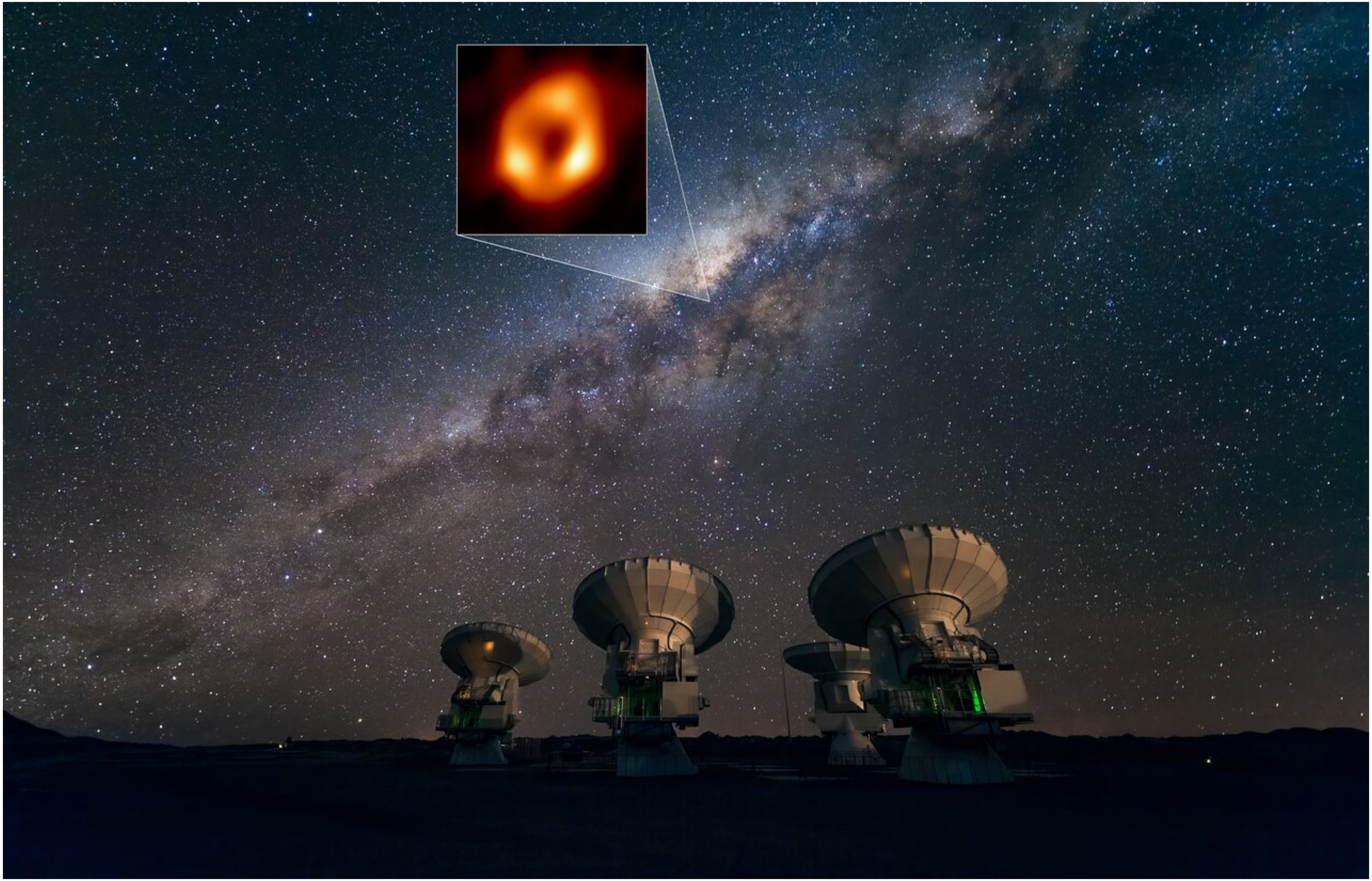
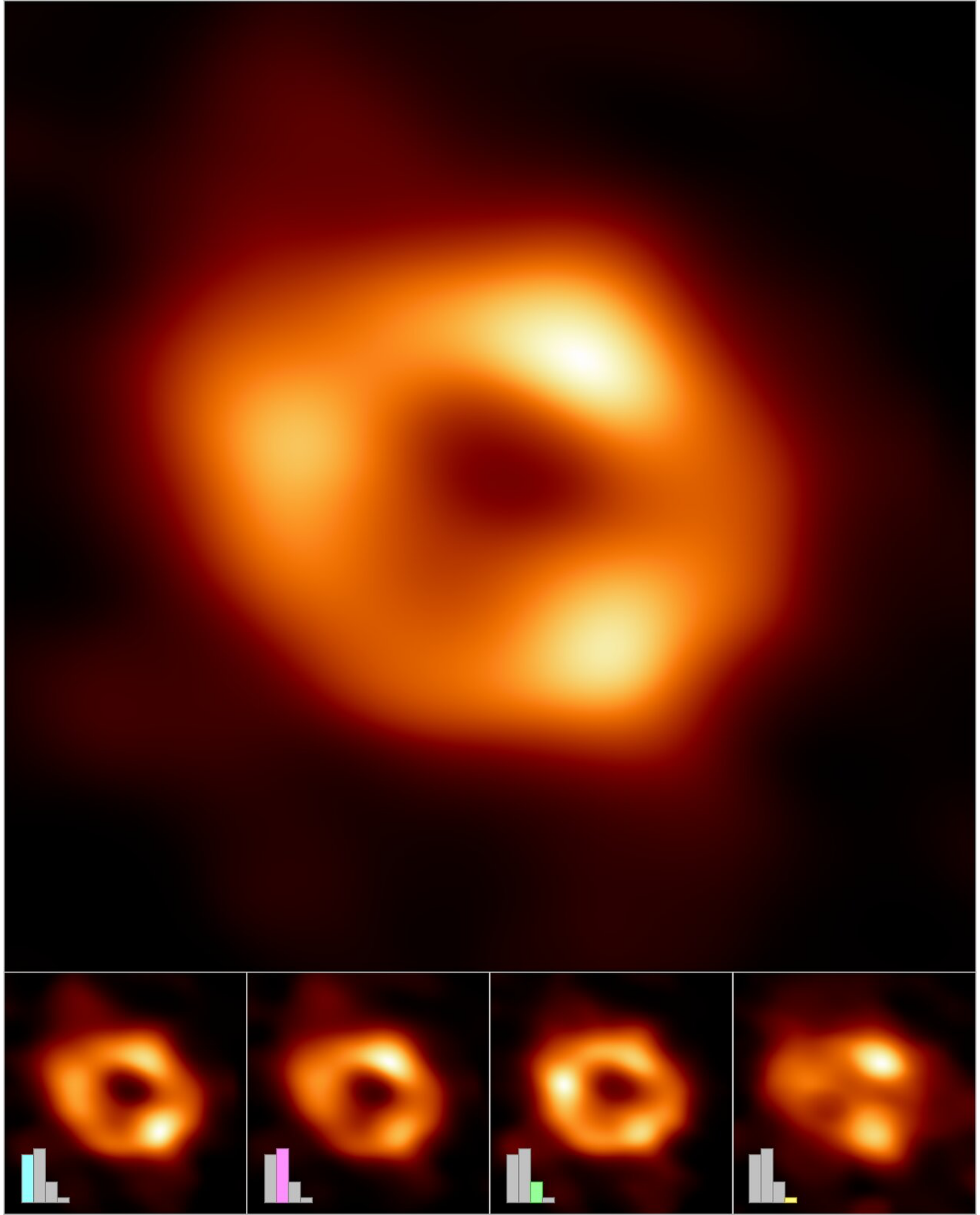
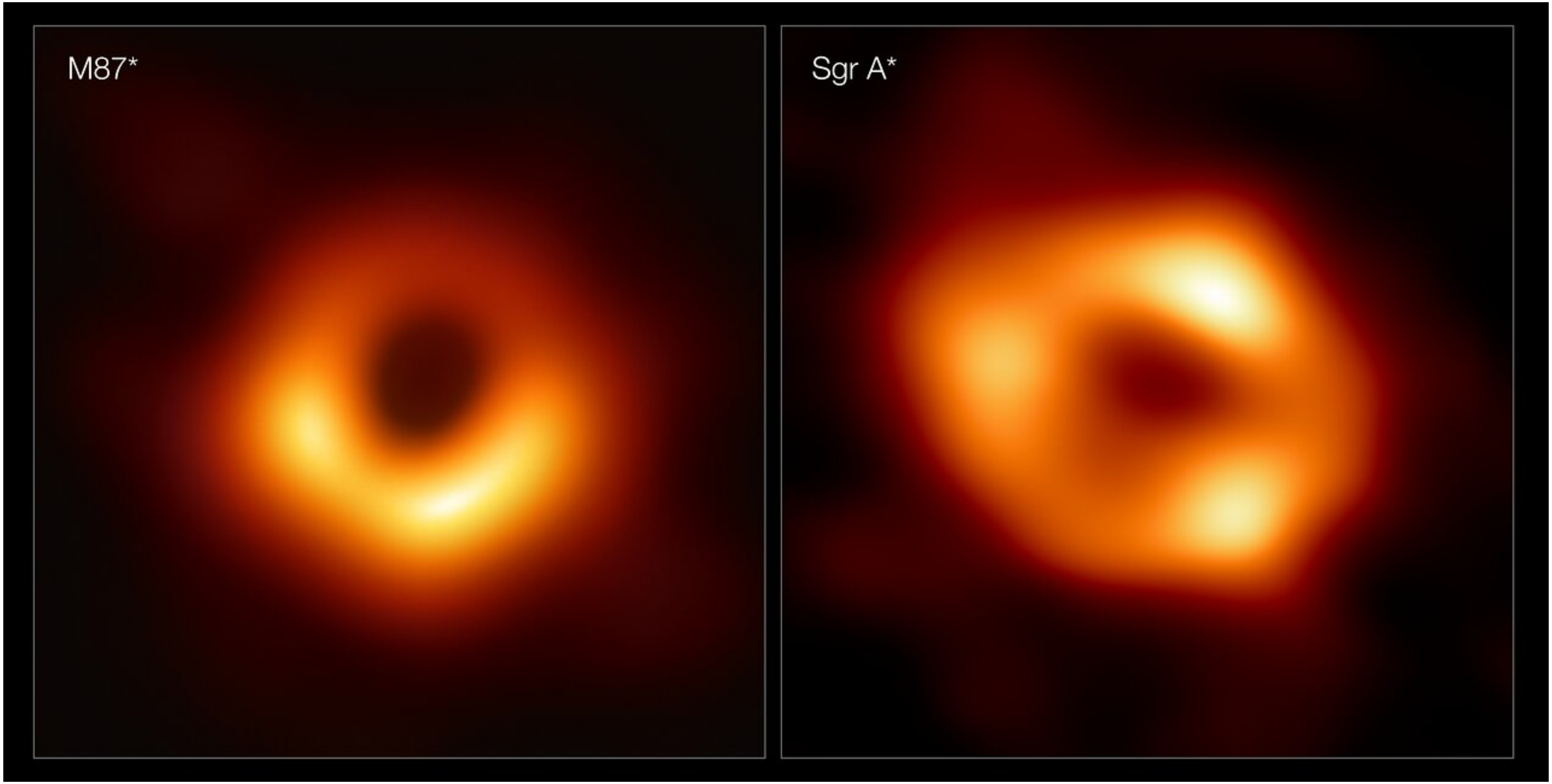
# Essentials of Radio and (Sub-)Millimeter Astronomy

Fabian Walter (MPIA)



GLT
NOEMA
30-M
SMT
Kitt Peak
JCMT
SMA
LMT
ALMA
APEX
SPT




M87*
Sgr A*

# Lecture 4

# Radiometers / Receivers I

slides: Essential Radio Astronomy by NRAO (Condon & Ransom)
+ lectures by Ohio State University Professor Adam Leroy
+ ASTRON’s Dr. Joeri van Leeuwen

https://www.astron.nl/astrowiki/lib/exe/fetch.php?media=ra_uva:2017:ra_uva_lecture5.pdf

# Radio Telescopes / Antennas

Radio photons are too wimpy to do very much - we cannot usually detect individual photons.

e.g. optical photons of 600 nm => 2 eV or 20000 Kelvin (hv/kT)

e.g. radio photons of 1 m => 0.000001 eV or 0.012 Kelvin

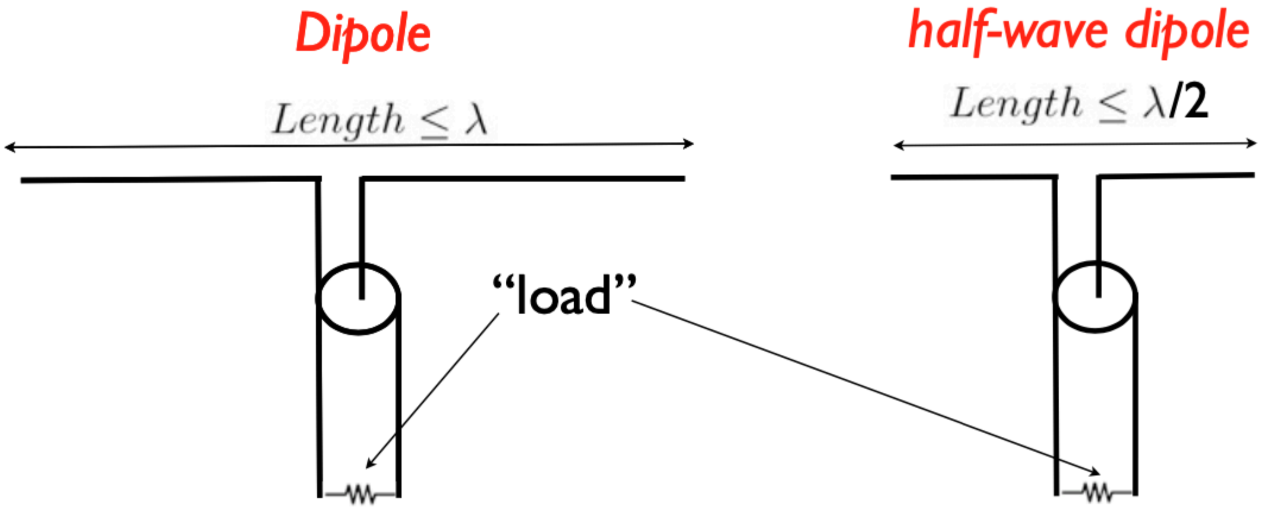
Photon counting in the radio is not usually an option, we must think classically in terms of measuring the source electric field etc.

i.e. measure the voltage oscillations induced in a conductor (antenna) by the incoming EM-wave

# Radio Telescopes / Antennas

Types of antenna or antenna arrays:

Wavelength > ~1 metre: simple wire antennas can be used...



E-field of incoming radiation sets up currents in the antenna ==> voltages can be measured across a resistor.

N.B. any antenna is only sensitive to one polarisation (current is induced by field that is parallel to dipole length).

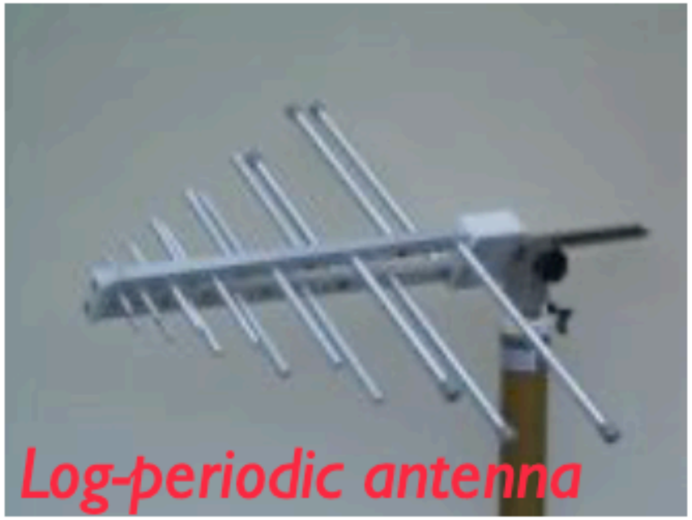
The simplest antenna is the half-wave dipole … The gain can be improved by combining together the output of several dipoles arranged in an array.

# Radio Telescopes / Antennas

Effective area can also be increased by (for example) using a Yagi antenna. *Parasitic* antennas direct the wave towards the dipole. Log-periodic antennas are suitable as receptors of broad-band signals.

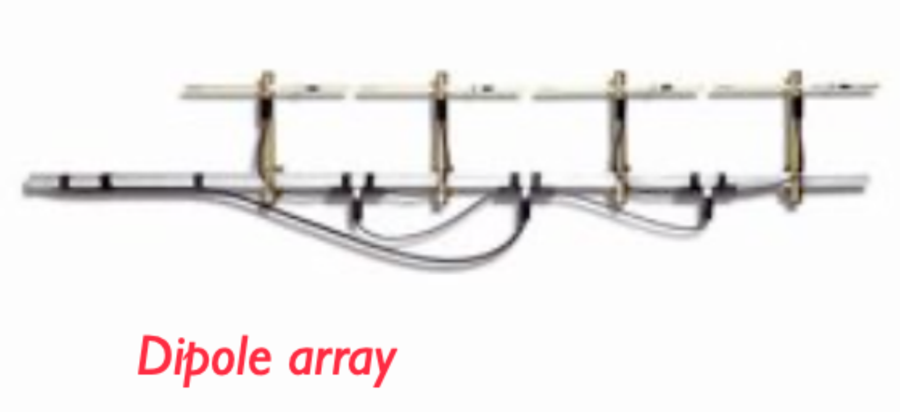
Yagi

Helix



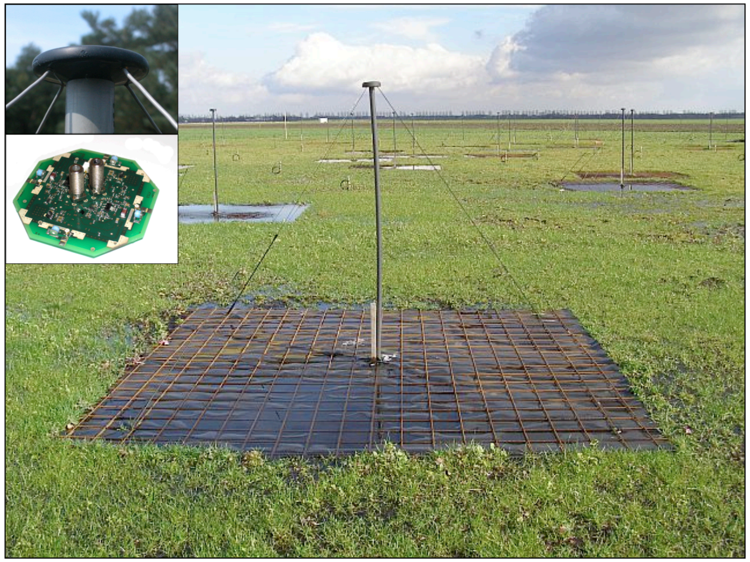
Log-periodic antenna

The gain of a single dipole can be greatly improved by combining together the output of many dipoles arranged in an array:



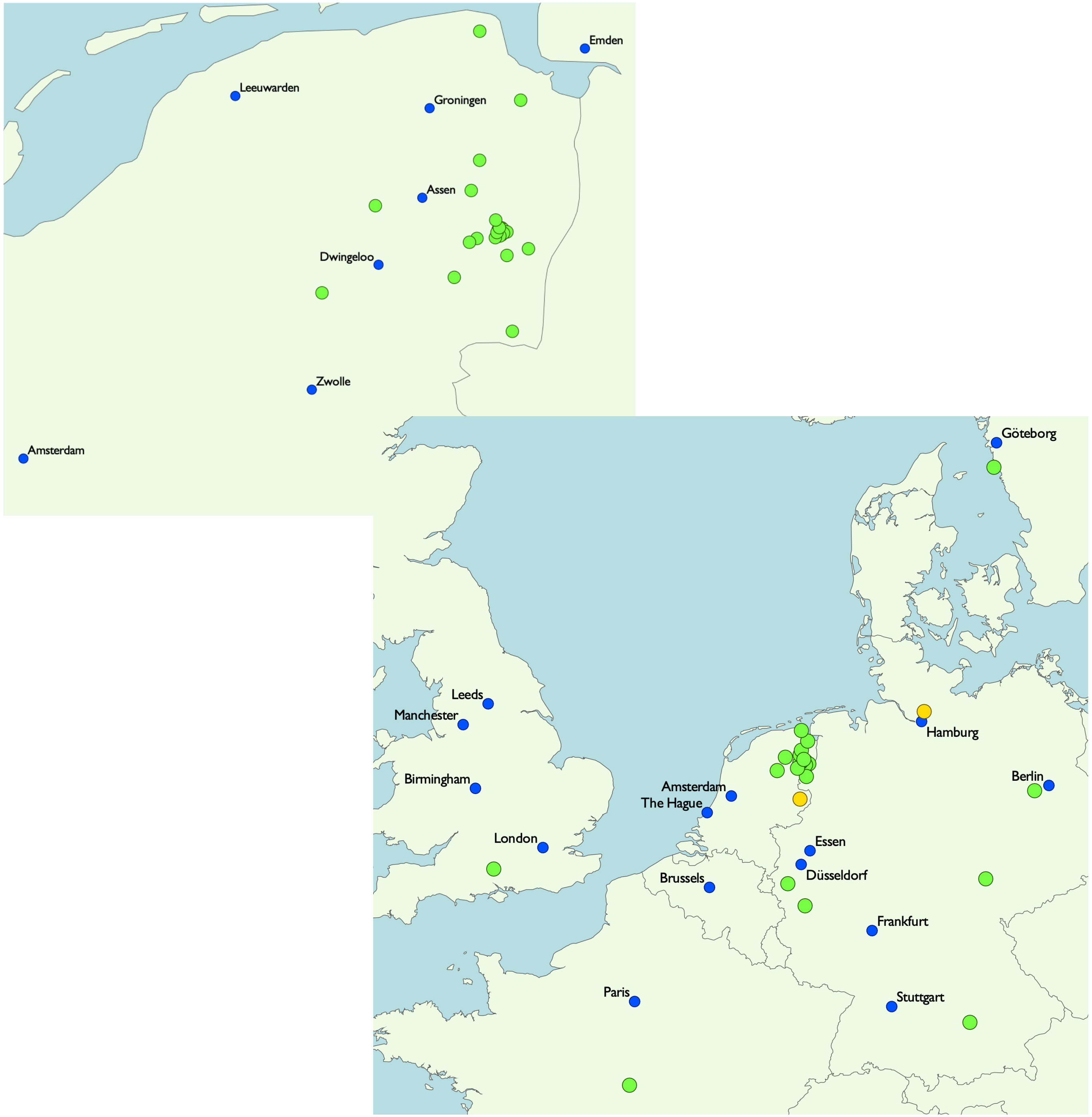
Dipole array

# e.g. LOFAR



# e.g. LOFAR


LOFAR
Borger-Odoorn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Leeds
Manchester
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Birmingham
Amsterdam
The Hague
Berlin
London
Essen
Düsseldorf
Brussels
Frankfurt
Paris
Stuttgart

# focusing emission

In parabolic telescopes incoming EM-wave electric field oscillations induce voltage oscillations at the *antenna focus*, in a device called a *feed*.

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At cm and mm wavelengths, parabolic collectors are usually optimal for focusing the incoming plane- waves at the focus - where the feed is placed.

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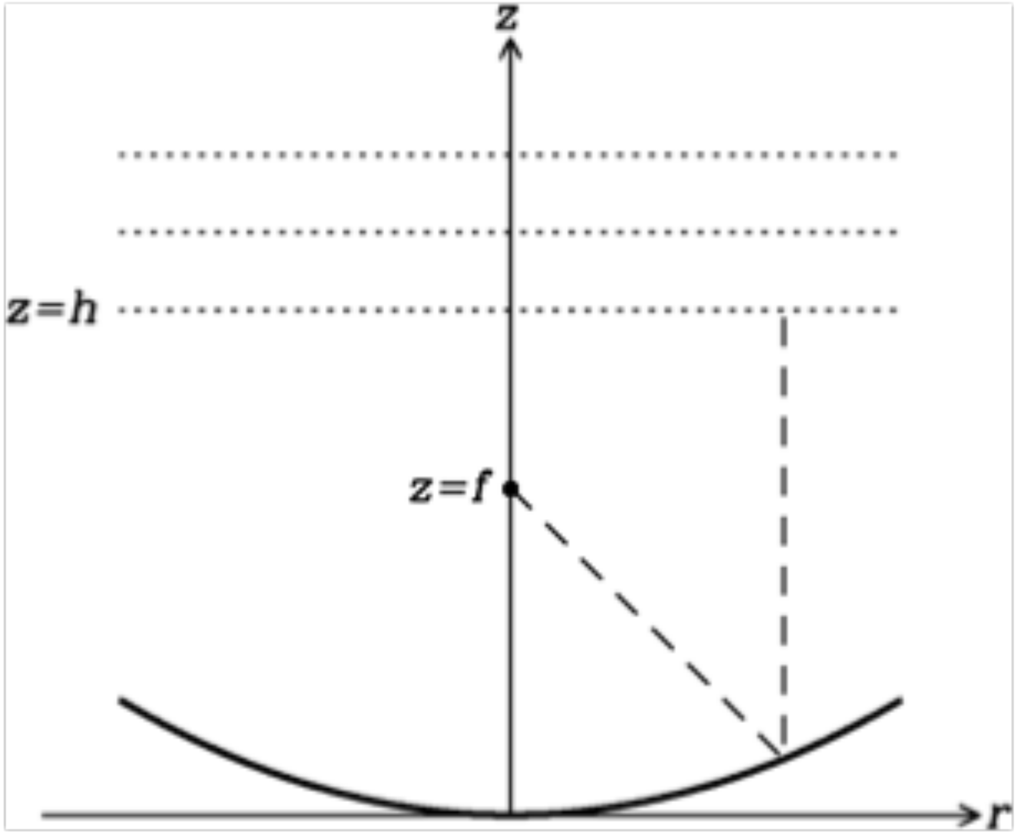
At cm and mm wavelengths, parabolic collectors are usually optimal for focusing the incoming plane- waves at the focus - where the feed is placed.

