Radio Astronomy: Introduction & Overview

SAGI Summer School 2024 (3S24)
Session RA-00

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Outline

I. Overview
   i. Radio astronomy
   ii. Radio telescopes
II. Sciences in Radio Astronomy
III. Radio-quiet site & spectrum policy
IV. Radio telescope instrumentation
V. Additional Reference & Resources

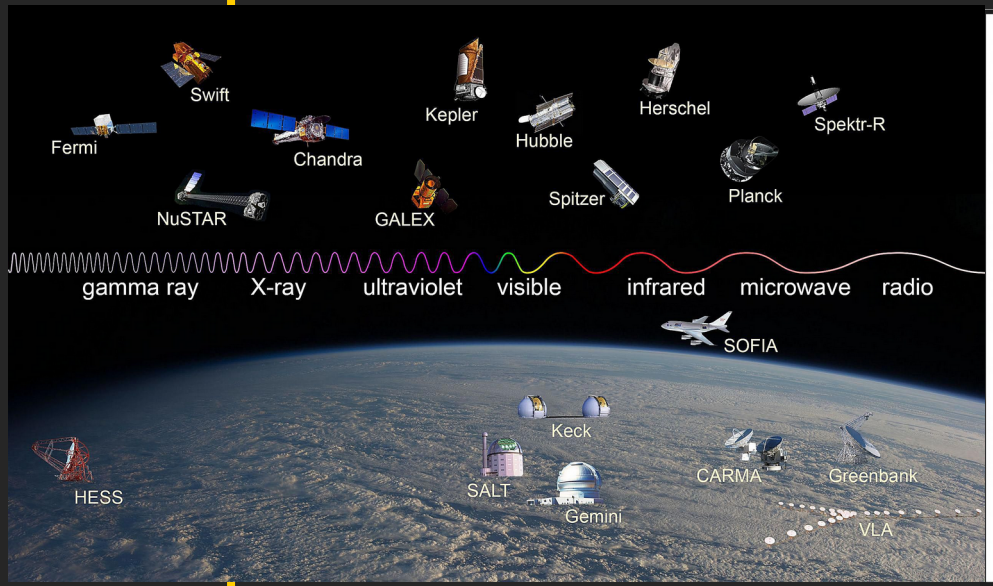
Radio Astronomy 101

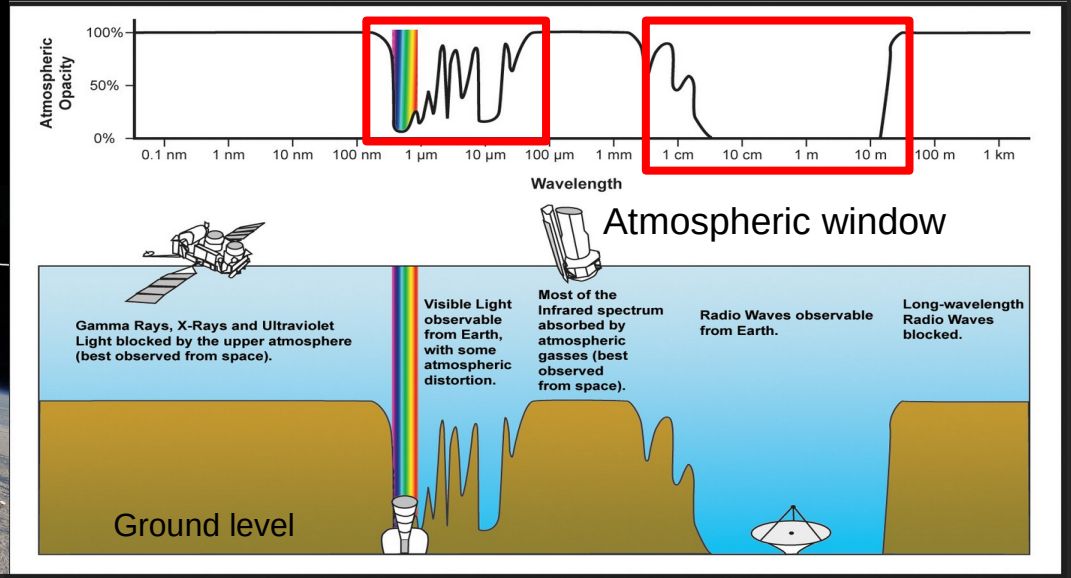
What?

Radio wave (1 cm – 10s m)
or (~10 MHz – 1 THz)
1 THz = 1e12 Hz

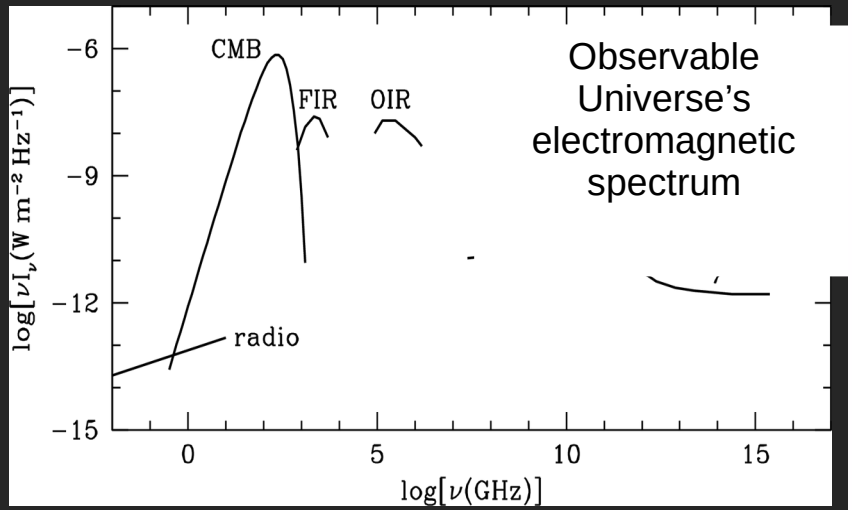
Why?

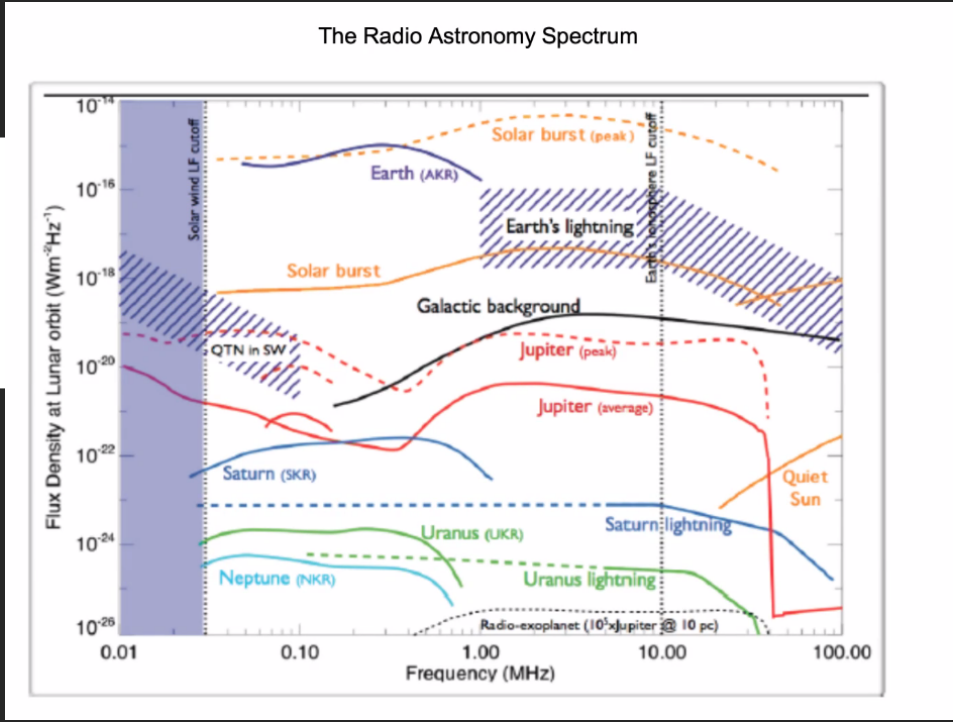
- Atmospheric window
- Study thermal & nonthermal radiation from astronomical sources & natural phenomena





Radio Astronomy 101

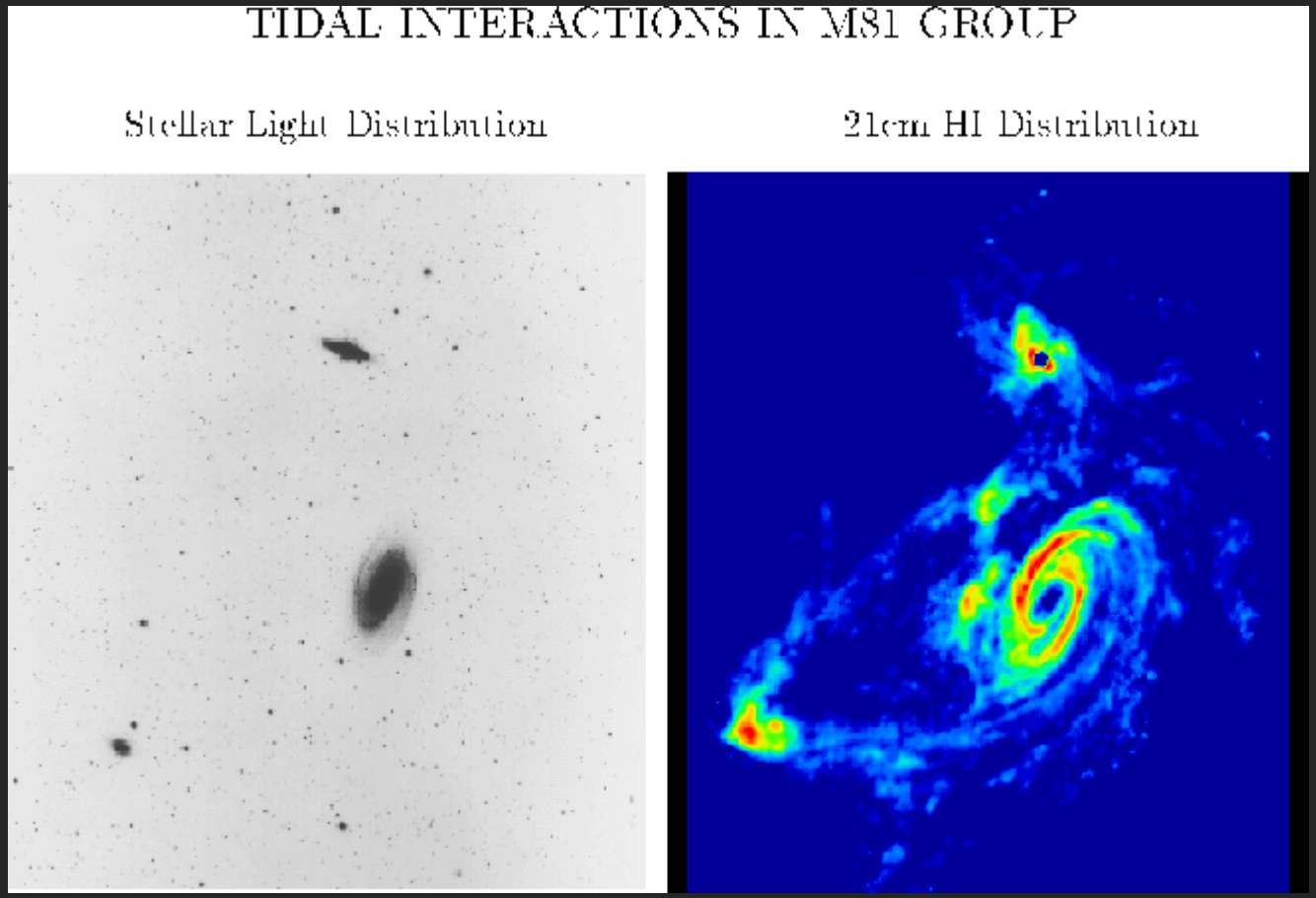




- Synchrotron radiation (Accelerated electron in magnetic field)
- Free-free radiation (Bremsstrahlung/braking)
- Recombination emission line
- Cherenkov radiation
- More on astronomical radio sources (https://en.wikipedia.org/wiki/Astronomical_radio_source)

Radio Astronomy 101

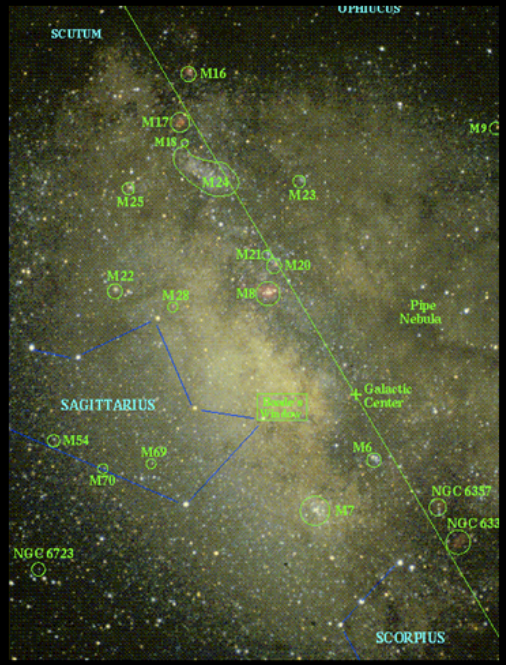
Radio sees thing optical cannot

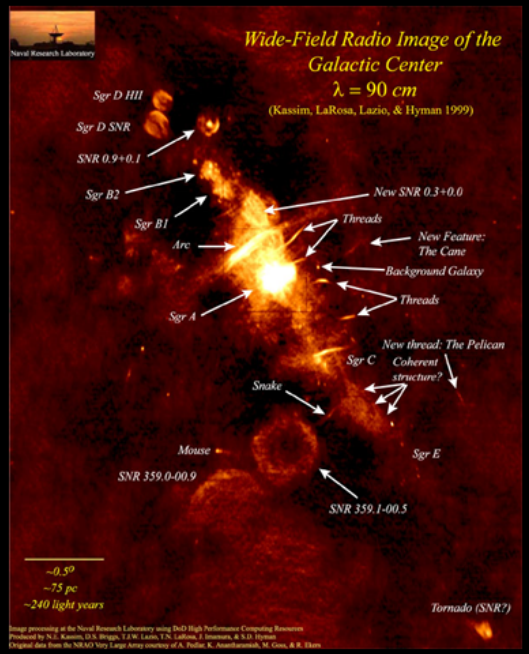


http://www.aoc.nrao.edu/intro/m81mosaic.gif

Radio Astronomy 101

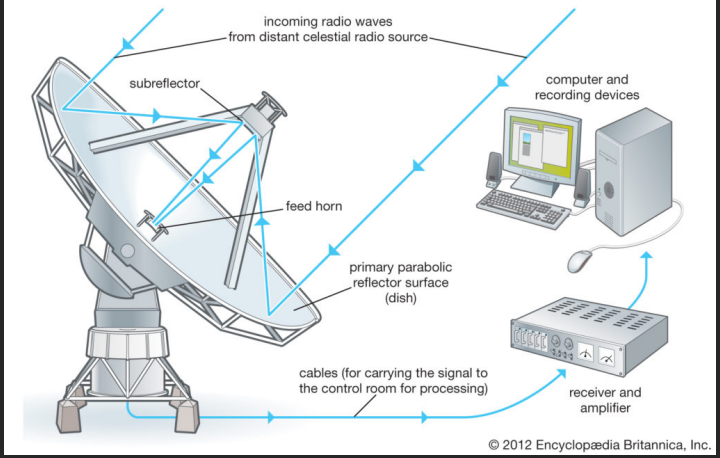
The Galactic Center
Optical vs Radio observations

