Radio Science and techniques for Space Exploration

PHYS 4330 3.0

Long Baseline Interferometry

PHYS 6190 3.0

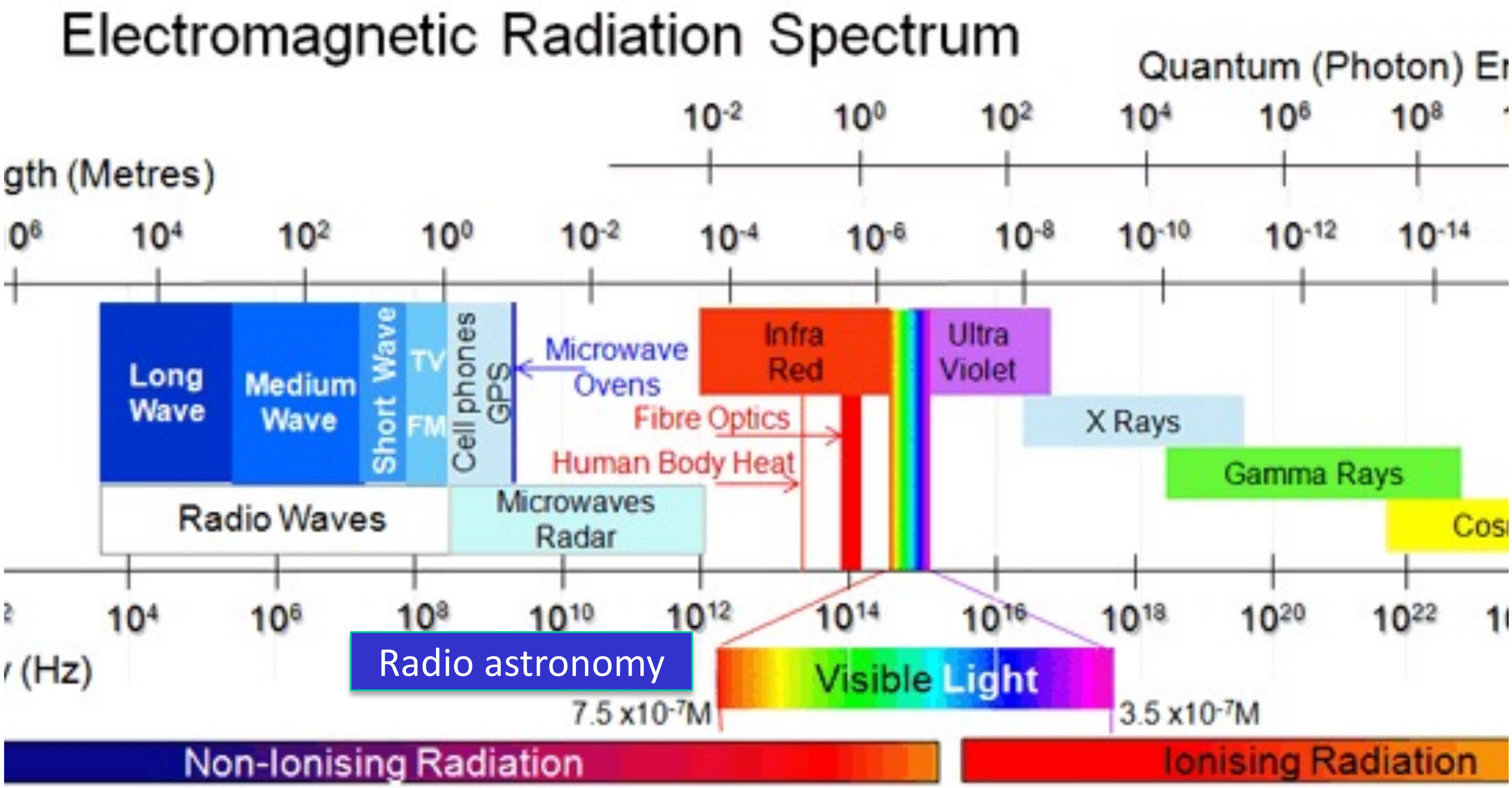
Norbert Bartel

Professor of Astrophysics

York University

PHYS 4330	Tu, Th 13:30 – 14:30	**ML 213**			
JANUARY		**FEBRUARY**		**MARCH - APRIL**	
Thursday 4	**0. Introduction**	Thursday 1	Cont.	Thursday 1	Cont.
Tuesday 9	**1. Signal Processing Fundamentals**	Tuesday 6	**2. Radio Astronomy Fundamentals**	Tuesday 6	
Thursday 11		Thursday 8		Thursday 8	**3. Radio observatory and DSN Instrumentation Fundamentals**
Tuesday 16		Tuesday13		Tuesday 13	
Thursday 18		Thursday 15		Thursday 15	
Tuesday 23		Tuesday 20	**Reading Week**	Tuesday 20	
Thursday 25		Thursday 22		Thursday 22	
Tuesday 30		Tuesday 27	**Midterm exam**	Tuesday 27	
				Thursday 29	**4.VLBI and DSN Appl. to Spacecraft Navigation**
				APRIL	**5. Introduction to Radar Systems -Radar Fundamentals**
				Tuesday 3	
				Thursday 5	

The electromagnetic spectrum



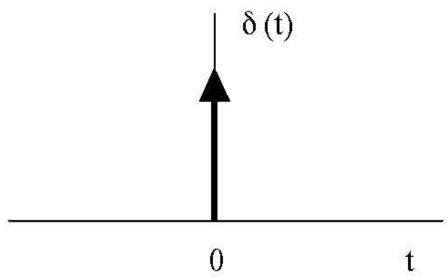
Radio range over 8 orders of magnitude from 10^4 to 10^{12} Hz

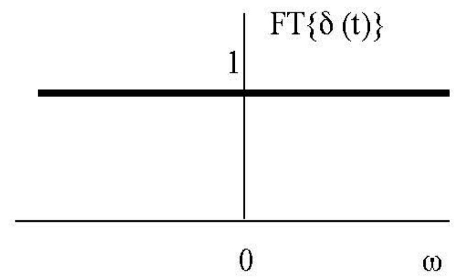
Radio astronomy over 5 orders of magn. from 10^7 to 10^{12} Hz

1. Signal processing fundamentals

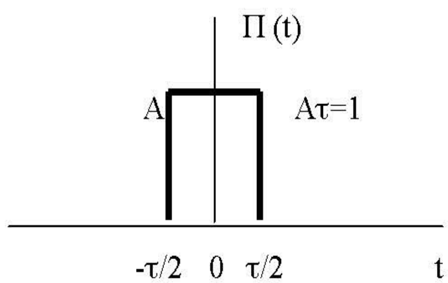
Chapter 1a

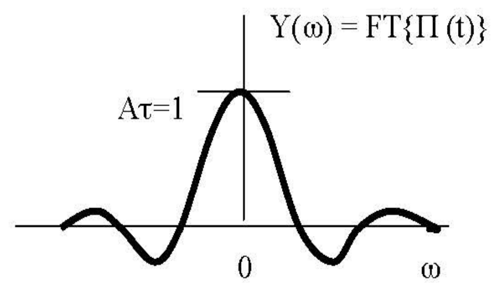
Fourier transforms





Note: This result can also be obtained through a limiting argument;

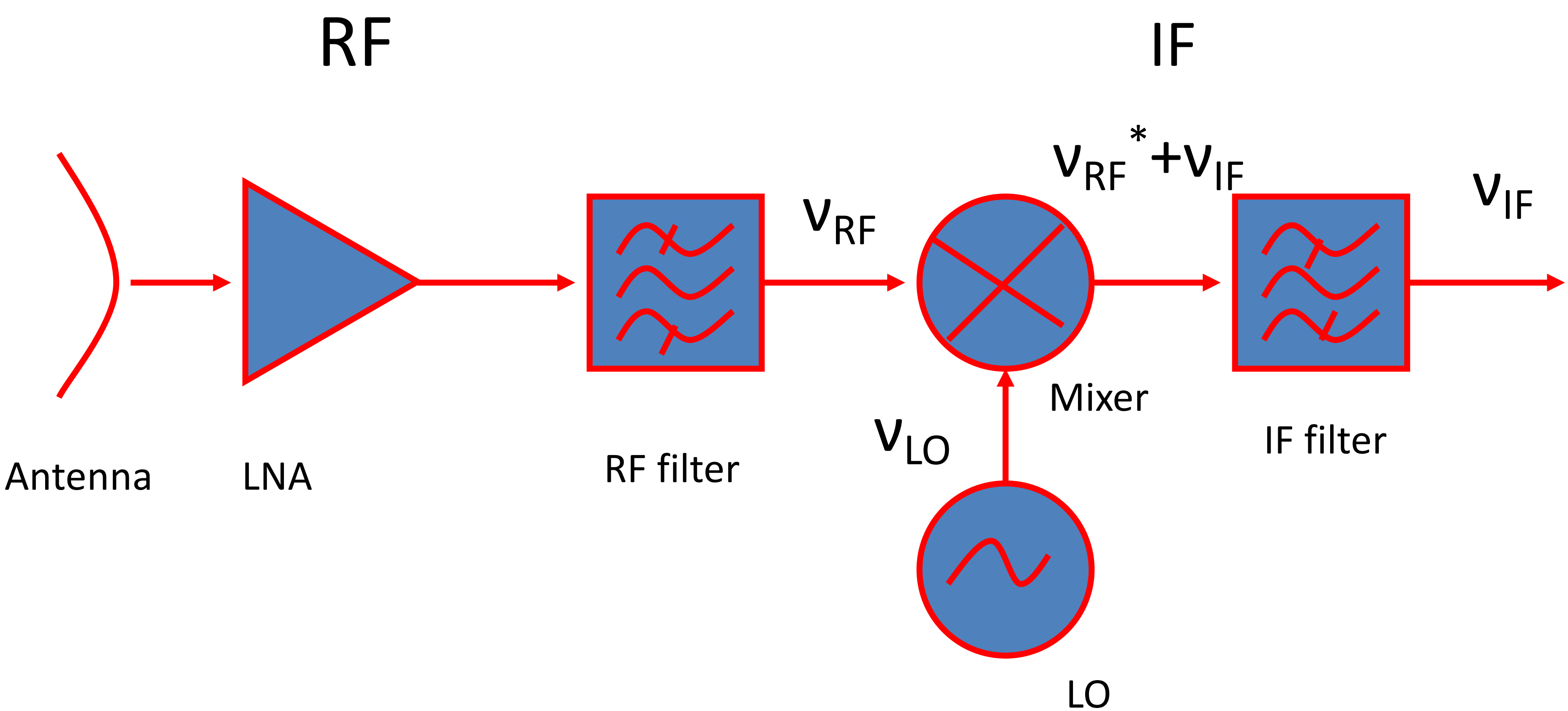




FT of a constant:

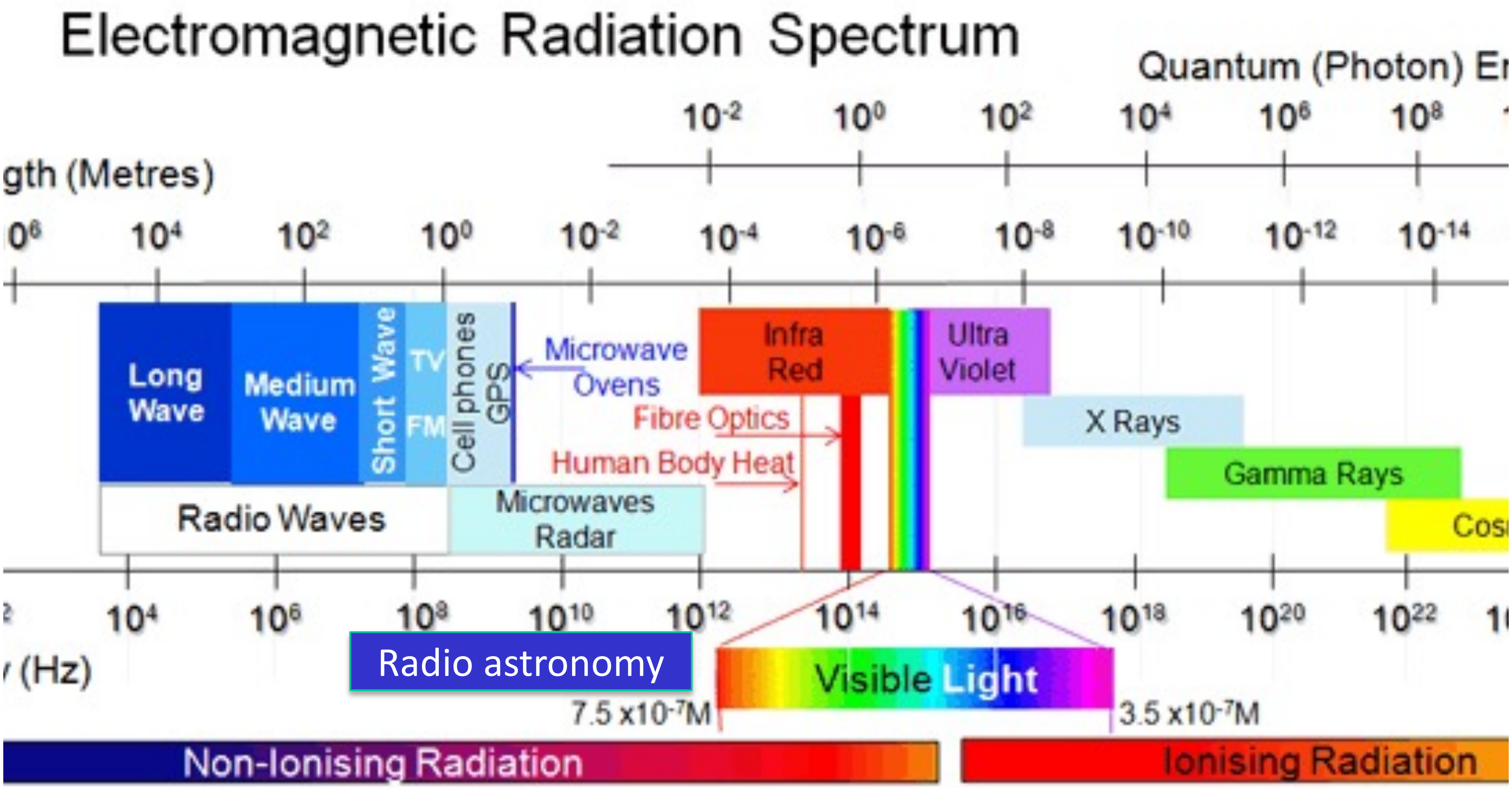
Chapter 1b

Filter theory



2. Radio astronomy fundamentals

The electromagnetic spectrum



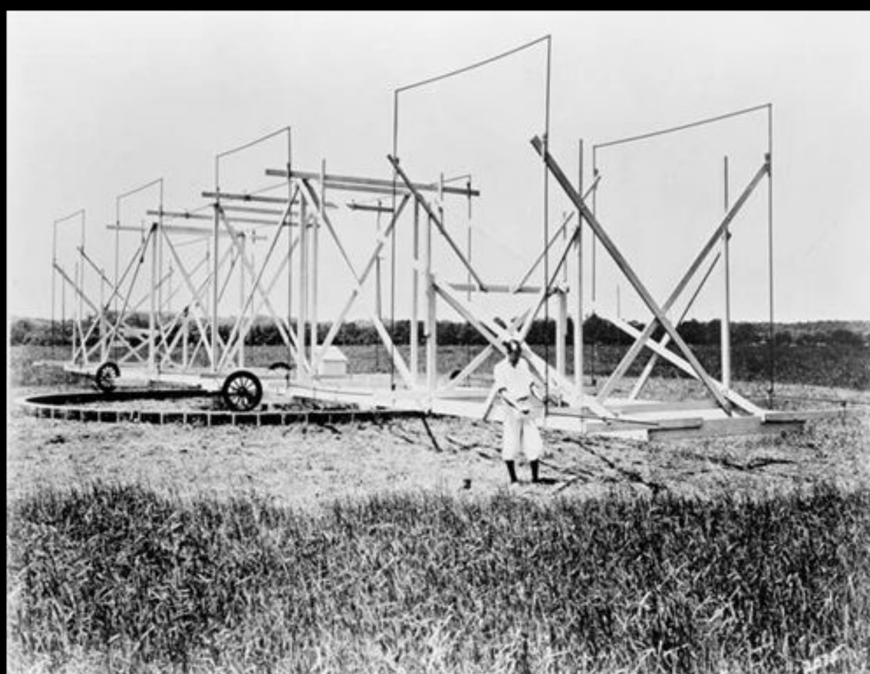
Radio range over 8 orders of magnitude from 10^4 to 10^{12} Hz

Radio astronomy over 5 orders of magn. from 10^7 to 10^{12} Hz

Karl Jansky (1905-1950)

