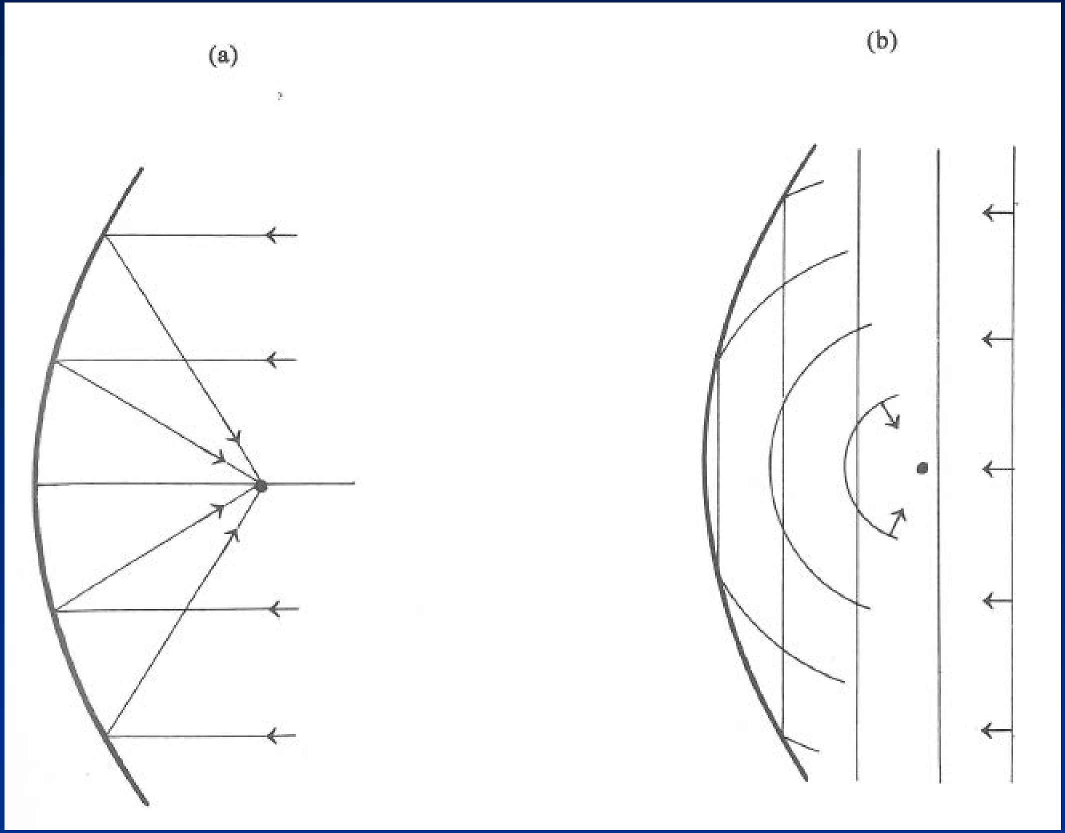
All wavelength ranges where the electromagnetic field can be directly accessed by the measurement equipment:

> ***I.e., field amplitudes and field phases accessible, not only the intensities!***
> ***(more of that in the Instruments/Receiver lecture)***

We have to take care of the wave nature of the incoming radiation …

Antenna theory … diffraction effects important.

Radio telescopes



Especially in the frequency range > 1 GHz: collimating reflectors in use

Large collecting areas possible also in case of short wavelengths

Keep in mind: celestial sources very far away → electromagnetic radiation reaching us is to a very good approximation a plane wave

A paraboloidal reflector in terms of:
(a) Ray optics (b) wavefronts

A fundamental relation

Reciprocity between transmission and reception in antenna theory (all relevant equations t-symmetric) →

Consider illumination of the main reflector by the receiver/sender device in the reflector focus

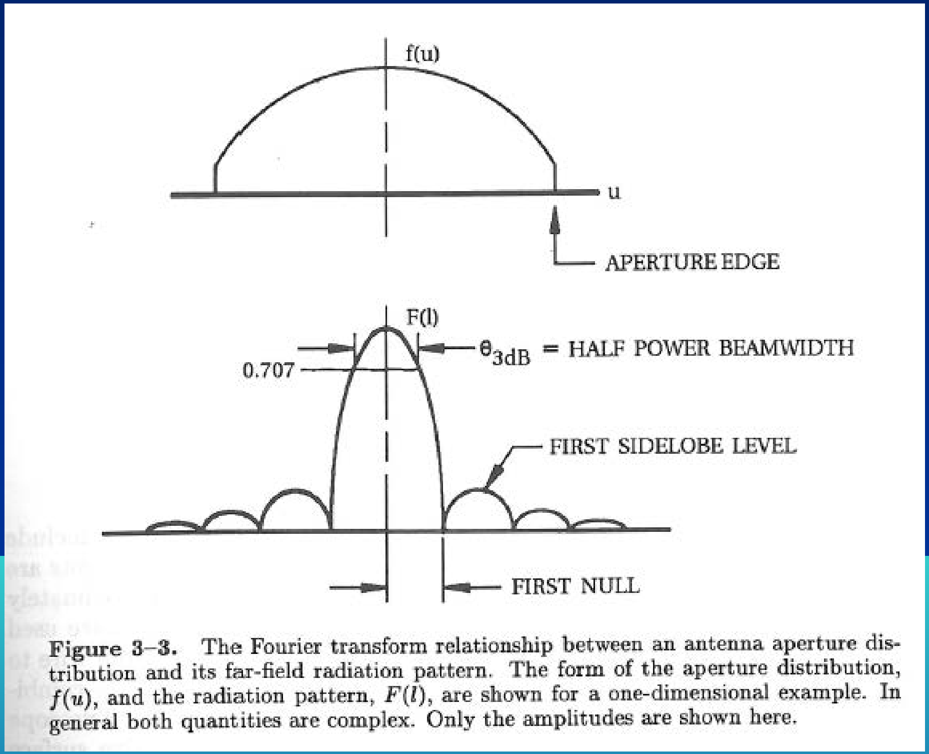


Figure 3–3. The Fourier transform relationship between an antenna aperture distribution and its far-field radiation pattern. The form of the aperture distribution, $f(u)$, and the radiation pattern, $F(l)$, are shown for a one-dimensional example. In general both quantities are complex. Only the amplitudes are shown here.