Nowadays, Paraboloids (dishes) are used at high frequencies and Dipole arrays at low frequencies - the boundary between antenna arrays and dishes is around 300 MHz. As technology advances, that boundary will probably shift towards higher frequencies ~ 1 GHz…

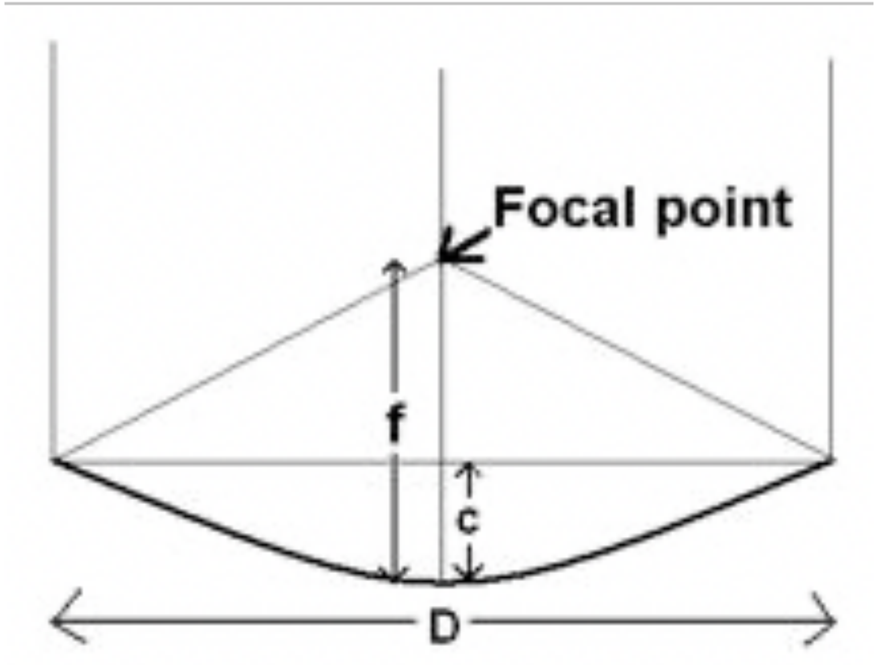
# focusing emission: paraboloid dishes

Requirement to have light striking the dish and reflecting arrive at the same point in phase leads naturally to parabolic dishes.

*Generally, ask that a ray along the axis reaches the a spot (f) at the same time as a reflected ray (dashed line), thus all rays arrive in phase with one another.*



# parabolic reflector



The focal length, f is given by:

$f = D^2/16c$

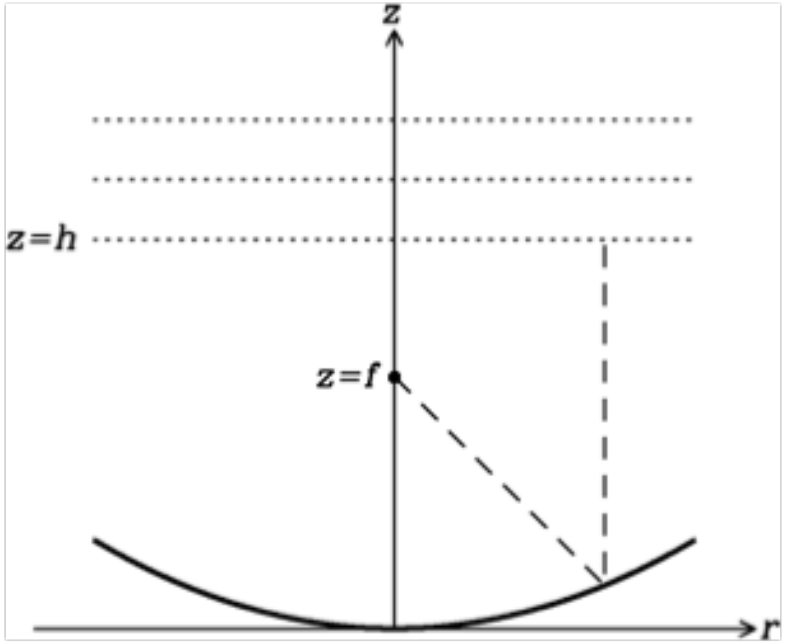
Typically the f/D (“f over D”) ratio of a radio telescope is about 0.5. e.g. the WSRT antennas. This typical value also ensures a rigid structure. This is very different from the optical!

# focusing emission: paraboloid dishes

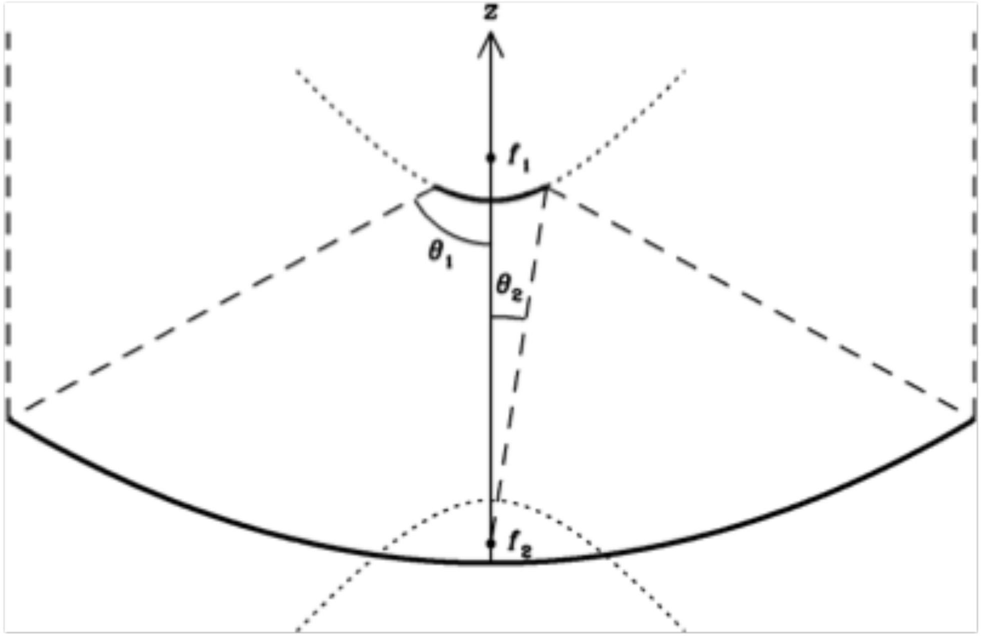
A parabaloid dish collects rays at the focus in phase without dependence on frequency, so that switching frequencies is just changing instrumentation (actual antenna) at the focus.

The focal ratio (focus length / diameter ~ f/D) is a semi-free parameter. Typically small (so dishes are deep) in radio for structural reasons (note contrast with optical).

Note that rays are in focus over an area **~ (f/D)²** – so a small focal ratio means small focal area (focal plane) to work with. This limits instrumentation suite (especially arrays).



*In practice a secondary reflector is more common than a receiver at the focus of the dish :*

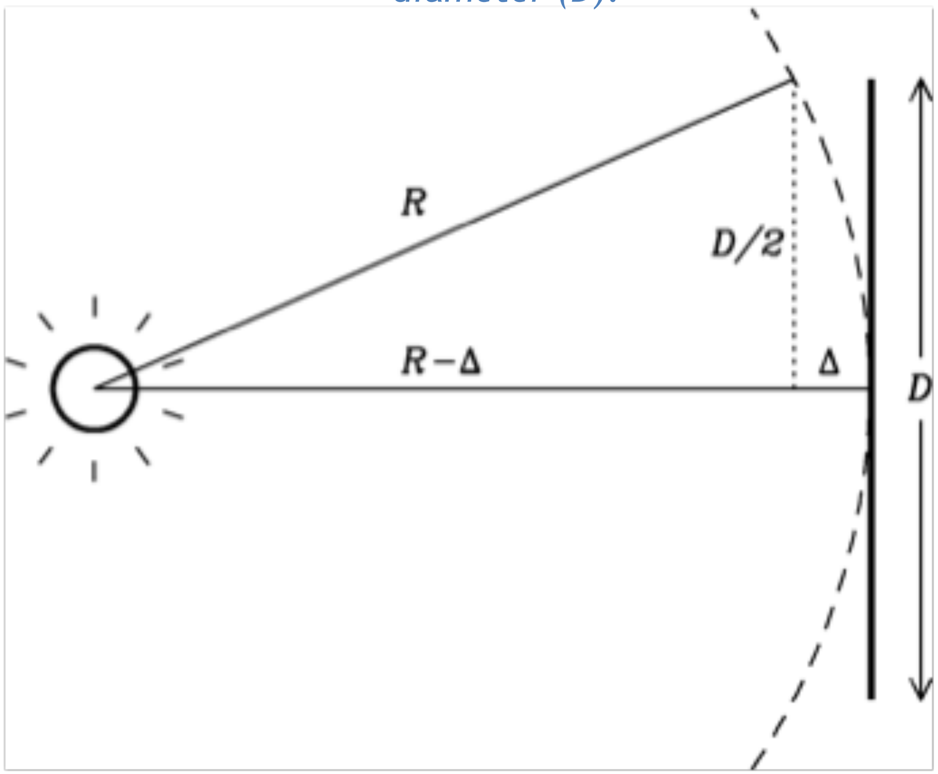


# far-field approximation

When is it okay to think about light as arriving at the telescope in a single plane wave perpendicular to the dish?

Define the deviation from the "far field" (parallel) approximation in terms of the difference in path length between the center and edge of the dish (Δ).

*Solve for Δ in terms of distance (R) and dish diameter (D).*



$$R^2 = (R-\Delta)^2 + \left(\frac{D}{2}\right)^2$$

$$R = \frac{\Delta}{2} + \frac{D^2}{8\Delta}\,.$$

$$R \approx \frac{D^2}{8\Delta}$$

*Imposing the somewhat arbitrary condition of no more than 1/16 of a wavelength:*

$$\Delta = \lambda/16$$

$$\boxed{R_{\rm ff} \approx \frac{2D^2}{\lambda}}$$

E.g., (see ERA) this works out to ~2,000 km for the GBT at 1 cm.

# apertures and beams

The aperture of a telescope is a plane through which all rays incident on a telescope pass (in phase in the far field approximation just discussed).

**Beam pattern** of a telescope: the power gain as a function of position on the sky.

Note the reciprocity theorem: this is both the pattern of power that would be transmitted by the telescope (in an active mode) and the sensitivity of the telescope (in passive mode) to power on the sky.

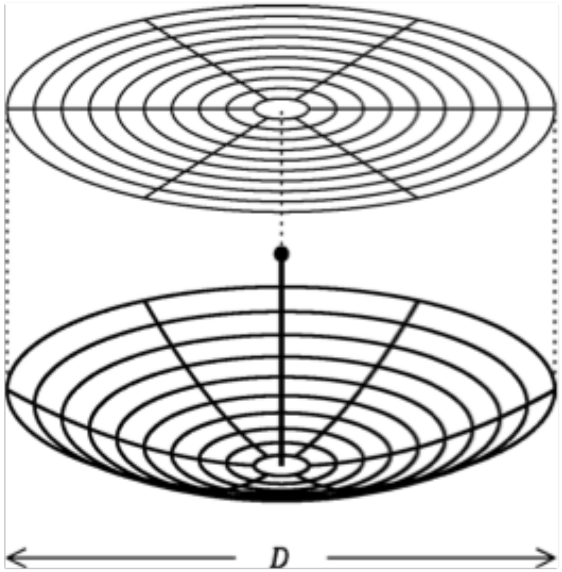
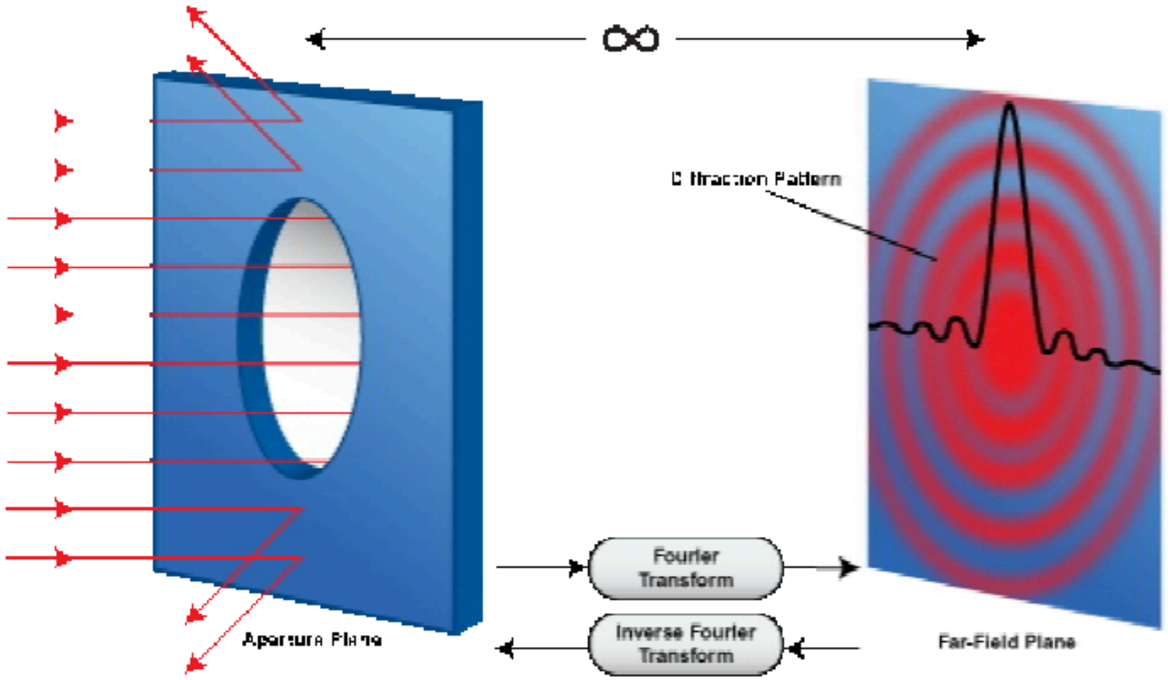


*Illustration of the associated aperture (top) for a circular parabolic reflector.*

# Radio Telescopes / Antennas

When considering the properties of a radio astronomy antenna its often useful to think in terms of it transmitting (rather than receiving).



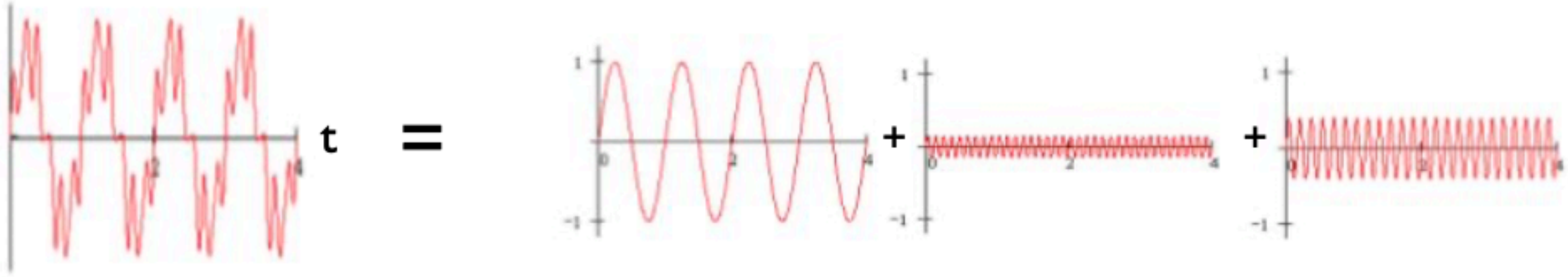
Two theorems...

- Reciprocity theorem: Performance of an antenna when collecting radiation from a point source at infinity may be studied by considering its properties as a *transmitter*:

- Far-field pattern (the antenna's "beam") is the Fourier Transform of aperture plane electric field distribution:

# Fourier Transforms

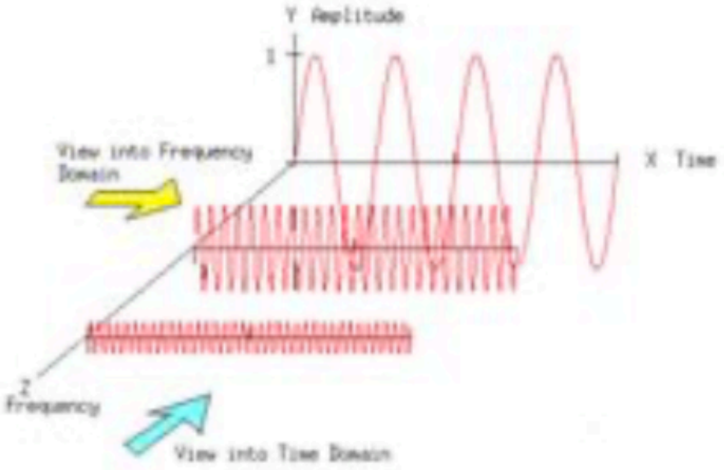
The use of Fourier transforms in radio astronomy is ubiquitous. In the 19th Century, Baron Fourier noticed that its possible to create some very complicated signals by summing up very simple sine and cosine waves of various amplitudes and frequencies:

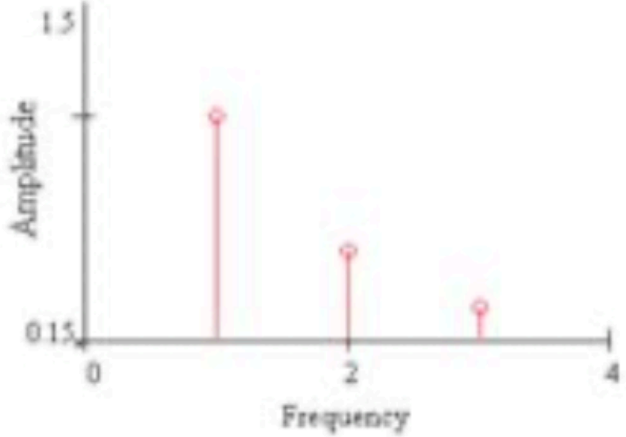


*Complex signal*

*3 simple sine waves added together*

We can also view the same signals in the frequency domain (z-axis):





# Fourier Transforms

FT from the time domain to the frequency domain:

$$F(\nu) = \int_{-\infty}^{\infty} f(t) e^{-2\pi i \nu t} dt$$ is the Fourier transform of $f(t)$

$$f(t) = \int_{-\infty}^{\infty} F(\nu) e^{2\pi i \nu t} d\nu$$ is the inverse FT of $F(\nu)$

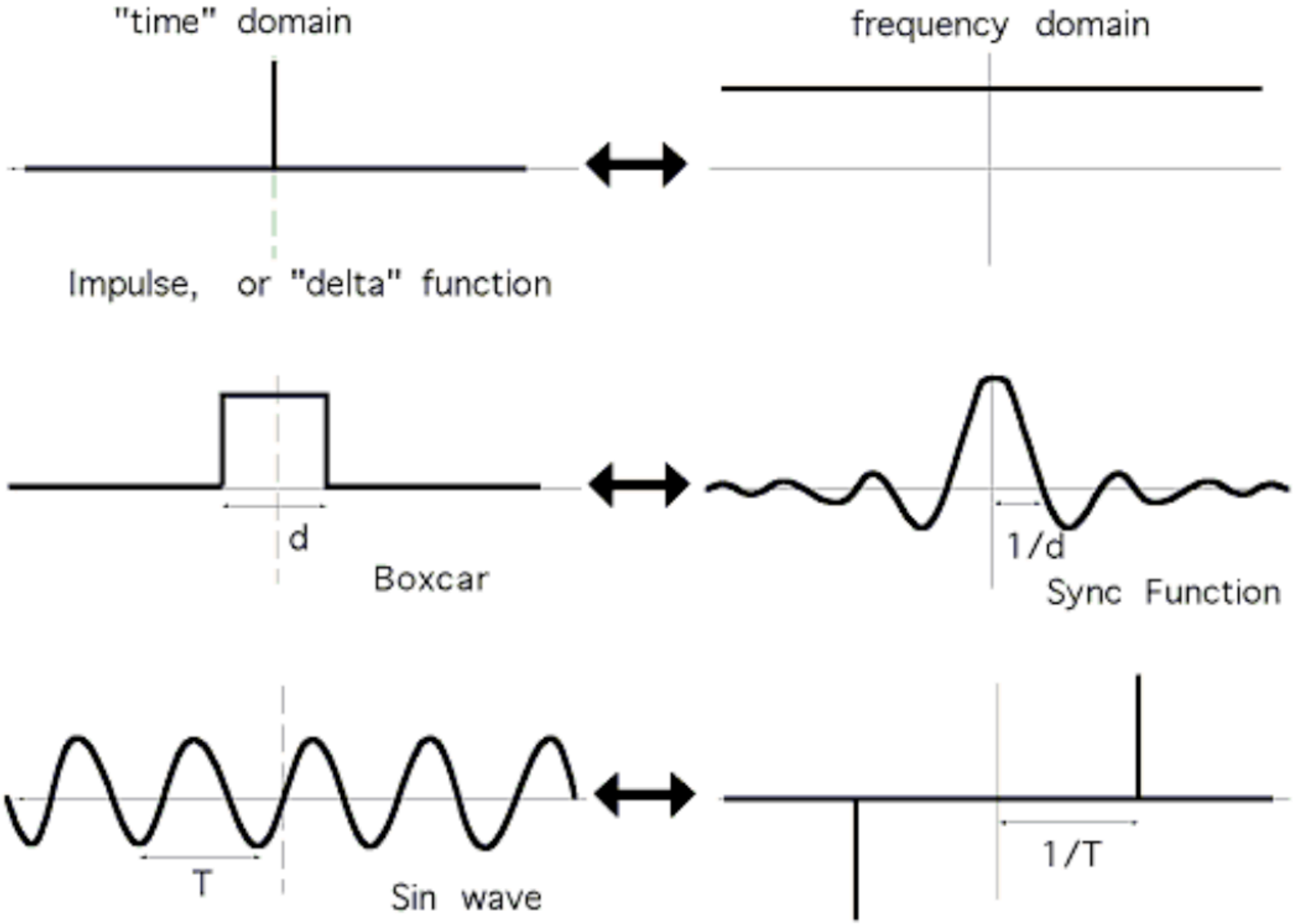
Basically, the idea is that any function can be expressed as the sum of a series of sines and cosines of varying amplitude and phase.

In other words, f(t) can be built up from the spectral distribution F(v) which is the power at frequency v.

See “The Fourier Transform and its applications” by Ronald Bracewell.

