Advances in Radio Astronomy

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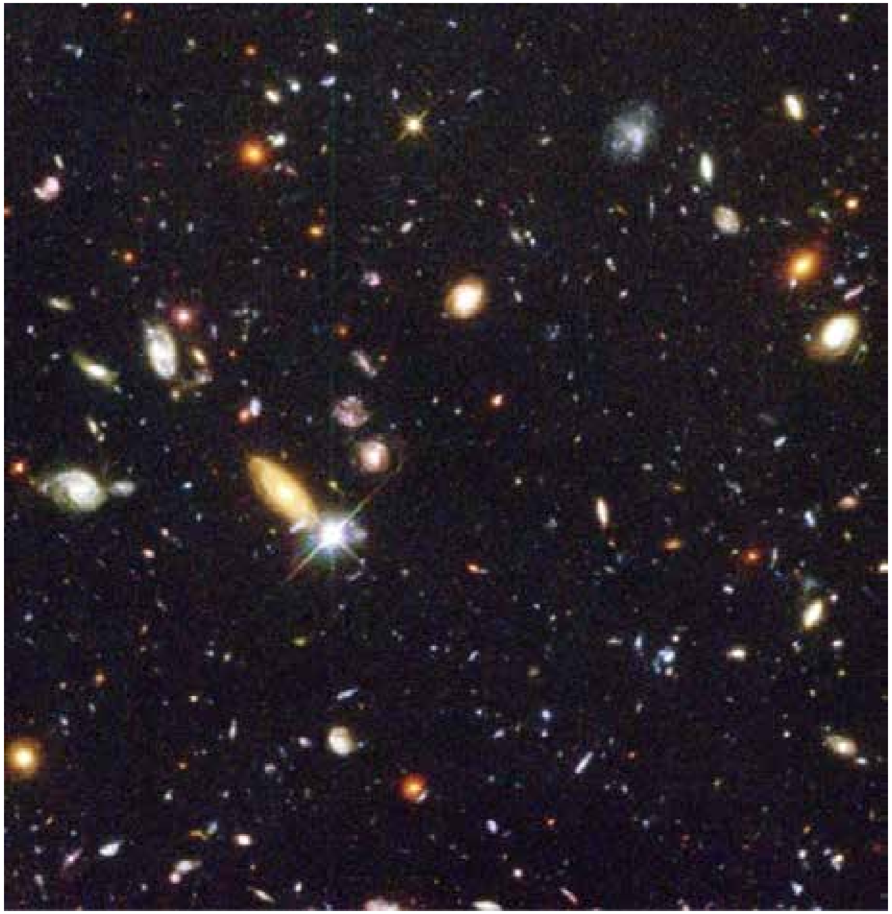
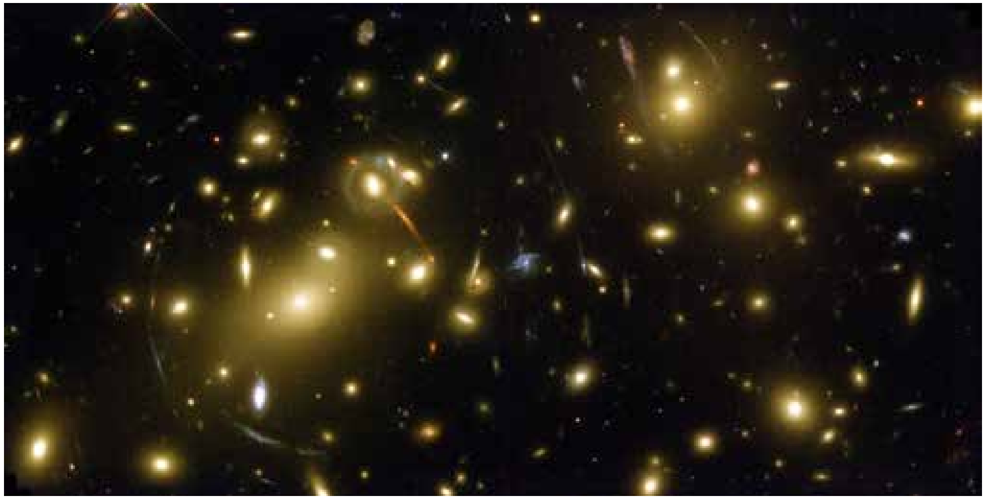
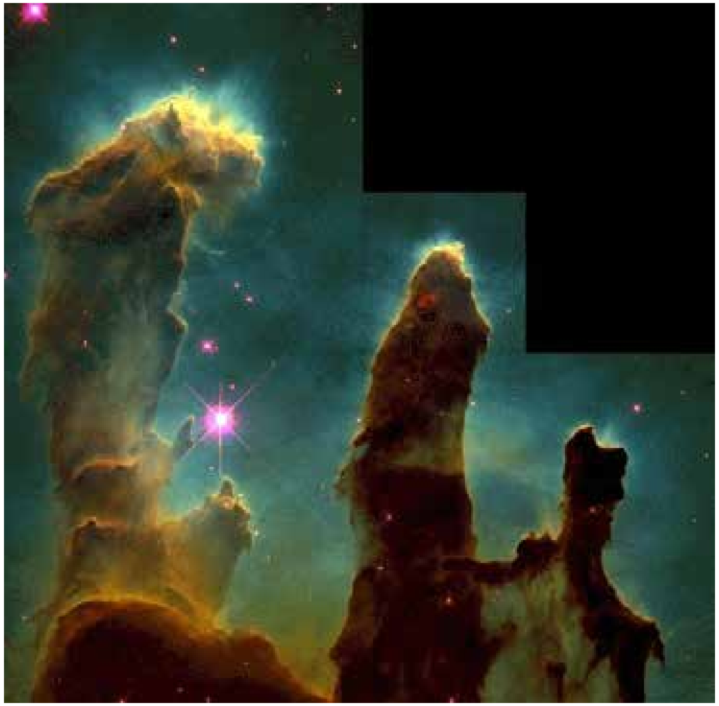
Astronomy

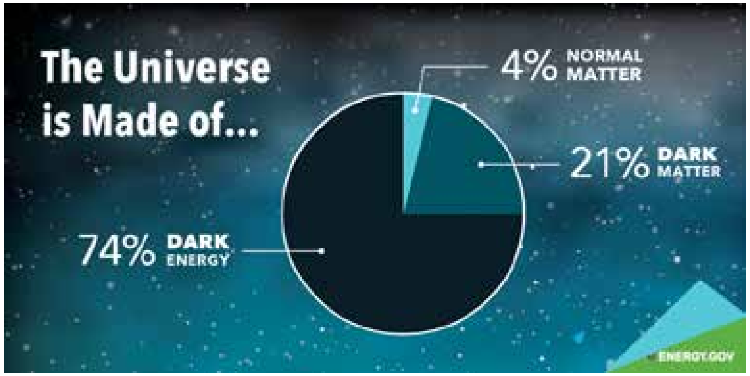






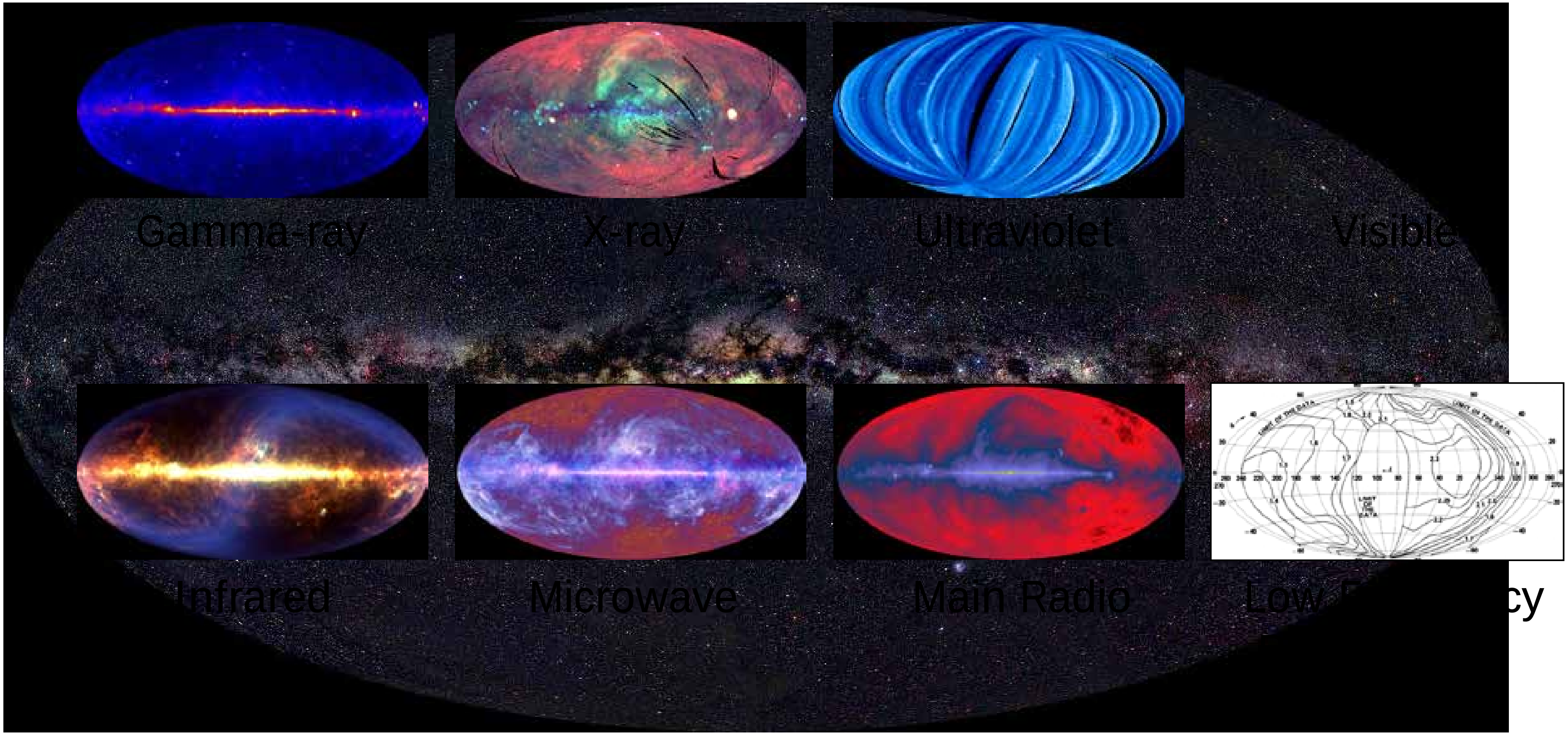
The 5 biggest questions about the Universe

- What is dark matter?
- What is dark energy?
- What came before the big bang?
- What's inside a black hole?
- Are we alone?