Distribution f(u) of electric current strengths along the telescope aperture (upper plot)

Emerging far-field radiation pattern F(l) (in send-mode) is the Fourier transform of the aperture distribution f(u) (lower plot)

$$F(l) = FT[f(u)]$$

Note: ratios measured here in dB (deciBel): $10 \cdot \lg(F_2/F_1)$ dB

Several effects affecting the antenna pattern

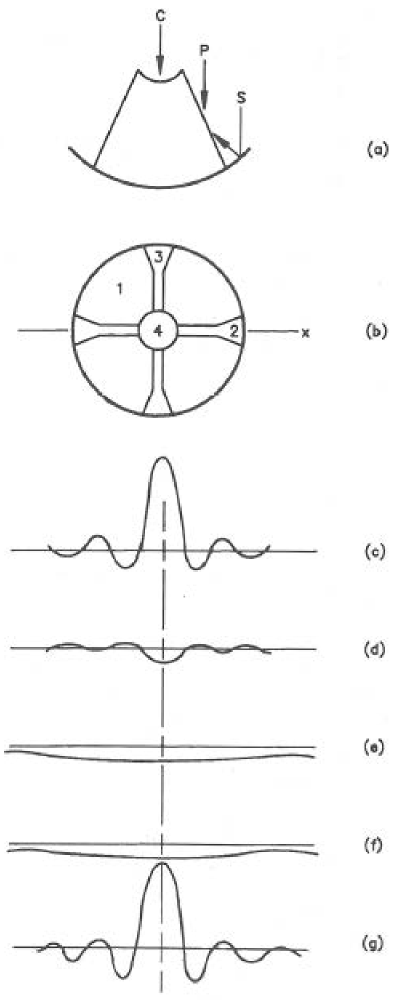


Figure 3–8. Effect of aperture blockage. (a) The three kinds of blockage in a reflector. c is central blockage, p is plane wave blockage on the struts, and s is spherical wave blockage on the struts. (b) The resulting aperture blockage for a quadrupod subreflector support. (c) Unblocked pattern in x-plane. (d) Blocked pattern for area 2. (e) Blocked pattern for area 3. (f) Blocked pattern for area 4. (g) Total pattern with blockage $= c + d + e + f$.

Schematic telescope side view

View onto obstructions from above

Unblocked pattern (in x-plane)

Contributions from obstructions

Total pattern with blockage as sum of all contributions

The power pattern $P(\theta,\varphi)$

Tthe far field pattern F(l) is on the level of the electric fields. But we also want to know the power distribution (energy/time per solid angle)

Power ~ square of field strengths … $E \cdot E^*$

Fourier Theory … autocorrelation theorem $f(x) \otimes f^*(-x) \leftrightarrow |F(s)|^2$

The power (gain) pattern $P(\theta,\varphi)$ is the Fourier transform of the autocorrelation of the aperture current density distribution (called f(u) in the previous slides).

Two versions of the power reception pattern

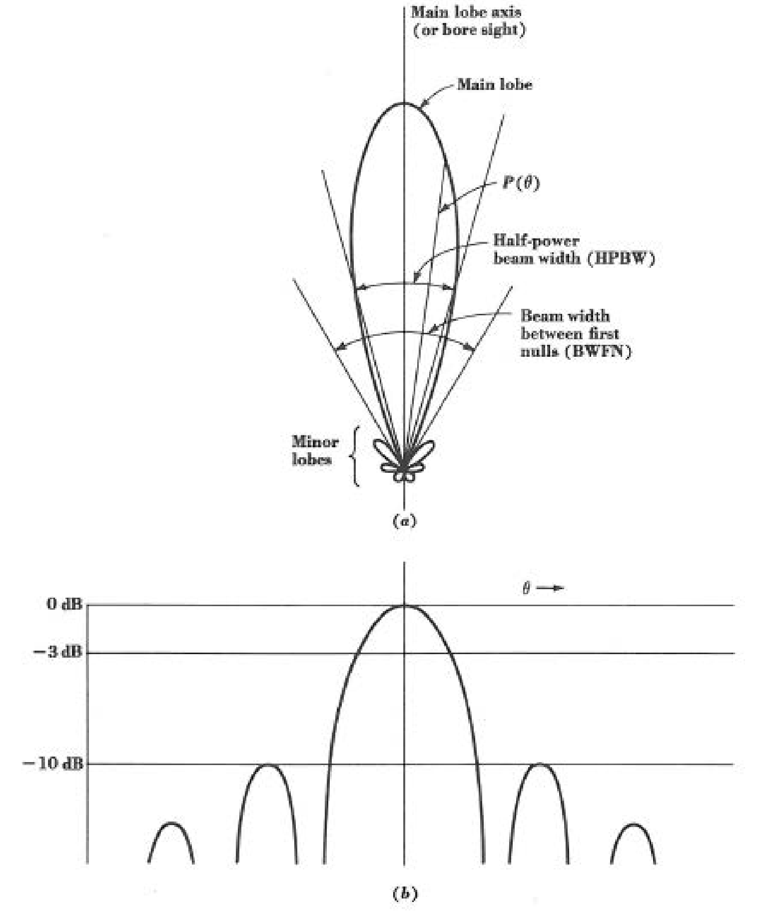


Fig. 6-1. (*a*) Antenna pattern in polar coordinates and linear power scale; (*b*) antenna pattern in rectangular coordinates and decibel power scale.