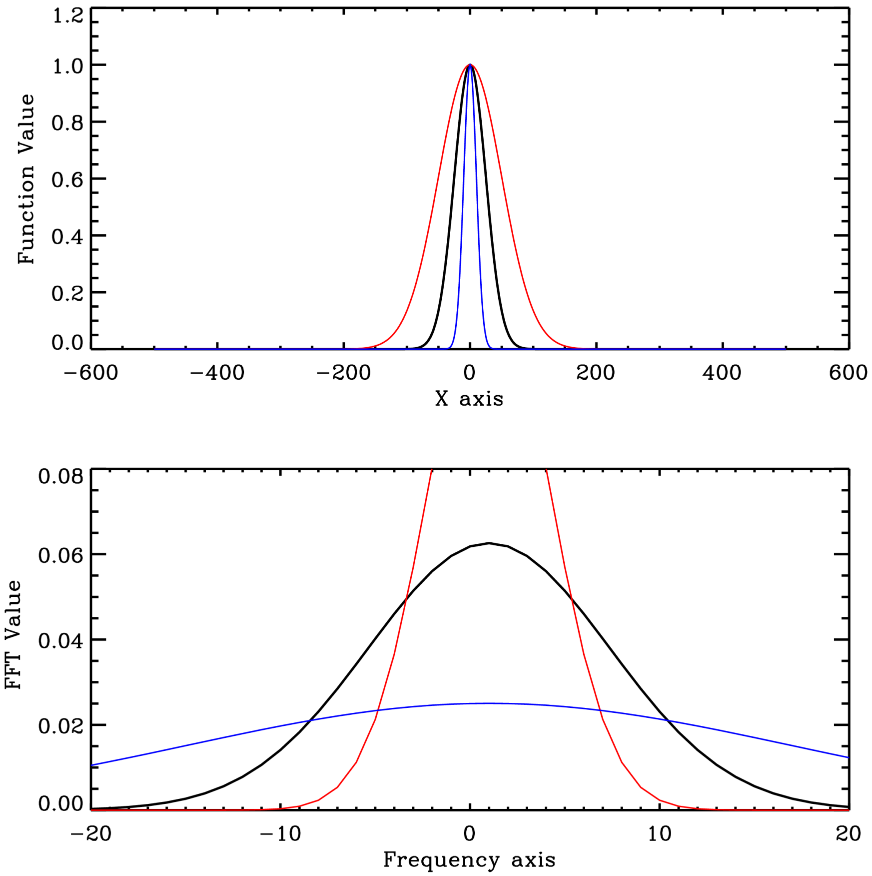
The fourier transform of a function e.g. f is often denoted as F (f) and the inverse is $F^{-1}$ (f).

# Fourier Transforms



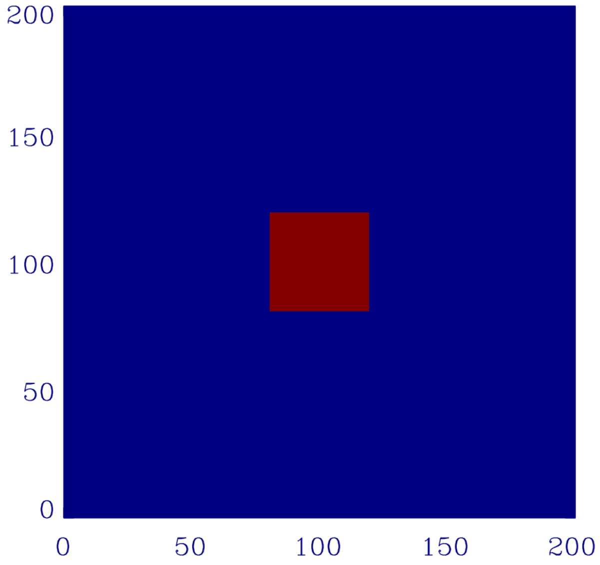
# Fourier Transforms

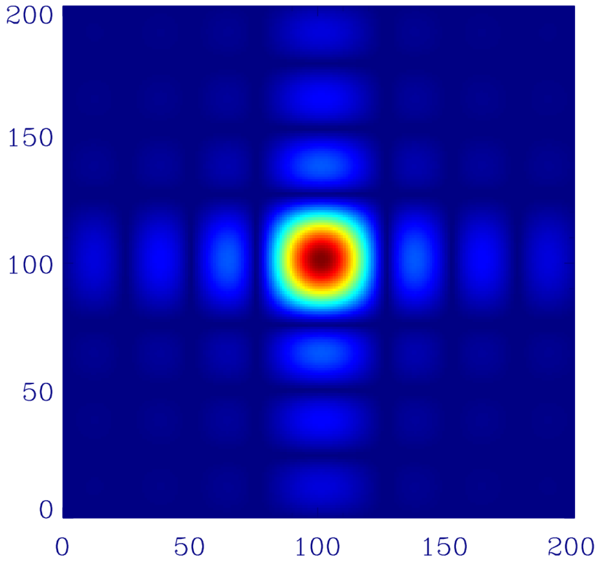
Fourier transform of a Gaussian is a Gaussian. Broad goes to narrow in the Fourier plane. A big dish gives a narrow beam, e.g.

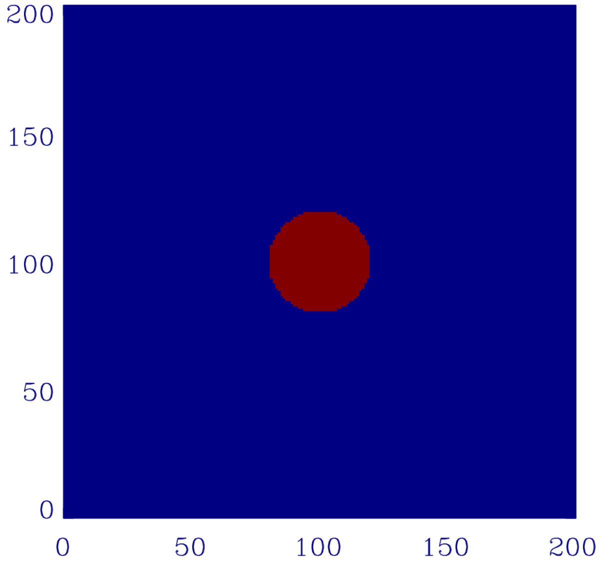


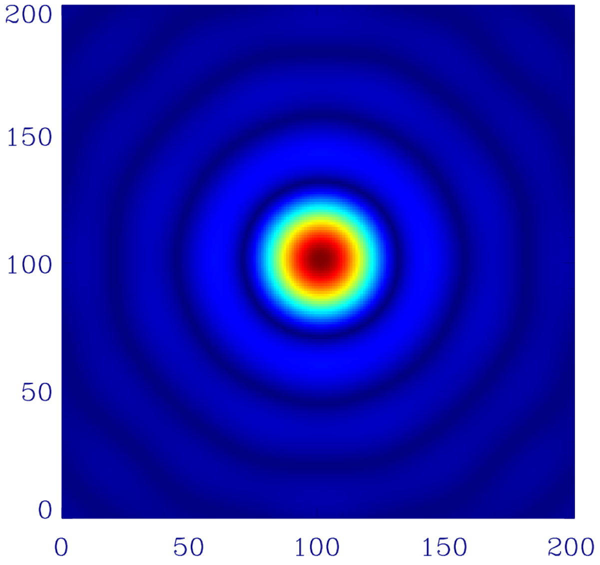
A general thing about FTs to keep in mind, is that a function which is *wide* in one domain is *narrow* in the other, and vice-versa.

# Fourier Transforms

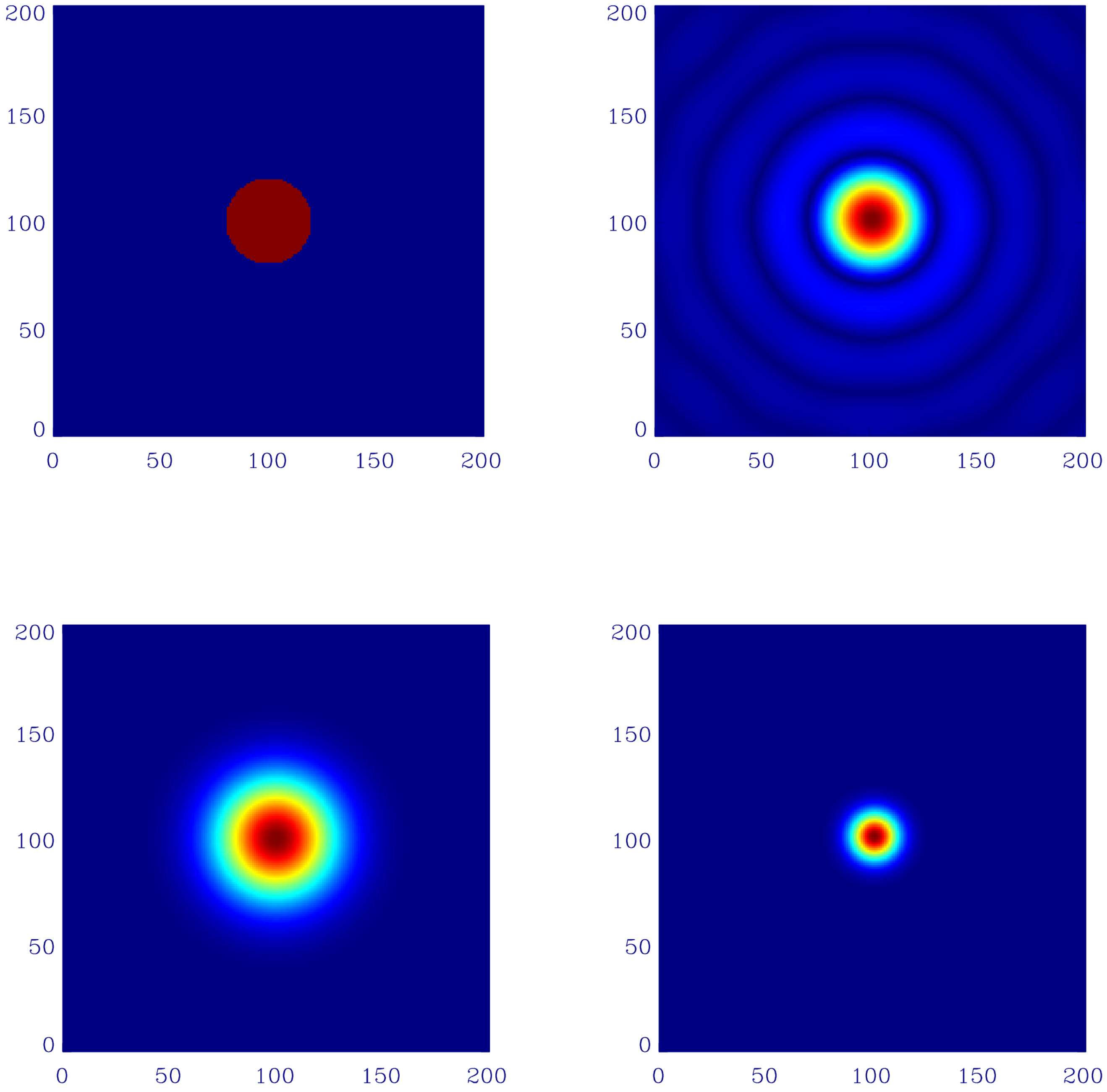






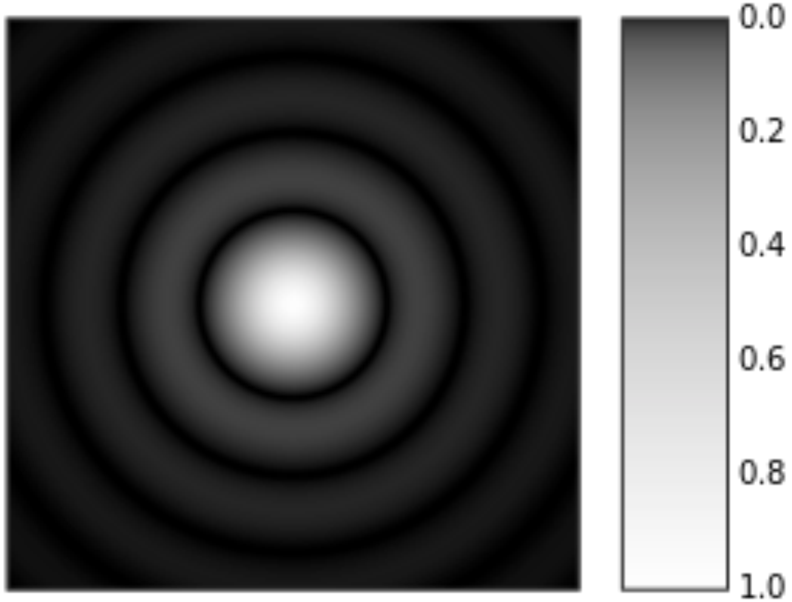


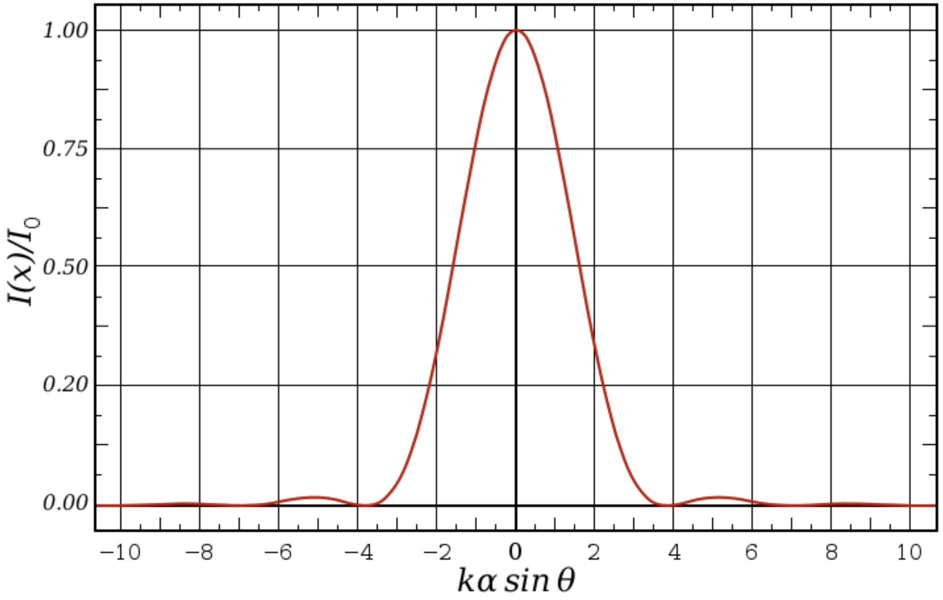
# Fourier Transforms

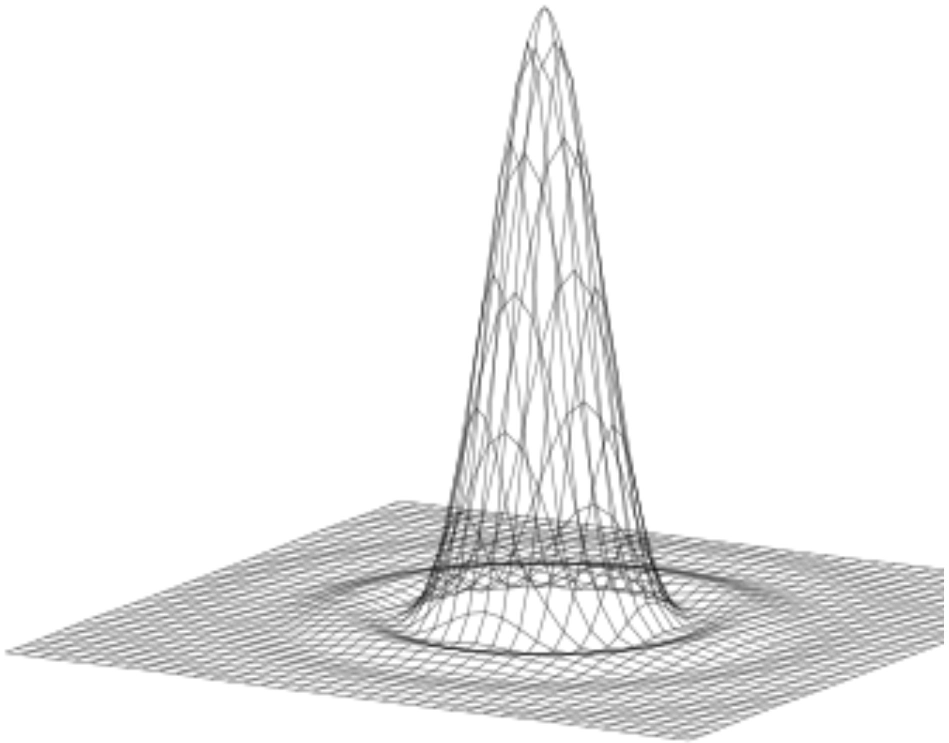


# response of one antenna

The response of a uniformly illuminated circle is the “Airy Pattern”.

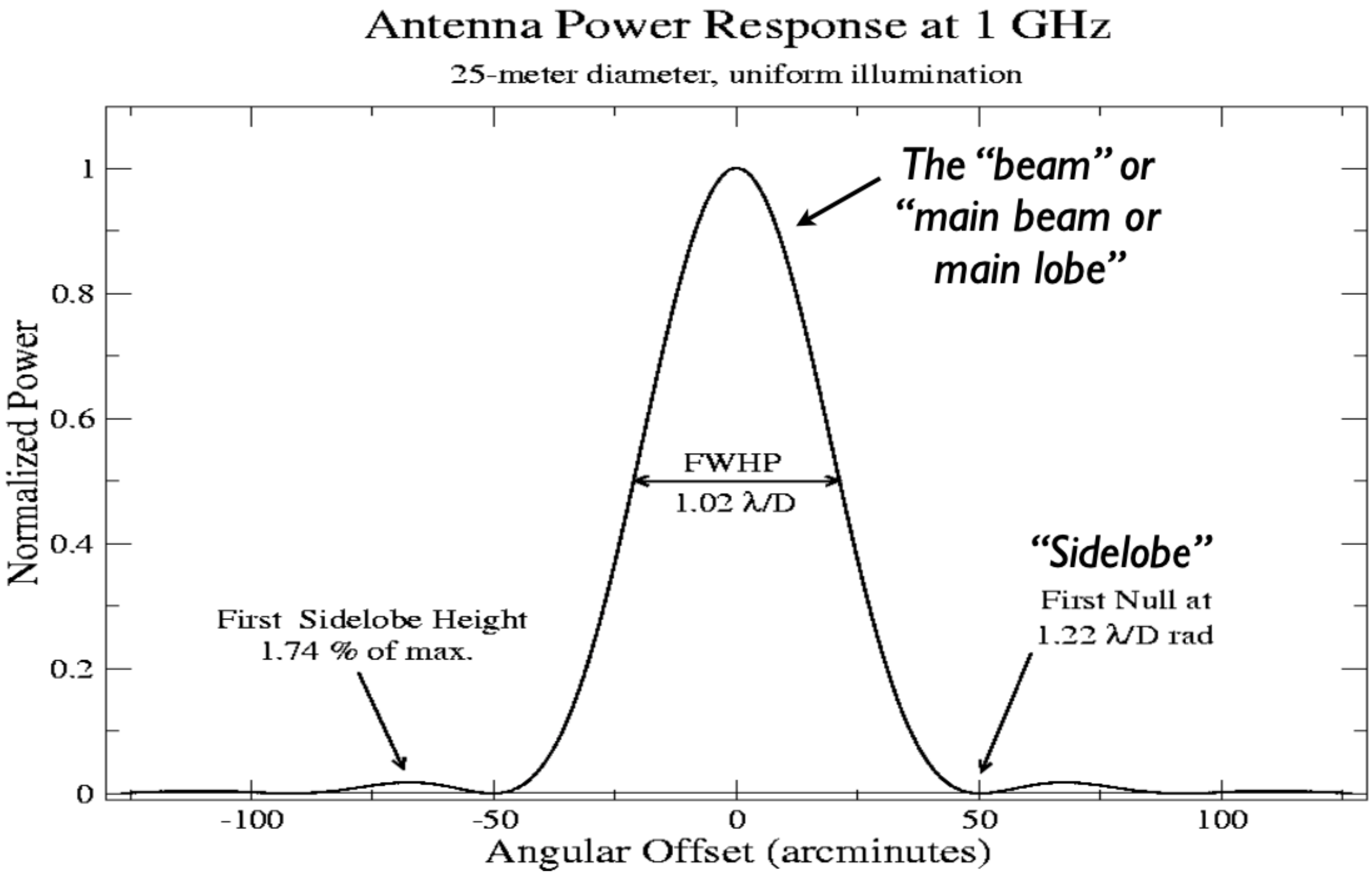






# response of one antenna

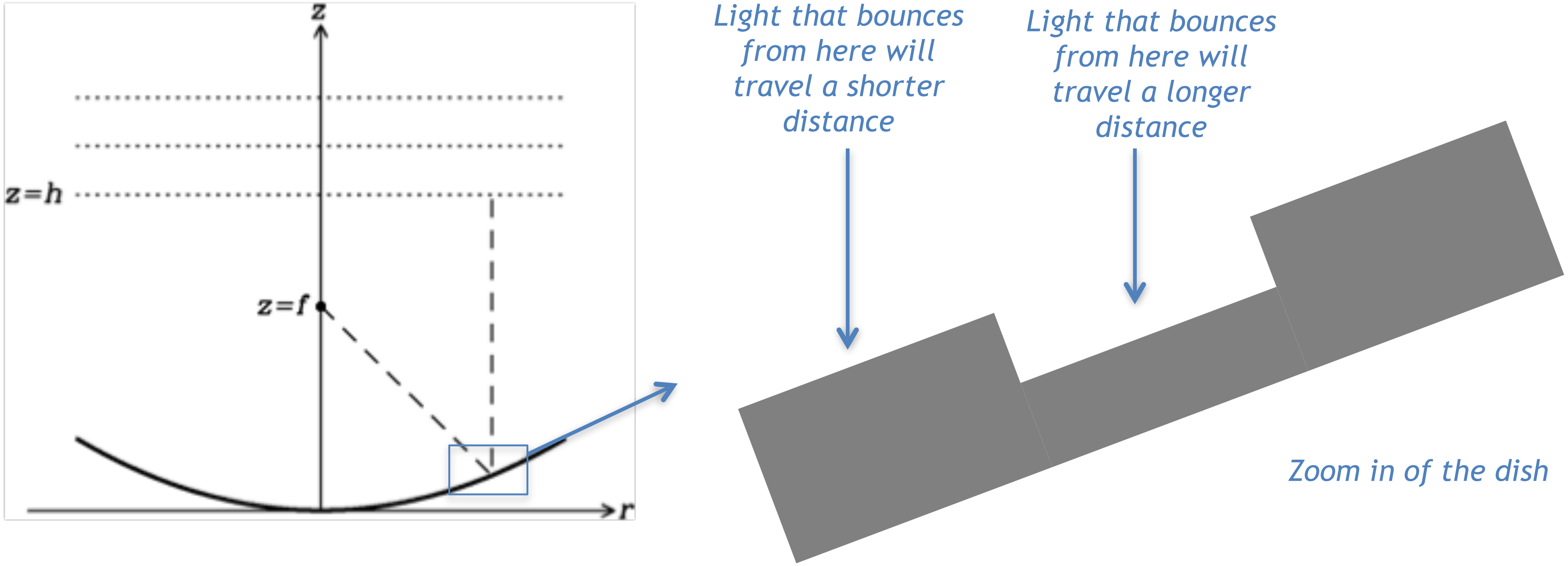
The response of a uniformly illuminated circular parabolic antenna of 25-metre diameter, at a frequency of 1 GHz



# how good does reflector have to be?

We motivated the parabaloid dish shape, but how good does the dish need to be in practice?

An uneven dish surface will induce variations in the the path length that cause light to arrive out of phase.



*Light that bounces from here will travel a shorter distance*

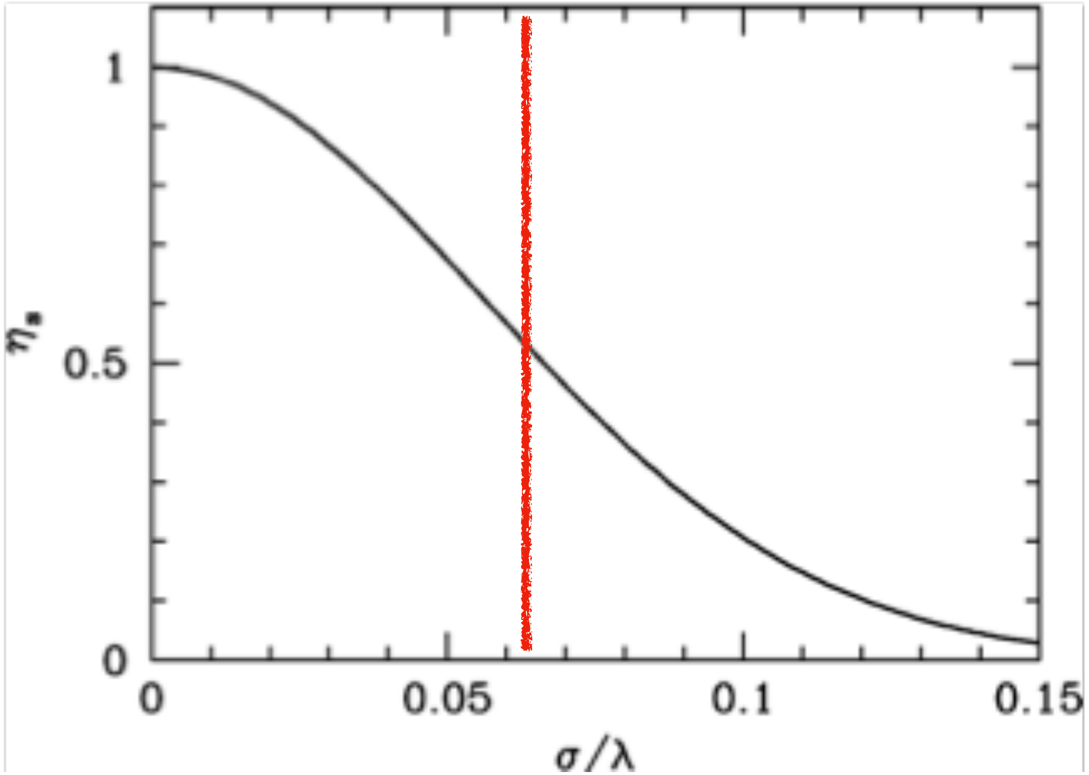
*Light that bounces from here will travel a longer distance*

*Zoom in of the dish*

Just looking at this sketch you can see that the path length variations will move light out of phase, since the mapping between phase and distance depends on the wavelength the precision to which the dish must be polished relative to the wavelength.

