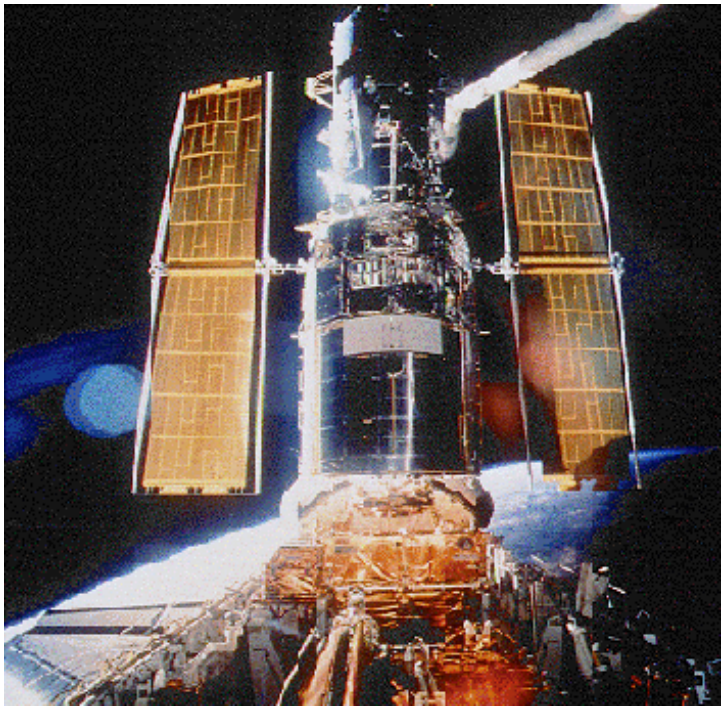
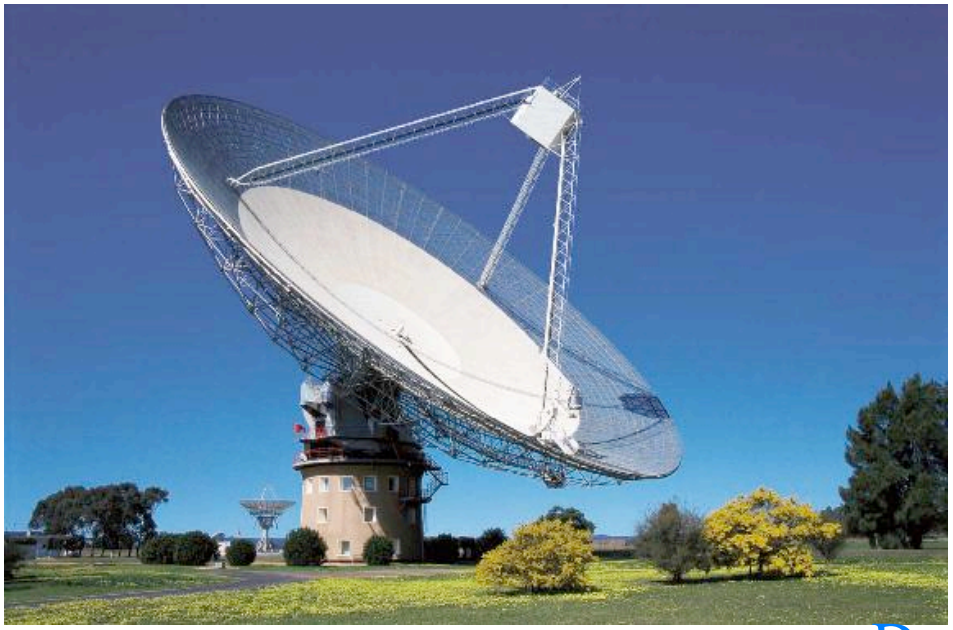


Telescopes



Donna Kubik PHYS162 Spring, 2006

Purpose of telescopes

To do what our eyes cannot

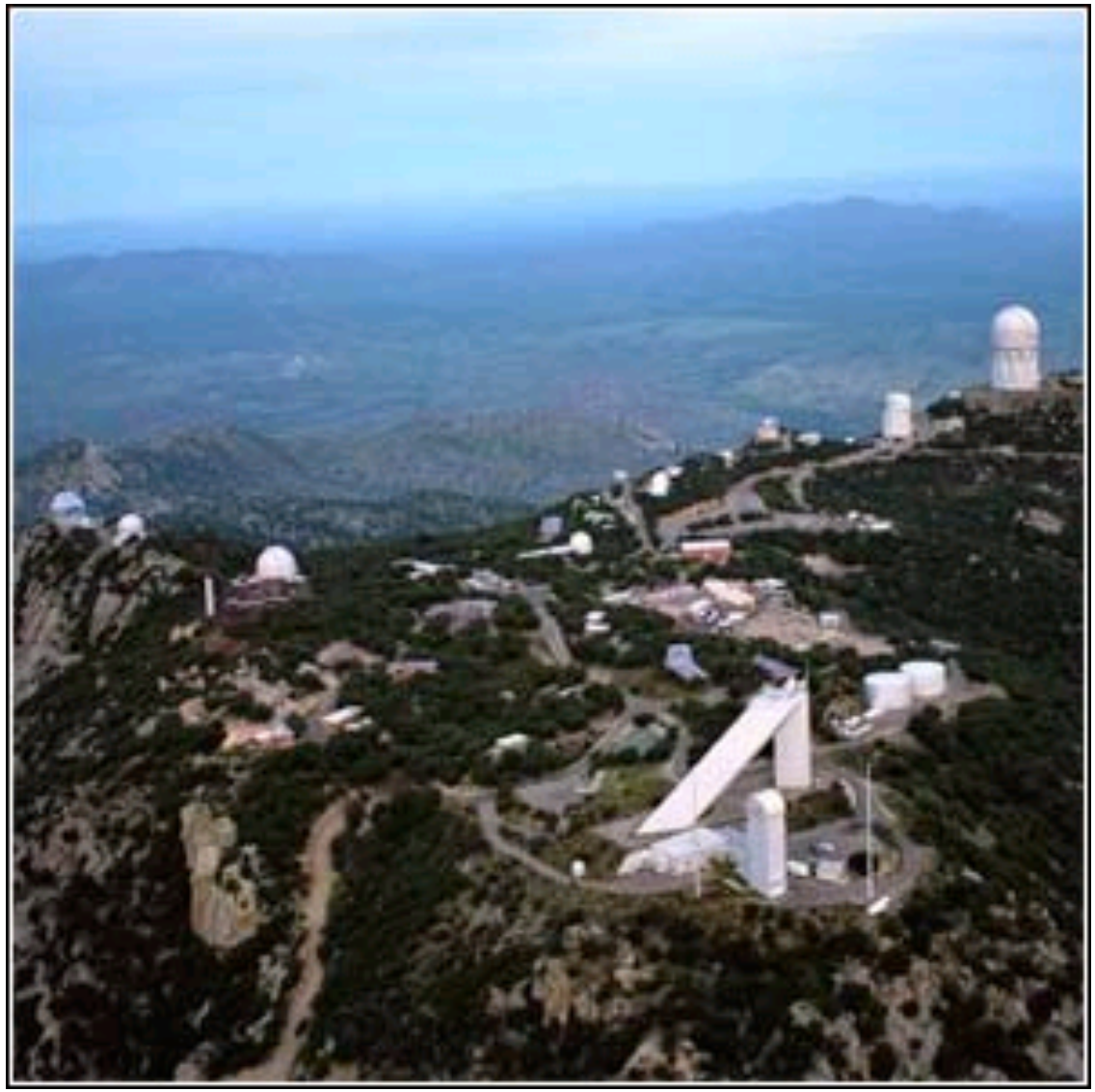
- Collect photons (from radio to gamma ray)
- Achieve higher resolution

Record the received photons

- Images
- Spectra

Recording

Rarely are your eyes used to directly look through a telescope, even for an optical telescope!



Types of EM radiation

Astronomers have constructed telescopes that have detected all forms of EM radiation, both visible and non-visible, emitted by objects in space.

Types of EM radiation

Radio

Millimeter

Sub-millimeter

Infrared

Optical

Ultraviolet

Xray

Gamma ray

Types of astronomers

Radio astronomers

Millimeter astronomers

Sub-millimeter astronomers

Infrared astronomers

Optical astronomers

Ultraviolet astronomers

X-ray astronomers

Gamma ray astronomers

Types of astronomy

Radio astronomy

Millimeter astronomy

Sub-millimeter astronomy

Infrared astronomy

Optical astronomy

Ultraviolet astronomy

X-ray astronomy

Gamma ray astronomy

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!

Effelsberg radio telescope, Germany

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!

NRAO 12 meter telescope, Kitt Peak Observatory

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

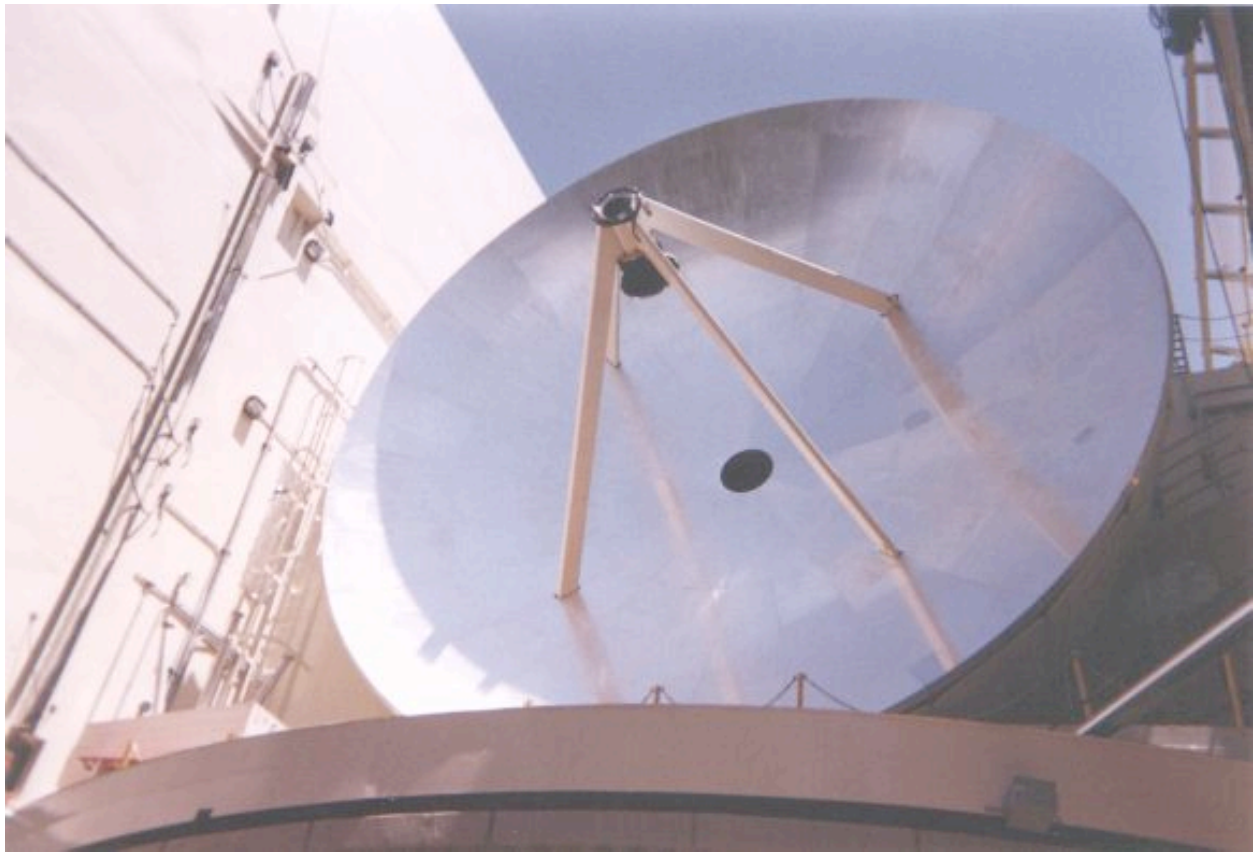
Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!



Sub Millimeter Telescope (SMT), Mt. Graham, AZ

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

Optical telescopes

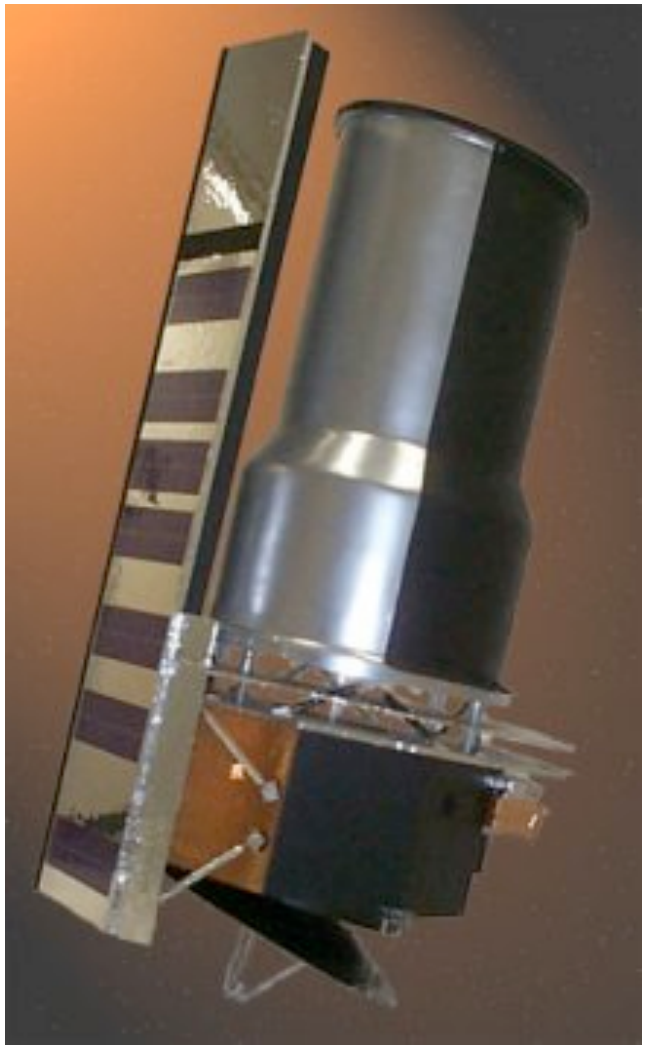
Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!

SIRTF
Space Infra Red Telescope Facility



Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

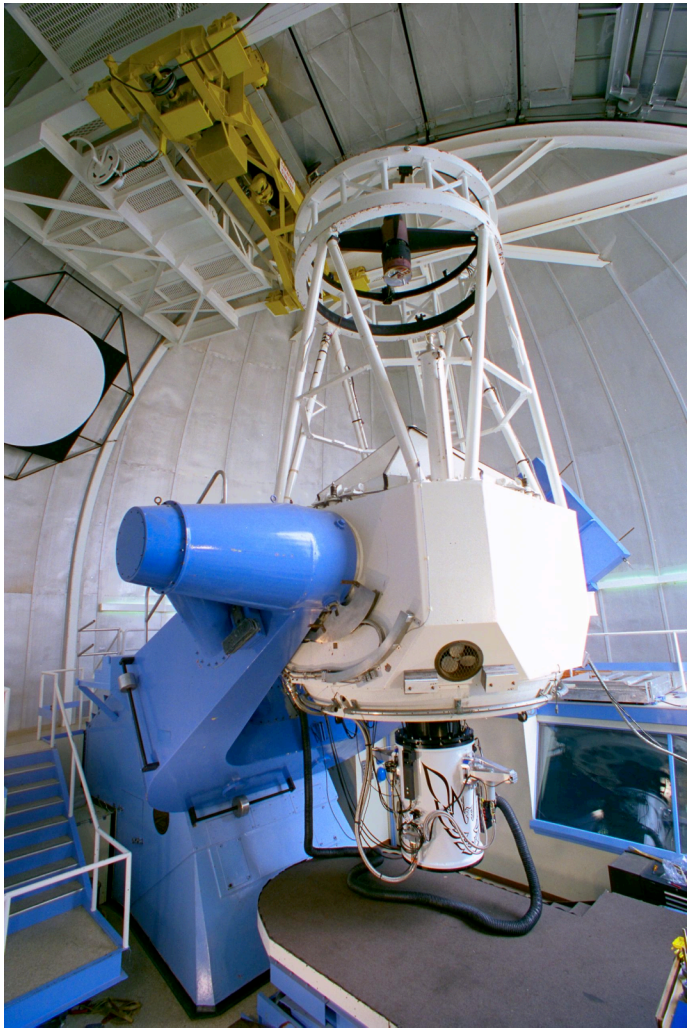
The telescopes look very different!

Yerkes 40-inch telescope,
Williams Bay, WI

World's largest refractor

The telescopes look very different!

KPNO
Kitt Peak National Observatory
2.1 meter telescope



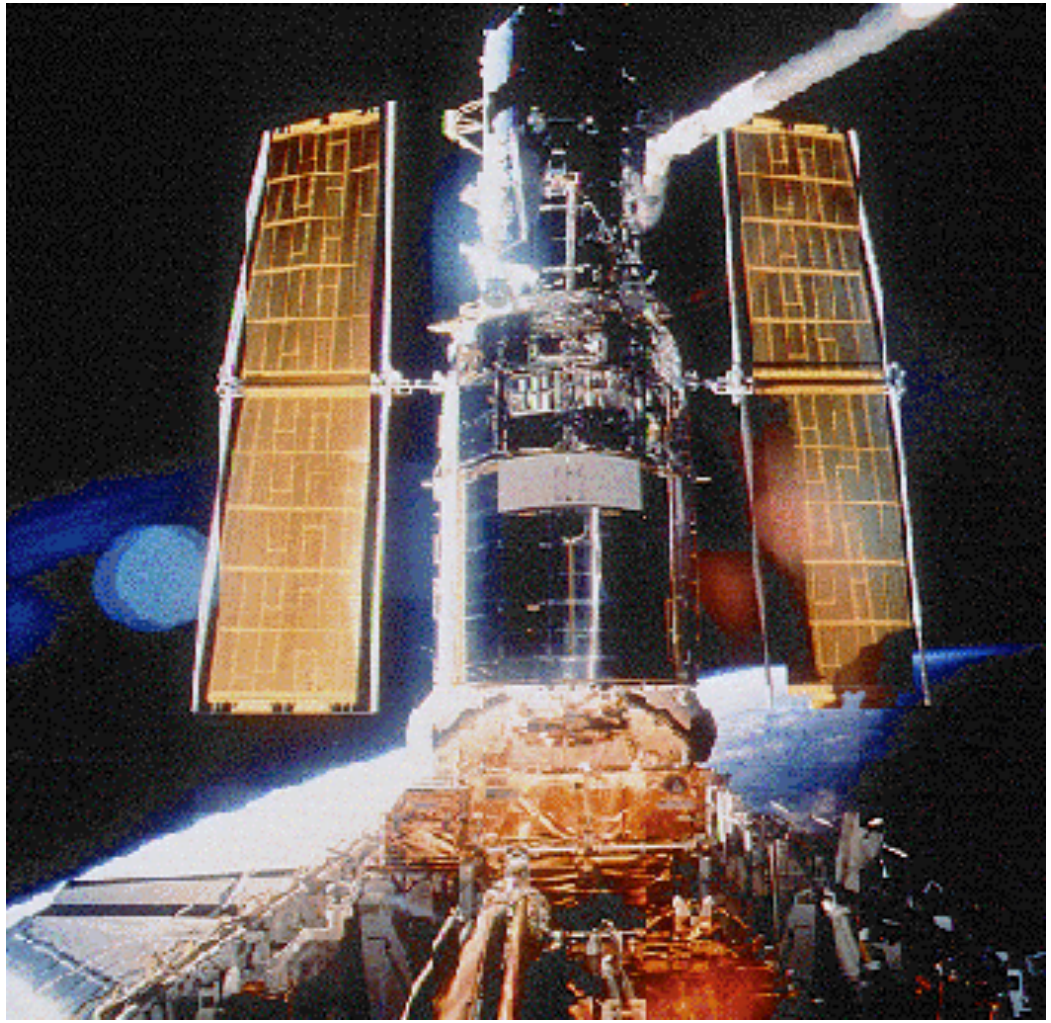
The telescopes look very different!

Keck optical telescopes

Mauna Kea, Hawaii

The telescopes look very different!

HST
Hubble Space Telescope



Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

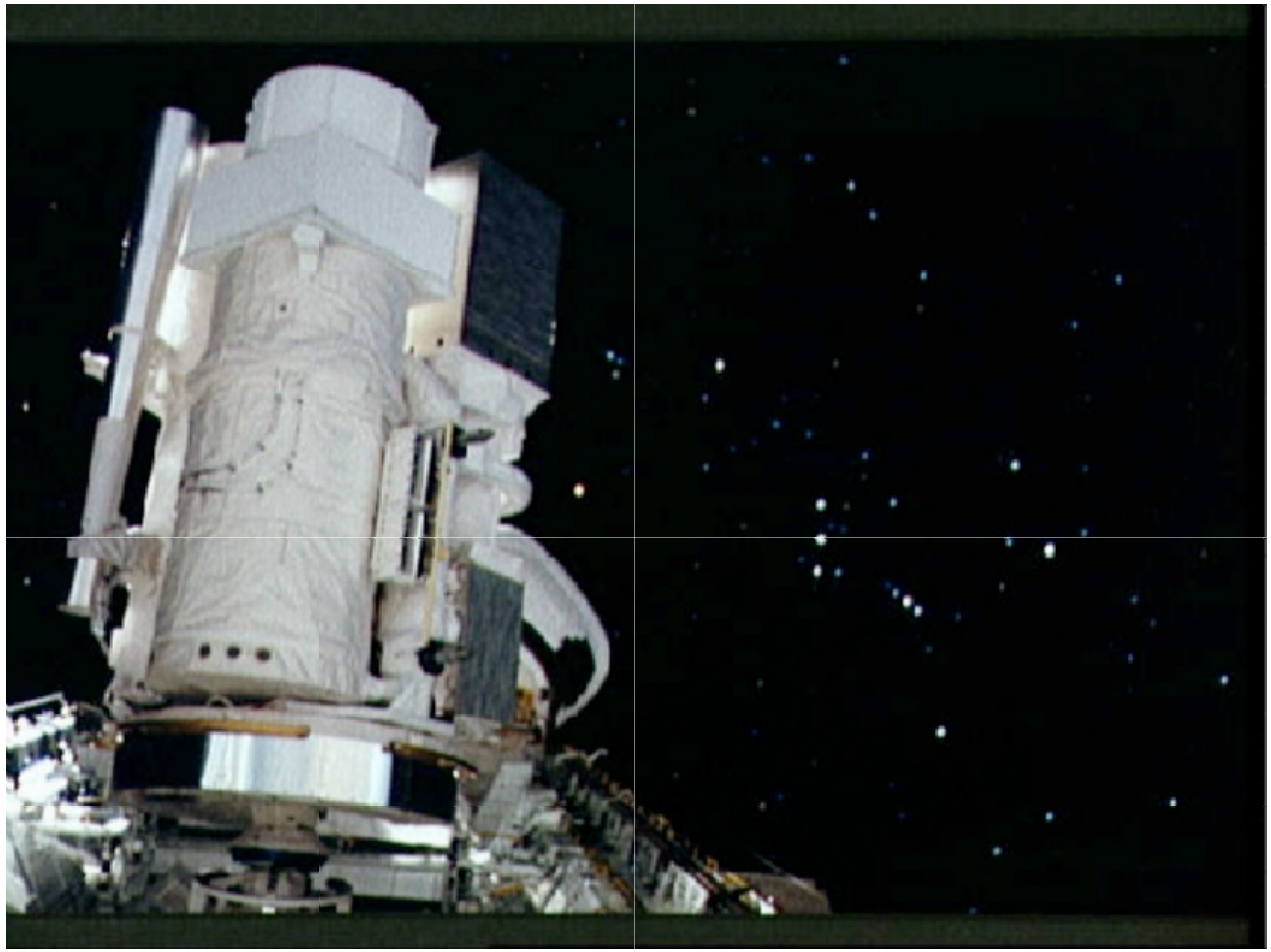
Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!