1 Jy= 10^{-26} W m^{-2} Hz^{-1}

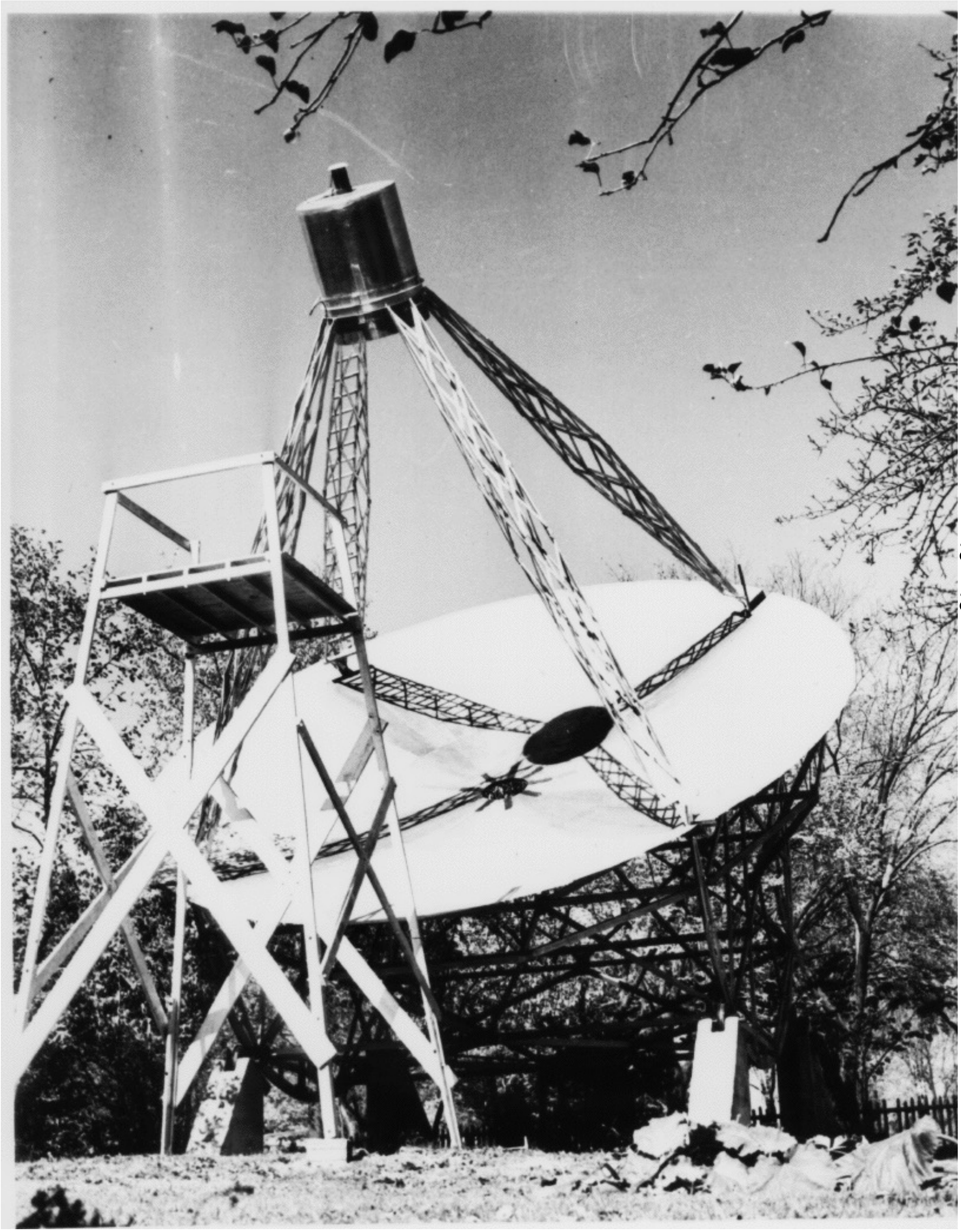
Jansky's Telescope



- Karl Jansky built a radio antenna in 1931.
  - Polarized array
  - Study lightning noise
- Detected noise that shifted 4 minutes each day.
  - Direction of Sagitarrius
  - Consistent with galactic source

Discovery of extraterrestrial radio waves

$\nu = 20.5\ MHz$



Grote Reber

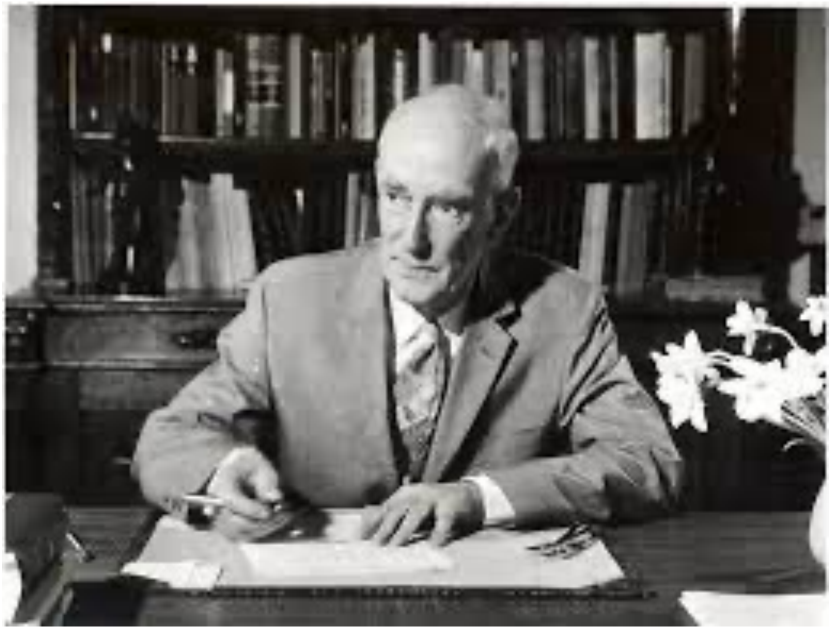
1911-2002

Pioneered work in radio astronomy.
Built 9 m paraboloidal radio telescope and conducted the first sky survey at radio frequencies.

$\nu = 160\ MHz$

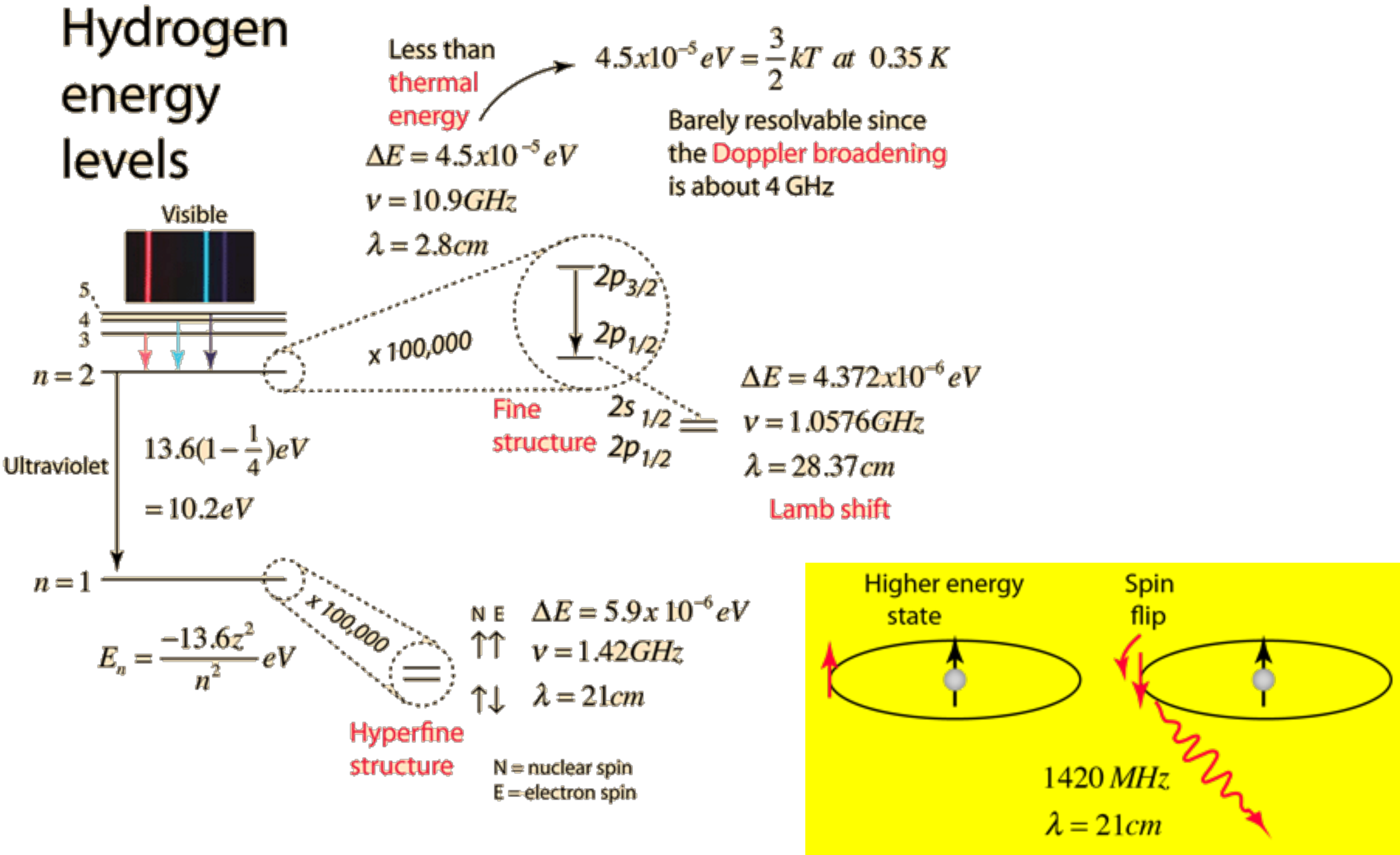
Jan Oort (1900-1992)

- Static must be broad band extending over the whole radio wavelength range.
- Realized that finding a spectral line in the radio would be groundbreaking.



Wikipedia

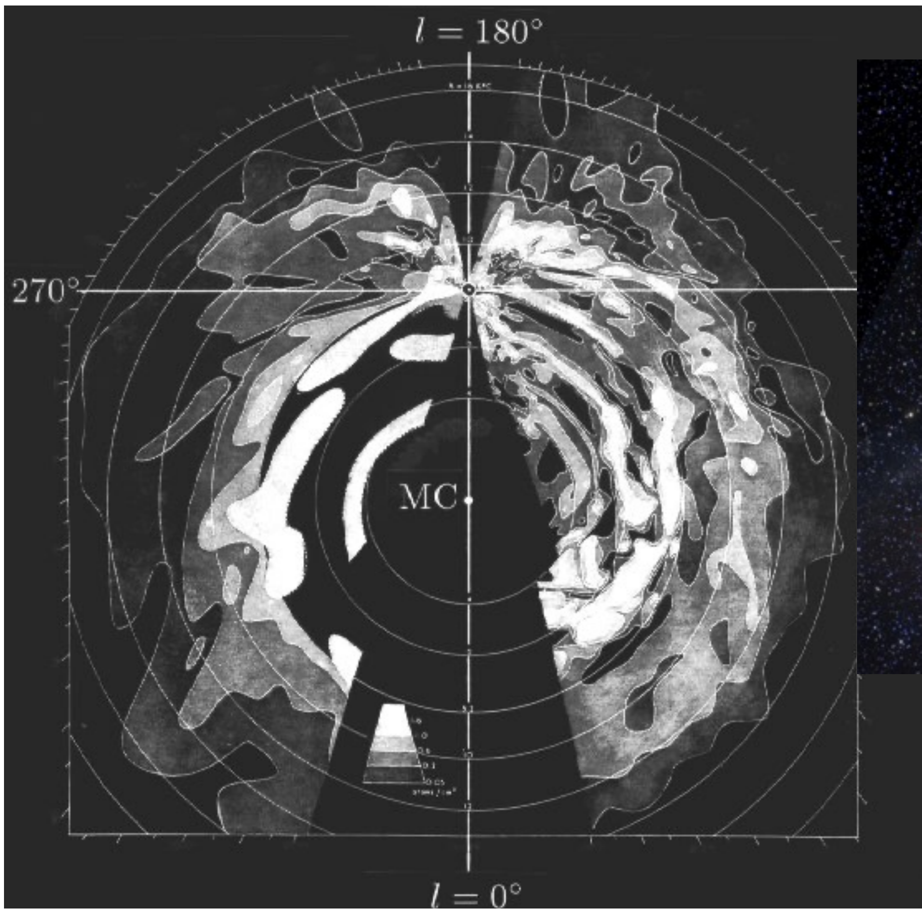
Van der Hulst suggested 21 cm hyperfine transition of neutral hydrogen may be observable

