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Radio astronomy at low frequencies

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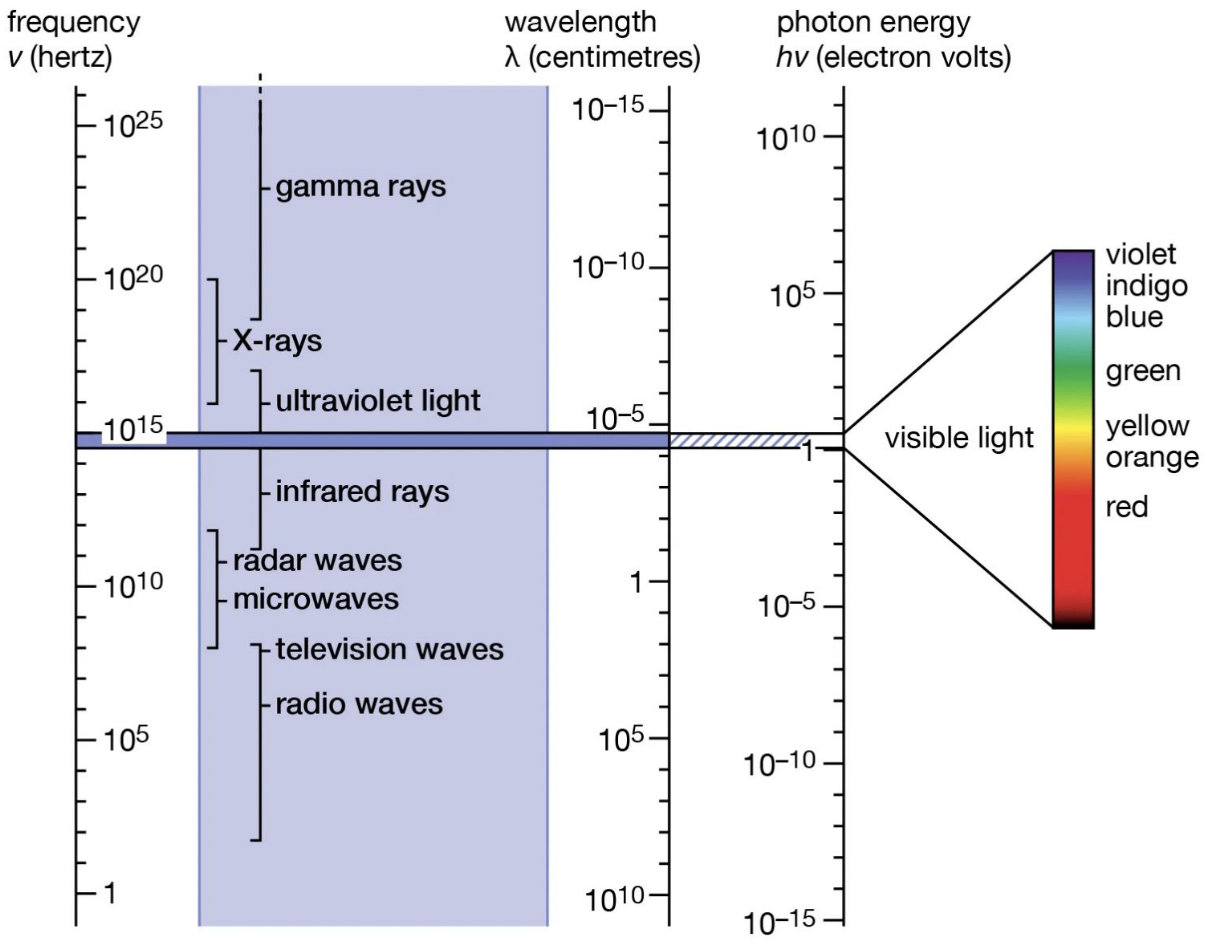
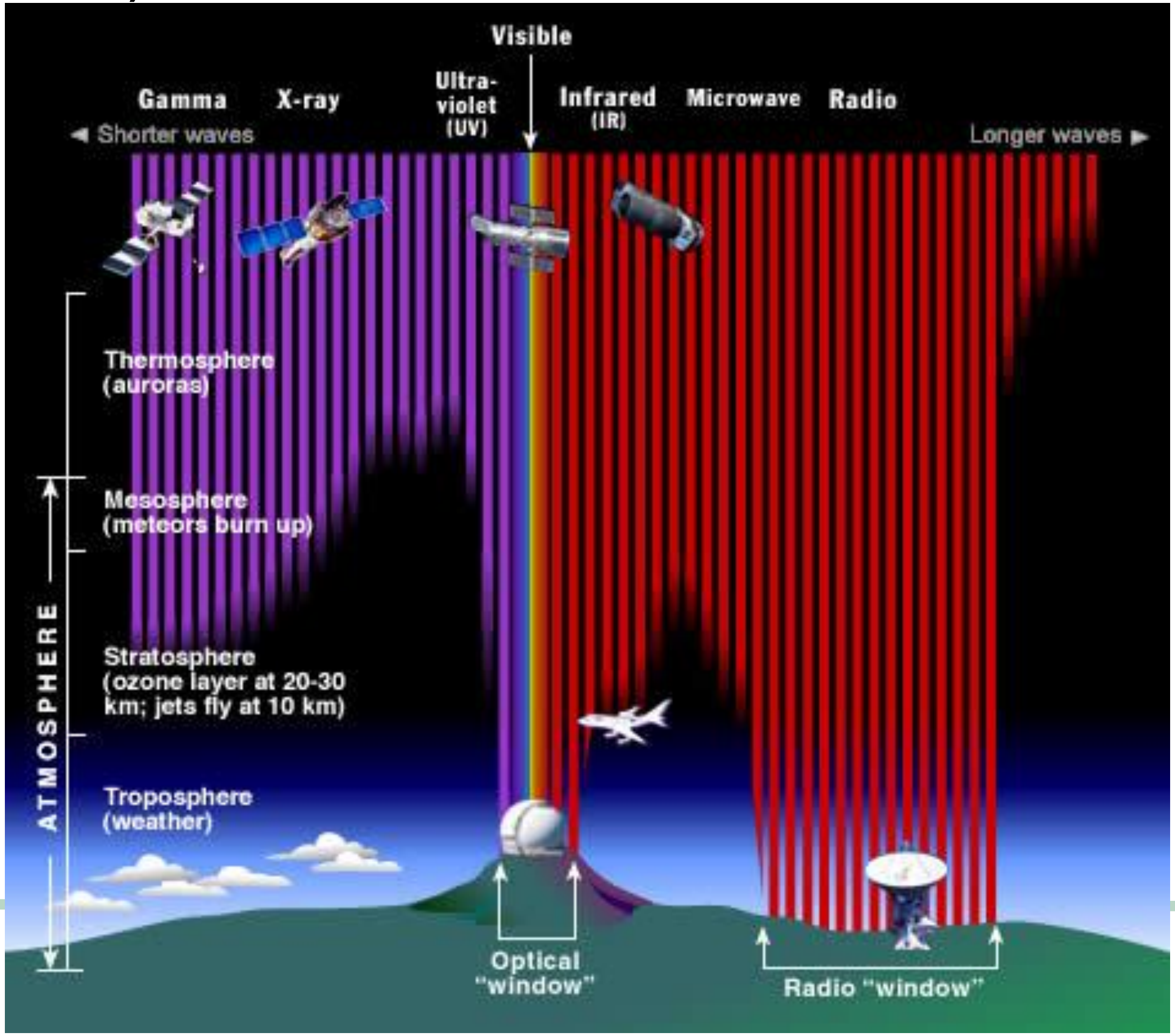
Low-frequency radio astronomy: 300 MHz (1 m) - kHz (300 km)

(Credit: STScI/JHU/NASA)





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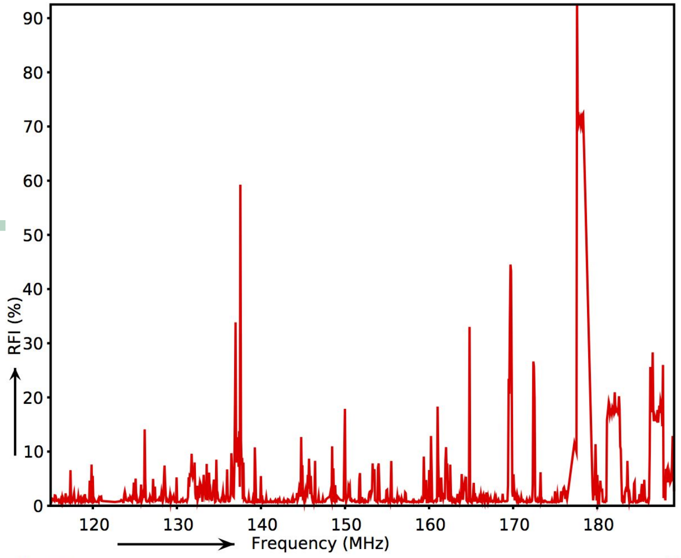
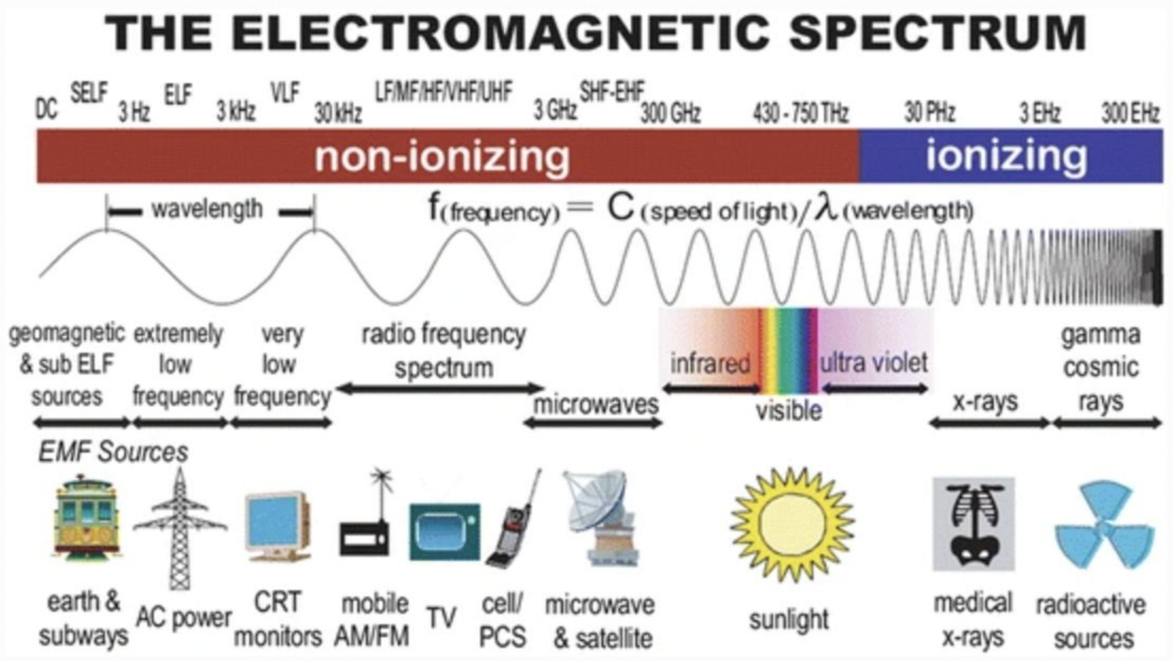
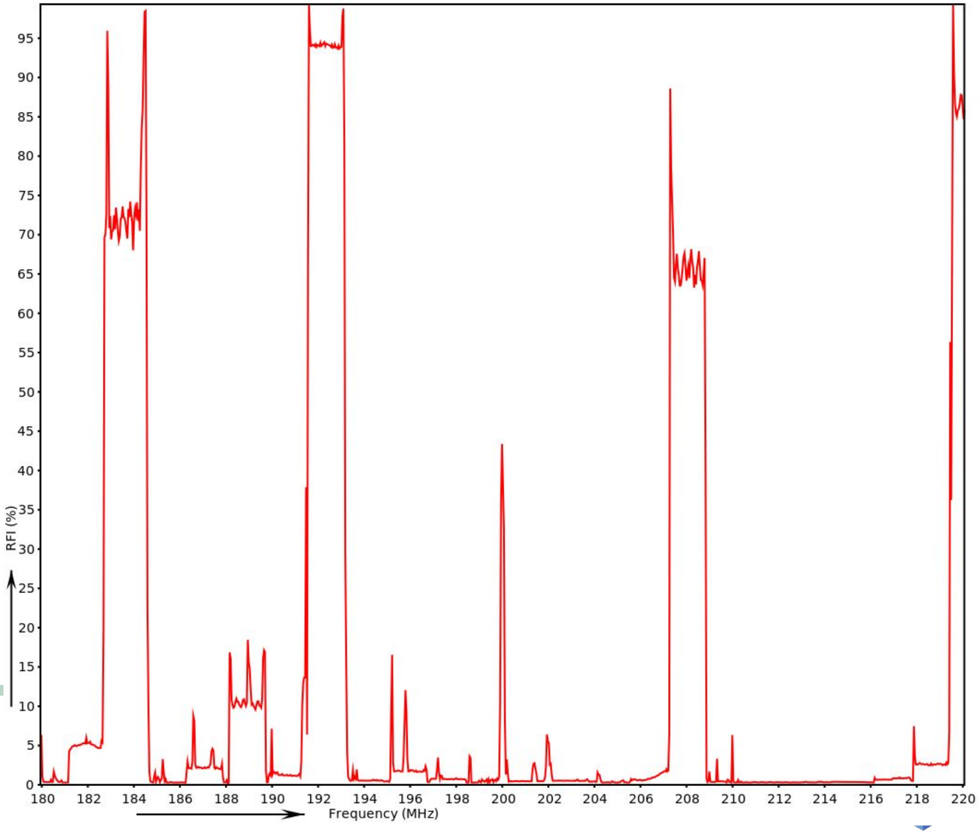


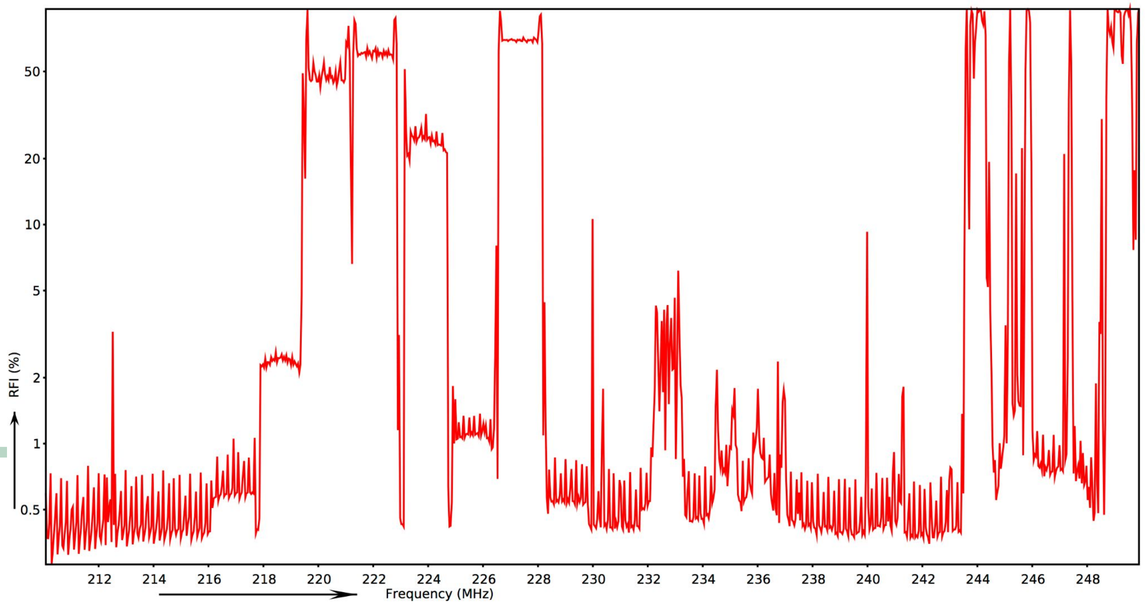
Radio frequency interference (RFI)