HUT Hopkins Ultraviolet Telescope

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!

XMM Xray MultiMirror telescope

Types of telescopes

Radio telescopes

Millimeter telescopes

Sub-millimeter telescopes

Infrared telescope

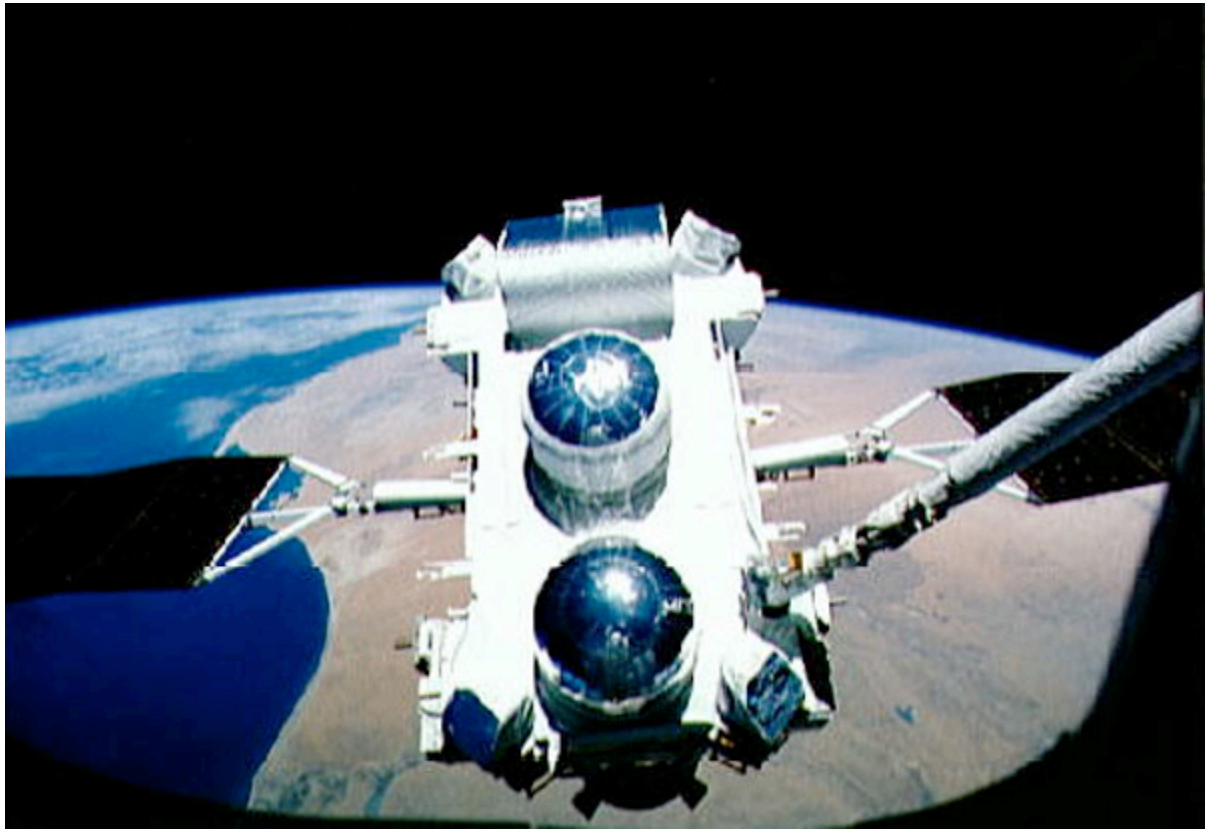
Optical telescopes

Ultraviolet telescopes

X-ray telescopes

Gamma ray telescopes

The telescopes look very different!



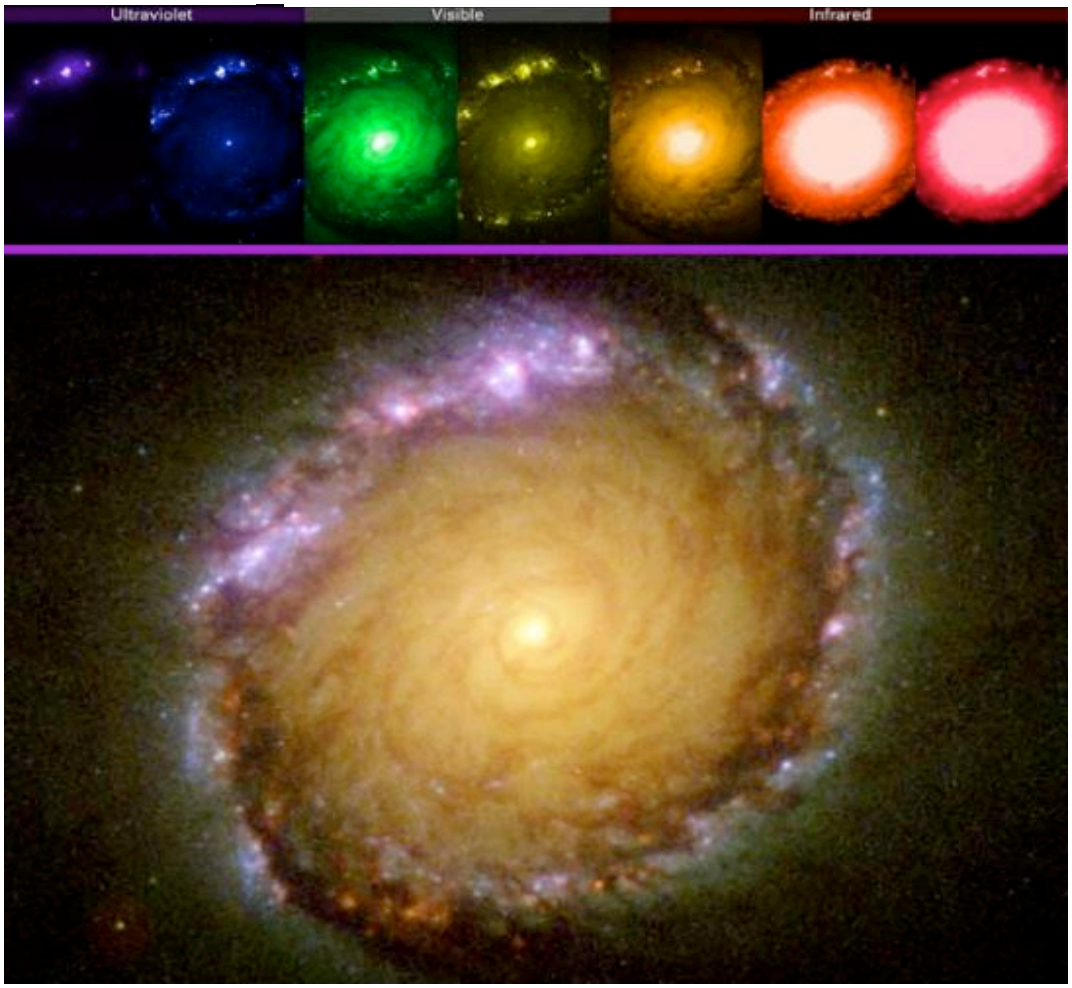
CGRO Compton Gamma Ray Observatory

And…..

the images from the different types of telescopes look very different!

The images look very different

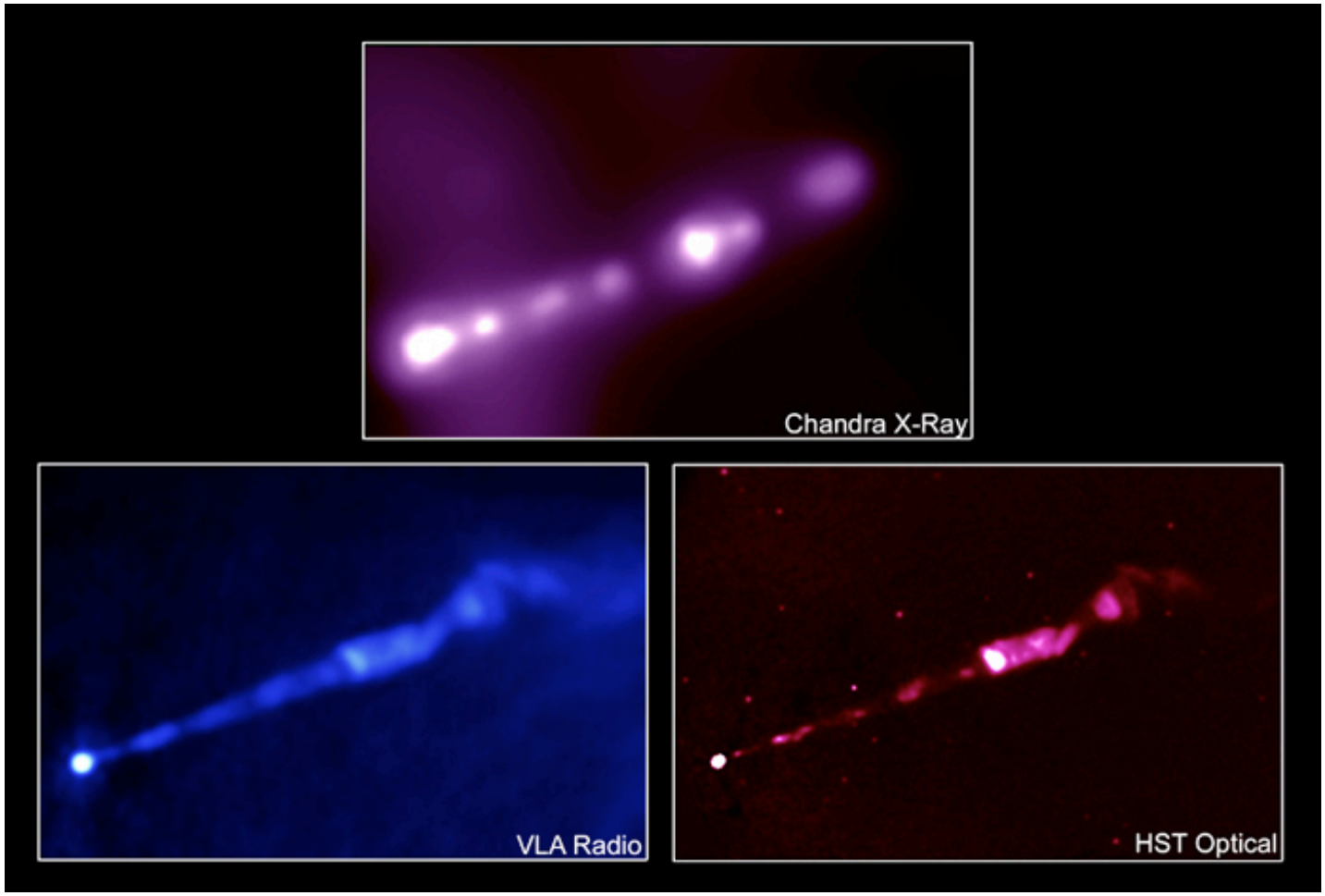
Ultraviolet Visible Infrared



NGC1512
barred spiral
galaxy

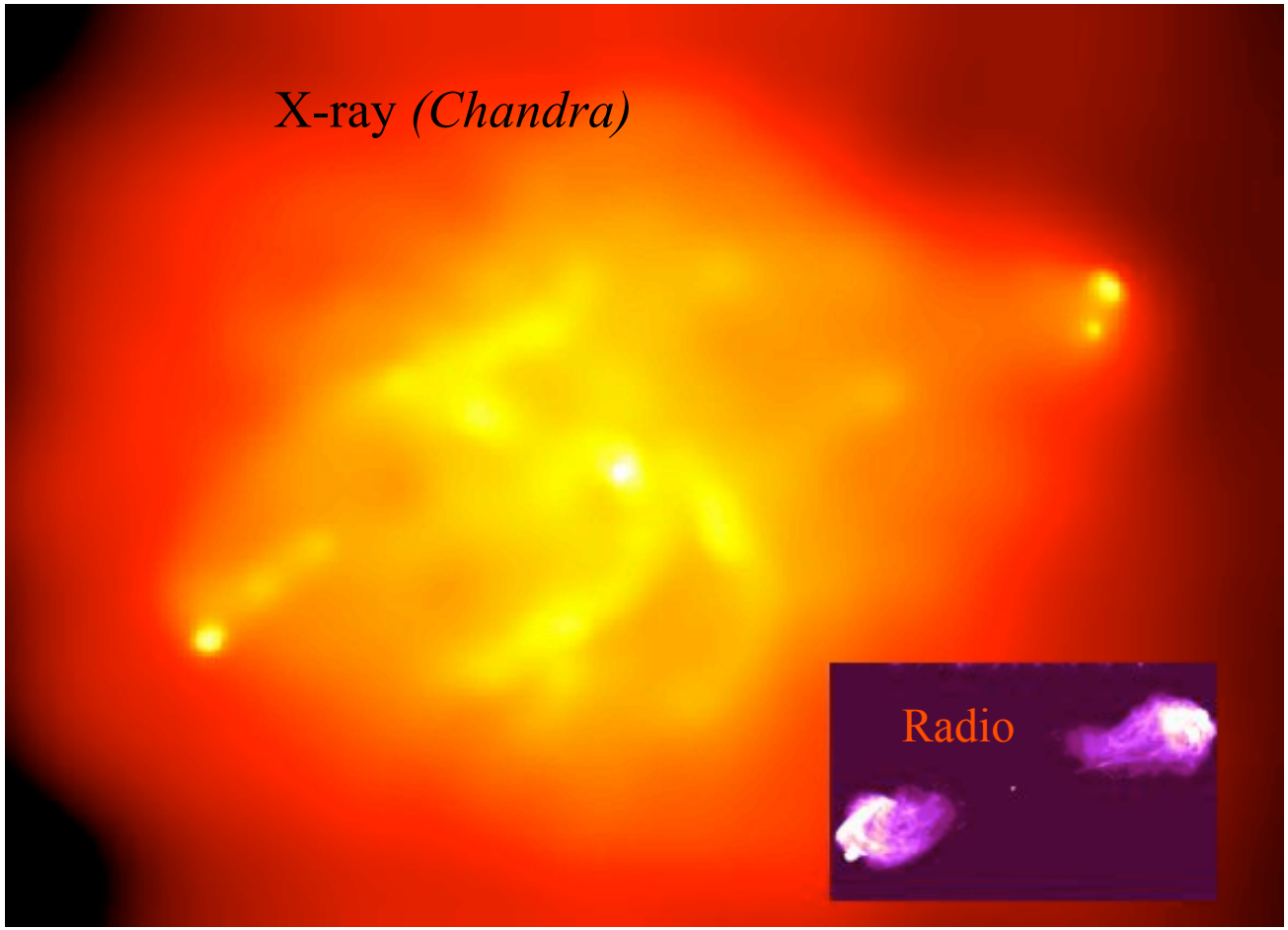
HST images

The images look very different



M87 giant elliptical galaxy in Virgo cluster

The images look very different

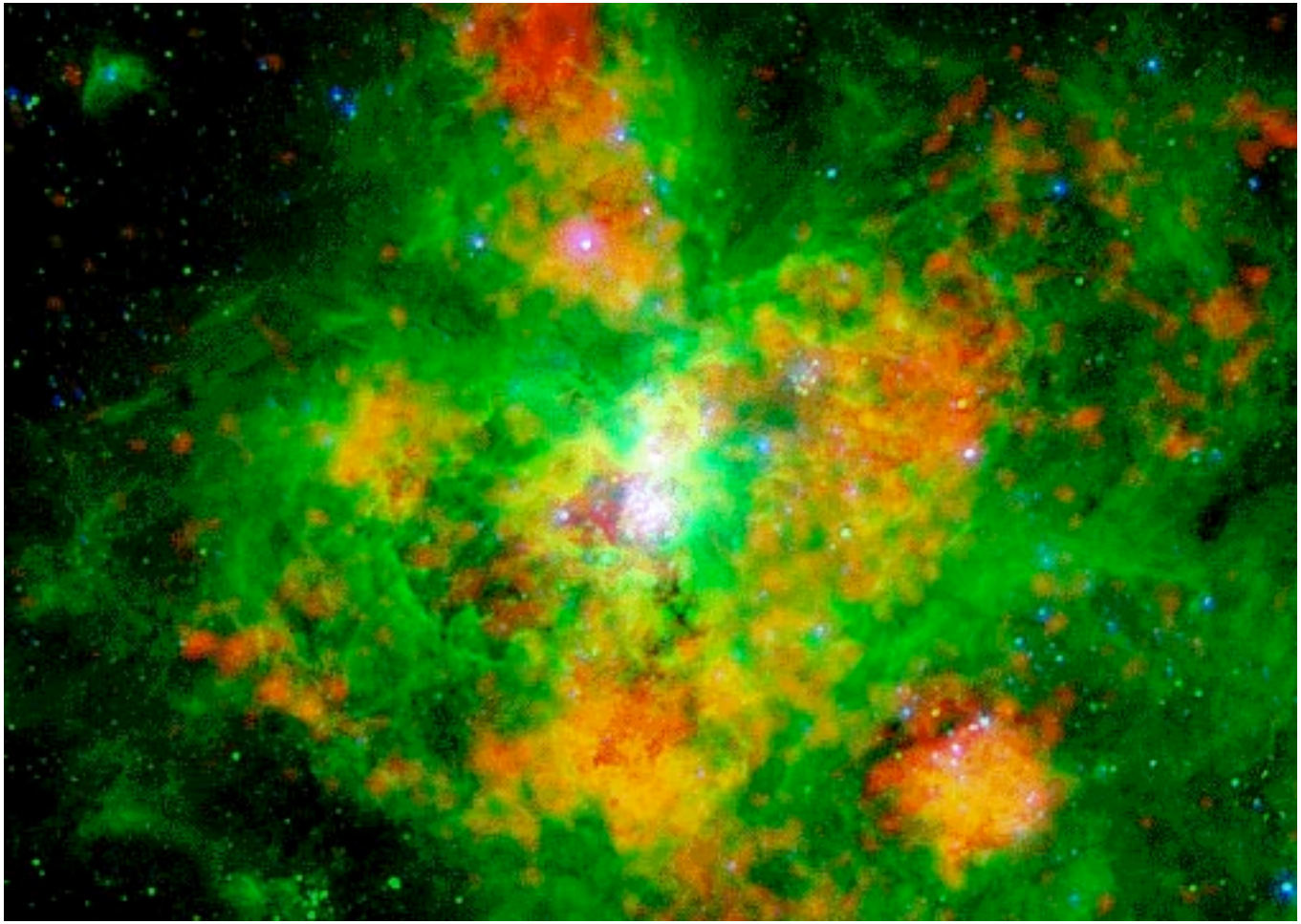


Cygnus A

The images look very different

30 Doradus
Open cluster
in LMC

red=xray
green=optical
blue=UV



Types of EM radiation

Why do the telescopes and images look so different?

Types of EM radiation

The difference between each type of EM radiation in each region is its energy!

Types of EM radiation

Because of their different energies, each type of EM radiation interacts differently with matter.

That's why the telescopes look so different.

That's why the images look so different.

And that's also why the telescopes are located at very different places...

Types of EM radiation

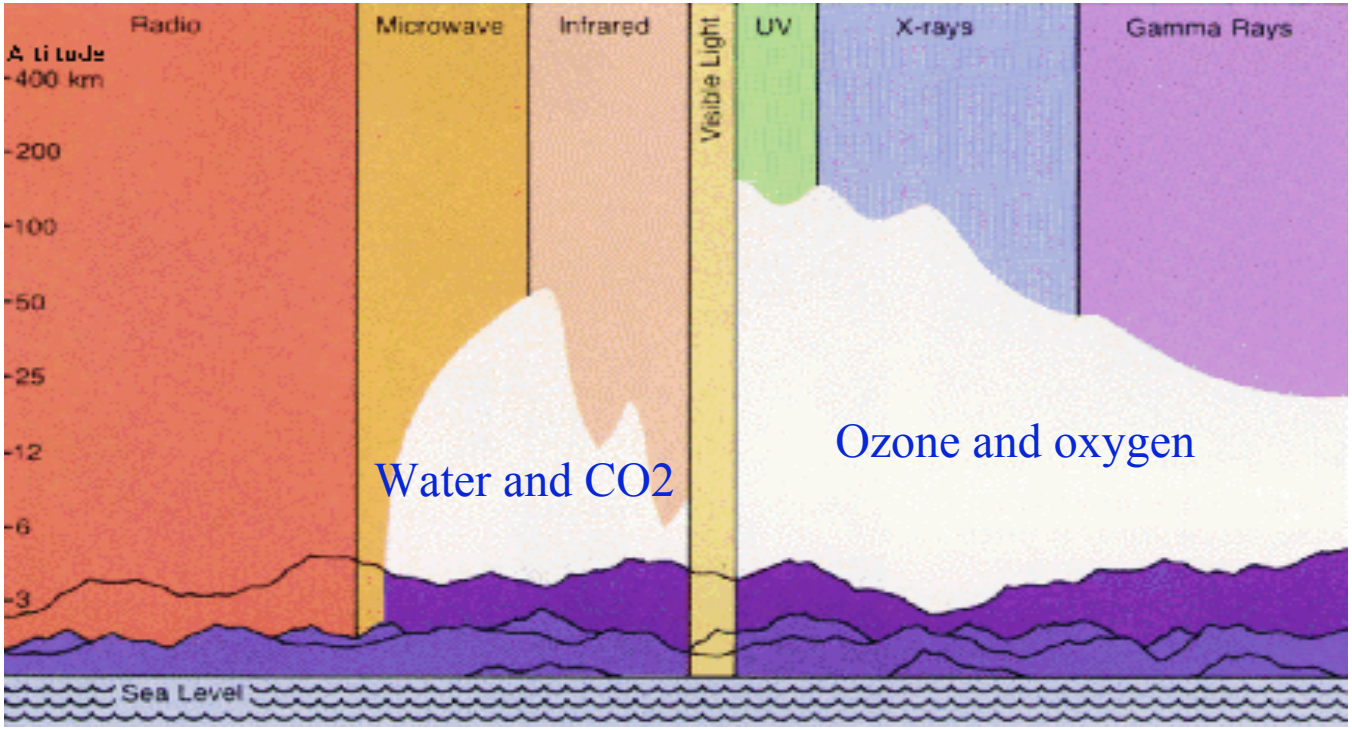
The energy (or freq or wavelength) determines how the radiation will react with the atmosphere.

Atmospheric windows

Radio,
millimeter,
sub-millimeter

Infrared and
optical

Ultraviolet
xrays, gamma rays



Location of radio, millimeter, and sub-millimeter telescopes

Radio

- Ground-based

Millimeter wave

- High and dry

Sub-millimeter

- Even higher and drier

Location of infrared and optical telescopes

Infrared

- High and dry

Optical

- Ground-based

Location of ultraviolet, xray, and gamma ray telescopes

Ultraviolet

- Space

Xray

- Space

Gamma ray

- Ground-based and Space

Types of EM radiation

Astronomers often group the different types of EM radiation into 3 groups according to their energy.