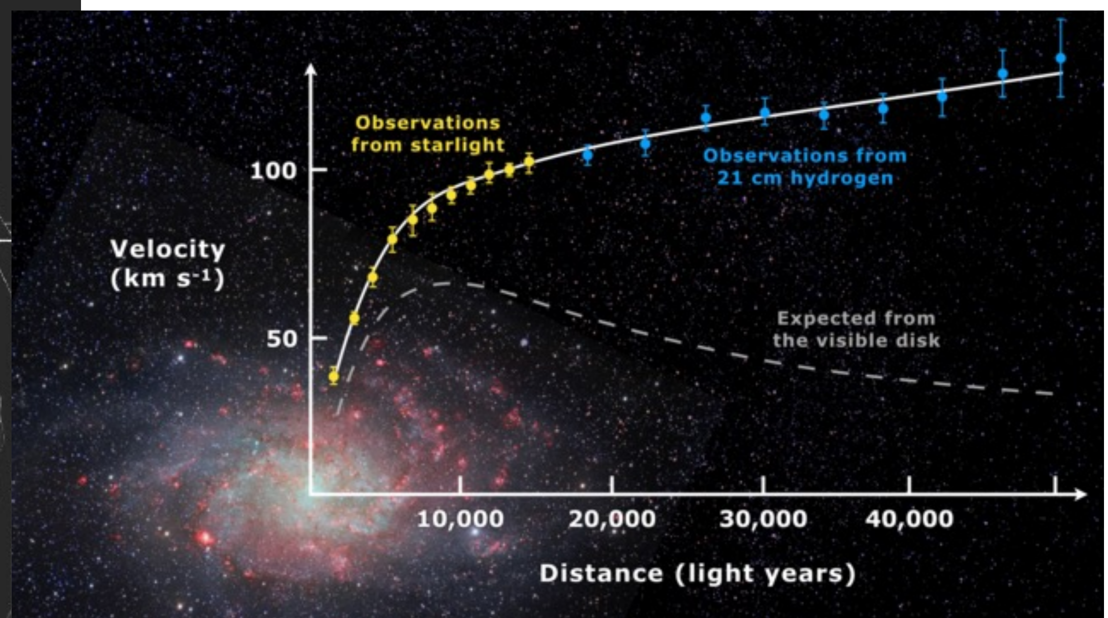


H. Ewen and E. Purcell discovered the 21 cm interstellar hydrogen line in 1951

HI neutral hydrogen

HII ionized hydrogen

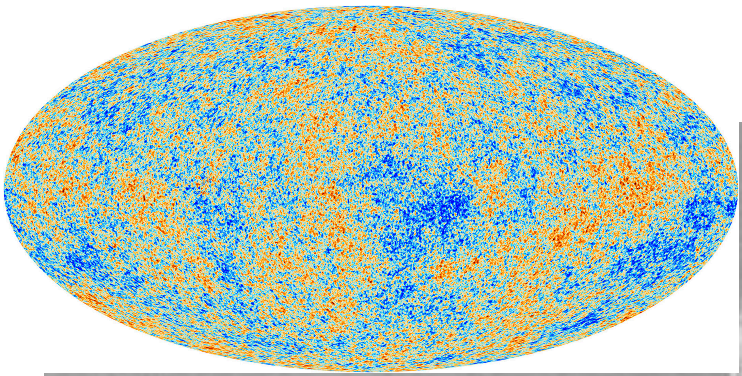




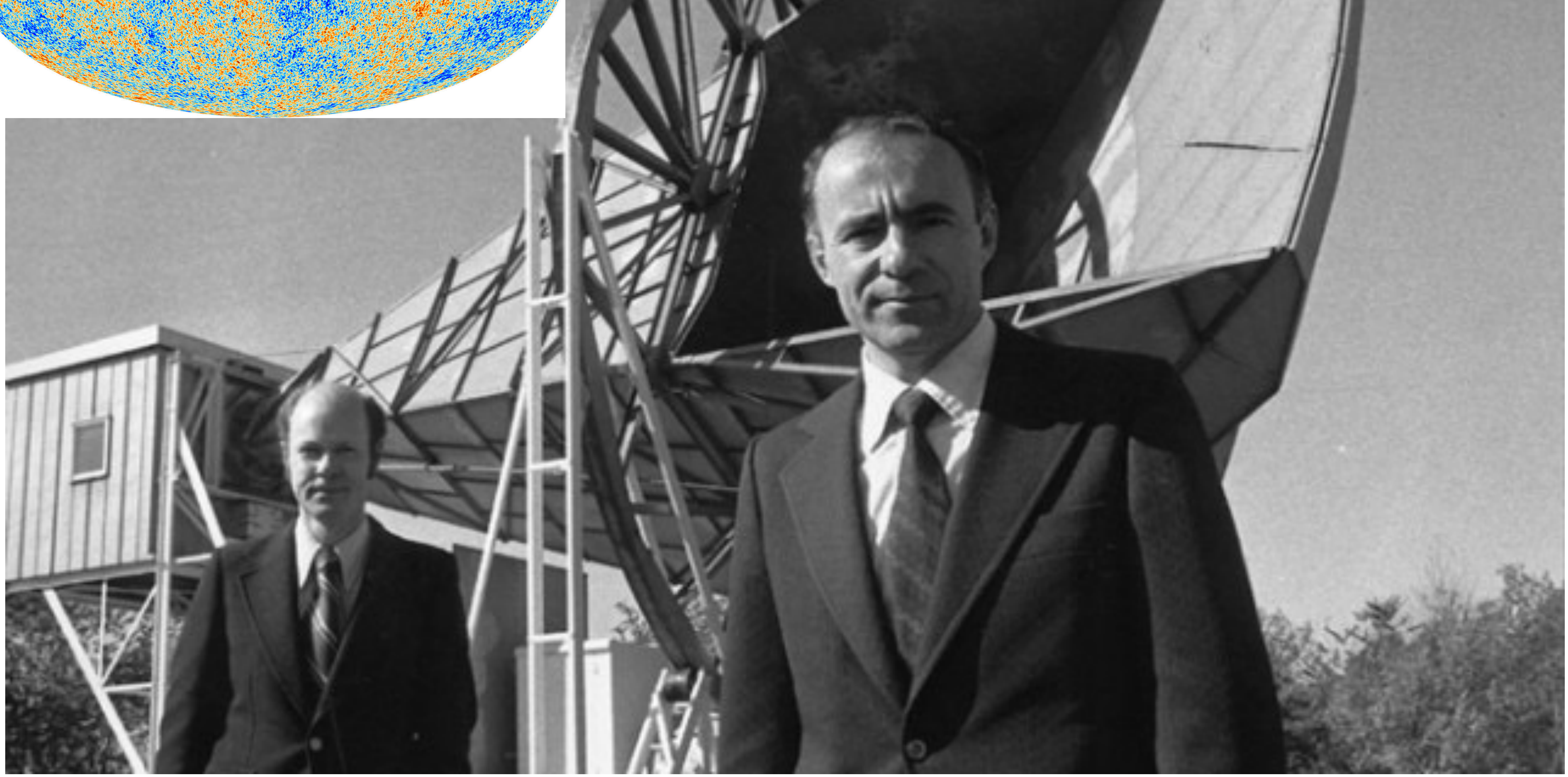
Wikipedia

Oort et al. 1958

Horn antenna



Penzias and Wilson discover cosmic microwave background



Large radio telescopes

Jodrell Bank, UK

76 m

The Independent

Large radio telescopes

Algonquin,
Canada

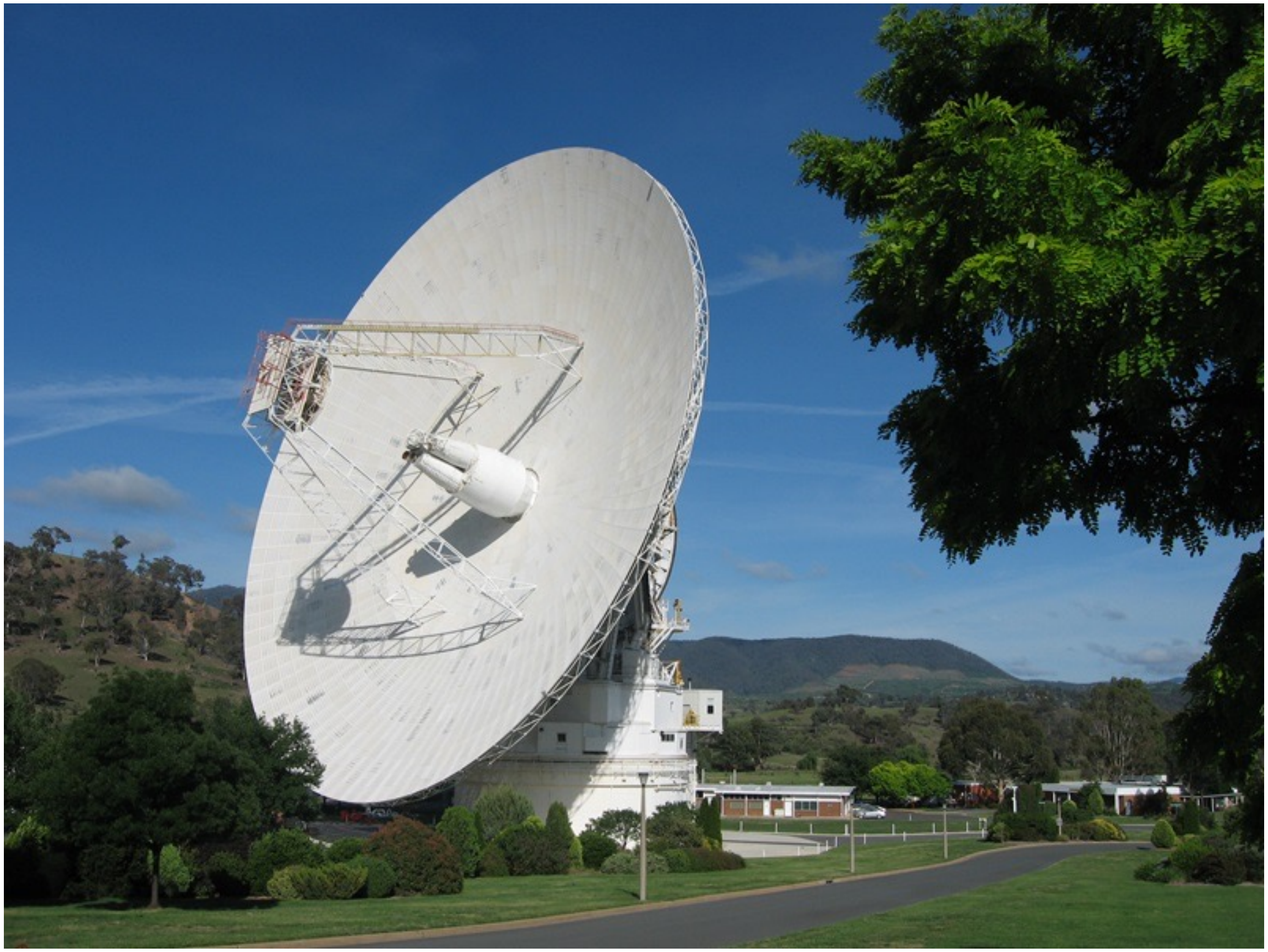
46 m

Large radio telescopes

NASA Deep Space Network antenna

Tidbinbilla,
Australia

70 m



Large radio telescopes

Effelsberg, Germany

100 m

Large radio telescopes

Green Bank,
USA

110 m

Large radio telescopes

Arecibo,
Puerto Rico

100 m

300 m

Large radio telescopes

Fast Telescope

China

500 m

Arrays of radio telescopes

Very Large Array (NRAO, New Mexico) – 27 x 25 m antennas

Arrays of radio telescopes

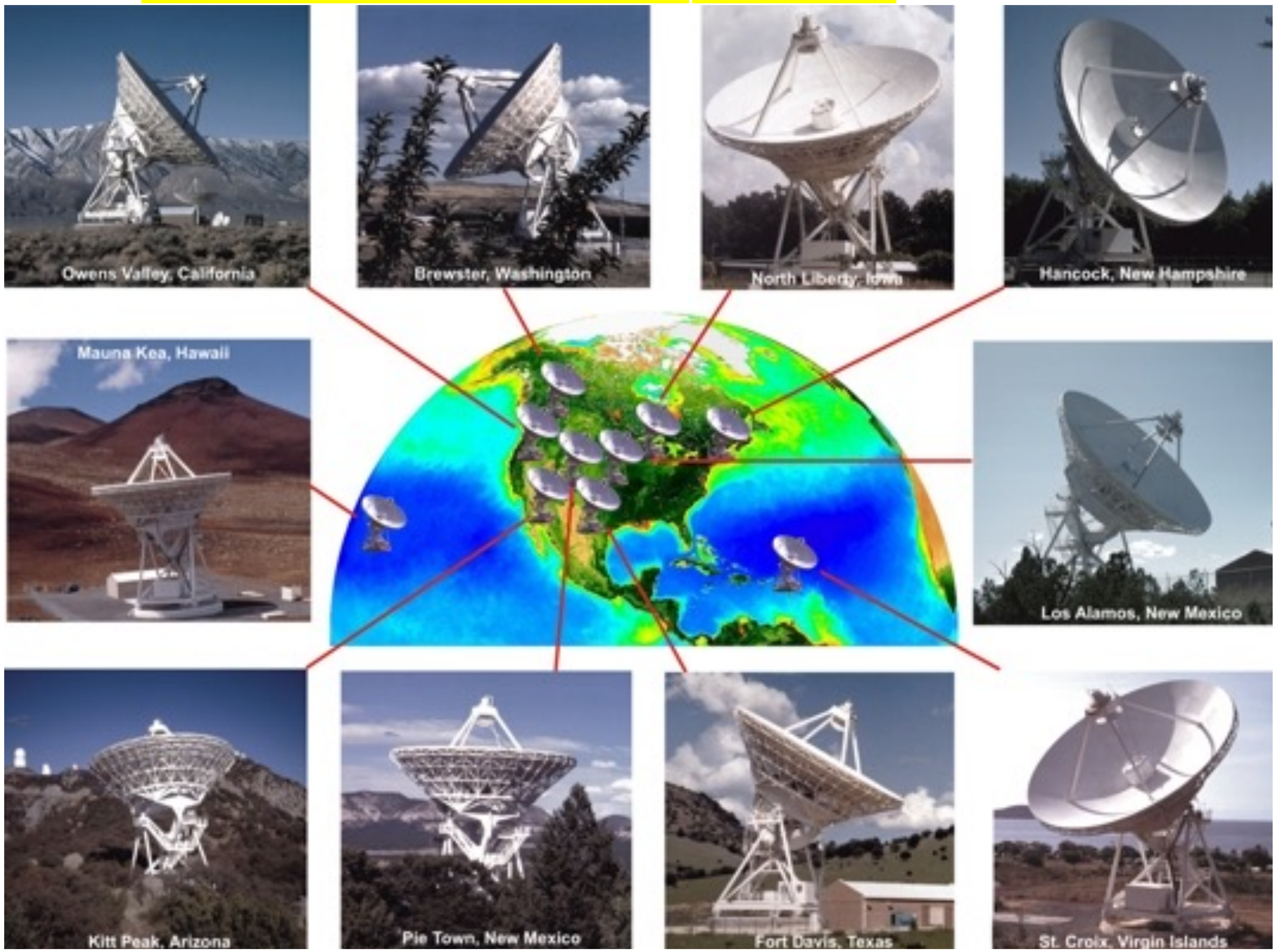
CHIME (Canadian Hydrogen Intensity mapping Experiment)

4x 20x100 m cylinder reflectors with no moving parts
128 receivers along each cylinder, 4 polarization channels ➔ 2048 inputs for the correlator

Arrays of radio telescopes

Very long baseline array (VLBA) –NRAO USA

10 x 25 m antennas



Space VLBI

Space very long baseline interferometry, RadioAstron (Russia and international partners)

2. Radio astronomy fundamentals

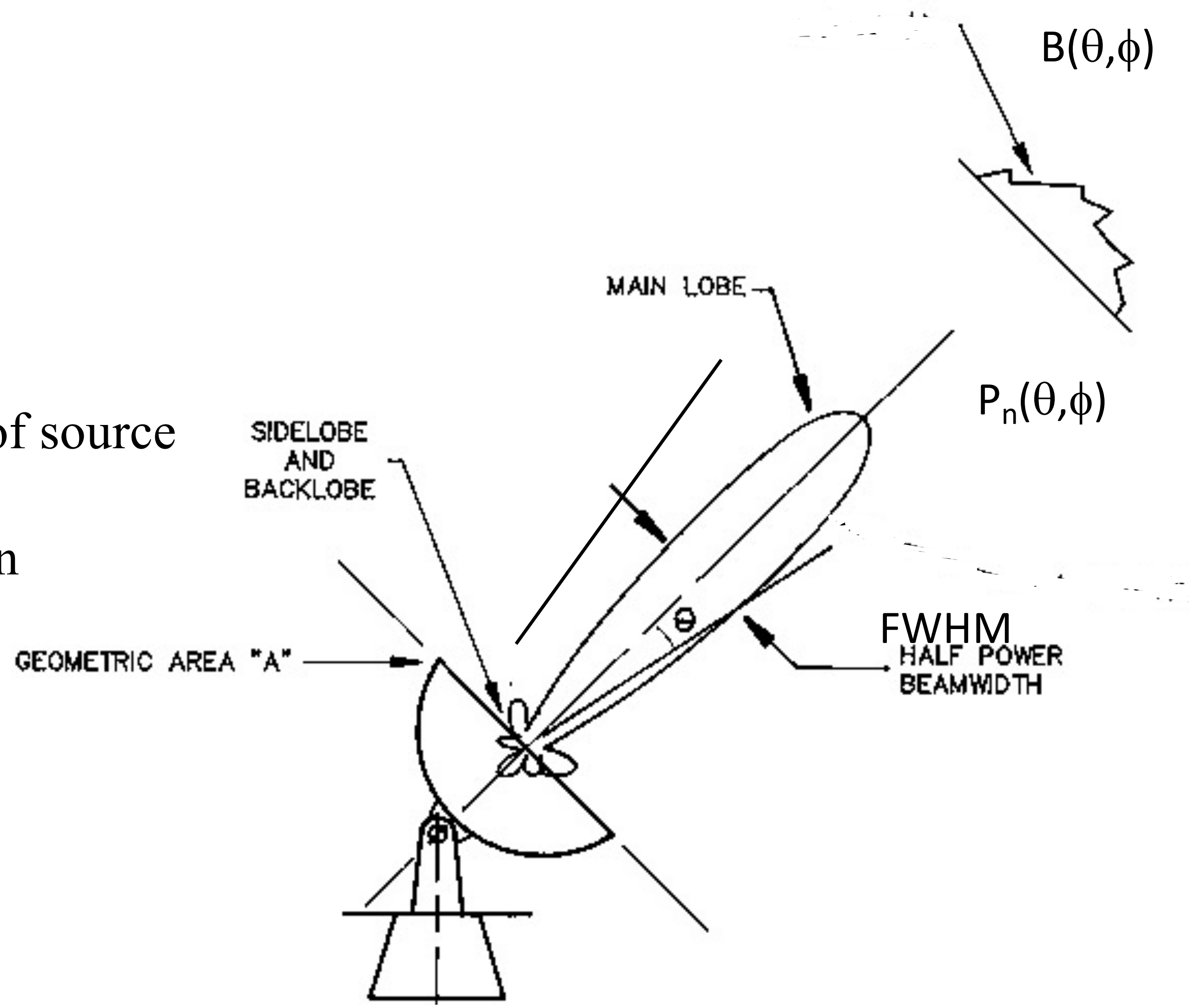
Chapter 2

A: aperture
G gain
λ wavelength
B brightness distribution of source
P beam pattern
P_n normalized beam pattern

$$G = P(0,0) / P_{isotropic}$$

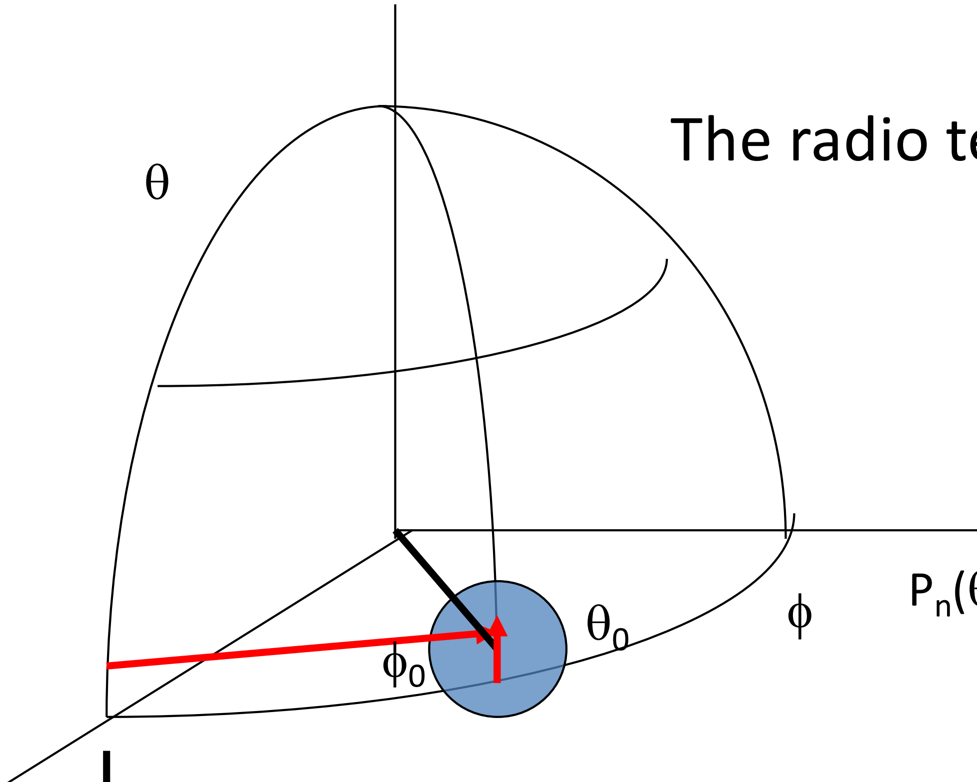
$$A_{eff} = \eta \frac{\pi D^2}{4}$$

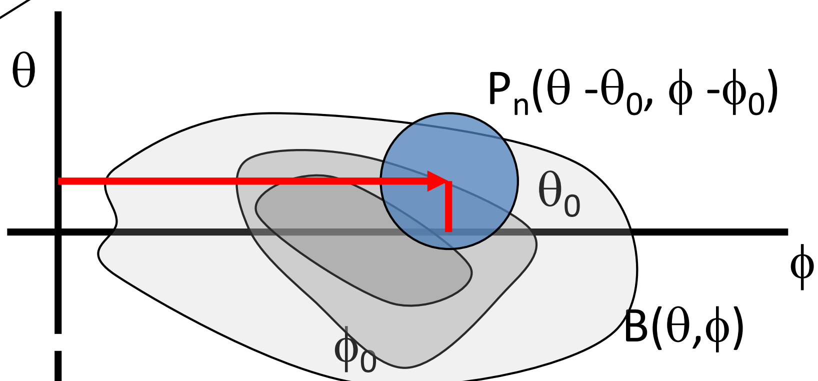
$$G = \frac{4\pi}{\lambda^2} A_{eff}$$

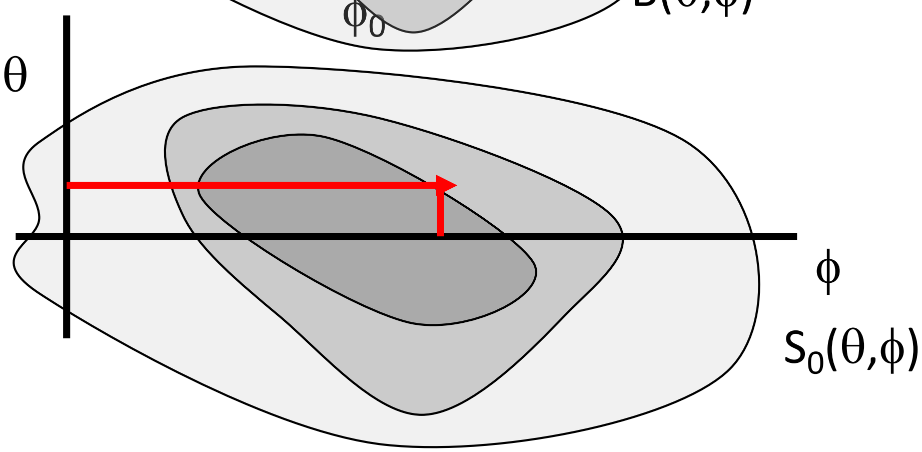


Convolution plays an essential role in this course

The radio telescope as a 1-pixel camera







$P_n(\theta,\phi)$ — Beam pattern (FWHM), normalized to 1

$P_n(\theta - \theta_0, \phi - \phi_0)$ — Beam pattern (FWHM) at pointing position, (θ_0,ϕ_0)