(from VitaTech Engineering, LLC)

https://link.springer.com/chapter/10.1007/978-3-319-24892-9_8





https://science.astron.nl/telescopes/lofar/lofar-system-overview/technical-specification/frequency-subband-selection-and-rfi/

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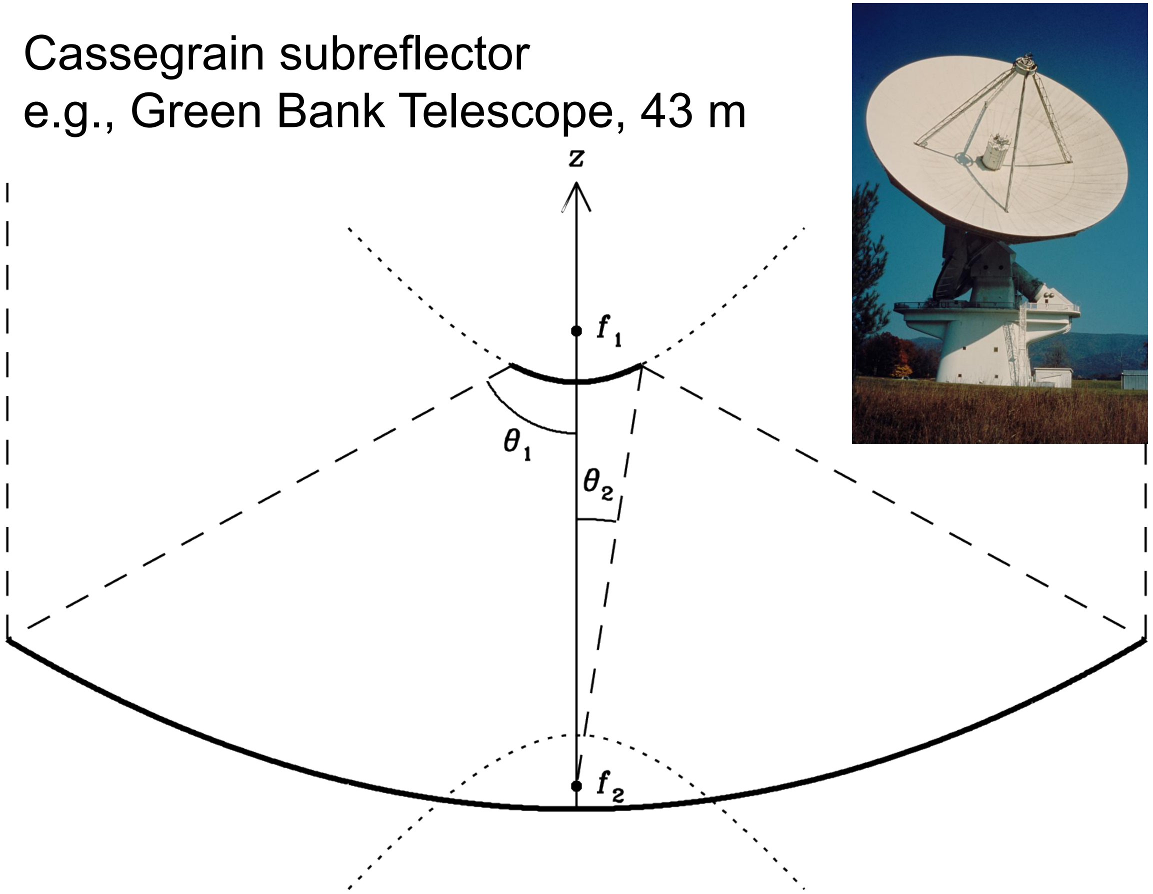
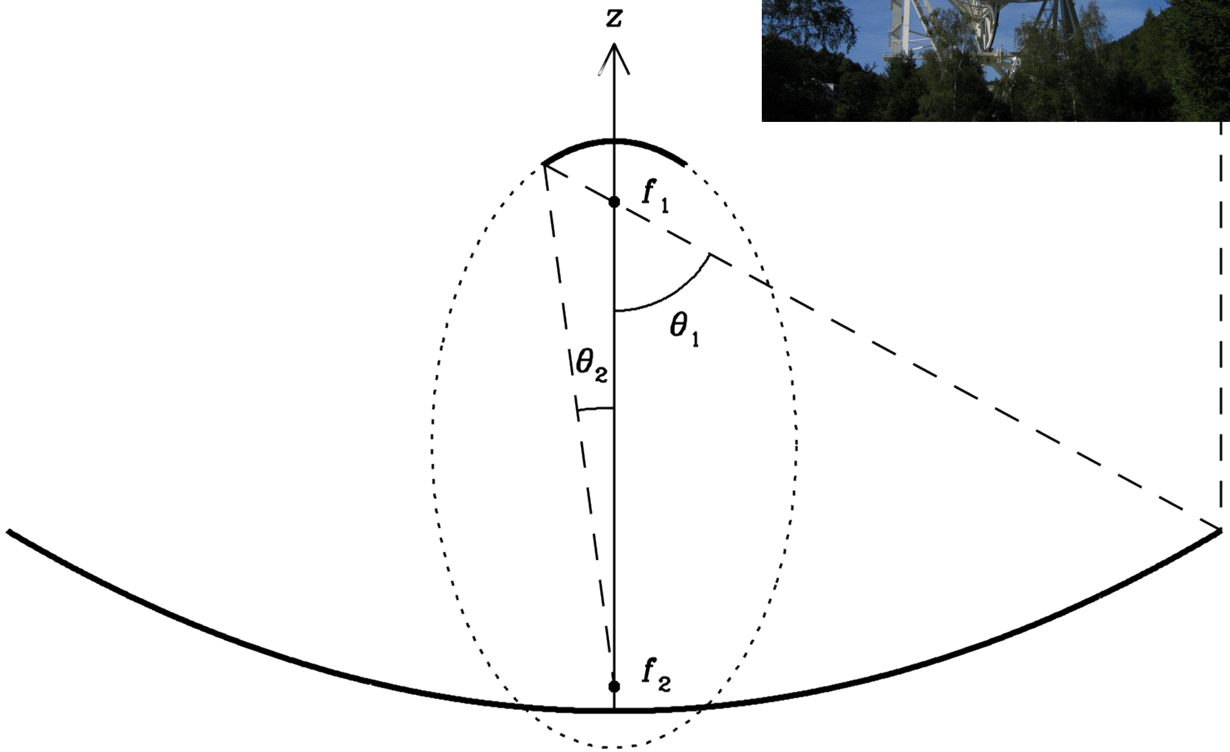
Antenna: parabolic main dish (practical for λ < 1 m; f > 300 MHz)

Cassegrain subreflector
e.g., Green Bank Telescope, 43 m



Gregorian subreflector
e.g. Effelsberg, 100 m



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

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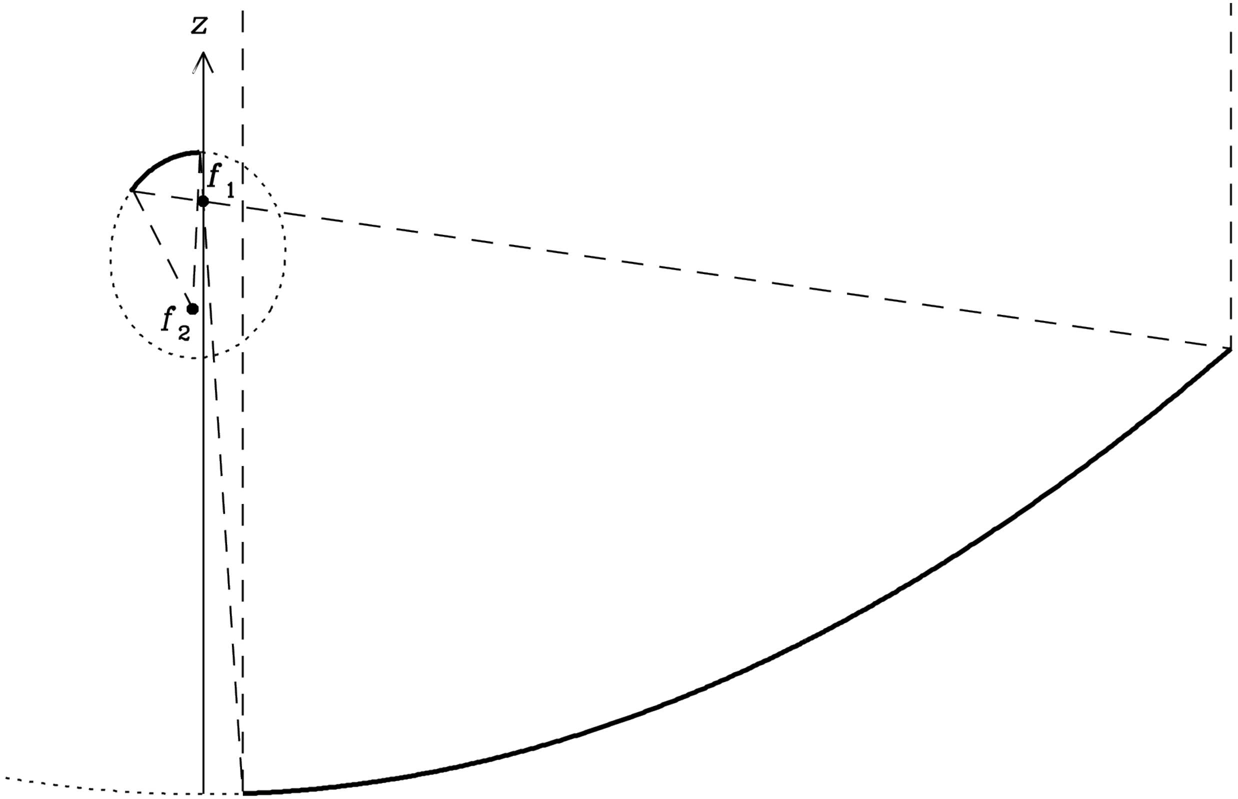
Antenna: parabolic main dish (practical for λ < 1 m; f > 300 MHz)

Offset Gregorian subreflector



100 m Robert C. Byrd Green Bank Telescope
https://greenbankobservatory.org/science/telescopes/gbt/

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

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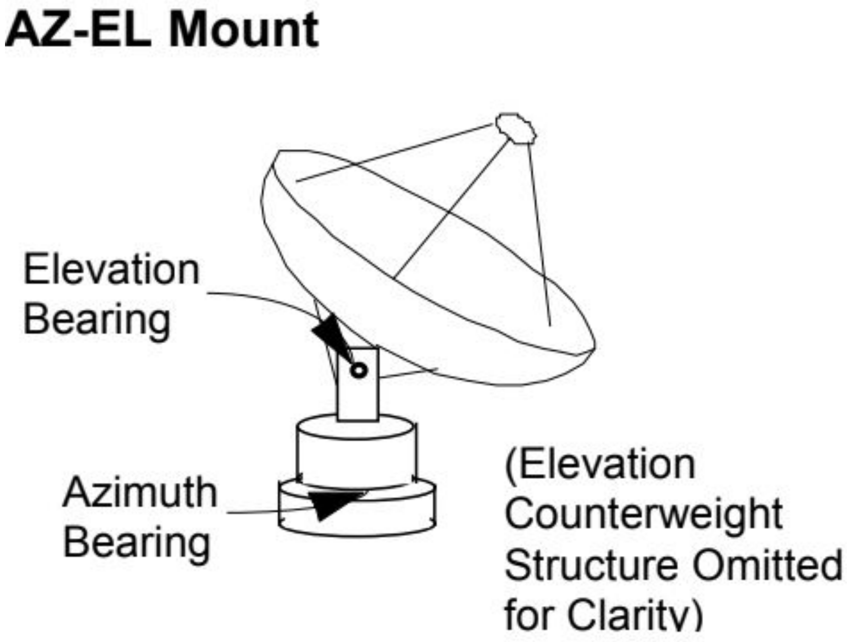
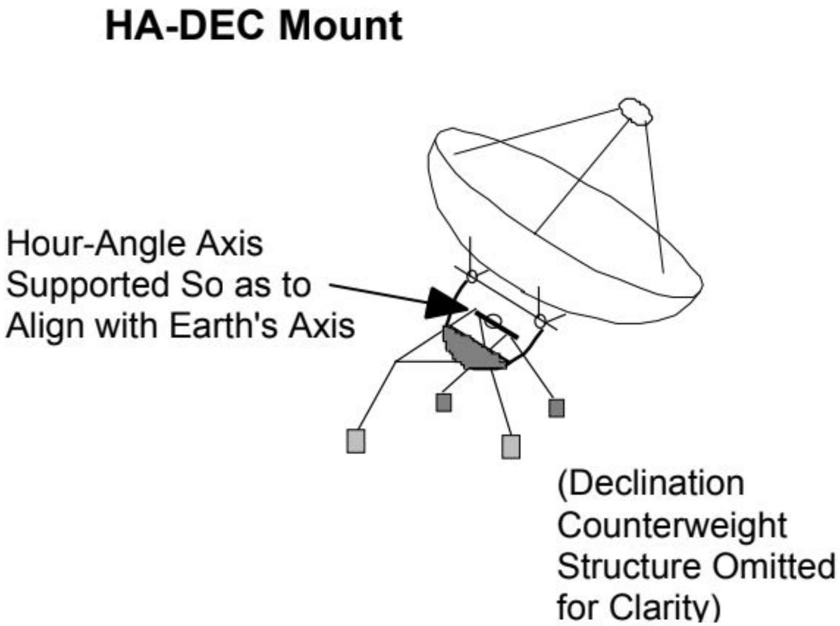
Antenna: mounting

Alt-Az (or azimuth-elevation)
(most radio telescopes)



Equatorial (or hour angle-declination)
(e.g., Green Bank Telescope, 43-m)
https://public.nrao.edu/gallery/an-equatorial-mount/