Types of EM radiation

Low frequency/long wavelength *LOW ENERGY*

Radio

Millimeter

Sub-millimeter

Mid frequency/mid wavelength *MID ENERGY*

Infrared

Optical

High frequency/short wavelength *HIGH ENERGY*

Ultraviolet

X-ray

Gamma ray

Types of telescopes

For each energy range, we'll discuss:

Single telescopes

Interferometers

More than one telescope linked together

Types of EM radiation

Low frequency/long wavelength *LOW ENERGY*

Radio

Millimeter

Sub-millimeter

Mid frequency/mid wavelength *MID ENERGY*

Infrared

Optical

High frequency/short wavelength *HIGH ENERGY*

Ultraviolet

X-ray

Gamma ray

Radio, millimeter, and submillimeter astronomy

The place of radio, millimeter, and submillimeter astronomy the study of astronomy

The parts of a radio telescope and how it works

The two big challenges of radio astronomy overcome by radio astronomers

- Tiny signal strength of radio signals
- Low angular resolution

Next generation radio, millimeter, and submillimeter telescopes

Low energy EM radiation

	frequency	wavelength
Radio	100MHz - 100GHz	3m-3mm
Millimeter	100GHz-300GHz	3mm-1mm
Submillimeter	300GHz-1000GHz	1mm-0.3mm

Discovery of CMB

Arno Penzias and Robert Wilson (1965)

Discovery of pulsars

Jocelyn Bell and 81.5 MHz radio telescope (1967)

Sources of radio, millimeter, and sub-millimeter radiation

HII regions

Synchrotron radiation

Interstellar atoms and molecules

Pulsars, quasars, radio galaxies

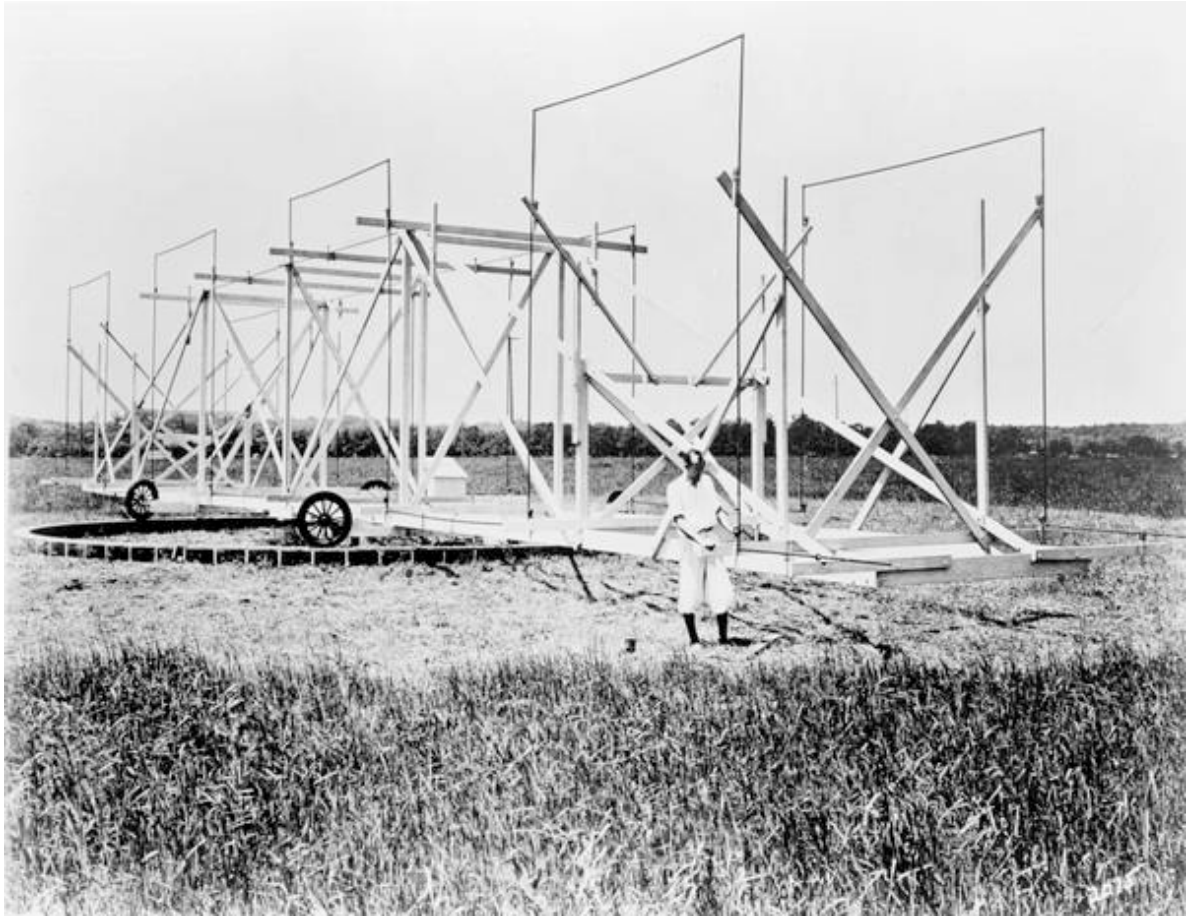
Cosmic microwave background

Carl Jansky's telescope

Jansky's vertically polarized beam antenna was built in 1931 to study the direction of thunderstorms, which were suspected to cause signal-to-noise problems in Bell Lab's initial transoceanic radio-telephone circuits.

In addition to detecting lightning, Jansky detected a signal that that appeared 4 minutes earlier each day and was strongest when Sagittarius was high in the sky.

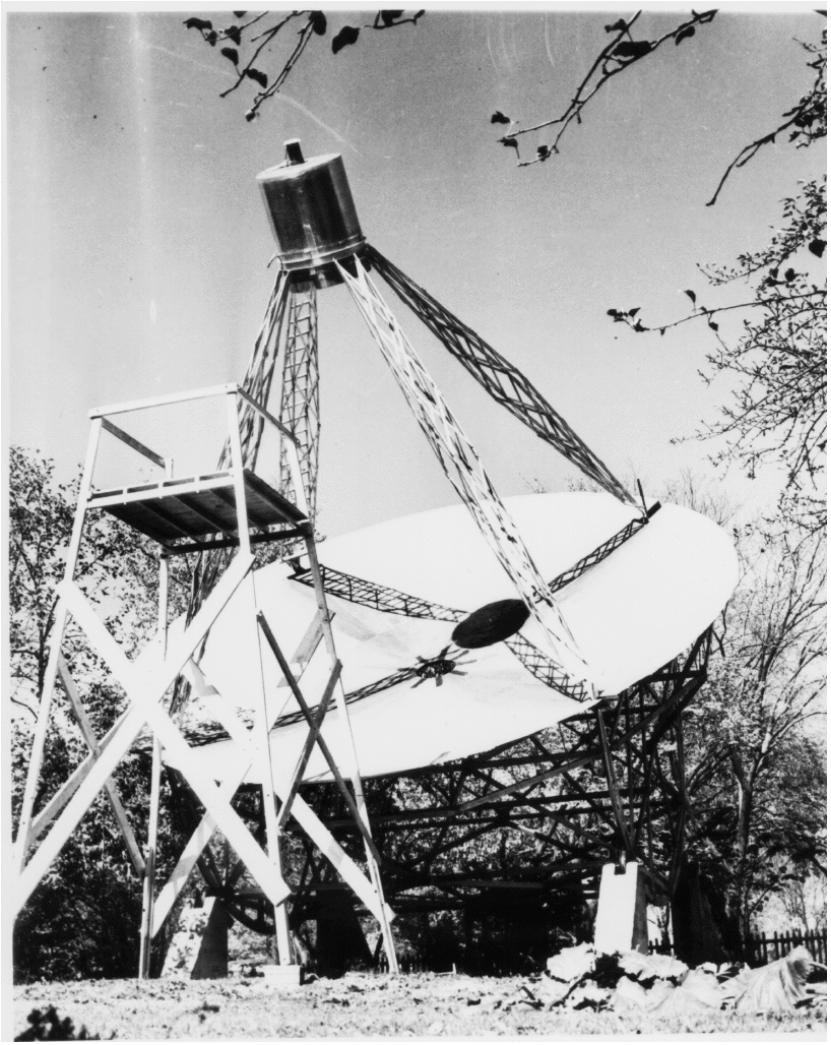
The center of the Galaxy is in the direction of Sagittarius, so Jansky concluded that he was detecting radio waves from an astronomical source



Grote Reber's telescope

Grote Reber read about Jansky's discovery.

In 1937, Reber built his own 32-foot-diameter parabolic dish antenna in his backyard in Wheaton, Illinois to seek cosmic radio emissions.



Grote Reber's telescope

In the spring of 1939, he was able to detect cosmic radio emissions with his equipment. In 1941, he made the first survey of the sky at radio wavelengths (160MHz).

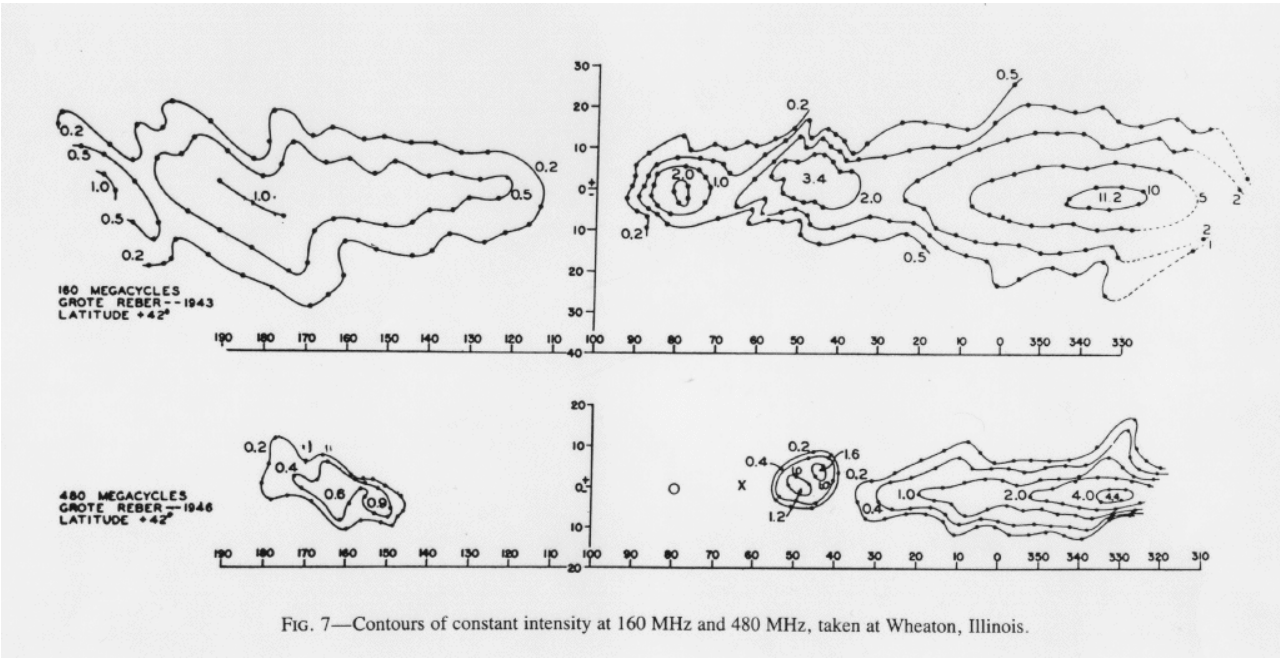


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Reber's telescope

On display at Greenbank Radio Observatory
Greenbank, WV

Radio, millimeter, and submillimeter astronomy

The place of radio, millimeter, and submillimeter astronomy the study of astronomy

The parts of a radio telescope and how it works

The two big challenges of radio astronomy overcome by radio astronomers

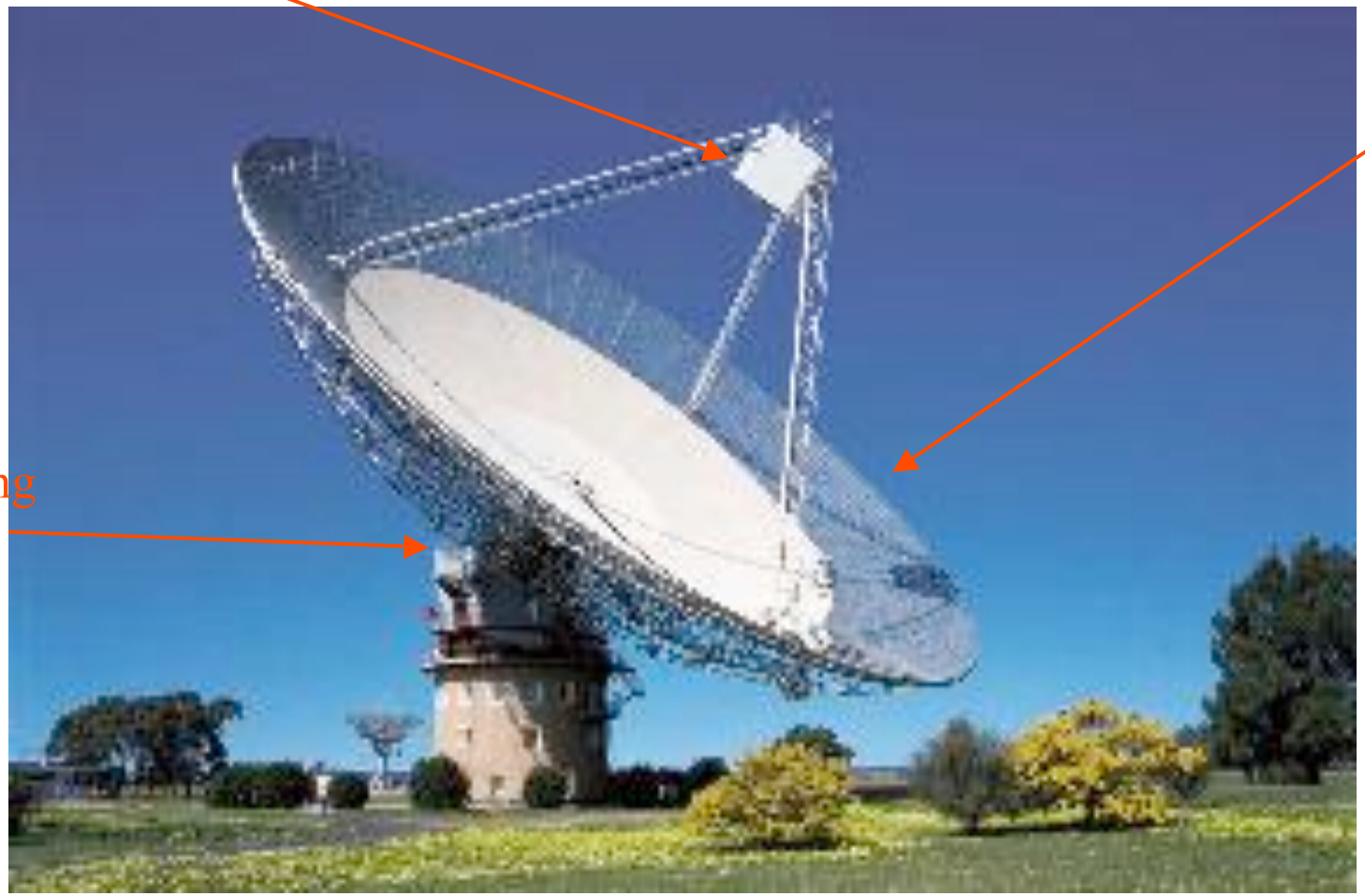
- Tiny signal strength of radio signals
- Low angular resolution

Next generation radio, millimeter, and submillimeter telescopes

Parts of a radio telescope

- Antenna
  - Collects the radiation
  - Focuses the radiation on the receiver horn
- Receiver
  - Horn
  - Amplifies the signal
  - Converts the radio-frequency signal to signals (current/voltage) we can record and analyze
- Steering gear
  - Moves the telescope as it tracks the observed object

Parts of a radio telescope



Parkes 64-meter radio telescope

Film clip of Parkes Radio Telescope
from
“The Dish”

Parts of a radio telescope

Hat Creek Radio Observatory

Parts of a radio telescope

Antenna

- Collects the radiation
- Focuses the radiation on the receiver horn

Receiver

- Horn
- Amplifies the signal
- Converts the radio-frequency signal to signals (current/voltage) we can record and analyze

Steering gear

- Moves the telescope as it tracks the observed object

Antenna surface errors

The surface error (accuracy of antenna surface and shape) should be less than 1/20 wavelength to keep losses to less than 30%

This results in much more stringent requirements for sub-millimeter telescopes than for radio telescopes.

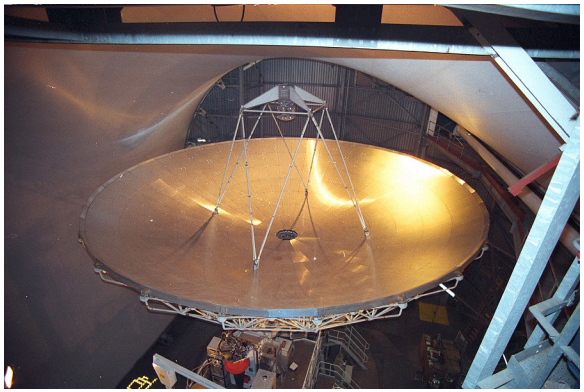
Antenna surface errors

Smooth

1/20λ=0.15mm
Radio

VLBA (3mm-3m)
Mauna Kea

Smoothest



1/20λ=0.015mm
Sub-millimeter

JCMT (0.3mm-2.0mm)
Mauna Kea

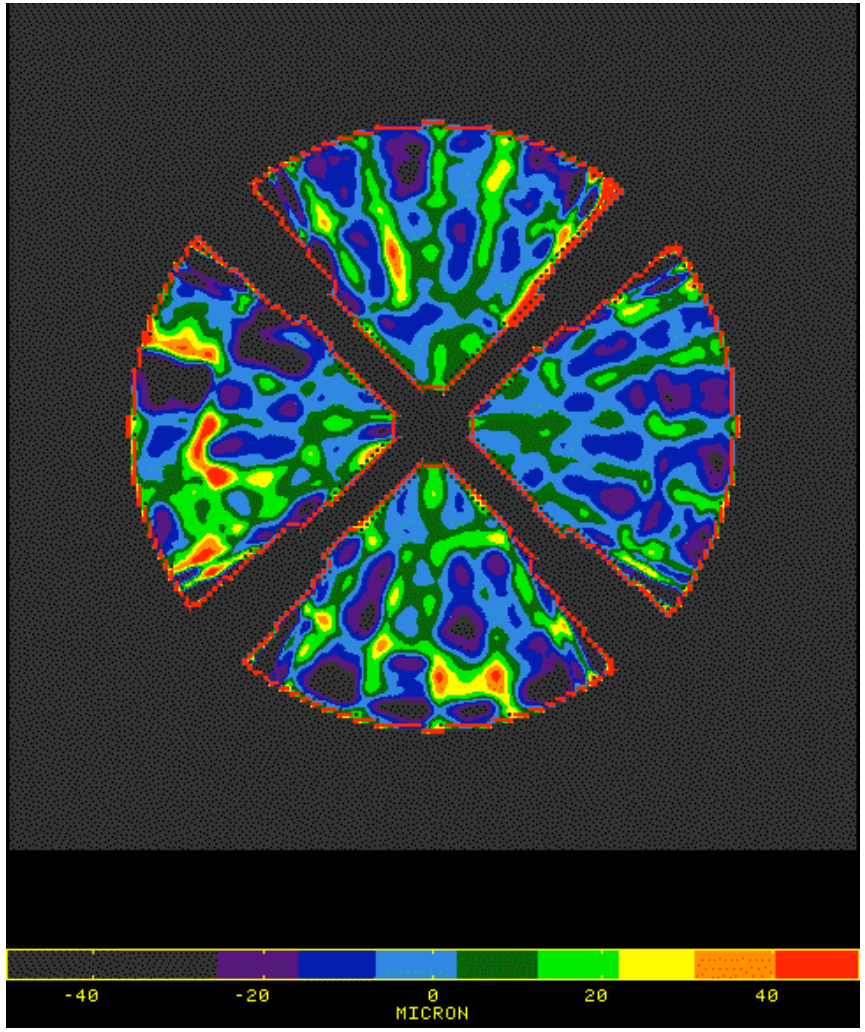
Smoother

1/20λ=0.05mm
Millimeter

NRAO 12 meter (1mm-3mm)
Kitt Peak

Antenna surface errors

This image was taken during the SMT reflector's holographic testing showing that the deviations of the reflector are nearing the targeted 0.015 microns (about the thickness of a human hair)



Parts of a radio telescope

Antenna

- Collects the radiation
- Focuses the radiation on the receiver horn

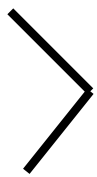
Receiver

- Horn
- Amplifies the signal
- Converts the radio-frequency signal to signals (current/voltage) we can record and analyze

Steering gear

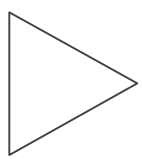
- Moves the telescope as it tracks the observed object

Receivers



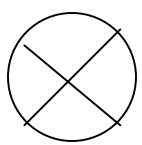
Horn

Purpose of the horn is to collect the radiation directed to it from the antenna.



Amplifier

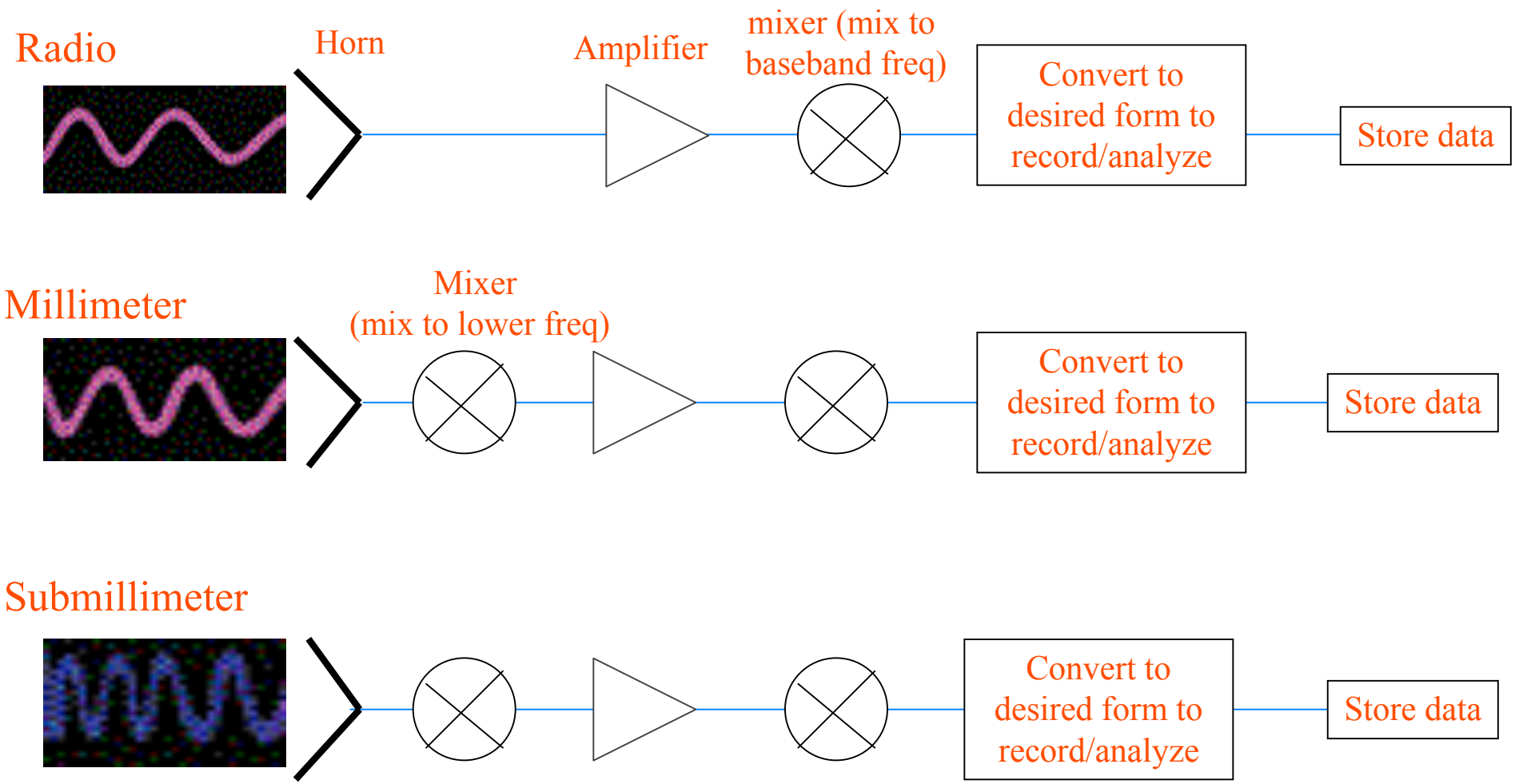
Increases the amplitude of the signal



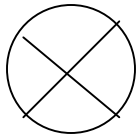
Mixer

Used to change the frequency to a more easily used frequency

Receivers


Radio
Horn
Amplifier
mixer (mix to baseband freq)
Convert to desired form to record/analyze
Store data
Millimeter
Mixer (mix to lower freq)
Convert to desired form to record/analyze
Store data
Submillimeter
Convert to desired form to record/analyze
Store data

Reasons to use a mixer



Amplifiers don't work at very high frequencies, so must change to a lower frequency before amplifying

Want all of the electronics that change the signal to forms we can record and analyze to only have to be designed for one frequency (called *baseband* frequency).