$B(\theta,\phi)$ — Brightness distribution of source

$S_0(\theta_0,\phi_0)$ — Measured flux density at pointing position, (θ_0,ϕ_0)

$$S_0(\theta_0,\phi_0) = \int B(\theta,\phi) P_n(\theta - \theta_0, \phi - \phi_0)\, d\phi\, d\phi$$

$$S_0 = B * P_n$$

3. Radio observatory and DSN instrumentation fundamentals


500 (~250) m FAST telescope


305-m Arecibo telescope


100-m Effelsberg telescope


110-m Green Bank telescope

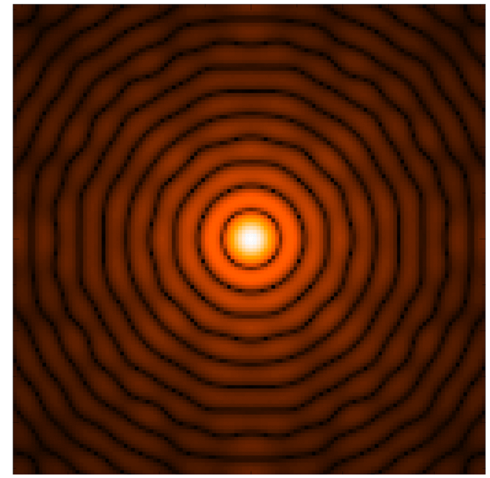
Beam pattern of a circular aperture

Aperture distribution

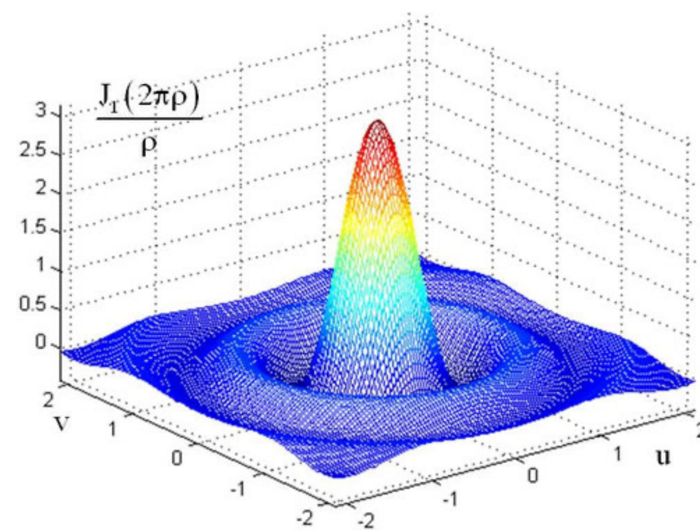
Disk

$\rightleftharpoons$

Field pattern



$J_1(x)$ Bessel function of first order



Antenna beam pattern

$f(u,v)$ = complex aperture field distribution
  u,v = aperture coordinates (in λ)

$F(l,m)$ = complex far-field voltage patt
  $l = \sin\theta\cos\phi$, $m = \sin\theta \sin\phi$

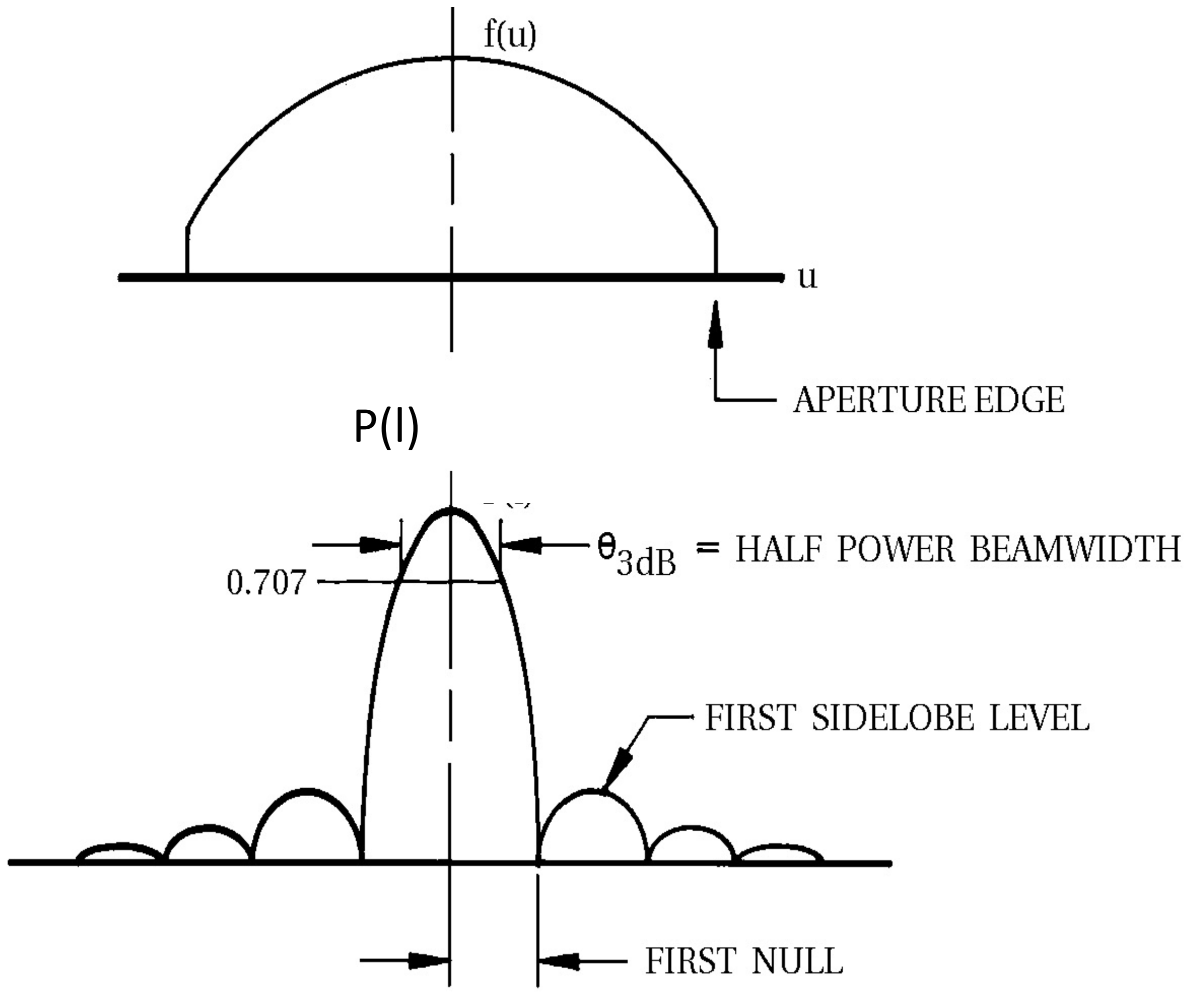
$F(l,m) = FT\{f(u,v)\}$

$P(l,m) = F(l,m)^2$
For small angles:

$P_n(\theta,\phi) = P(l,m)/P_{max}(l,m)$

FWHM ~ $1.2\lambda/D$ [rad]

For D=25m, λ = 3.6 cm:
FWHM = 6 arcmin

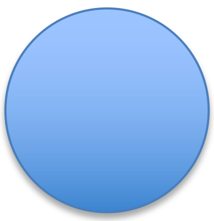


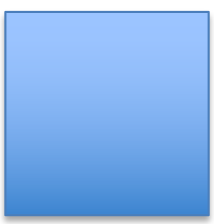
B. Hayward NRAO Synthesis Imag. school

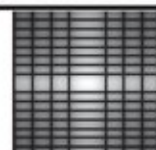
Circular and quadratic aperture

Aperture

Beam pattern
(Point spread function





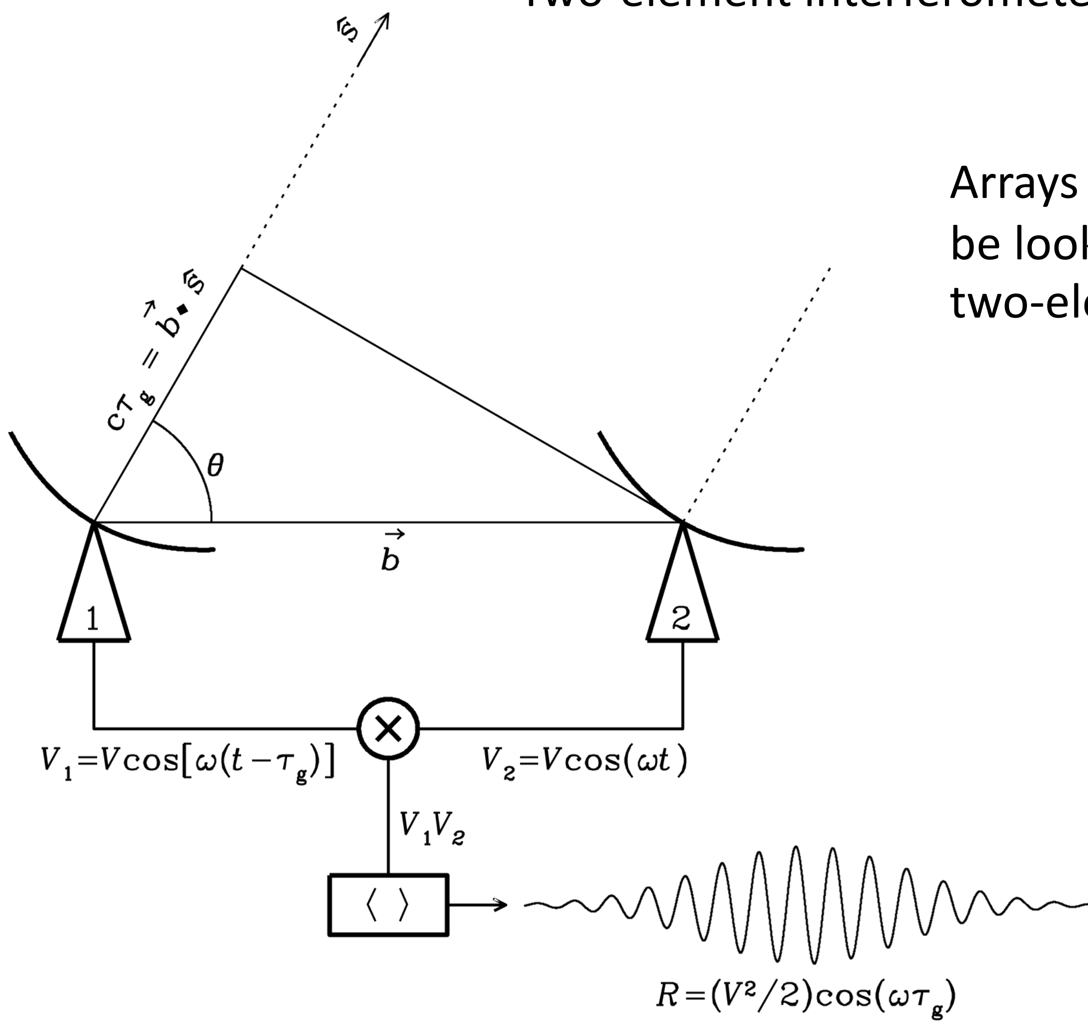
Aperture	PSF	PSF equation
round, diameter d_x		$\left[\frac{2J_1(x)}{x}\right]^2$
rectangle, sides $d_{x,y}$		$\left(\frac{\sin x}{x}\right)^2\left(\frac{\sin y}{y}\right)^2 = \lvert f(l,m)\rvert^2$