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Antenna: spherical at cm-λ

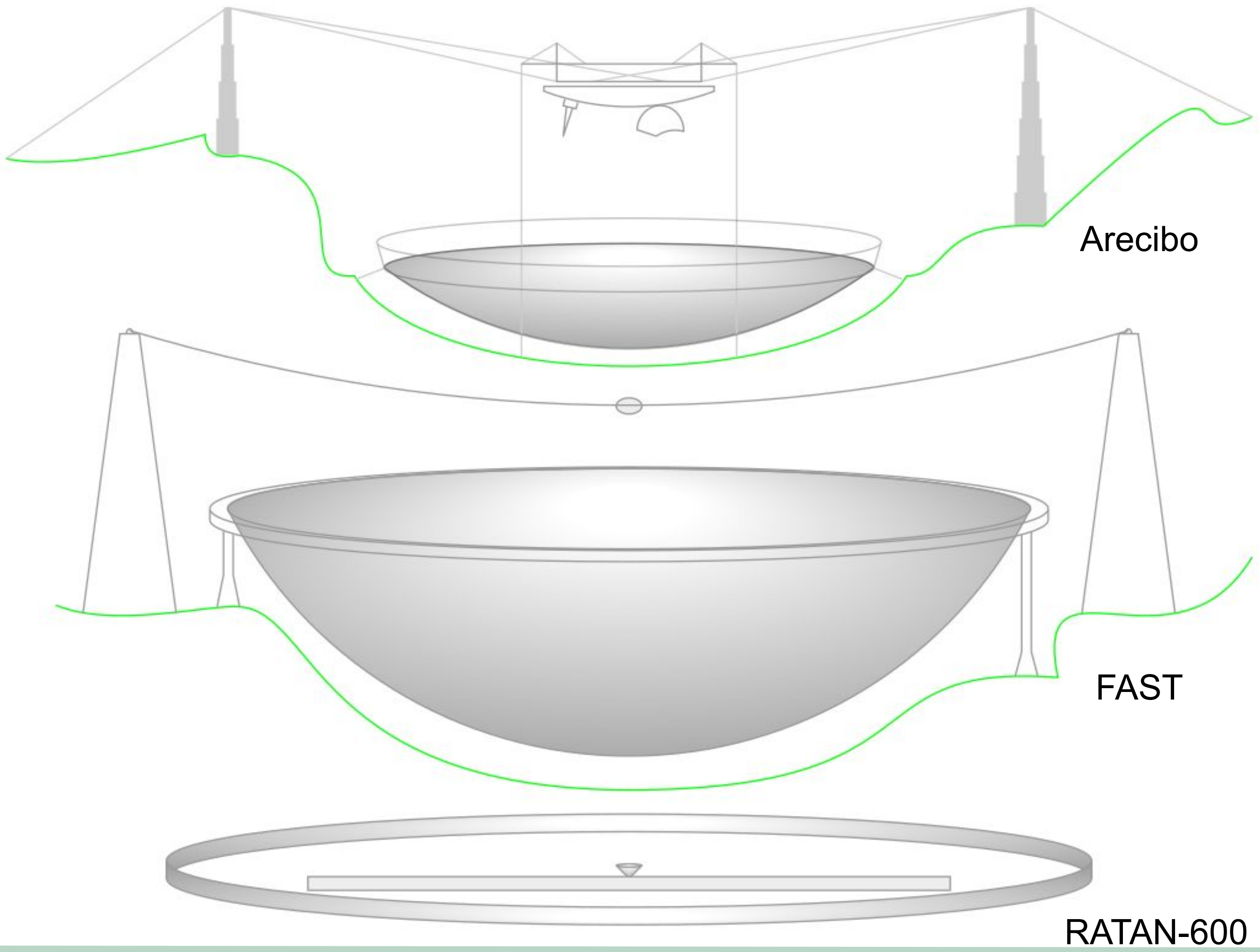
fixed main dish, steerable feed

FAST
500 m Aperture Spherical Telescope (China)
300 m aperture/illuminated surface
70 MHz - 3 GHz

resolution:
- angular/spatial: ~2.9’ (7’’ @ 3 GHz)
- frequency: 400 MHz bandwidth
- temporal: ~ ? msec

sensitivity: ~ 11-16 K/Jy

https://fast.bao.ac.cn/



https://commons.wikimedia.org/wiki/File:Comparison_FAST_Arecibo_Observatory_profiles.svg

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Antenna: elliptical designs

Nancay, France, 1 - 3.5 GHz
https://www.obs-nancay.fr/radiotelescope-decimetrique/

Ooty, India, 330 MHz
https://en.wikipedia.org/wiki/Ooty_Radio_Telescope

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Antenna: dipole (practical for λ > 1 m; f < 300 MHz) (what we have)

Whip / Monopole Antenna

Works best for narrow range and can be collapsable.
Used on small radios and vehicles.

Dipole Antenna

Two Monopoles facing away from each other.
Used to create a powerful signal in a restricted space.

Yagi Antenna

Ideal for long distance range
and directional applications. Can reach multiple frequencies.

Loop Antenna

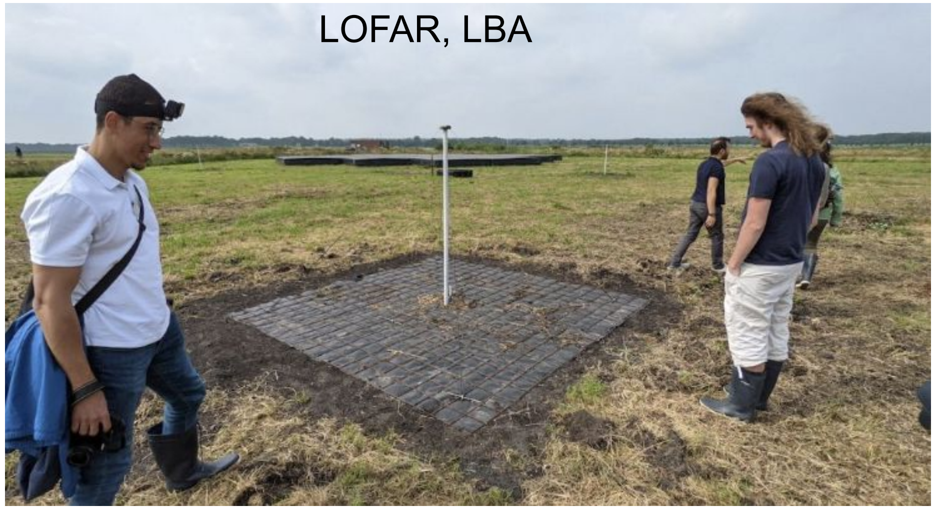
Works like a Dipole and can reach multiple frequencies.
Commonly used for TV and RFID Systems.

Bowtie Antenna

Another type of Dipole.
Angles can be set to work well with different frequencies.

Dish Antenna

Large surface space collects a lot of signal.
Works well for high frequencies, TV and sound.



https://www.rfsolutions.co.uk/blog/rf-basics-antenna-types-and-characteristics/

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https://stellar-h2020.eu/index.php/2021/08/03/lofar-science-workshop-at-astron/

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Sensitivity

- a measure of the minimum signal that a telescope can distinguish above the random background noise
- a telescope of larger primary mirror or lens is more sensitive than one with a smaller primary
- more sensitive - more light it can gather from faint objects - the fainter the object (or the more distant for a given class of object) that can be studied photometrically or imaged

https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/sensitivity

Freq. (MHz)	λ (m)	Sensitivity Superterp (mJy)	NL Core (mJy)	Full NL (mJy)	Full EU (mJy)
15	20.0	...	...	...	...
30	10.0	36	9.0	5.7	3.8
45	6.67	29	7.4	4.7	3.1
60	5.00	25	6.2	3.9	2.6
75	4.00	44	10.8	6.8	4.5
120	2.50	1.5	0.38	0.30	0.20
150	2.00	1.3	0.31	0.24	0.16
180	1.67	1.5	0.38	0.30	0.20
200	1.50	(2.5)	(0.62)	(0.48)	(0.32)
210	1.43	(2.5)	(0.62)	(0.48)	(0.32)
240	1.25	(5.6)	(1.4)	(1.1)	(0.73)

https://science.astron.nl/telescopes/lofar/lofar-system-overview/observing-modes/lofar-imaging-capabilities-and-sensitivity/

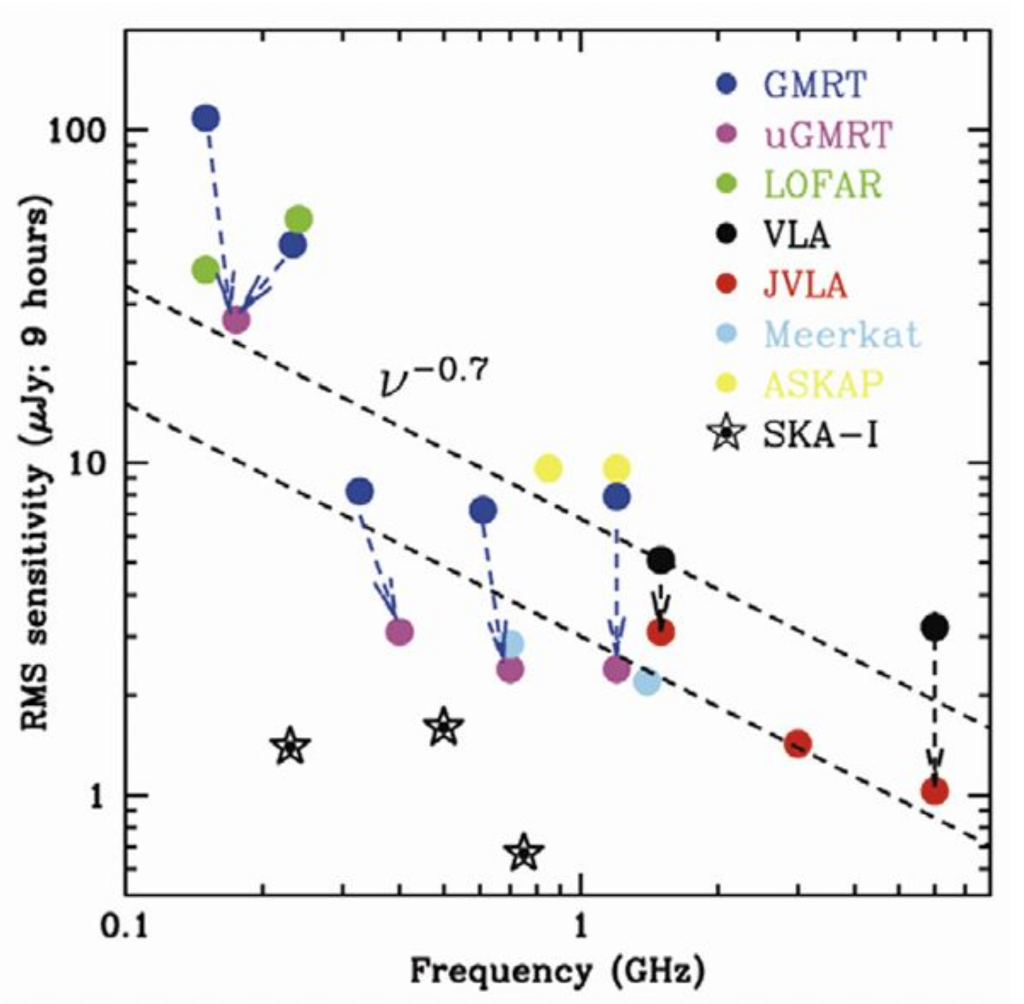

Figure 2. Comparison between the continuum sensitivities of existing and upcoming radio interferometers, for a 9 h on-source integration. The points show the sensitivities of GMRT, VLA, JVLA, uGMRT, LOFAR, MeerKAT, ASKAP and SKA-1-Mid in the colours and symbols as indicated in the key, for different parts of the spectrum in which these facilities operate (see text for more details). As can be seen, uGMRT will be the most sensitive interferometer in the world at frequencies 250–1500 MHz until the advent of Phase-1 of the SKA.

http://www.gmrt.ncra.tifr.res.in/doc/ugmrt.pdf (2017)

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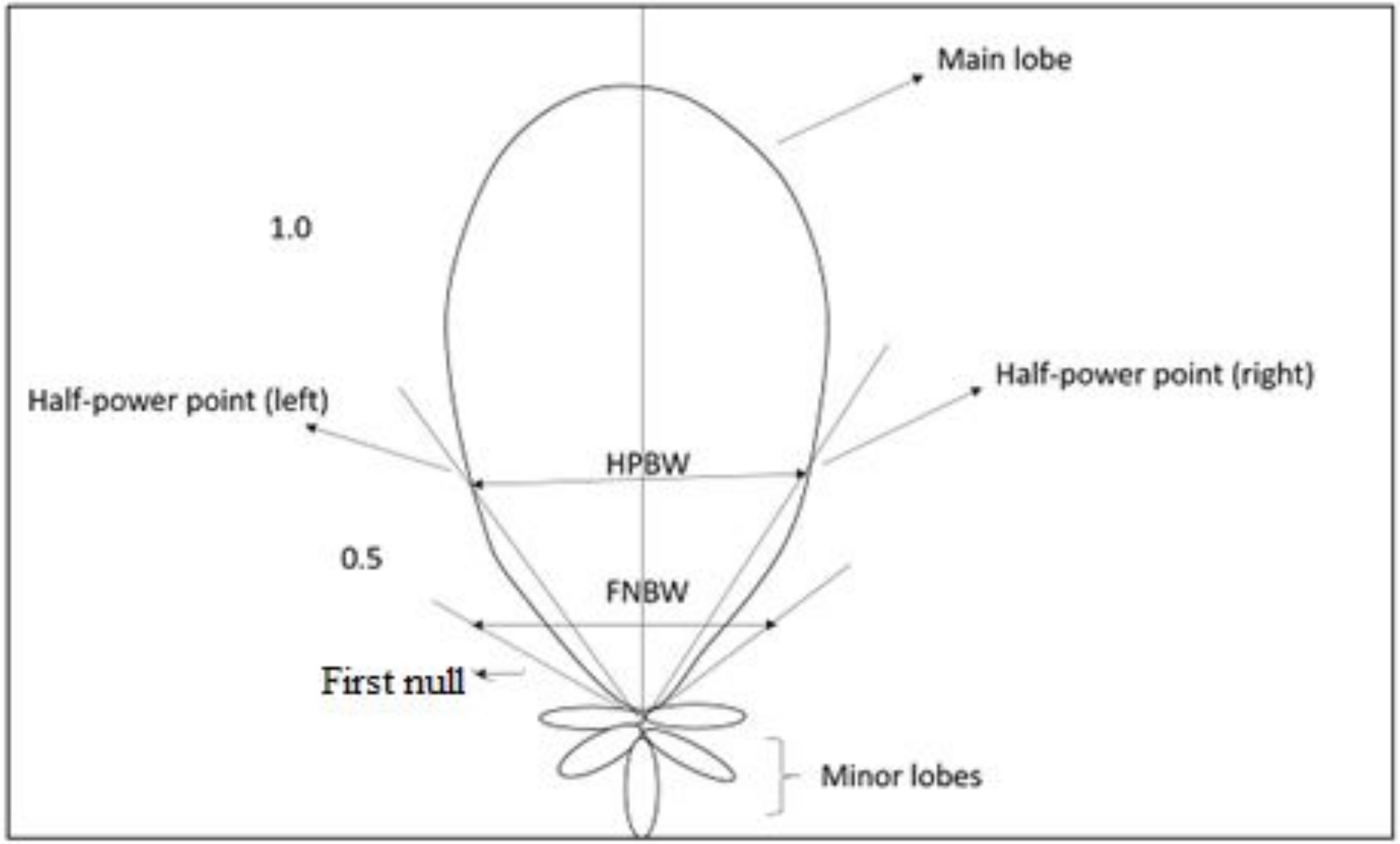
Beam width

beam solid angle: $\Omega \approx (2/\pi)(\lambda/D)$

field of view (FOV) = 1.02 (λ/D)

antenna with D>>λ is highly directive
antena with D ~ λ is isotropic

The angular separation, in which the magnitude of the radiation pattern decreases by 50% (or -3dB) from the peak of the main beam, is the Half Power Beam Width.
θ_HPBW = 0.89 λ/D



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(effective) Collecting area

Effective area is the area of the receiving antenna, which absorbs most of the power from the incoming wave front, to the total area of the antenna, which is exposed to the wave front.