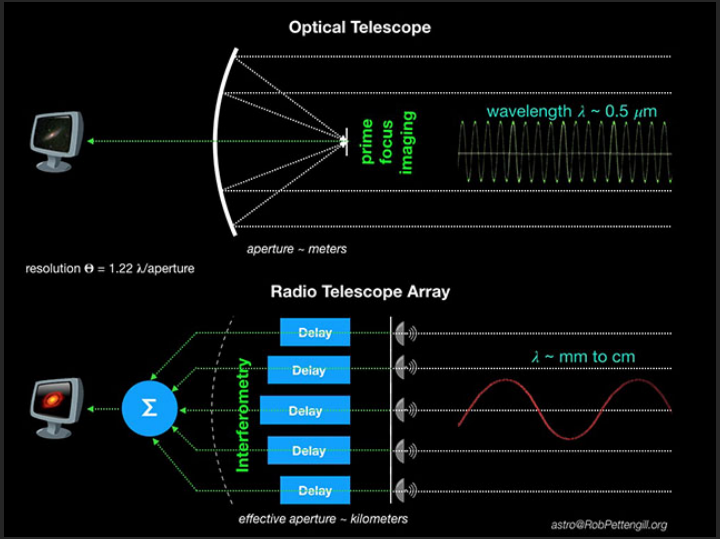


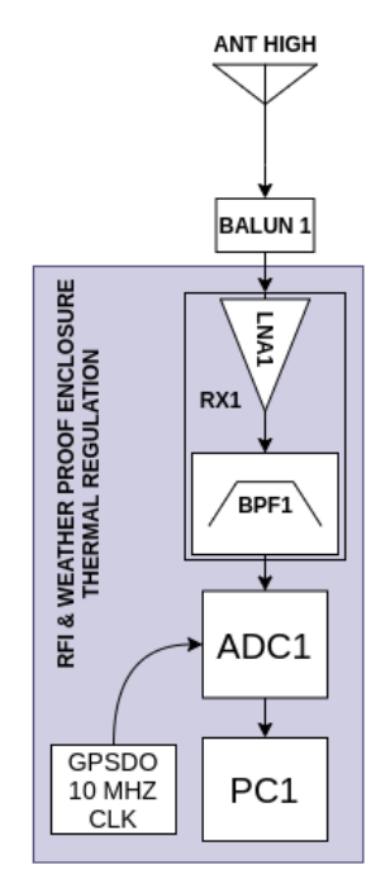


www.sliderbase.com

Radio Telescope







Antenna (Optics)

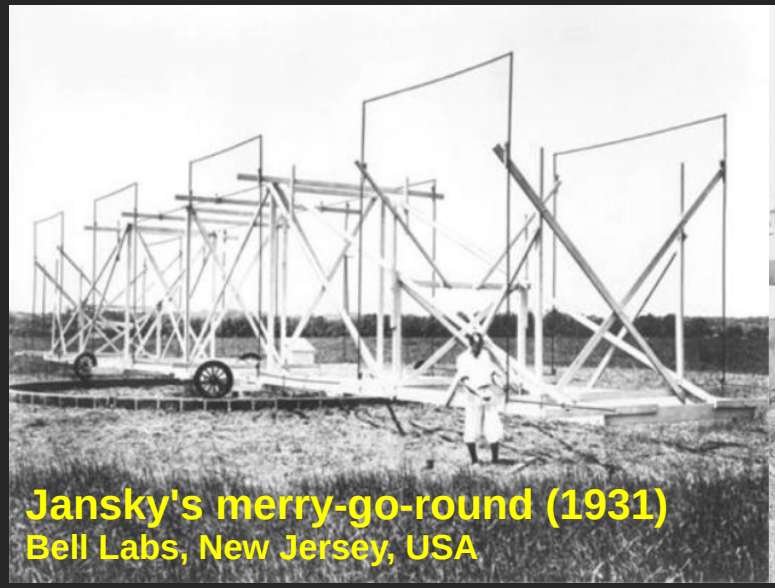
Balun

Low-noise amplifier

Bandpass filter

Analog-digital converter

Early Radio Telescopes



Karl Jansky
(1905-1950)

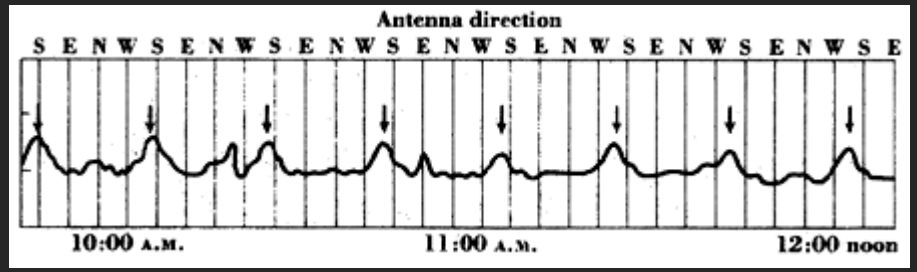
@ 20.5 MHz

"Serendipity"

(Sự tình cờ)

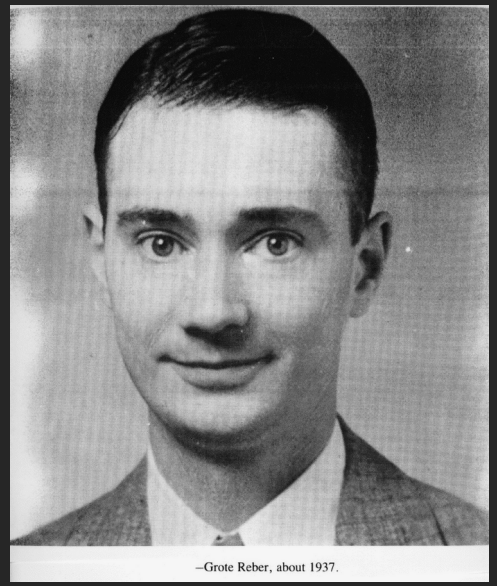
- Nearby thunderstorms
- Distant thunderstorms
- A faint steady hiss of unknown origin → from direction of Sagittarius A*

  → from the Milky Way

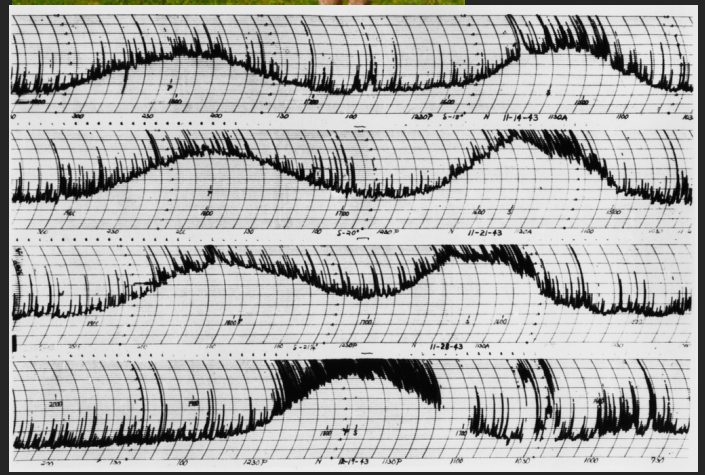


http://legacy.nrao.edu/epo/aoc/puente/jansky/hist_jansky.shtml

1 Jansky = 1 Jy = 10^{-26} Watt/meter^2/Hertz



–Grote Reber, about 1937.



Grote Reber
(1911-2002)

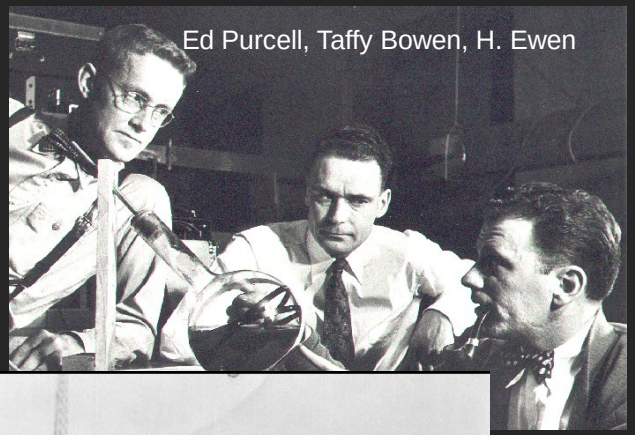
cir. 1937, backyard in Wheaton, IL
(Suburb of Chicago)

Parabolic dish
Diameter = 31.4 feet
Feed point = 20 feet

Prevent chromatic aberration
→ wide wavelength range

- Detect radio emission from the Milky Way @ 160 MHz
  - → Confirm Jansky's result
- Conduct radio sky survey btw 1938-43
  - → Founded radio astronomy after WW2

https://www.nist.gov/blogs/taking-measure/grote-reber-radio-astronomer



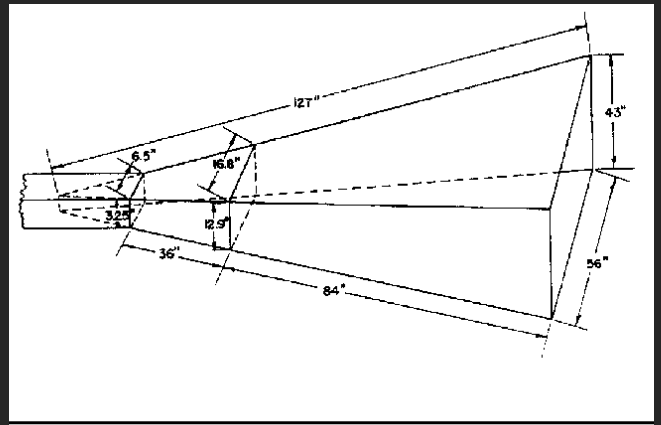
Harold Irving Ewen (1922-2015)
Edward Mills Purcell (1912-1997)

Horn antenna

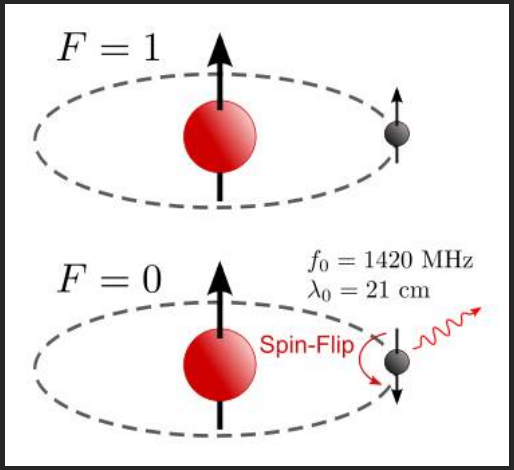
Neutral Hydrogen 21-cm line @ ***1420.405 MHz***

First predicted by H. van de Hulst in 1944

Ewen & Purcell confirmed in 1951



HORN ANTENNA



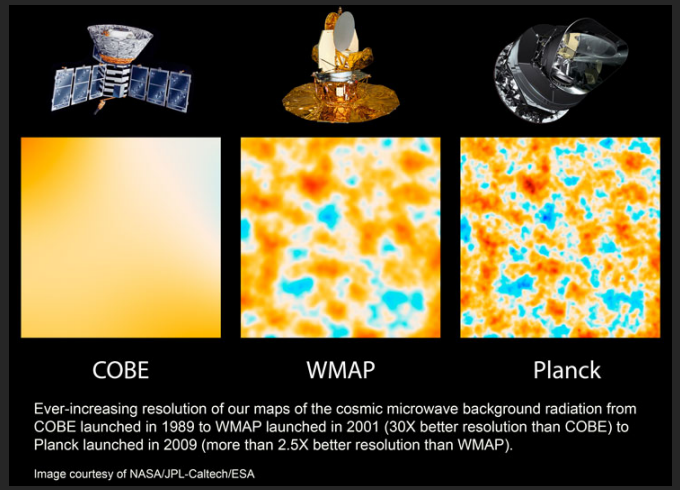
https://www.gb.nrao.edu/fgdocs/HI21cm/ephorn.html

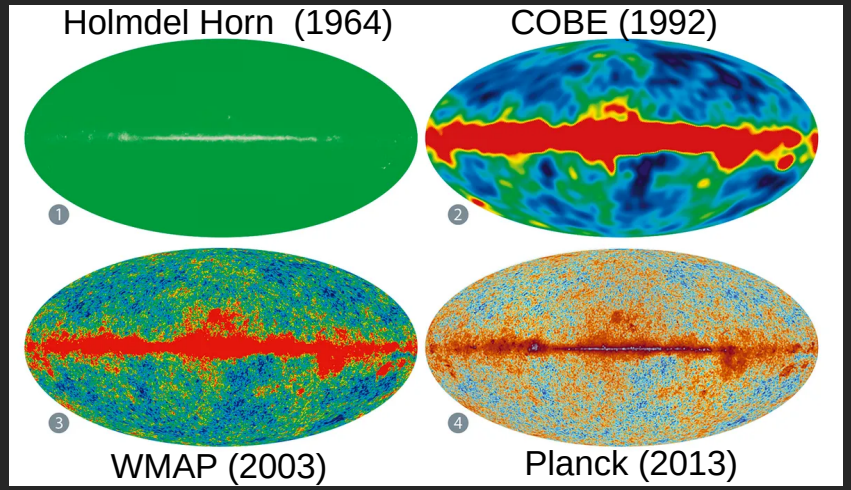
https://www.bell-labs.com/about/awards/1978-nobel-prize-physics/