Reception pattern in polar coordinates and linear power scale (This is a 1-dimensional cut through the pattern, shown is the received or emitted power as a function of an angle on the sky, measured from the telescope normal direction)

Reception pattern in rectangular coordinates (u = sin θ) and logarithmic power scale (in decibel)
Remember: -3 dB ~ 50% on linear scale

The power pattern (beam) size

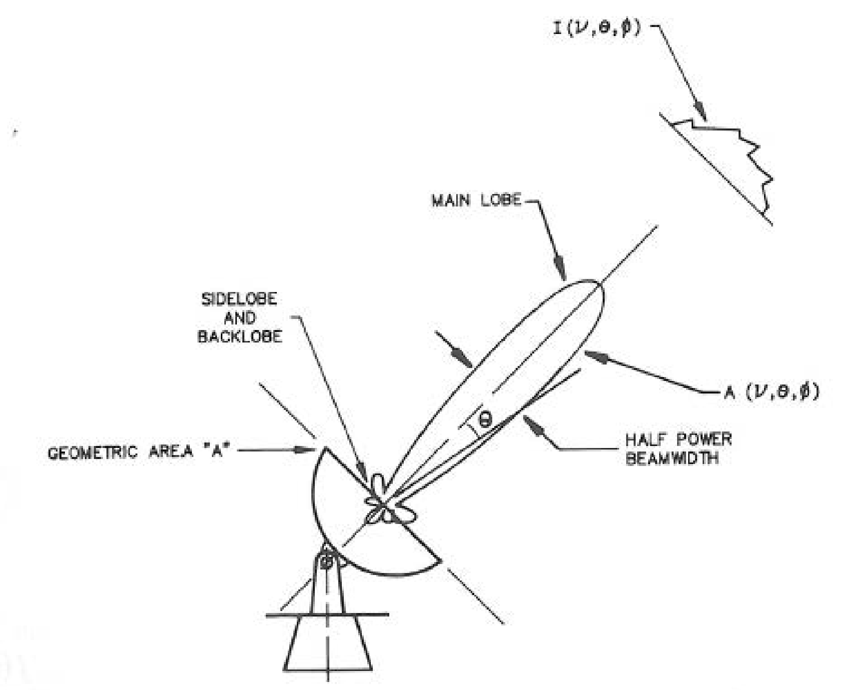


Figure 3–2. The reception pattern of an antenna.

Common misconception: half-power beamwidth (HPBW) of antenna power pattern is 1.22 λ / D

This is NOT correct! The above relation gives the angular distance from the direction of maximum power to the first null of that pattern.

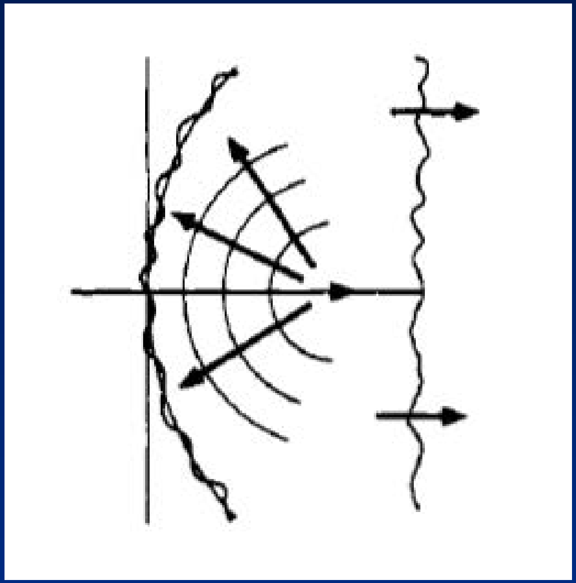
The half-power beam width for an antenna with uniform illumination (aperture current strength distribution) is 1.02 λ / D !

However, such an antenna has high side-lobe levels …

Different designs deviating from uniform reflector illumination can lower the side-lobe, But the diameter of the main lobe (i.e., the “beam”) will get larger → slightly degraded spatial resolution as a result

Usually the HPBW ranges between 1.05 …1.20 λ / D

Diffraction pattern and error beam



Wave distortion due to diffraction at a rough reflection surface

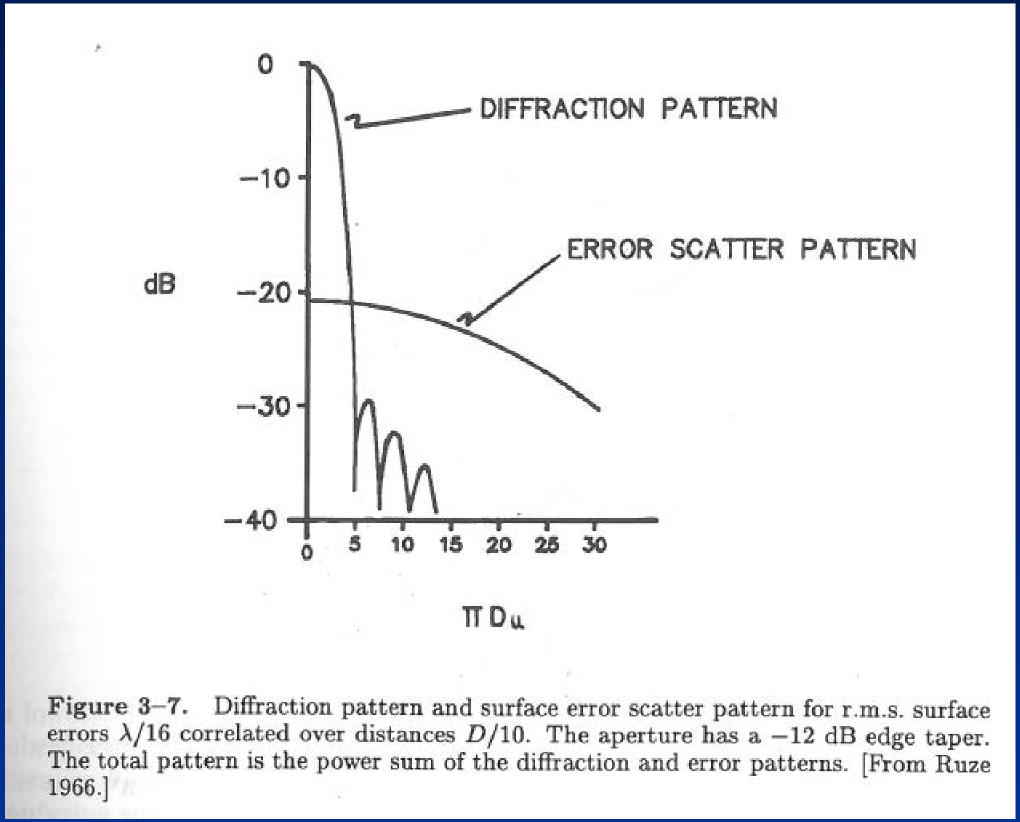


Figure 3–7. Diffraction pattern and surface error scatter pattern for r.m.s. surface errors $\lambda/16$ correlated over distances $D/10$. The aperture has a −12 dB edge taper. The total pattern is the power sum of the diffraction and error patterns. [From Ruze 1966.]