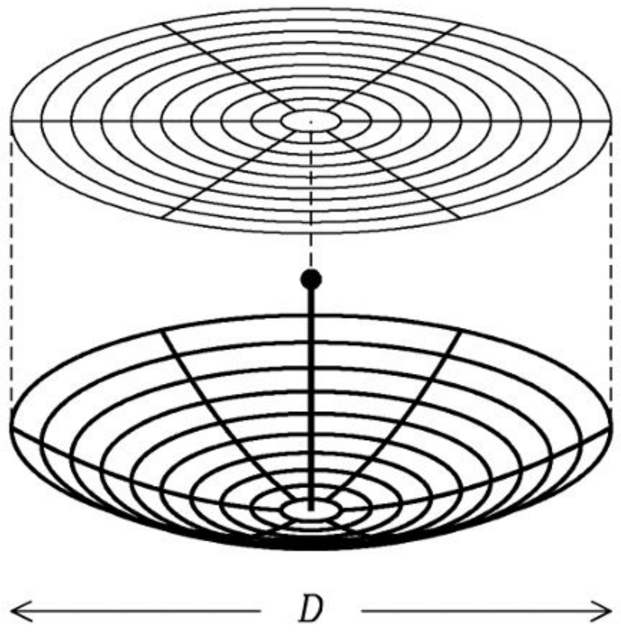
$$\langle A_e \rangle = \frac{\lambda^2}{4\pi}$$

geometrical (cross-sectional) area

Ag = <aperture efficiency> . Ae

Aperture (A): plane where all rays pass

- waveguide horn: the simplest aperture
- paraboloid antenna: plane circle with the same diameter as the dish



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

McKean, Lecture notes

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Spatial (or angular) resolution
(depends on the diffraction limit of the antenna)

$\theta \approx 1.22\ \lambda/D$ (single dish, D - diameter of the dish)
$\theta \approx 1.22\ \lambda/B$ (interferometer array, B - longest baseline)

Worked example: What is the spatial resolution (in arcseconds) of the $D = 500$ m FAST radio telescope, operating at $\nu = 5$ GHz?

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^8 \text{ m/s}}{5 \times 10^9 \text{ Hz}} = 0.06 \text{ m}$$

$$\theta_{\text{resolution}} \sim \frac{0.06 \text{ m}}{500 \text{ m}} \times \frac{180}{\pi} \times 3600 = 25 \text{ arcsec}$$

Arecibo: 50 arcsec
GBT: 150 arcsec

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Temporal resolution

data rate
integration time

microsec - nanosec (pulsars)

Frequency resolution

(channel) bandwidth
offset between subsequent frequencies

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Two-element interferometer

- baseline
- time delays between antennas
- visibilities
- Fourier transform
- 'dirty' beam/image
- image reconstruction (e.g., CLEAN)

Aperture synthesis

Earth rotation

1. An Interferometer measures the interference pattern produced by two apertures.
2. The interference pattern is directly related to the source brightness. In particular, for small fields of view the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

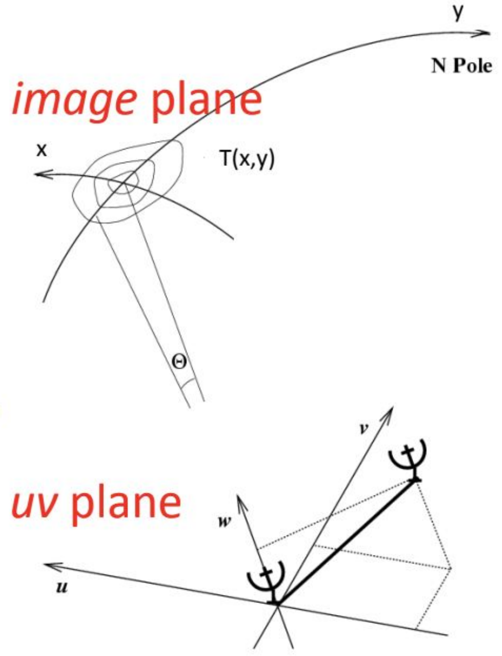
(van Cittert-Zernike theorem)

Fourier space/domain

$$V(u,v) = \int\int T(x,y)e^{2\pi i(ux+vy)}dxdy$$

$$T(x,y) = \int\int V(u,v)e^{-2\pi i(ux+vy)}dudv$$

Image space/domain



Andrea Isella :: CASA Radio Analysis Workshop :: Caltech, January 19, 2012

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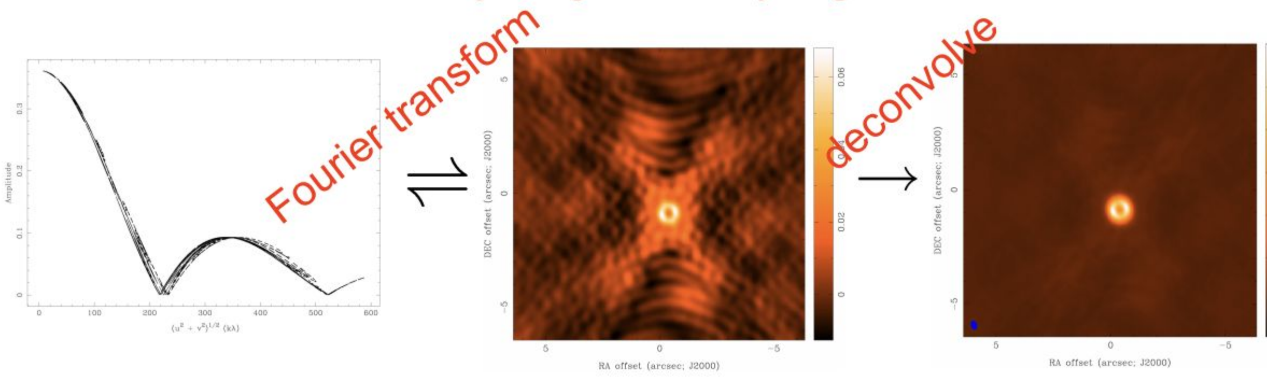
Radio images

radio telescope detects a math product of the source radio intensity (what is needed) and the given antenna configuration/ duration of observations/etc.

- uv plane analysis
  - best for “simple” sources, e.g. point sources, disks
- image plane analysis
  - Fourier transform V(u,v) samples to image plane, get T′(x,y)
  - but difficult to do science on dirty image
  - deconvolve b(x,y) from T′(x,y) to determine (model of) T(x,y)



Andrea Isella :: CASA Radio Analysis Workshop :: Caltech, January 19, 2012

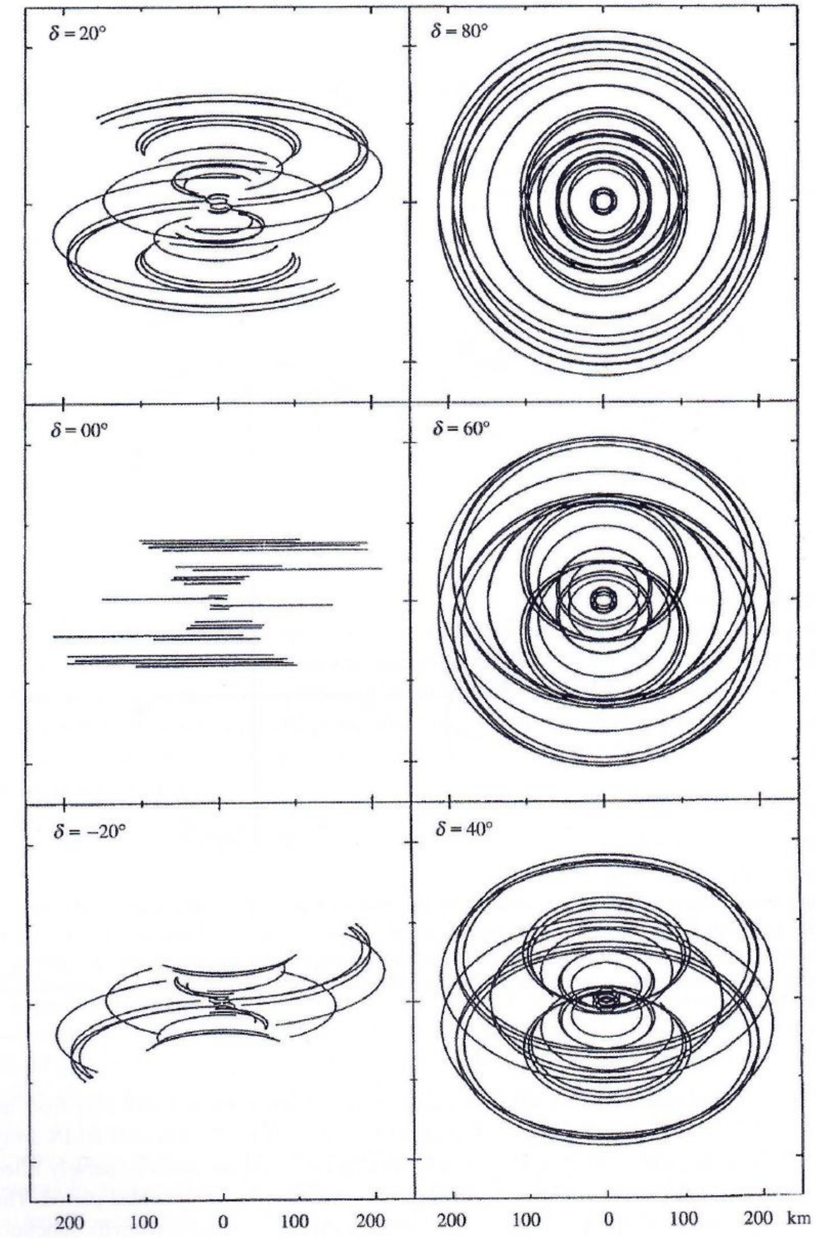


Figure 10.7. Results of the MERLIN interferometer array using six telescopes: the single-frequency u, v coverage for complete tracking observations at six declinations.

Credit: Introduction to Radio Astronomy, 2019

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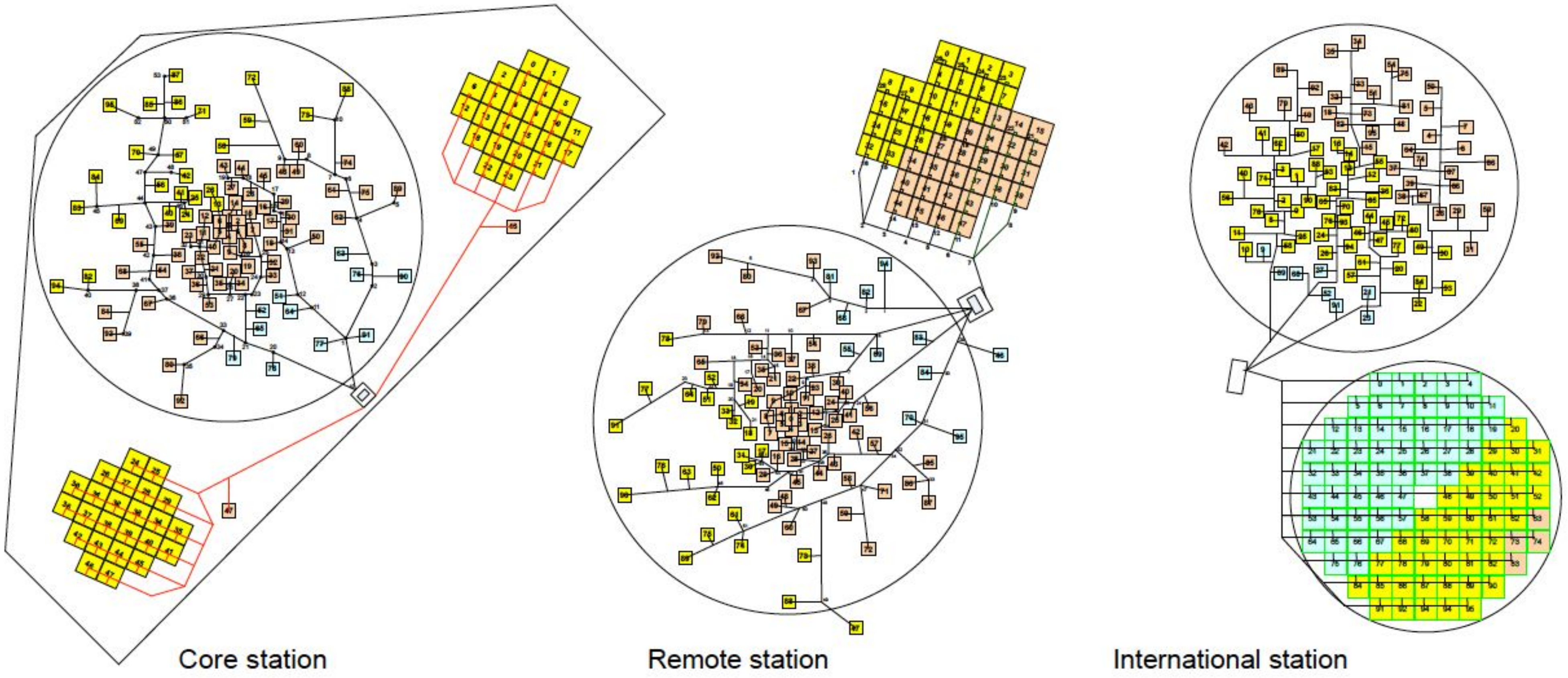
Antenna: arrays

- east-west
- T
- Y
- spiral
- irregular



LOFAR
https://doi.org/10.1051/0004-6361/201220873

Fig. 4. Station layout diagrams showing core, remote and international stations. The large circles denote the LBA antennas while the arrays of small squares indicate the HBA tiles. Note that the station layouts are not shown on the same spatial scale.