$x = \pi l \frac{L_x}{\lambda}$

$y = \pi m \frac{L_y}{\lambda}$

Interferometer

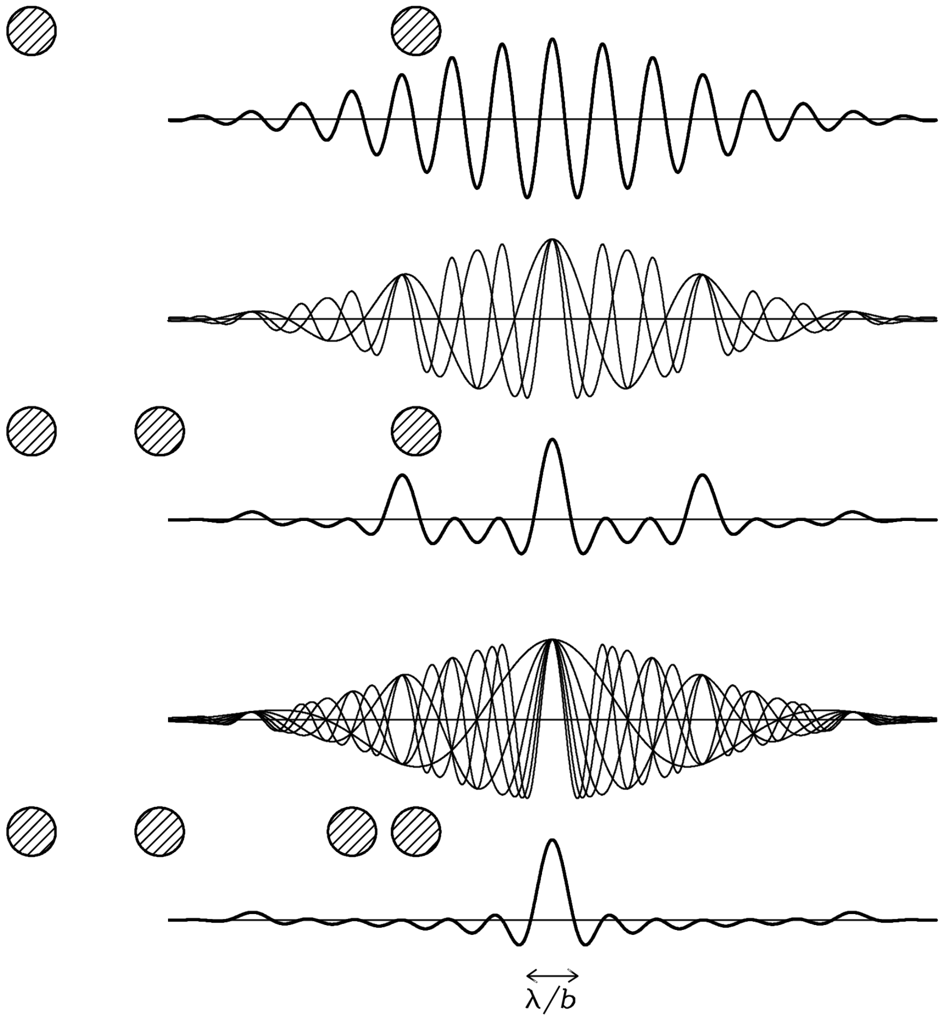
Two-element interferometer



Arrays of N antennas can be looked at as N(N-1)/s two-element interferometers

http://www.cv.nrao.edu/~sransom/web/Ch3.html

Radiation pattern of an array of two-element interferometers



http://www.cv.nrao.edu/~sransom/web/Ch3.html

Westerbork Synthesis radio Telescope
The Netherlands

Australian Telescope Compact Array

Very Large Array
USA

Very Long Baseline Array
USA

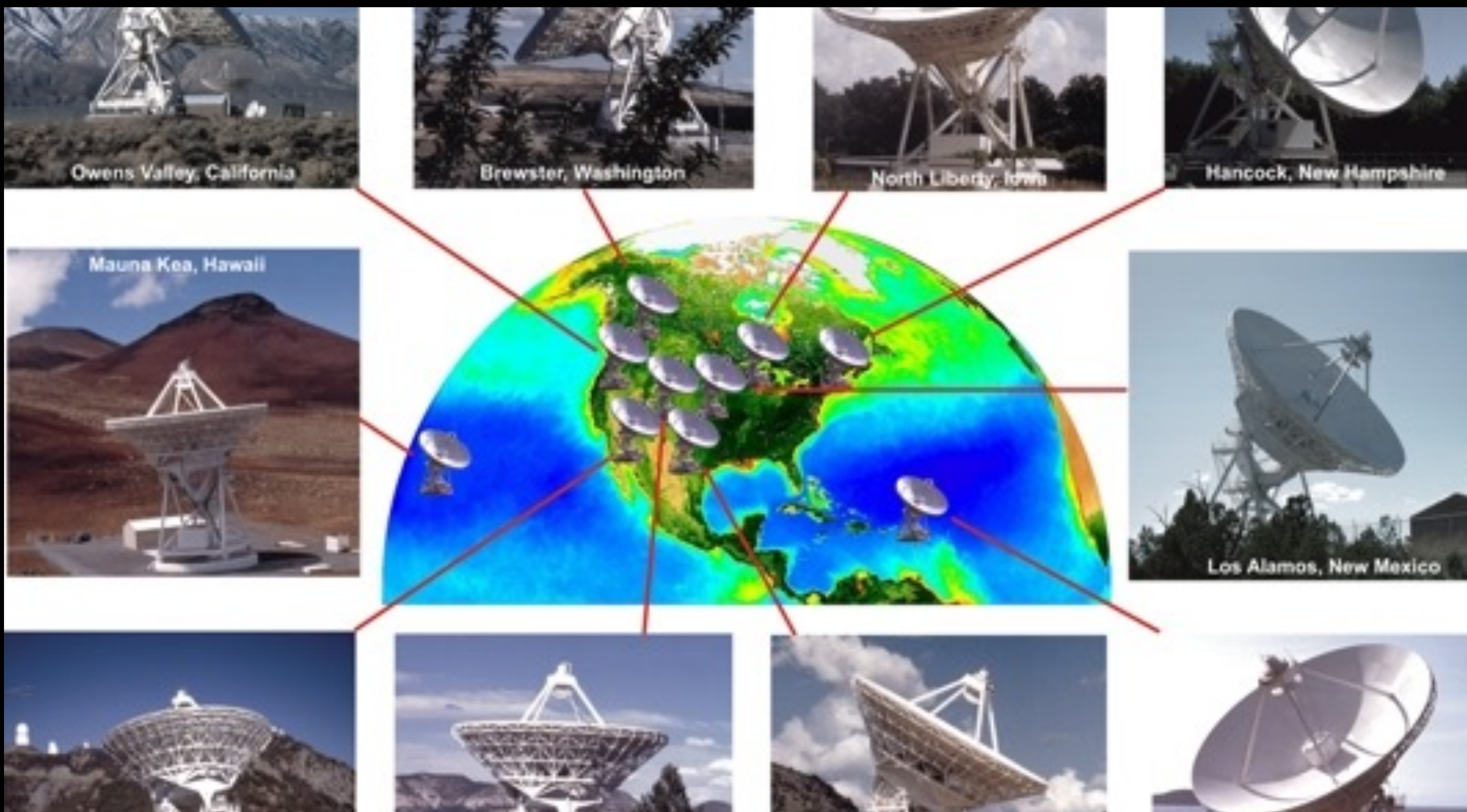
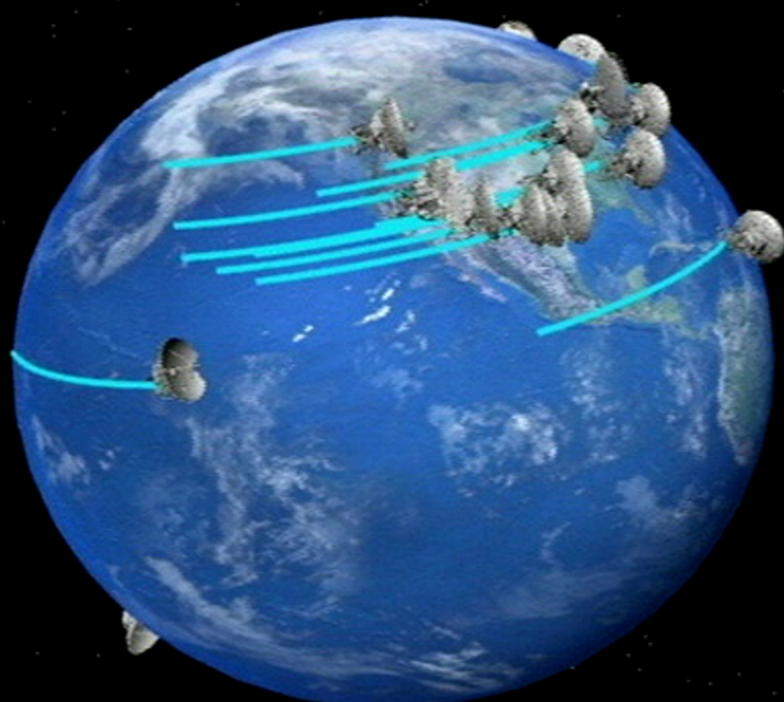
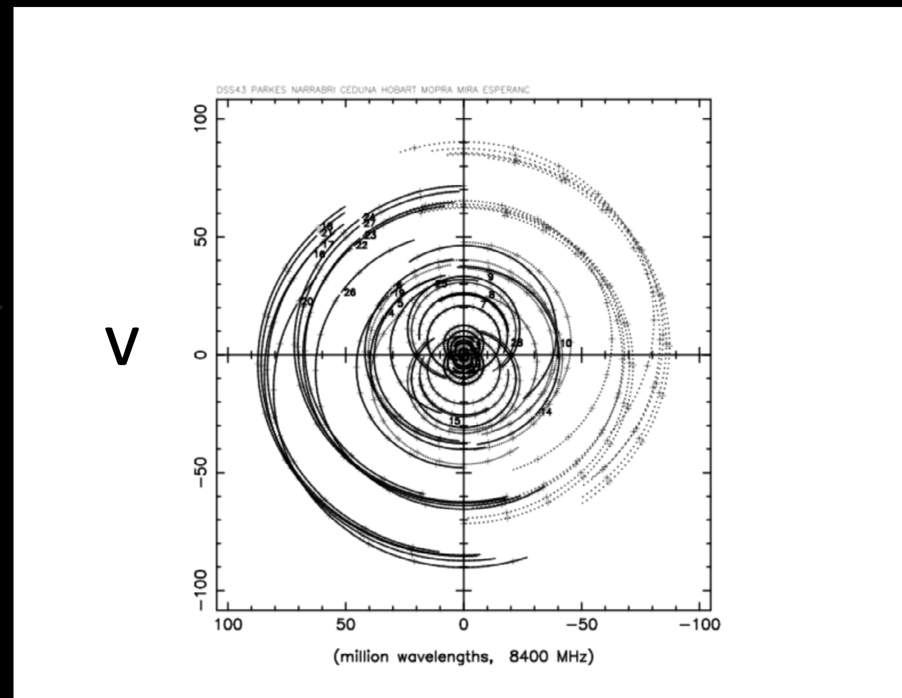


Image courtesy of NRAO/AUI and Earth image courtesy of the SeaWiFS Project NASA/GSFC and ORBIMAGE

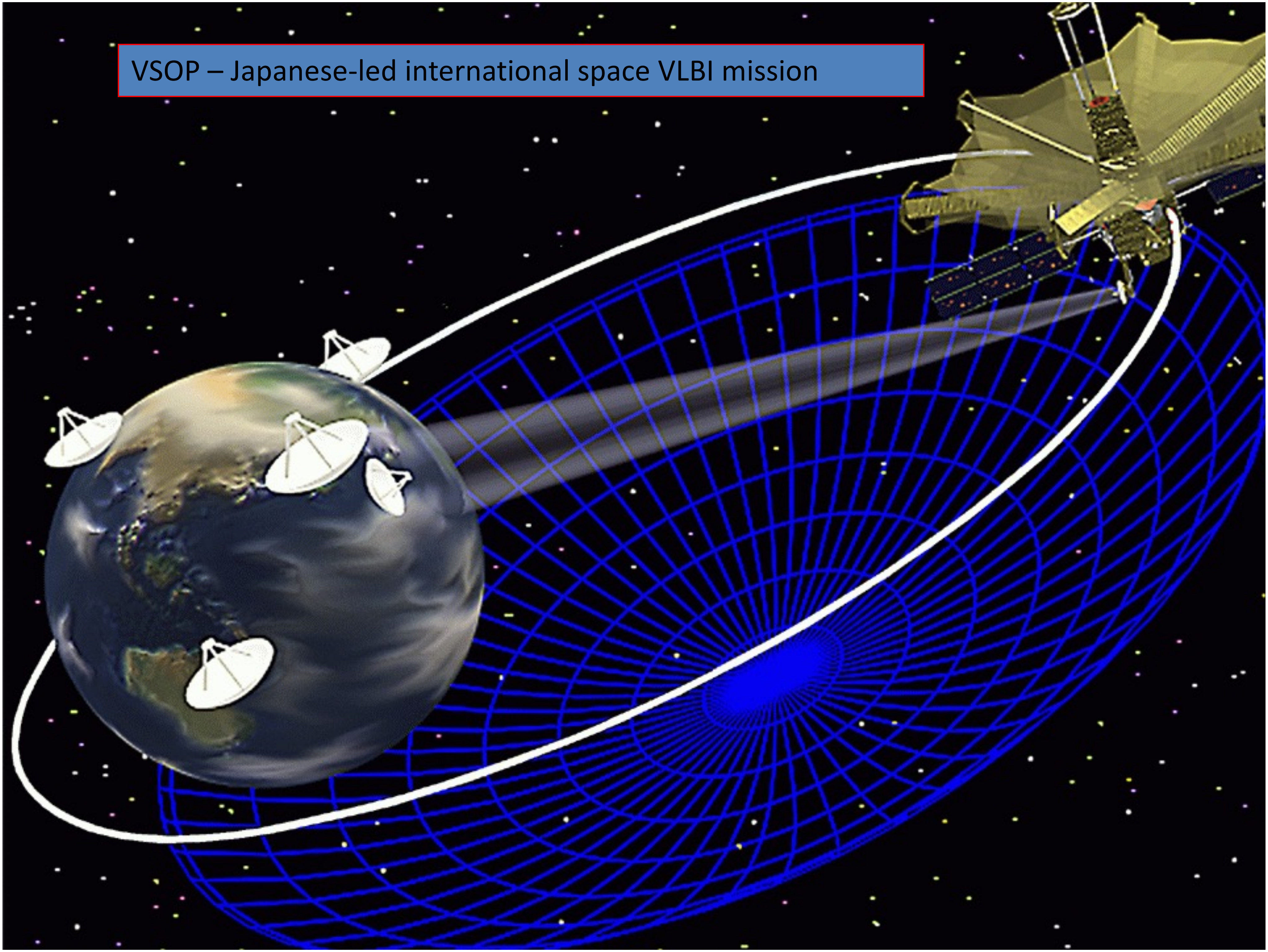
Very Long Baseline Interferometry
Global



V



Max baseline: 10,000 km
D=10,000 km
λ = 1.3 cm
FWHM = 0.3 mas


VSOP – Japanese-led international space VLBI mission

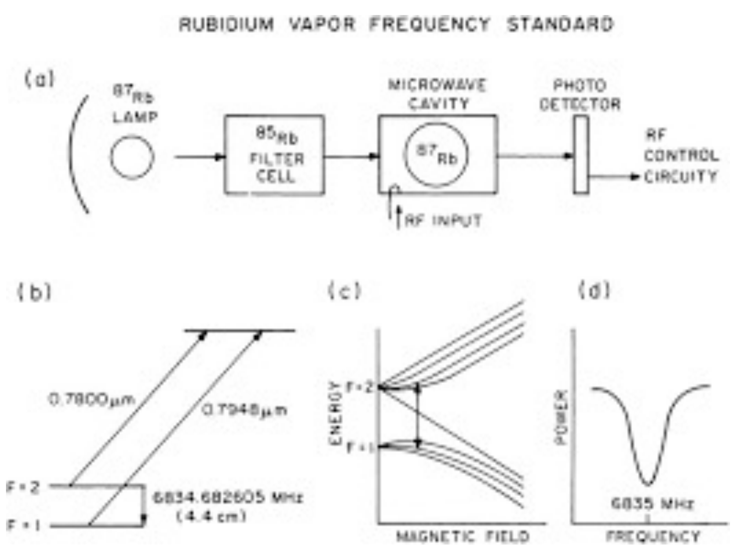

CHIME

Time and frequency standards

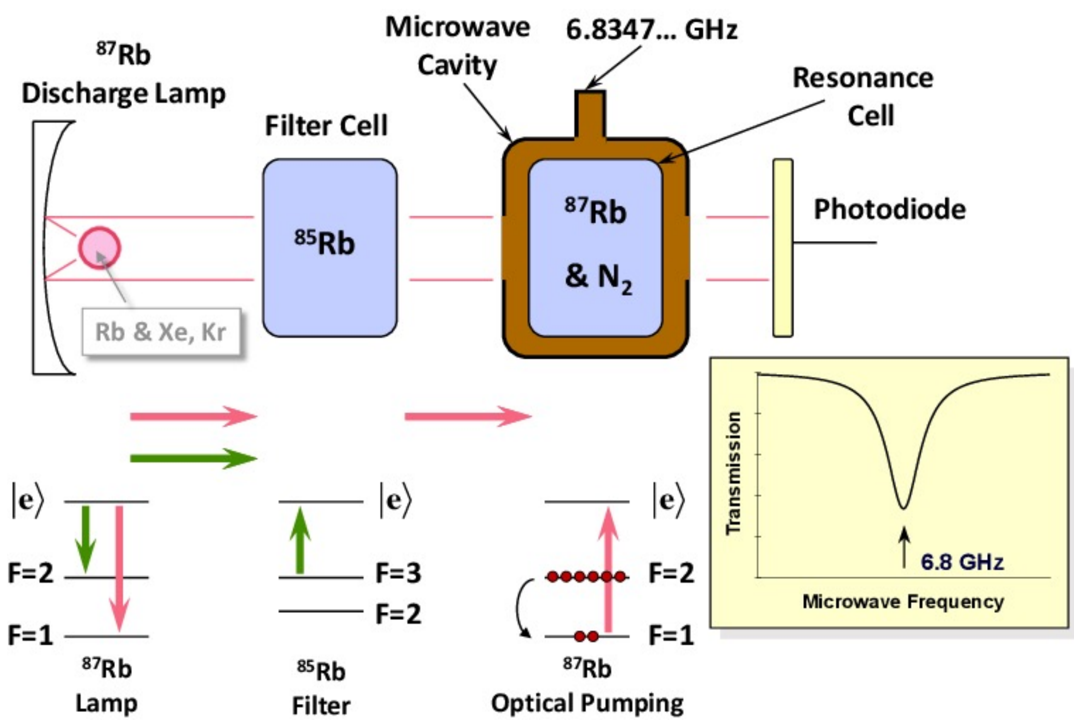
- Rubidium standards
- Cesium standards
- Hydrogen masers
- Optical clocks

Rubidium standard

- The rubidium atomic clock is the smallest, most widely used and cheapest of the atomic frequency standards. They are also the least accurate of the atomic frequency standards and often used as secondary standards.
- All commercial rubidium frequency standards operate by disciplining a crystal oscillator to the rubidium hyperfine transition of 6.8 GHz (6834682610.904 Hz). The intensity of light from a rubidium discharge lamp that reaches a photodetector through a resonance cell will drop by about 0.1% when the rubidium vapor in the resonance cell is exposed to microwavepower near the transition frequency. The crystal oscillator is stabilized to the rubidium transition by detecting the light dip while sweeping an RF synthesizer (referenced to the crystal) through the transition frequency. (Wikipedia).