"Images" from space

- Celestial sky: has been mapped for nearly every type of electromagnetic radiation
- major exception: ultra-low frequency radiowaves (<30 MHz)



“Sounds” from space

Galactic background

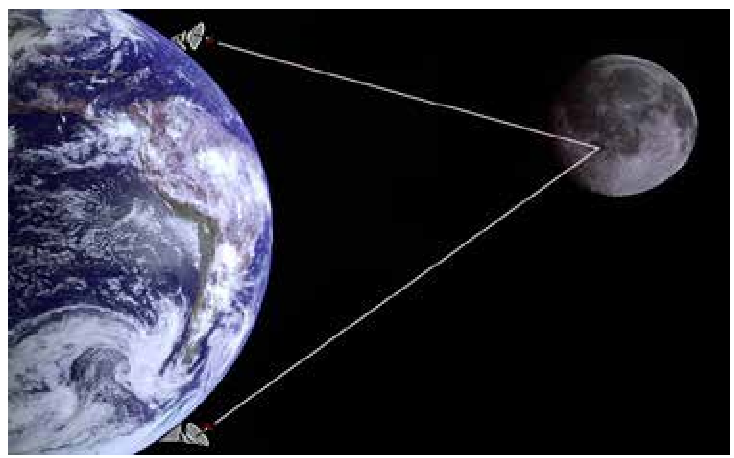
Pulsars

Crab

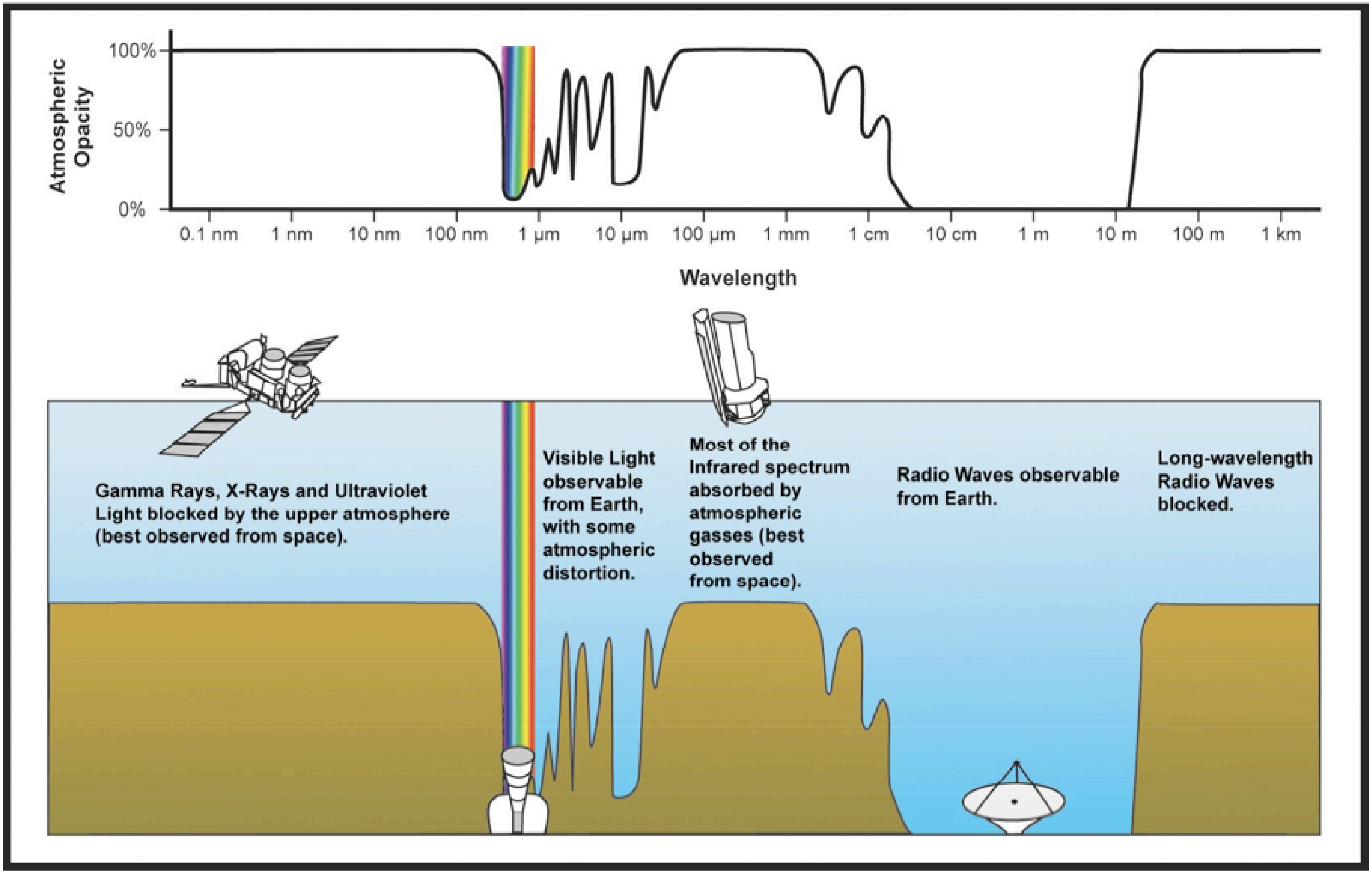
B0329

Vela

Earth-Moon-Earth



How to capture the signals



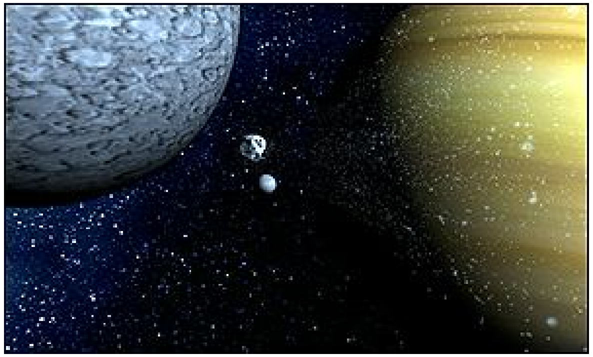
Optical

Radio

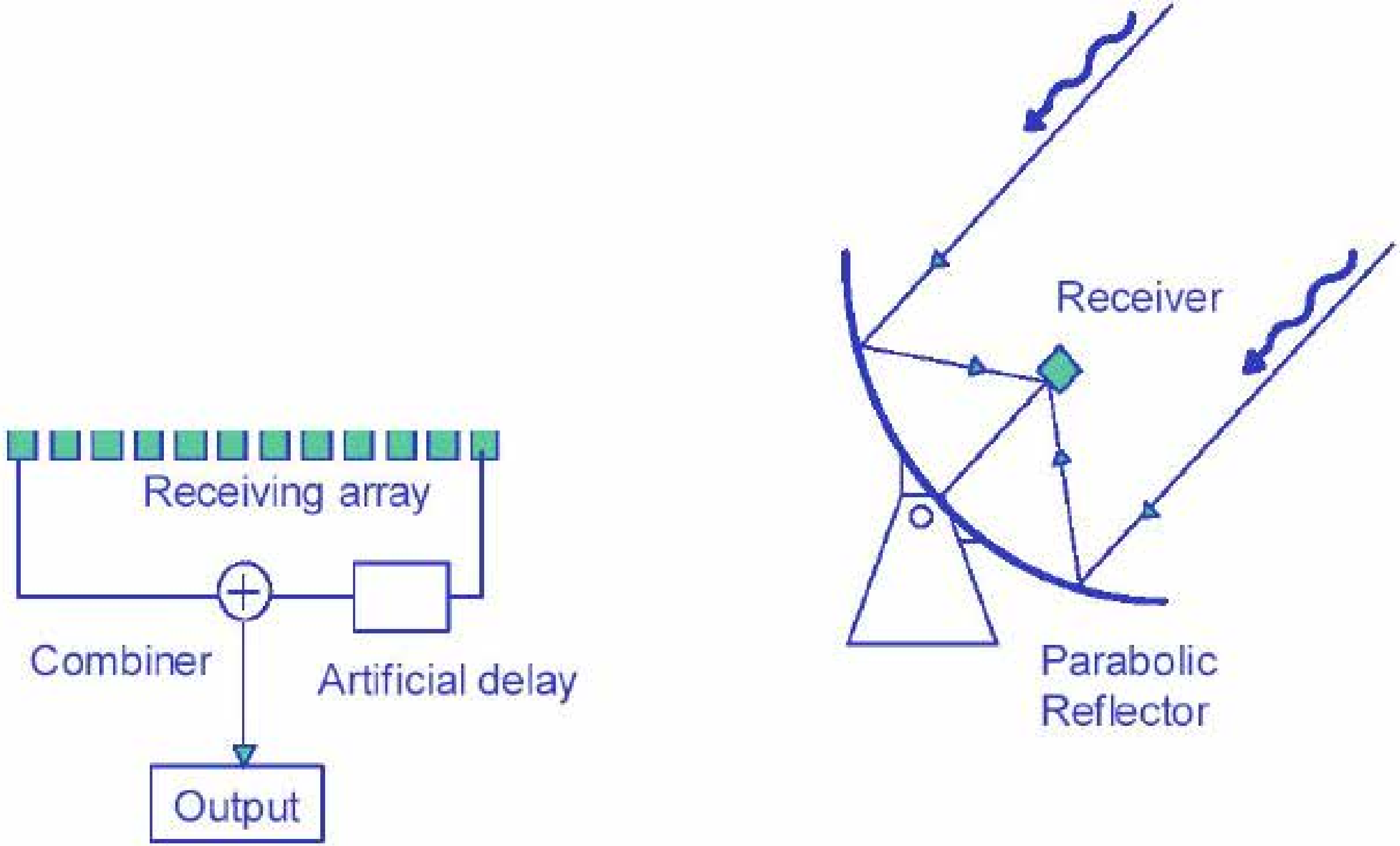
Advances in Radio Astronomy

Today:

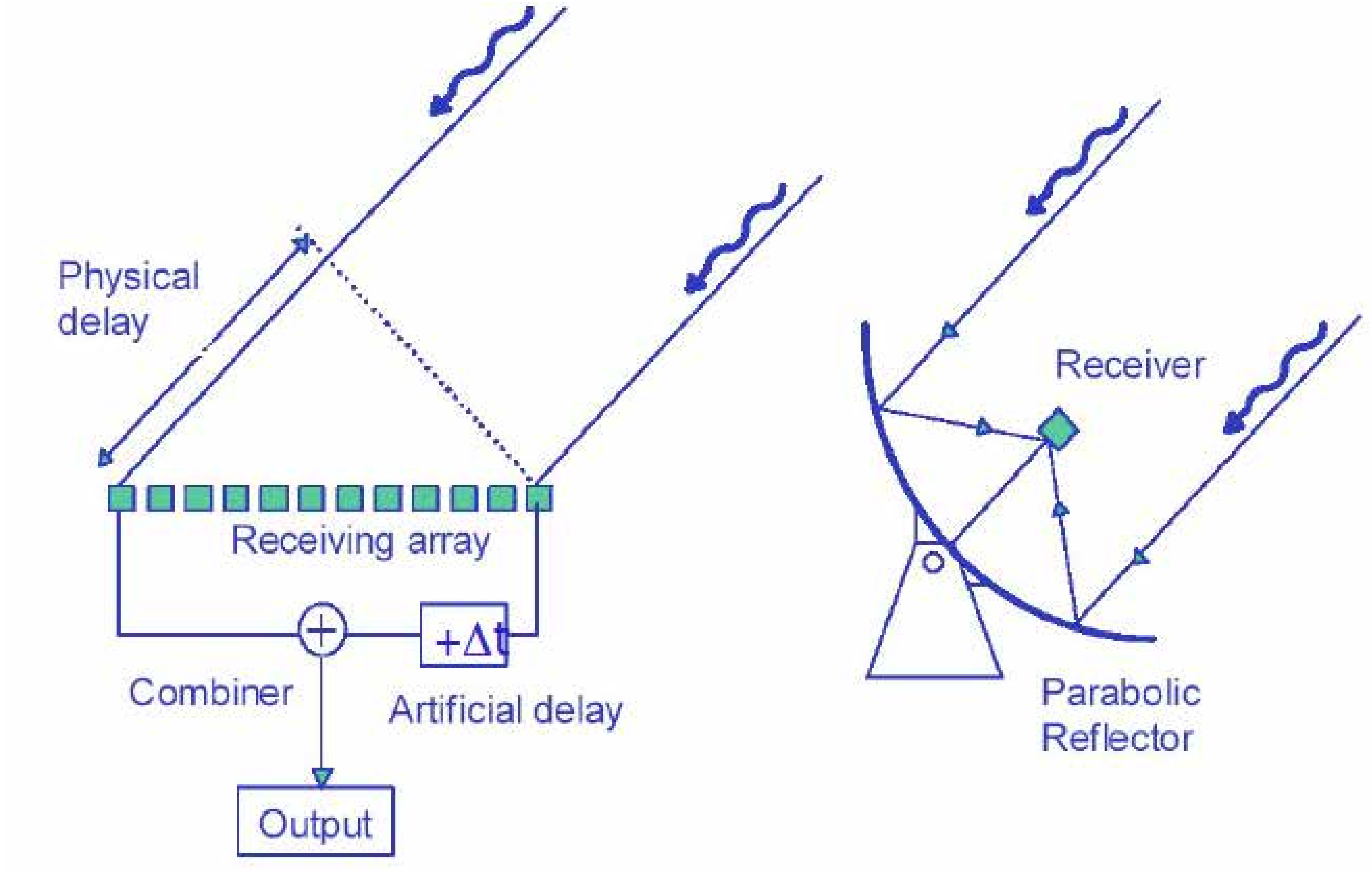
- Aperture arrays
- Low frequency observations