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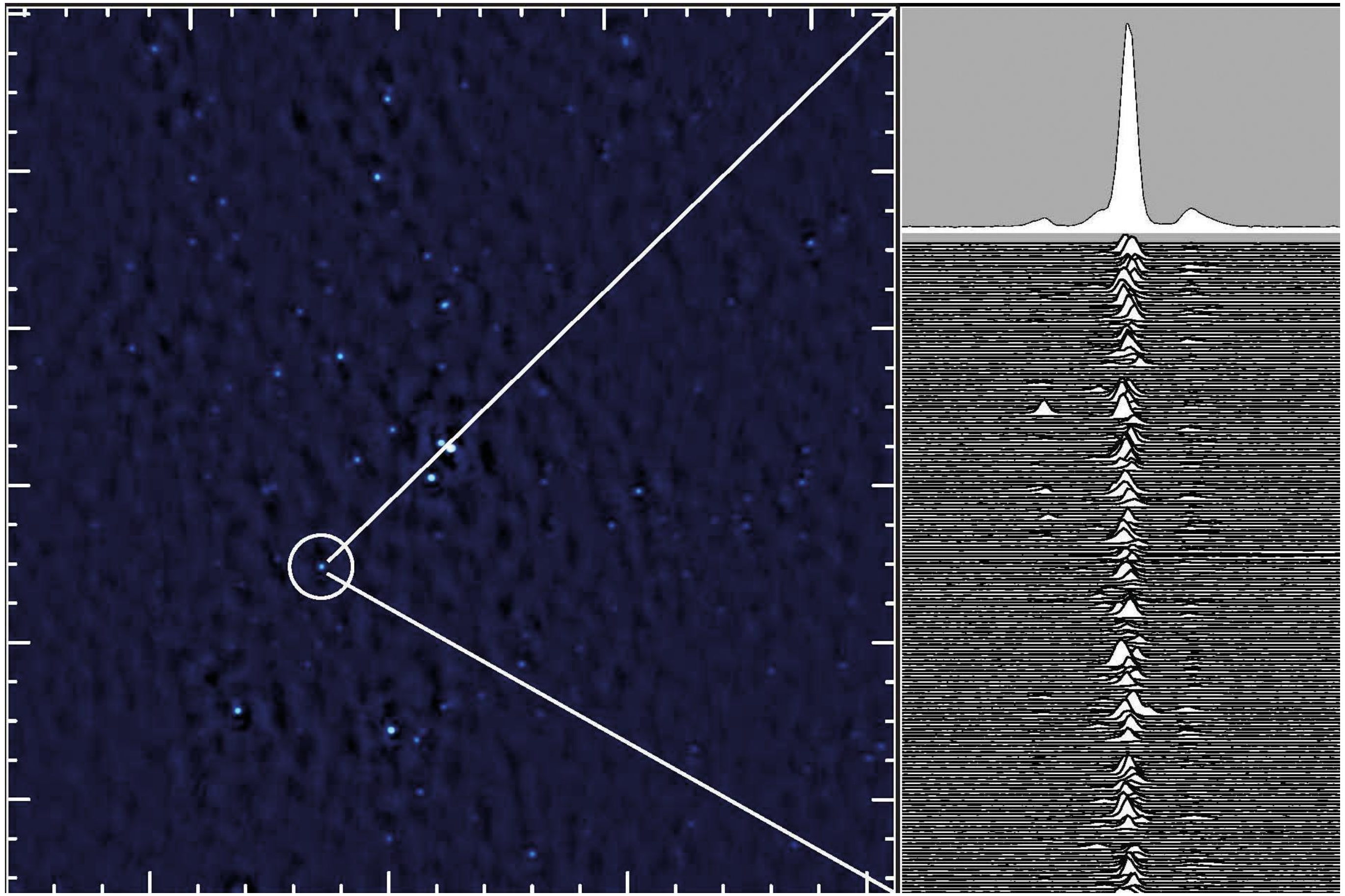
- **Light curves (intensity @ fixed frequencies)**
- **Dynamic spectra (intensity vs. frequency range)**
- Spectra (intensity vs. frequency range)
- Images: (intensity vs. on-sky-area @ fixed frequencies) contours/color-coded



https://www.astron.nl/telescopes/lofar/

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- Light curves (intensity @ fixed frequencies)
- Dynamic spectra (intensity vs. frequency range)
- **Spectra (intensity vs. frequency range)**
- Images: (intensity vs. on-sky-area @ fixed frequencies) contours/color-coded

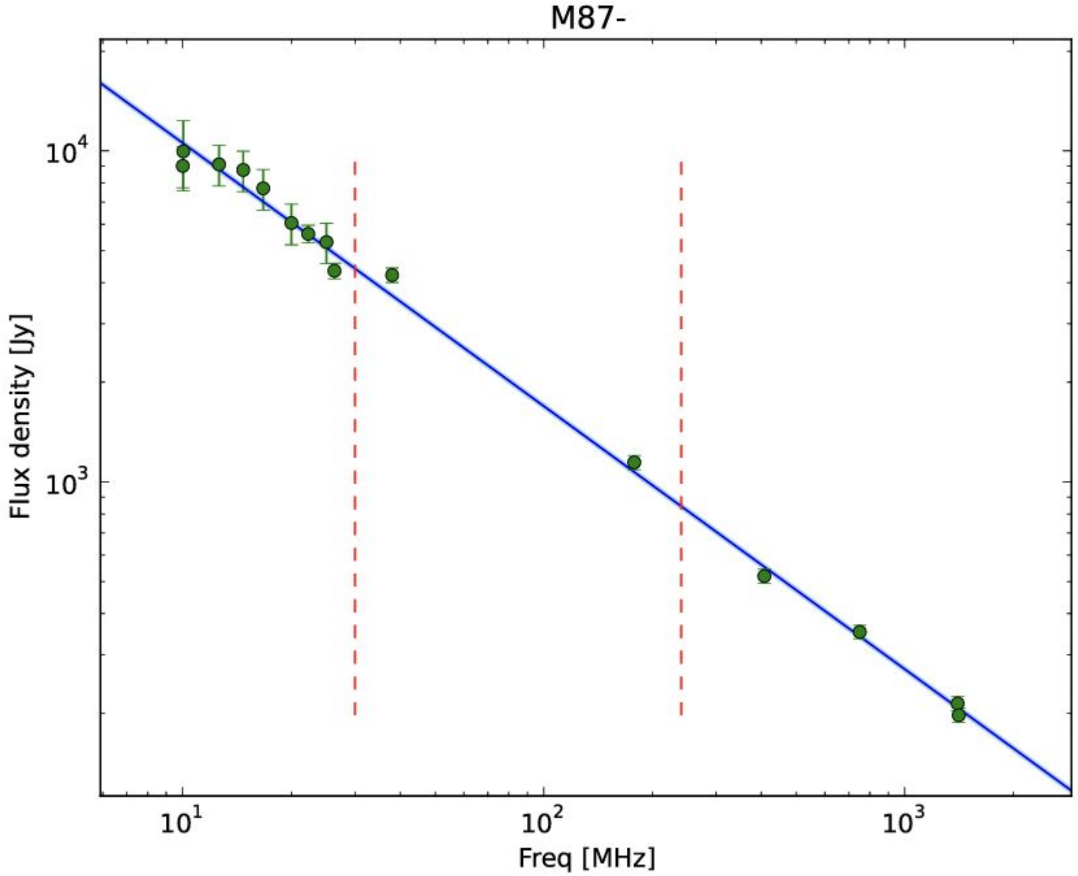

Fig. 4. Integrated flux of Virgo A at different frequencies obtained from archival data. The line is a linear fit (slope: −0.79) obtained as described in the text. The two vertical dashed lines indicate the boundaries of the LOFAR observing band.

https://doi.org/10.1051/0004-6361/201220209

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- Light curves (intensity @ fixed frequencies)
- Dynamic spectra (intensity vs. frequency range)
- Spectra (intensity vs. frequency range)
- **Images: (intensity vs. on-sky-area @ fixed frequencies) in contours/color-coded**

https://cds.cern.ch/record/965840/files/20125_S_Ananthakrishnan_060208.pdf

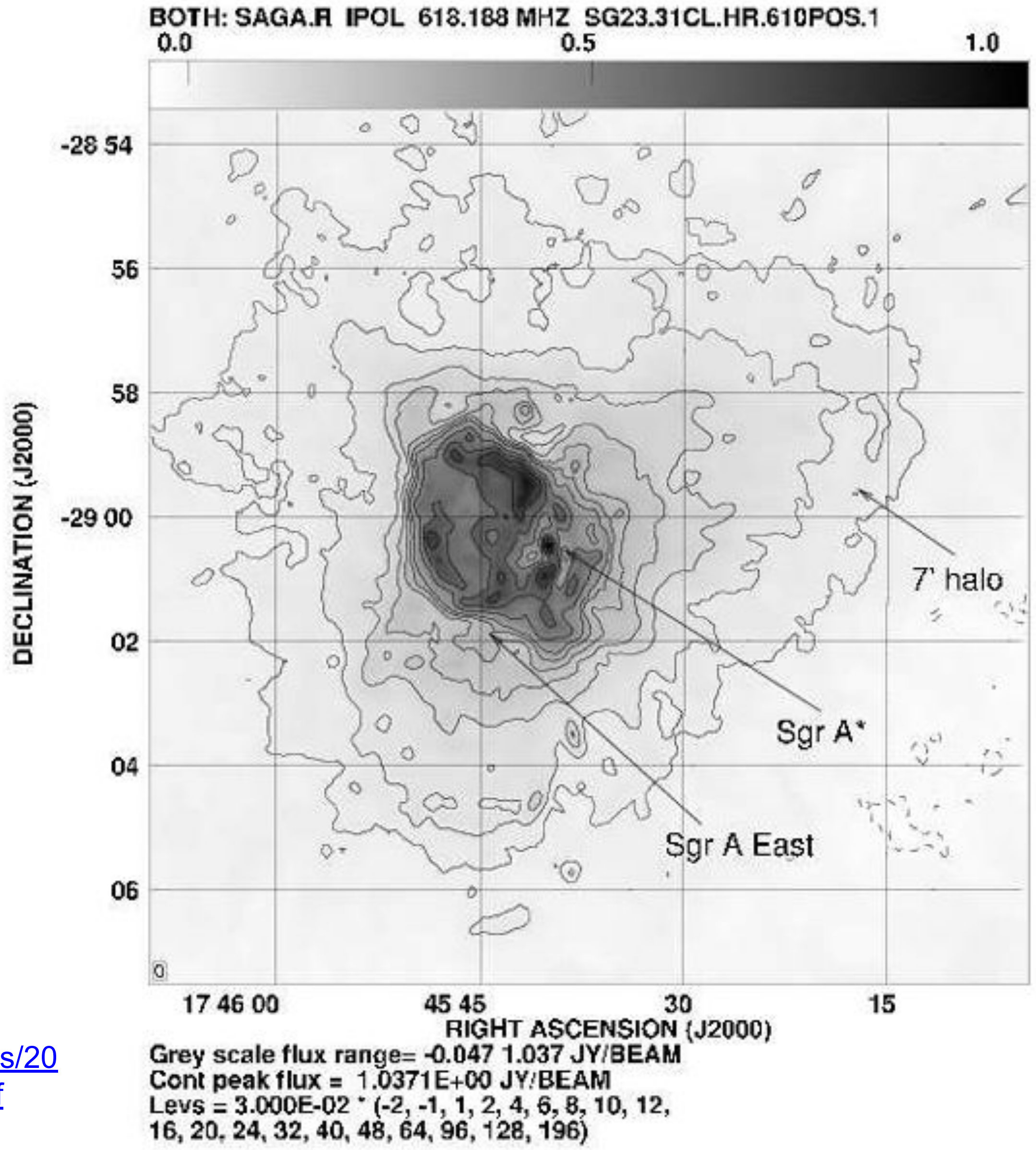

Figure 7. 49cm GMRT image of Sgr A

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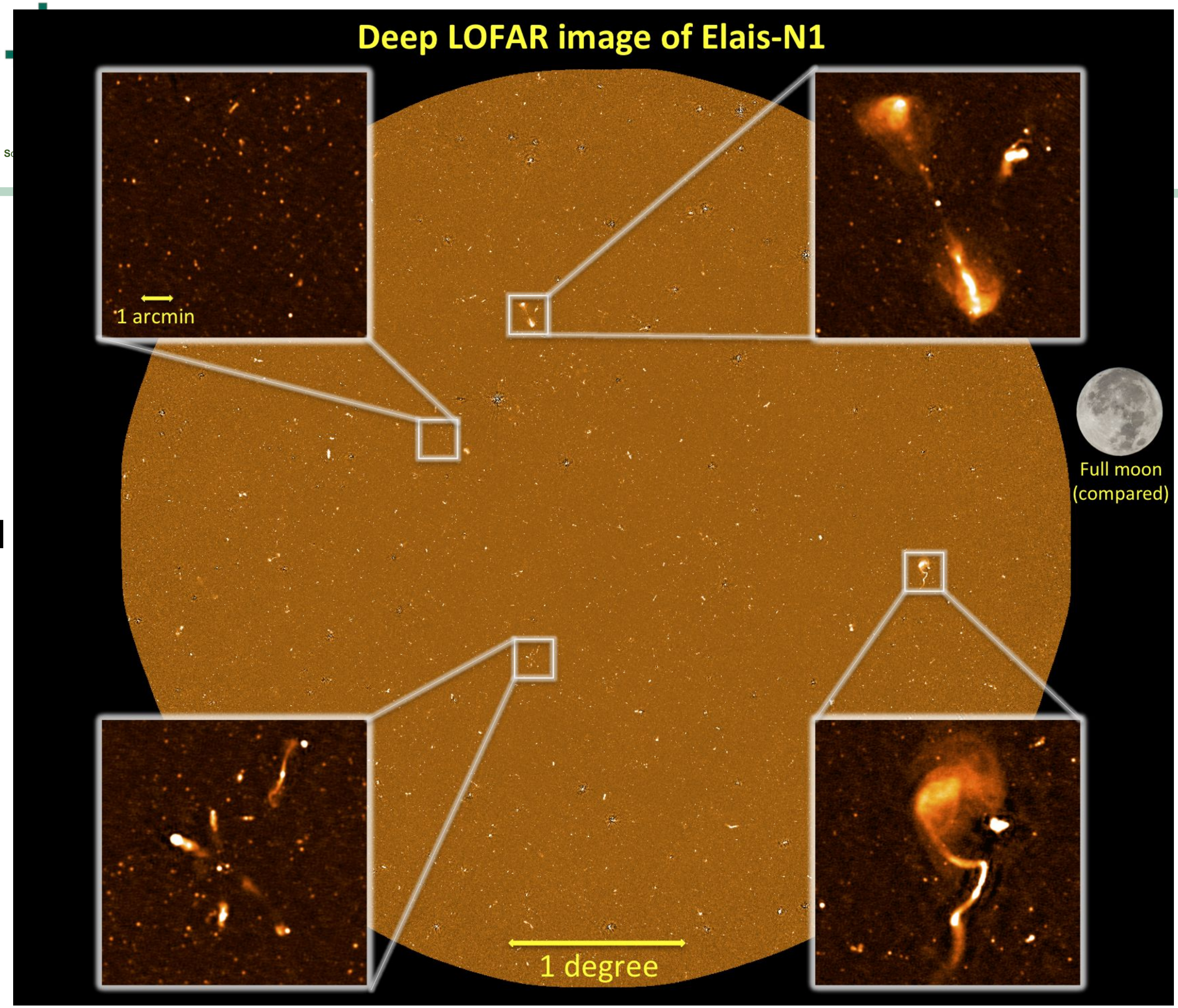
- Light curves (intensity @ fixed frequencies)
- Dynamic spectra (intensity vs. frequency range)
- Spectra (intensity vs. frequency range)
- **Images: (intensity vs. on-sky-area @ fixed frequencies) contours/color-coded**

LOFAR deep field
“The image arises from a single LOFAR pointing observed repeatedly for a total of 164 hours. Over 80,000 radio sources are detected; this includes some spectacular large-scale emission arising from massive black holes, but most sources are distant galaxies like the Milky Way, forming their stars (see insets). Credits: Philip Best, Jose Sabater, and the LOFAR surveys team.”



https://lofar-surveys.org/gallery.html?file=static/gallery/LoTSS_Deep_PRimage.png

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Radio observatories: (MHz) GHz-range