Arno Penzias (1933-2024)
Robert Wilson (1936-)

@ 4080 MHz
Nobel Prize in Physics (1978)

"Serendipity"
(Sự tình cờ)





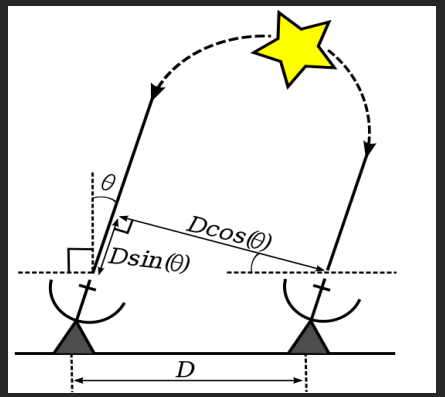
Single Dish

Parkes (64 m)
Australia

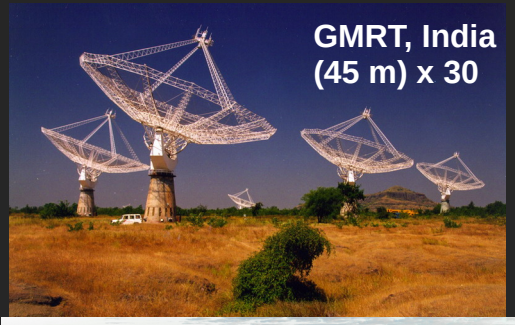
Effelsberg (100 m)
Germany

Radio Interferometer Array

Two-element interferometer
(Giao thoa kế)



Baseline

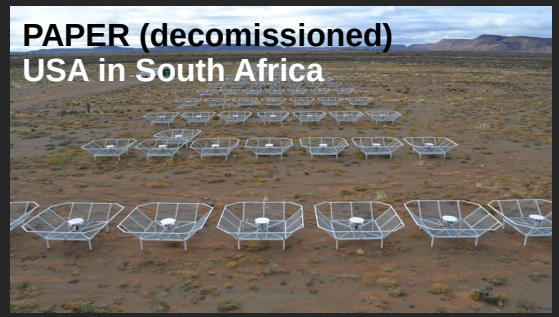


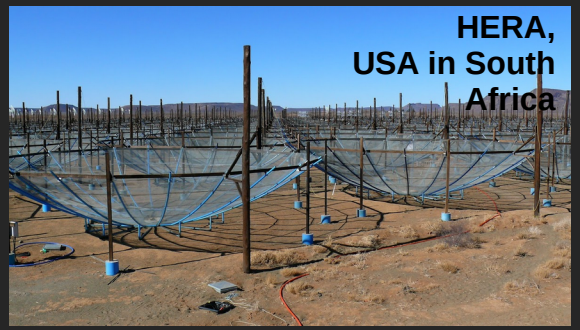
- Combine signal arrived at dish by correcting the phase
- **Many small dishes ~ 1 large dish**
- Baseline = distance between element
  - Large baseline = better angular resolution
  - Small baseline = worse angular resolution
- General purpose science instruments

See RA-01b
(Wed, 7/24)
Interferometry

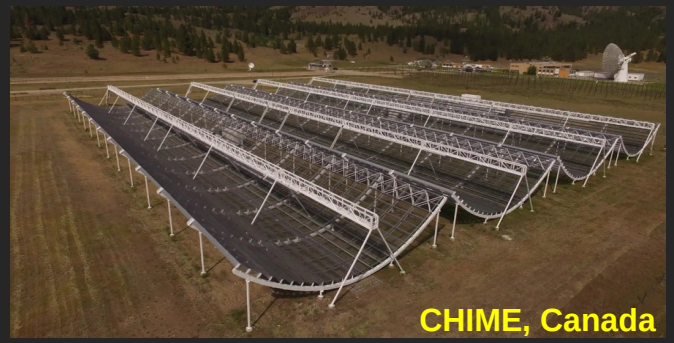
For low-frequency (<200 MHz) : (Specialized scientific objective)

Lower frequency = longer wavelength

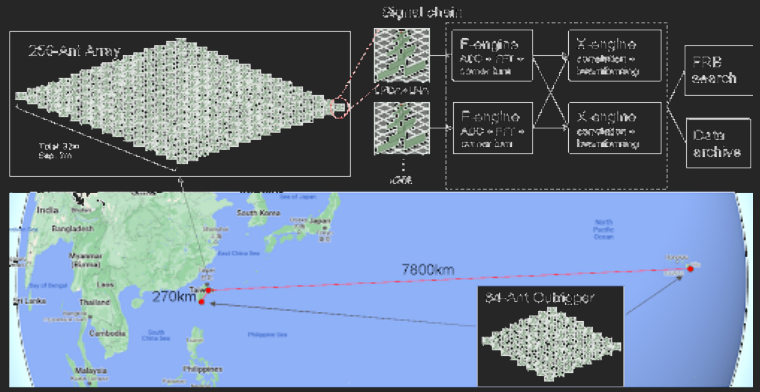




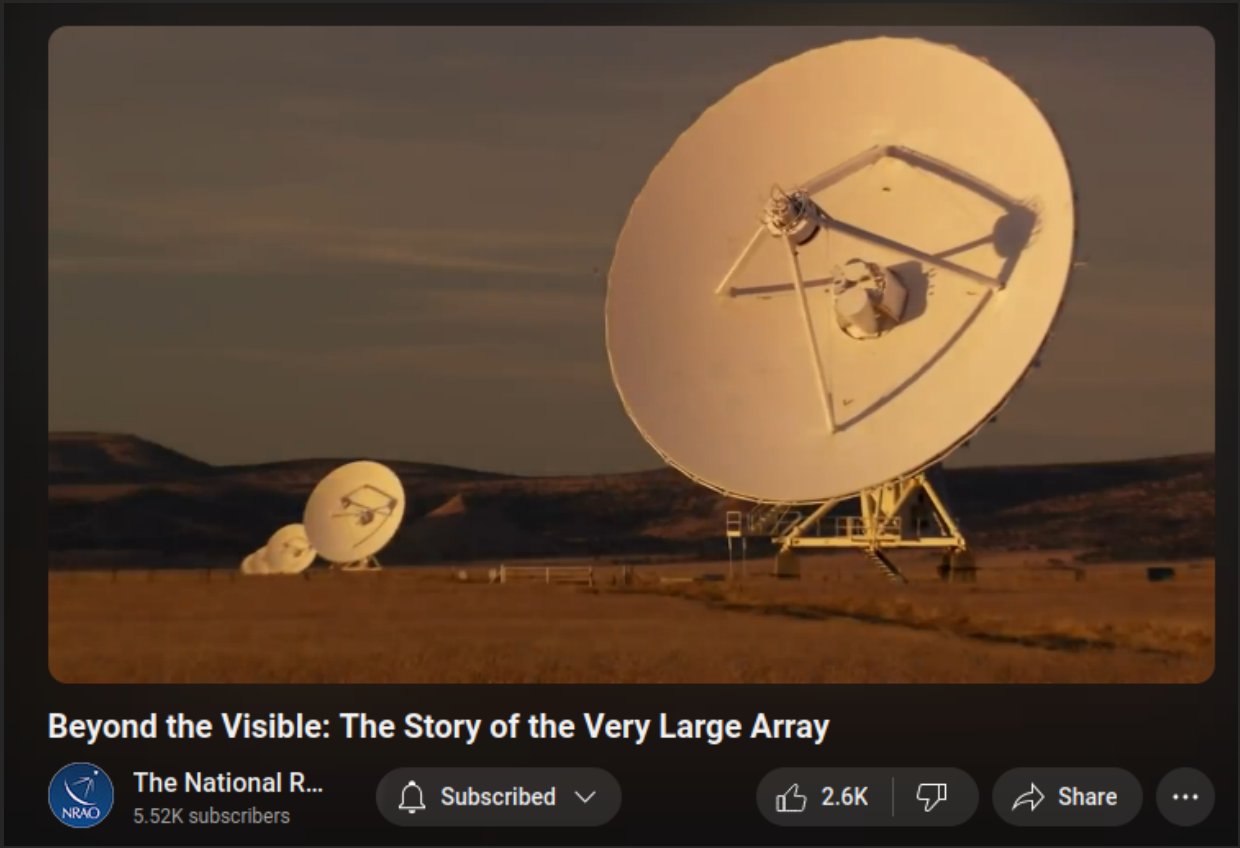
21-cm Intensity mapping & Fast transient events (e.g., Fast Radio Burst (FRB) (~200 MHz- 2GHz)



BURSTT, Taiwan (Concept)

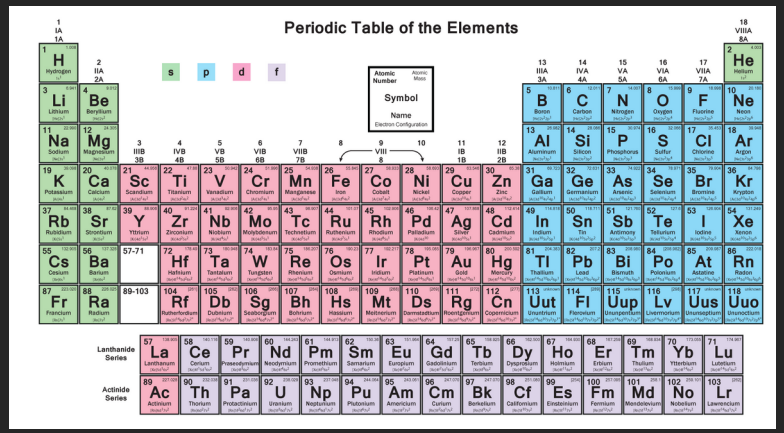


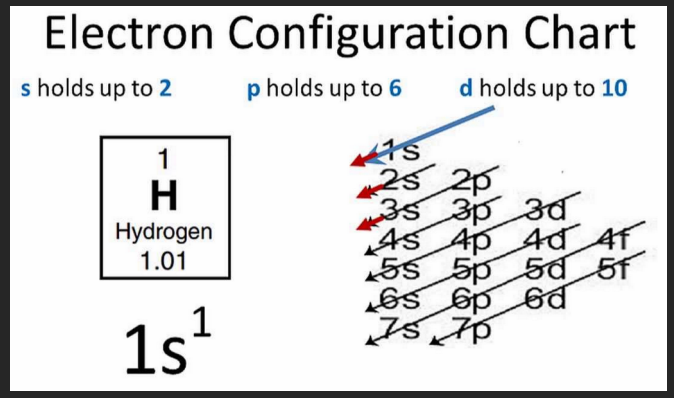
“Beyond the visible: The Story of the Very Large Array” documentary

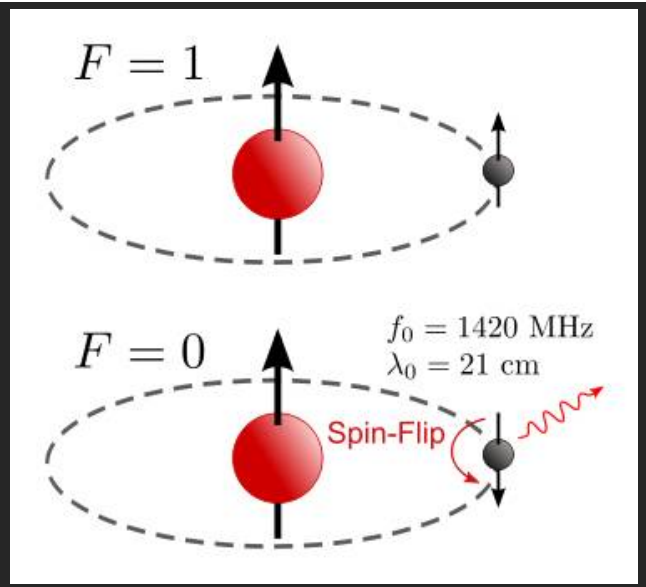


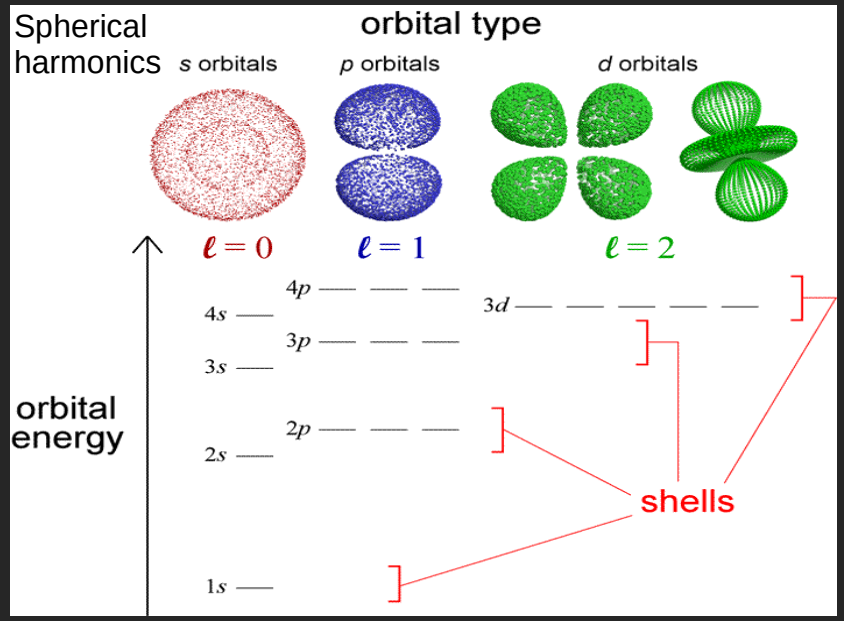
https://www.youtube.com/watch?v=RqX9vLj3_7w&t=278s