If the signal must be transmitted a long distance, there will be less loss if the frequency is first shifted to a lower frequency

Receivers

The design of the receiver is effected greatly by whether the radiation observed is radio, millimeter, or submillimeter.

Receivers

The size of the electronics gets smaller as the wavelength gets shorter (higher frequencies)

So devices associated with radio telescope receivers (long wavelength) are larger than the devices associated with millimeter and submillimeter receivers (shorter wavelengths).

Radio receivers

Radio

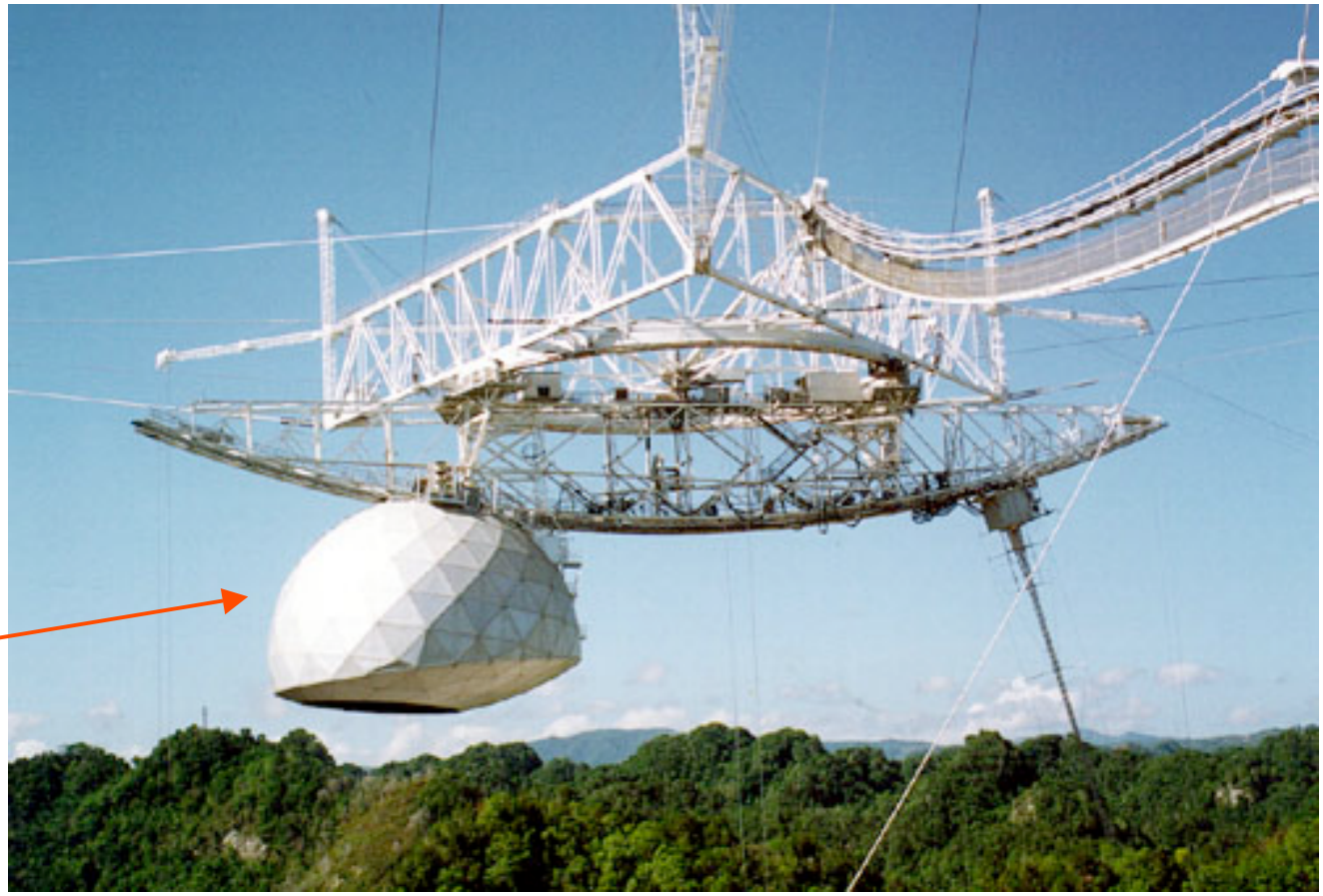
100MHz - 100GHz

3m-3mm

Radio receivers

Arecibo Observatory

Arecibo radio telescope

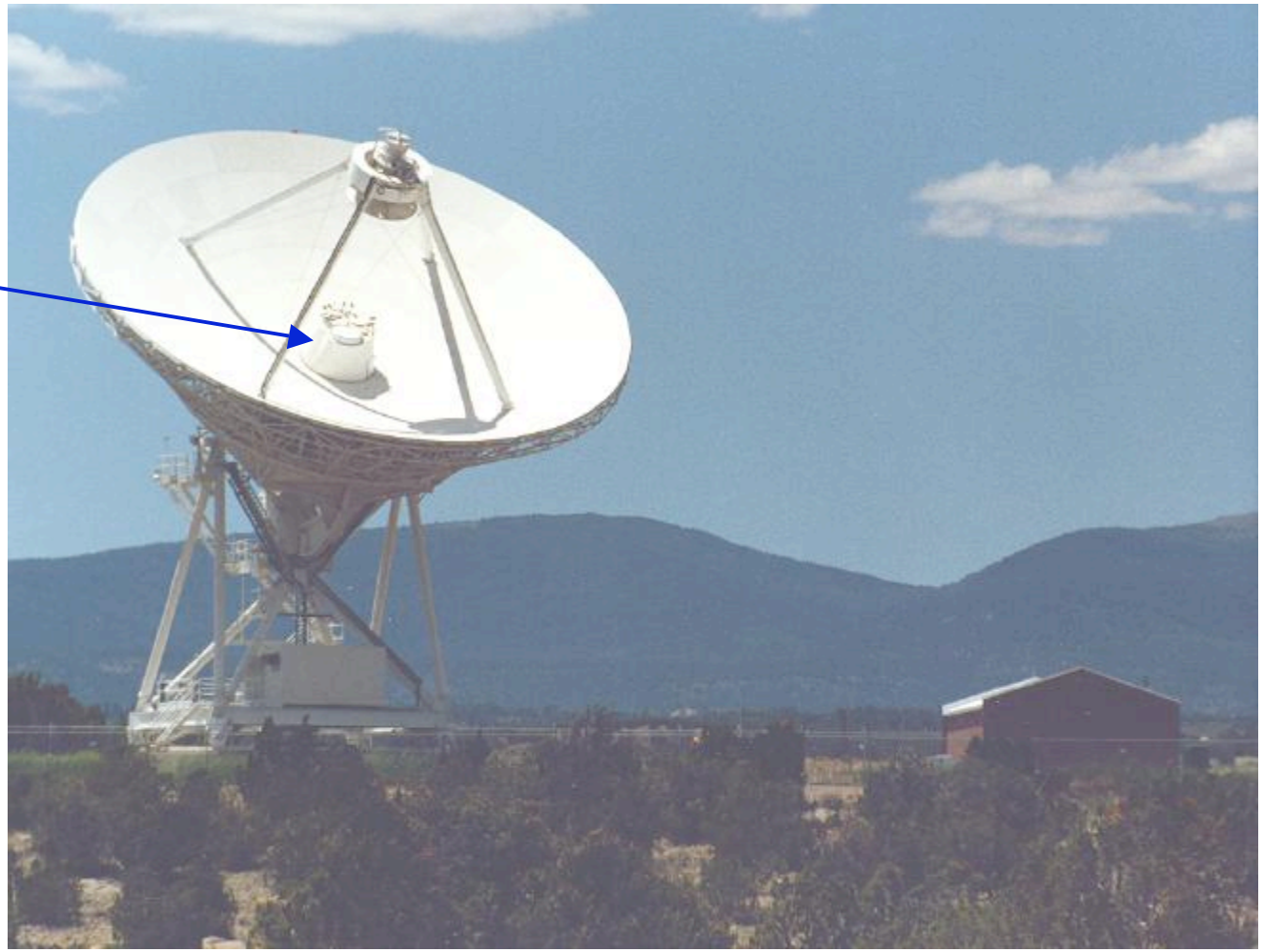


Receivers are
inside
the dome

Radio receivers

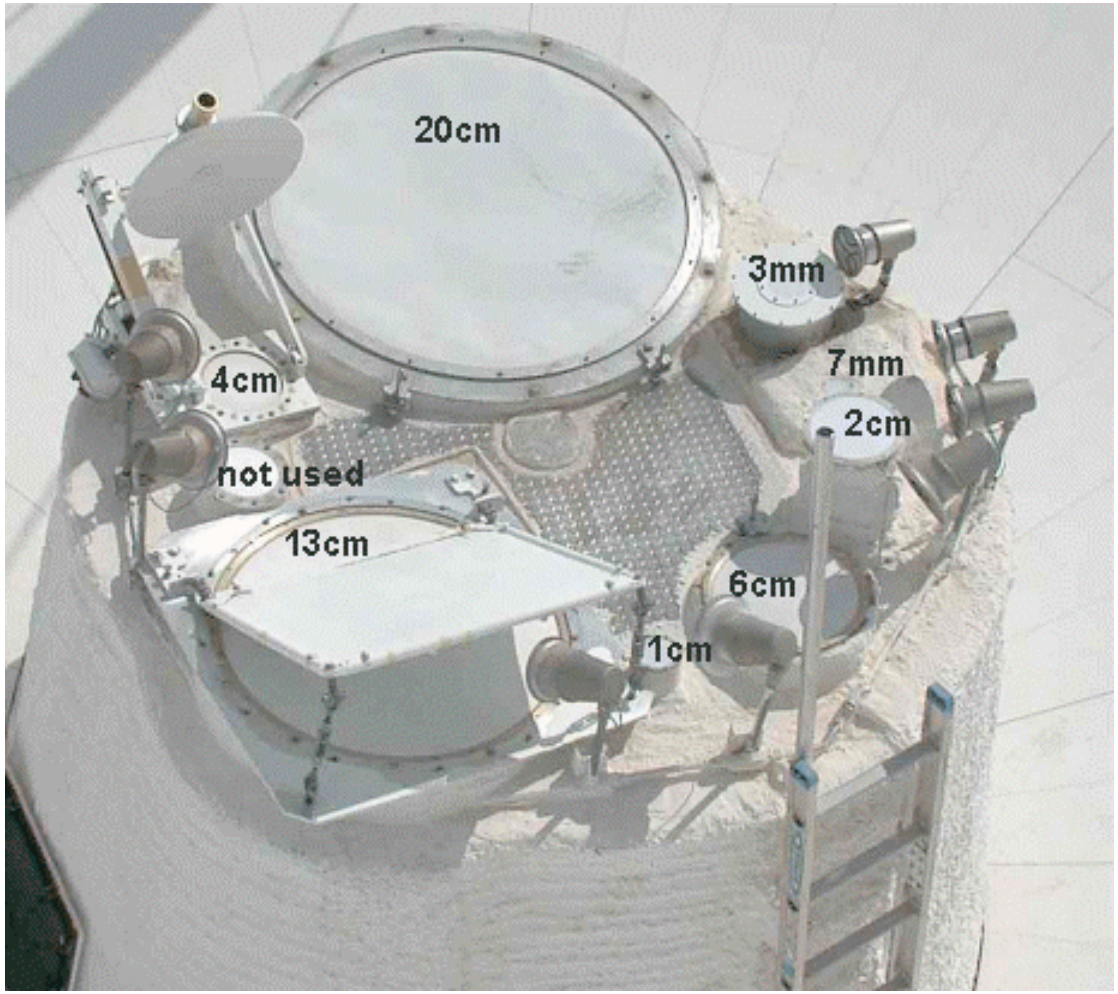
Radio receivers

Radio receivers



VLBA telescope

Radio receivers



VLBA telescope

Radio horns

~1 meter

VLBA telescope

Millimeter receivers

Millimeter

100GHz-300GHz

3mm-1mm

Millimeter wave receiver

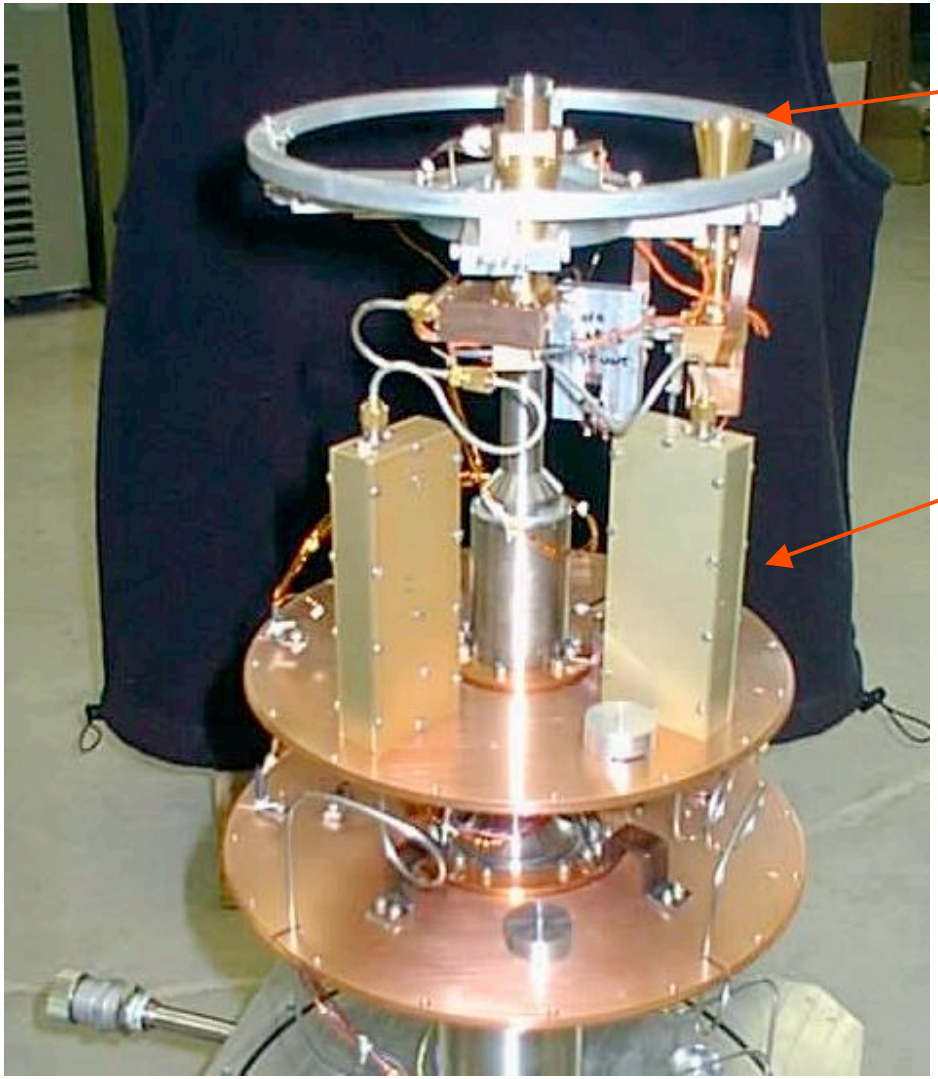
Hat Creek Radio Observatory

Receivers

Millimeter wave receiver

Millimeter wave receiver

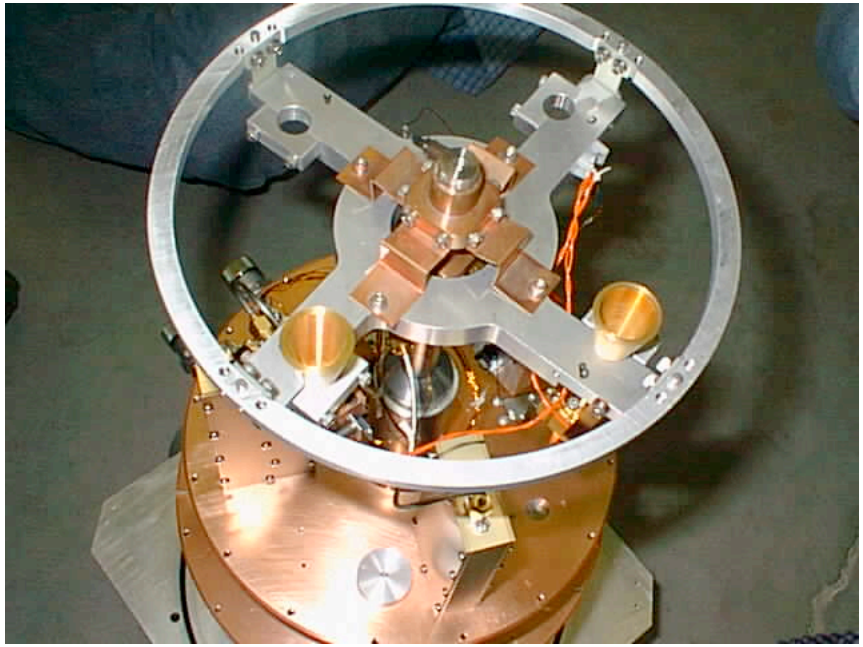
~0.5 m

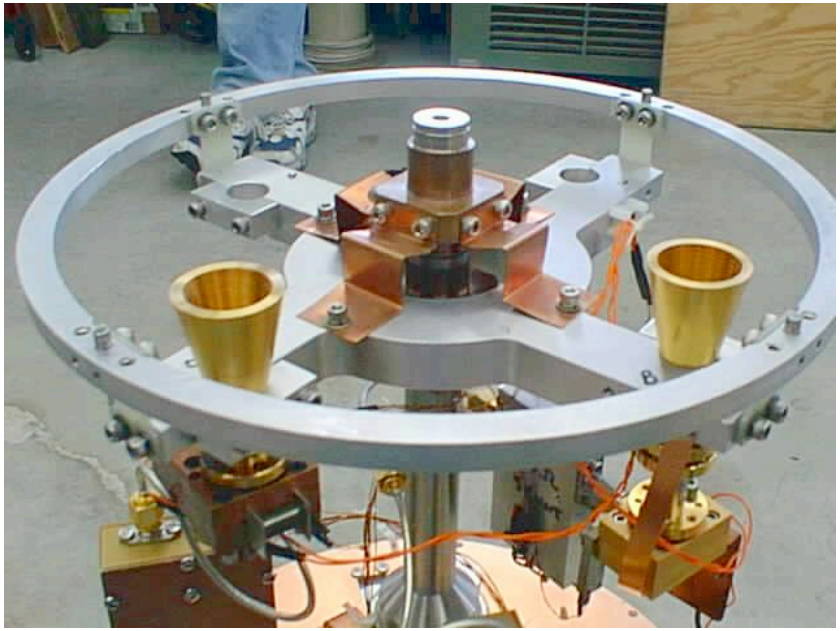


Horns

Amplifiers

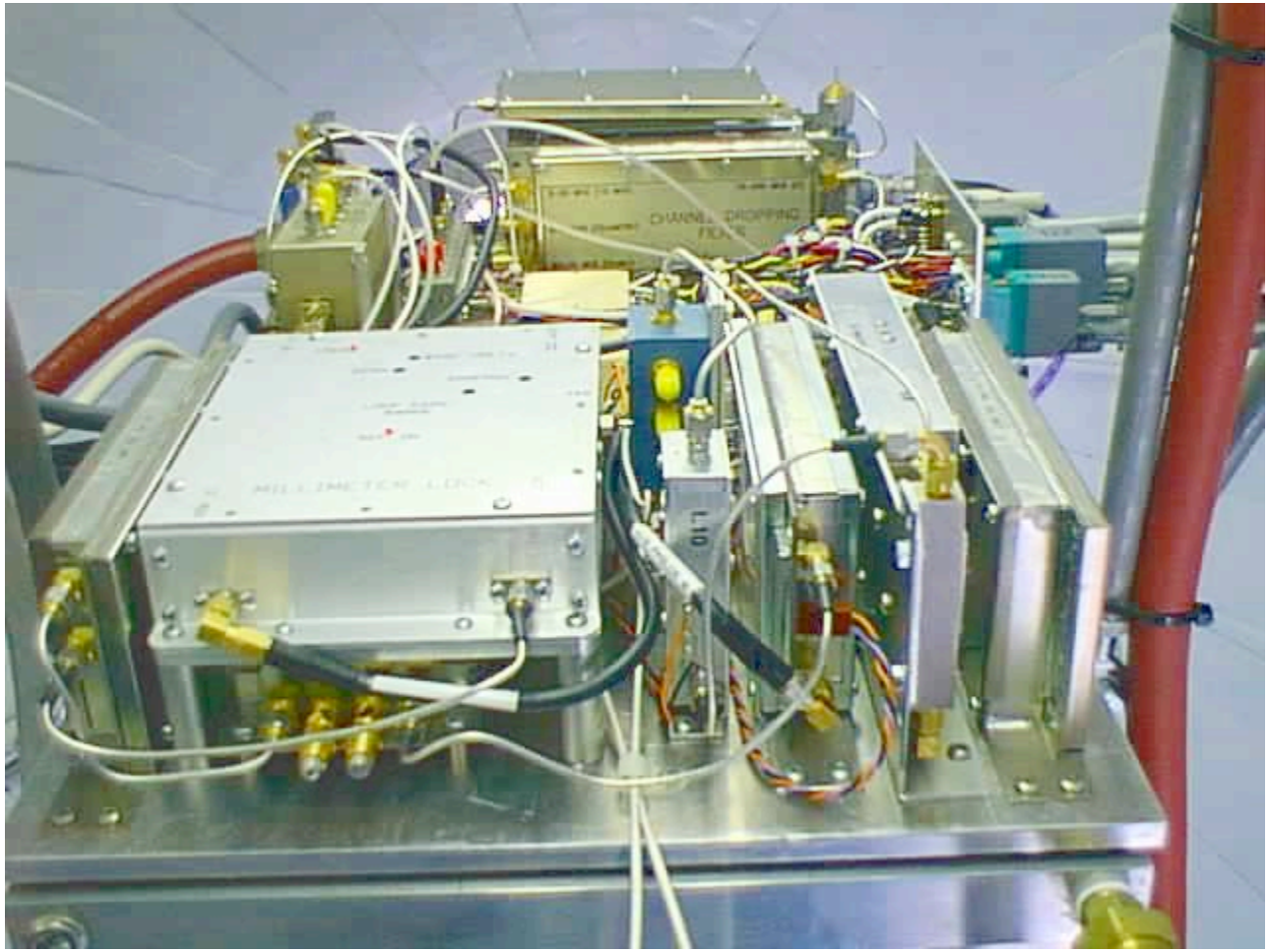
Millimeter wave horns





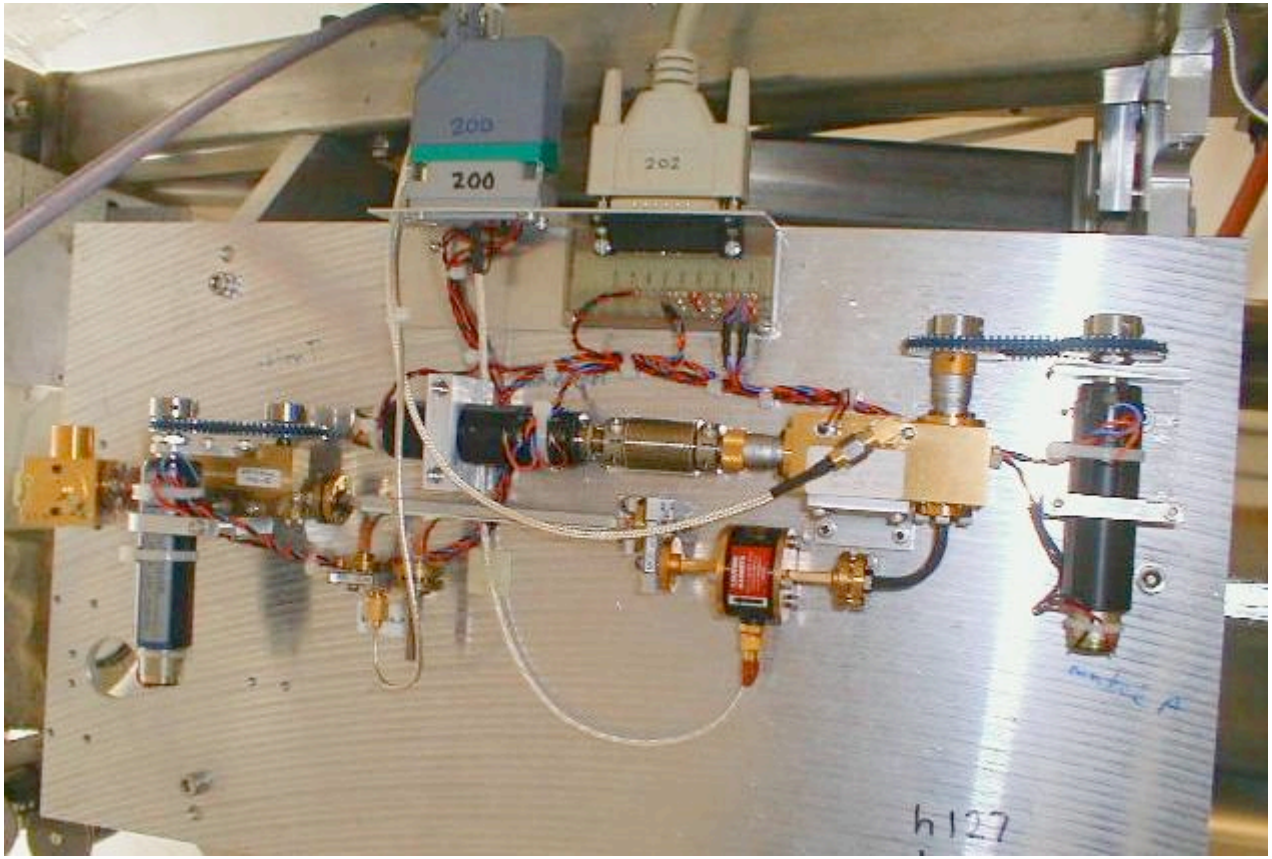
~2cm

Millimeter wave receiver electronics



Intermediate frequency (IF) plate

Millimeter wave electronics



Local oscillator

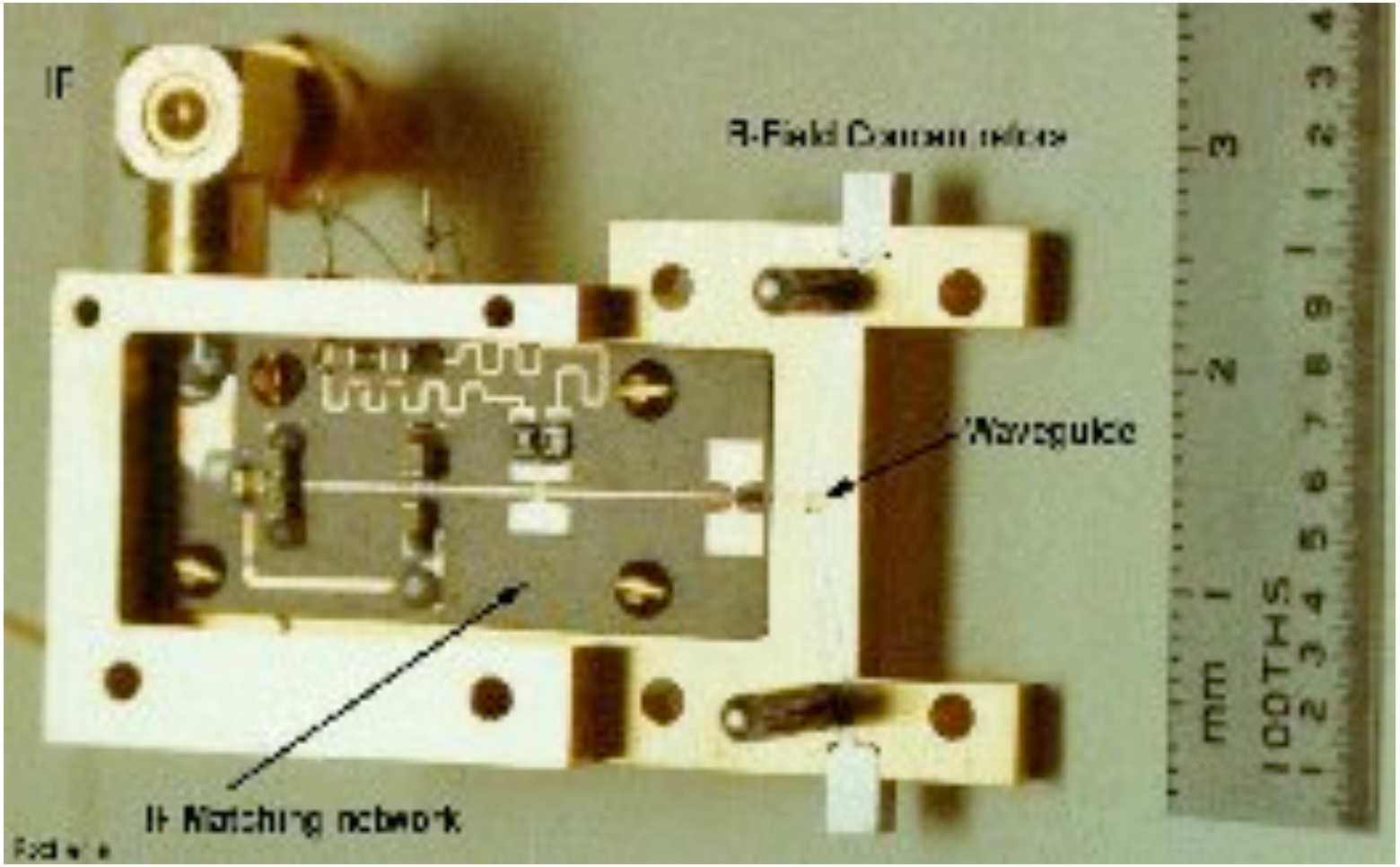
Submillimeter receivers

Submillimeter

300GHz-1000GHz

1mm-0.3mm

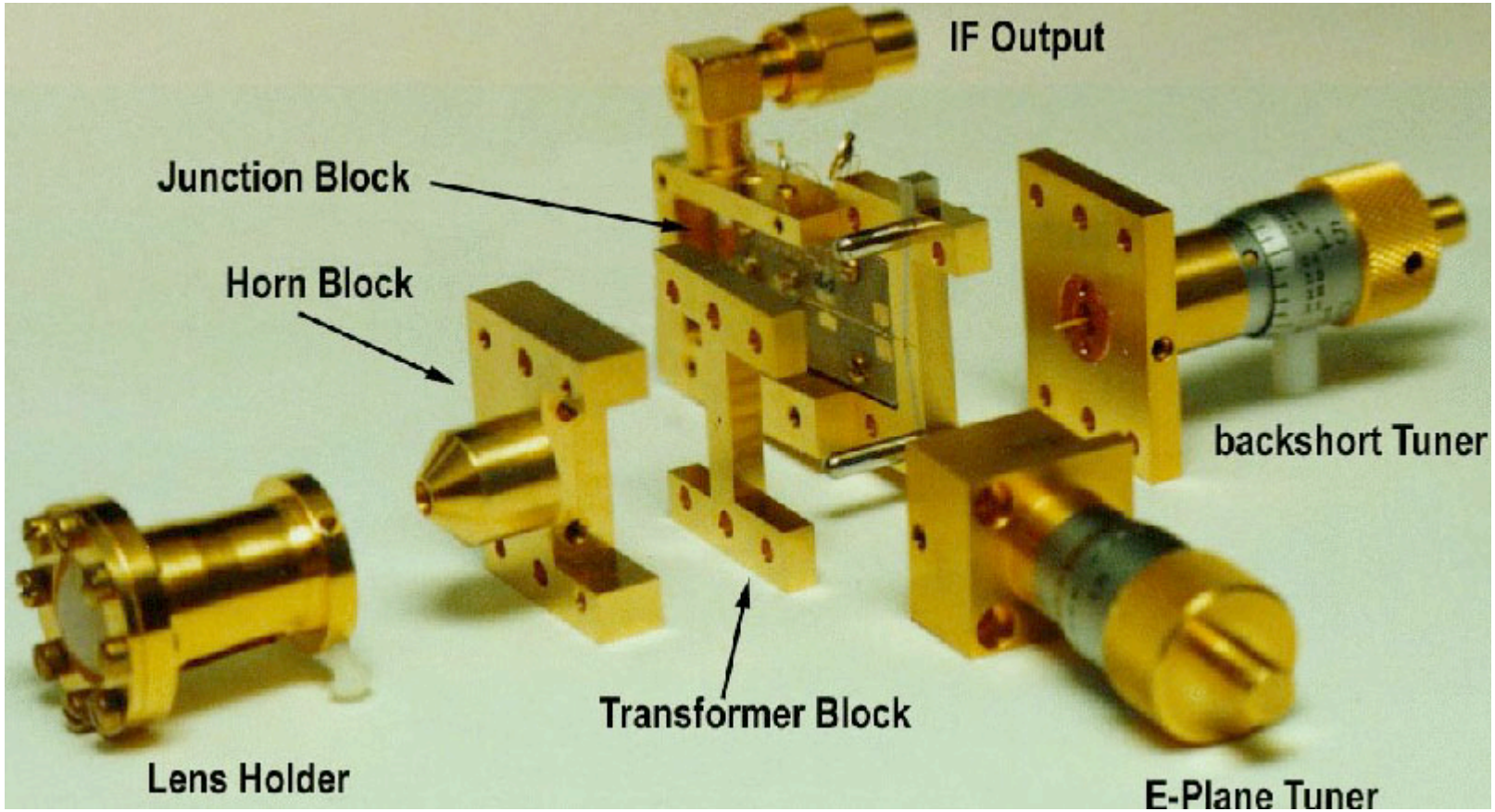
Submillimeter receiver



230 GHz mixer block

CSO, Mauna Kea

Submillimeter receiver



CSO, Mauna Kea

Submillimeter receivers

All of the receivers shown are called COHERENT detectors.