# how good does reflector have to be?

The efficiency as a function of accuracy in units of wavelength (derivation see ERA):



ERA quotes a common effective cutoff of σ ~ λ/16 for a dish to operate effectively at a particular wavelength. At this precision the efficiency is ~ 0.54.

# example: LMT ‘50m’

# performance

The antenna aperture efficiency $\eta$ = $\dfrac{\text{Power collected by feed}}{\text{Power incident on antenna}}$

There are many different potential loss factors: $\eta = \eta_{sf}\eta_{bl}\eta_{sp}\eta_{t}\eta_{misc}$

$\eta$ ~ 0.65 <==

Surface efficiency ~ 0.9

Aperture blockage efficiency ~ 0.9

Feed spillover efficiency ~ 0.9

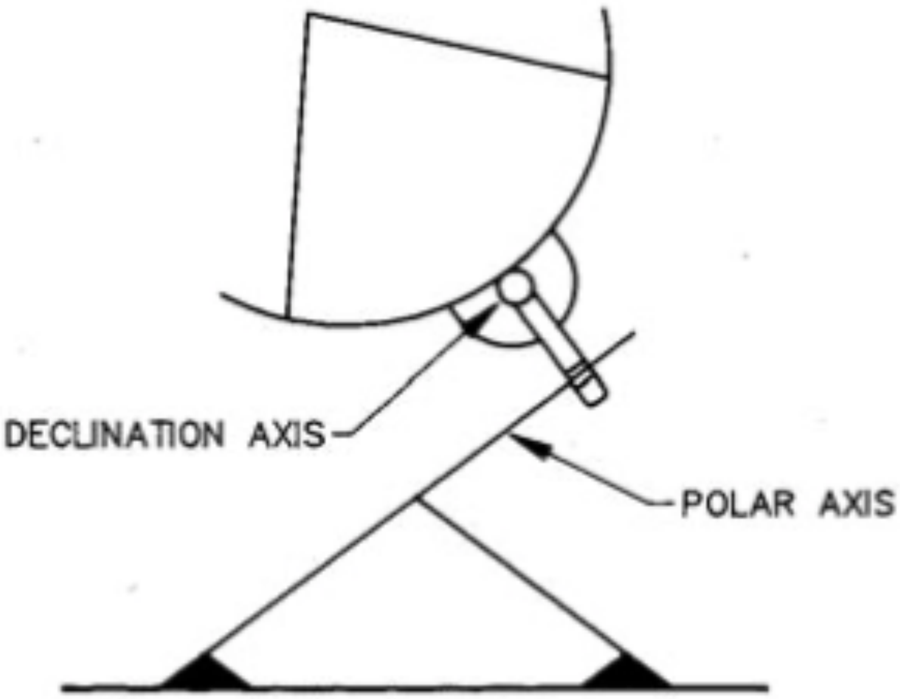
Feed illumination efficiency ~ 0.9

Misc. - other minor losses e.g feed mis-match.

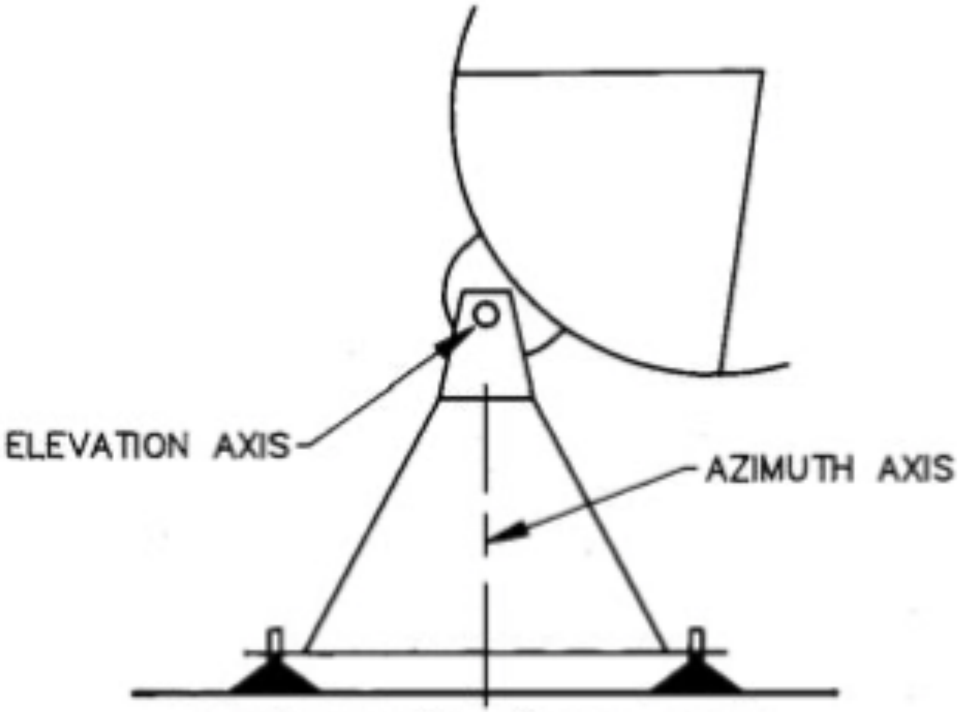
# different mounts

Different types of mount:

Modern antennas are mostly **alt-az** (rotate around 2-axes) because they are cheaper to build and well-balanced mechanically (important for large, heavy telescopes).



EQUATORIAL MOUNT



ALTITUDE OVER AZIMUTH MOUNT

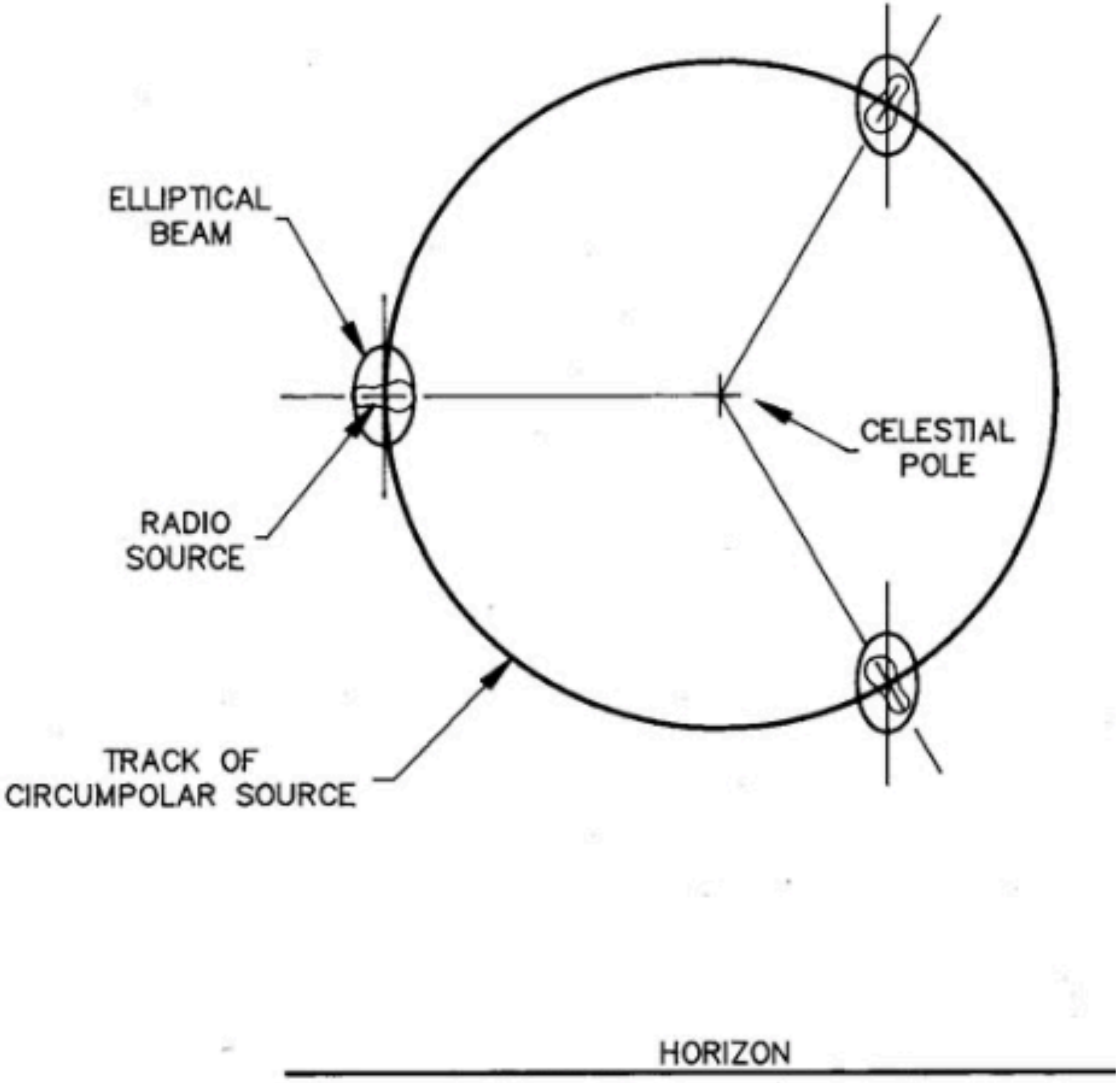
# different mounts

**Polar mount** rotates around 1-axis.

Disadvantage of Polar mount: heavy counterweights, harder to build

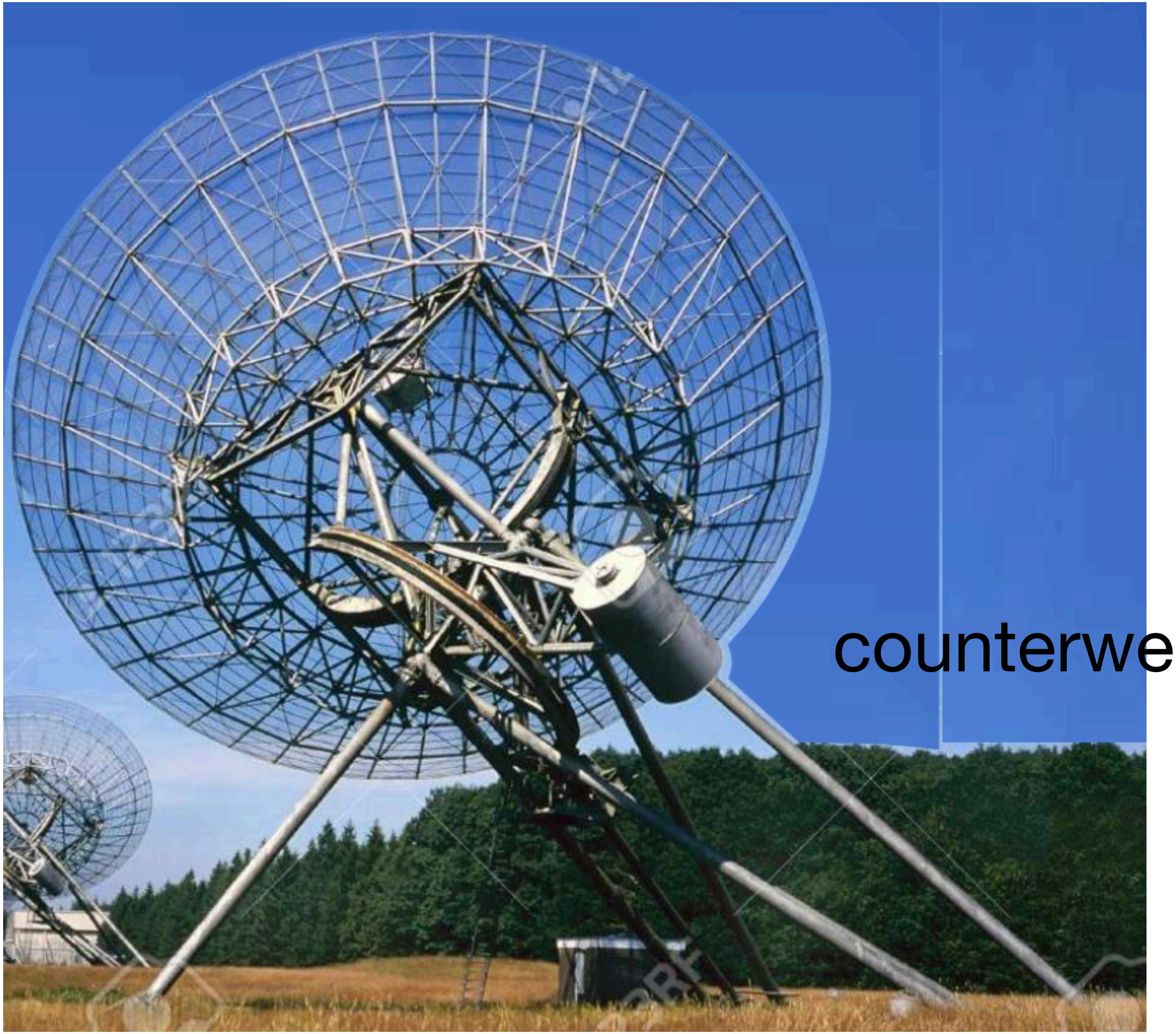
Disadvantage of alt-az telescopes is that the orientation of the telescope beam changes (rotates) as the source moves across the sky (see left). This needs to be corrected for in software e.g. for polarisation measurements.

also: changing bright sources pass through sidelobes!



alt-az mount

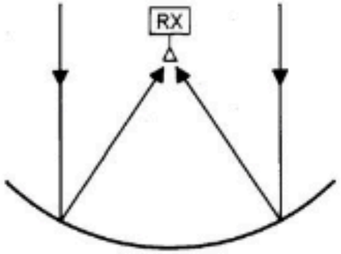
Equitorial (polar) mount



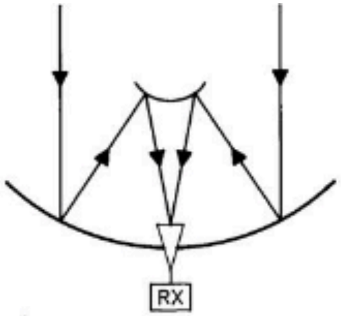
counterweight!

# reflector types

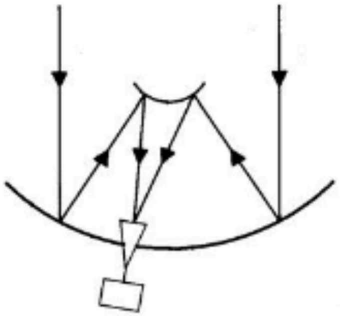
Prime Focus



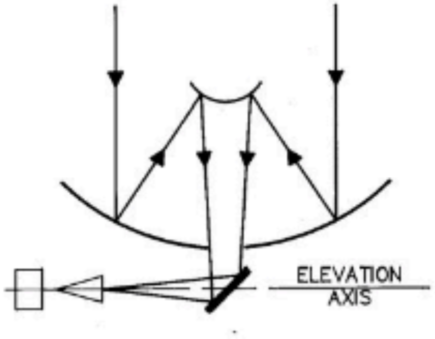
Cassegrain Focus



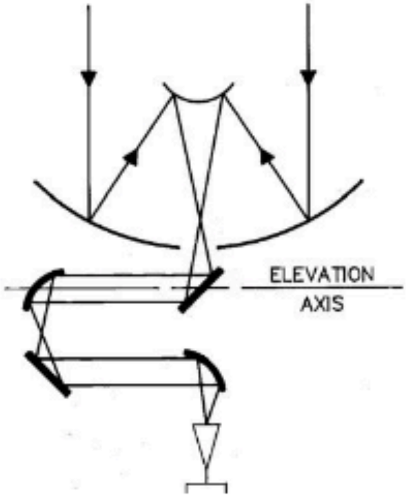
Offset Cassegrain



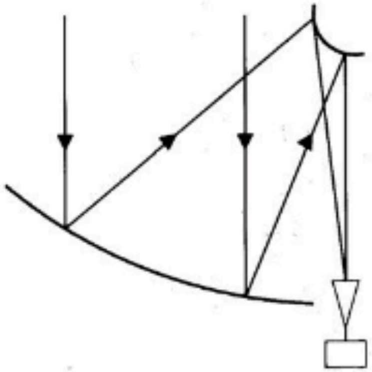
Naysmith



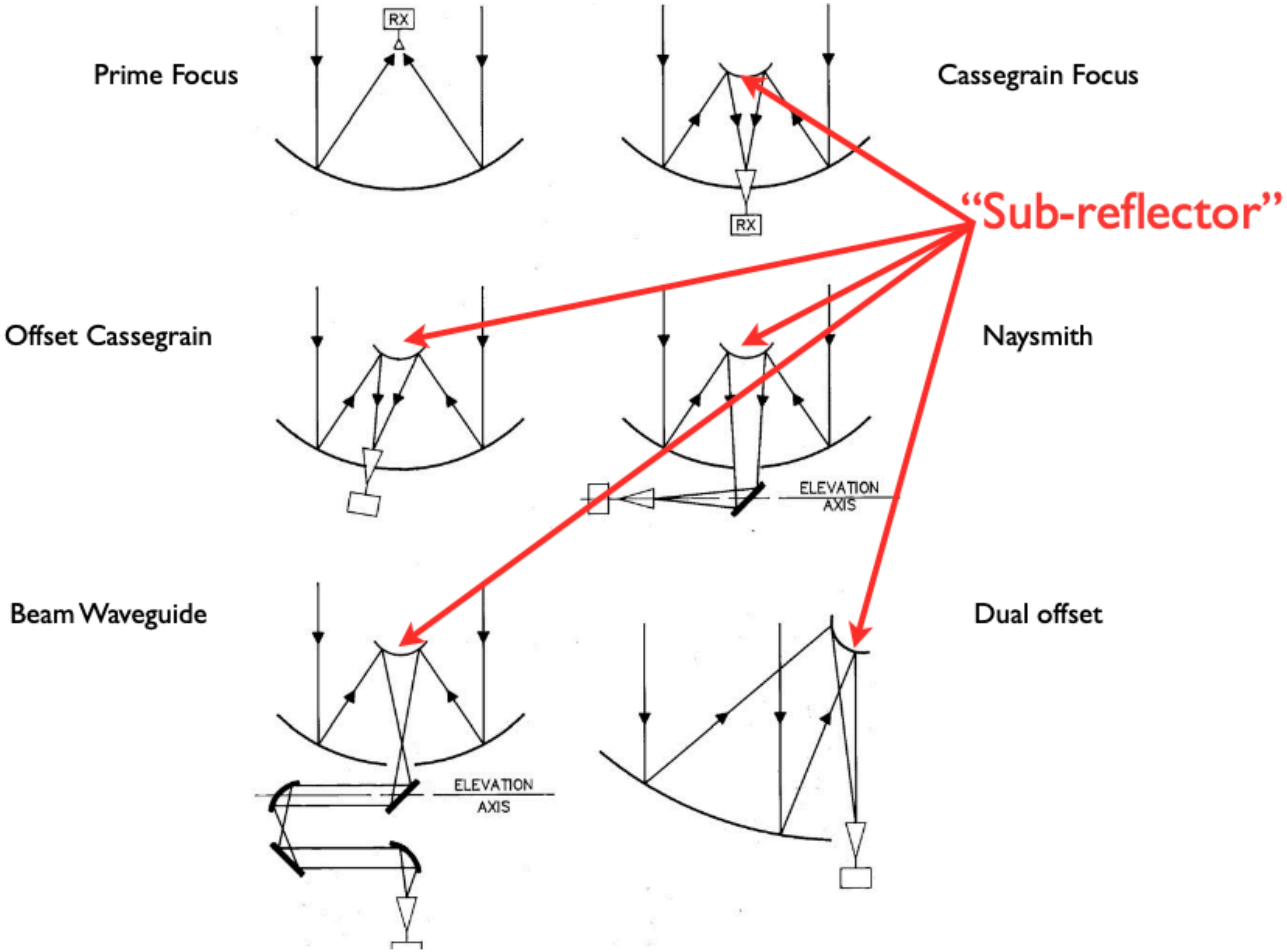
Beam Waveguide



Dual offset



# reflector types



# reflector types

- prime focus - can be used across full frequency range of antenna but access to receiver is restricted
- Cassegrain (and other non-prime focus e.g. Naysmith and waveguide) provide good access to receivers but low-frequency receivers become impractically large and must be placed at prime focus.
- Off-axis Cassegrain (e.g.VLA antennas) enables frequency flexibility; receivers located in a circle can be quickly rotated to the focus. However, the assymetry of the offset optics introduces nasty polarisation characteristics that can limit imaging results.

# reflector types

Prime Focus
e.g. GMRT

Cassegrain Focus
e.g. Mopra (AT)

Offset Cassegrain
e.g.VLA and
ALMA

Naysmith
e.g. OVRO

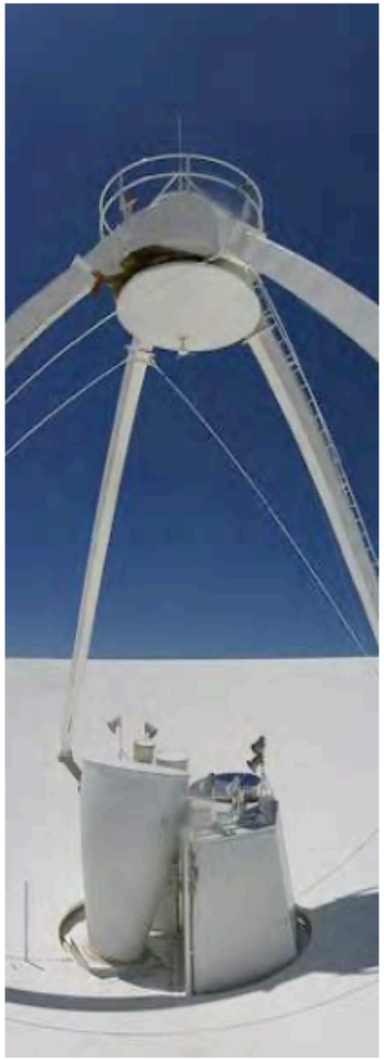
Beam Waveguide
e.g. NRO

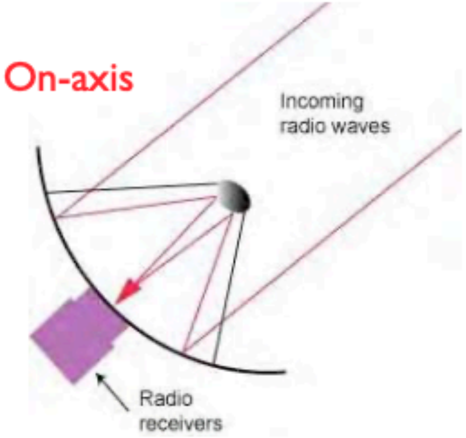
Dual gregorian
offset
e.g. ATA

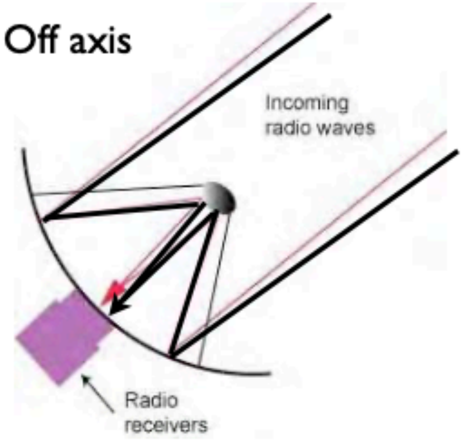
# off-Gregorian

The VLA uses a rotating turret to position each of its feeds (receivers) slightly off-axis. Leads to some calibration problems.

Gregorian Receiver Room



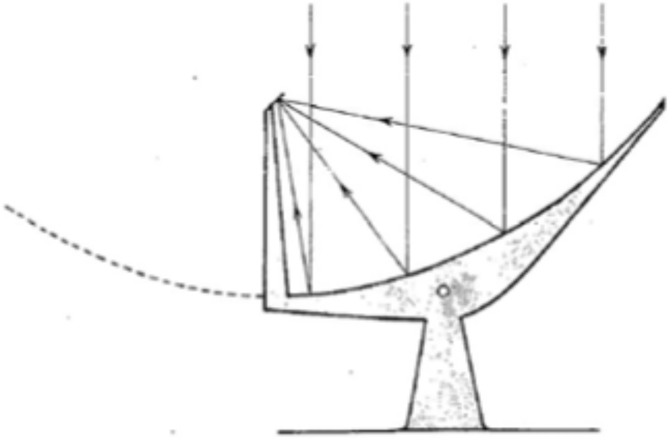




# blockage of aperture

Offset gregorian has no blockage of the aperture.