Chemistry refresher: Neutral hydrogen spin-flip 21-cm

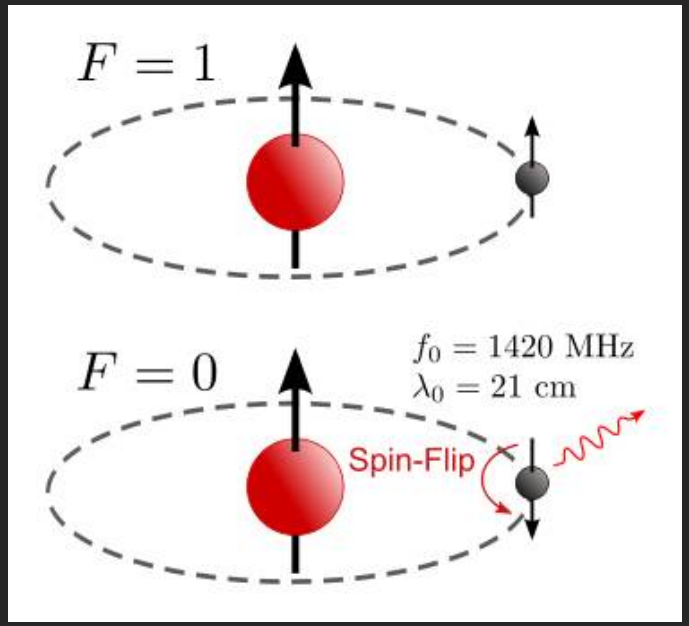


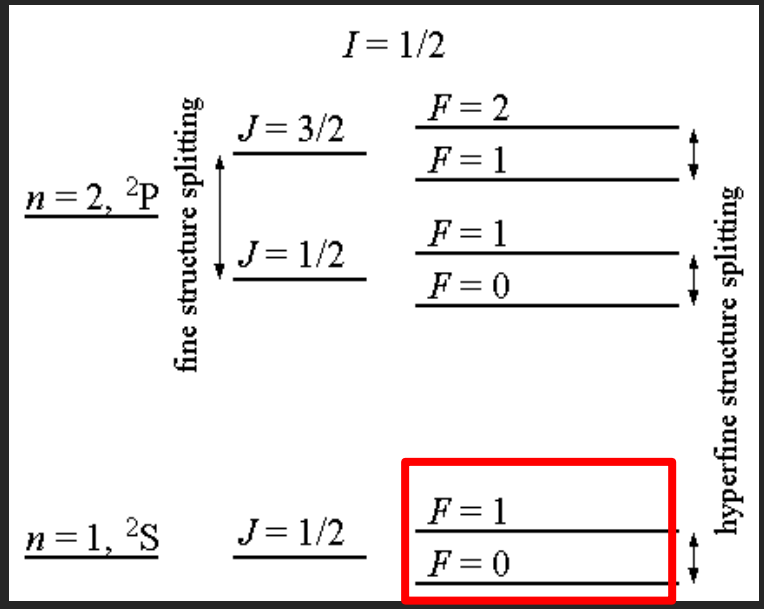






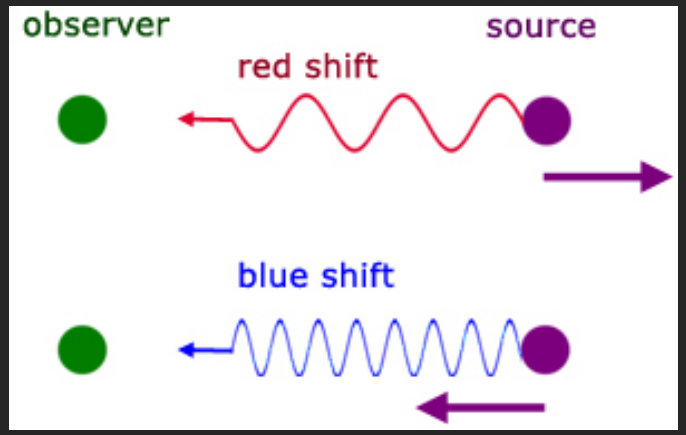
Chemistry refresher: Neutral hydrogen spin-flip 21-cm

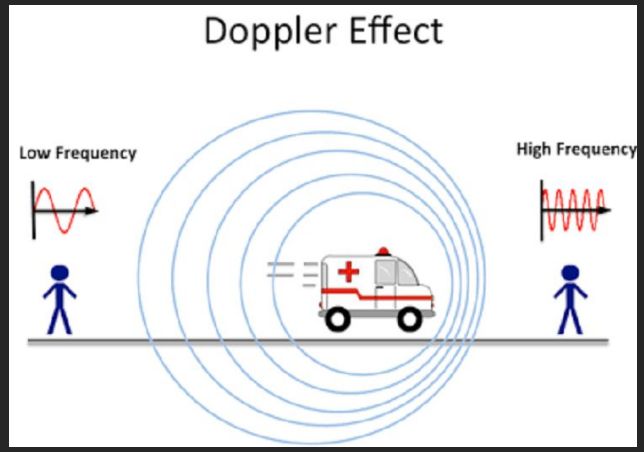




- The electron wants to stay in lower energy state
- The energy transition between upper and lower states emits a photon at 1420 MHz

Physics Refresher: Redshift (Dịch chuyển đỏ)

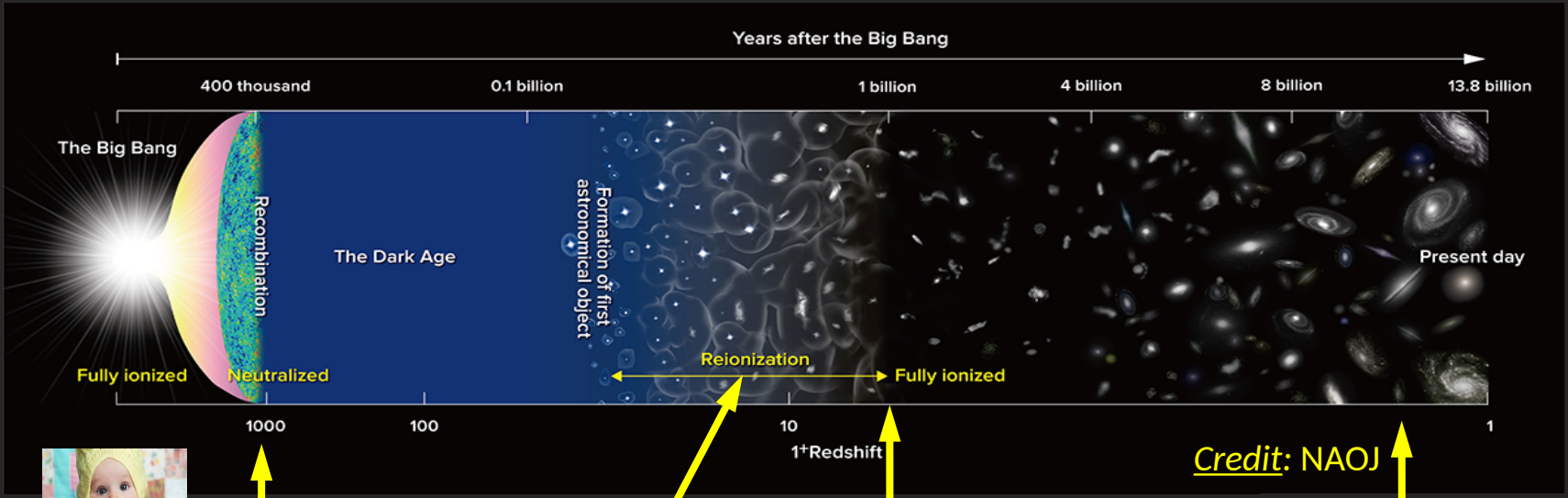




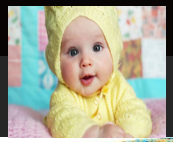
Based on wavelength	Based on frequency
$z = \frac{\lambda_{\text{obsv}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}$	$z = \frac{f_{\text{emit}} - f_{\text{obsv}}}{f_{\text{obsv}}}$

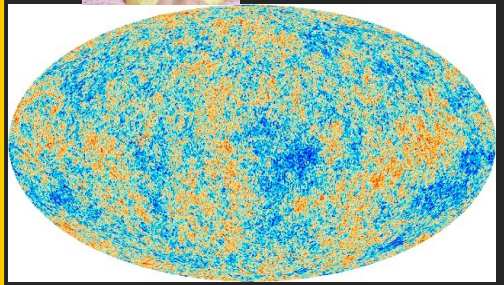
- Larger z → further away from us (back in time)
- Smaller z → closer to us
- z = 0 → present time

Early Universe (~400,000 years after the Big Bang)



Credit: NAOJ



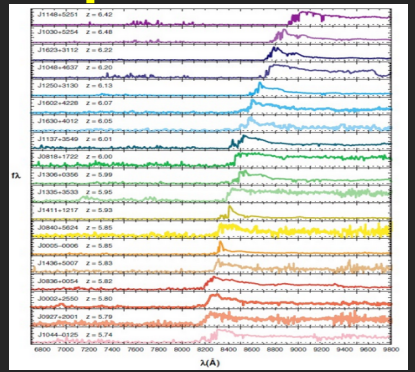


Credit: Planck Collaboration (2016)

CMB (z ~ 1,100)

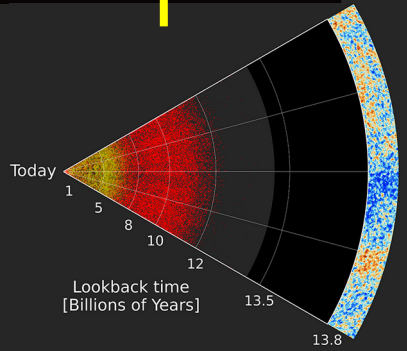
Credit: Naidu et al. (2022)

JWST (z ~ 12)



Credit: Fan et al. (2006)

Gunn-Petterson Troughs
EoR ends (z ~ 6-10)

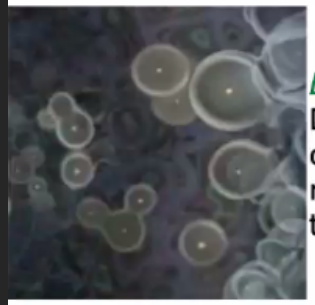


Credit: Anand Raichoor

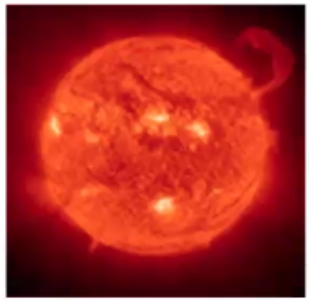
SDSS (Red = quasars, yellow = galaxies)

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics

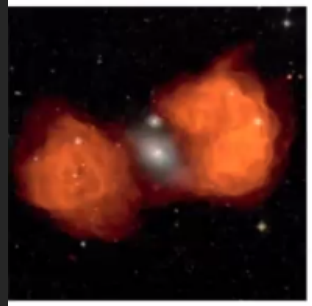
Sciences in Radio Astronomy



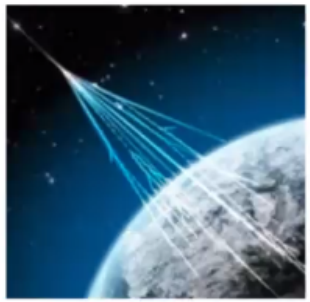
Epoch of Reionization (EoR)
Detection and statistical characterization of the reionization of the IGM by the first stars & galaxies.



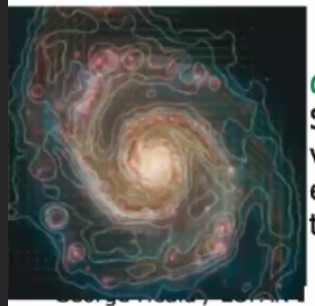
Solar & Space Weather
Characterization of the Sun at low radio frequency, detection and study of CMEs and solar wind.



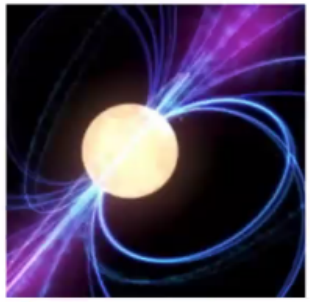
Surveys (SKSP)
Detection of high-z RGs, deep surveys of the radio sky at low frequency. Synergy with high frequency!



Ultra high energy cosmicrays
Detection of cosmic ray showers, characterization of particle mass and origin. Also particle detection.

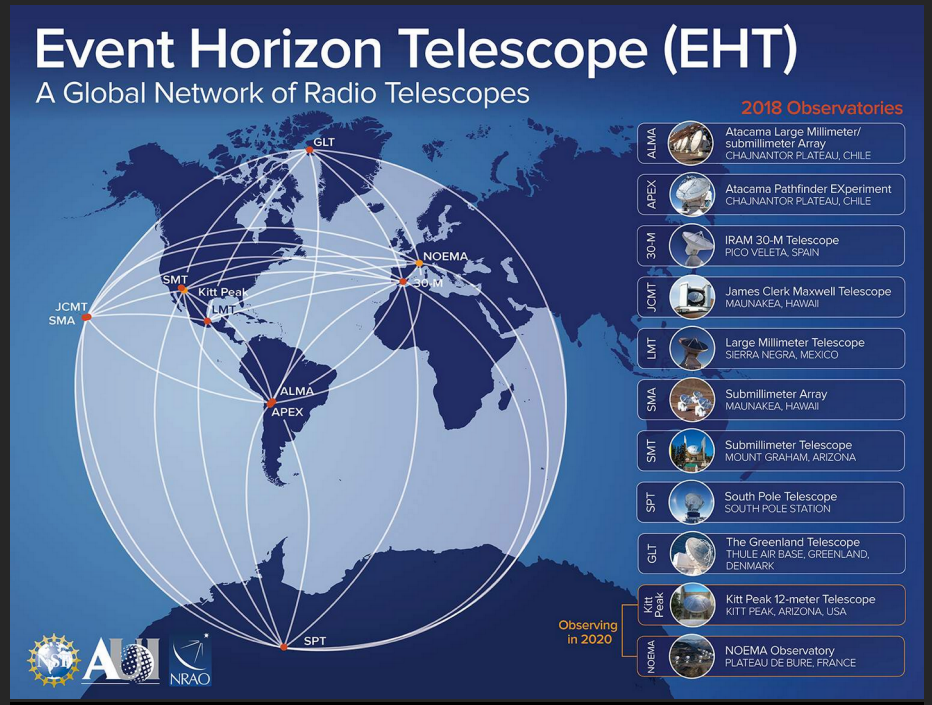


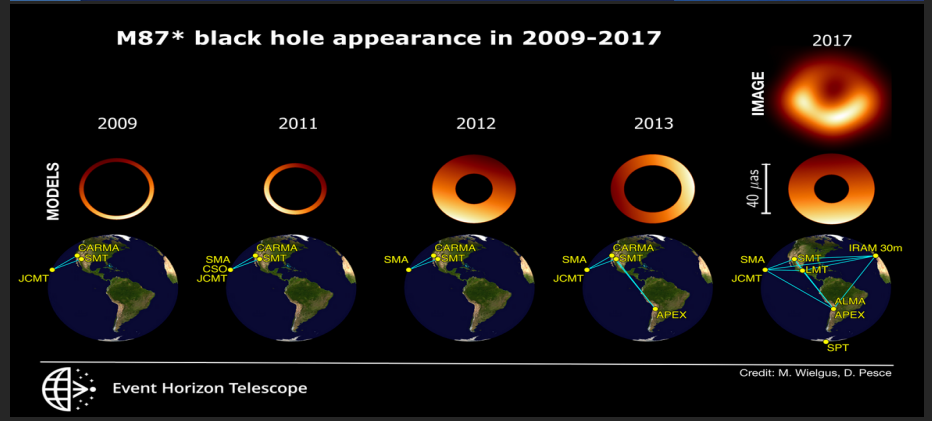
Cosmic magnetism (MKSP)
Study of magnetic fields in various astrophysical objects, e.g. galaxies, and possibly the IGM.