COHERENT detectors preserve the phase information and spectral information is retained.

Another type of receiver is called INCOHERENT detector.

INCOHERENT detectors respond only to the total power of the signal.

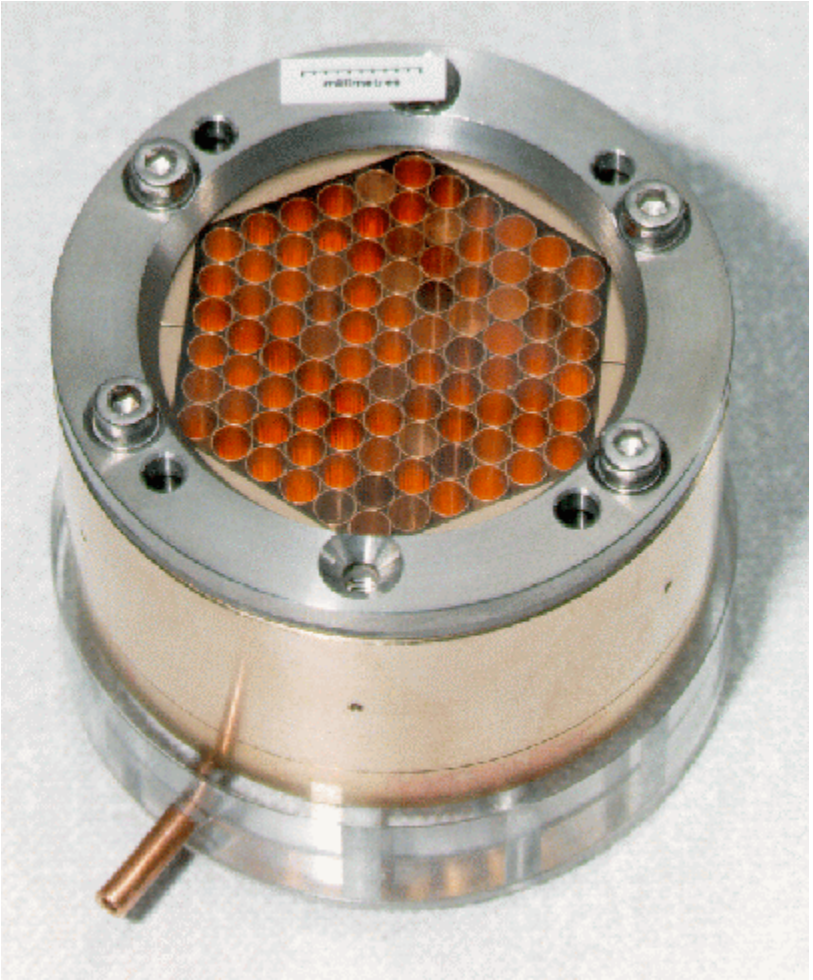
Submillimeter receivers

A type of INCOHERENT detector is called a bolometer.

A bolometer is a device that changes its electrical resistivity in response to heating by illuminating radiation.

Bolometers may be made of cooled semiconductors coated with an appropriate absorber for the wavelength which is to be observed.

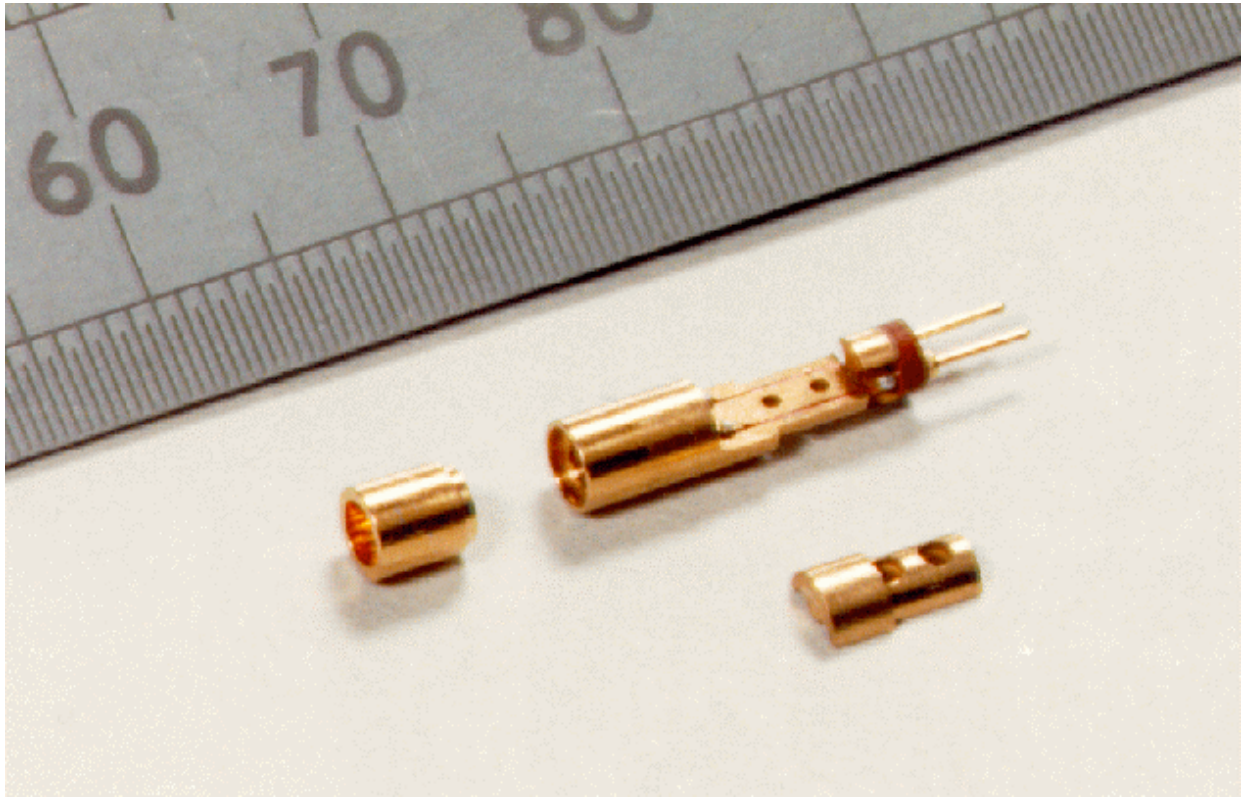
Submillimeter receivers



JCMT, Mauna Kea

SCUBA The Submillimeter Common-User Bolometer Array

Submillimeter receivers



JCMT, Mauna Kea

SCUBA The Submillimeter Common-User Bolometer Array

Parts of a radio telescope

Antenna

- Collects the radiation
- Focuses the radiation on the receiver horn

Receiver

- Horn
- Amplifies the signal
- Converts the radio-frequency signal to signals (current/voltage) we can record and analyze

Steering gear

- Moves the telescope as it tracks the observed object

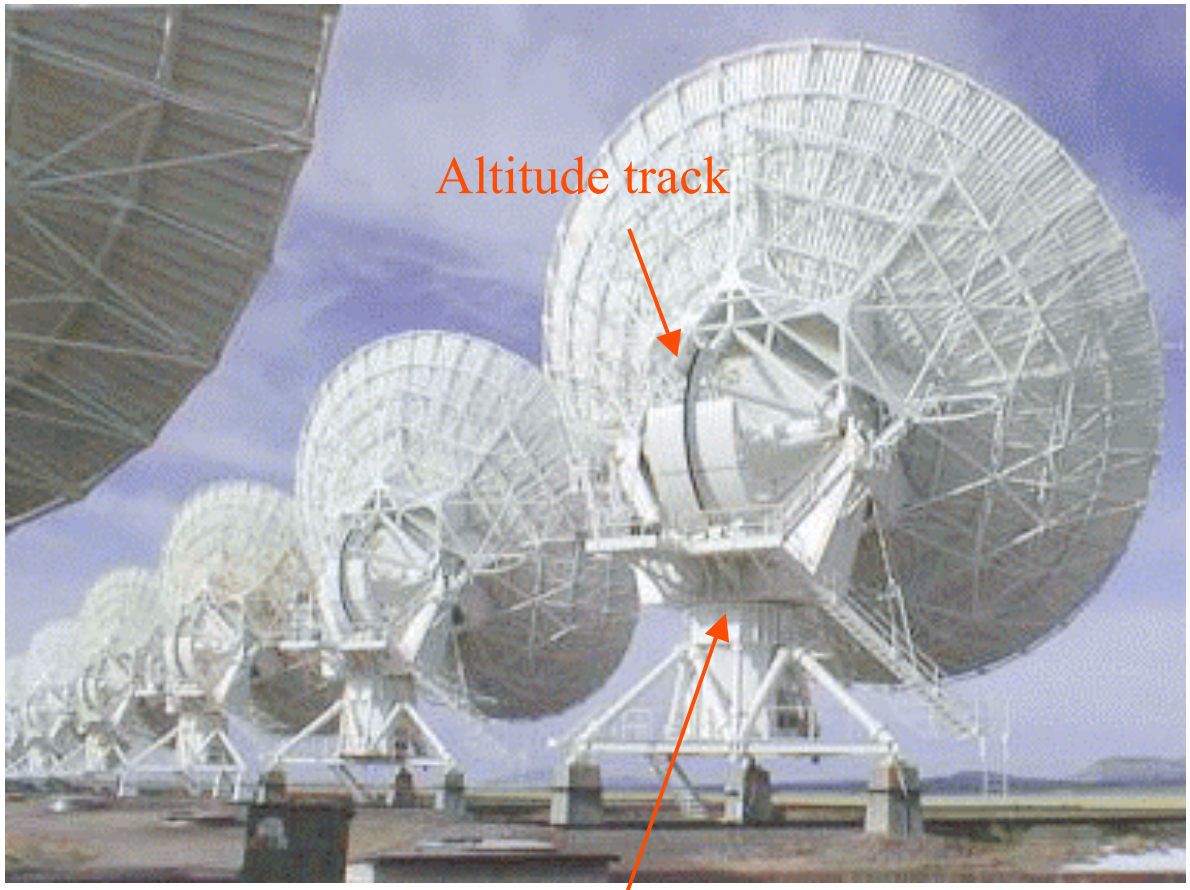
Steering gear

There are 2 styles of steering gear:

Altitude-azimuth mount

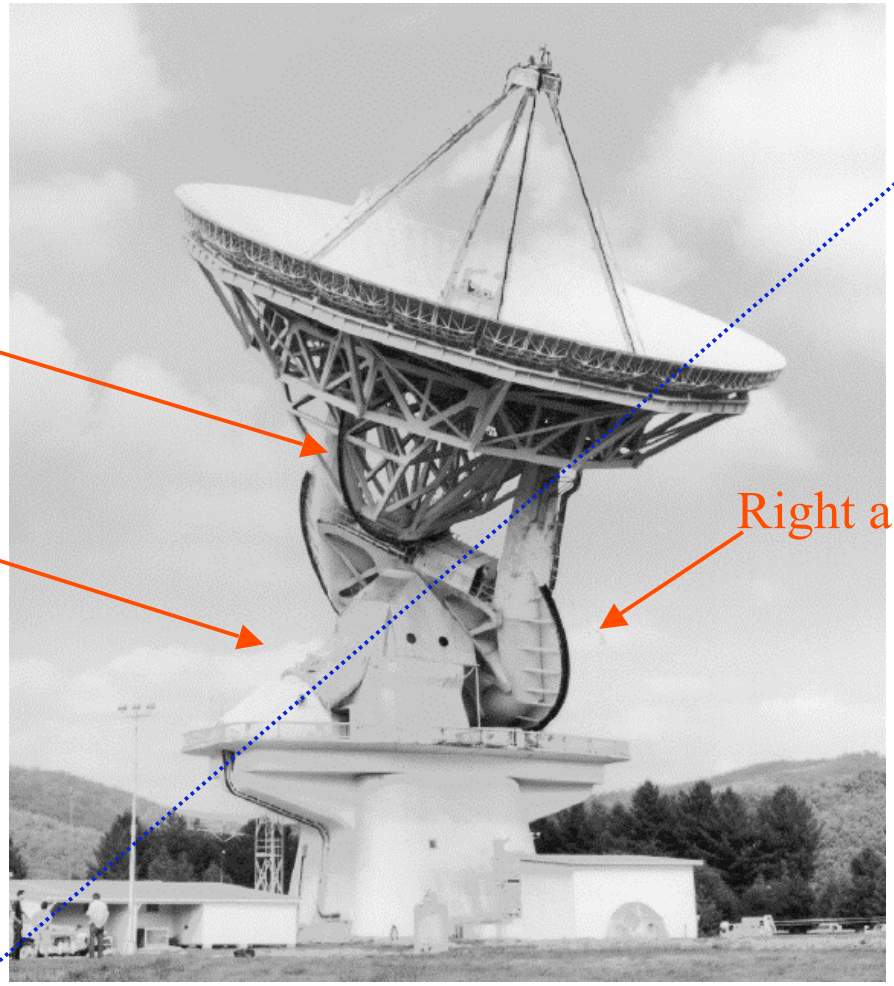
Equatorial mount

Altitude azimuth mount



VLA Very Large Array

Equatorial mount



Green Bank 140 ft

Radio, millimeter, and submillimeter astronomy

The place of radio, millimeter, and submillimeter astronomy the study of astronomy

The parts of a radio telescope and how it works

The two big challenges of radio astronomy overcome by radio astronomers

- Tiny signal strength of radio signals
- Low angular resolution

Next generation radio, millimeter, and submillimeter telescopes

Cosmic radio signals are very weak!