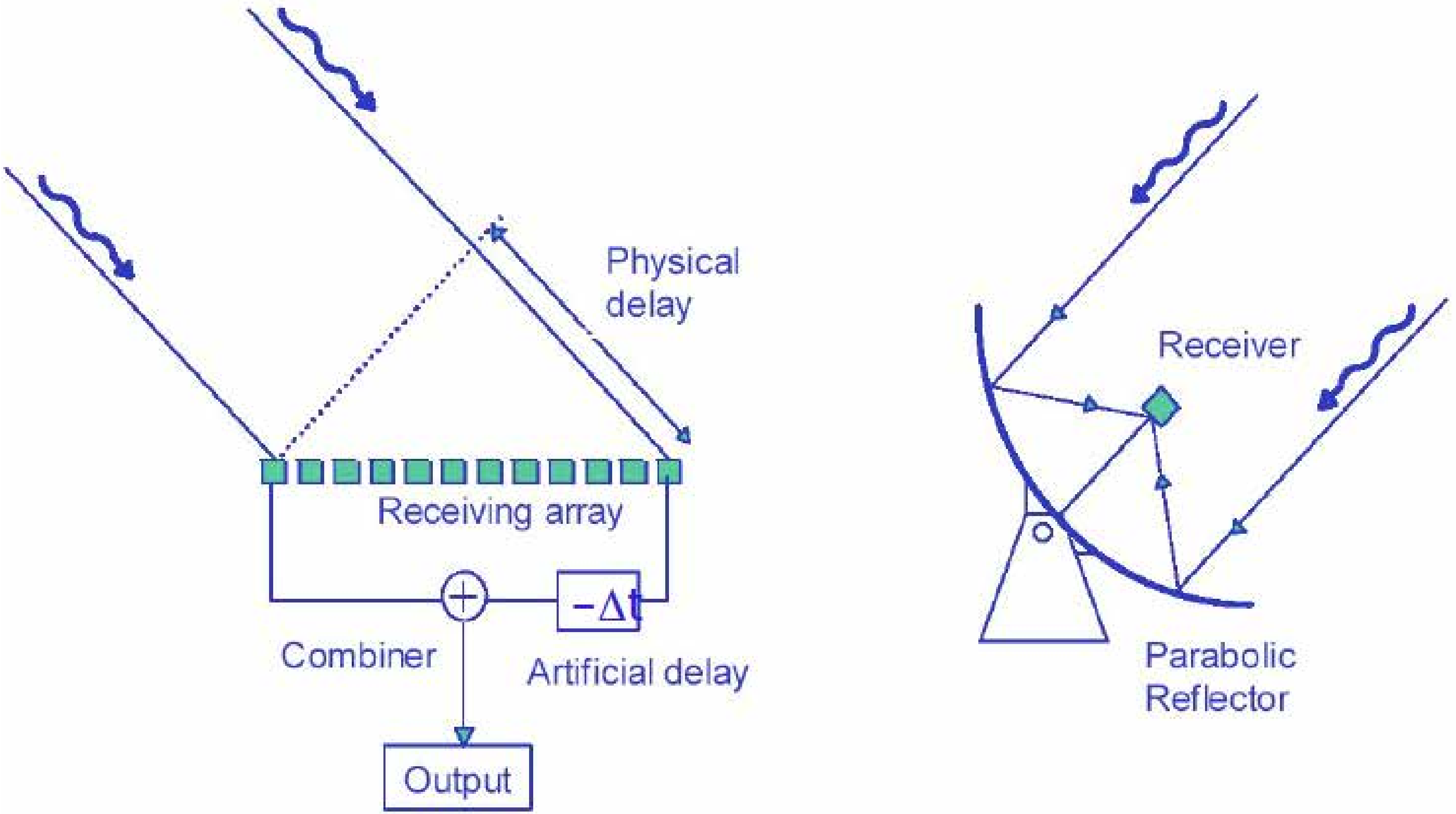
Aperture Arrays

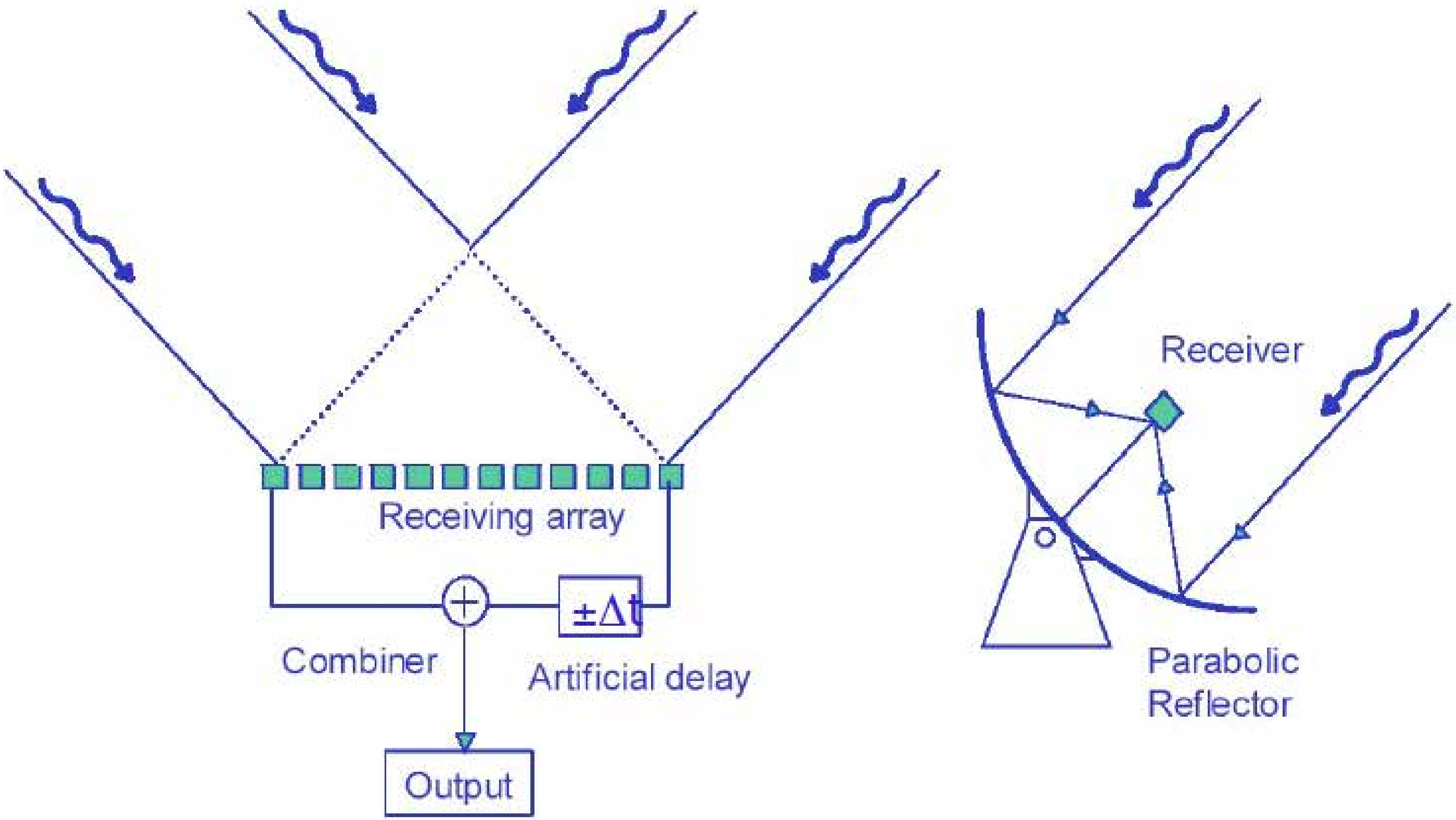


Aperture Arrays

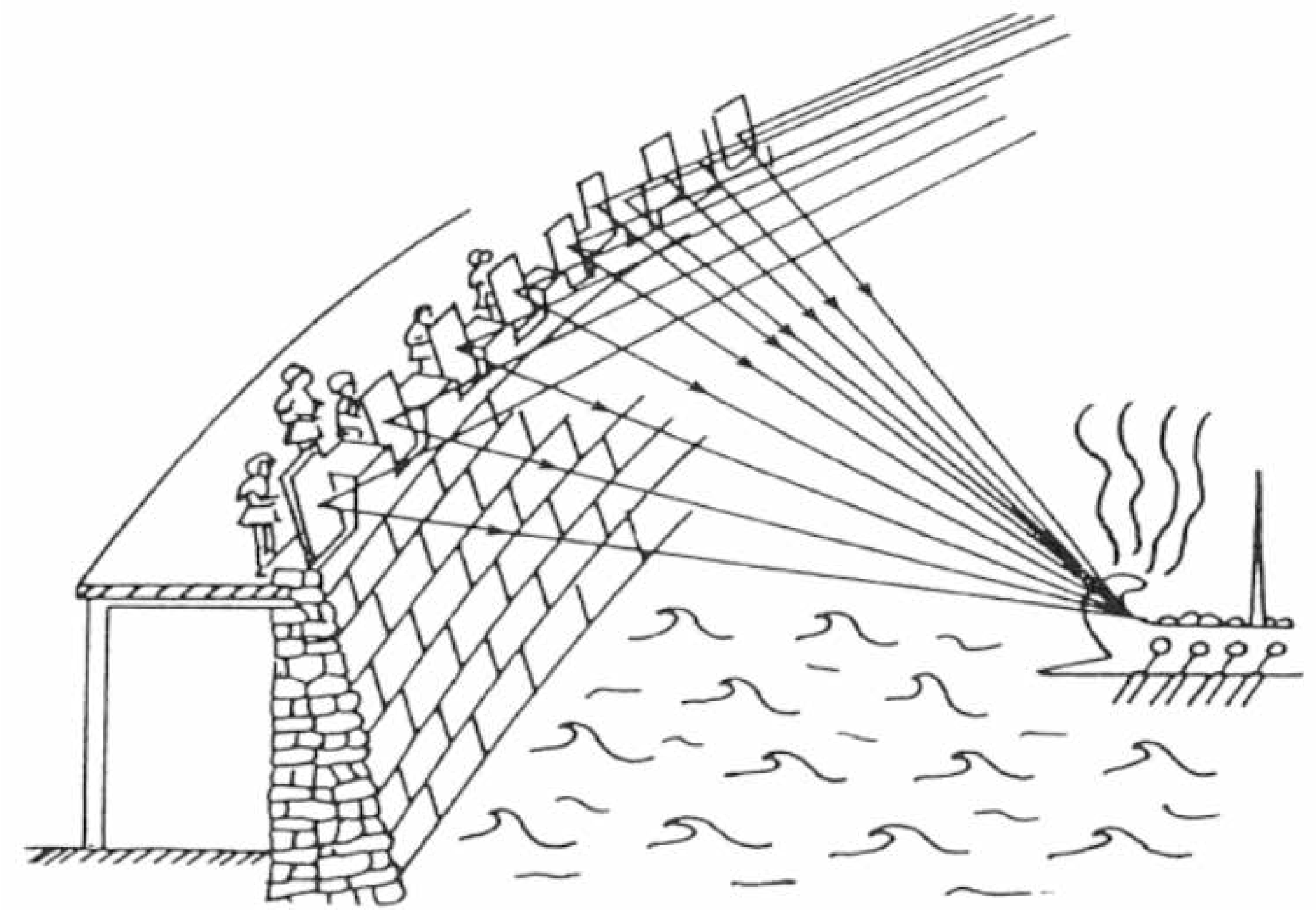


Aperture Arrays



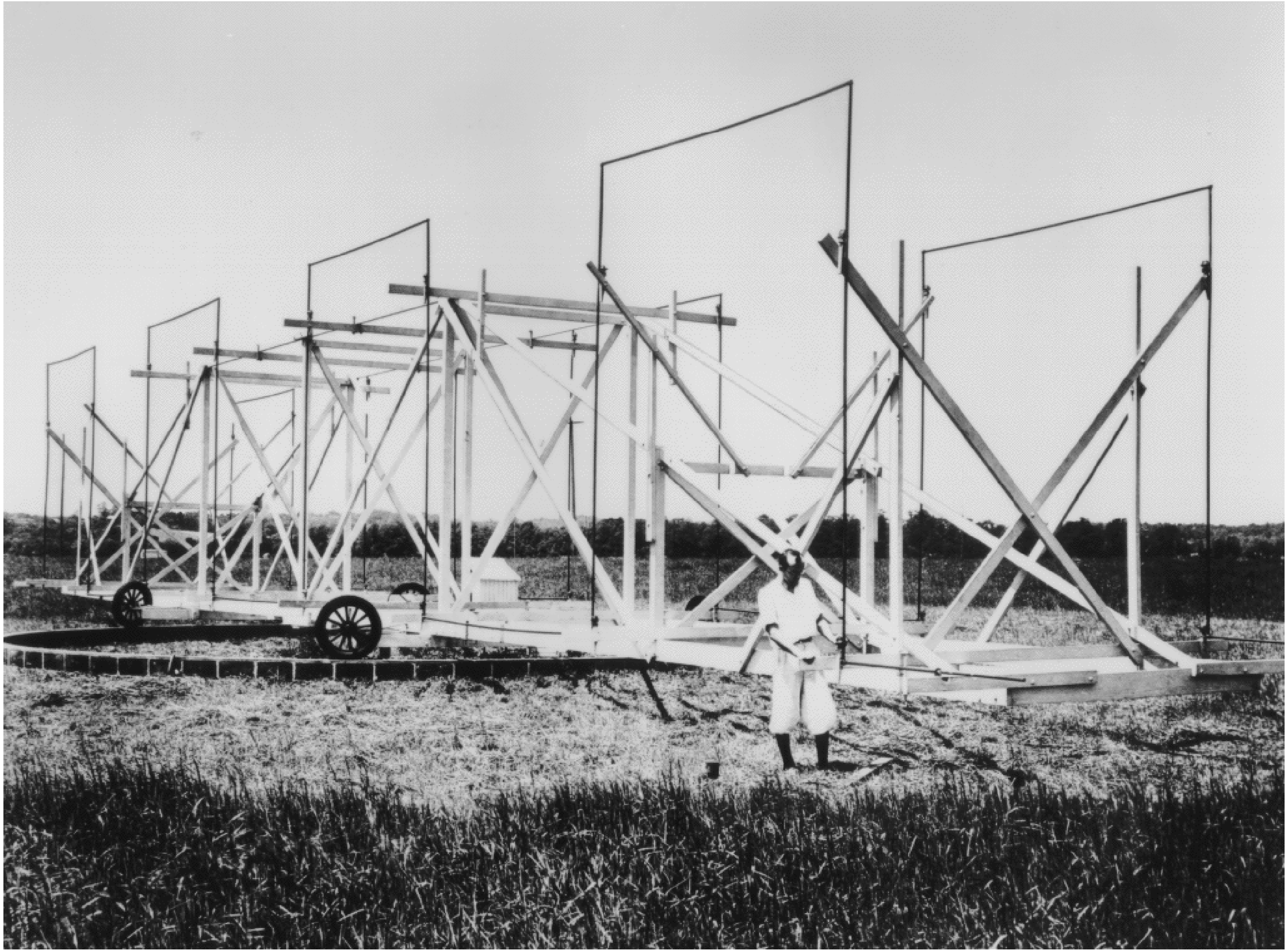

Receiving array
±Δt
Combiner
Artificial delay