Common demand on surface accuracy: r.m.s better than wavelength / 10 (but there is larger variety on that number, can go from 8 to 20)

Note: ratios measured here in dB (deciBel): $10 \cdot \lg(F_2/F_1)$ dB

Different reflector foci … not radio antenna specific …

Prime focus

Off-axis Cassegrain

Beam waveguide

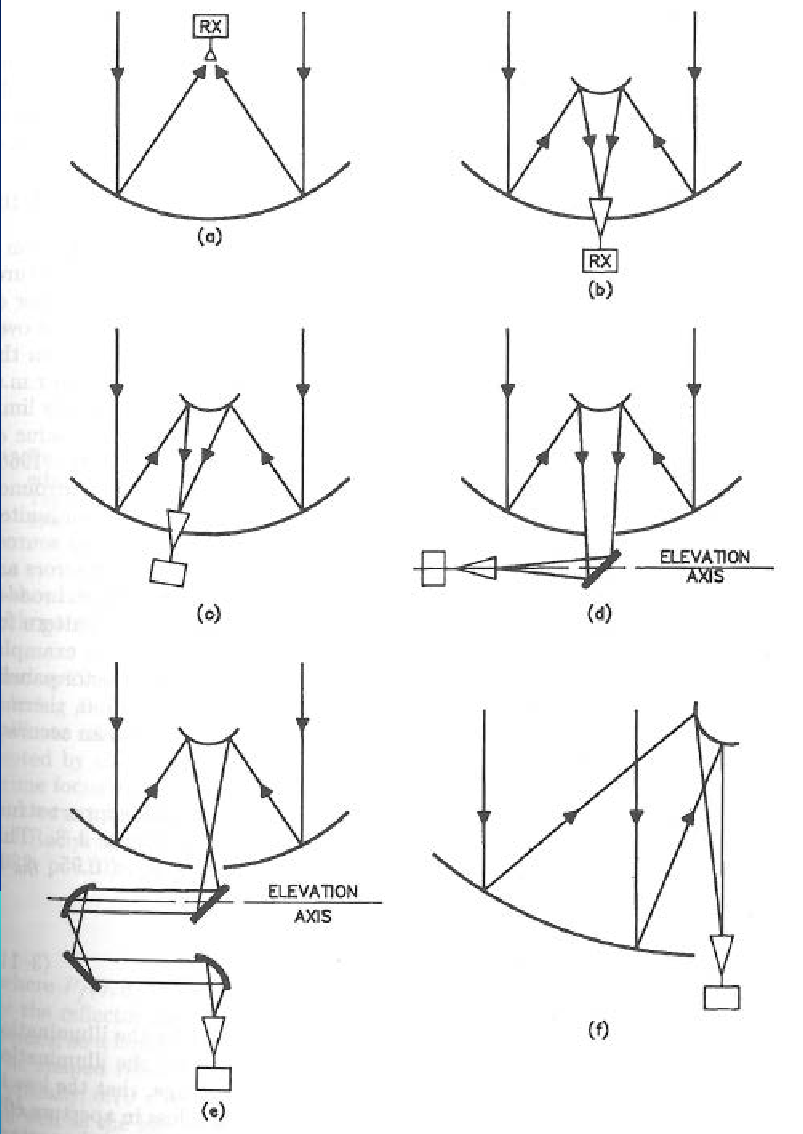


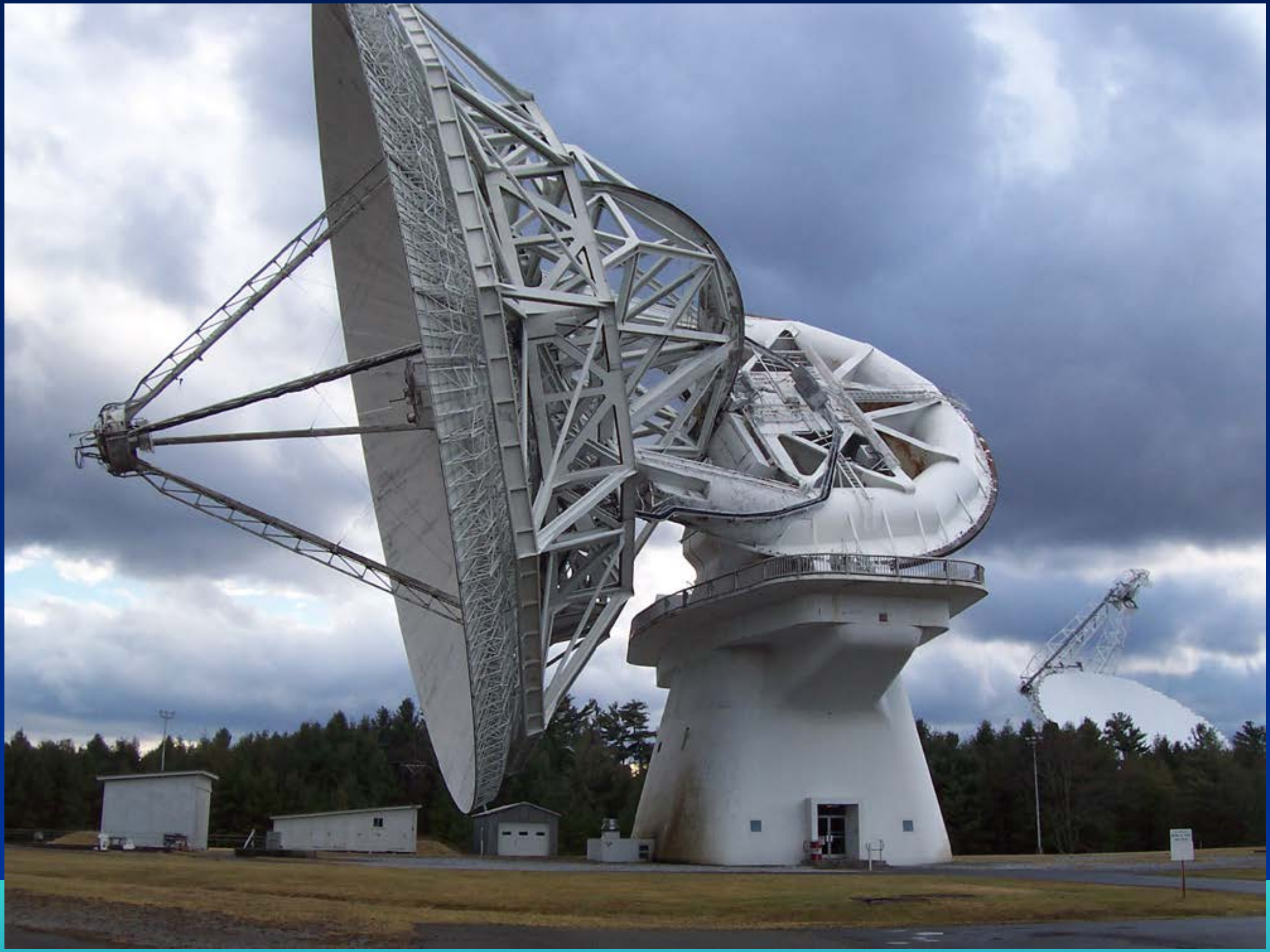
Figure 3–6. Optical systems for radio telescope reflectors. (a) Prime focus, (b) Cassegrain, (c) Off-axis Cassegrain, (d) Naysmith, (e) Beam waveguide, (f) Offset Cassegrain.