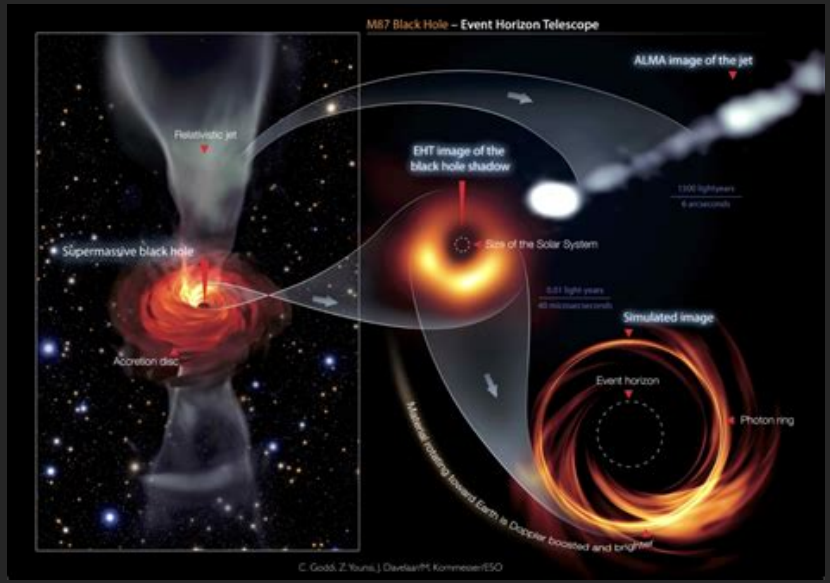


Transients (TKP)
Search for fast transients (e.g. Lorimer bursts, pulsars) and slow transients (e.g. supernovae).

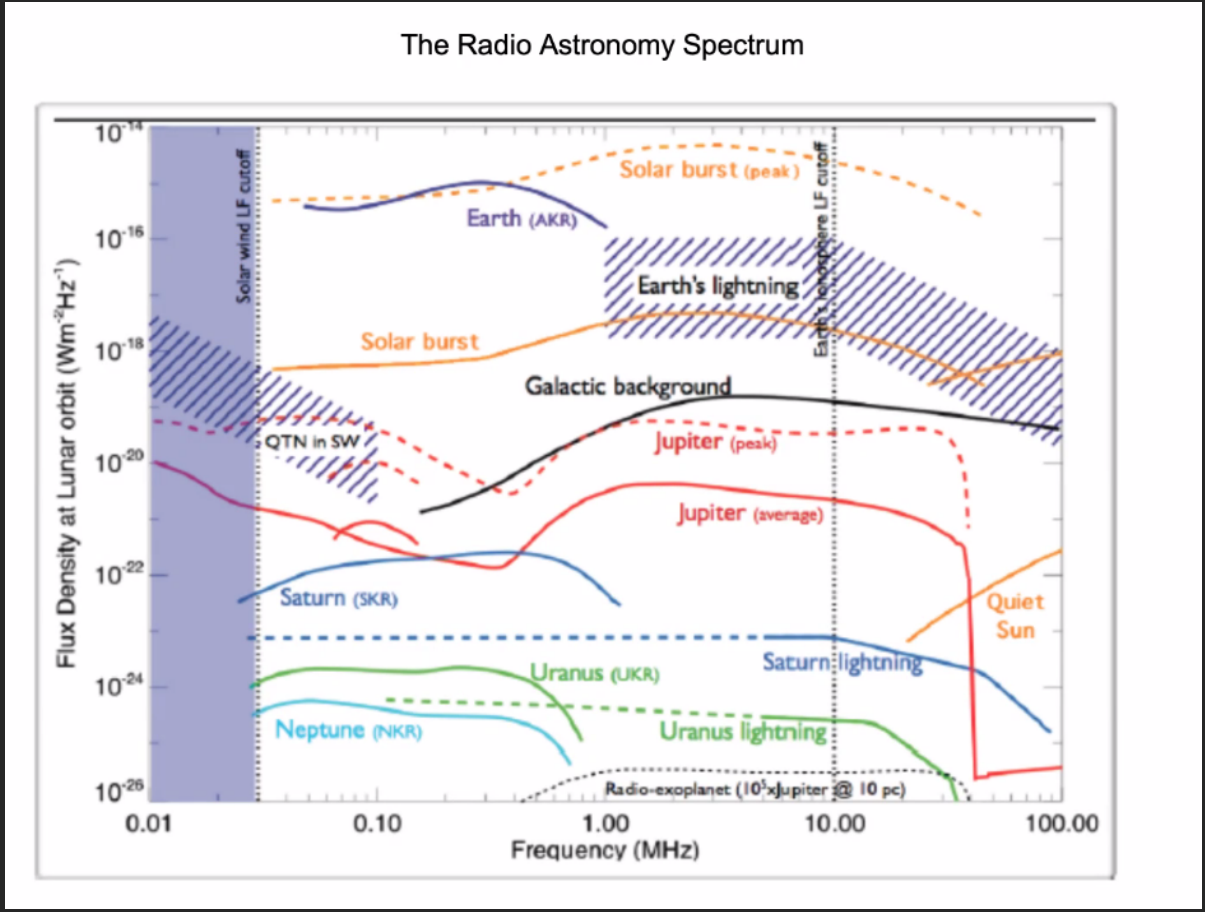
Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics





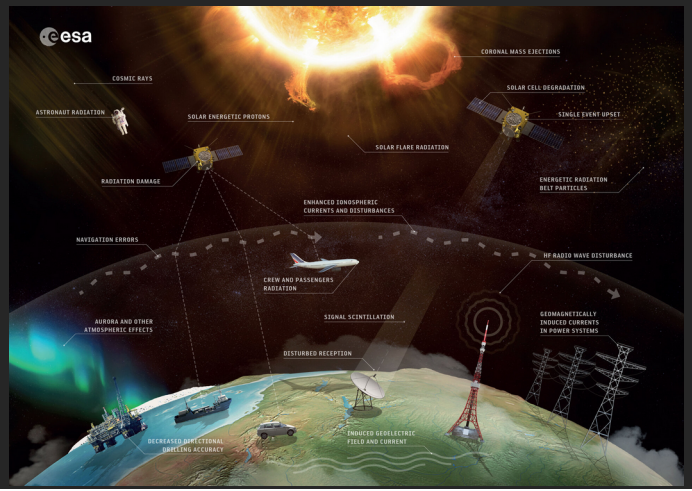


Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.

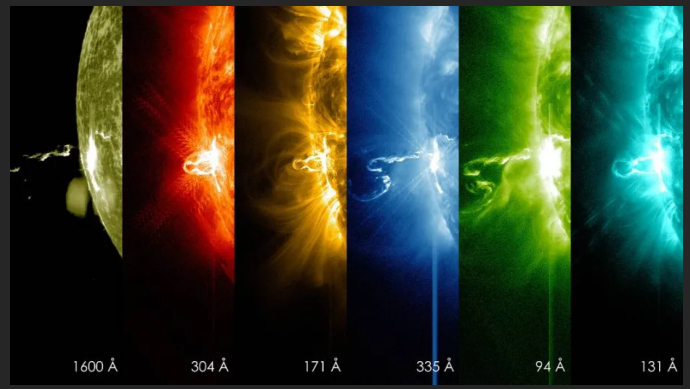


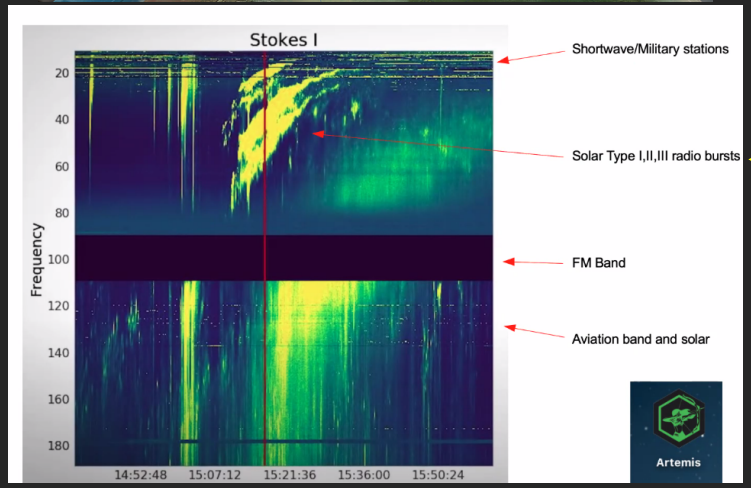
Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing

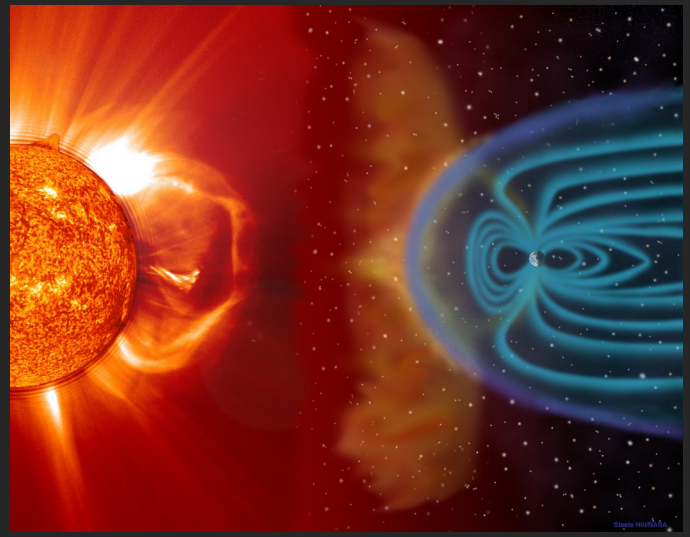
Space weather
(Thời tiết vũ trụ)



Solar bursts
(Vụ nổ năng lượng mặt trời)

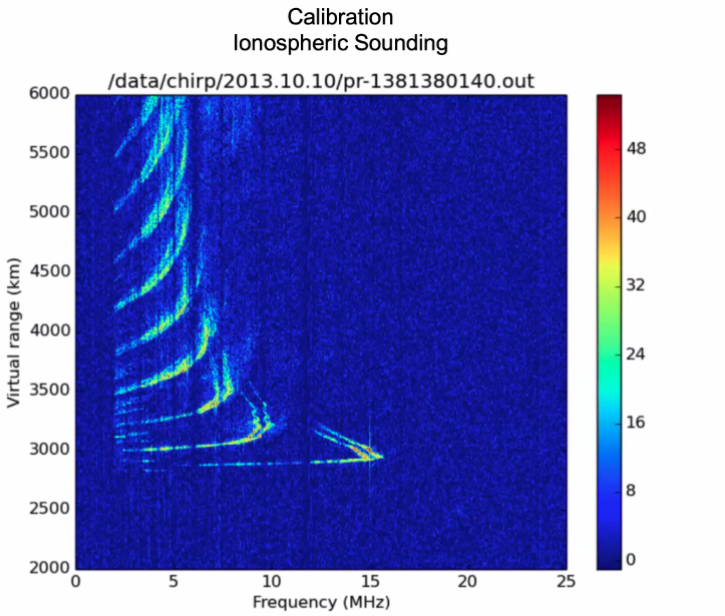






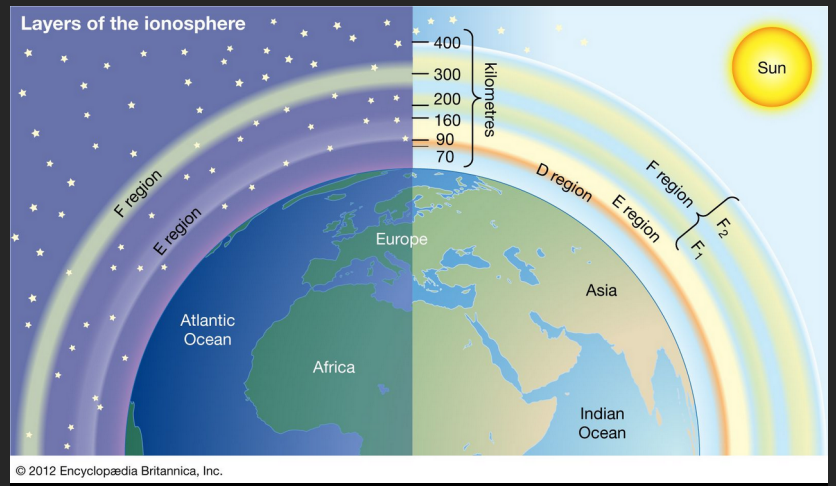
Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing

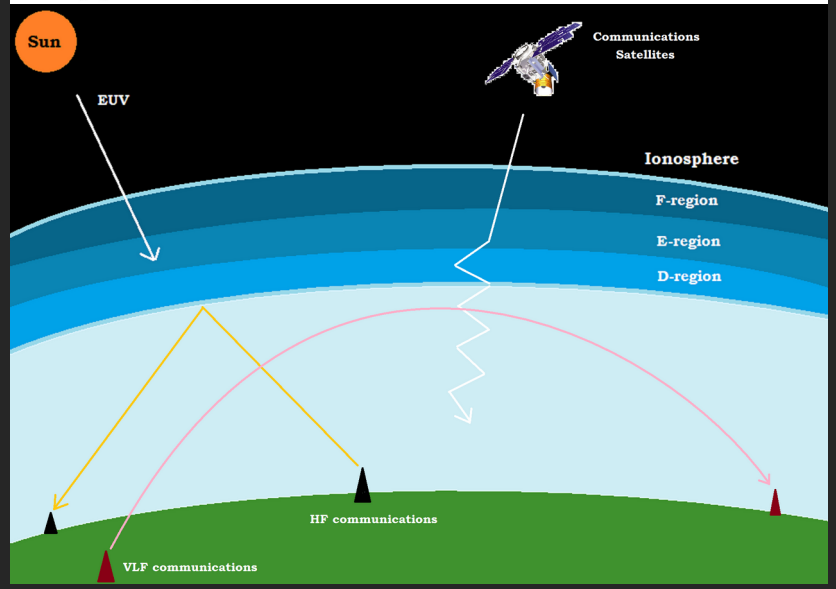
Ionosphere (Tầng điện ly)



A sounding from Puerto Rico demonstrating the new adaptive filtering feature that removes HF broadcast stations.