Output
Receiver
Parabolic
Reflector

Not a new idea, however



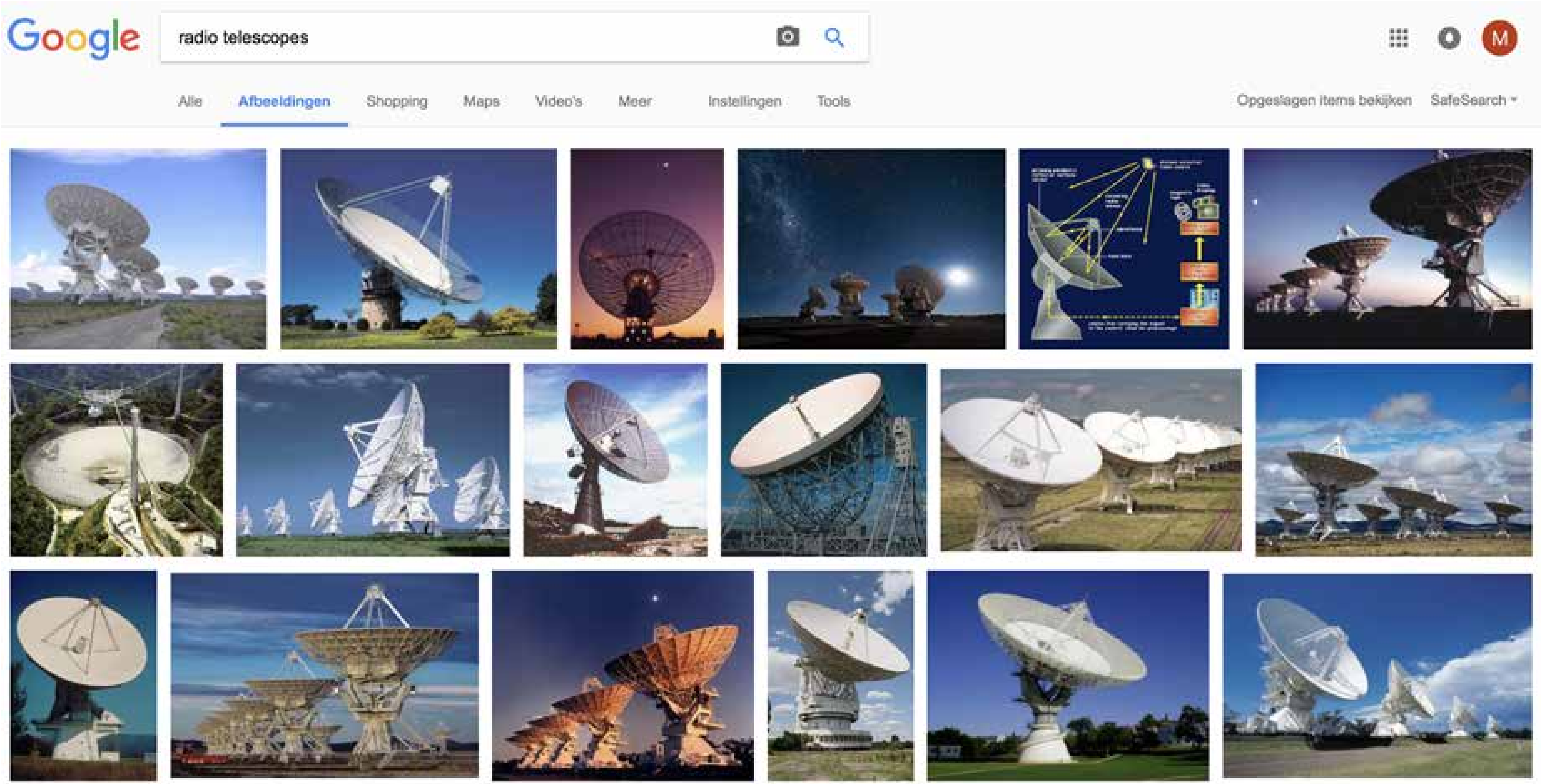
Archimedes (212 BC)

Phased arrays and Radio Astronomy

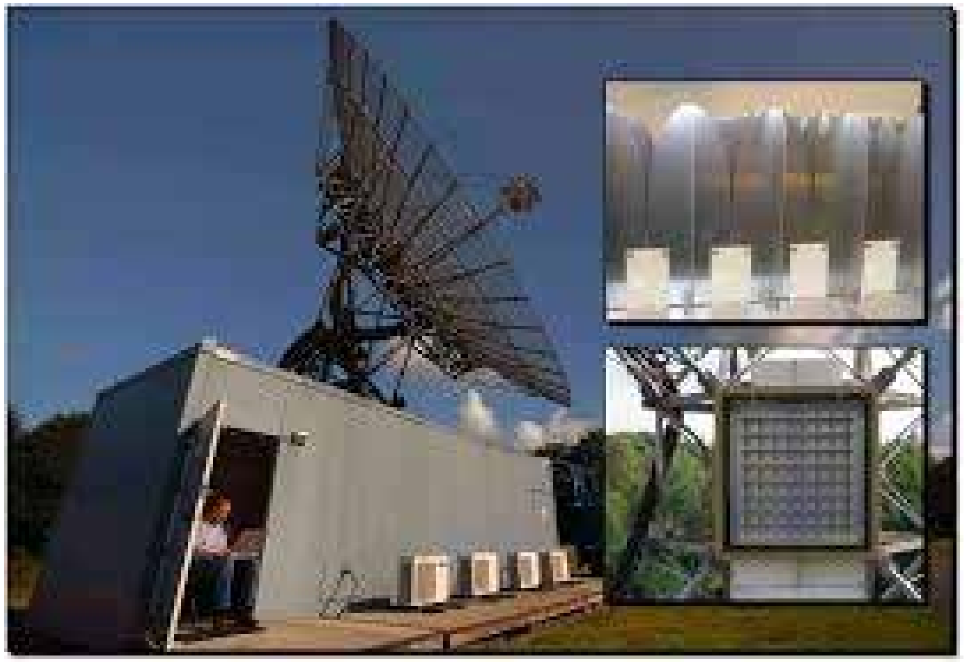


Phased arrays and Radio Astronomy

But after that ....