All the energy collected by all the radio telescopes on Earth during the >60 year history of radio astronomy amounts to no more than the energy released when a few raindrops hit the ground!

Cosmic radio signals are very weak!

This places strict requirements on the design of a radio telescope!

Design to overcome small signal strength

Antenna

LARGE COLLECTING AREA

Receiver

LOW NOISE

Design to overcome small signal strength

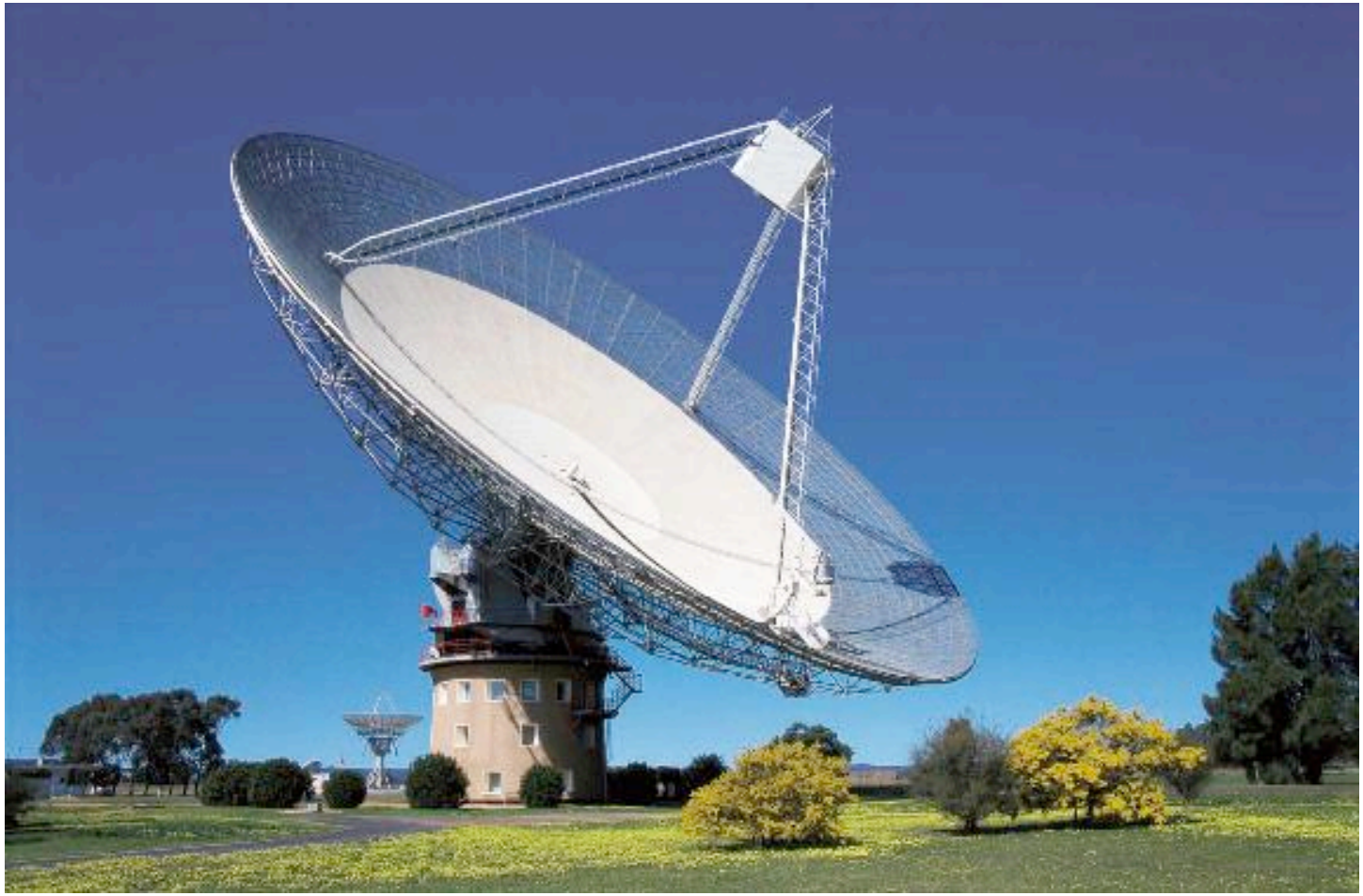
Antenna

LARGE COLLECTING AREA

Receiver

LOW NOISE

Large collecting area



Parkes 64-meter radio telescope

Larger collecting area

100-meter GBT Green Bank Telescope (Great Big Telescope)

Largest collecting area

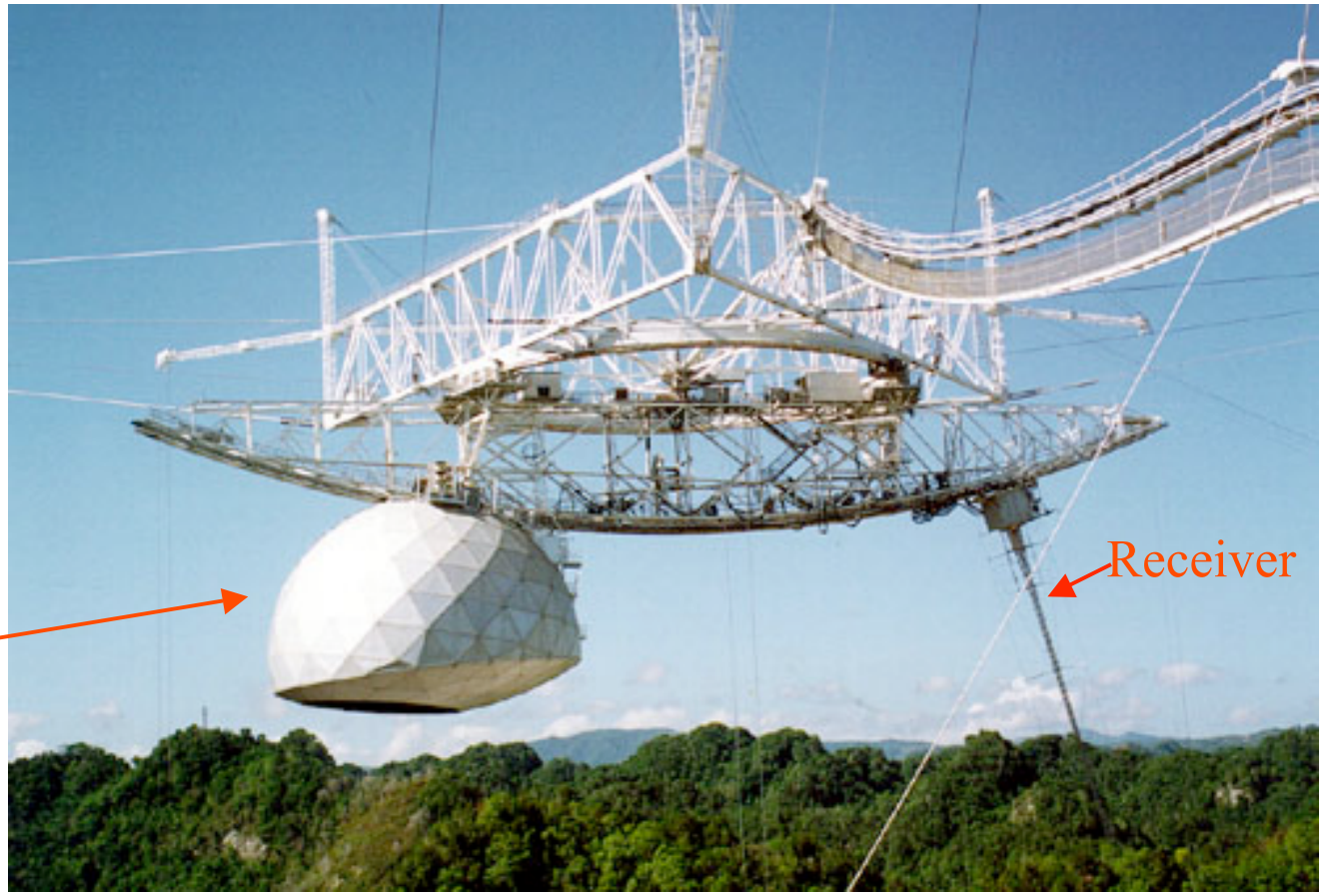
300 meter radio telescope, Arecibo Observatory

Largest dish
(but not fully steerable)

300 meter radio telescope at Arecibo Observatory

Arecibo radio telescope

Since Arecibo's dish is not moveable, tracking is accomplished by moving the receivers instead.

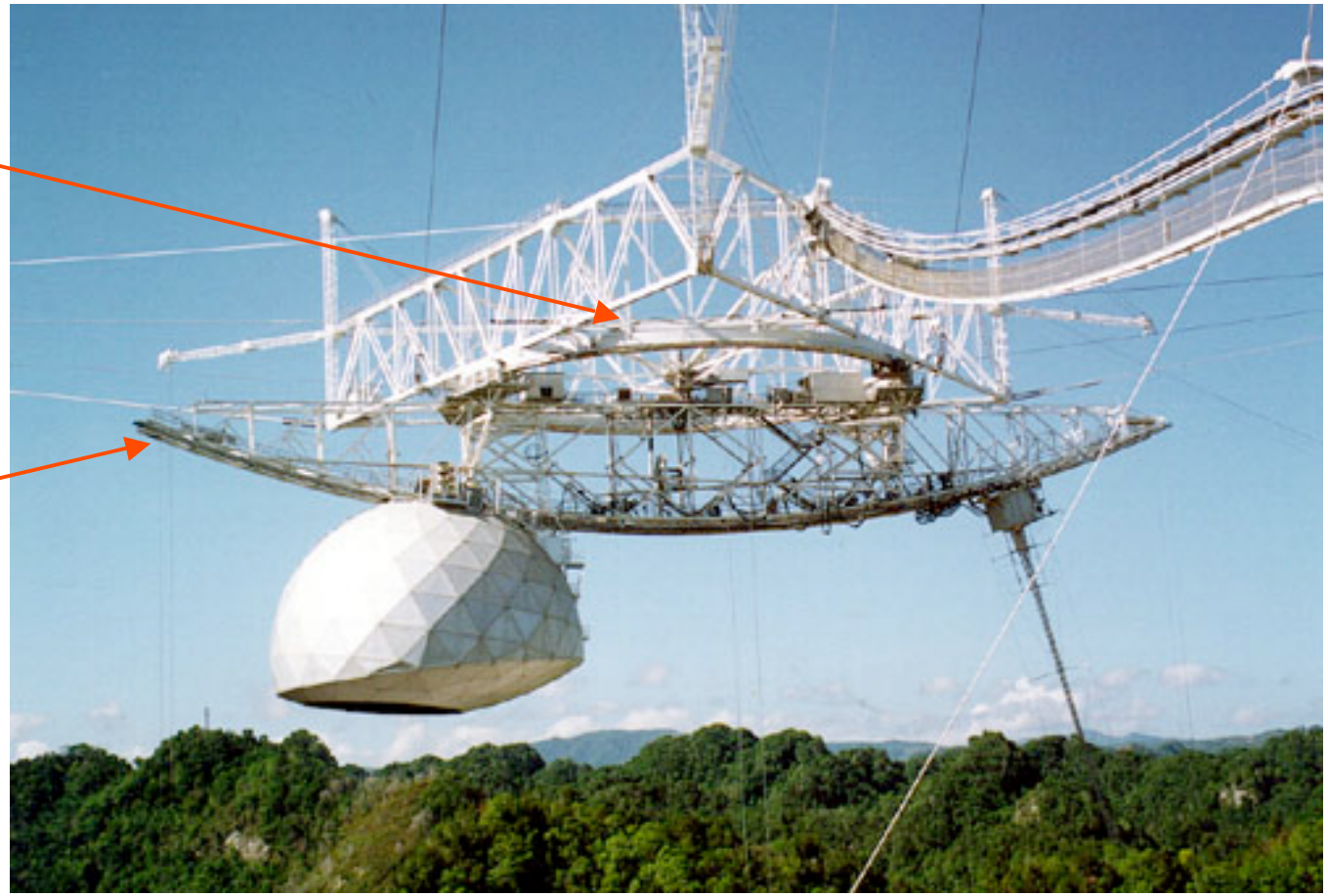


Receivers are inside the dome

Arecibo radio telescope

Azimuth track

Altitude track



Requirements of a radio telescope

Antenna

LARGE COLLECTING AREA

Receiver

LOW NOISE

Cryogenics

One way to lower noise is to operate all the electronics at low temperatures.

This lowers the thermal noise resulting in a higher signal to noise S/N ratio.

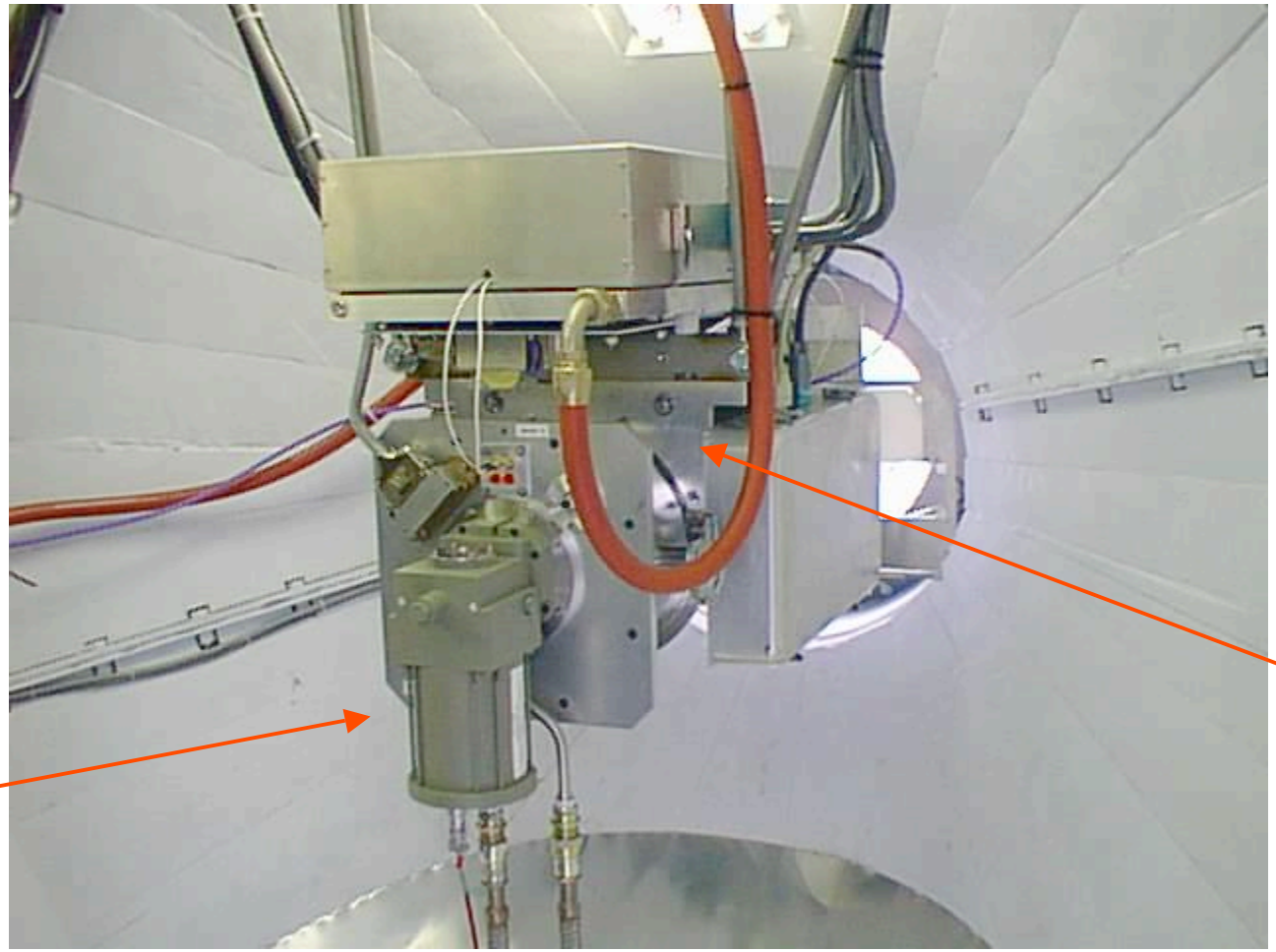
Cryogenics

The desired cooling to less than 20K is accomplished with high pressure helium gas.

Most telescopes are equipped with helium compressors.

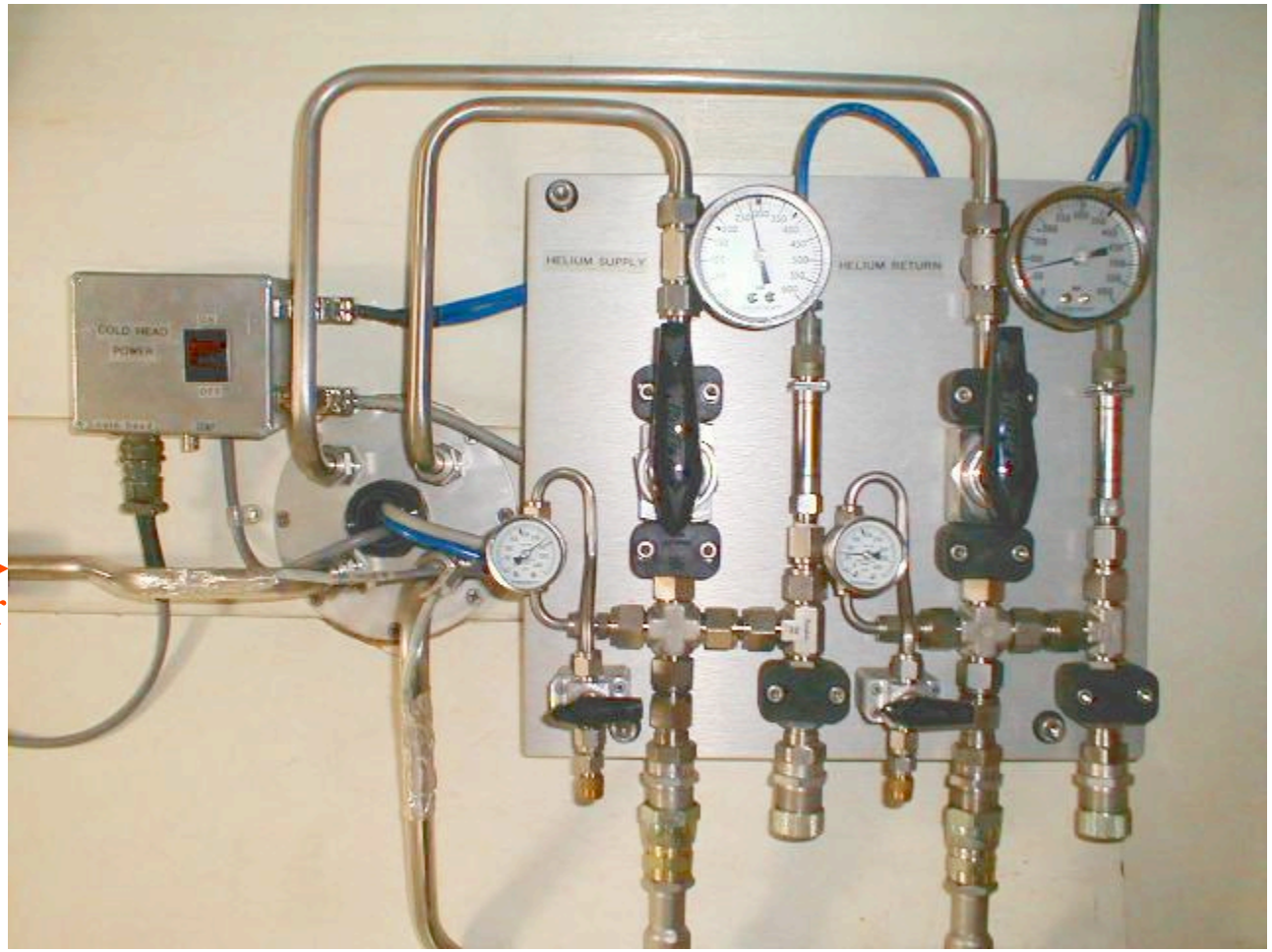
The electronics are operated in a cryostat (thermos) containing high pressure helium gas.