Cassegrain focus

Nasmyth focus

Offset Cassegrain

Classical Radio Telescopes



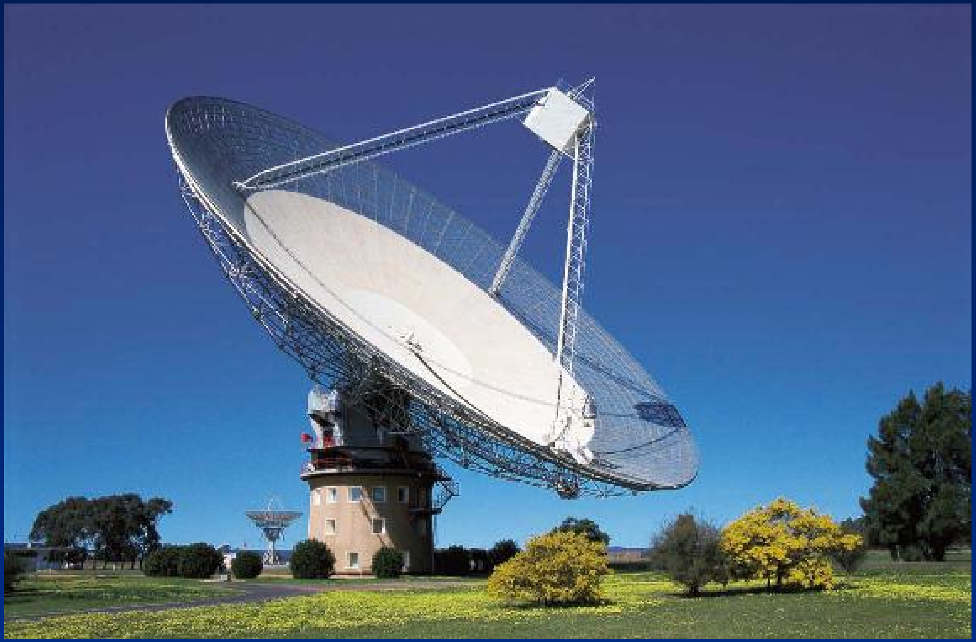
140 foot NRAO telescope (43 m dish diameter)

One of the largest telescopes with a classic equatorial mount (also called polar mount)

Advantage: tracking just around one axis

But: mechanically very demanding for larger telescopes

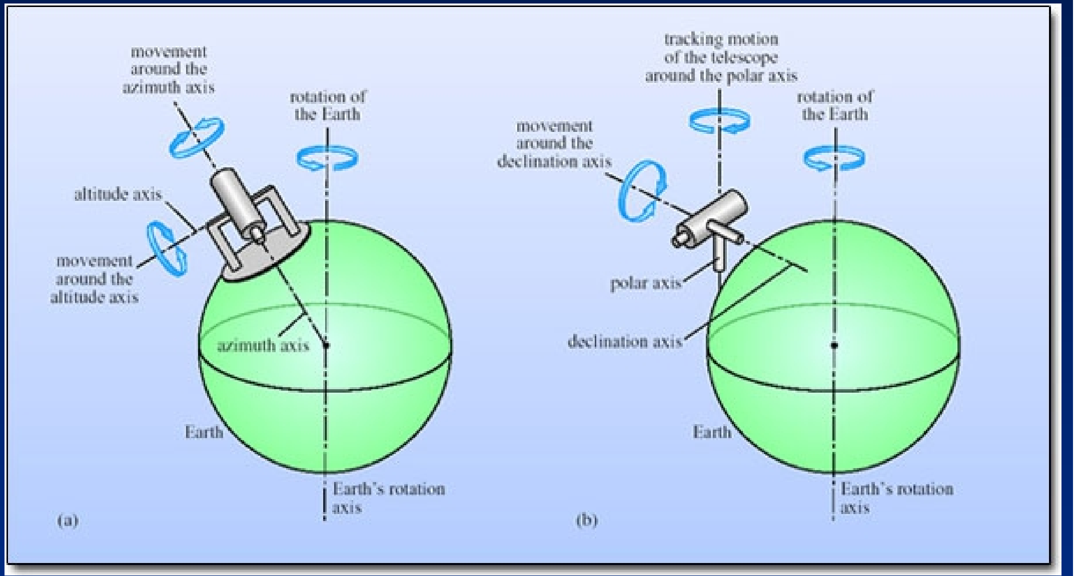
Classical Radio Telescopes



Parkes 64-m Telescope ("The Dish") in Australia

Designed in the 1960s

Paved the way for large Alt-Az telescopes



Very schematic comparison of altitude-azimuth ("Alt-Az") and Equatorial mounts

Alt-Az challenges:
- tracking accuracy near zenith
- field rotation

Effelsberg 100-m telescope

Main dish diameter: 100 meters
secondary reflector: 6.5 meters

surface accuracy in the inner 80 meters: 0.45 mm

Fully steerable telescope

Rotating assembly diameter: 64 meters

16 electro-engines a 17.5 kW for azimuth tracking, further 4 ones for elevation tracking