A good example of this system includes the Green Bank Telescope (GBT):



# 50 years of Effelsberg

inauguration took place on May 12, 1971

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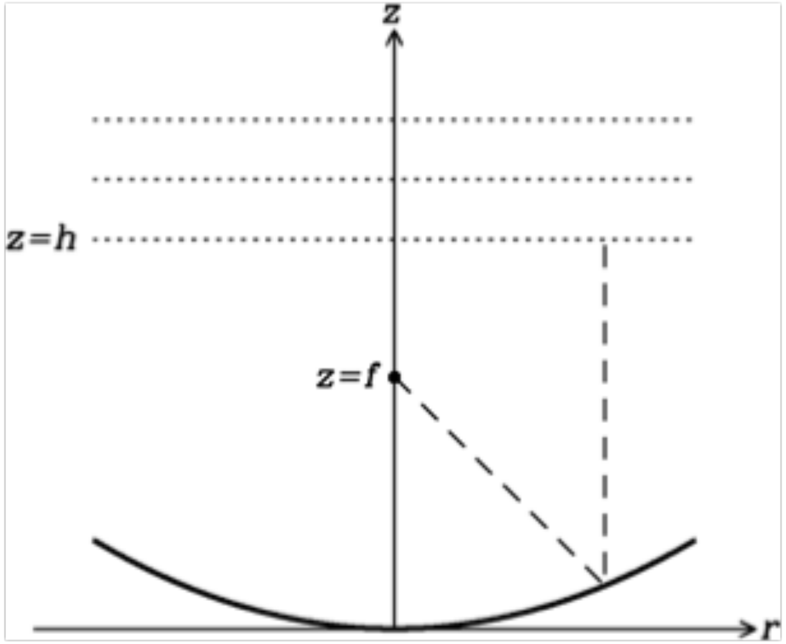
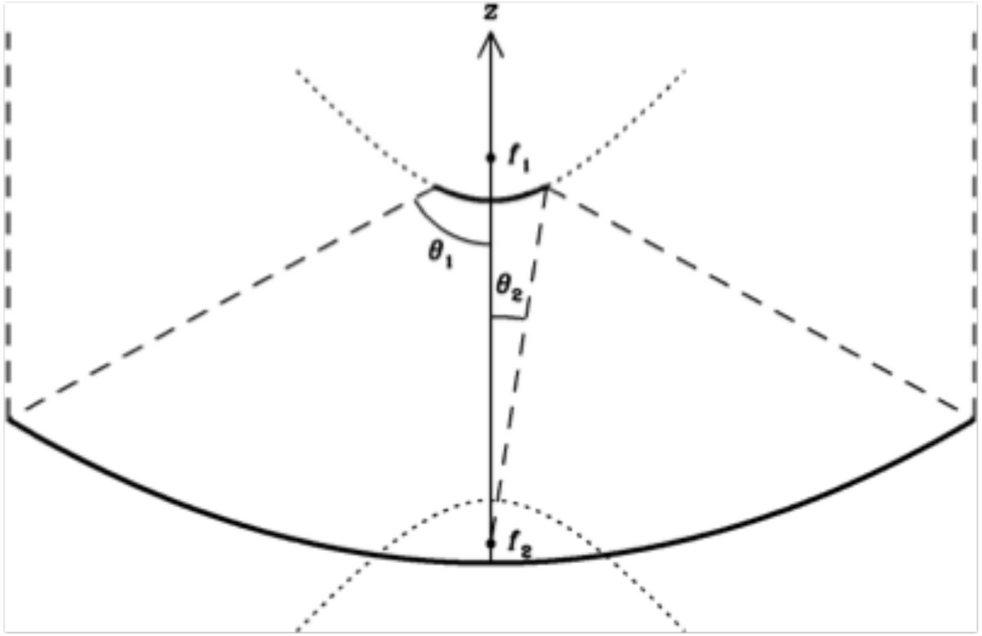
The focal ratio (focus length / diameter ~ f/D) is a semi-free parameter. Typically small (so dishes are deep) in radio for structural reasons (note contrast with optical).

Note that rays are in focus over an area **~ (f/D)²** – so a small focal ratio means small focal area (focal plane) to work with. This limits instrumentation suite (especially arrays).

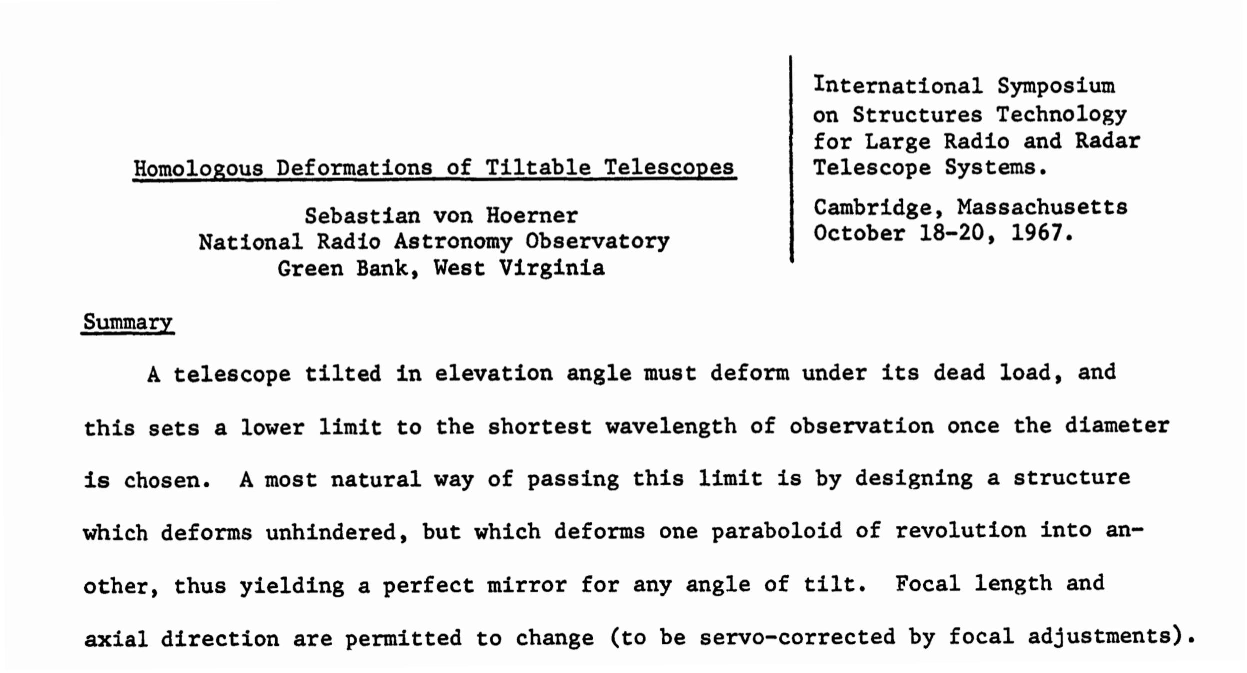


*In practice a secondary reflector is more common than a receiver at the focus of the dish*

*:*



# homology



International Symposium
on Structures Technology
for Large Radio and Radar
Telescope Systems.

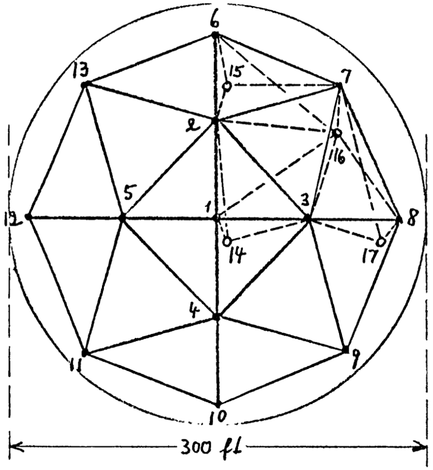
Cambridge, Massachusetts
October 18-20, 1967.

## Homologous Deformations of Tiltable Telescopes

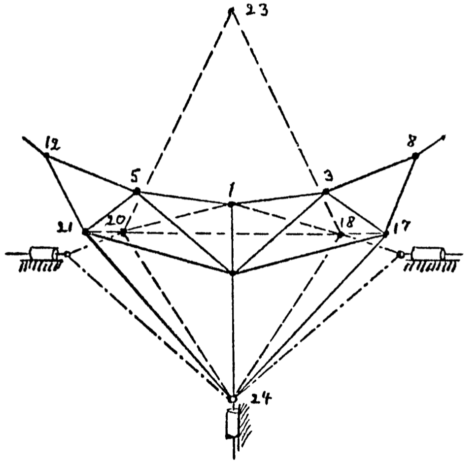
Sebastian von Hoerner
National Radio Astronomy Observatory
Green Bank, West Virginia

### Summary

A telescope tilted in elevation angle must deform under its dead load, and this sets a lower limit to the shortest wavelength of observation once the diameter is chosen. A most natural way of passing this limit is by designing a structure which deforms unhindered, but which deforms one paraboloid of revolution into another, thus yielding a perfect mirror for any angle of tilt. Focal length and axial direction are permitted to change (to be servo-corrected by focal adjustments).



c) Surface and layer 2 (one quadrant).
Circle = rim of surface pannels.



d) Side view of plane 12-8-24,
octahedron and suspension.

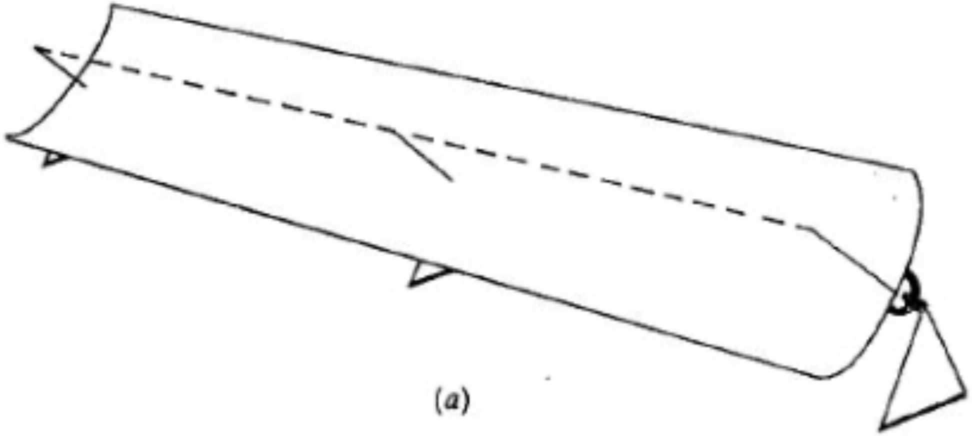
# less conventional reflector types

The Jodrell Bank Mark 2 telescope (1964). Was considered to be a prototype of the then planned giant 300-metre MkIV. The aperture is elliptical - the idea was that a 300-metre would require an elliptical surface in order to reduce the height of the structure off the ground.

# less conventional reflector types

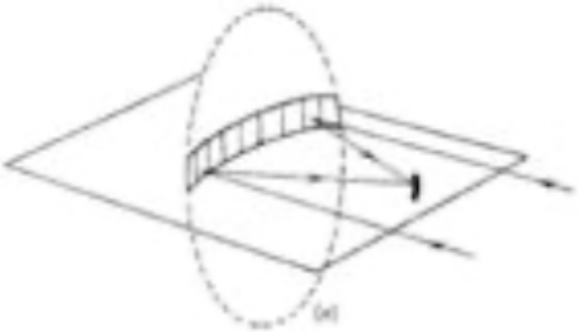
The off-axis cylinder radio telescope at Ooty. India (1970).

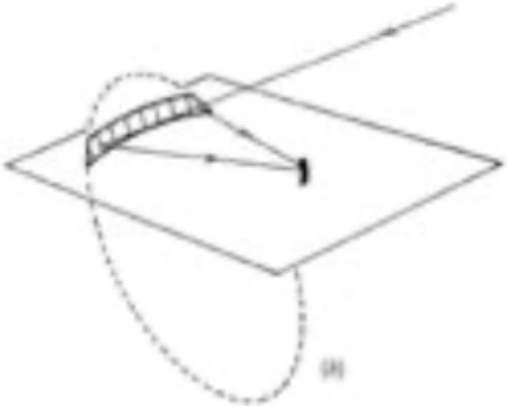
Cylinders are cheaper to build than paraboloids but have non- symmetrical beam patterns.

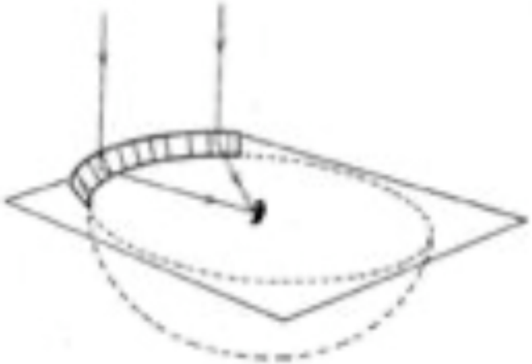


(a)

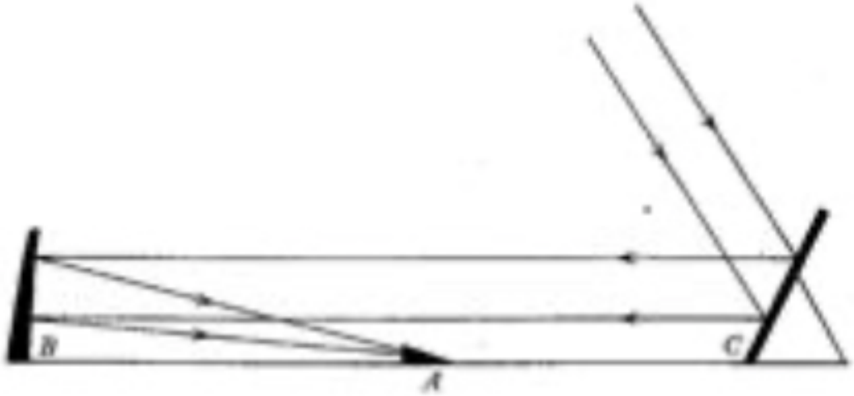
# less conventional reflector types



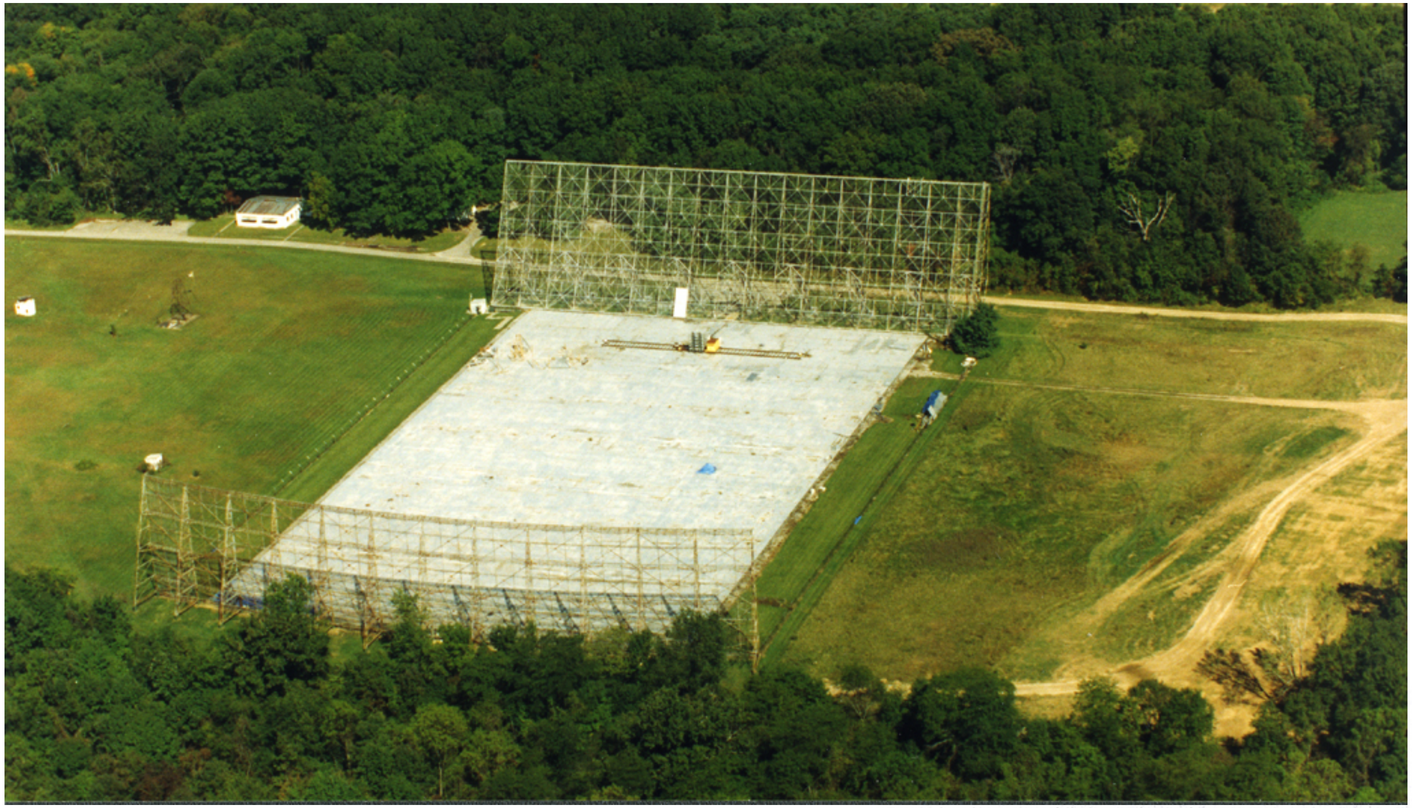




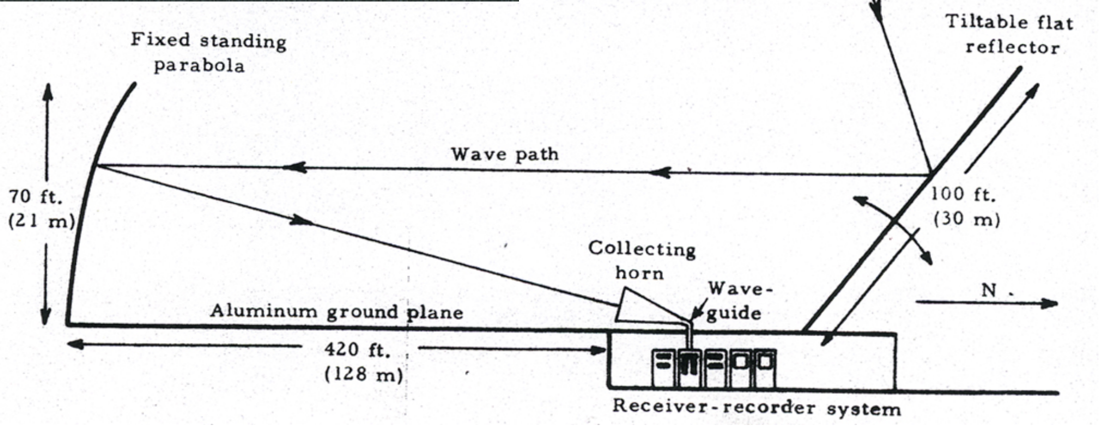
Instead of building a large paraboloid the **Kraus antenna** employs (sub-) sections of a parabolic surface. To steer the beam the reflector needs to be tilted



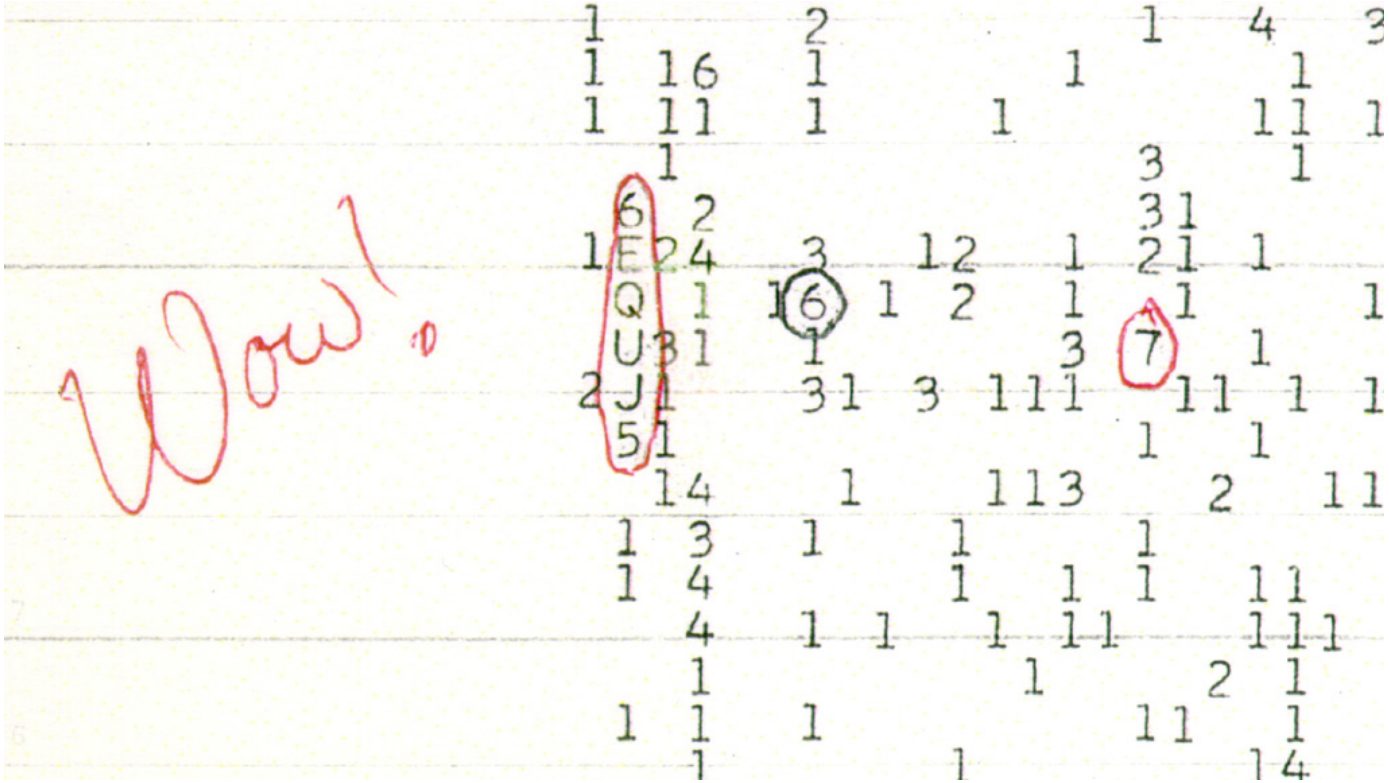
# Big Ear Telescope



Big Ear telescope



# Big Ear’s ‘Wow!’ signal (SETI)



never confirmed…

https://en.wikipedia.org/wiki/Wow!_signal

# RATAN-600

600m diameter!

# RATAN-600

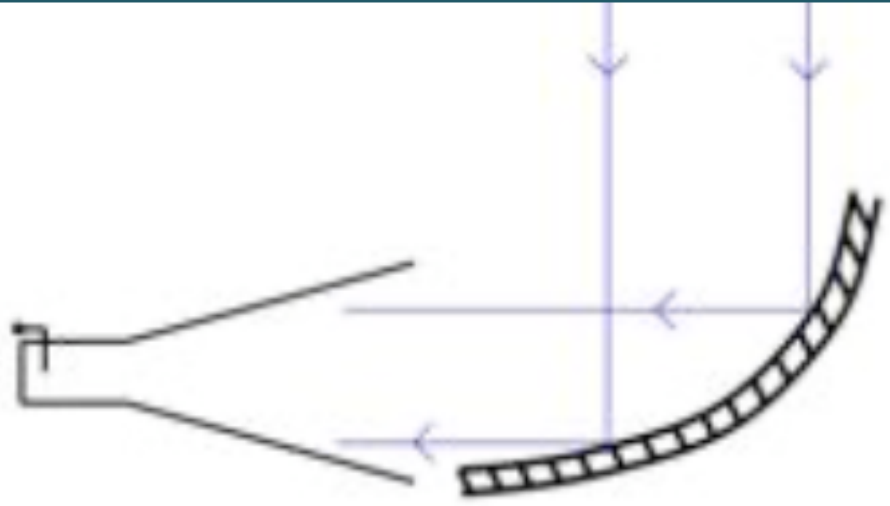
# RATAN-600


радиотелескоп РАТАН - 600
1987
ПОЧТА СССР
20к


Timur Agirov | timag82.livejournal.com

# horn antenna

The reflecting “ear” reflects the incoming radio waves towards a horn or bare dipole.



extremely broad-band, good aperture efficiency, and the sidelobes are so minimal that hardly any thermal energy is picked up from the ground.