Microsemi.com



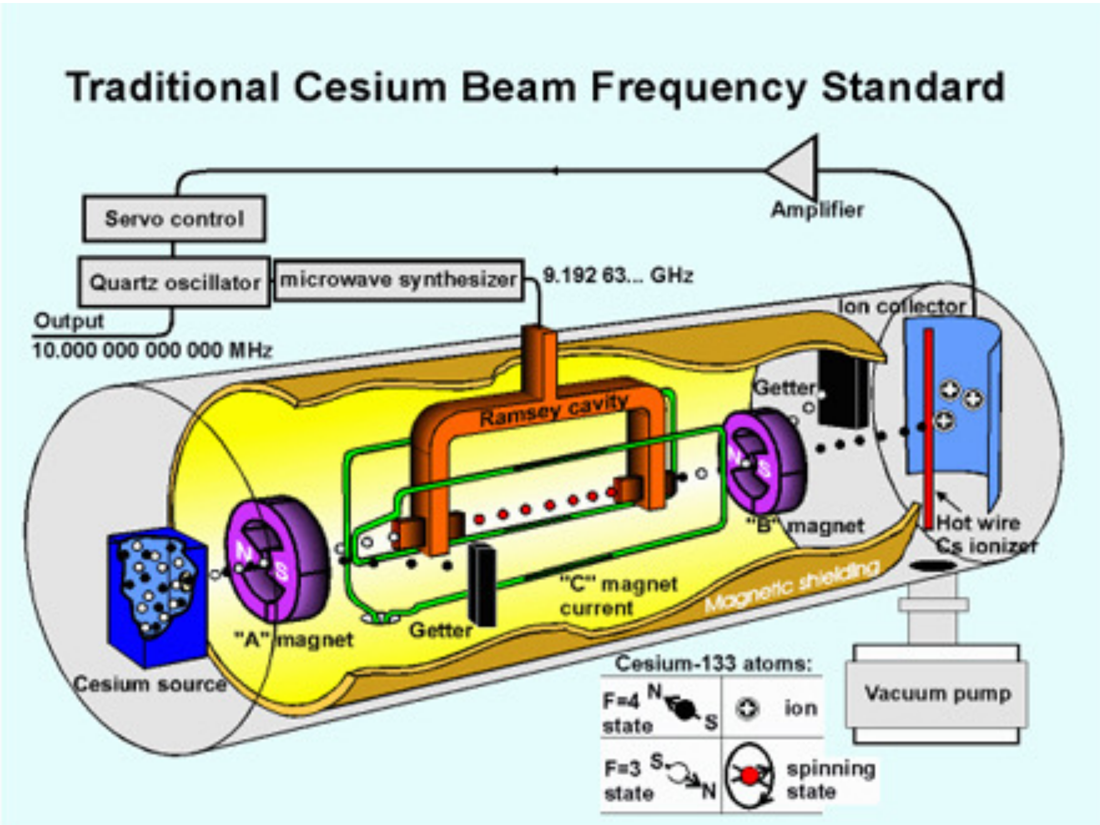
Semantic scholar

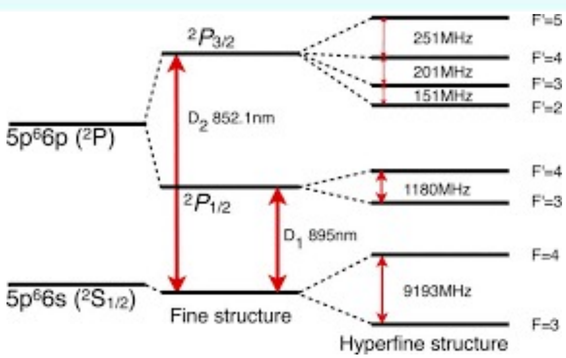
Caesium clock

National Research Council Canada

https://nrc.canada.ca/en/certifications-evaluations-standards/canadas-official-time/what-cesium-atomic-clock

Caesium clocks

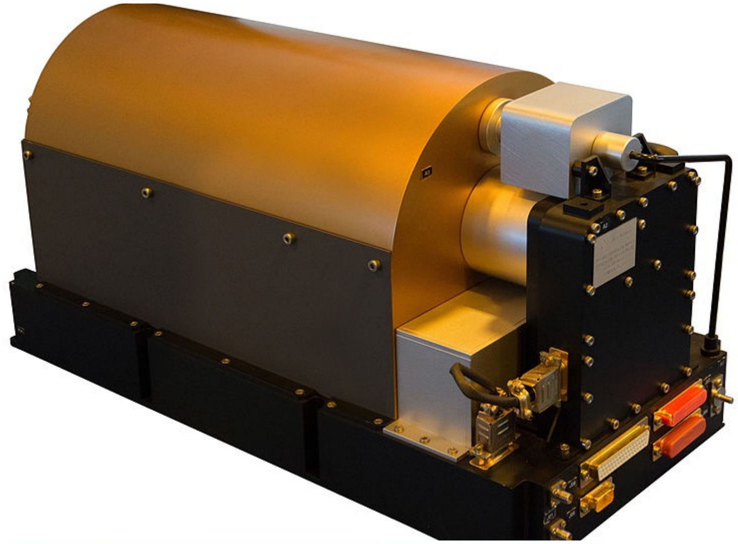




NRC Canada

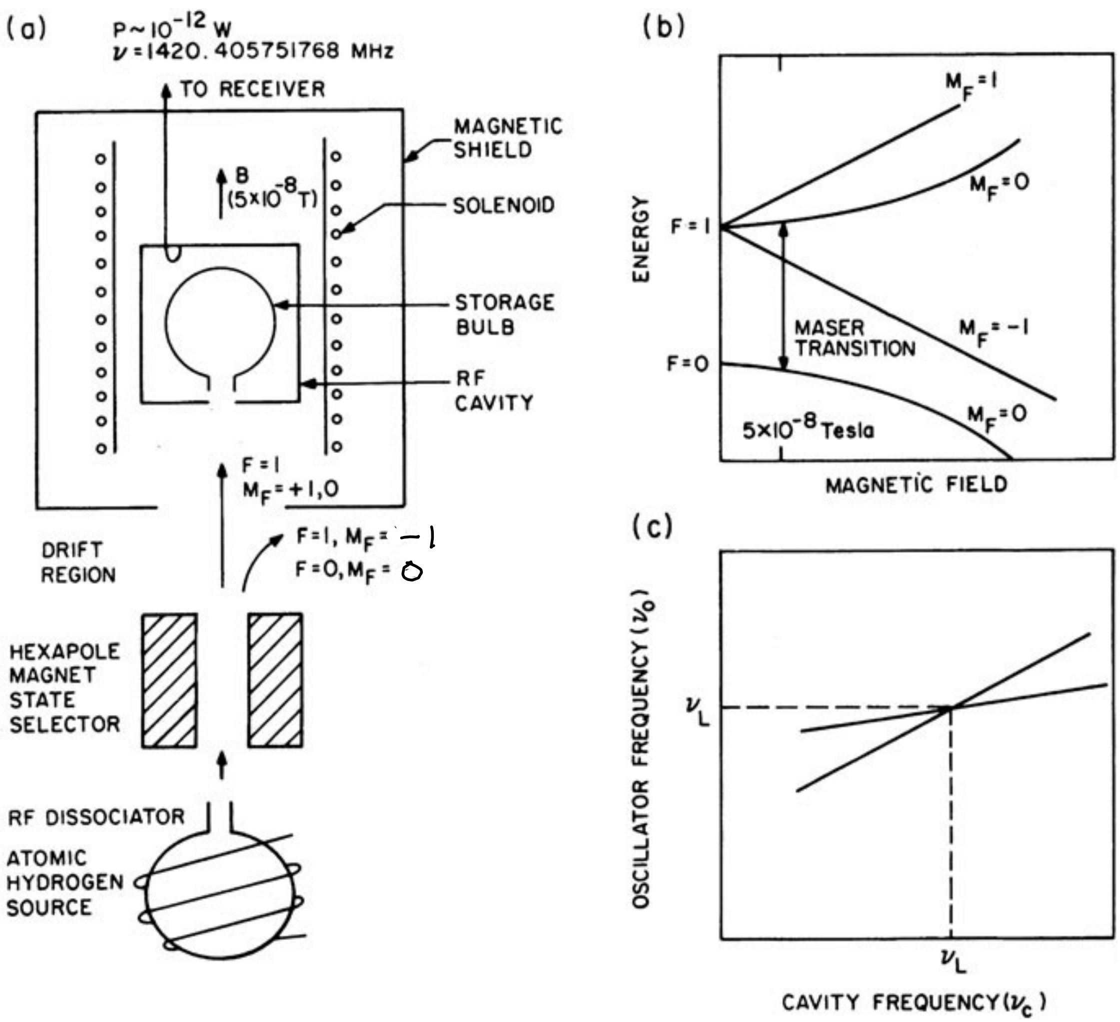
- Cs 133 is evaporated
- Magnet A splits path of Cs in F3 and F4, latter are absorbed
- Ramsey cavity is resonant at the transition frequency of
- 9192631770 Hz. Transitions occur.
- B magnet splits F3 and F4 Cs atoms
- F3 atoms are absorbed by hot wire, F4 atoms are collected and counted by electron multiplier.
- Quartz oscillator is fine tuned so that the Cs F4 atom numbers are maximized , measured by the electron multiplier output.
- This constitutes the measurement of the atom's resonance frequency.
- 9192631770 Hz is divided down to 10 MHz and used in a servo-loop to lock the quartz oscillator
- Every 10 million cycles 1 pulse is issued, exactly 1 s apart.

NASA Deep space network station Goldstone, CA



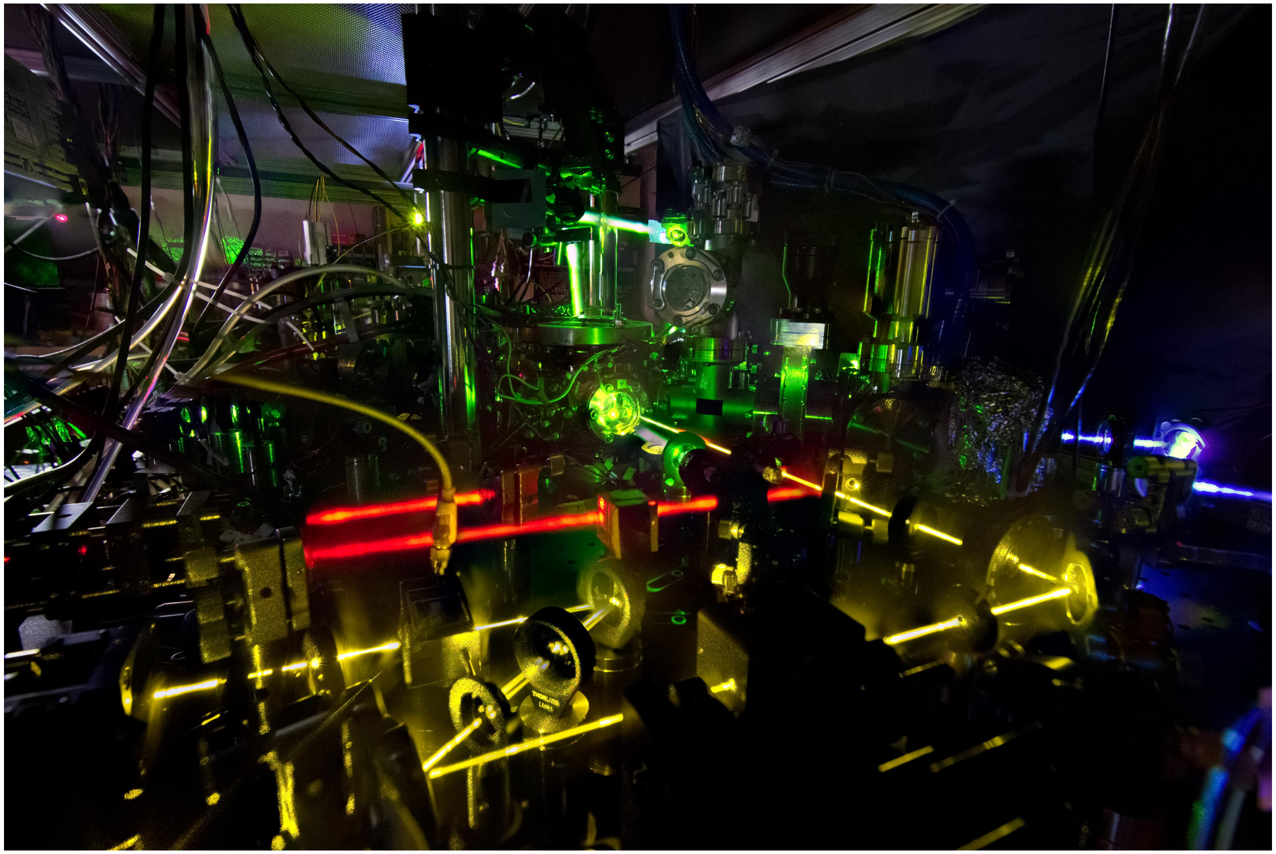
ESA Galileo space hydrogen maser

The hydrogen maser uses the hyperfine transition of the neutral hydrogen atom for generating pulses exactly 1 s apart. This transition is at a frequency of 1420.405751768 MHz



- H_2 gas is dissociated into H atoms
- Magnet splits path of atoms in different hyperfine energy levels.
- Upper level atoms get into storage bulb
- Solenoid creates homogeneous magnetic field to allow maser transitions to occur
- Cavity is tuned close to transition frequency
- Maser will oscillate
- Transition frequency is detected by RF probe
- Signal is used to phase-lock a crystal oscillator that also provides the cavity frequency in a servo loop
- The resonance frequency is divided down so that pulses are generated exactly 1 s apart.

Optical clock



- Optical clocks operate on the basis of transitions in the optical rather than transitions in the radio.
- Stability Proportional to frequency and inversely proportional to line width
- ~ 10^3 to 10^6 times higher accuracy expected

https://www.nist.gov/news-events/news/2016/11/nist-debuts-dual-atomic-clock-and-new-stability-record

Allan deviation

The Allan deviation is a measure of the frequency stability in frequency standards or clocks. It was first introduced by W. Allan.

The desired stable signal is v(t)=$v_0 \cos(2\pi\nu_0 t)$. However realistically because of instabilities, we get v(t)=$v_0 \cos(2\pi\nu_0 t+\theta(t))$. This is equivalent to a frequency change

$$\mathrm{d}\nu(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt}$$

Which leads to the fractional frequency change

$$y(t)=\frac{\mathrm{d}\nu(t)}{\nu_0}=\frac{1}{2\pi\nu_0}\frac{d\theta(t)}{dt}$$

and the average fractional frequency deviation

$$\bar{y}_k=\frac{1}{\tau}\int_{t_k}^{t_k+\tau} y(t)dt$$

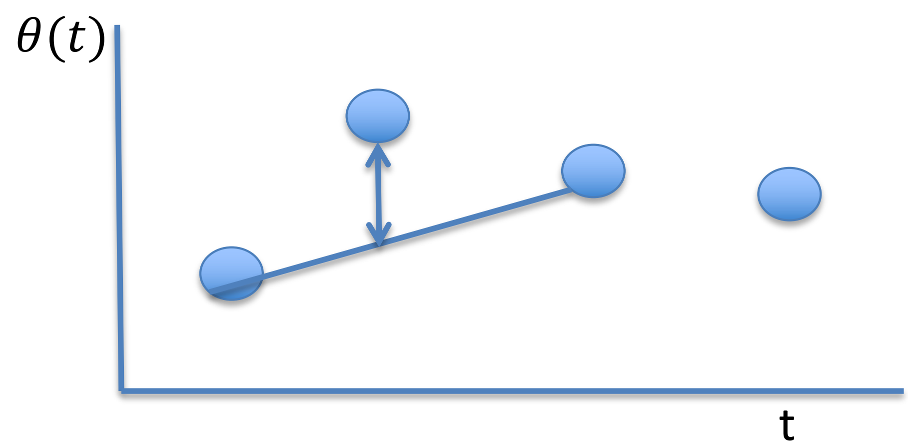
which becomes

$$\bar{y}_k=\frac{\theta(t_k+\tau)-\theta(t_k)}{2\pi\nu_0\tau}$$

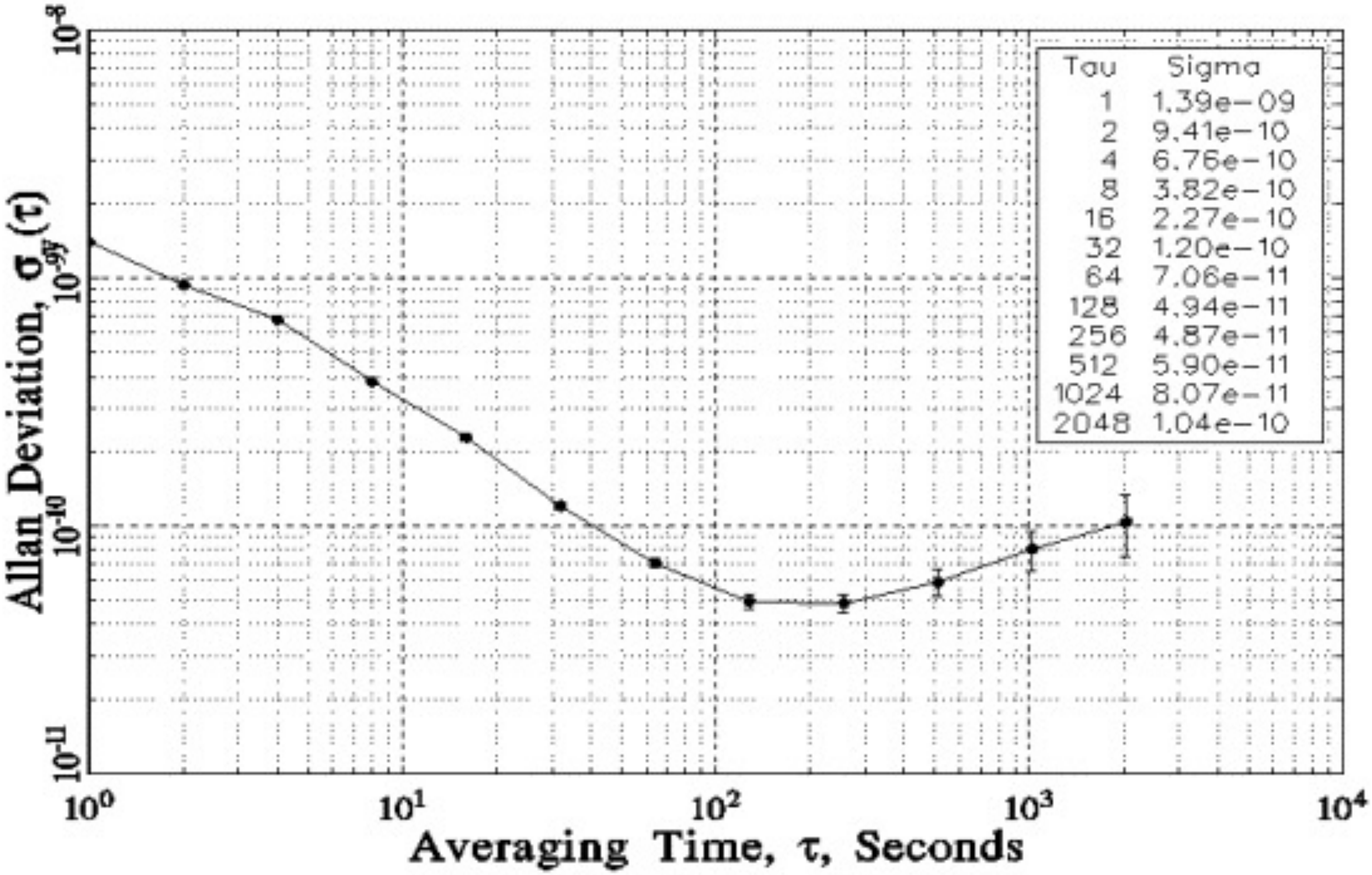
$$\sigma_y^2(\mathrm{t})=\frac{\langle(\bar{y}_{k+1}-\bar{y}_k)^2\rangle}{2}$$