Event Horizon Telescope (EHT)	GHz	20 micro ‘’	8 instruments	global, https://eventhorizontelescope.org
Atacama Large Millimeter Array (ALMA)	35 GHz - 950 GHz	0.01’’	54 x D = 12 m 12 x D= 7 m	Chile, 2013, https://almaobservatory.org/en/home/
Very Large Array (VLA)	73 MHz - 50 GHz	0.2’’	27 x D = 25 m	USA, 1980, https://science.nrao.edu/facilities/vla/
Green Bank Telescope (GBT)	290 MHz - 100 GHz	6.5’’	D = 100 m	USA, 2000, https://greenbankobservatory.org/science/telescopes/gbt/
(upgraded/expanded) Giant Metrewave Radio Telescope (GMRT)	50 MHz - 1.45 GHz	2’’	30 x D = 45 m	India, 1995, http://www.gmrt.ncra.tifr.res.in/
500 m Aperture Spherical Telescope (FAST)	30 MHz - 3 GHz	4’’ (2.9’ @21 cm)	D = 500 m; A = 300 m	China, 2016, https://fast.bao.ac.cn/

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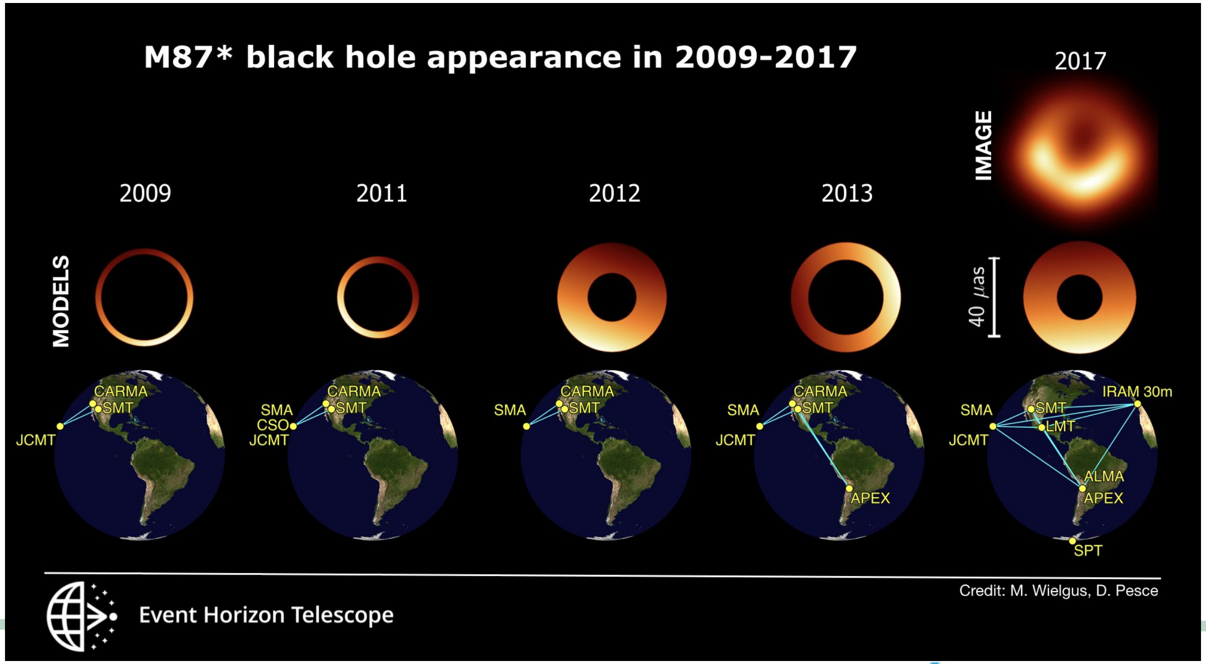
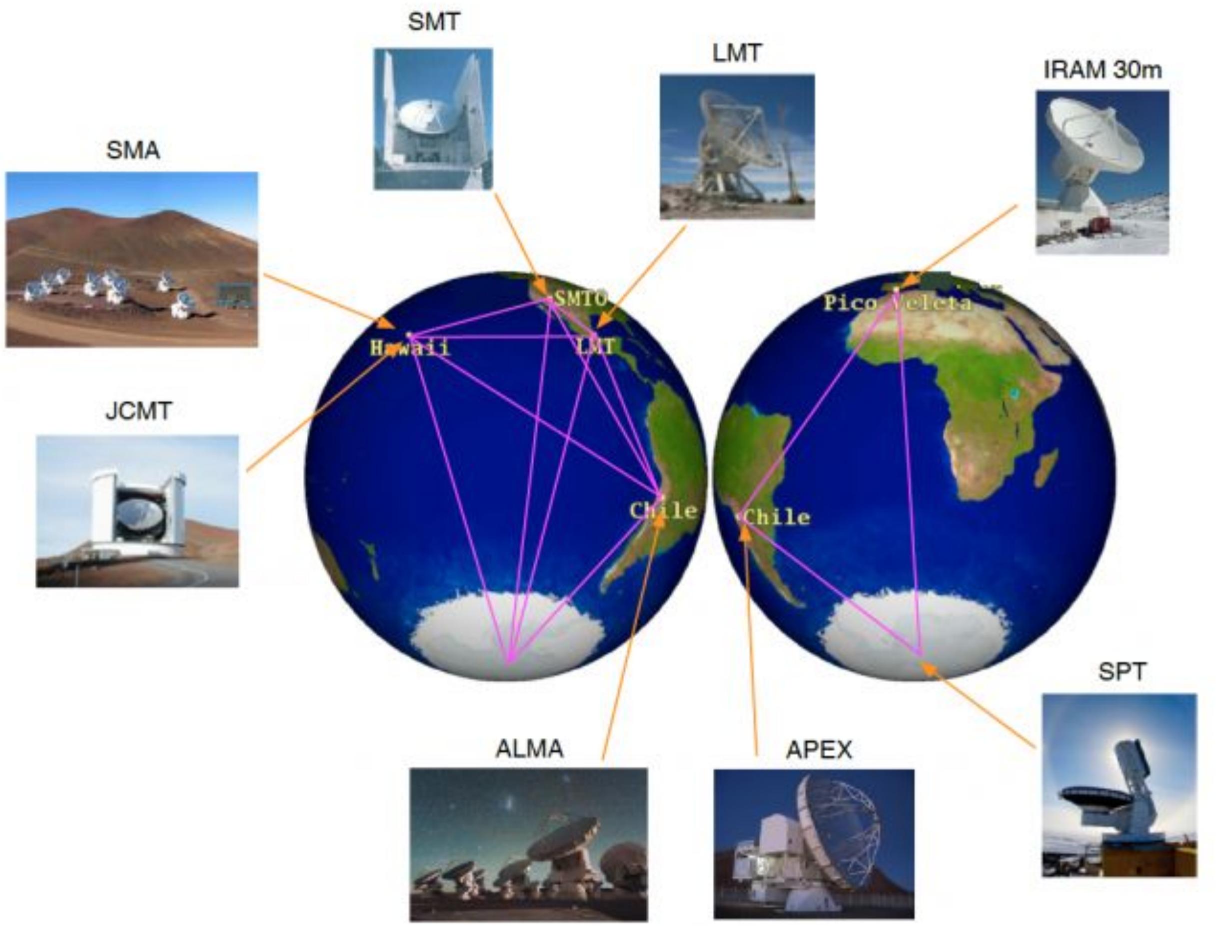
Radio observatories: GHz-range

EHT
8 instruments
mm-waves/100s GHz
Very Long Baseline Interferometry (VLBI) technique





https://eventhorizontelescope.org/

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https://www.ru.nl/astrophysics/black-hole/event-horizon-telescope-collaboration-0/

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Radio observatories: GHz-range

ALMA

Chile
35 GHz to 950 GHz

1 location; 66 antennas
max baseline: ~16 km
resolution:

- angular/spatial: ~0.01''
- frequency: 3.8 kHz-15.6 MHz bandwidth
- temporal: ~ ? sec

sensitivity: ~? mJy

https://almaobservatory.org/en/factsheet/
https://almascience.eso.org/about-alma/alma-basics
https://public.nrao.edu/telescopes/alma/

full Moon's diameter = 31' = 1900''

https://alma-telescope.jp/en/column/almabasics-2e
https://alma-telescope.jp/en/about

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Radio observatories: MHz - GHz-range

Karl G. Jansky VLA

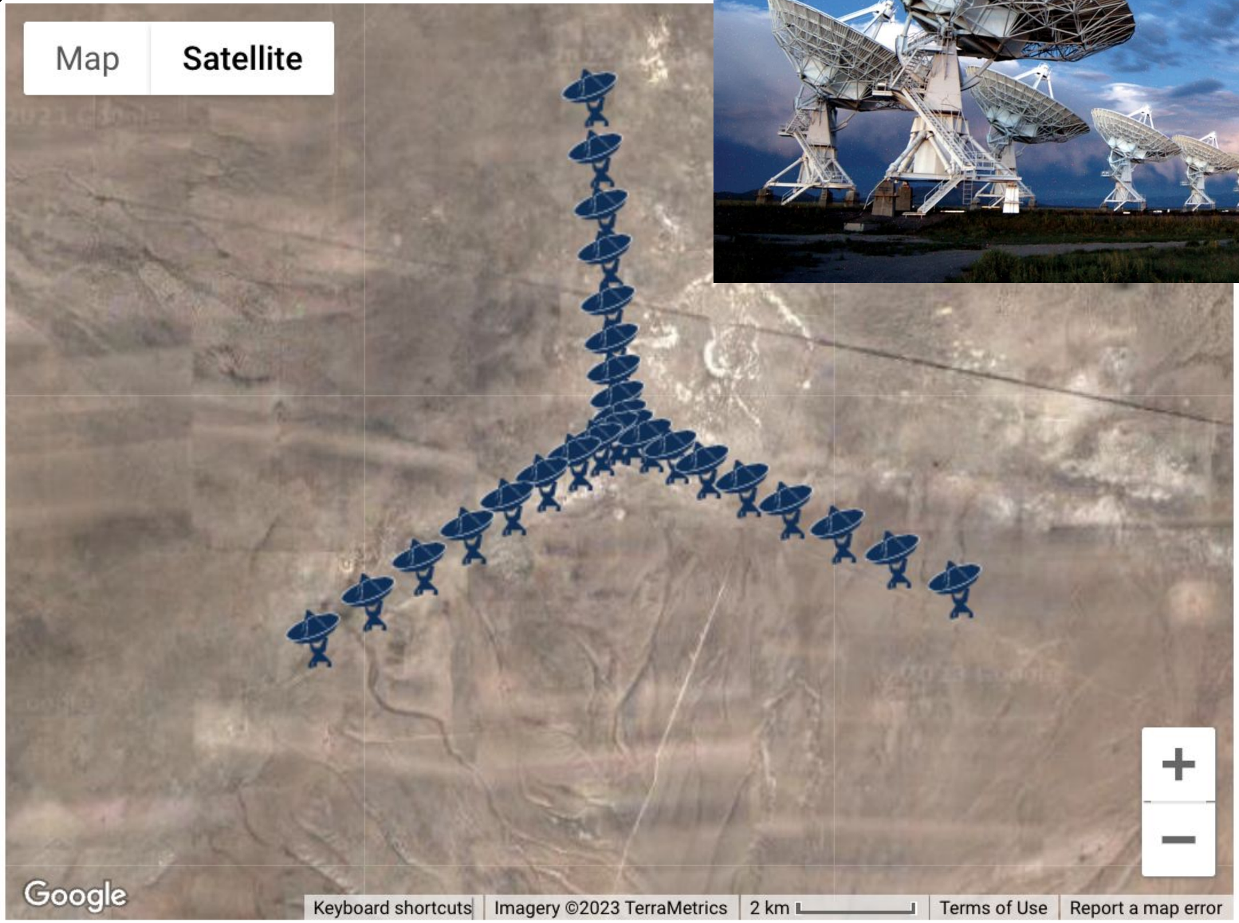
USA
73 MHz - 50 GHz

1 location; 27 antennas x 25 m
max baseline: ~36 km (A, B, C, D configurations)
resolution:

- angular/spatial: ~0.03’’ @ 50 GHz
- frequency: ~? MHz bandwidth
- temporal: ~ ? msec

sensitivity: ~ 1-10 μJy

https://science.nrao.edu/facilities/vla/docs/manuals/oss
https://public.nrao.edu/vla-configurations/



AS

The VLA Configuration B
2023 Jan 19 - 2023 May 29*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952439.

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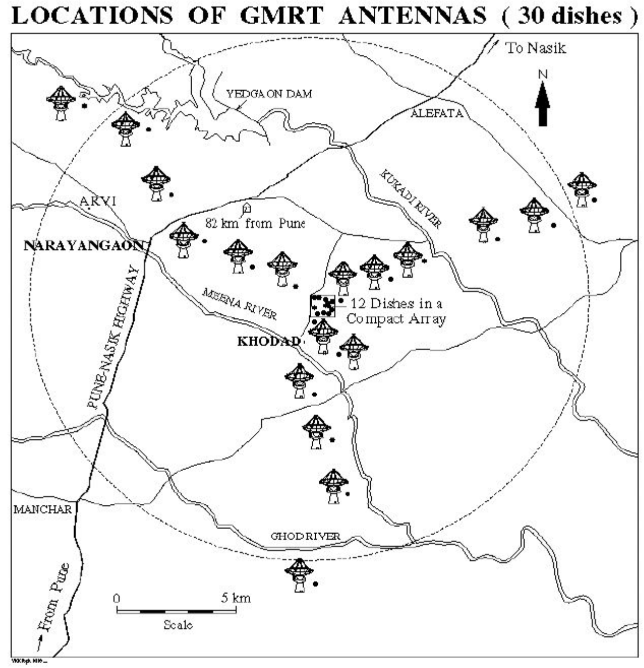