Total weight: 3200 tons

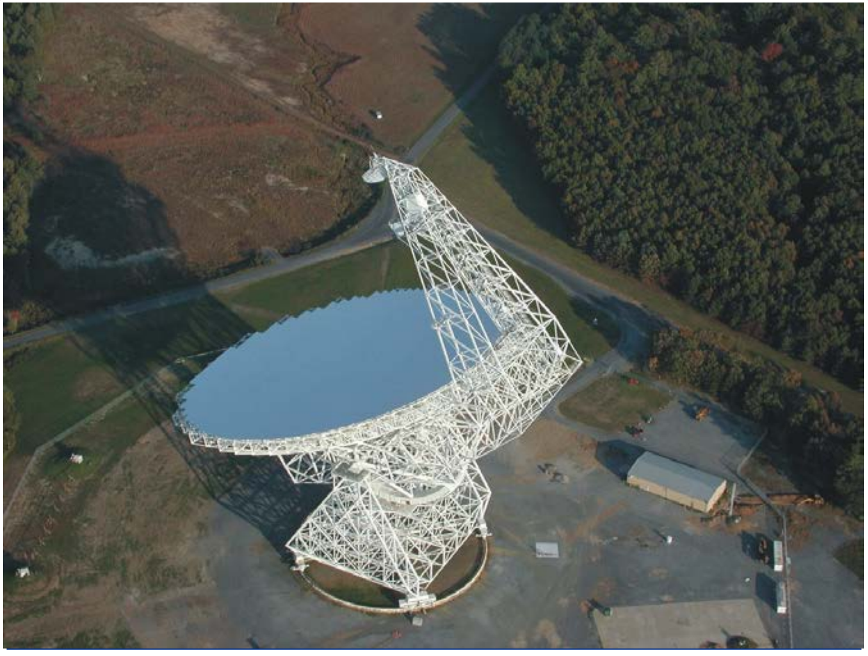
Effelsberg: the first large homologous telescope

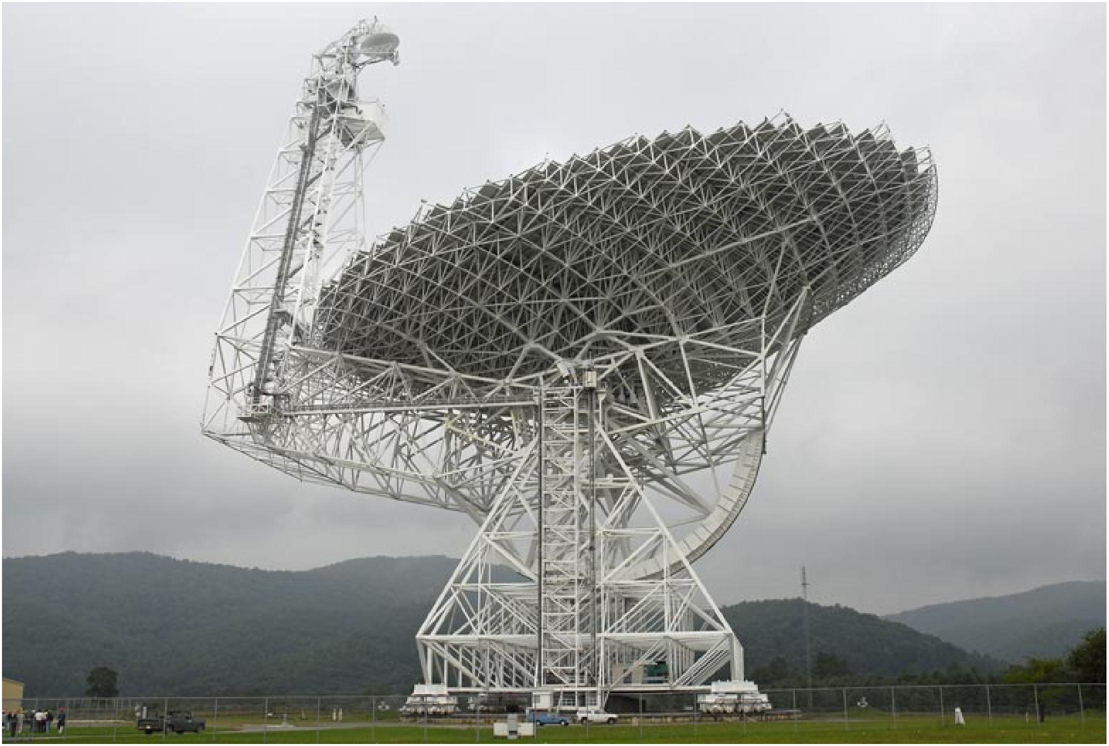
Large heavy telescopes:
different degrees of deformation at different elevations due to gravity

→ Homology: transition from one parabola to another one, aided by special support structure;
only focus needs (automatised) adjustment

Larger and larger Antennas (II)

110-m Green-Bank Telescope (GBT) in West Virginia (USA)