New revival at this moment - AAs



Why aperture arrays

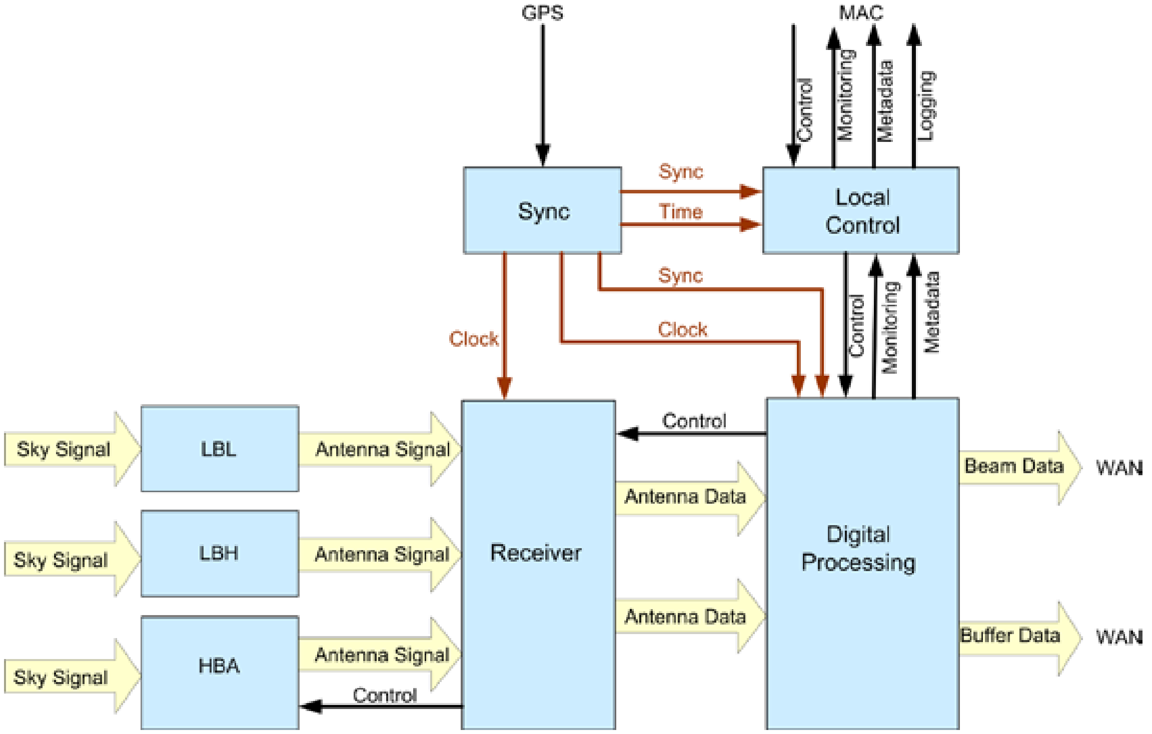
- Sensitivity.

$$q \sim l / D$$

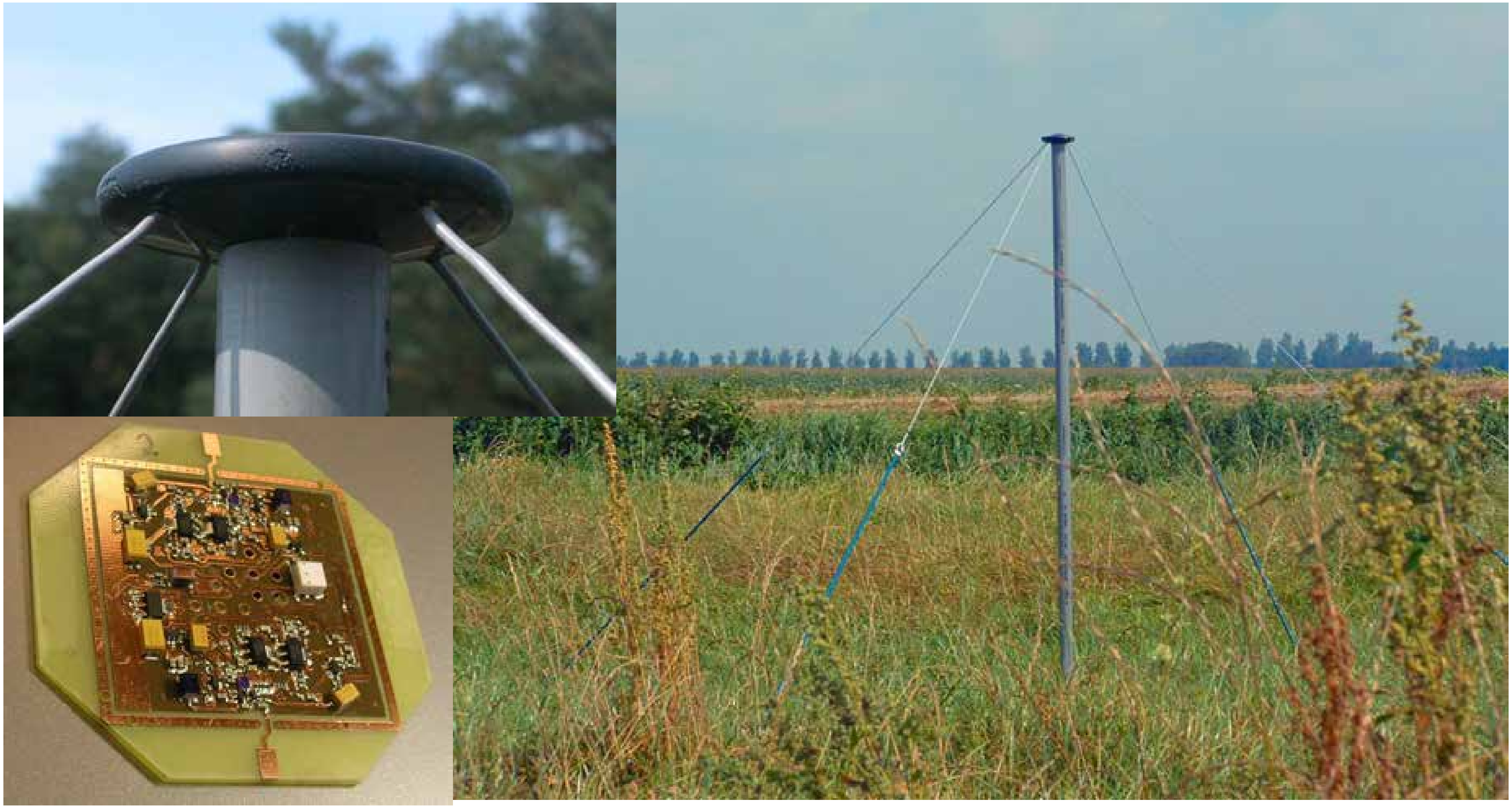
- Unblocked aperture with full view of the whole sky!
- Ultimate flexibility with no moving parts
- Beams are formed and controlled electronically at element level
- Permits concurrent, possibly associated, multi-beam observations
- Technology of choice at frequencies < ~1.5 GHz

What is an aperture array?

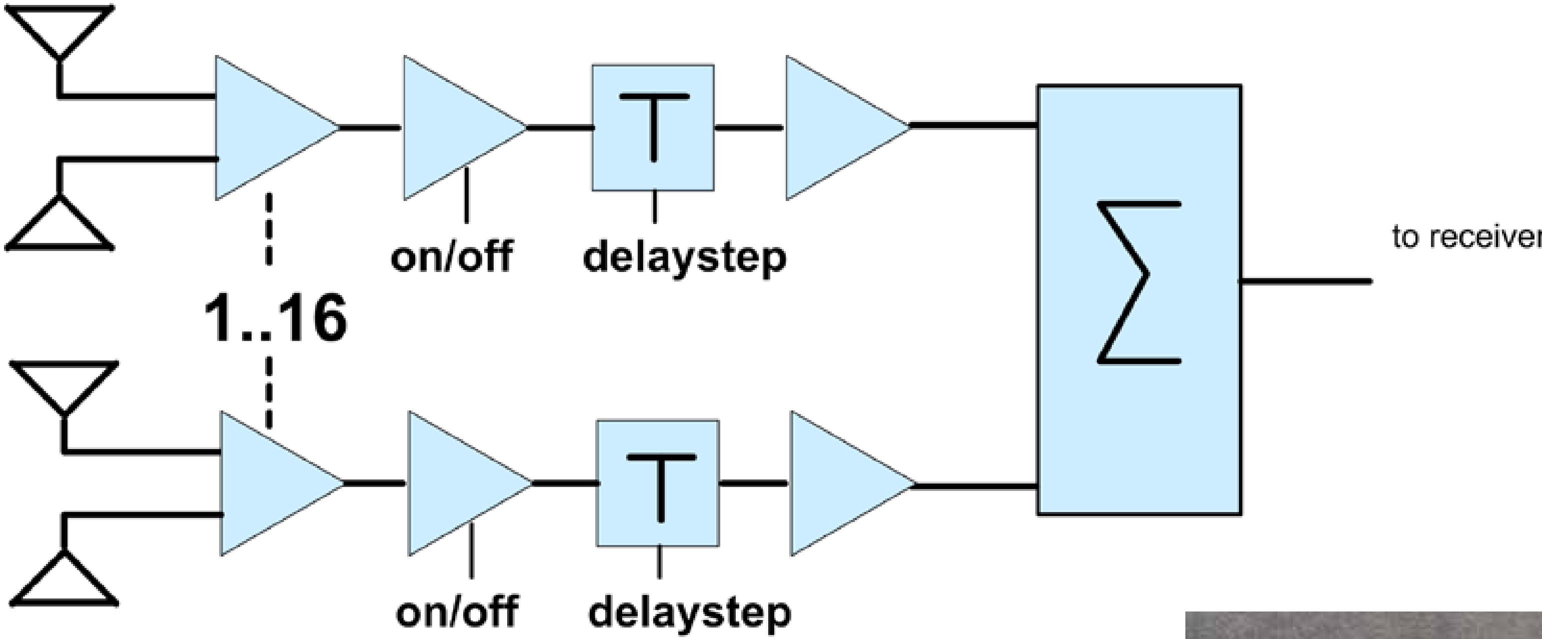
- Lot's of antenna's
- LNAs
- Receivers
- Beam formers
- Interferometer

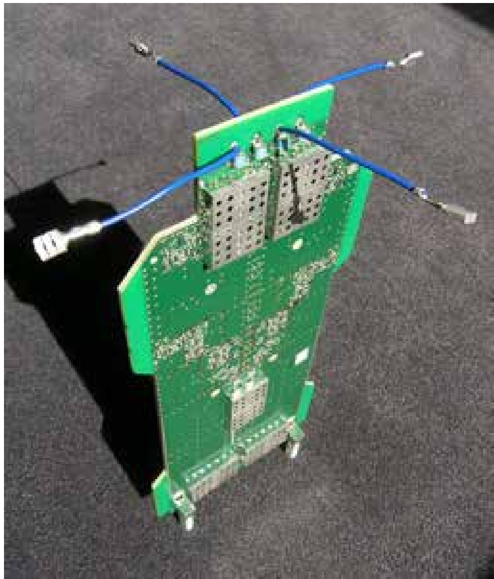


Low Band Antenna (30-80 MHz)

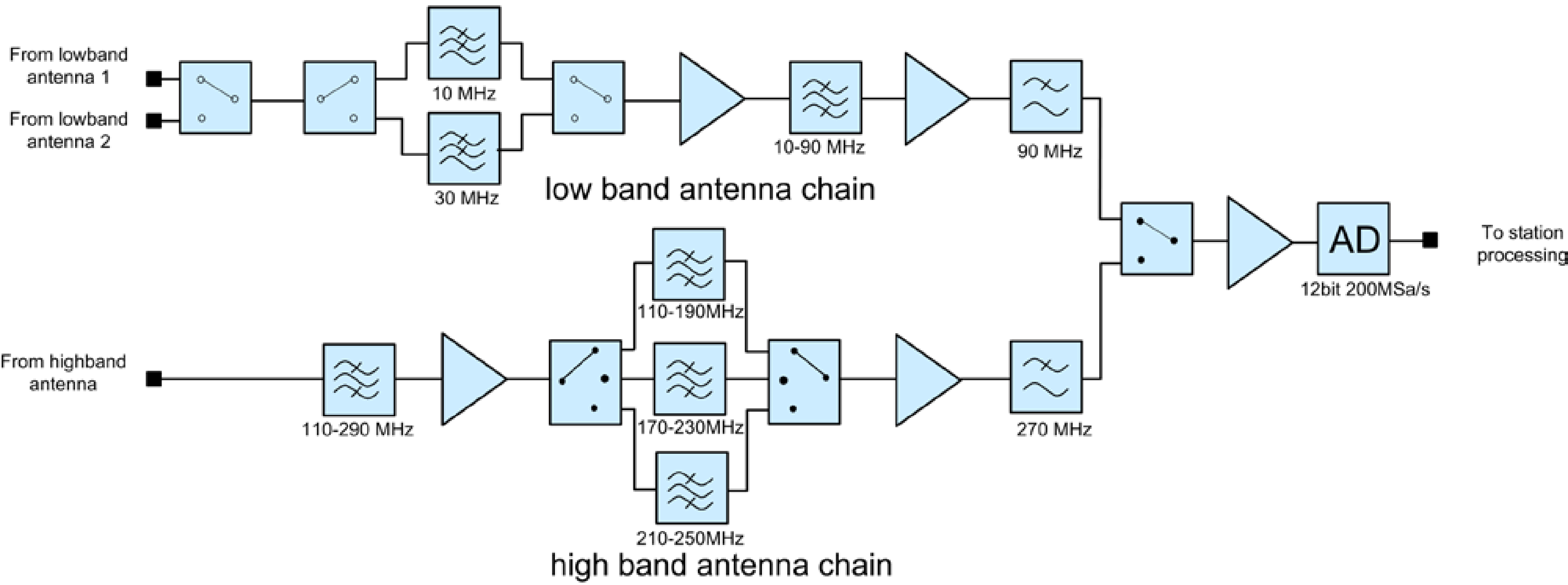


High Band Antenna (120-270 MHz)