Radio observatories: MHz - GHz-range

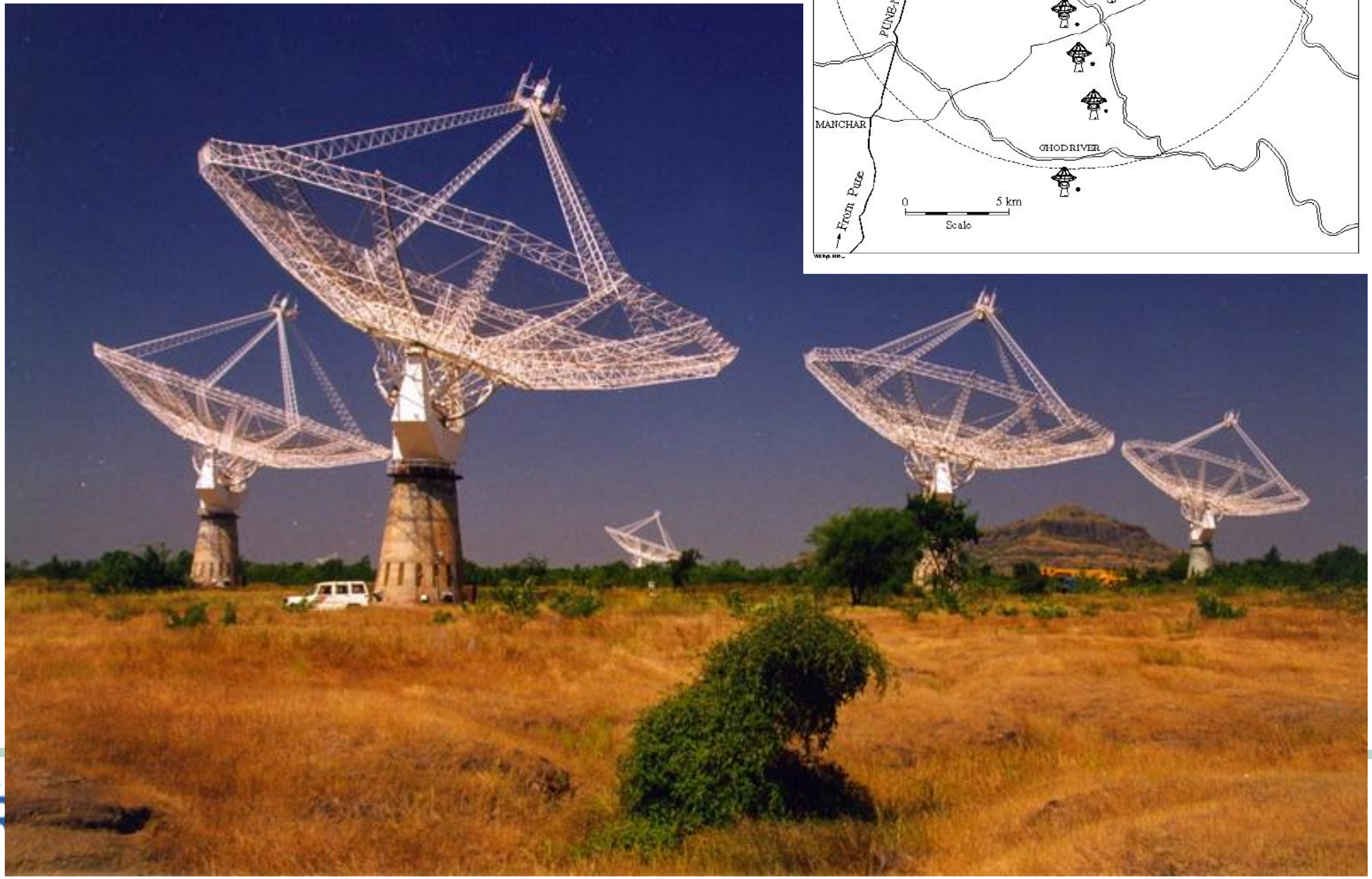
upgraded/expanded GMRT

India
50 MHz - 1.45 GHz

1 location; 30 antennas x 45 m
max baseline: ~25 km
resolution:
- angular/spatial: ~1”
- frequency: ~? MHz bandwidth
- temporal: ~ ? sec

sensitivity: ~30 μJy

https://cds.cern.ch/record/965840/files/20125_S_Ananthakrishnan_060208.pdf
http://www.gmrt.ncra.tifr.res.in/



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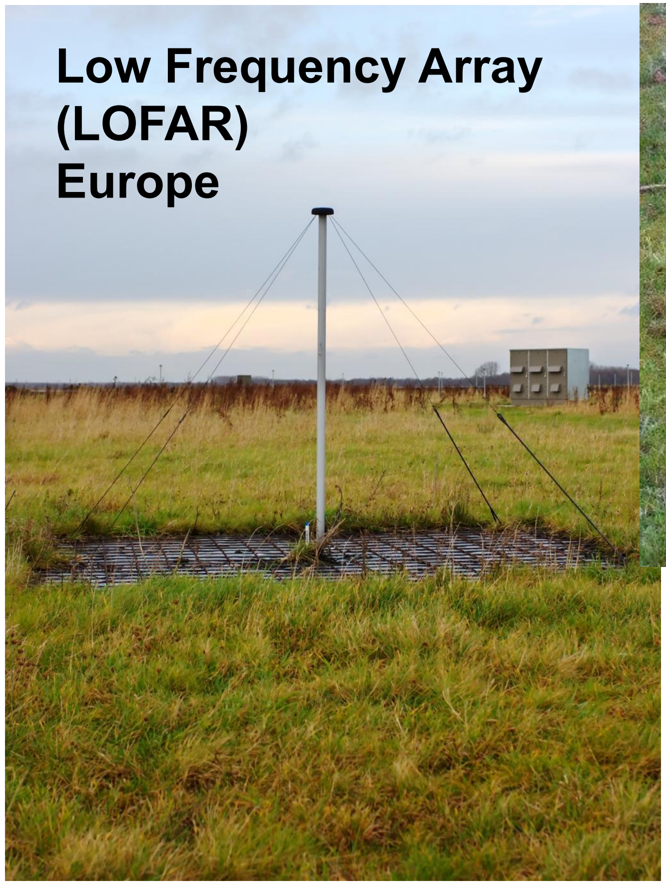
NATIONAL ASTRONOMICAL OBSERVATORY

Radio observatories: MHz-range

Low Frequency Array (LOFAR)
Europe



LOFAR - Low Band Antenna (10-80 MHz)
Credit: A. R. Offringa

LOFAR - High Band Antenna
(100-240 MHz)
https://wwwmpa.mpa-garching.mpg.de/

52 stations; ~20 000 dipoles;
max baseline: ~1000 km
resolution:

- angular/spatial: 0.21’’ @240 MHz
- frequency: ~1 kHz
- temporal: ~msec

sensitivity: 0.03-3 mJy

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Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

https://www.astron.nl/telescopes/lofar/
https://lofar.bg/

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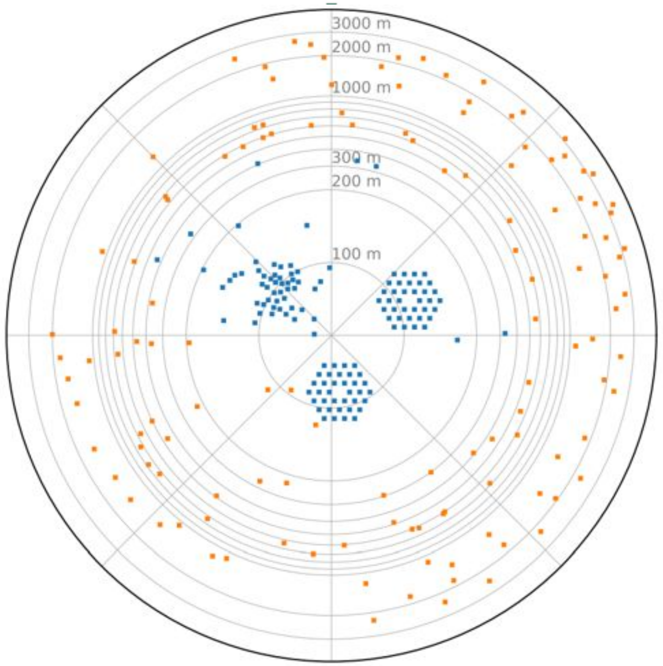


Radio observatories: MHz-range

Murchison Widefield Array (MWA)
Australia
70 - 300 MHz

256 stations/tiles (512 planned);
16 bowtie-antenna (1 tile)
max baseline: ~3 km (diameter area)
resolution:

- angular/spatial: ~70”≈1’ @300 MHz
- frequency: ~31 MHz bandwidth
- temporal: ~ nsec

sensitivity: ~10 mJy

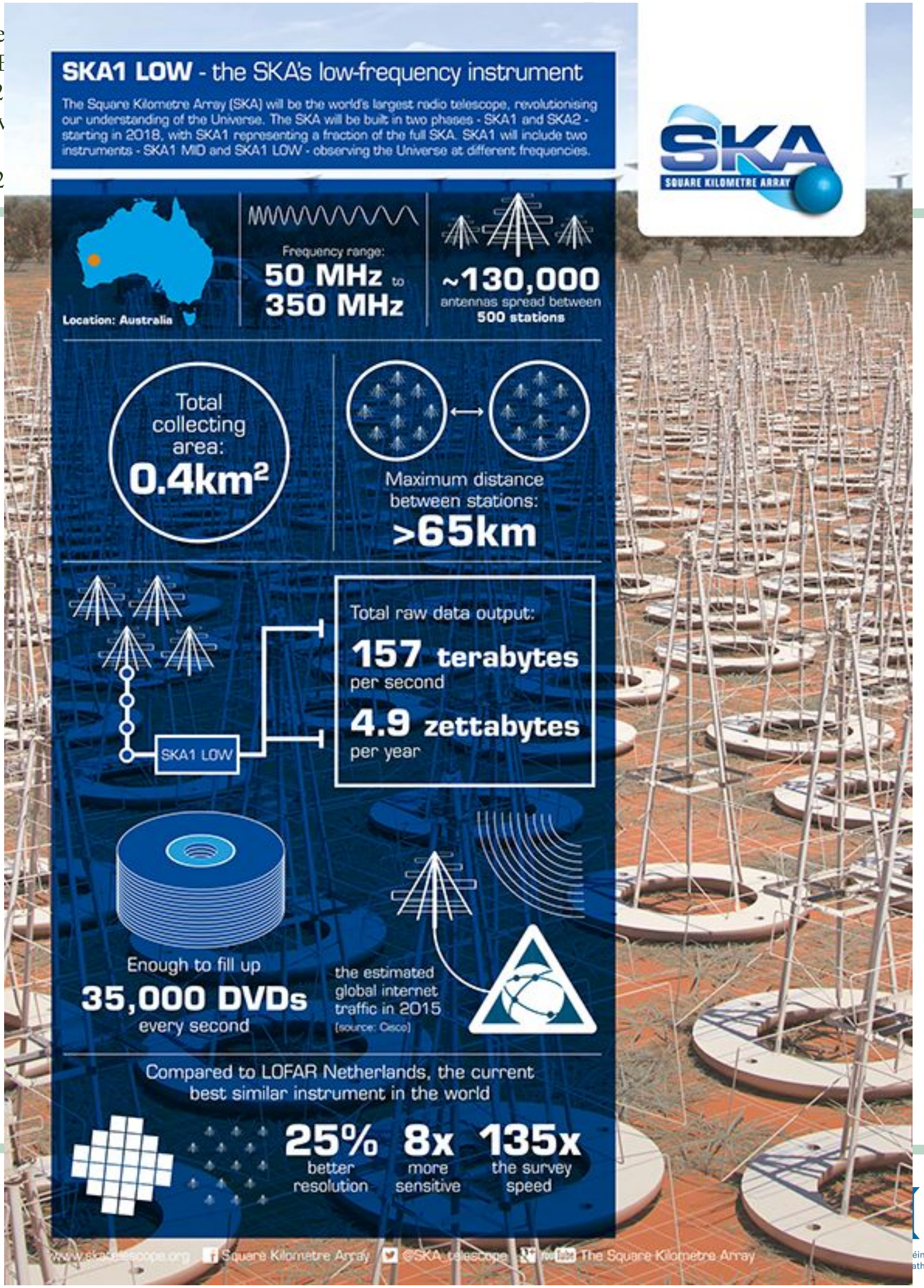
https://www.cambridge.org/core/journals/publications-of-the-astronomical-society-of-australia/article/murchison-widefield-array-the-square-kilometre-array-precursor-at-low-radio-frequencies/ED20FE56B17C253DAB94836785D887F0

https://www.mwatelescope.org/telescope

This project has re
funding from the E
Union's Horizon 2
research and innov
programme under
agreement No 952

Radio observatories: MHz-GHz range

Square Kilometre Array (SKA)
Australia &
S. Africa
under construction



https://www.skao.int/en

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The Nobel Prize in Physics 2006

Photo: P. Izzo
John C. Mather
Prize share: 1/2

Photo: J. Bauer
George F. Smoot
Prize share: 1/2

The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

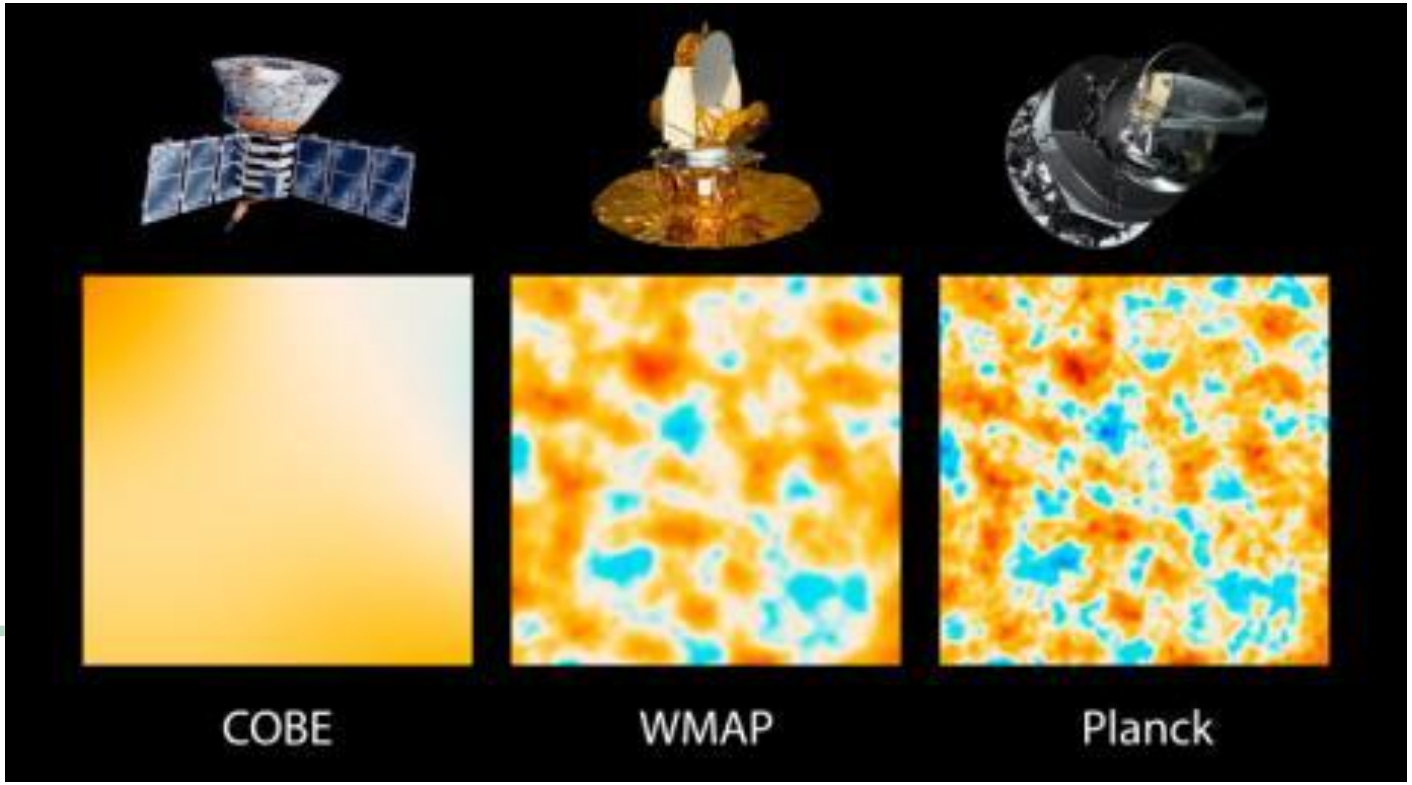
https://www.nobelprize.org/prizes/physics/2006/summary/