Consequently it is an ideal radio telescope for accurate measurements of low levels of weak background radiation.

A famous example is the horn antenna located at Bell Telephone Laboratories in Holmdel, New Jersey, used by Penzias and Wilson to detect the relic radiation of the big bang.

Horn antennas have many practical applications - they are used in short-range radar systems, e.g. the hand- held radar “guns” used by police to measure the speeds of approaching or retreating vehicles.

# horn antenna

The Bell Telephone Laboratories horn in Holmdel, New Jersey.

Note the rotation axis that permits the horn to be directed at different points in the sky.

## FIRST PHONE CALL VIA MAN-MADE SATELLITE!

"Project Echo" satellite went into a near-perfect circular orbit 1000 miles high, circling the earth once every two hours. Its orbital path covered all parts of the U. S.

## BELL TELEPHONE LABORATORIES BOUNCES VOICE OFF SPHERE PLACED IN ORBIT A THOUSAND MILES ABOVE THE EARTH

Think of watching a royal wedding in Europe by live TV, or telephoning to Singapore or Calcutta—*by way of outer-space satellites!* A mere dream a few years ago, this idea is now a giant step closer to reality.

Bell Telephone Laboratories recently took the step by successfully bouncing a phone call between its Holmdel, N. J., test site and the Jet Propulsion Laboratory of the National Aeronautics and Space Administration (NASA) in Goldstone, California. The reflector was a 100-foot sphere of aluminized plastic orbiting the earth 1000 miles up.

### Dramatic application of telephone science

Sponsored by NASA, this dramatic experiment—known as "Project Echo"—relied heavily on telephone science for its fulfillment . . .

- The Delta rocket which carried the satellite into space was steered into a precise orbit by the Bell Laboratories Command Guidance System. This is the same system which recently guided the remarkable Tiros I weather satellite into its near-perfect circular orbit.
- To pick up the signals, a special horn-reflector antenna was used. Previously perfected by Bell Laboratories for microwave radio relay, it is virtually immune to common radio "noise" interference. The amplifier—also a Laboratories development—was a traveling wave "maser" with very low noise susceptibility. The signals were still further protected from noise by a special FM receiving technique invented at Bell Laboratories.

"Project Echo" foreshadows the day when numerous man-made satellites might be in orbit all around the earth, acting as 24-hour-a-day relay stations for TV programs and phone calls between all nations.

This experiment shows how Bell Laboratories, as part of the Bell System, is working to advance space communication. Just as we pioneered in world-wide telephone service by radio and cable, so we are pioneering now in using outer space to improve communications on earth. It's part of our job, and we are a long way toward the goal.

Giant ultra-sensitive horn-reflector antenna which received signals bounced off the satellite. It is located at Bell Telephone Laboratories, Holmdel, New Jersey.

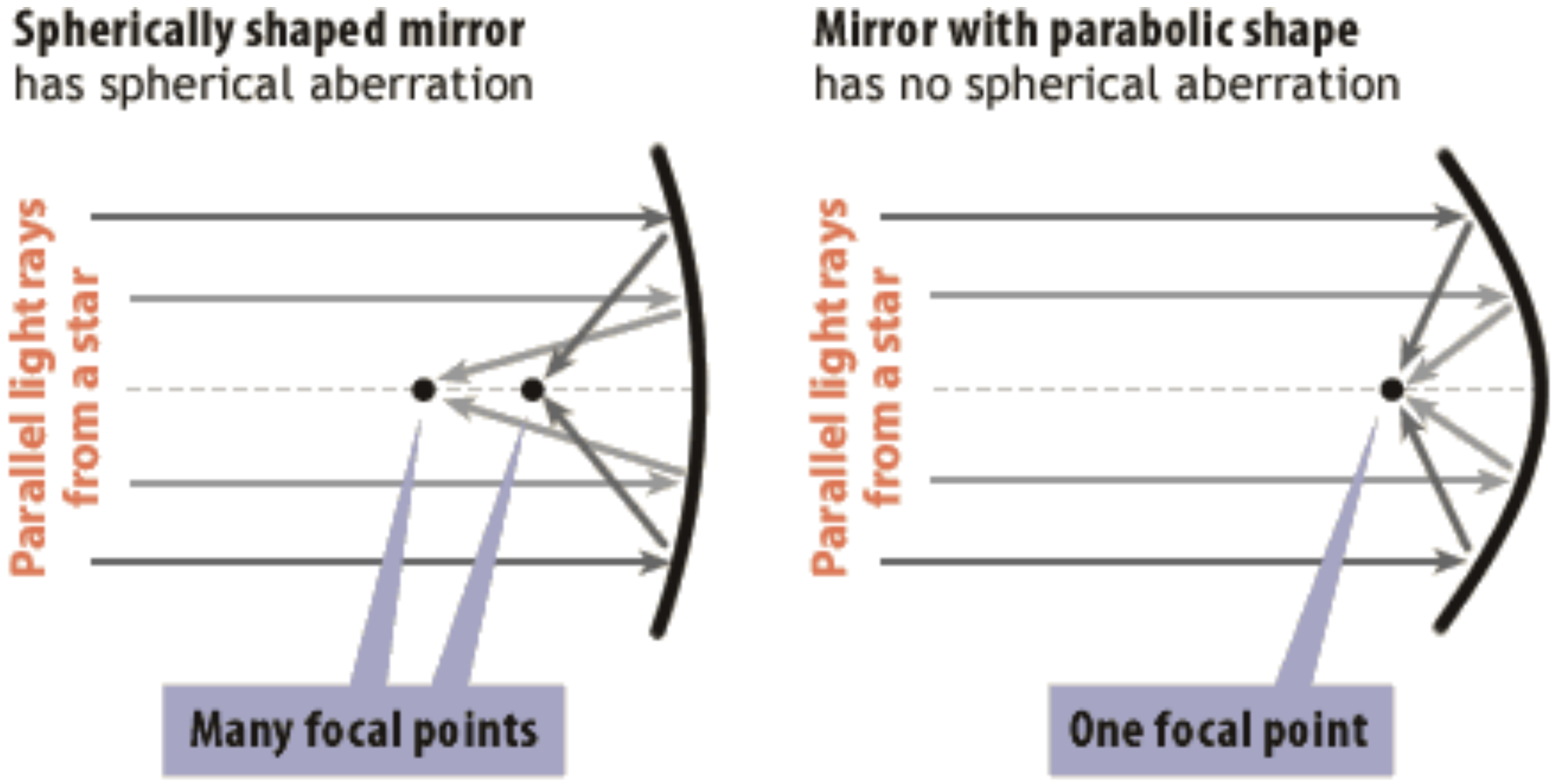
**BELL TELEPHONE LABORATORIES**

WORLD CENTER OF COMMUNICATIONS RESEARCH AND DEVELOPMENT

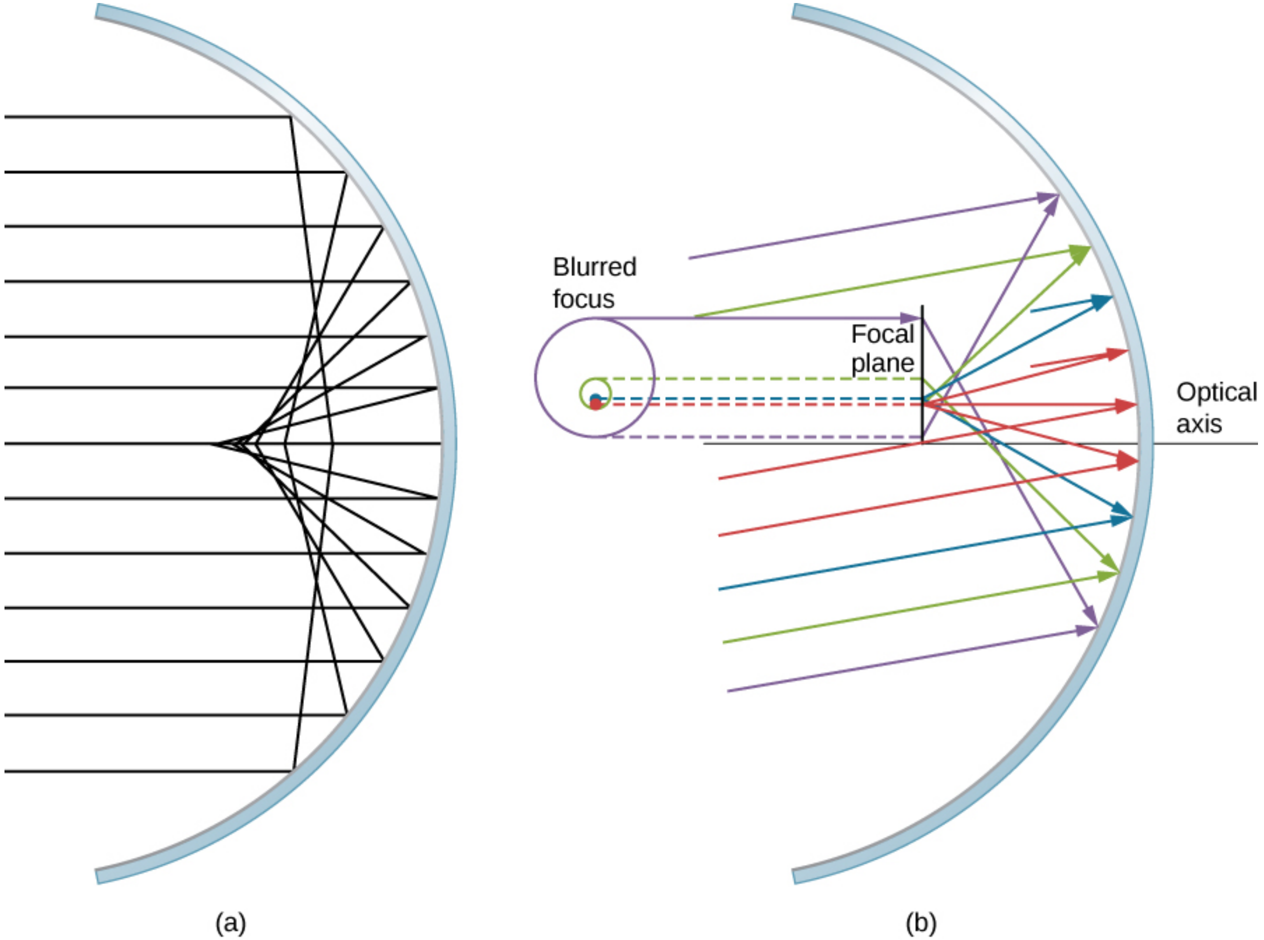
horn antenna

(later used to detect CMB)

# spherical vs parabolic mirror



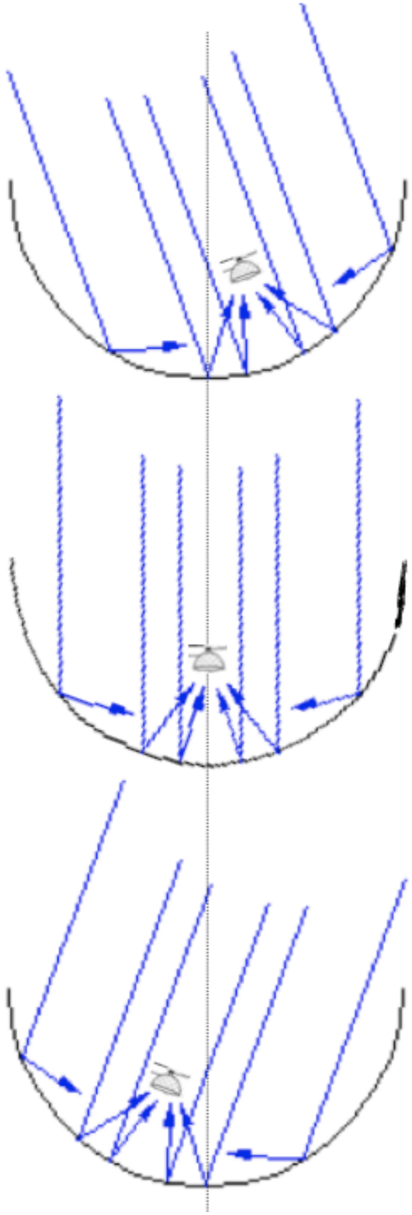
# a spherical mirror



By having a moving secondary a spherical reflector can be pointed in different (but still somewhat limited) directions on the sky.

Note that only part of the total surface area is useable for any given direction - for Arecibo the effective parabolic area typically available is about 2/3 of the physical area.

# different sky positions with spherical mirror

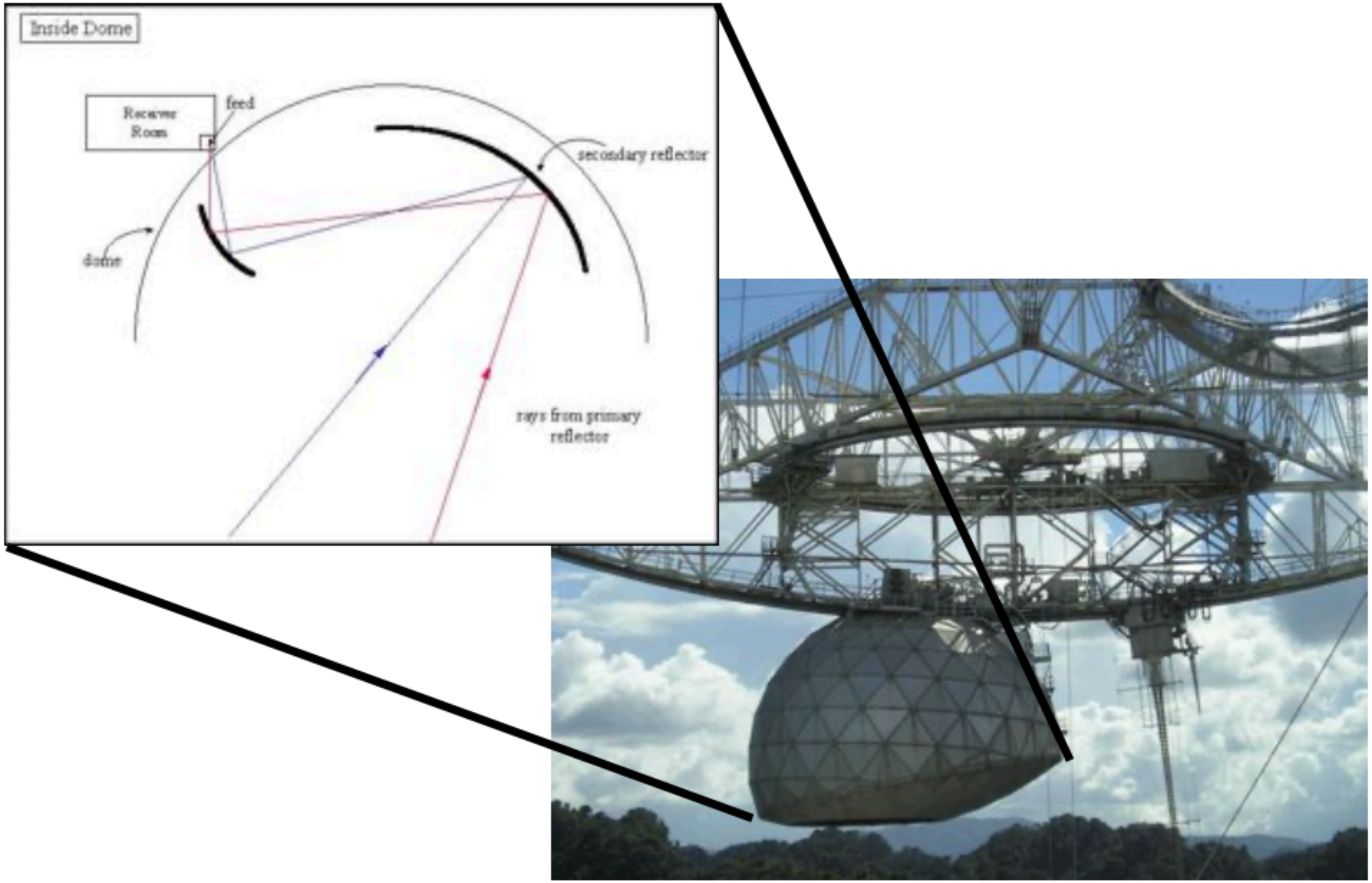


Typically, such a telescope can track a specific source for 2-3 hours. However the declination range is restricted.

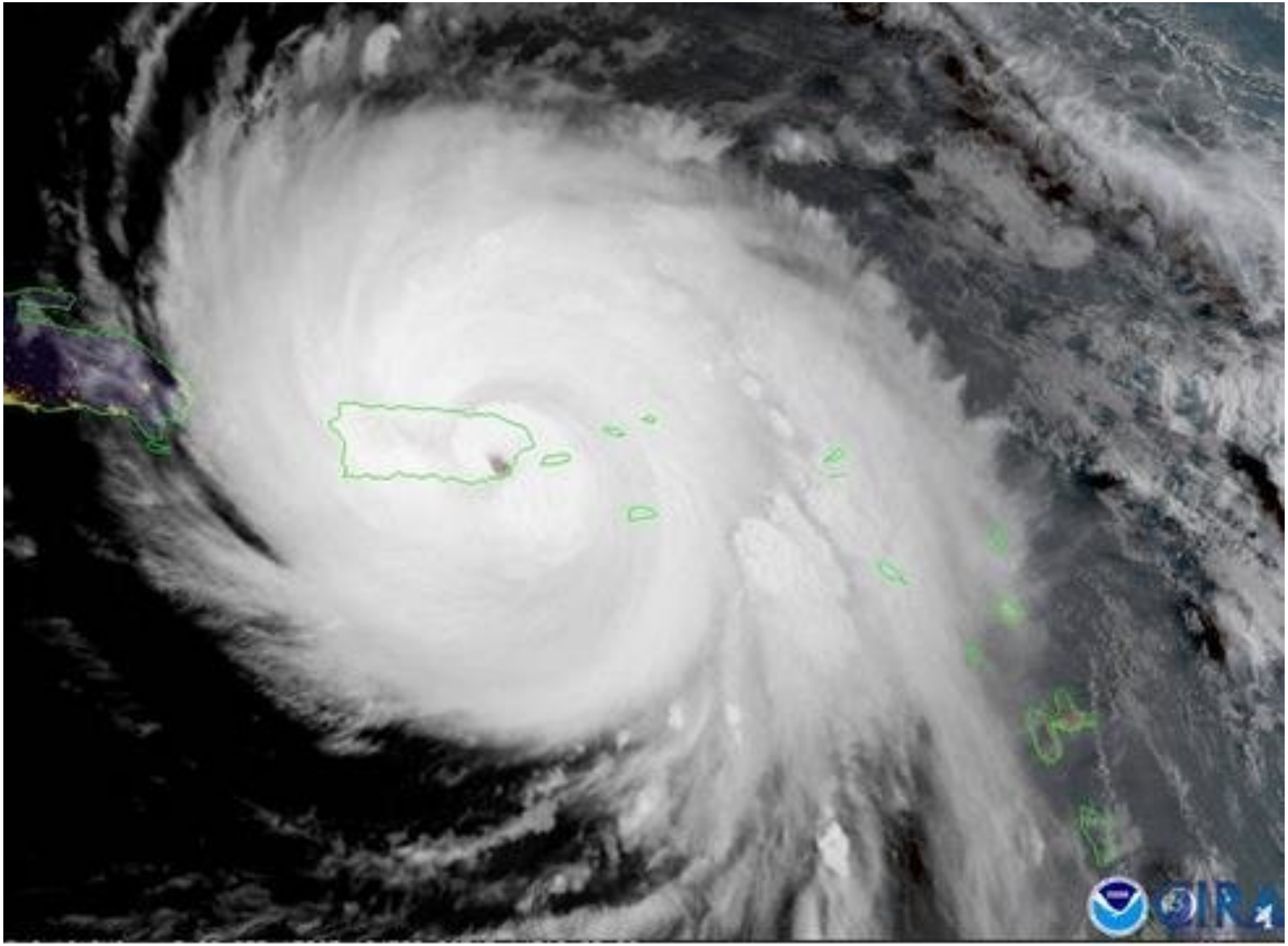
# Arecibo - 300m spherical telescope

# Arecibo - HUGE (and heavy) receiver cabin

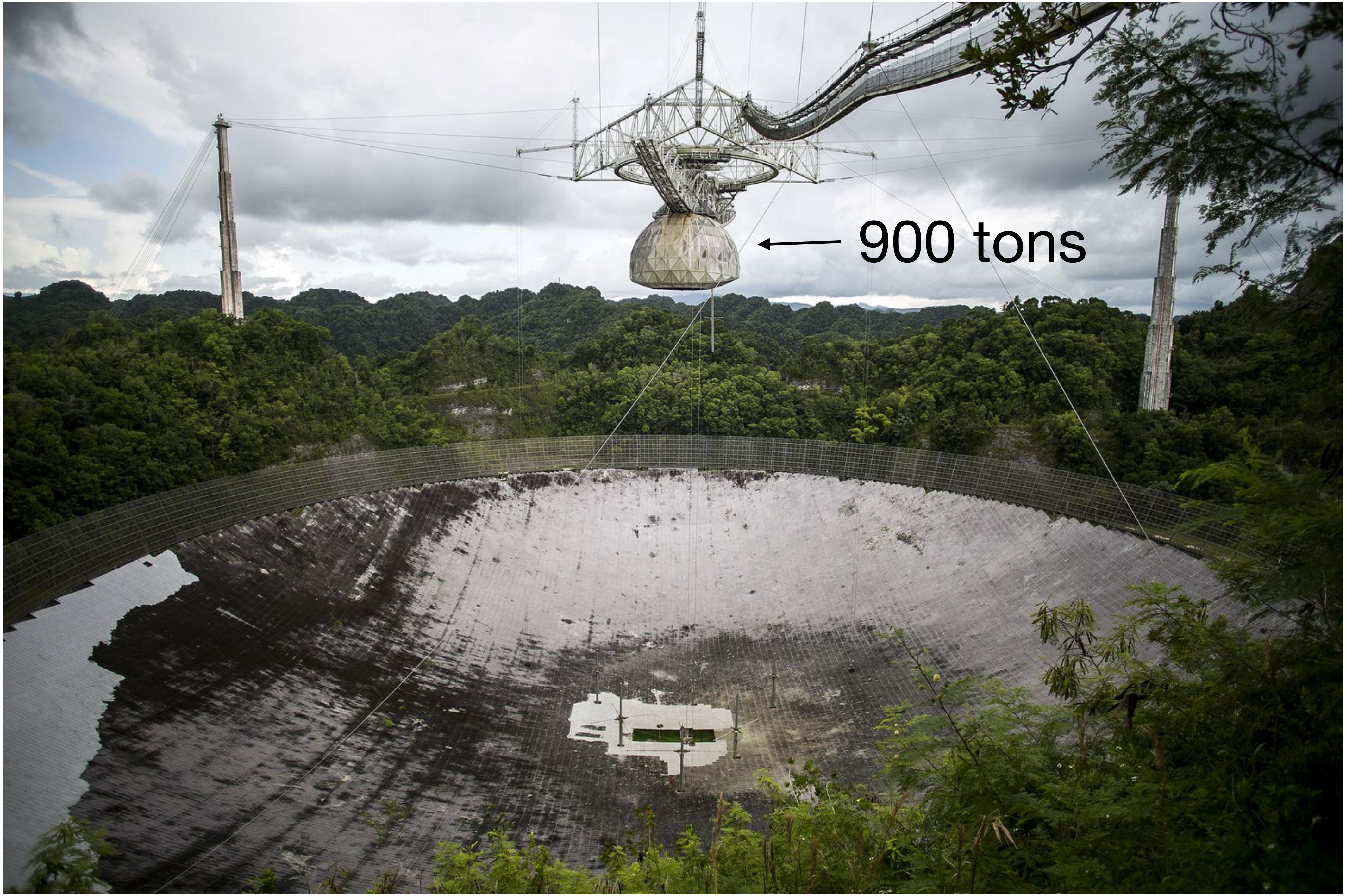
The large secondary feeds a tertiary reflector which in turn feeds a receiver room that has a broad range of receivers.:



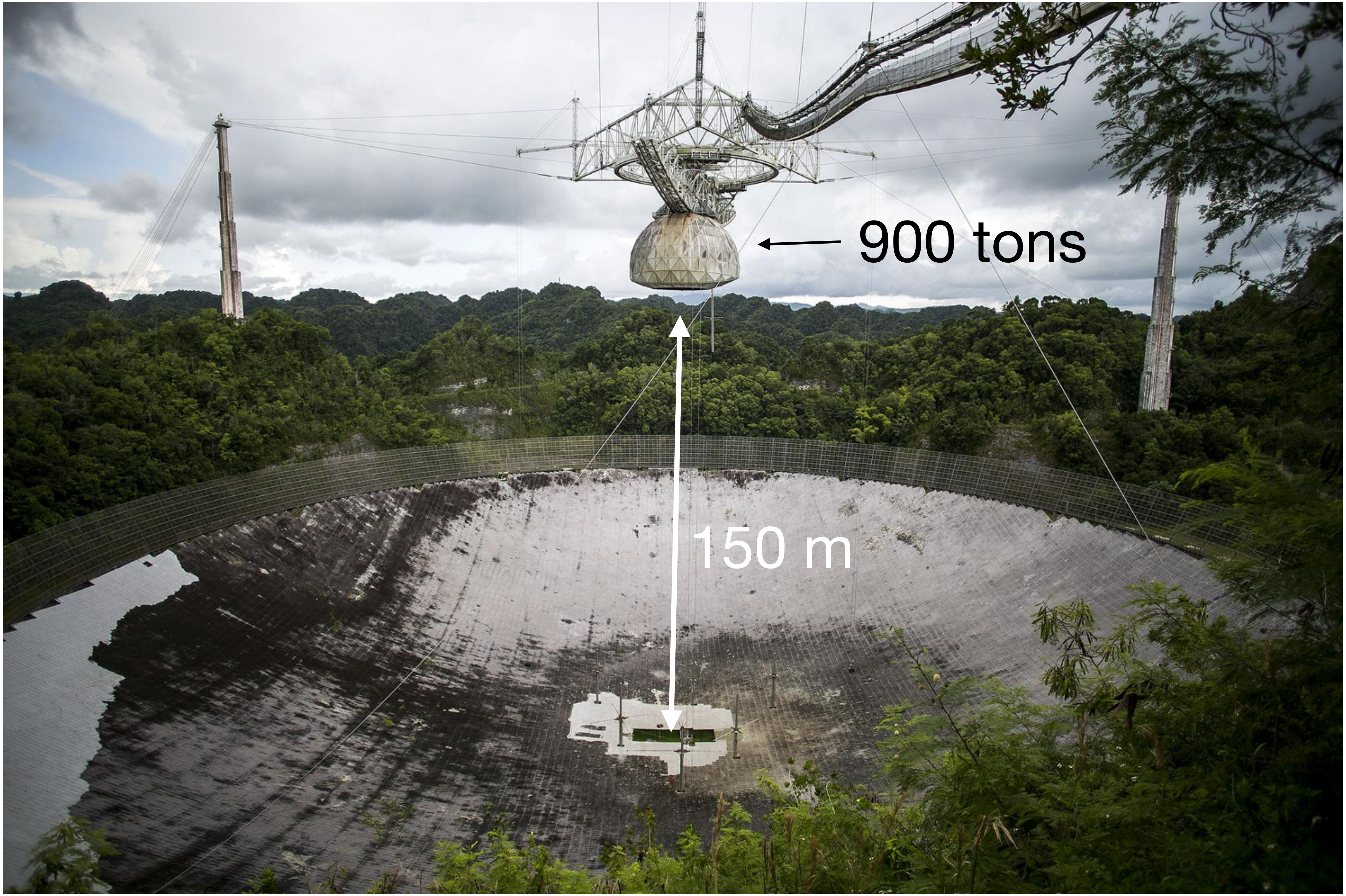
# Hurricane Maria 2017




Hurricane Maria
Sept. 20, 2 p.m
Arecibo
Dorado
Cataño
San Juan
Toa Baja
Roberto Clemente
Coliseum
Toa Alta
La Plata dam
Naranjito
Río de
la Plata
PUERTO RICO
Comerio
8 a.m.
Mayagüez
Yabucoa
Hurricane Maria
Sept. 20, 6:15 a.m
Ponce
Guayama
10 MILES



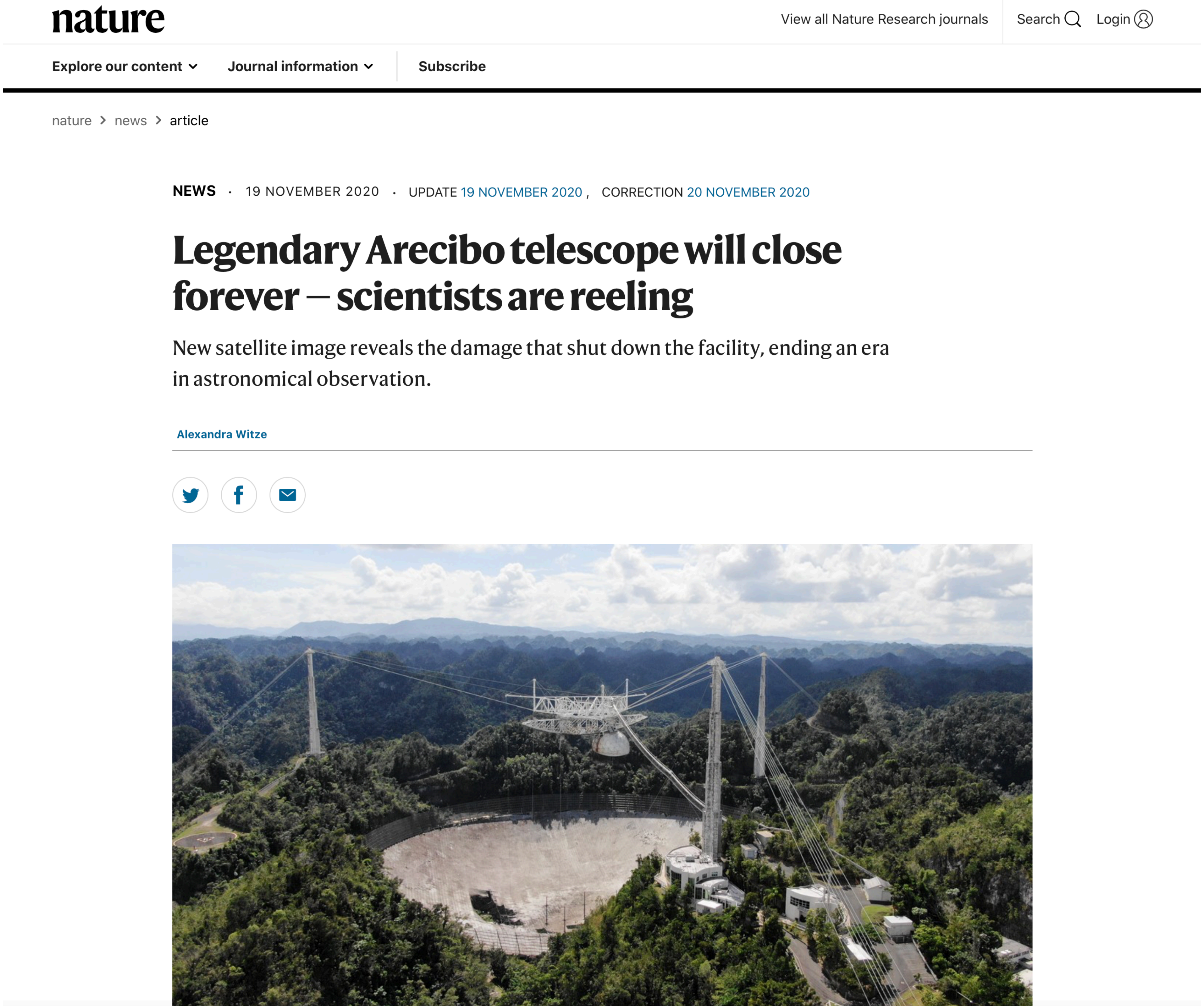
← 900 tons


900 tons
150 m

# Arecibo - before…

# Arecibo - first cables coming down…

# Arecibo - first cables coming down…



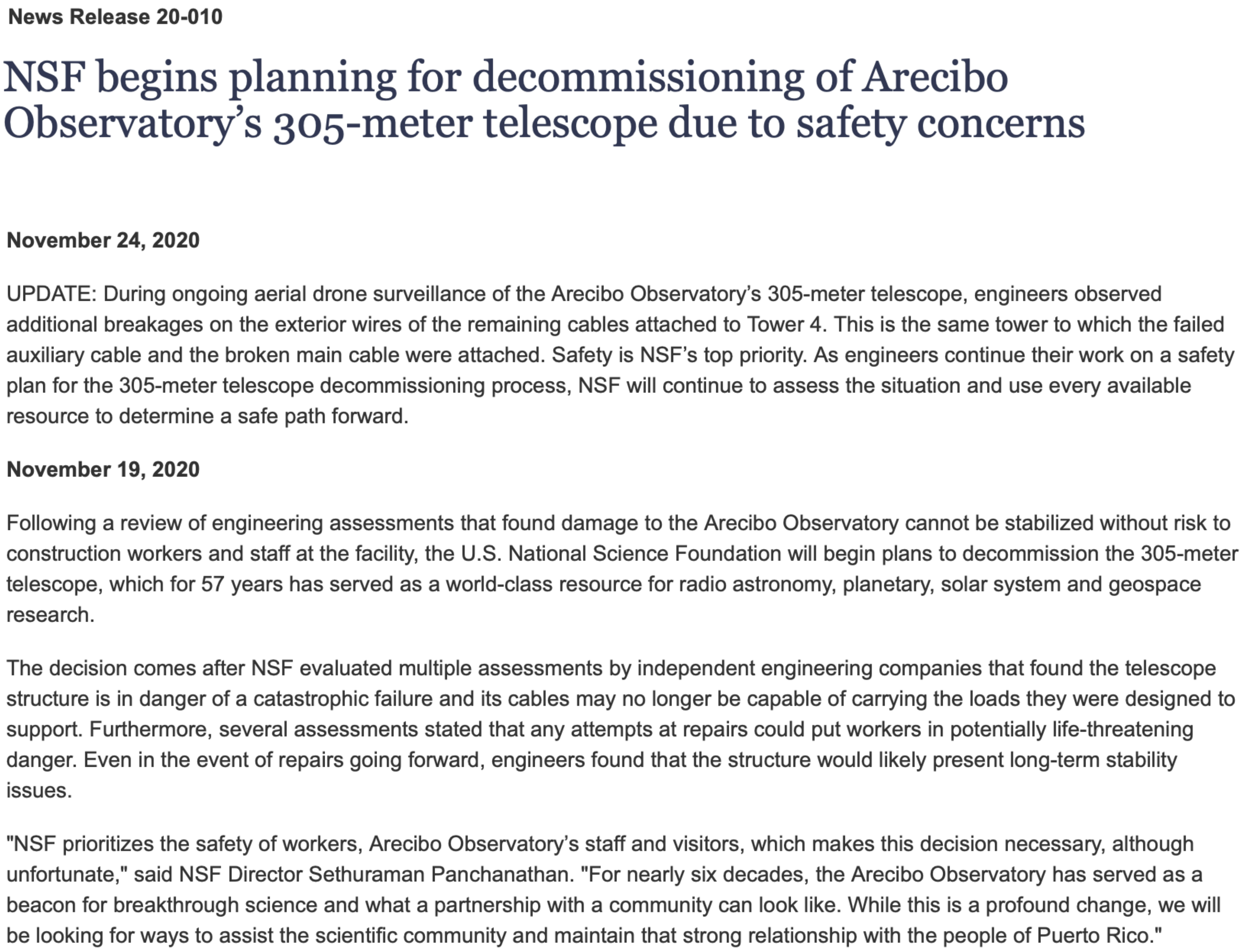
**NEWS** · 19 NOVEMBER 2020 · UPDATE 19 NOVEMBER 2020 , CORRECTION 20 NOVEMBER 2020

# Legendary Arecibo telescope will close forever — scientists are reeling

New satellite image reveals the damage that shut down the facility, ending an era in astronomical observation.

Alexandra Witze

# Arecibo - decommissioning *before* collapse



**News Release 20-010**

## NSF begins planning for decommissioning of Arecibo Observatory's 305-meter telescope due to safety concerns

**November 24, 2020**

UPDATE: During ongoing aerial drone surveillance of the Arecibo Observatory's 305-meter telescope, engineers observed additional breakages on the exterior wires of the remaining cables attached to Tower 4. This is the same tower to which the failed auxiliary cable and the broken main cable were attached. Safety is NSF's top priority. As engineers continue their work on a safety plan for the 305-meter telescope decommissioning process, NSF will continue to assess the situation and use every available resource to determine a safe path forward.

**November 19, 2020**

Following a review of engineering assessments that found damage to the Arecibo Observatory cannot be stabilized without risk to construction workers and staff at the facility, the U.S. National Science Foundation will begin plans to decommission the 305-meter telescope, which for 57 years has served as a world-class resource for radio astronomy, planetary, solar system and geospace research.

The decision comes after NSF evaluated multiple assessments by independent engineering companies that found the telescope structure is in danger of a catastrophic failure and its cables may no longer be capable of carrying the loads they were designed to support. Furthermore, several assessments stated that any attempts at repairs could put workers in potentially life-threatening danger. Even in the event of repairs going forward, engineers found that the structure would likely present long-term stability issues.

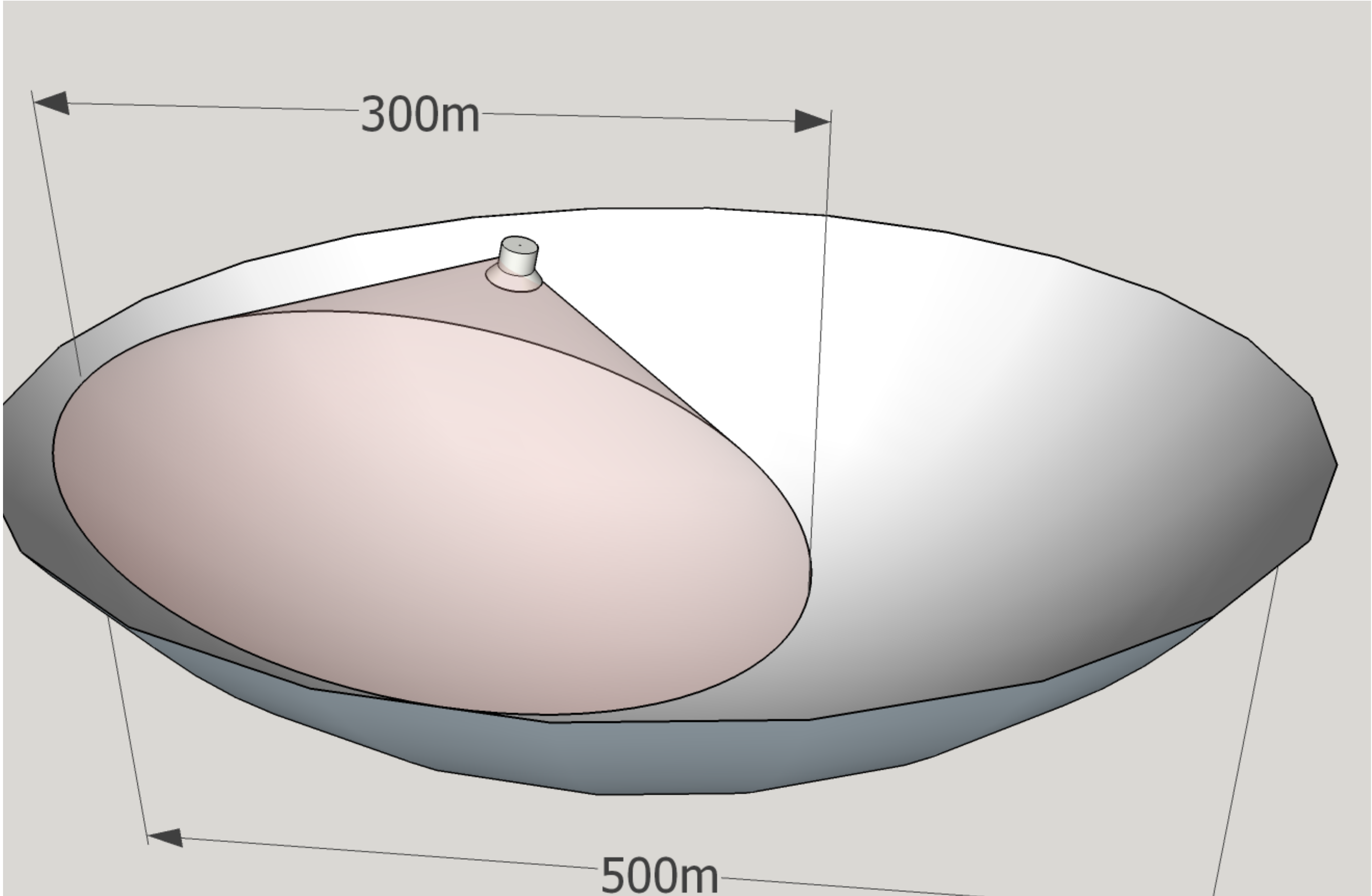
"NSF prioritizes the safety of workers, Arecibo Observatory's staff and visitors, which makes this decision necessary, although unfortunate," said NSF Director Sethuraman Panchanathan. "For nearly six decades, the Arecibo Observatory has served as a beacon for breakthrough science and what a partnership with a community can look like. While this is a profound change, we will be looking for ways to assist the scientific community and maintain that strong relationship with the people of Puerto Rico."

# Arecibo - after the collapse

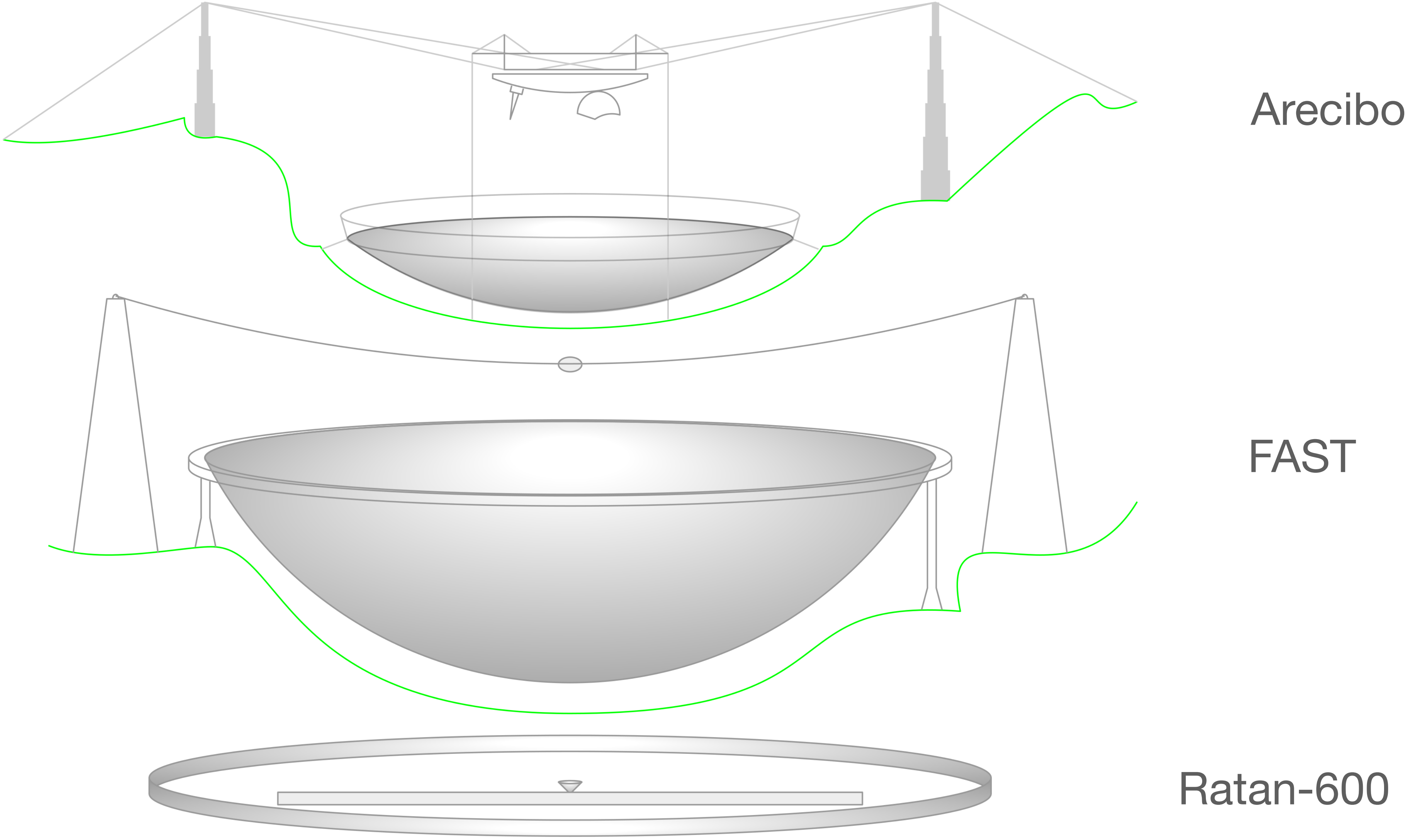
# Arecibo - after the collapse

# Green Bank - 300 foot - metal fatigue

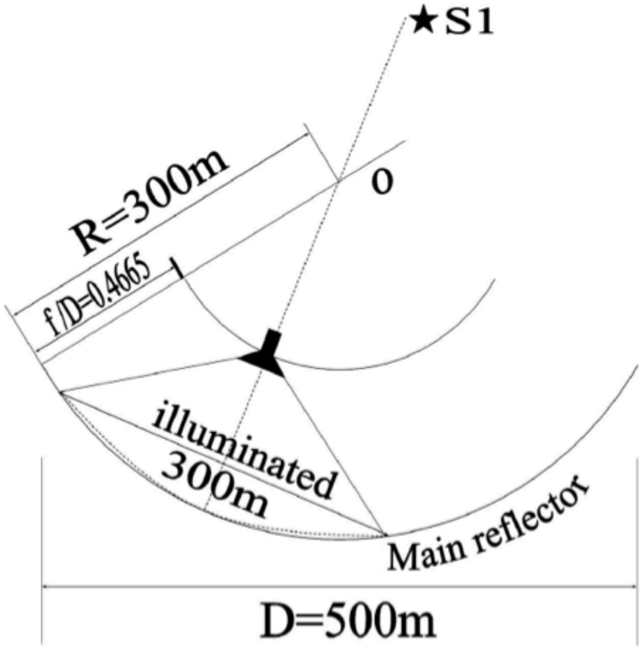
# FAST - the biggest radio telescope


300m
500m

# size comparison



# FAST - the biggest radio telescope



“the supporting structure should enable the surface formation of a paraboloid from a sphere in real time through active control. Fortunately, the peak deviation of the paraboloid of revolution from the spherical surface is only about 0.67m [5] across the illuminated aperture of about 300 m”

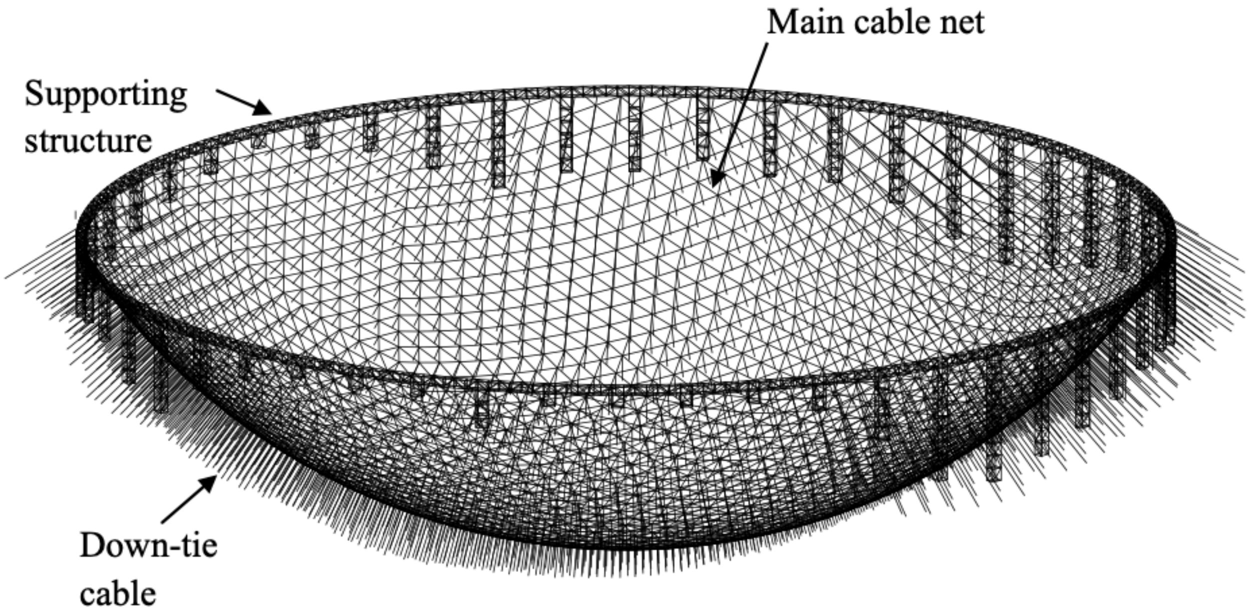


Figure 5 Concept of the adaptive cable-net structure, the supporting structure for the FAST reflector

https://arxiv.org/pdf/1105.3794.pdf

# FAST - the biggest radio telescope

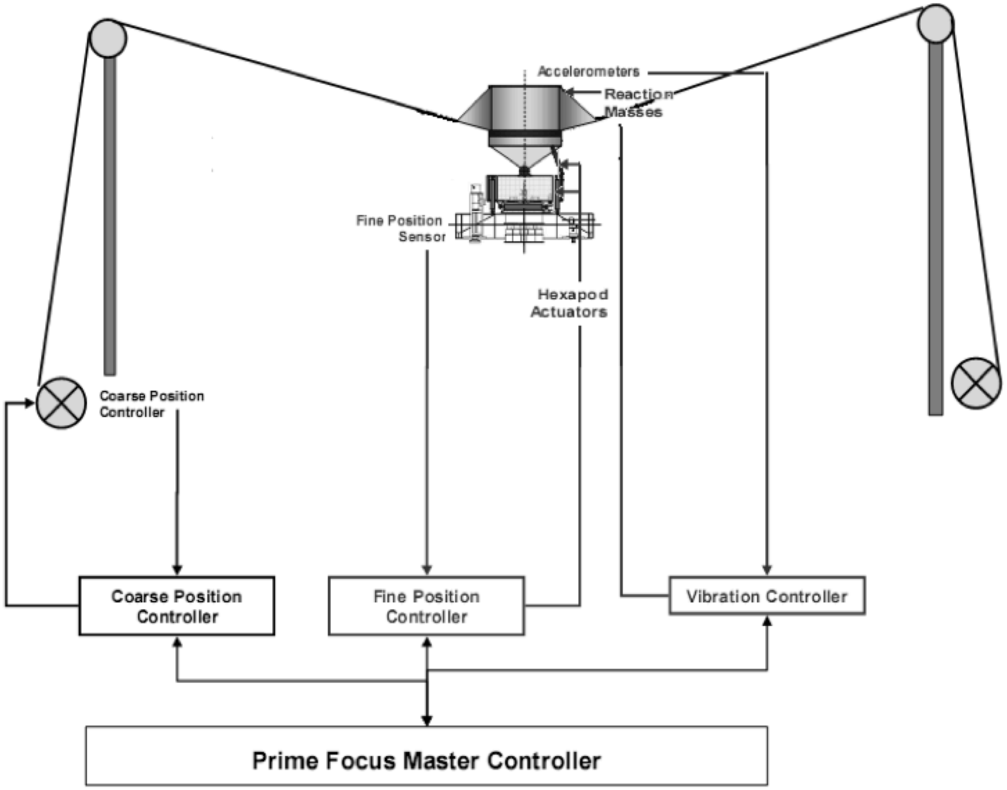


Figure 11 Sketch of the cabin suspension system.