See RA-01a
(Wed, 7/24)
Radio sciences

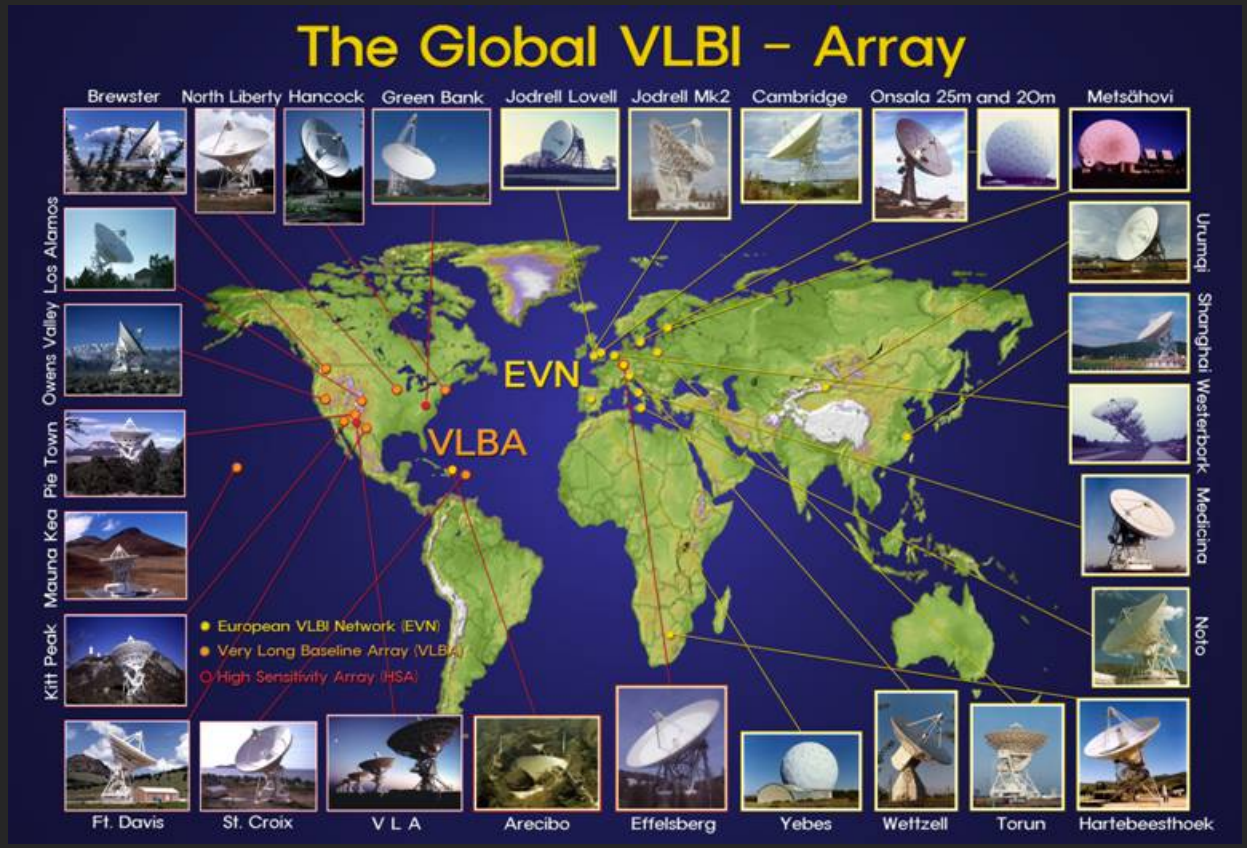




Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing

Very Long-baseline Interferometry (VLBI)

(Geodesy, Geophysics, Climate Sciences)

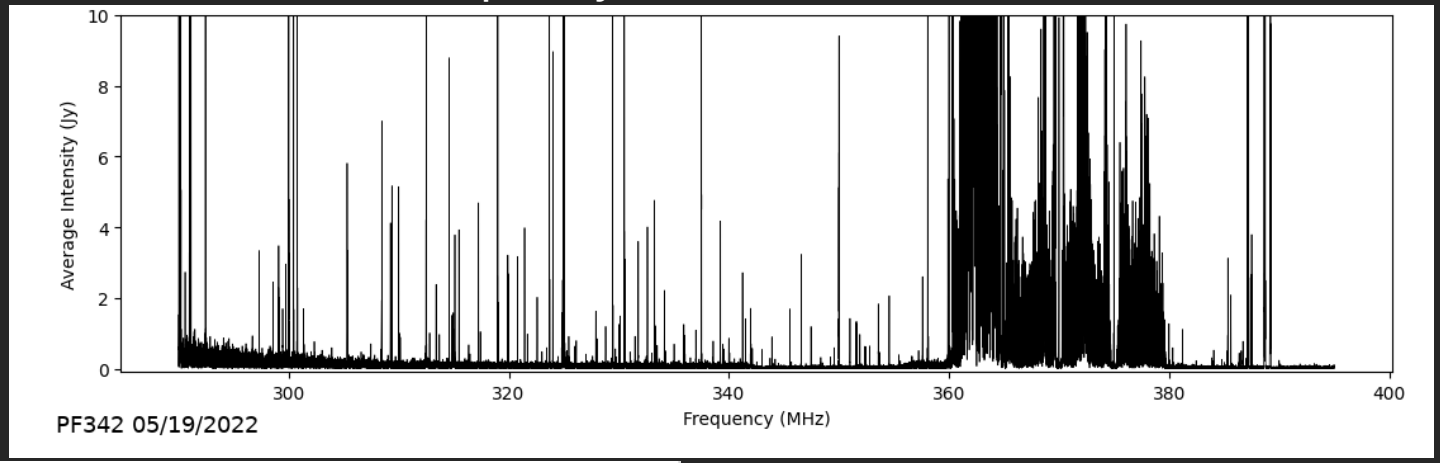


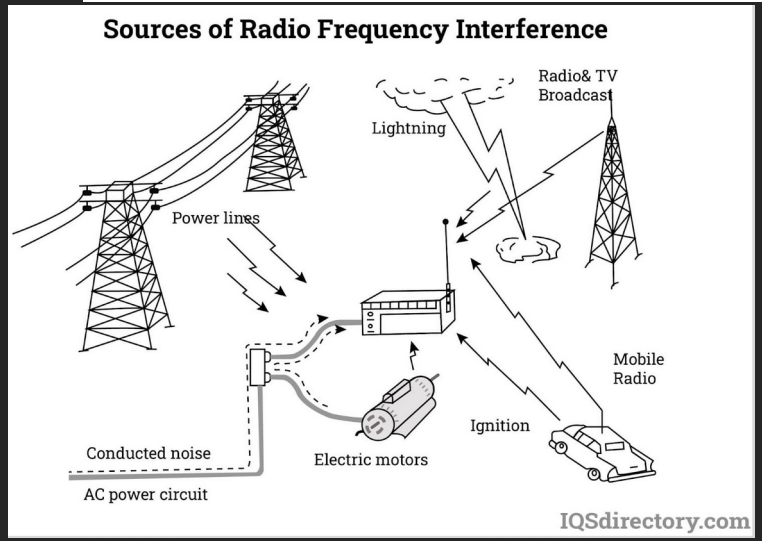
https://www.youtube.com/watch?v=XcSZjT3oDSY

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet

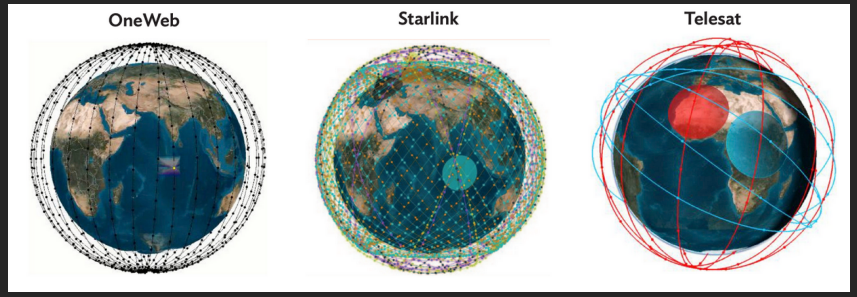
Radio Quiet

RFI = Radio Frequency Interference = Bad contamination





Satellite constellation downlink transmission

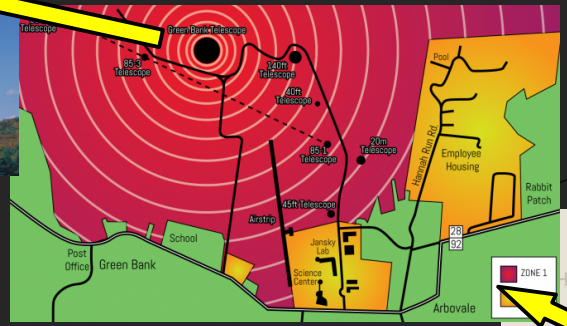


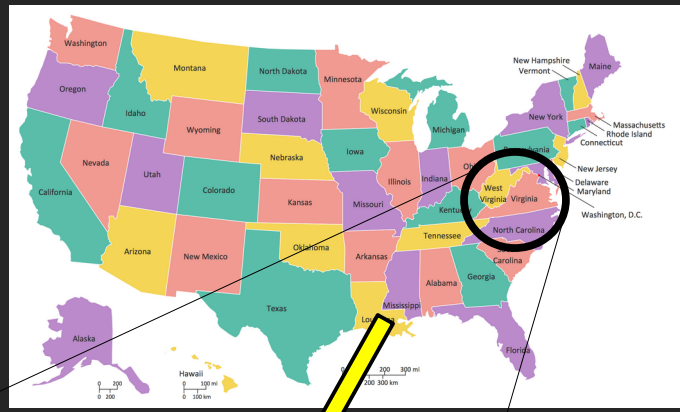
Del Portillo, et al. 2019, Acta Astronautica 159

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet

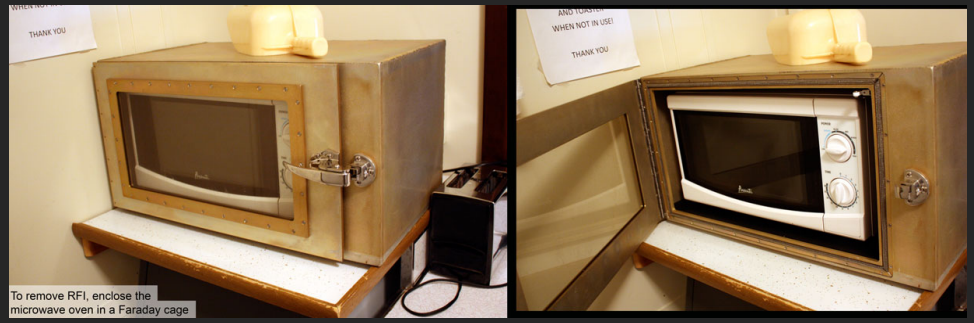
Radio Quiet Zone

- Far from cities in remote area
- No wifi/cellphone





Double layer microwave oven shielding



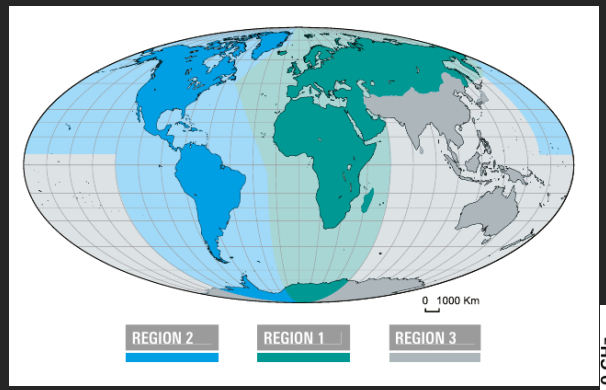
To remove RFI, enclose the microwave oven in a Faraday cage

https://greenbankobservatory.org/about/interference-protection/

Protect radio astronomy from satellite constellations video

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation

World Spectrum Allocation

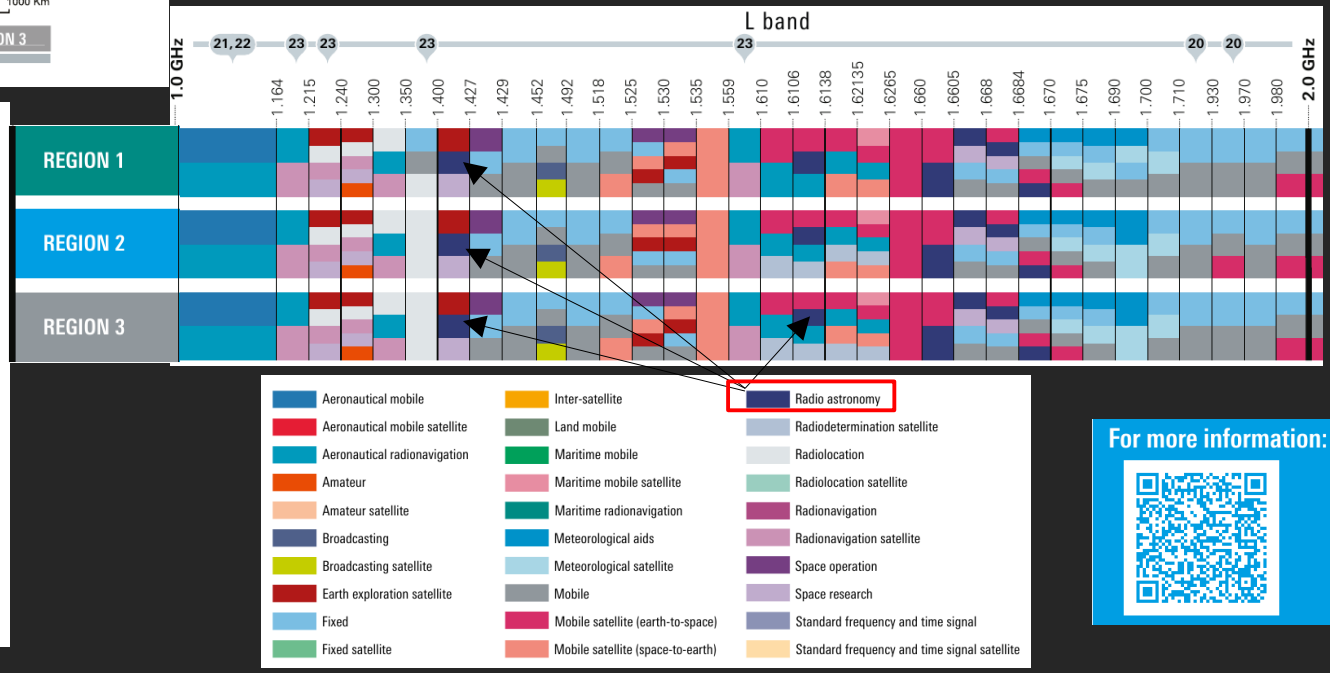


International Telecommunication Union

International Astronomical Union

IEEE bands

Band	Frequency range
HF band	3 MHz to 30 MHz
VHF band	30 MHz to 300 MHz
UHF band	300 MHz to 1000 MHz
L band	1 GHz to 2 GHz
S band	2 GHz to 4 GHz
C band	4 GHz to 8 GHz
X band	8 GHz to 12 GHz
K_u band	12 GHz to 18 GHz
K band	18 GHz to 27 GHz
K_a band	27 GHz to 40 GHz
V band	40 GHz to 75 GHz
W band	75 GHz to 110 GHz
G band	110 GHz to 300 GHz