Radio observatories: kHz-range

space-based **astro**-dedicated instruments:
Ariel-series (mid-1960)
Submillimeter Wave Astronomy Satellite
Odin

other satellites, e.g., for measuring **CMB**

- Cosmic Background Explorer (COBE)
- Wilkinson Microwave Anisotropy Probe (WMAP)
- Plank



https://photojournal.jpl.nasa.gov/catalog/PIA16874

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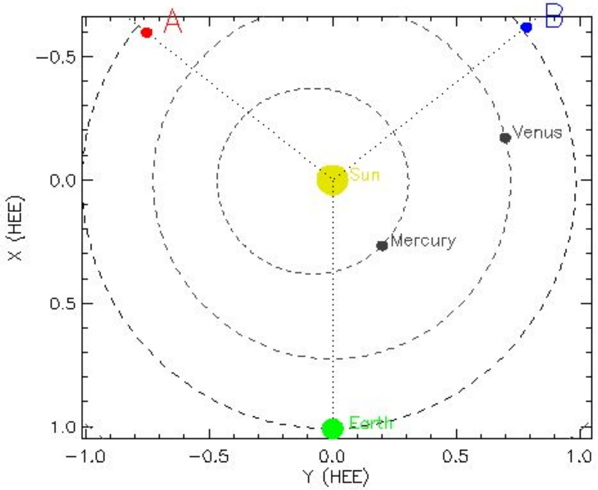
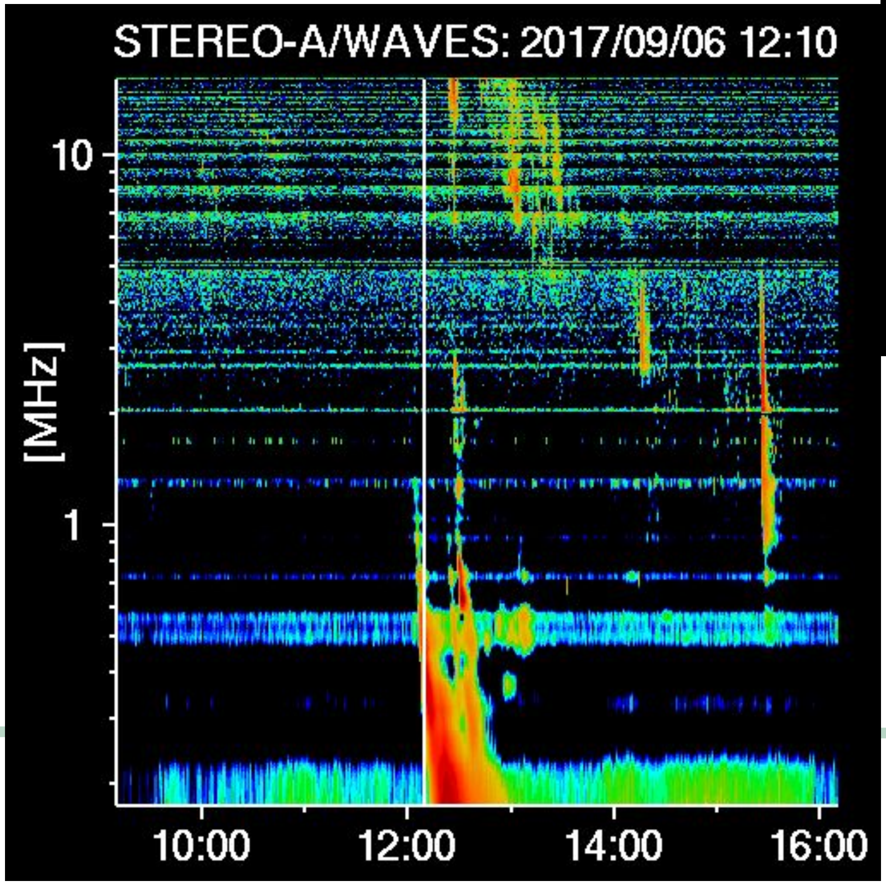
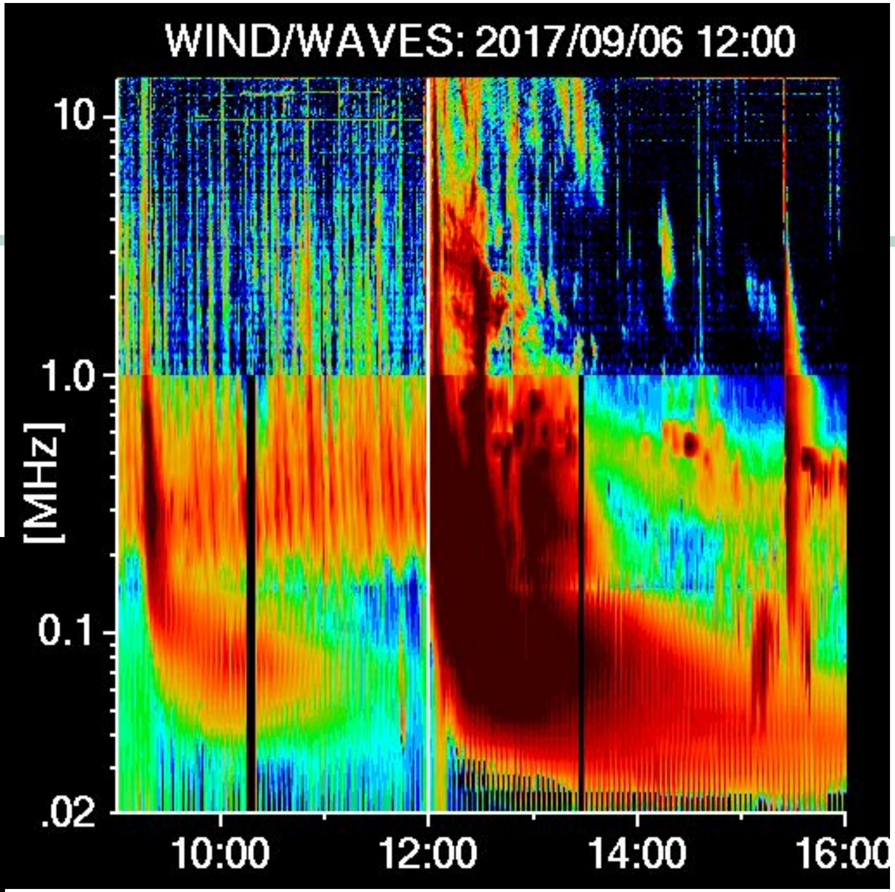


Radio observatories: kHz-range

space-based **solar**-dedicated instruments (dynamic spectra):

- Wind/WAVES (Earth view): 20 kHz–14 MHz
- STEREO/WAVES: 10 kHz–16 MHz
- Parker Solar Probe/FIELDS: 10.5 kHz–19.2 MHz
- Solar Orbiter/RPW: kHz–16 MHz





https://cdaw.gsfc.nasa.gov/

https://stereo-ssc.nascom.nasa.gov/cgi-bin/make_where_gif

https://secchirh.obspm.fr/

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Radio observatories: MHz-GHz range

https://secchirh.obspm.fr/

http://soleil.i4ds.ch/solarradio/callistoQuicklooks/

https://solar.nro.nao.ac.jp/norh/html/daily/

ground-based **solar**-dedicated instruments

I. Light curves

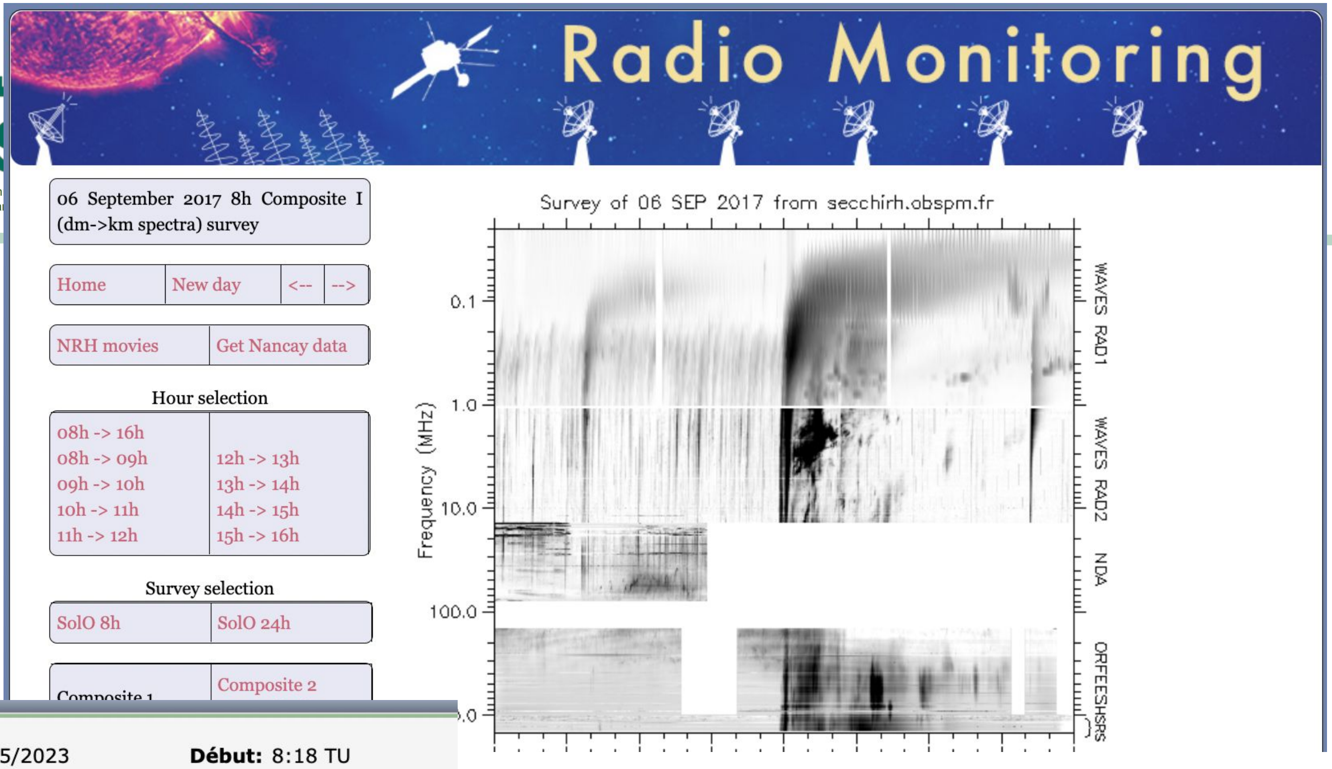
II. Dynamic spectra, e.g.,

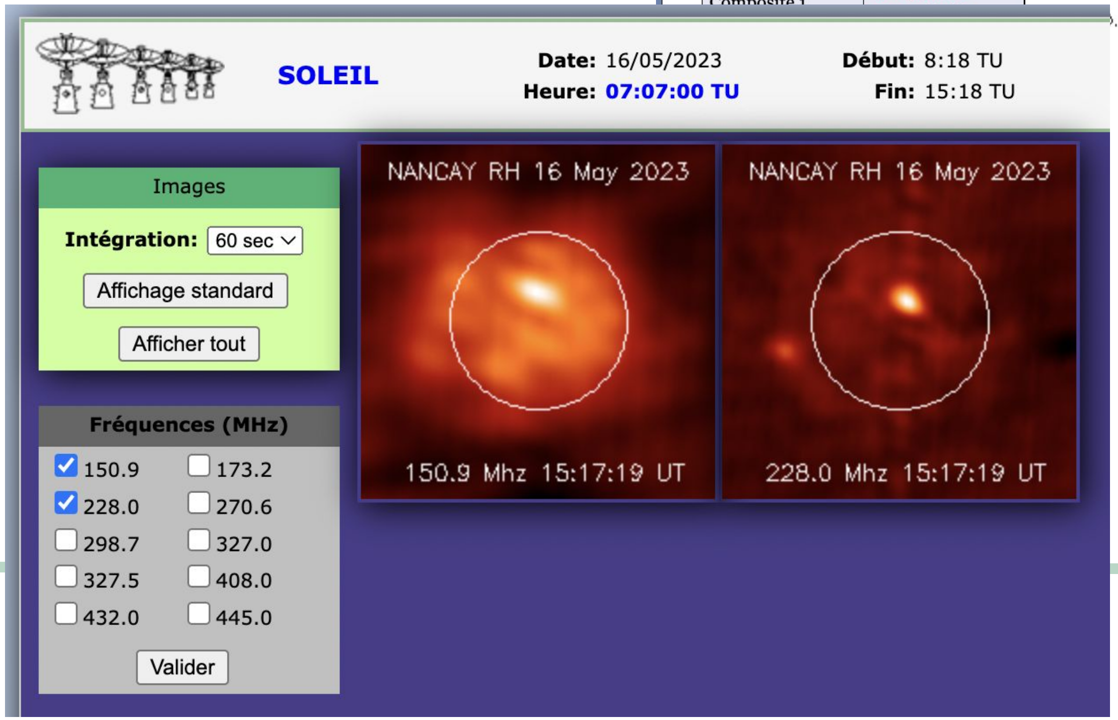
- RSTN
- e-Callisto

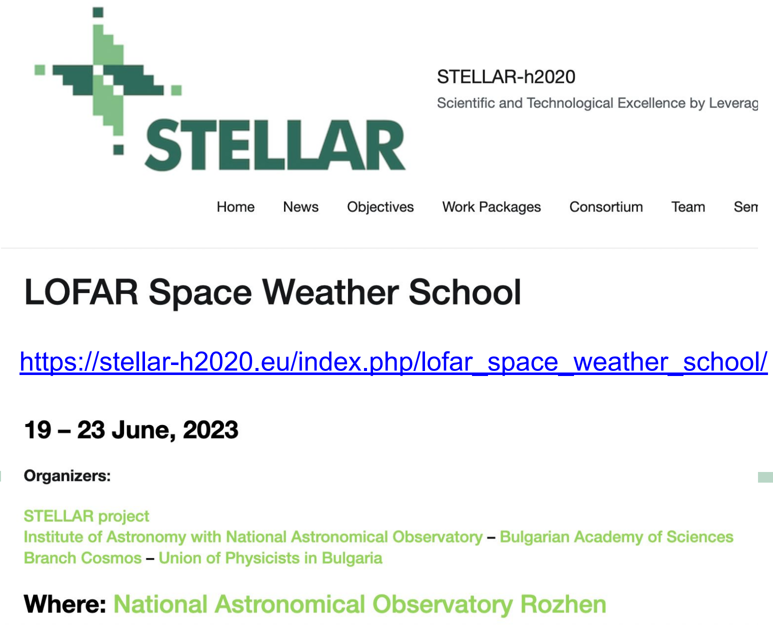
III. Heliographs, e.g.,

- Nancay
- Nobeyama (GHz, <2020)

IV. 3D reconstructions







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Selected links

http://home.ustc.edu.cn/~pjer1316/lofarsun/

https://lofar-sun-tools.readthedocs.io/en/latest/

https://doi.org/10.1051/0004-6361/201220873

http://www.ncra.tifr.res.in/ncra/gmrt/gmrt-users/low-frequency-radio-astronomy

https://www.cv.nrao.edu/~sransom/web/xxx.html

https://web.njit.edu/~gary/728/

https://en.wikipedia.org/wiki/List_of_radio_telescopes

https://science.astron.nl/telescopes/lofar/lofar-system-overview/observing-modes/lofar-imaging-capabilities-and-sensitivity/

https://www.omnicalculator.com/physics/wavelength

https://www.justintools.com/unit-conversion/

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