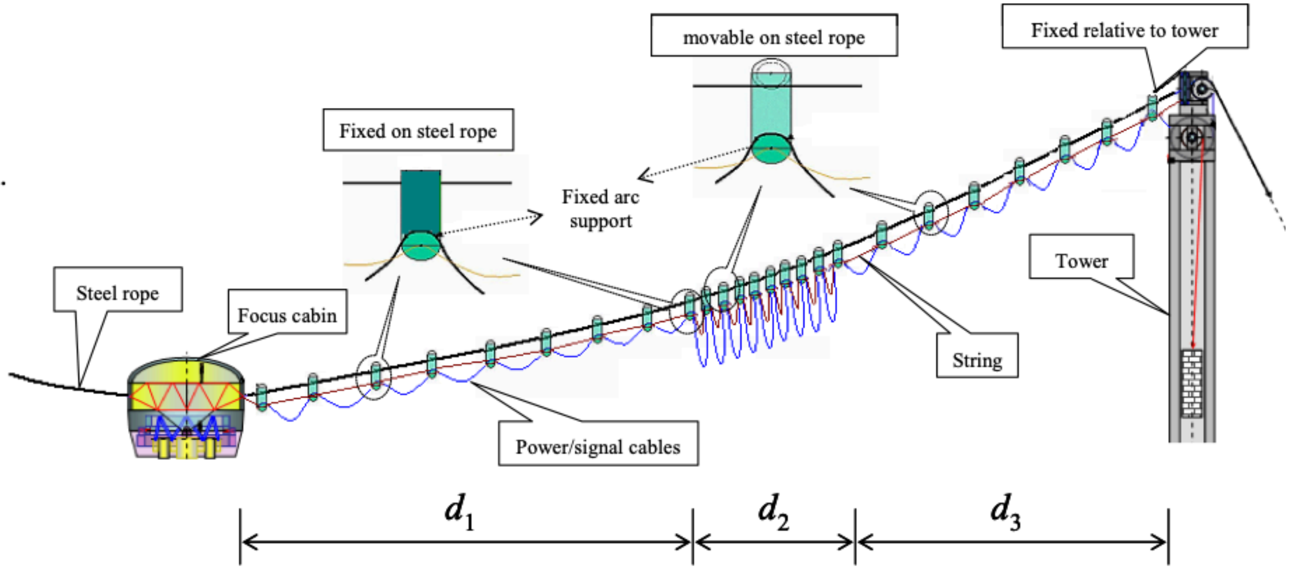
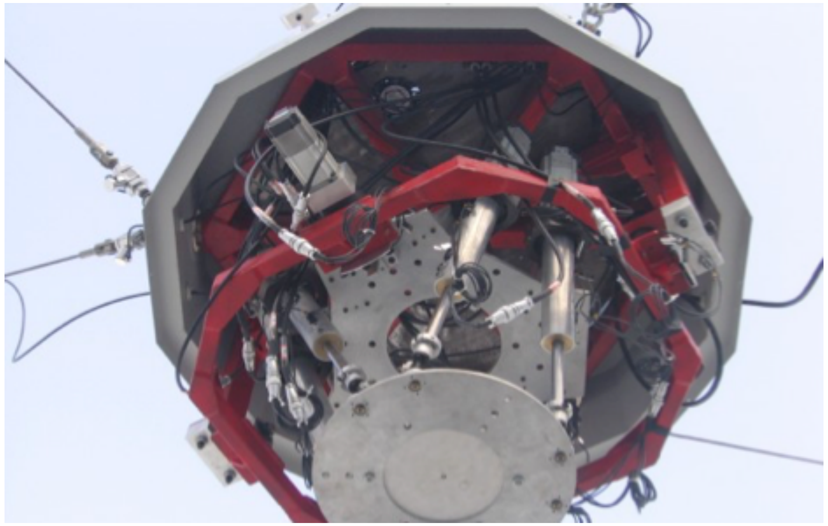
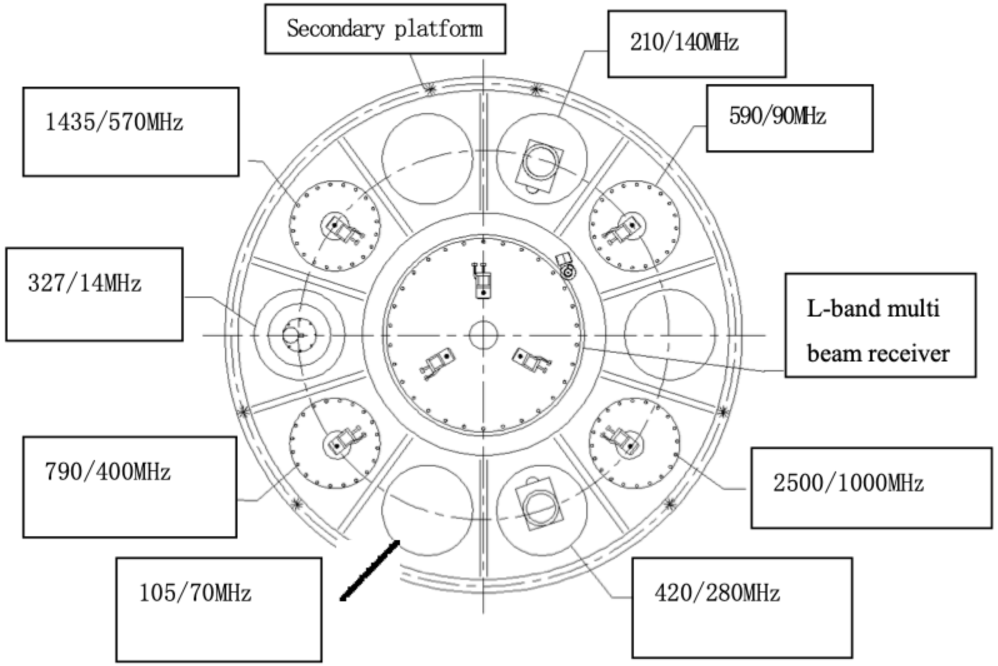


Figure 13 Curtain-like hanging-up mechanisms of power/signal cables

# FAST - the biggest radio telescope

focus cabin: only 3 tons!
(note: Arecibo: 900 tons)





# FAST - the biggest radio telescope

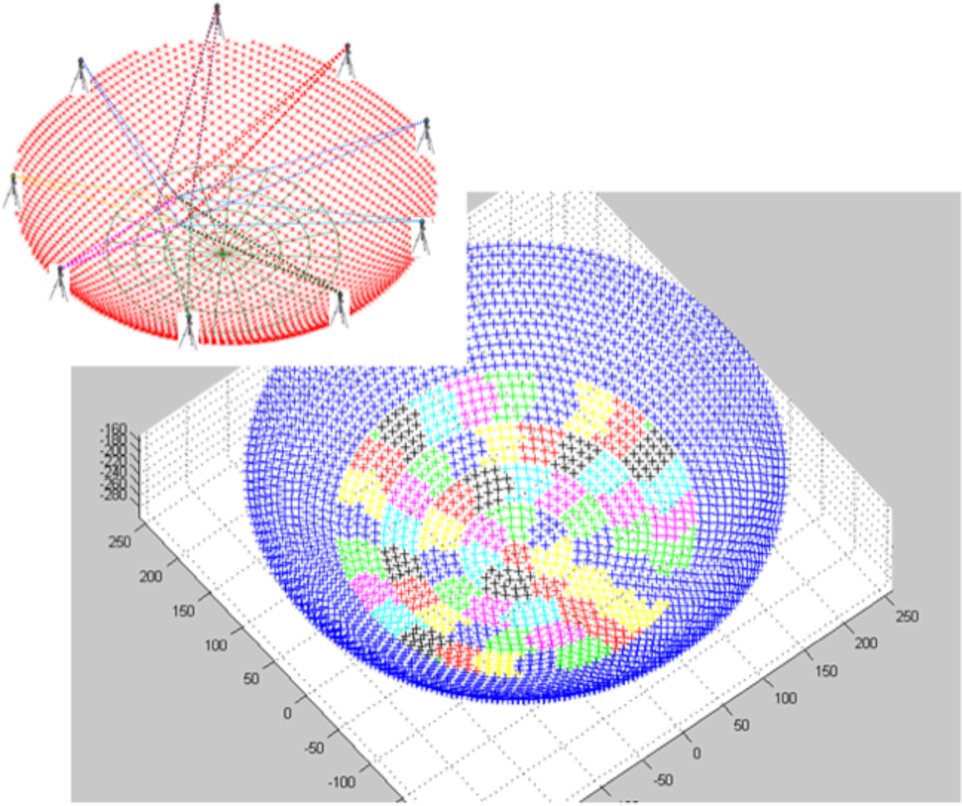
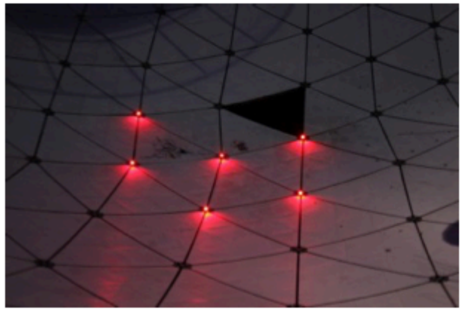


Figure 22 The layout of digital measuring equipment on the edge of the top of the reflector



# large radio telescopes - challenges

**How can we possibly achieve a 350 µm accuracy *(the thickness of three human hairs)* – over a 100 metre diameter surface – an area equal to 2 football fields!**

**==> *“active surface”.***

# active surface at the Green Bank telescope

*GBT Surface has 2004 panels*
*average panel rms: 68μm.*

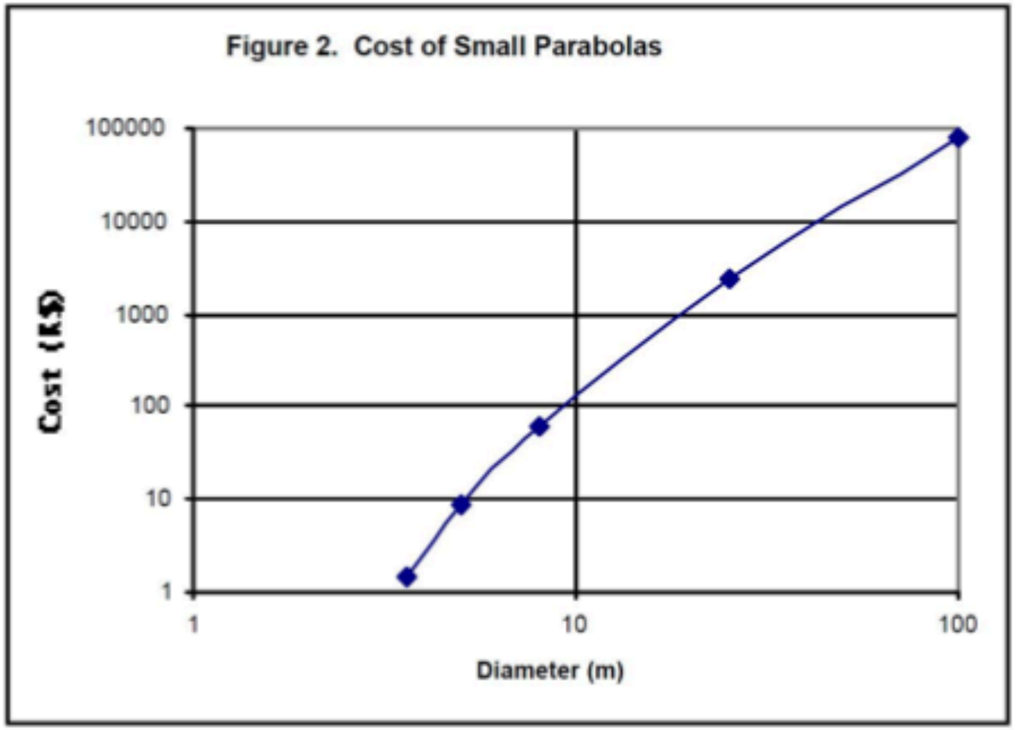
*More than 2000 precision actuators are located under the surface panel corners*

*Actuator Control Room (left):*
*26000 control and supply wires terminate in this room!*

# how big can a telescope be?

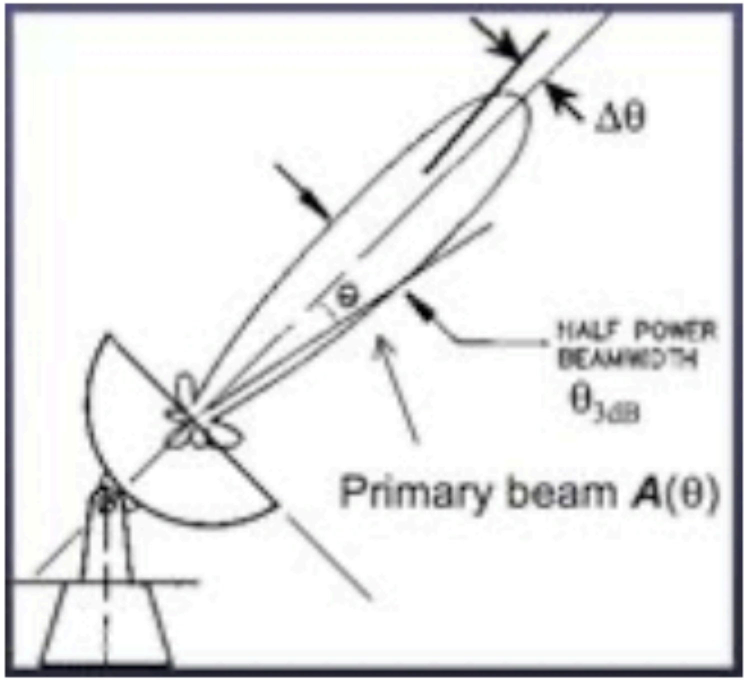
As the size (diameter) of a radio telescope increases, the gravitational and wind loads on the structure become difficult to manage. The worst problem is the problem of surviving a storm. The degree of wind distortion between paraboloids of different diameters (D) scales as $D^3$.

The cost of antennas also scales roughly as $D^3$.



Telescopes like the Jodrell Bank Mark V (right) with a diameter of ~ 305 metres (1970), will probably always remain in model form!

# antenna pointing errors



WSRT pointing errors are typically < 30 arcseconds (or about $\theta_{3db}$ /10) at 8 GHz.

The typical goal is: $\Delta\theta < \theta_{3db}/20$

where $\theta_{3db}$ is the FWHM of the main lobe of the antenn beam.

N.B. If the antenna moves $\theta_{3db}/20$ off the true pointing centre, this will result in < 1% loss of intensity for a source located on the central axis of the beam.

However, a source located at $\theta_{3db}$ will see a 10% loss! This can badly affect the quality of a radio source image towards the edge of the field

At higher frequncies (~ 20 GHz) pointing checks are often made on nearby bright sources to update the pointing model (offsets).

Typically pointing becomes more difficult at higher frequencies and with larger antennas (i.e. smaller primary beams).

# antenna servos speeds

The speed at which an antenna can move from one part of the sky to another is also an important performance factor.

This is required for:

(i) observing efficiency

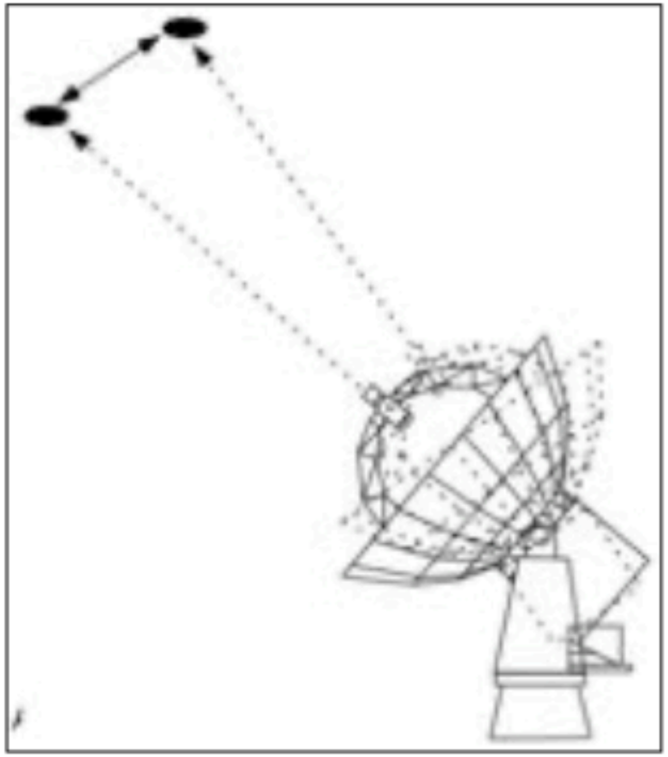
(ii) calibration (e.g. fast switching between nearby sources in the case of phase-referencing).

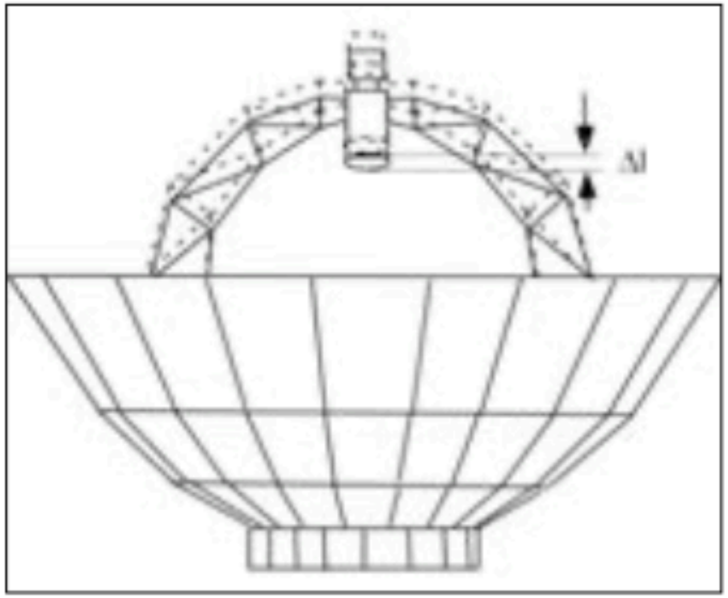
Typical driving rates of modern antennas (e.g. VLBA):

- 90 deg/min in azimuth; 30 deg/min in elevation;
- Settle time ~ 2 secs;
- Time to accelerate to full speed ~ 2 secs.

A rigid structure is important as this:

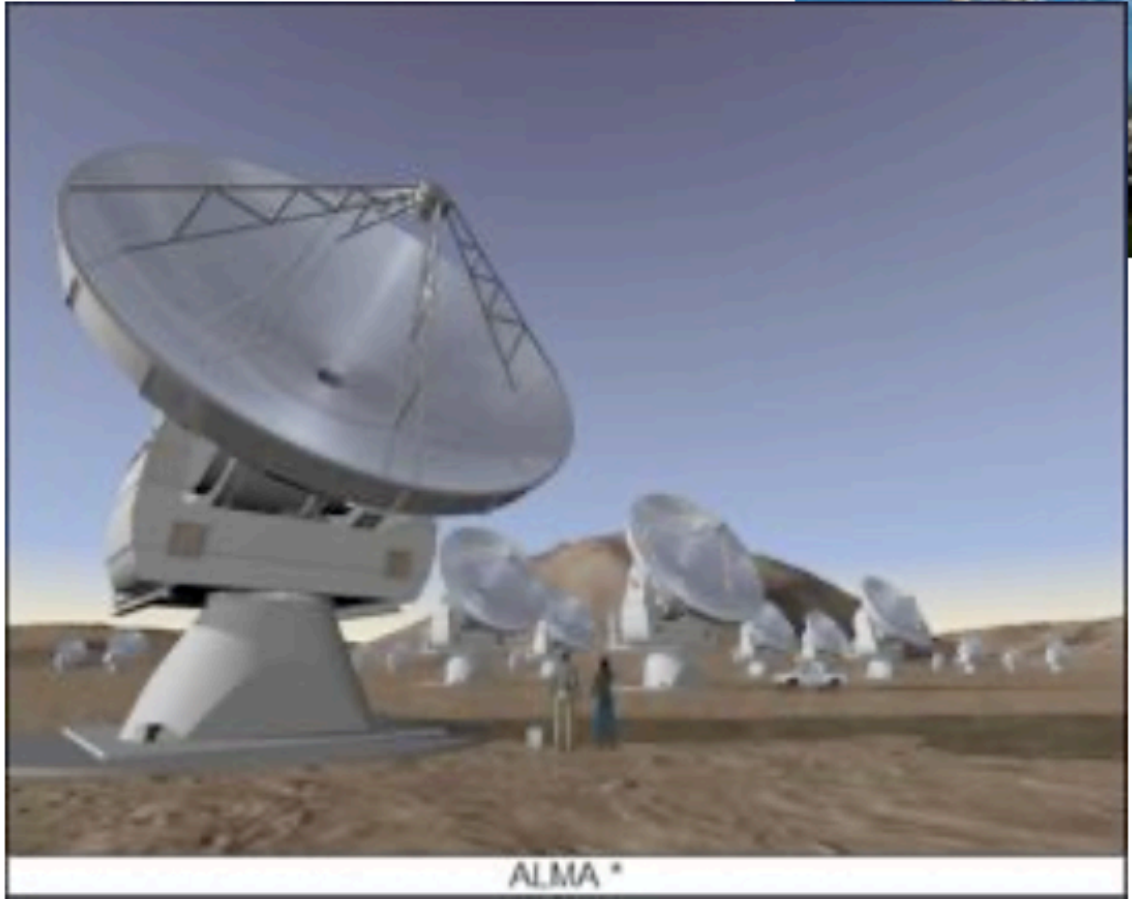
- minimises "settle time" - the time it takes for antenna to firmly settle on source.
- maintains the optical geometry of the telescope - important for "phase referencing"





# antenna examples

e.g. Lovell telescope (right) old, heavy structure is not stiff - leads to over-shooting, long slew and settling times etc.



e.g. ALMA antennas - v. stiff and highly accurate pointing for THz obs.

# weight of one(!) ALMA antenna ~100 tons!

Photo (C) Karsten Palt

flugzeuginfo.net - das Flugzeuglexikon / the Aircraft Encyclopedia

Photo (C) Karsten Palt

flugzeuginfo.net - das Flugzeuglexikon / the Aircraft Encyclopedia

https://www.eso.org/public/teles-instr/alma/antennas/