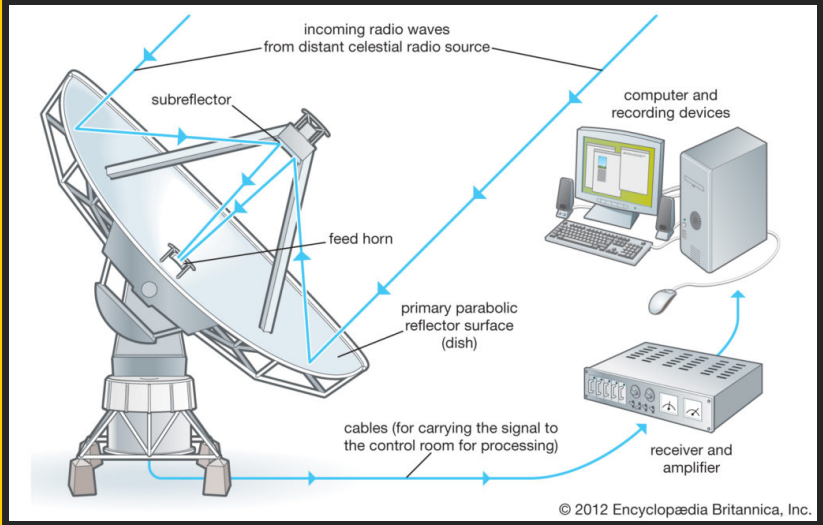


For more information:

https://www.allaboutcircuits.com/uploads/articles/Worldwide_Spectrum_Allocations.pdf

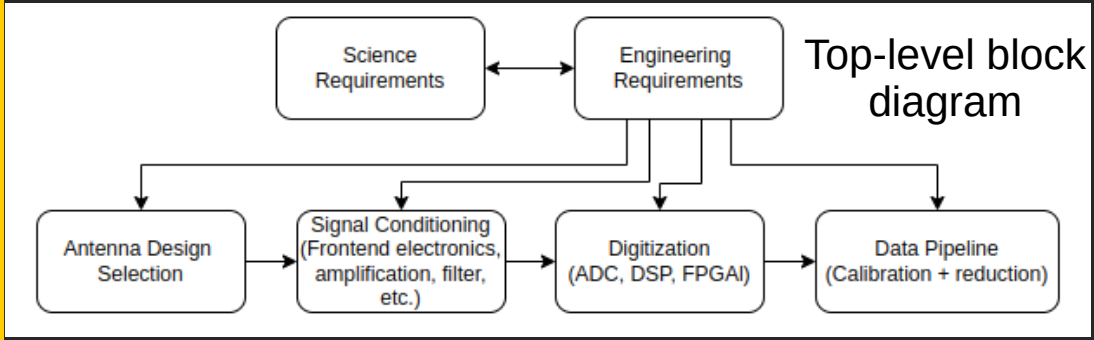
Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation

Radio telescope instrumentation



General steps of a radio telescope:

1. Antennas as sensors
2. Measure Voltage vs Time (Signal conditioning)
3. Digitization with Analog-to-Digital Converter (ADC)
4. Compute spectrum (quang phổ) with Fourier Transform (Digital Signal Processing, DSP)
5. Calibration (Instrument response)
6. Data reduction & analysis
7. Science results



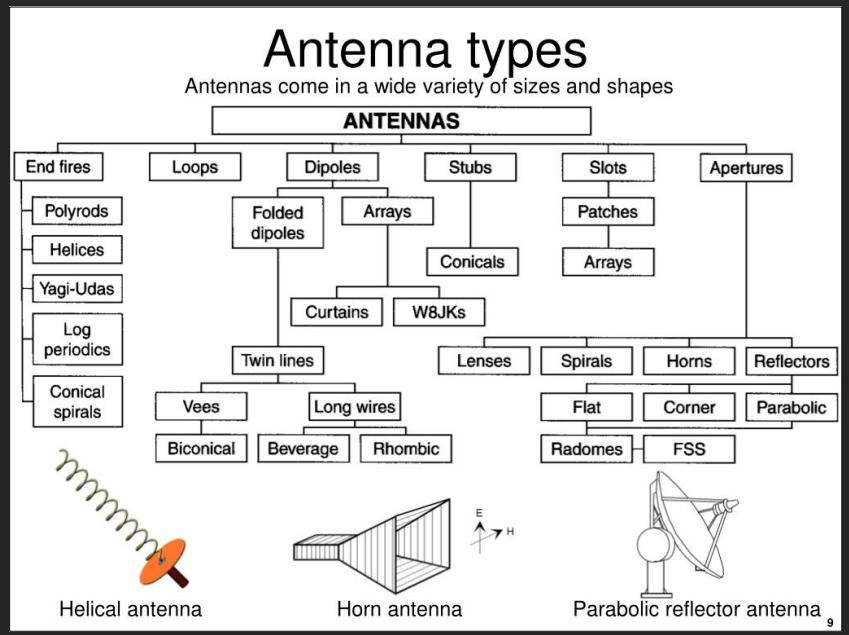
Top-level block diagram

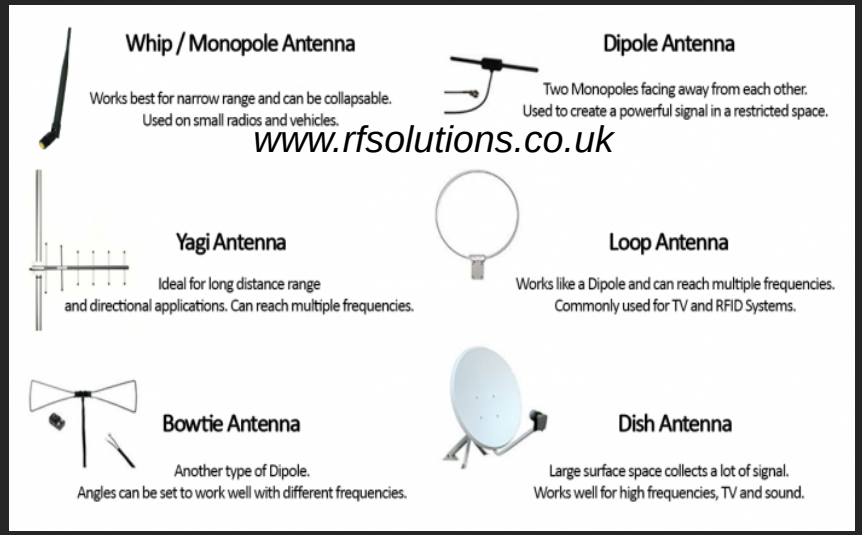
Science requirement examples:

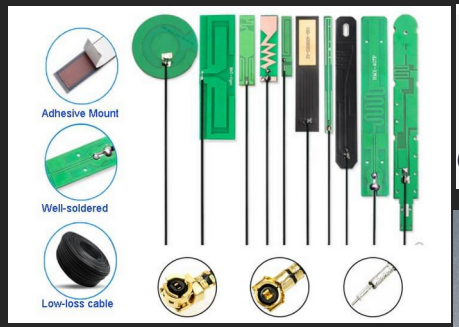
- Frequency range
- Spatial resolution
- Frequency resolution
- Time resolution (how fast to record the data)
- Integration time (reduce noise)

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas

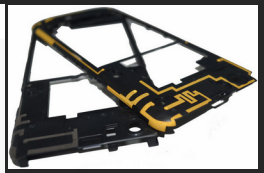
Sensors: Antennas



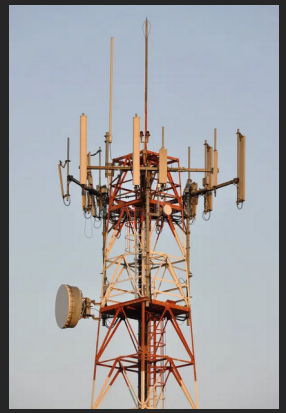




Bluetooth



Smart phone



Car shark fin

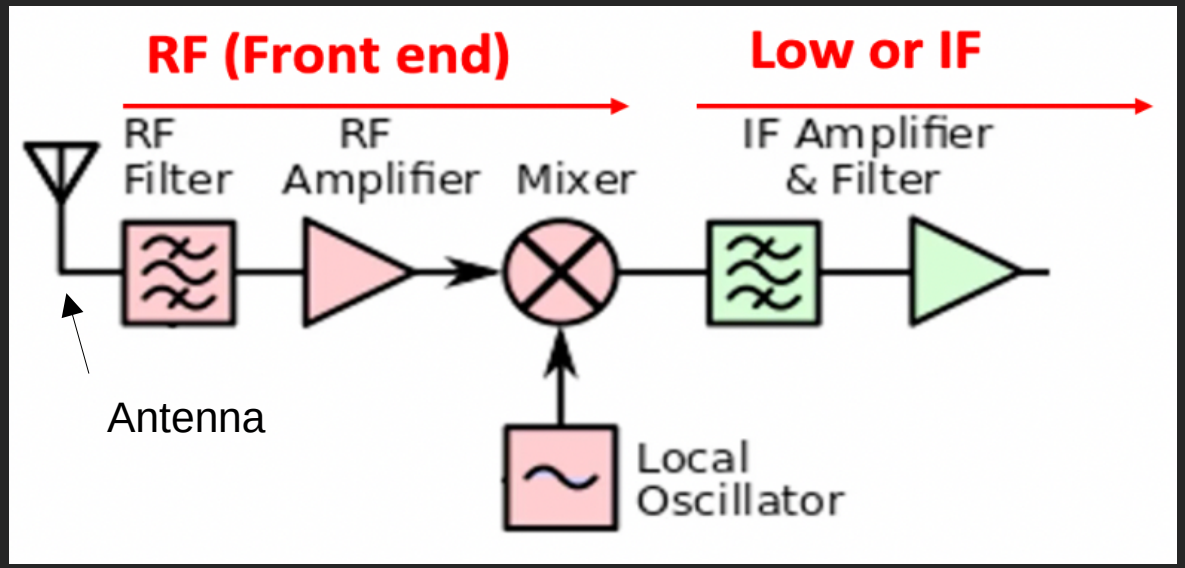
WIFI router

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver

Heterodyne receiver

(Heterodyne = frequency mixing or conversion)

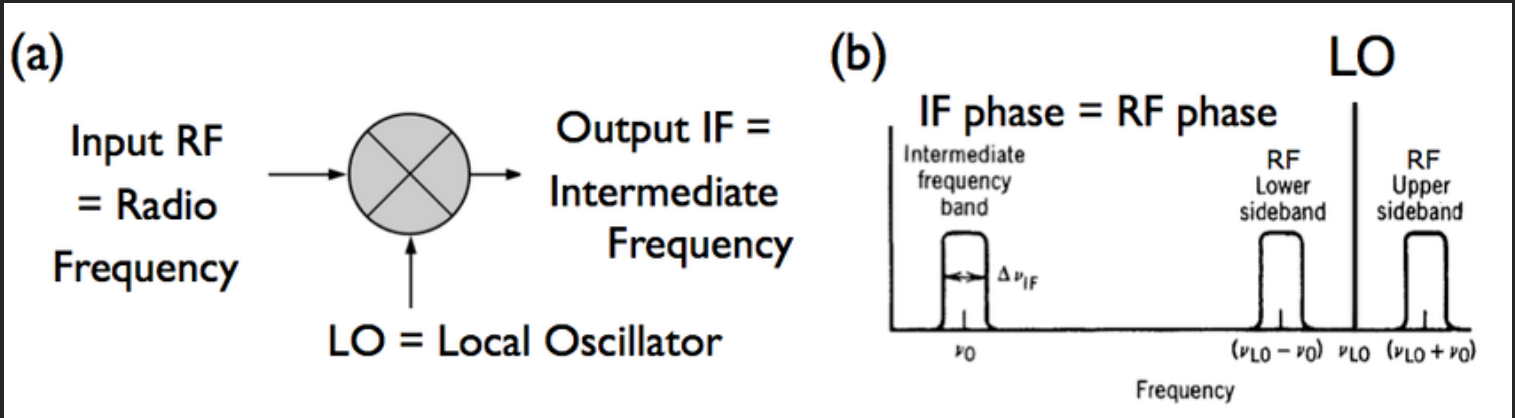
See RA-03a & b
(Thu, 7/25)
RF analog



Working principle:
- Signal with too high frequency can't be recorded correctly by electronics
- Need to slow the signal's frequency down by multiply it with an LO to Intermediate Frequency (IF)

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver

Heterodyne receiver: Mixer



Trigonometry (lượng giác)

$$\cos(\alpha + \beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$
$$\cos(\alpha - \beta) = \cos\alpha\cos\beta + \sin\alpha\sin\beta$$

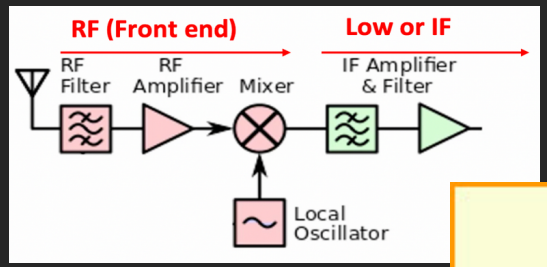
Mixer = multiply
Input signal = frequency 1
Local oscillator (LO) = freq 2