Receiver/cryostat



Cryogenics

Helium
from compressor



Helium manifold

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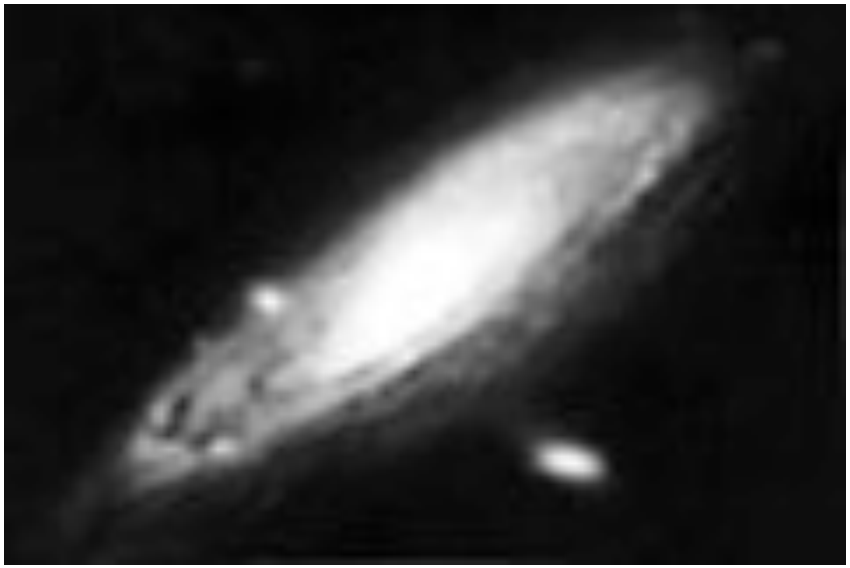
Next generation radio, millimeter, and submillimeter telescopes

What is resolution?



Low resolution

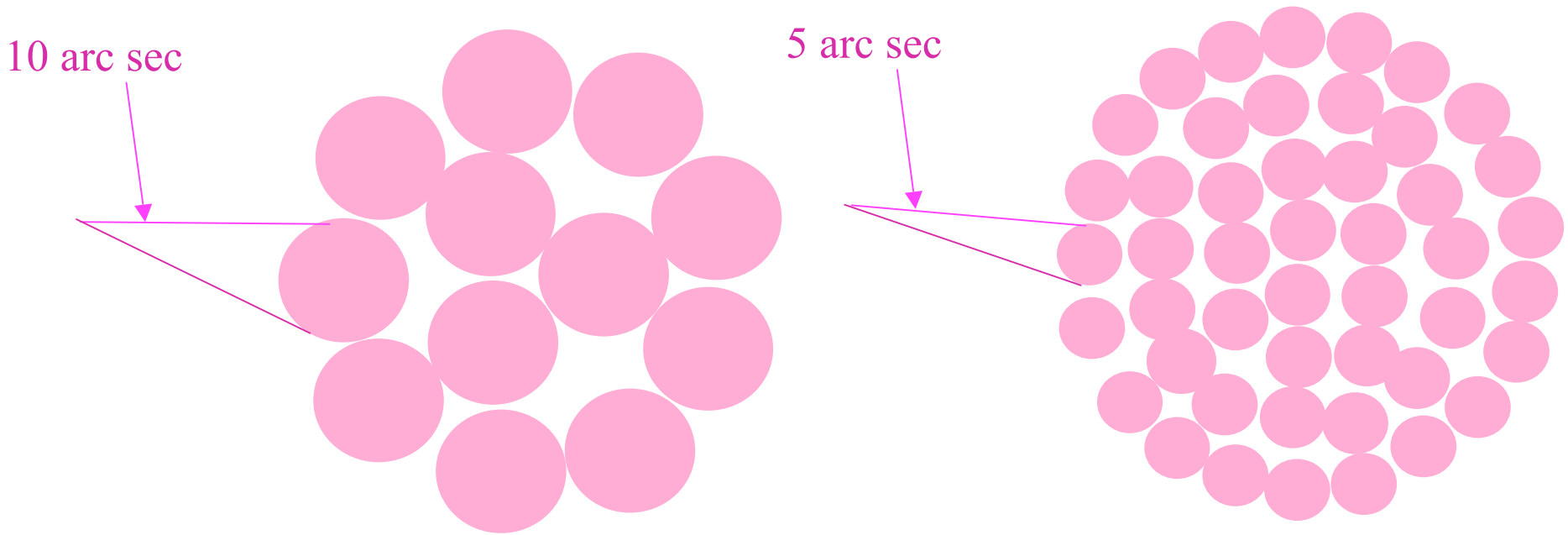
High resolution

Andromeda galaxy

What is resolution?

The resolution of a telescope is expressed as an angle.

What is resolution?



Greatly magnified views

What is resolution?

The resolution of a telescope is equal to:

$$\frac{\text{wavelength}}{\text{telescope diameter}}$$

Since radio waves have longer wavelengths than all other forms of EM waves, the resolution of radio images in inherently lower.

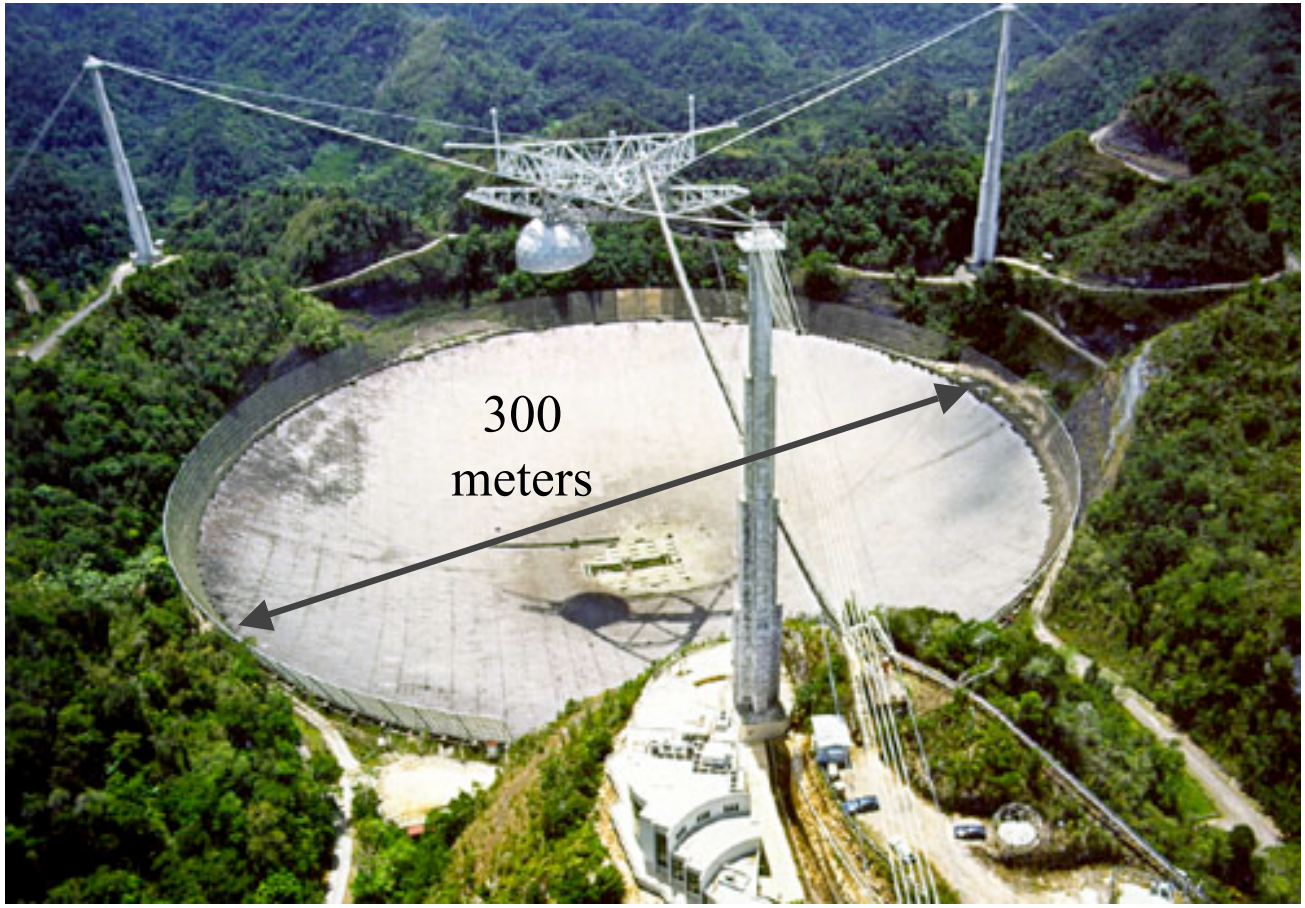
What is resolution?

The resolution of a telescope is equal to:

$$\frac{\text{wavelength}}{\text{telescope diameter}}$$

One way to increase the resolution is to increase the diameter of the telescope.

What is resolution?



Arecibo Observatory

This is about the biggest diameter that is practical to build

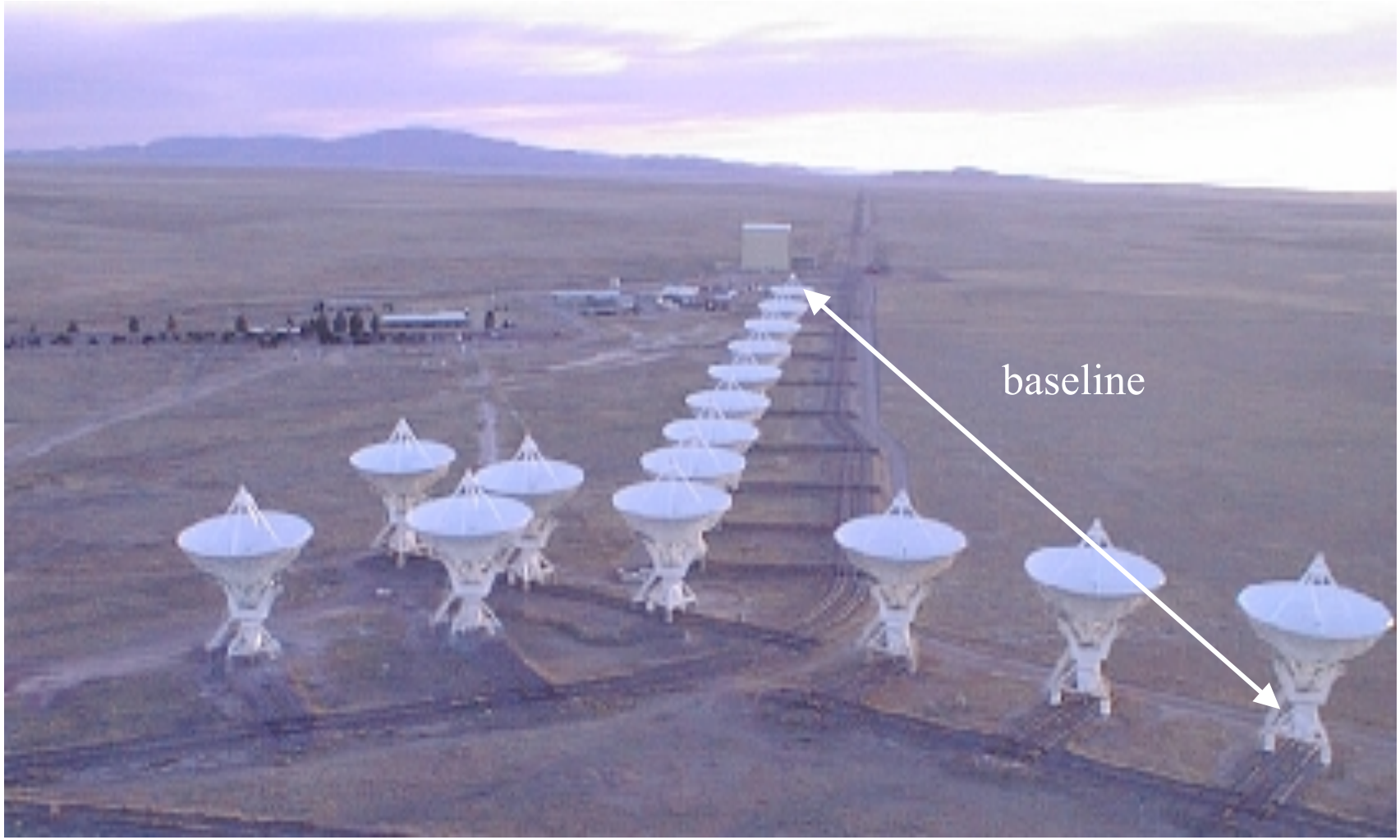
What is resolution?

Another way to increase the resolution is to build an interferometer.

The resolution of an interferometer is equal to:

$$\frac{\text{wavelength}}{\text{baseline}}$$

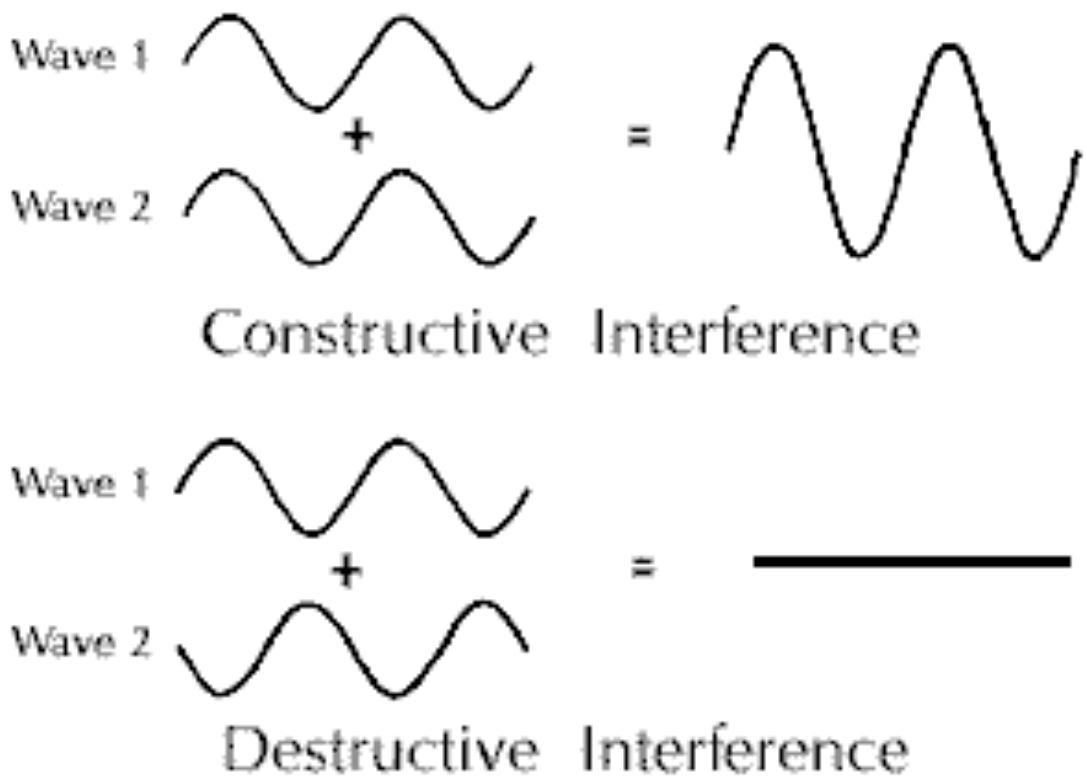
Radio interferometer



VLA

Film clip of the Very Large Array (VLA)
from
“Contact”

Interference



Sea interferometer

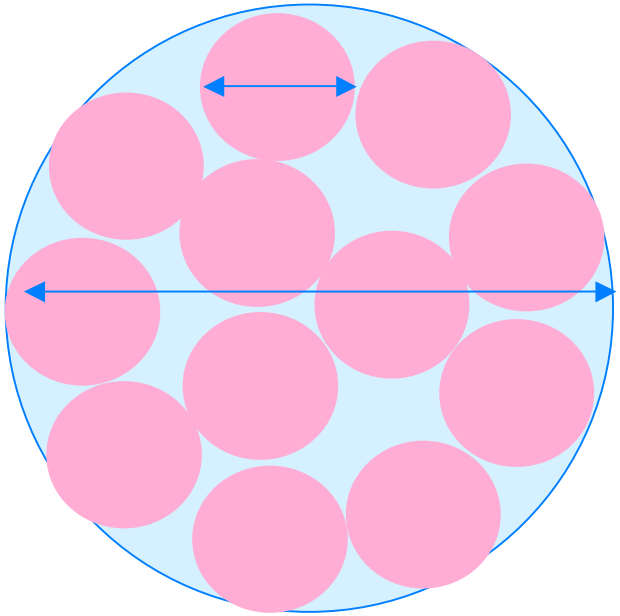
1947 First radio interferometric observations by McCready (Sydney, Australia)

The "Sea Interferometer", was formed by combining Yagi arrays with the surface of the sea near Syndey, Australia.

The antenna could observe both direct radiation from the sun and those reflected from the surface of the sea. The direct and reflected waves interfered with each other producing the characteristic fringe pattern of an interferometer with a baseline roughly twice that of the cliff.

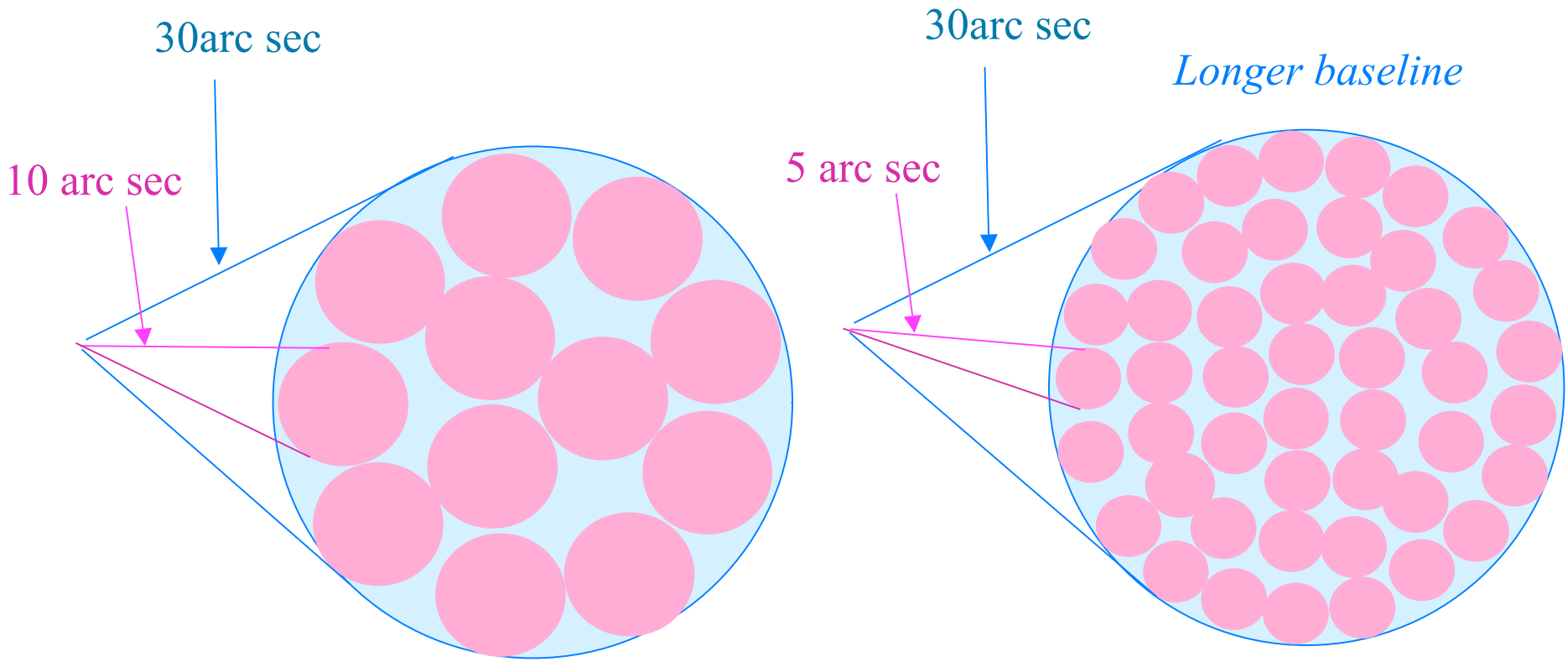
Resolution of an interferometer

Resolution = Wavelength / baseline



Field of view = Wavelength / dish diameter

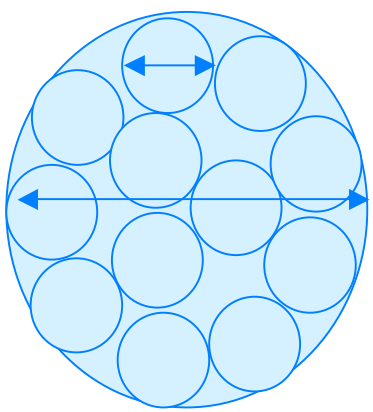
Resolution of an interferometer

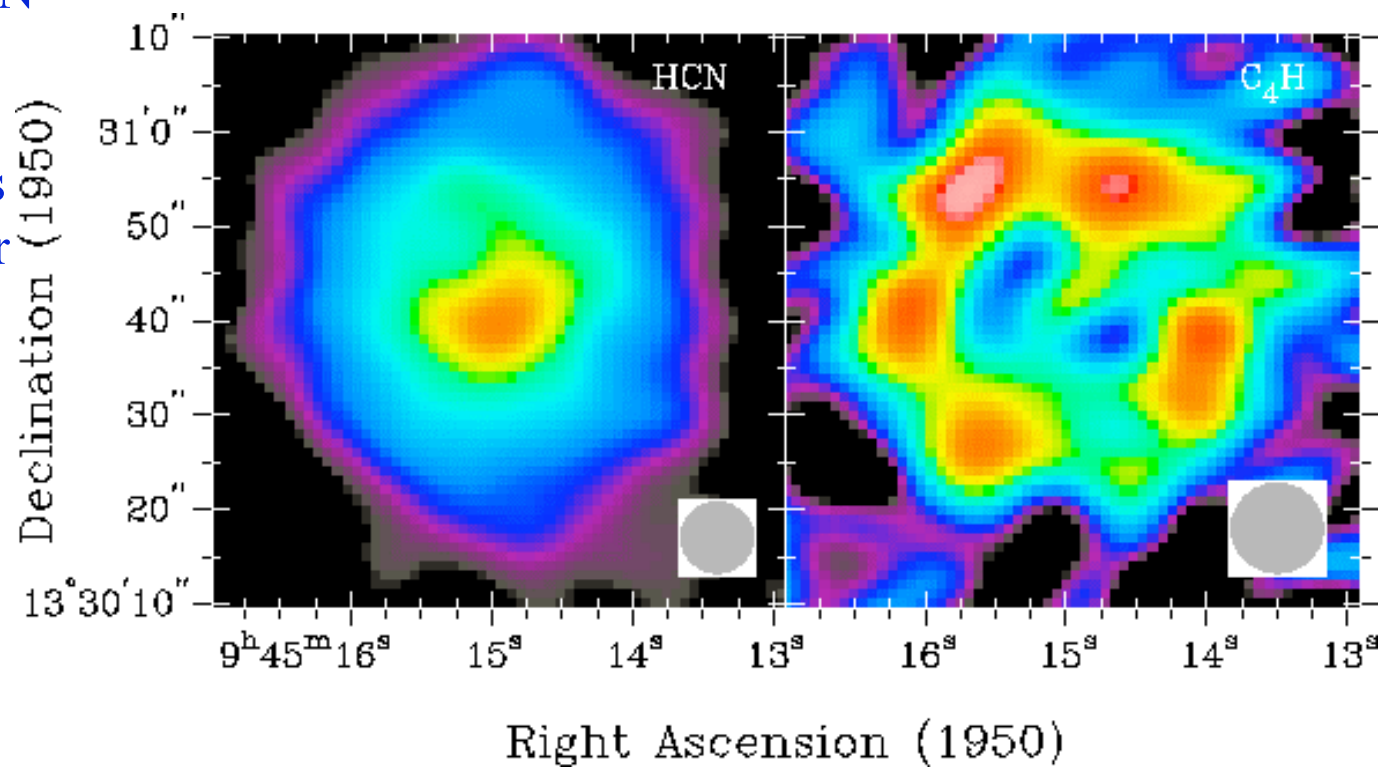


Greatly magnified views

Resolution of an interferometer

BIMA observations of the emission from HCN and C4H in IRC+10216. The synthesized beamsizes are shown in the lower right of each panel.