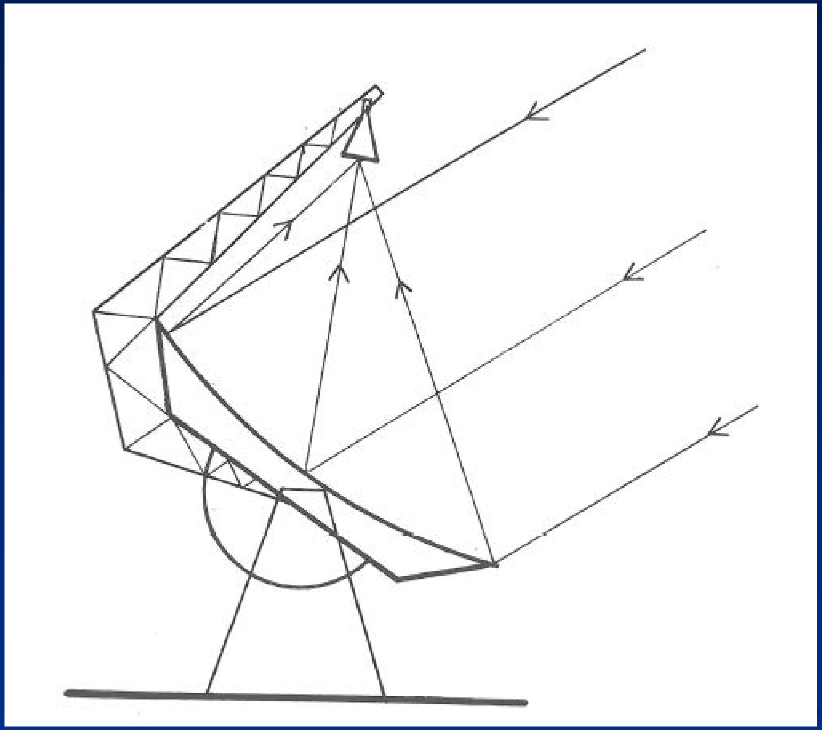




Special design with offset focus

Wavelengths as short as 3 mm can be handled ...

GBT and its special offset design

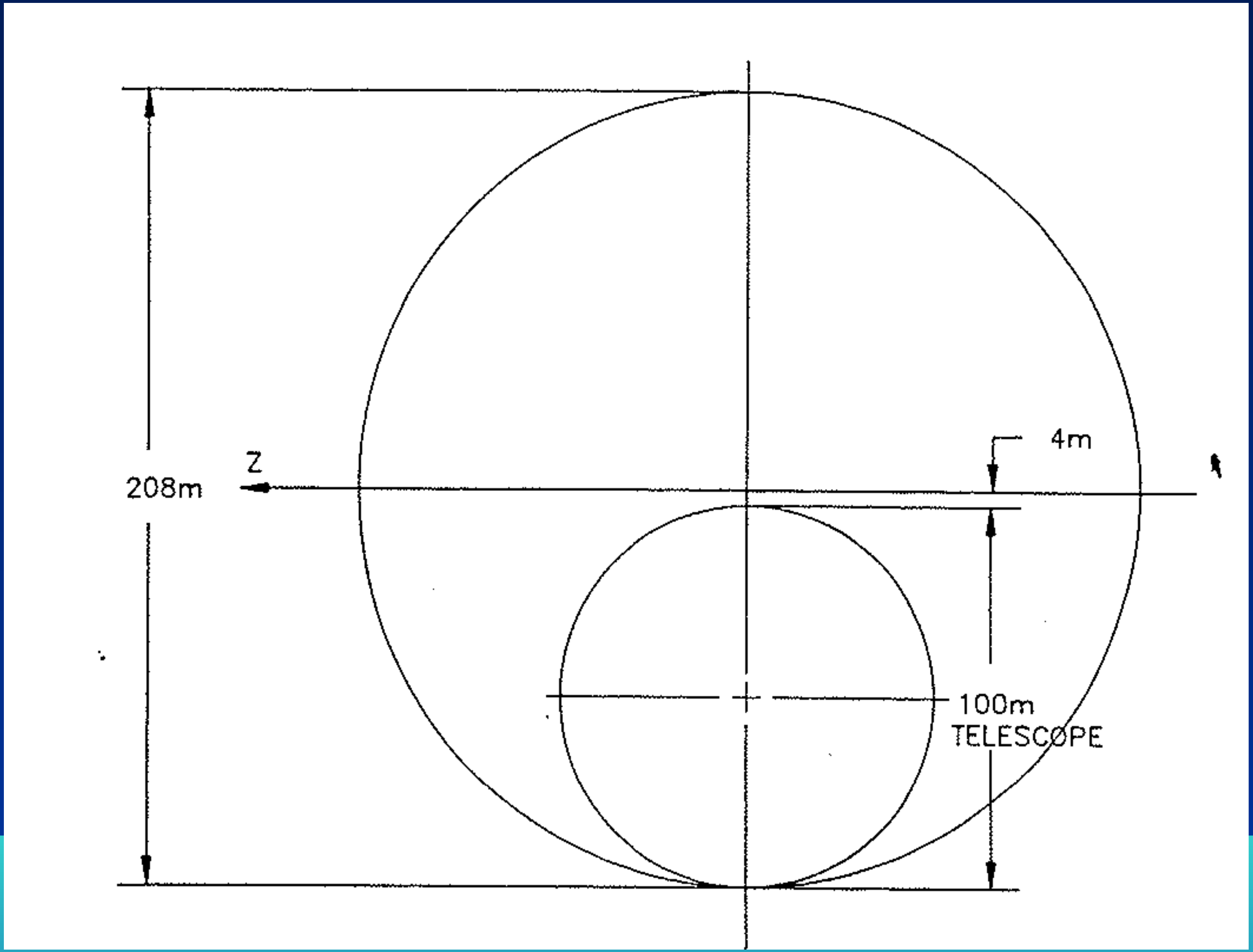


Recurring problem with classic on-axis radio telescopes: standing waves between main and sub-reflector cause “ripples” in signals from strong sources

Solution: offset design

Drawback: Homology can not be implemented easily
→ active surface control loops and piezo adjustment necessary