Allan deviation and variance

$$\sigma_y(\tau)=\sqrt{\sigma_y^2(\tau)}$$

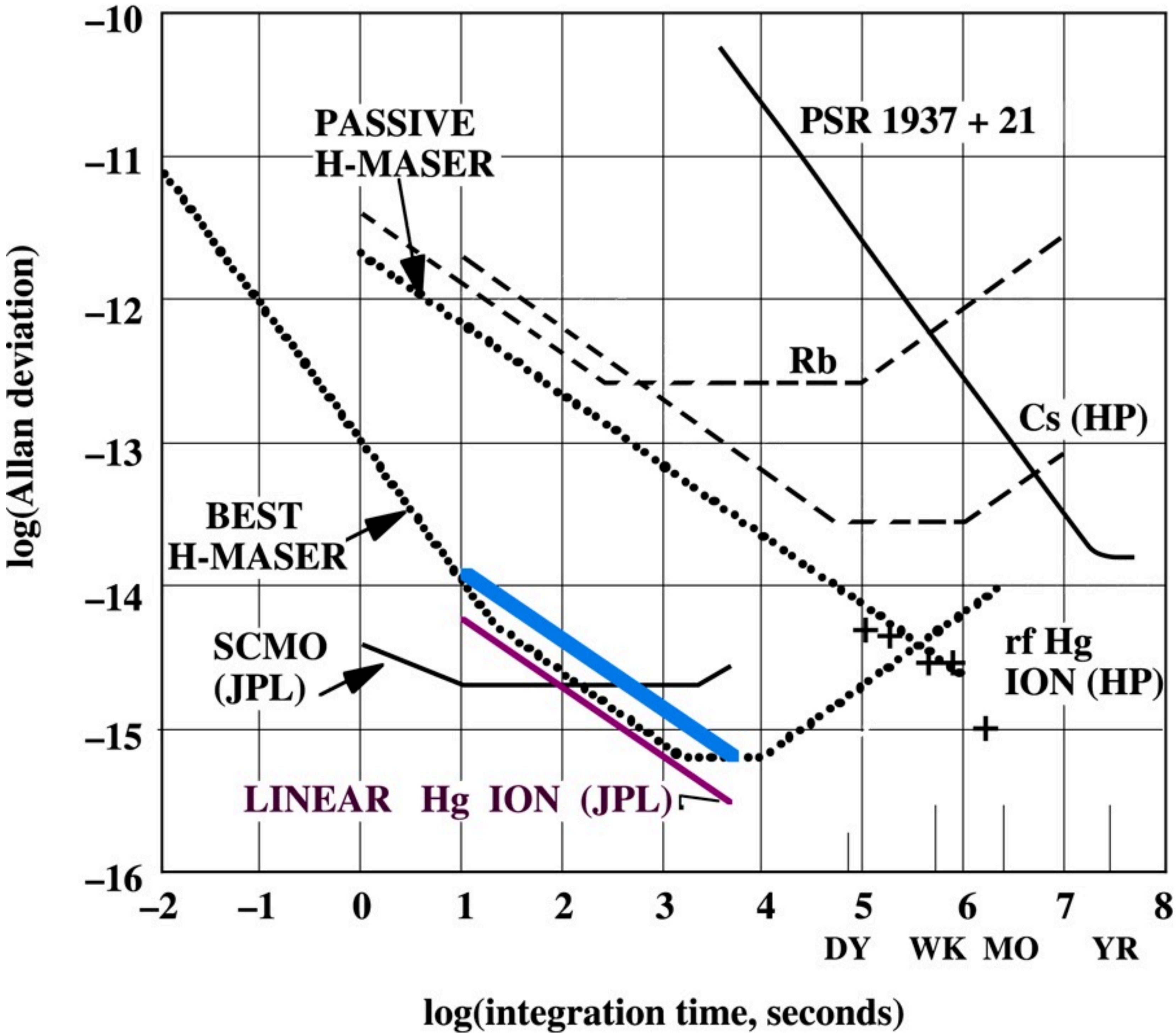


Frequency Stability



An Allan deviation of $3.3\text{x}10^{-10}$ for samples 1 s apart and averaged over 1s. ➔ Instability between 2 observations has a rms of $3.3\text{x}10^{-10}$. For a clock with 1 GHz output, The output frequency has an rms deviation of 0.33 Hz.

http://www.nist.gov/pml/div688/grp40/glossary.cfm

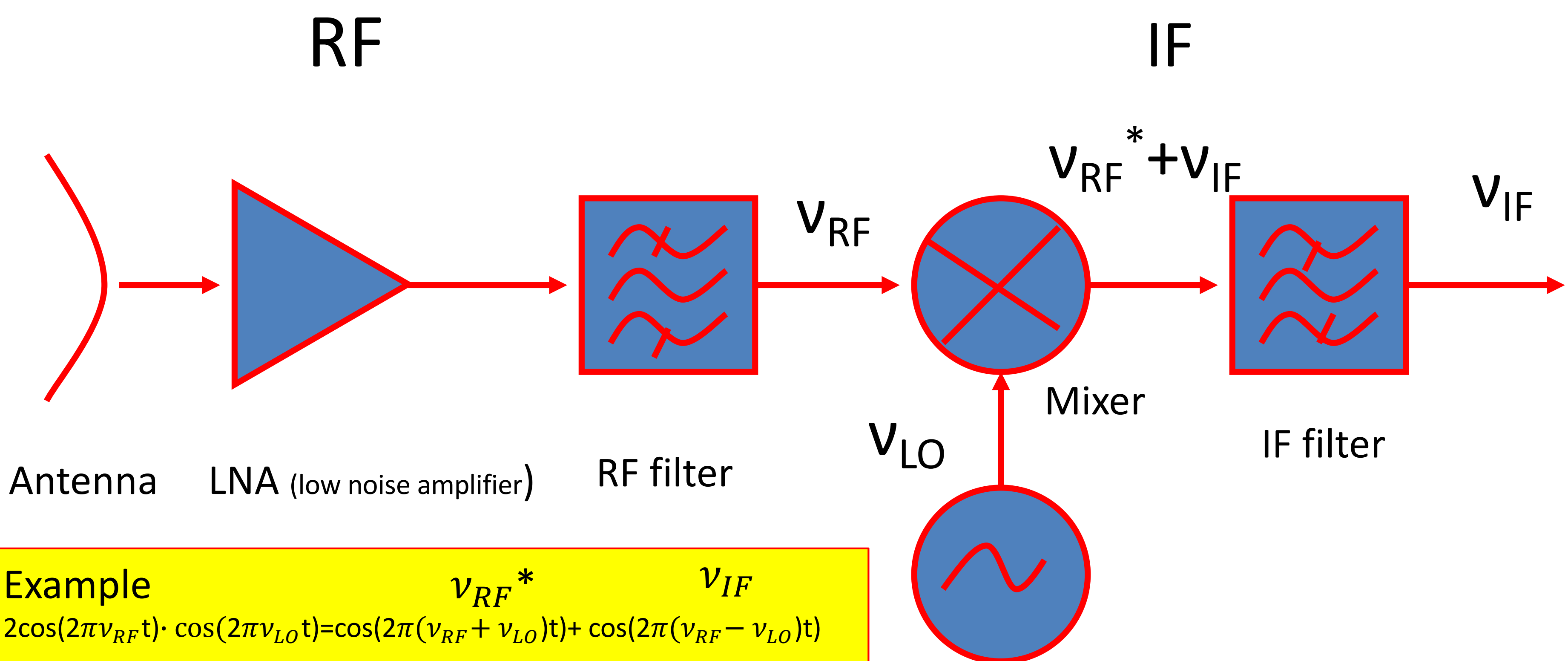


PSR 1937 + 21
PASSIVE
H-MASER
Rb
Cs (HP)
BEST
H-MASER
SCMO
(JPL)
rf Hg
ION (HP)
LINEAR Hg ION (JPL)
log(Allan deviation)
–10
–11
–12
–13
–14
–15
–16
–2
–1
0
1
2
3
4
5
6
7
8
DY
WK
MO
YR
log(integration time, seconds)

EMIS.de

Superheterodyne receivers

Superheterodyne receivers use a mixing and filtering scheme to convert a high frequency signal (RF: radio frequency) to an intermittent frequency (IF). It is widely used in radio science and techniques. The signal can then further mixed down to baseband to be sampled at the Nyquist frequency.



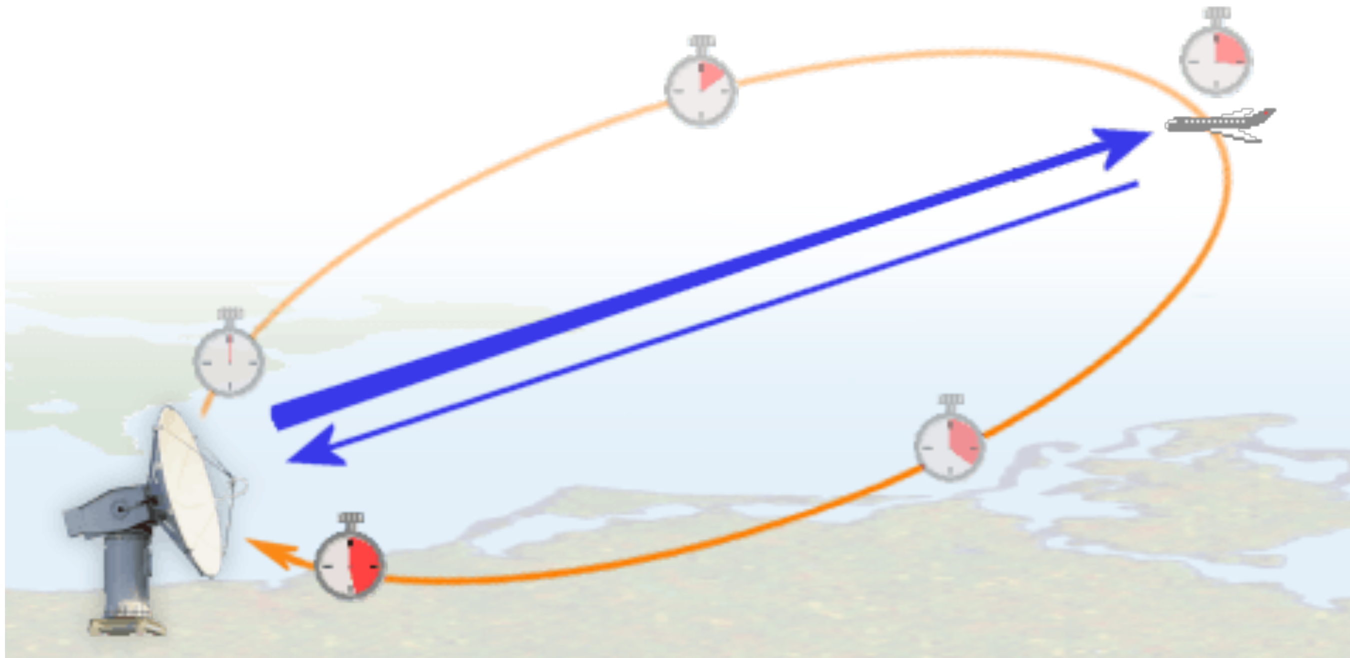
Example $\nu_{RF}{}^{*}$ ν_{IF}

$2\cos(2\pi\nu_{RF}t)\cdot\cos(2\pi\nu_{LO}t)=\cos(2\pi(\nu_{RF}+\nu_{LO})t)+\cos(2\pi(\nu_{RF}-\nu_{LO})t)$

ν_{RF}=5000 MHz ν_{LO}=4500 MHz $\nu_{RF}{}^{*}$=9500 MHz ν_{IF}=500 MHz

5. Radar fundamentals

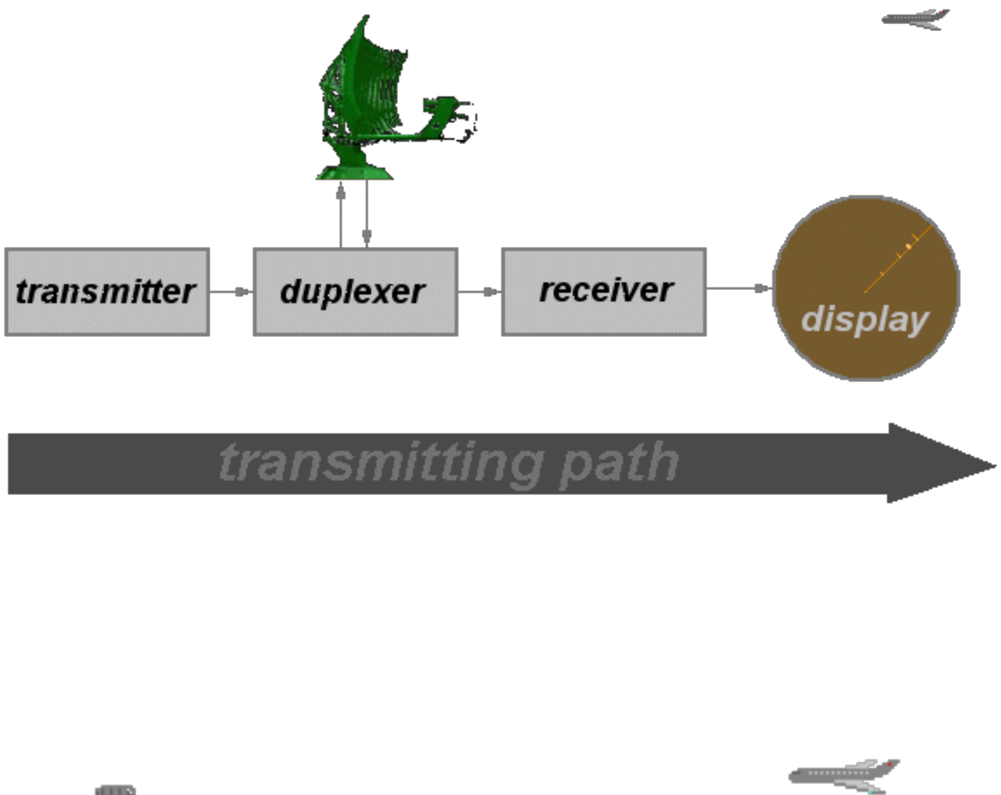
https://www.radartutorial.eu/01.basics/Physical%20fundamentals%20of%20the%20radar%20principle.en.html

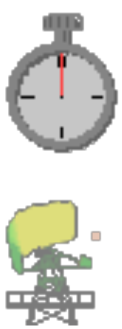


Azimuth
Elevation
Range
Range rate

Advantages over visual devices:
Operate:
day and night over long distances
in all weather conditions,
penetrate walls and layers of snow
Observe whole hemisphere
Automatic service over days possible