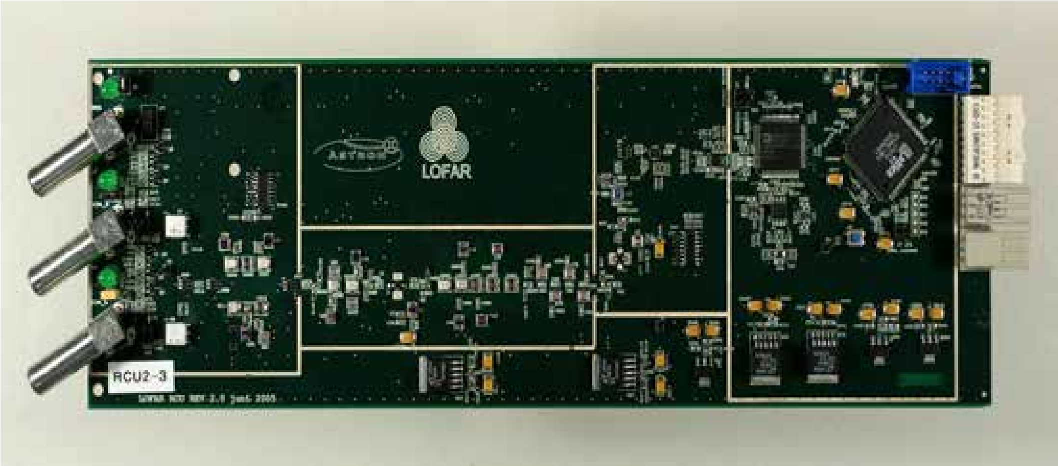




Receiver



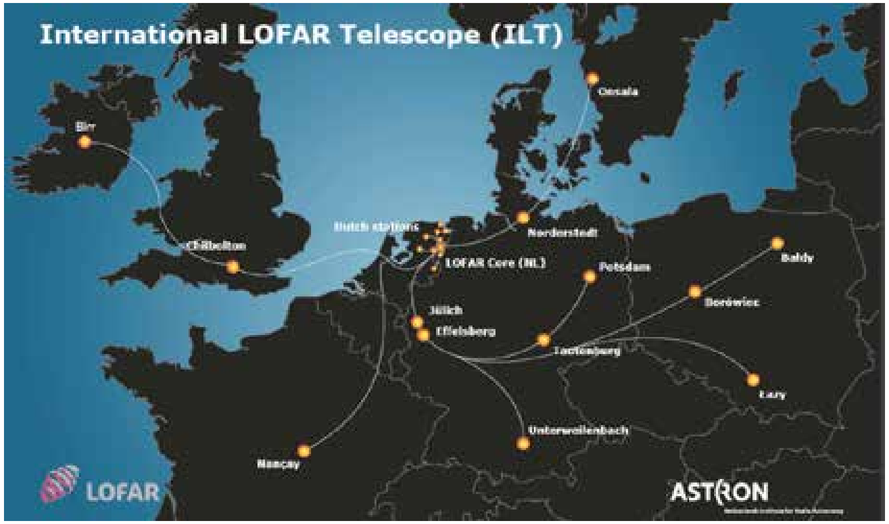
From lowband antenna 1
From lowband antenna 2
10 MHz
30 MHz
10-90 MHz
90 MHz
low band antenna chain
AD
12bit 200MSa/s
To station processing
From highband antenna
110-190MHz
110-290 MHz
170-230MHz
270 MHz
210-250MHz
high band antenna chain



LOFAR
RCU2-3

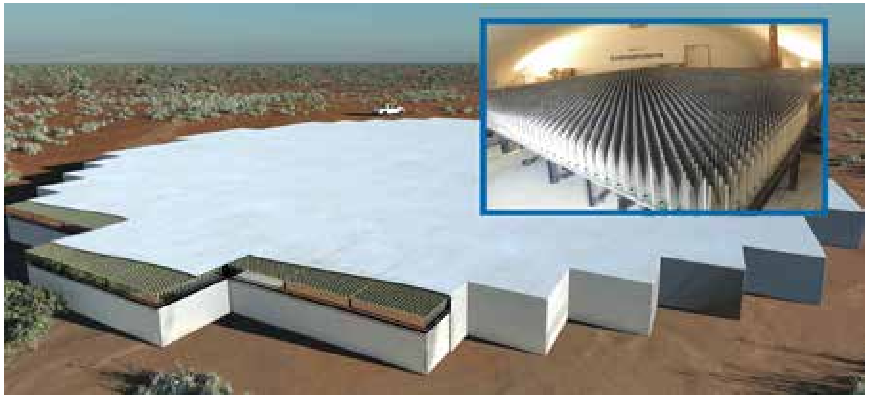
The future of aperture arrays

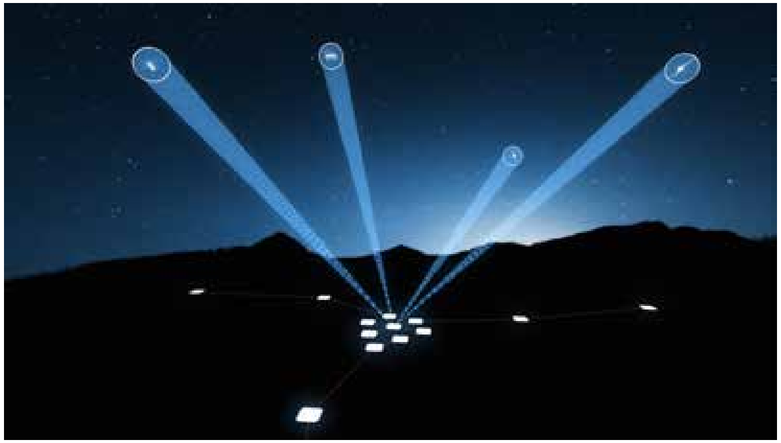
- Aperture Array concept now firmly established as technology of choice at frequencies < ~ 400 MHz:



The future of aperture arrays

- Higher frequency > 2 GHz
- PAFs – Phased array feeds
- LNA cooling
- Compact receiver systems
- Fully digital beamforming
- Multi-beams
- Wide bandwidth





Advances in Radio Astronomy

Today:

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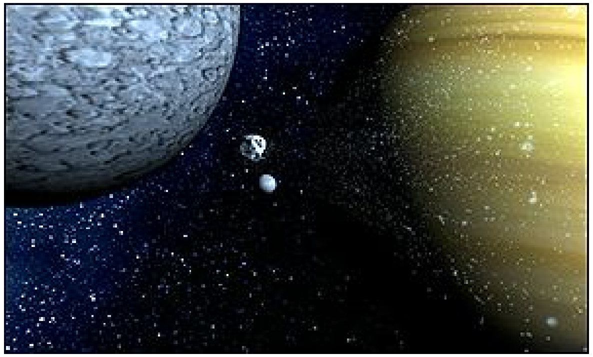
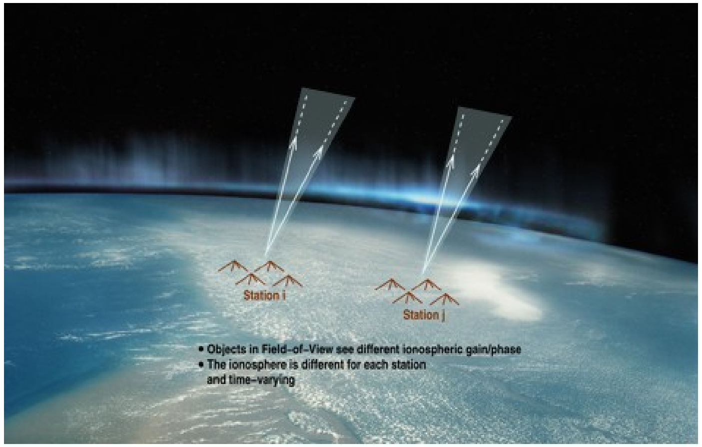
- Low frequency observations



Goal: an ultra long wavelength radio telescope

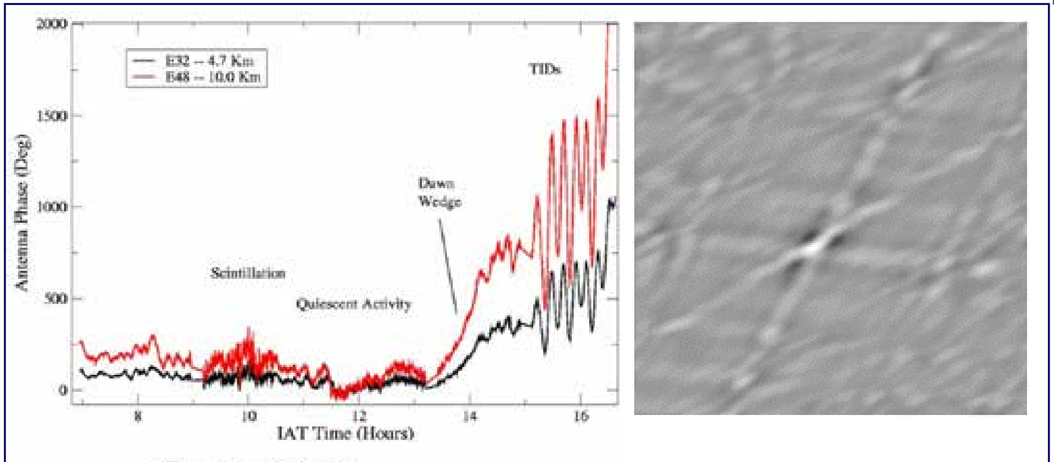
- Low frequency : below 30 MHz
- > ~30 MHz : LOFAR



è Opening up the last unexplored frequency regime

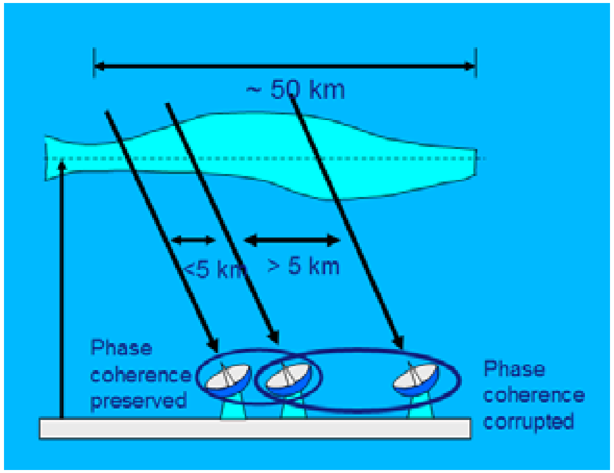
Why in space: ionospheric disturbance and cut-off