Aperture synthesis

Another name for interferometry is aperture synthesis.

One is trying to synthesize the aperture of a large single dish with several smaller dishes.

Aperture synthesis

Advantage

- Increased resolution

Disadvantage

- Less sensitivity

Aperture synthesis

VLA

Some examples of interferometers

Radio interferometer

Very Large Array (VLA),NM

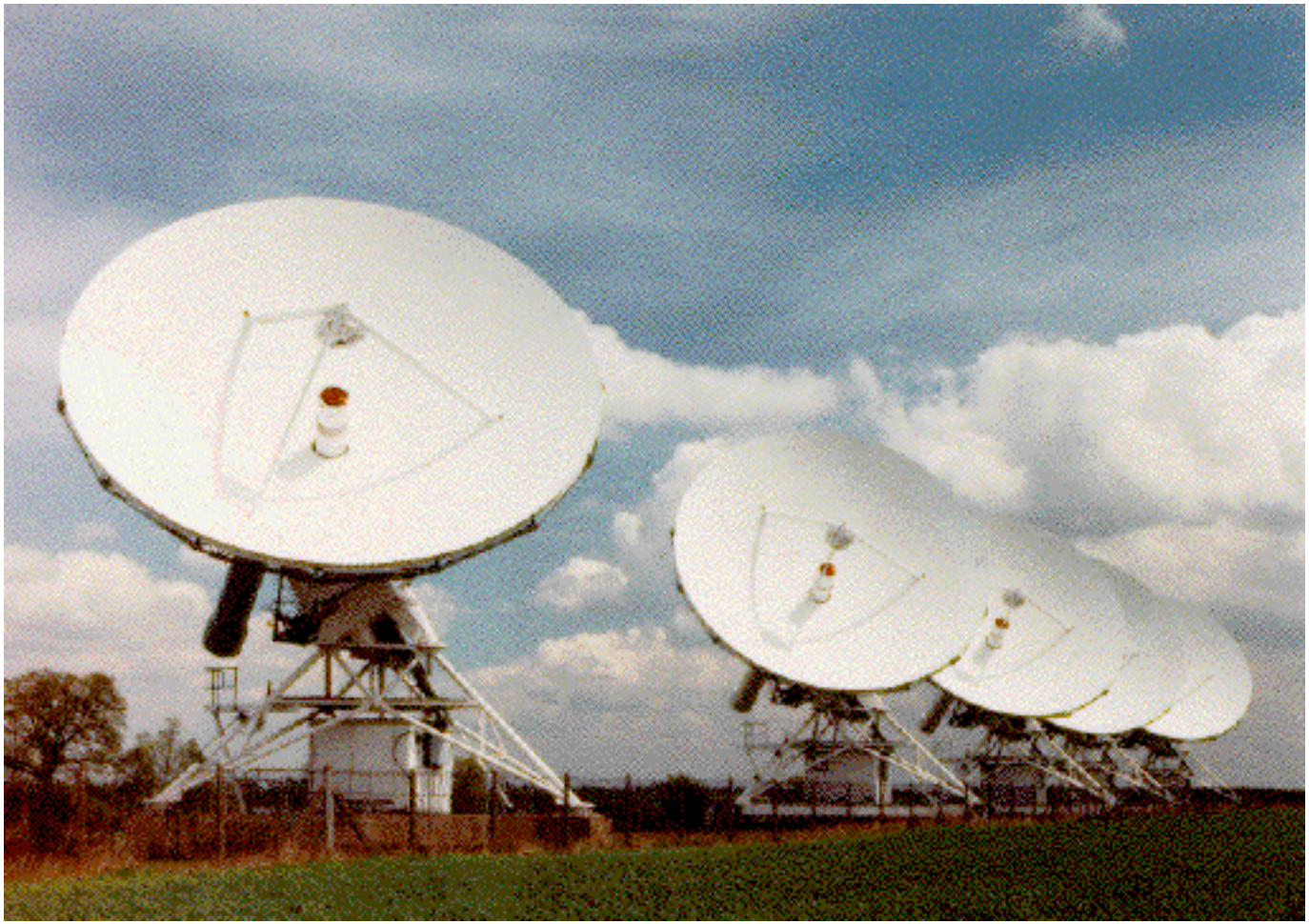
27 25-meter telescopes

Radio interferometer

RYLE telescope

England

8 14-meter telescopes



Radio interferometer

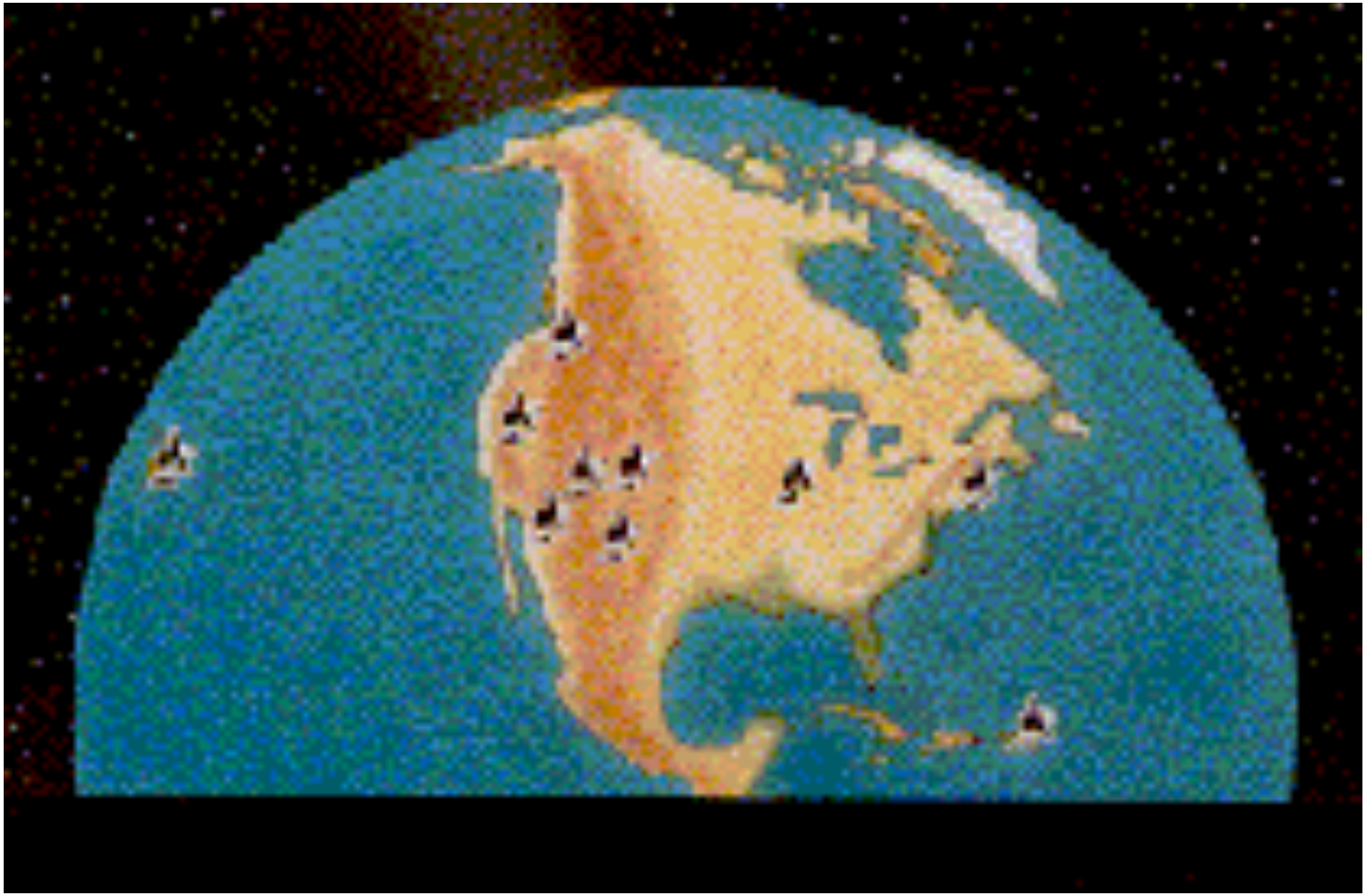
Westerbork Synthesis Radio Telescope

(WSRT)

Netherlands

14 25-meter telescopes

VLBA
Very Long Baseline Array



10 telescopes from Hawaii to St. Croix

Millimeter interferometer

Hat Creek Radio Observatory CA 10 elements, 6-meter telescopes

Millimeter interferometer

Owen's Valley Radio Observatory (OVRO), CA 6 10.4-meter telescopes

Millimeter interferometer

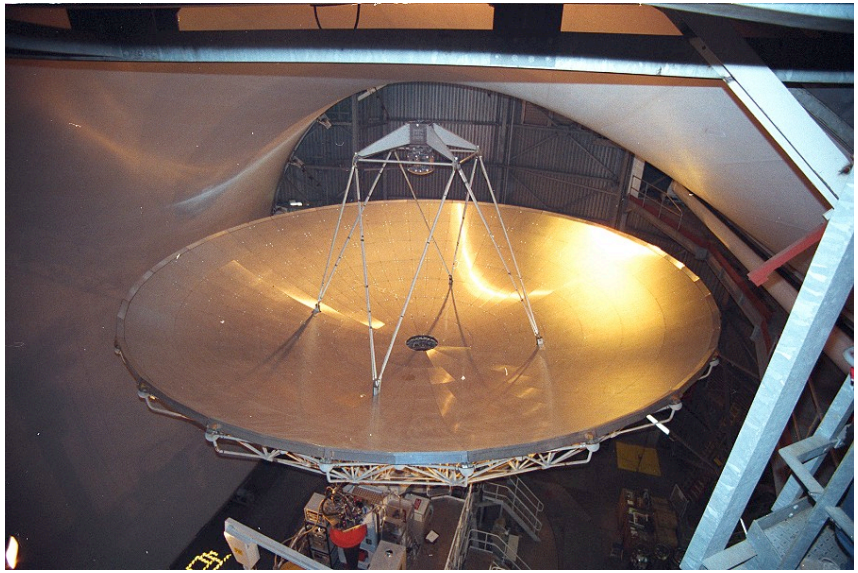
Nobeyama Millimeter Array

(NMA)

Japan

6 10-meter telescopes

Submillimeter interferometer

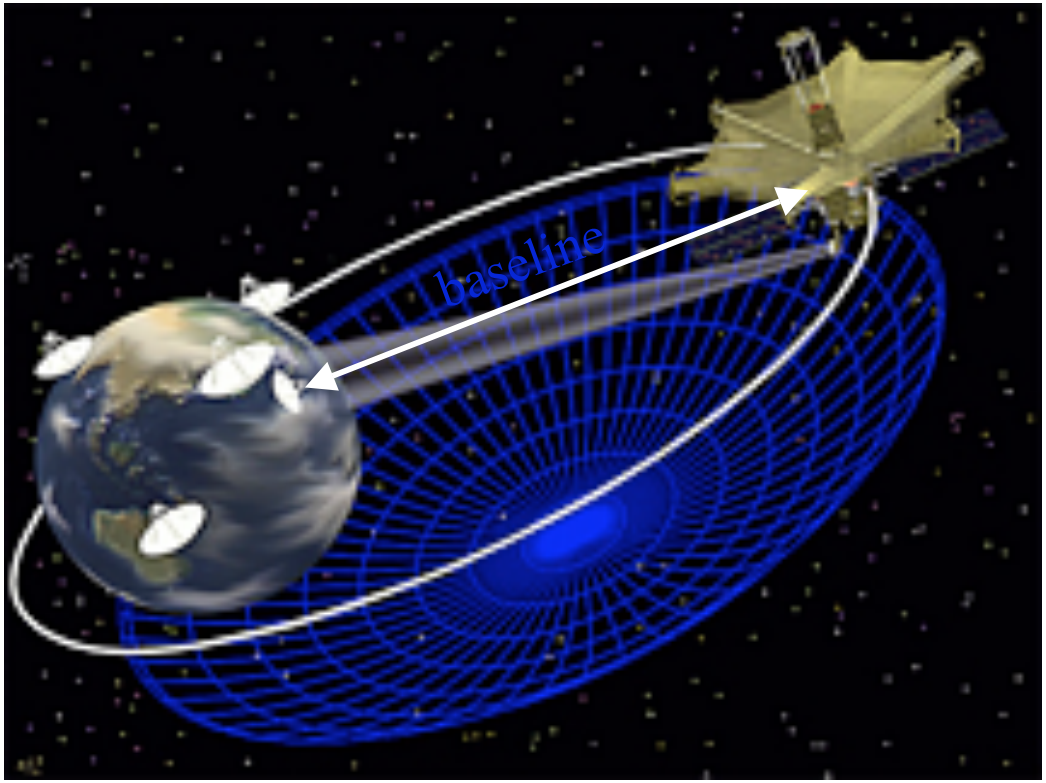


CSO/JCMT Interferometer, Mauna Kea
First astronomical interferometer to operate at submillimeter frequencies
151.91m baseline, 1.1” resolution at 345GHz

Aperture synthesis

What is the longest
baseline achieved?

Aperture synthesis



HALCA, Highly Advanced Laboratory for Communications and Astronomy.

In Japanese, HALCA means `far away'

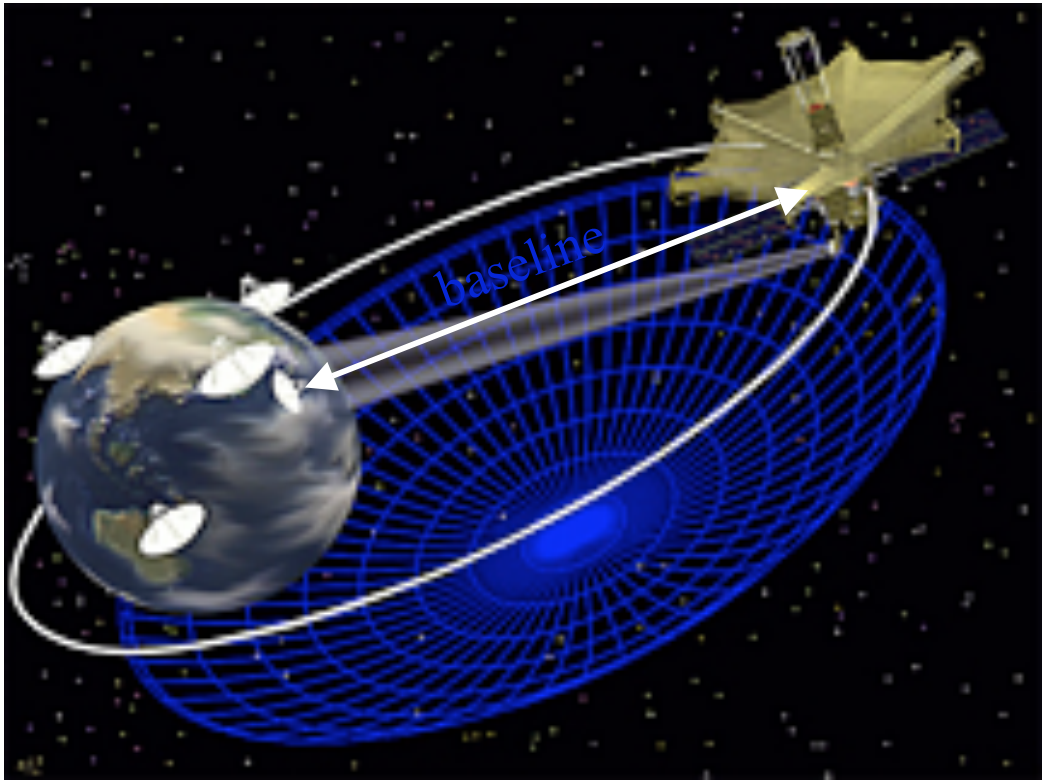
8-meter radio telescope in elliptical earth orbit

21,000 km at apogee

Provides baselines 3 times longer than earth-based observations (earth's radius = 6378 km)

1.6GHz, 5GHz, 22GHz

Aperture synthesis



HALCA

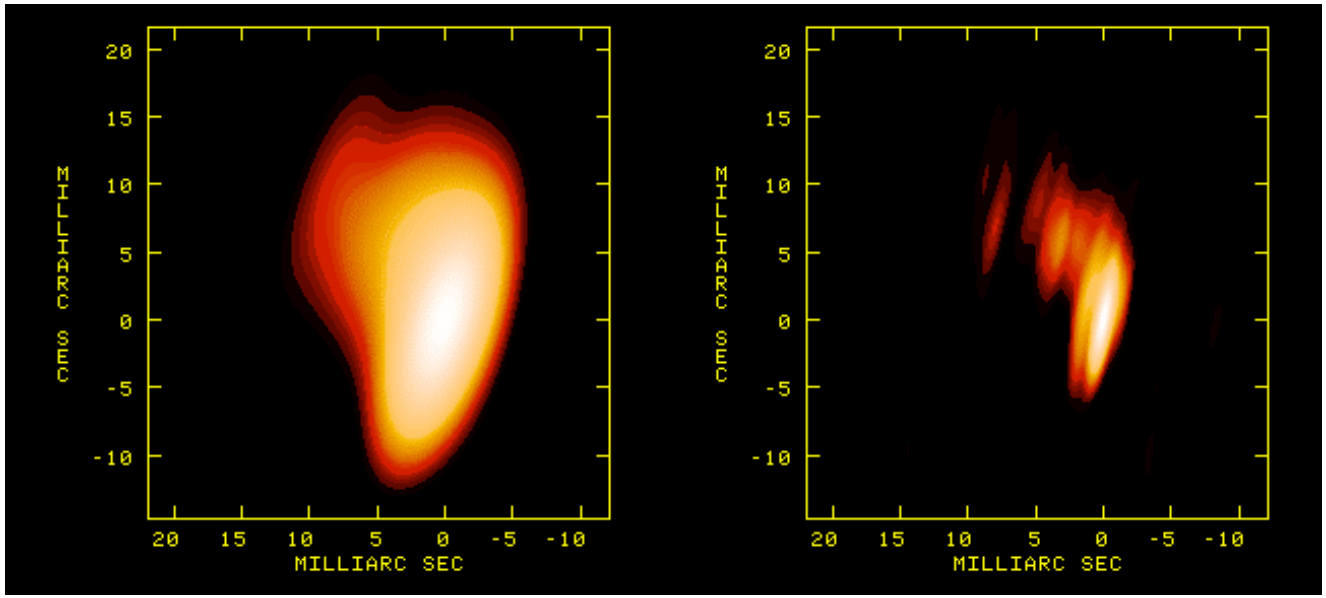
Resolution = 2cm/24,000km

Resolution = 0.002”

Space VLBI

The strongest radio signals are produced near the center of a quasar where astronomers believe that hot gas and stars are interacting with a super-massive black hole.

The material which is being blown out from the quasar can be seen more clearly in the HALCA image.



Ground-based telescopes only

HALCA with 10 earth-based telescopes

Radio, millimeter, and submillimeter astronomy

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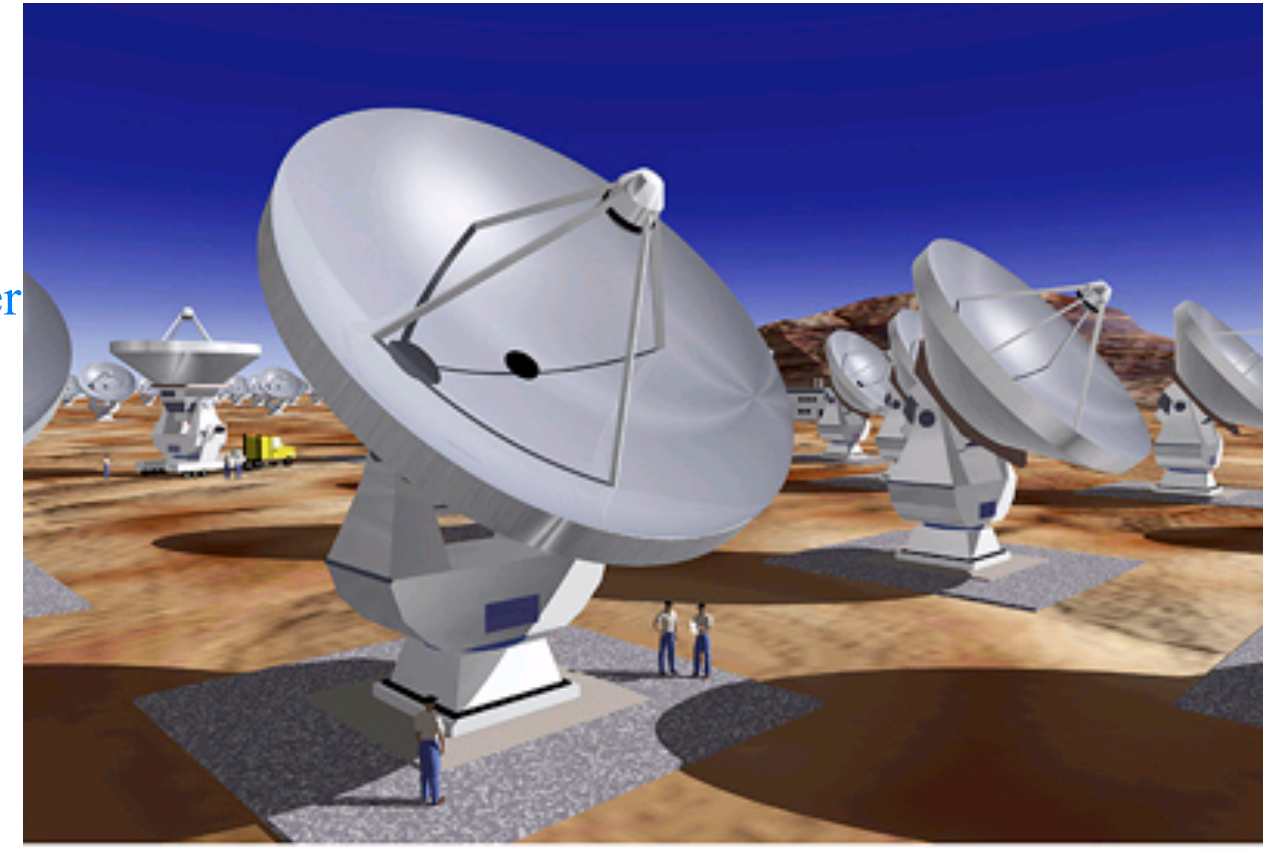
Next generation radio, millimeter, and submillimeter telescopes

ALMA
Atacama Large Millimeter Array

Increase current sensitivity of millimeter/submillimeter telescopes by 40 times.

Sixty-four 12-meter diameter antennas



ESO PR Photo 24a/99 (8 June 1999)

Artist's Impression of ALMA
(Atacama Large Millimetre Array)

© European Southern Observatory

SKA
Square Kilometer Array

To see galaxies during the earliest epochs of their formation requires at least 20 times more collecting than is provided by the largest radio telescope in operation today.

Such sensitivity would be provided by a radio telescope that has a collecting area one square kilometer.

Next lecture

Low frequency/long wavelength *LOW ENERGY*

Radio

Millimeter

Sub-millimeter

Mid frequency/mid wavelength *MID ENERGY*

Infrared

Optical

High frequency/short wavelength *HIGH ENERGY*

Ultraviolet

X-ray

Gamma ray