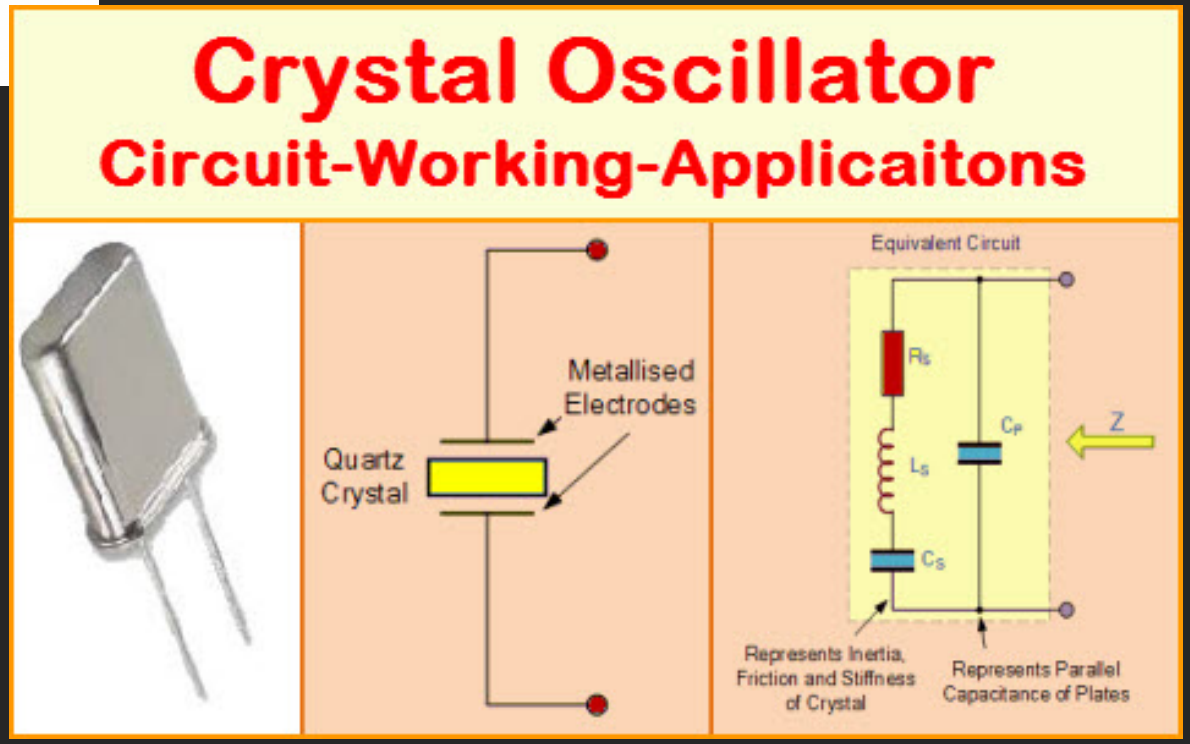
Working principle:

$$\cos(2\pi f_1 t)\cos(2\pi f_2 t) = \frac{1}{2}\cos[2\pi(f_1 - f_2)t] + \frac{1}{2}\cos[2\pi(f_1 + f_2)t]$$

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver

Heterodyne receiver: Local Oscillator





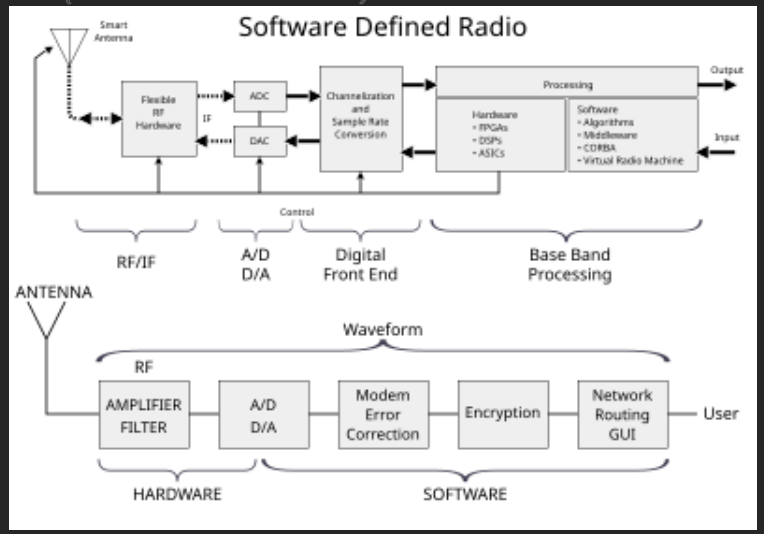
Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver
ADC/DSP

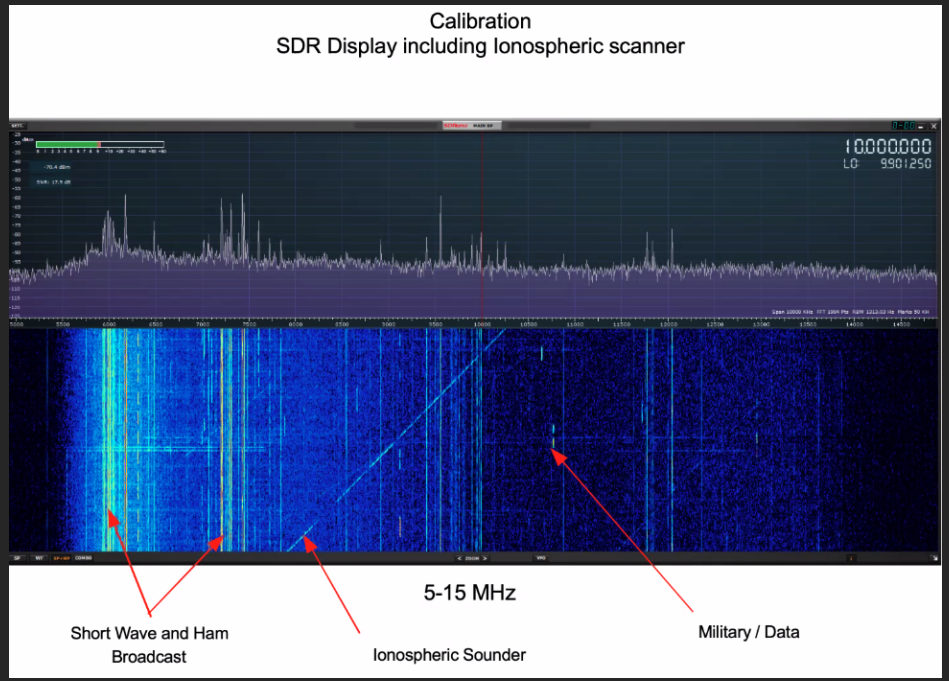
DAQ – Data Acquisition with Software Define Radio (SDR)

See RA-03a (Mon, 7/29) SDR

Amateur/Hobbyist **($-$$)**

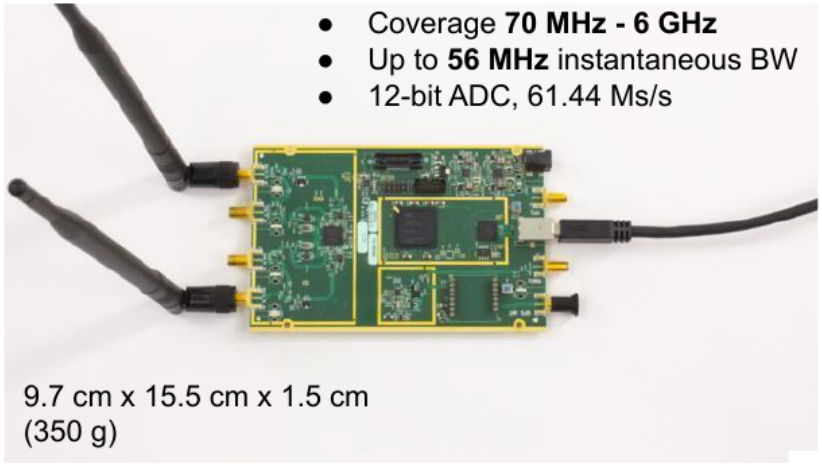
(www.onelectrontech.com)



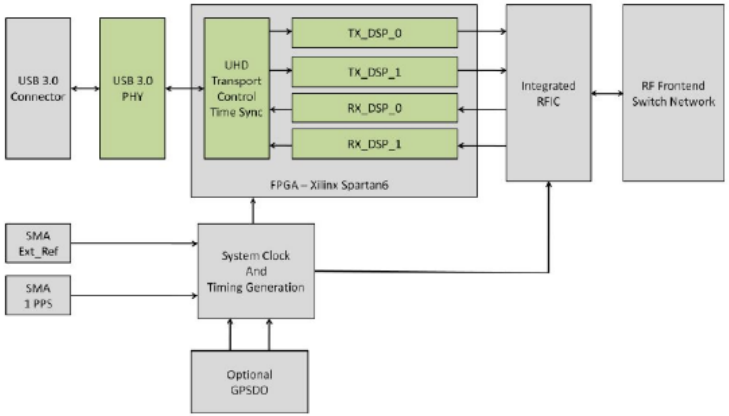


Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver
ADC/DSP

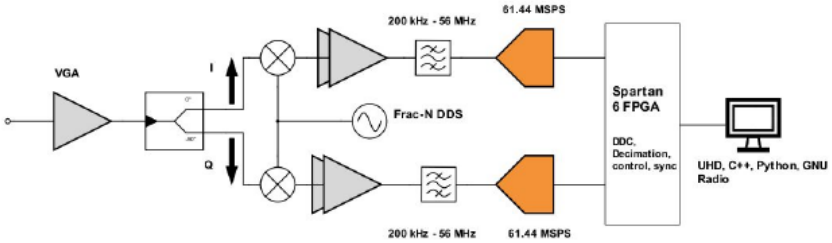
Ettus B210 SDR



- Coverage **70 MHz - 6 GHz**
- Up to **56 MHz** instantaneous BW
- 12-bit ADC, 61.44 Ms/s

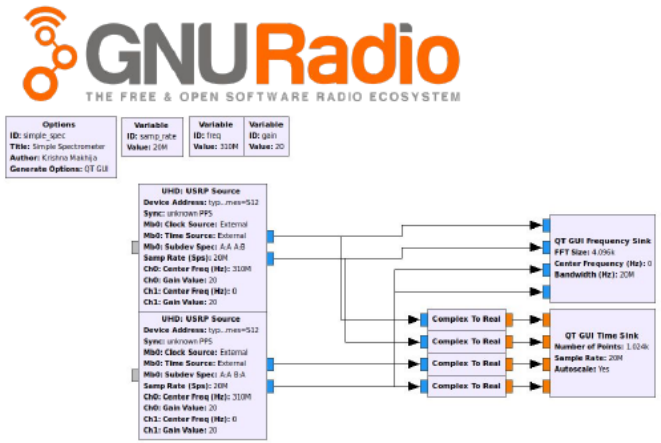


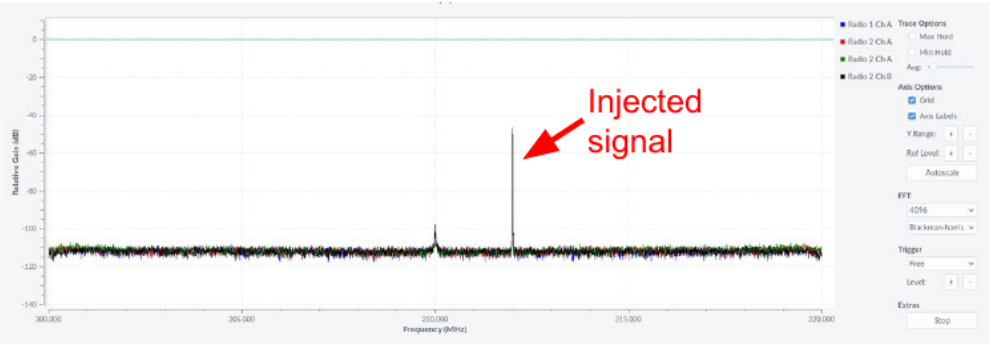
- I/Q sampling
- Internal LO & mixer
- MIMO (2x TX & RX/unit), can be synced with 10 MHz & 1pps, GPSDO supported

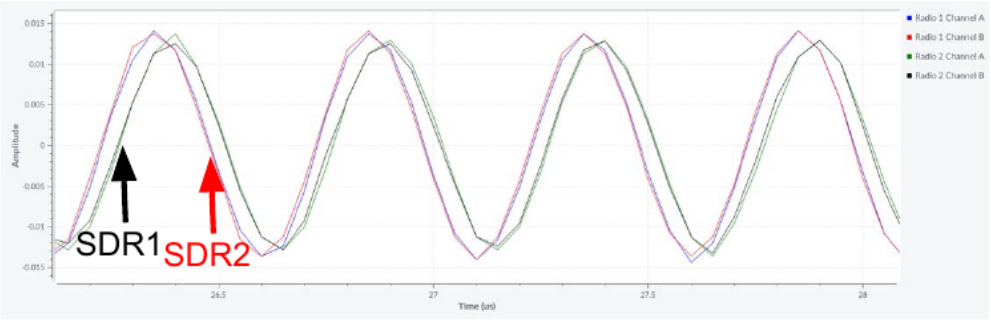


Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver
ADC/DSP

USRP + GNURadio Example: A simple 4-channel spectrometer







- ***Phase coherence*** can be achieved using an external reference.
- However, there is a new ***phase offset*** and delay in effect at each bootup which needs to be calibrated out.
- Notes: USRP is also supported by MATLAB & Simulink (Communication Toolbox)

Courtesy: Krishna Makhija (NRAO/U. Virginia)

Overview
Radio Astronomy
Radio Telescopes
Early radio tel.
Modern tel.
Sciences
21-cm HI
Redshift
Cosmology
Astrophysics
Planetary Sci.
Remote Sensing
Radio Quiet
Spec. Allocation
Instrumentation
Antennas
Receiver
ADC/DSP
Reference & Resources

Other resources

- Dr. Scott Ransom's (NRAO) Essential Radio Astronomy Lecture Note
- UC Berkeley – Radio Astronomy Lab wiki AstroBaki
- VNSC's article "Radio Astronomy In Vietnam: Recent Development"
  - VNSC Department of Astro-Physics group
- Dr. Võ Bích Hiển @ the Vietnamese-German University (VGU)
- FB's Amateur Radio Astronomy Group
- Some NRAO YouTube videos:
  - NRAO's Baseline Video Series
  - The VLA movie might be nice if there is time:
  - NRAO Highlight videos
  - ALMA movie