- Phase coherence through ionosphere
  - Corruption of coherence of phase on baselines
- Isoplanatic Patch Problem:
  - Calibration changes as a function of position



(Perley; VLA)

VLA image (movie) showing ionospheric disturbances of sky image, Perley, Lazio, 74 MHz



Maximum antenna separation:
< 5 km vs. >10^2 km
Angular resolution at 10 MHz:
q > 0.3° vs. < 10^{-2} °

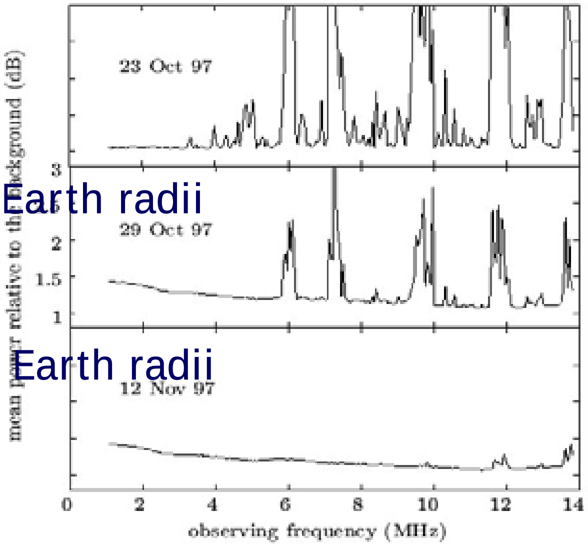
Why in space: radio frequency interference

Typical man-made interference received by the WAVES instrument on Wind

40 Earth radii

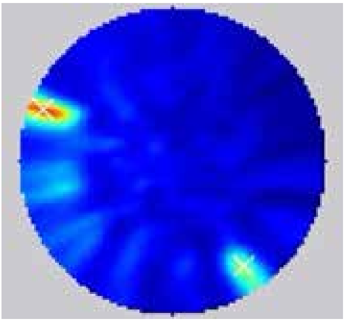
93 Earth radii

157 Earth radii

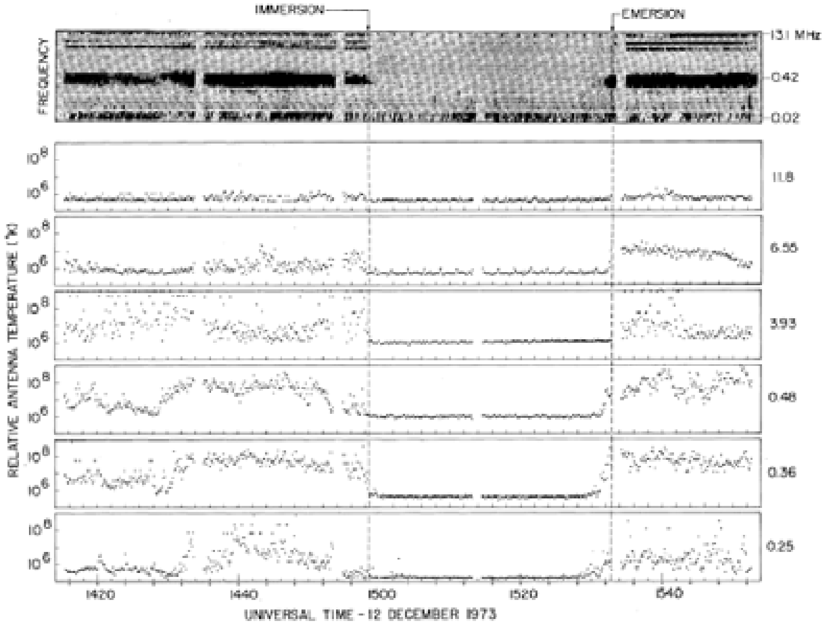


G. Woan from ESA study SCI(97)2

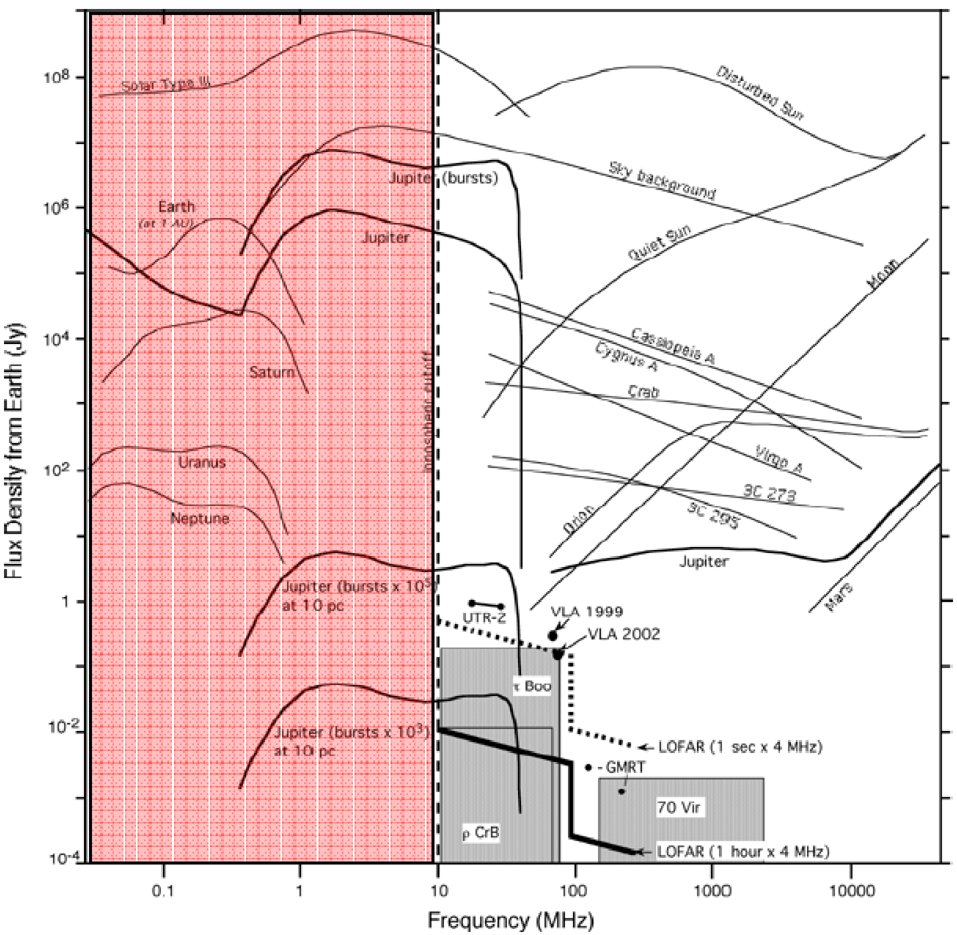
All-sky image (movie) of LOFAR ITS at 15.004 MHz
(Moren, Boonstra, 2007)



RAE B (1973) in Lunar orbit, Kaiser 1975



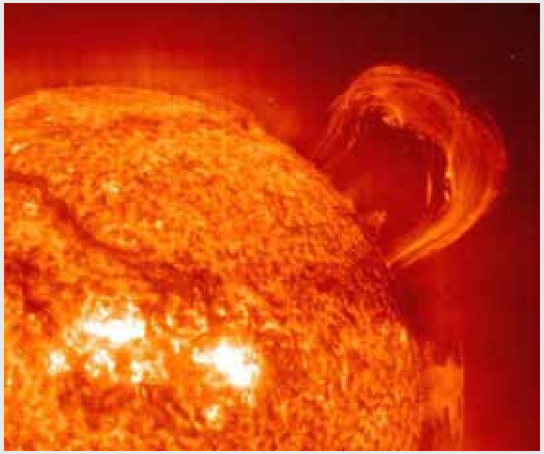
Why is it interesting: New frequency window

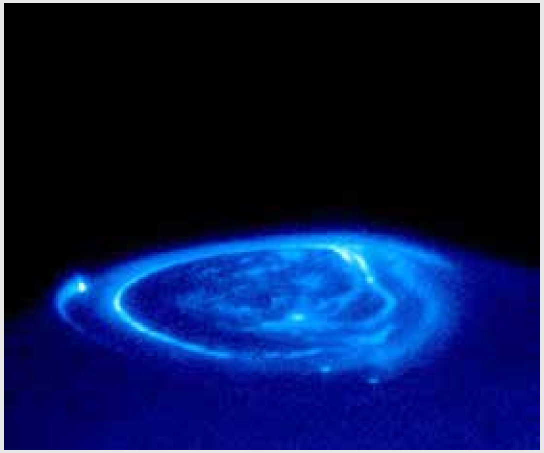


- At very low frequencies the universe is virtually unexplored
- The earth's ionosphere masks the key low frequencies
- Science cases:
  - Extra-galactic surveys
  - Transients (Jupiter-like flares, Crab-like pulses, extra-solar planetary burst, etc)
  - Solar activity and Space Weather
  - Coronal activity in atmospheres of large planets
  - Detection of Exo-Planets
  - On the moon: lunar geology & impacts of neutrino's and UHECR

Why is it interesting: Radio sources

Astronomical radio sources





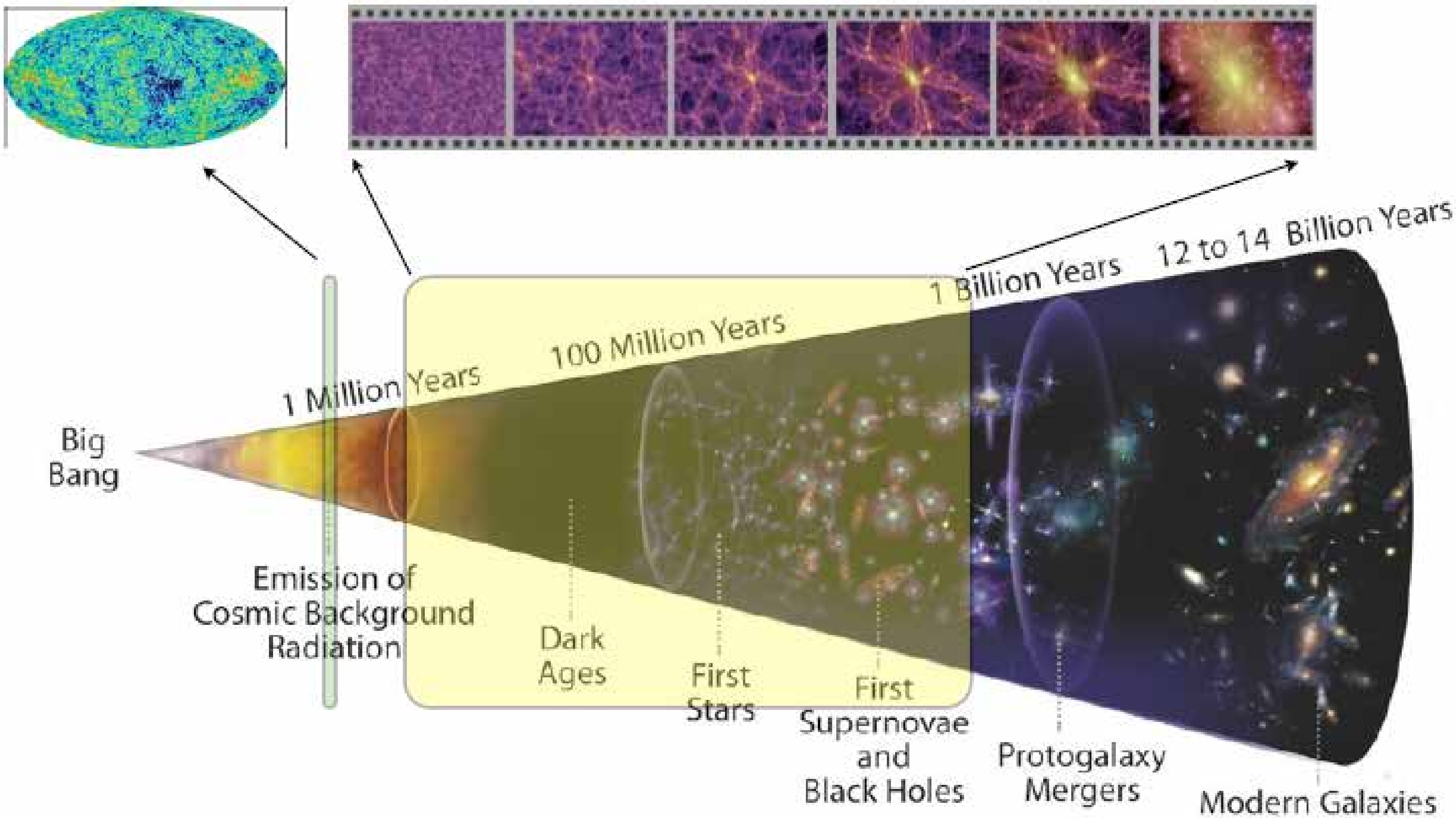
Radio galaxies	**Solar eruptions**	**Aurora’s of planets**
(static source)	(transient source)	(transient source)