Basics





Transmitter: produces RF pulse of short duration with high power

Duplexer: electronic switch for transmit and receive operation with same antenna

Receiver amplifies RF signal and prepares it for display

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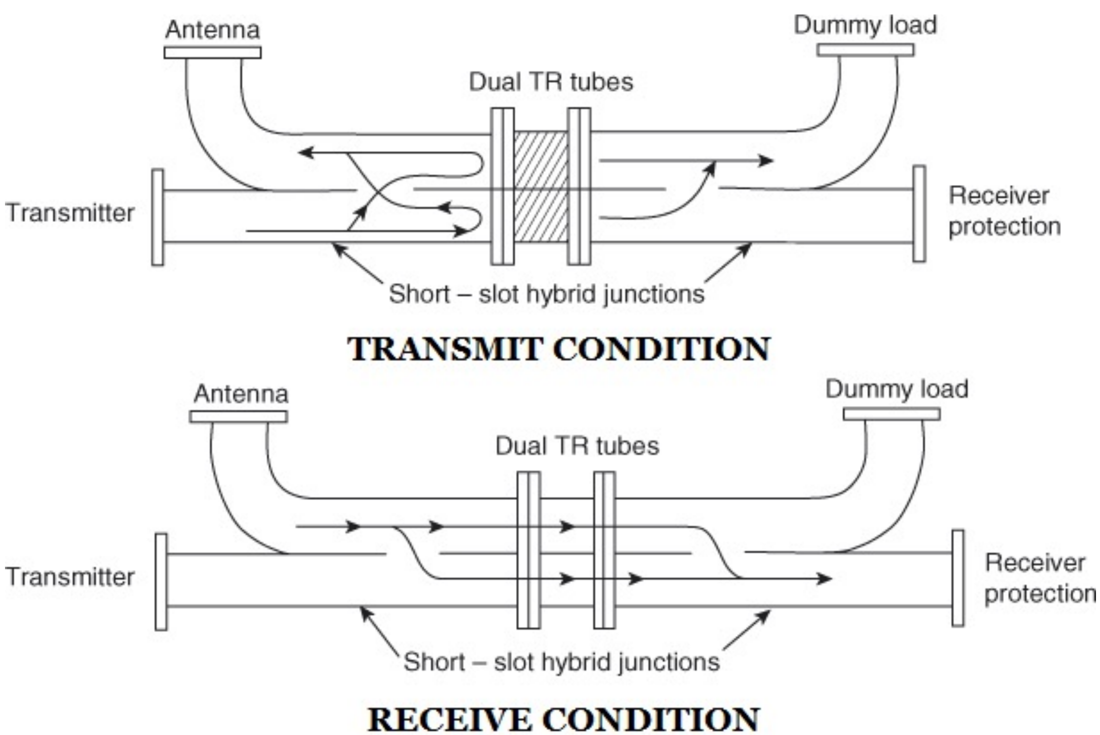
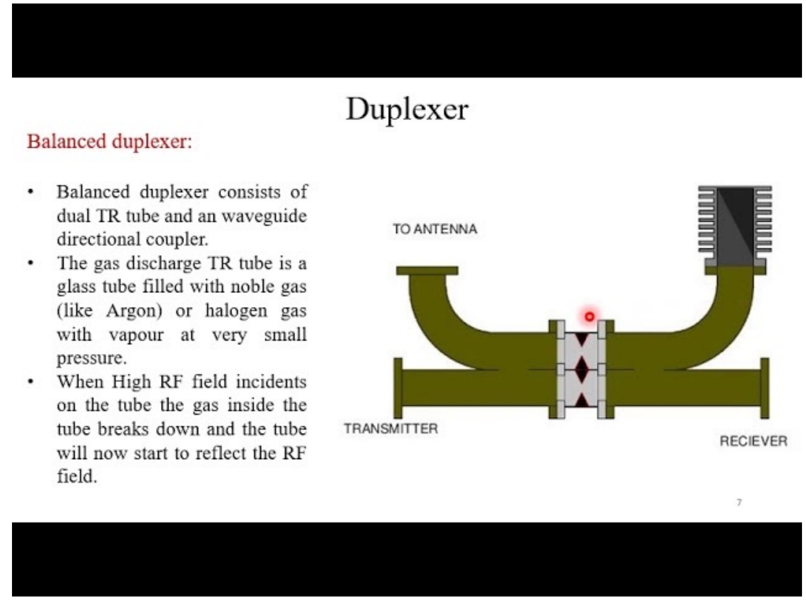
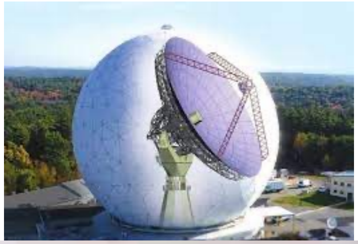
Duplexer

Electronic switch



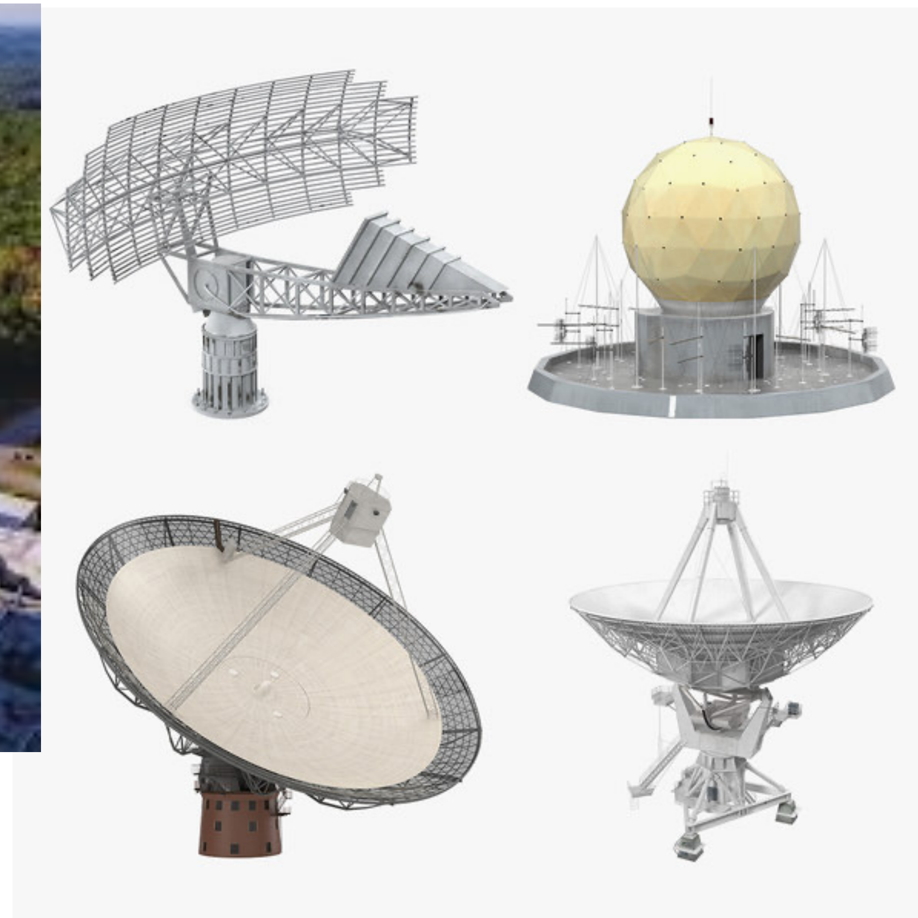


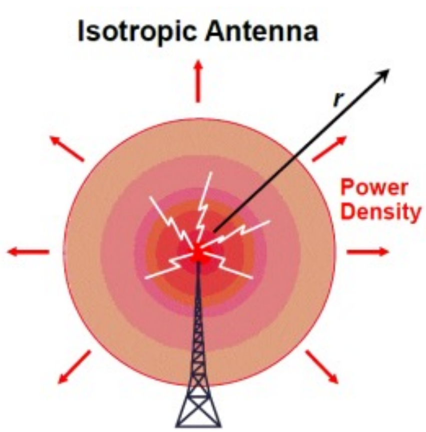
Engineeringdone.com

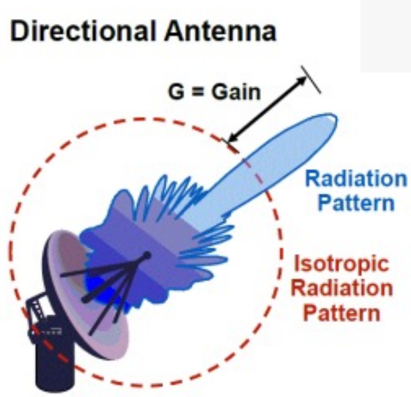


Antennas

Haystack, MIT antenna





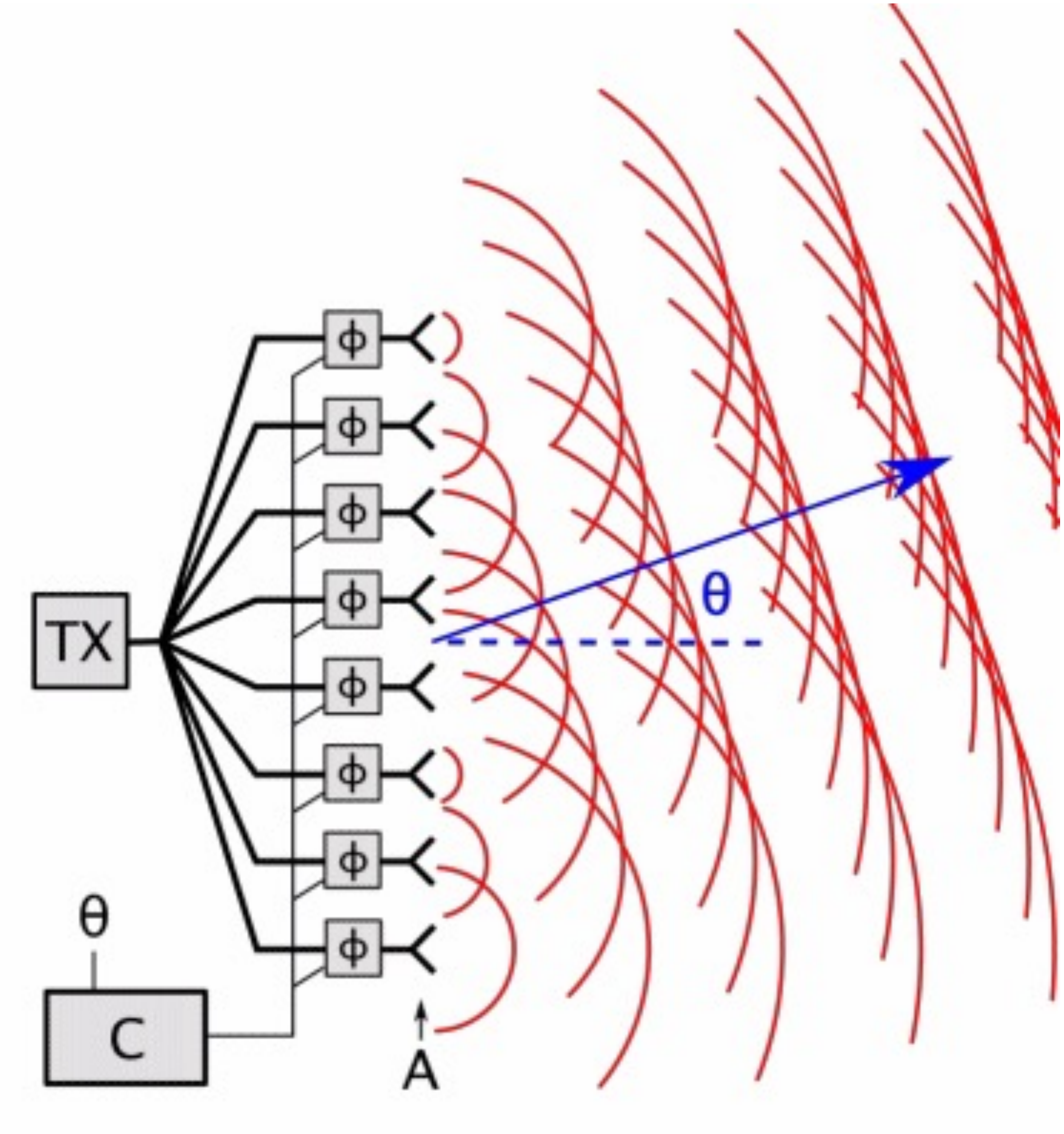


Phased arrays

Wikiwand

everythingrf.com

Military and Aerospace electronics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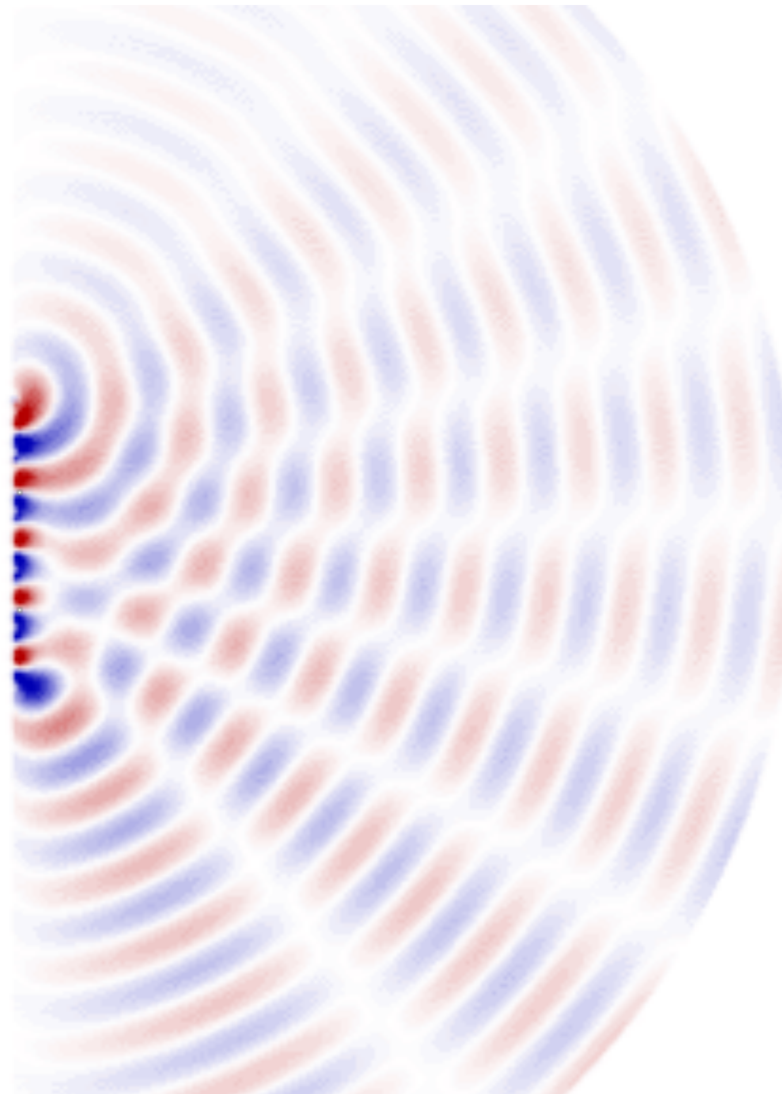


Synthetic aperture radar

Instead of an array of antennas, SAR samples data at the Nyquist frequency at one antenna at different positions, stores the data and then and synthesizes an image

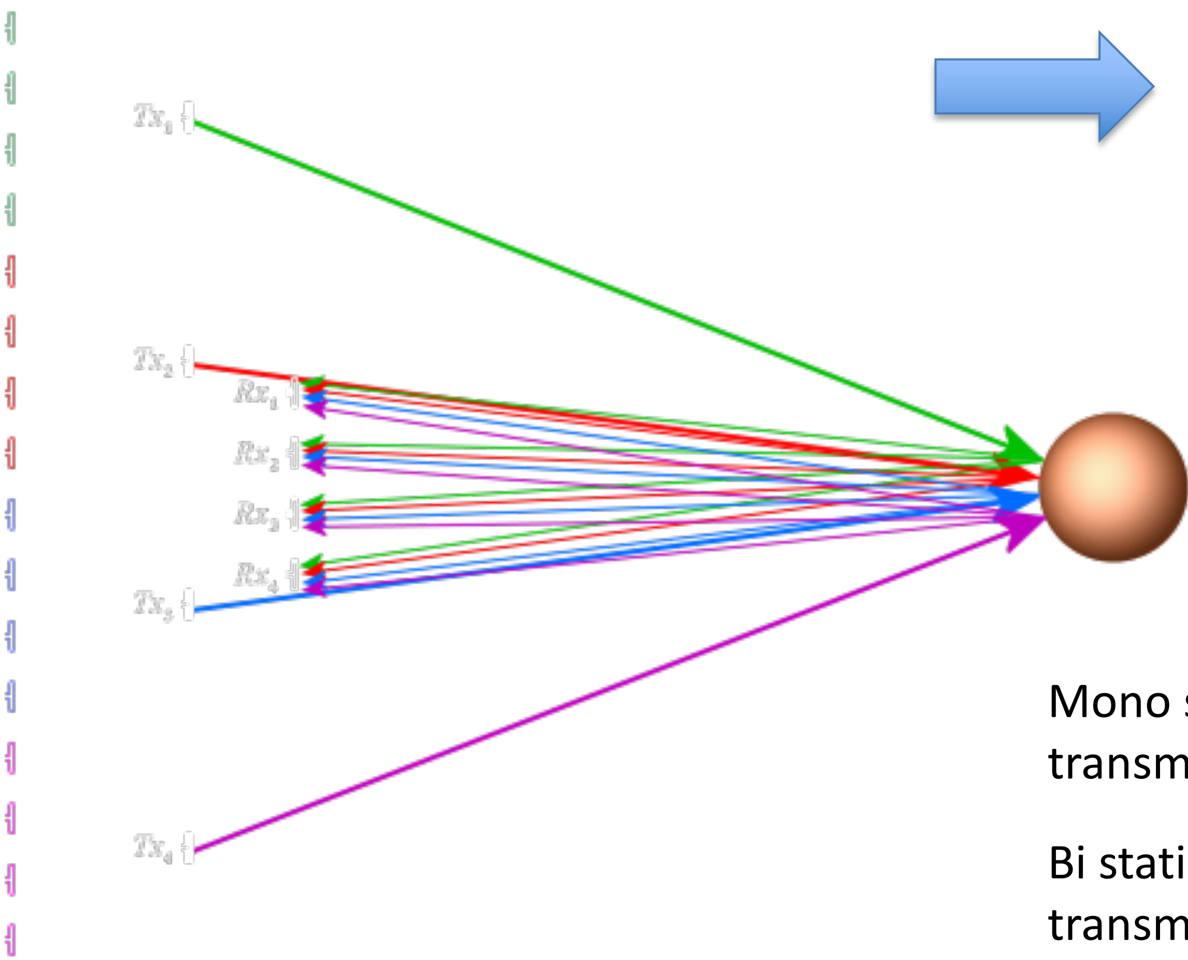
SAR

Image of ship

radartutorial.eu

Multiple input multiple output (MIMO) radar systems

With N transmitters and K receivers an array of antennas with NxK elements can be synthesized



Enlarged size of aperture,
better aperture distribution,
smaller side lobes,
less interference

Mono statis MIMO:
transmit and receive antennas are nearby

Bi static MIMO:
transmit and receive antennas are far apart