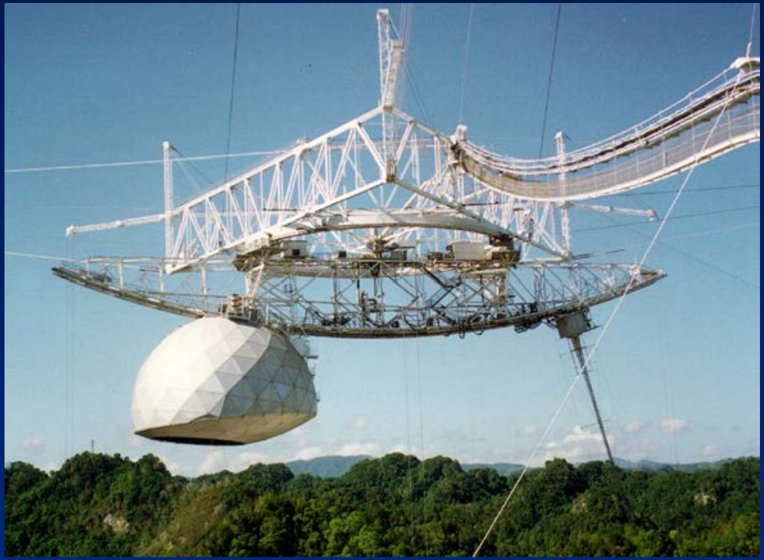
GBT and its special offset design



The GBT dish is actually an offset part of a virtual 208 m diameter dish;
the 4 m distance to the center is important for the final 100 x 110 m aperture NOT to be partially blocked by the sub-reflector.

Arecibo: 305m telescope with a spherical reflector

Main dish not steerable, celestial objects tracked by moving the secondary mirror



Spherical mirror prevents coma and astigmatism, but spherical aberration occurs → special design for receiver and subreflector geometry necessary; huge collecting area (>73,000 m²)

The missing link between single-dish telescopes and interferometers

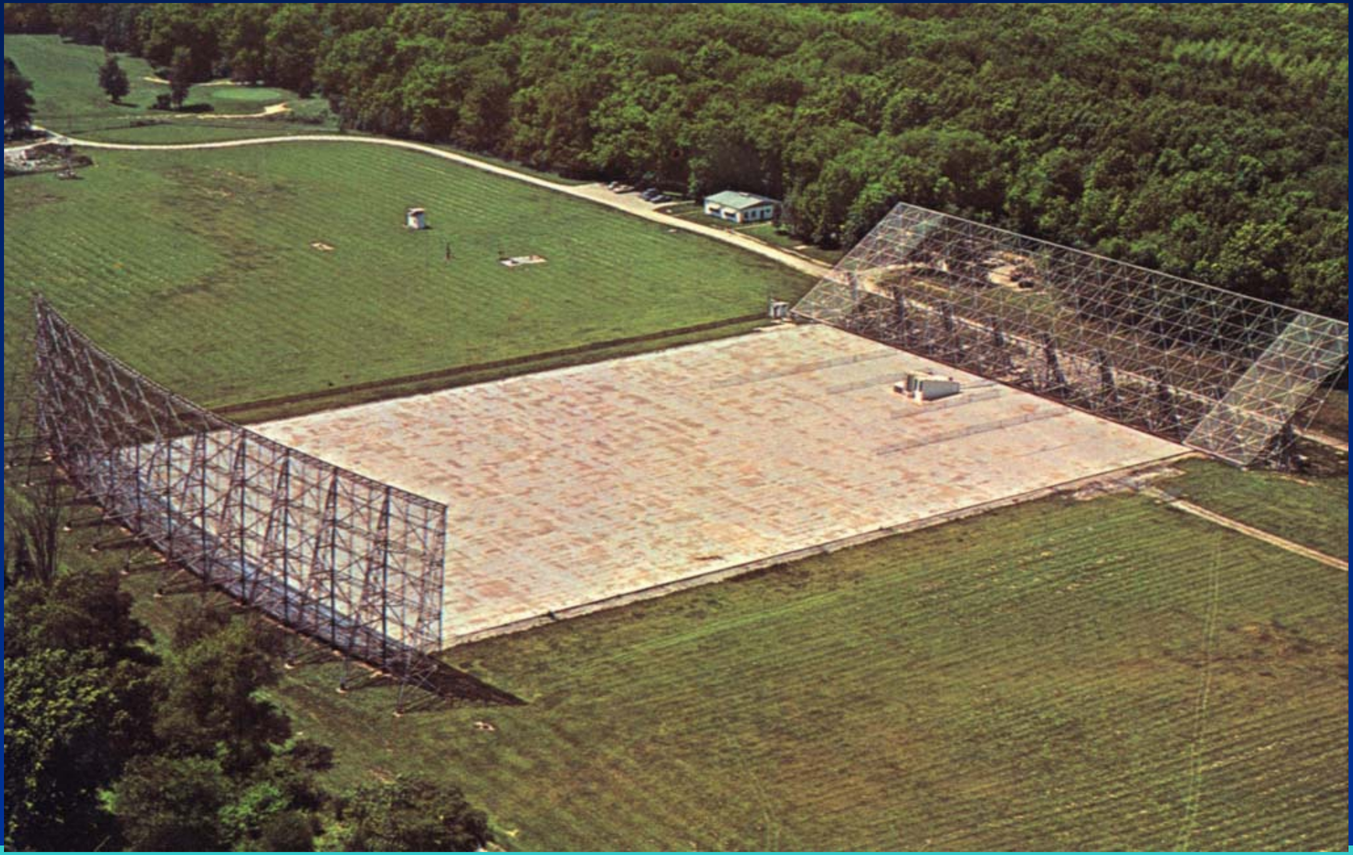
Kraus-type radio telescopes (after John D. Kraus, 1910-2004):

transit instruments, where the flat primary reflects radio light towards the spherical secondary, which focuses it towards a mobile focal carriage (moving east-west to track objects around transit)

Can be large assemblies of reflecting panels at rather large distances from the central focus
→ mimicking large aperture telescopes

Examples: Ohio State University radio telescope “Big Ear” (USA)
Nançay Decimetric Radio Telescope (France)
RATAN-600 (USSR/Russia)

Examples: Ohio State University radio telescope “Big Ear” (USA)



RATAN-600 Telescope in КарачаевоЧеркесия (Caucasus, in the south of the European part of Russia)

consists of a 576 m circle of 895 elements (each is 2 m x 11.5 m) and 5 independent focus stations

RATAN-600 Telescope in КарачаевоЧеркесия (Caucasus, in the south of the European part of Russia)

2 of the 5 independent focus stations in the foreground ... plus some haystacks ... (Photo copyright: P. Boley)

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http://www.mpia.de/homes/beuther/lecture_ws1213.html

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