Why it is interesting: exoplanets

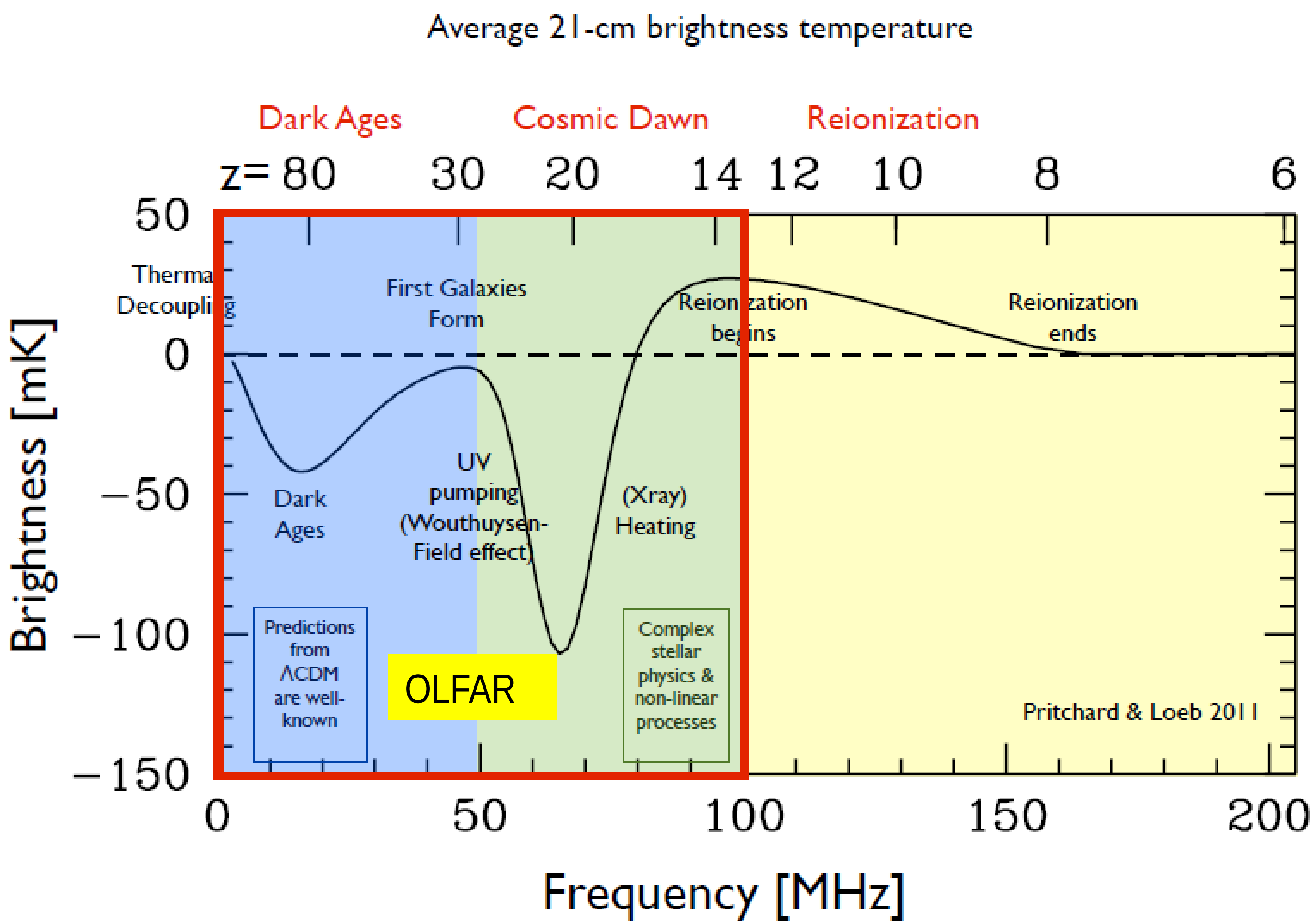
Why is it interesting: Dark ages

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving "movie" of baryonic structure formation. ($<10^9$ yrs)



Dark ages explorer

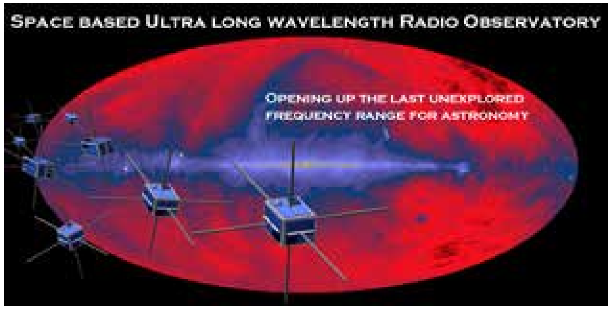


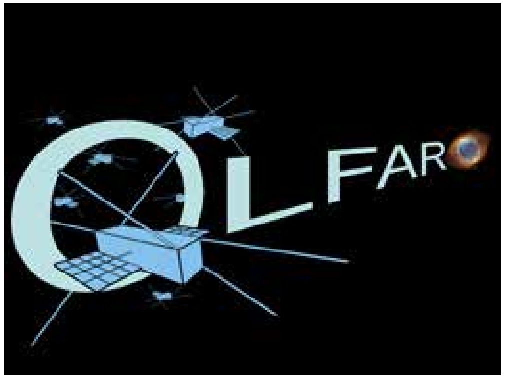
Science overview

1. **LF sky mapping + monitoring** : radio galaxies, large scale structures (clusters with radio halos, cosmological filaments, ...), including polarization, down to a few MHz
2. **Cosmology** : measurements of the red-shifted HI line that originates from before the formation of the first stars (dark ages, reionization)
3. **Interaction of ultra-high energy cosmic rays and neutrinos with the lunar surface**
4. **Low-frequency radio bursts from the Sun** : CME, ... Space weather
5. **Auroral emissions from the giant planets' magnetospheres in our solar system**: rotation periods, modulations by satellites & SW, MS dynamics, seasonal effects, ...
6. **Detection of pulsars down to ULF**, with implications for interstellar radio propagation
7. **The unknown** …

Current interest

- ALFA (Jones et al., 1998)
- DARIS (Bentum, Boonstra, et al. 2010)
- FIRST (Bergman et al. 2009)
- SURO (Baan, Bergman, Boonstra, Bentum et al, 2012)
- VLFA (Smith, 1990)
- MERIT (Jones et al., 2007)
- DEX (Bentum, Klein-Wolt M. et al., 2013)
- LORAE (Burns, 1990)
- DARE (Burns et al., 2012)
- SOLARA (Knapp, Babuscia et al, 2012)
- NOIRE (Cecconi et al. 2015)
- …



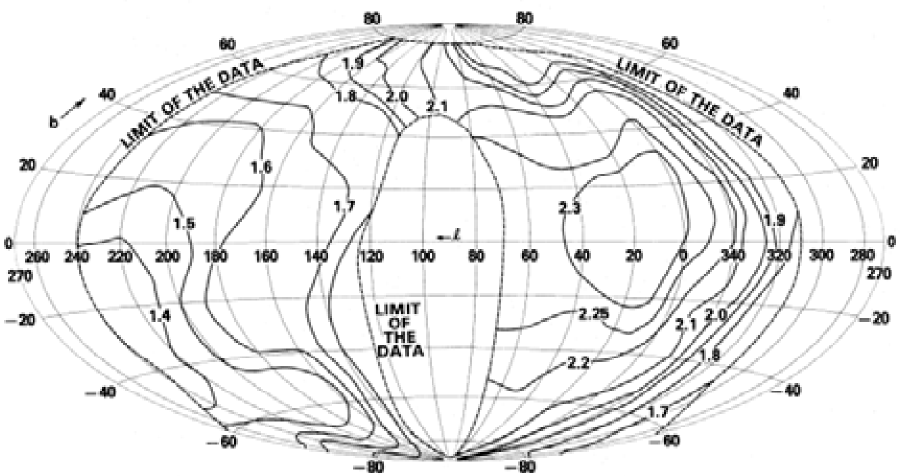


Current Status at Long Wavelengths

Extremely poor resolution, strong diffuse Galactic emission

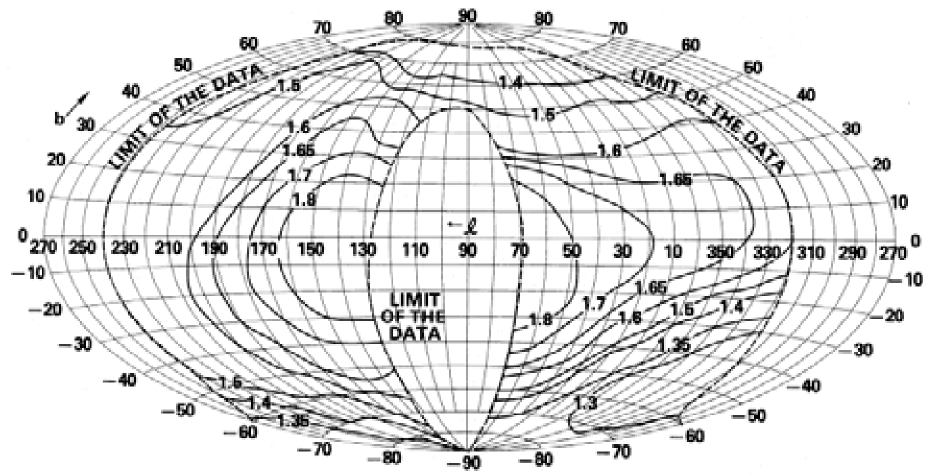
RAE-2 observations at
1.3 and 4.7 MHz, Novaco
& Brown 1978

slide from G. Woan



CONTOURS ARE IN UNITS OF 10^6K

FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz



CONTOURS ARE IN UNITS OF 10^7K

FIG. 8.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 1.31 MHz

Requirements for such an instrument

Parameter	Symbol	Range
Frequency range	f	0.1-30 MHz
Sensitivity	S_{min}	< 10 Jy in 1 hour; < 64 mJy in 1 Y
Distance, maximum baselines	D	100 km
Angular resolution	Δα	1 arcminute
Spectral resolution	df	1 kHz
Bandwidth (fractional bandwidth)	Δf	10 MHz
Snapshot integration time	Δt	≥ 1 s
Survey integration time	ΔT	≥ 1 year, nominal 3 years
Number of satellites	Nsat	>50
Range accuracy	ΔD	0.1 λ

Strawman designs

Moon-based: Earth-RFI shielded

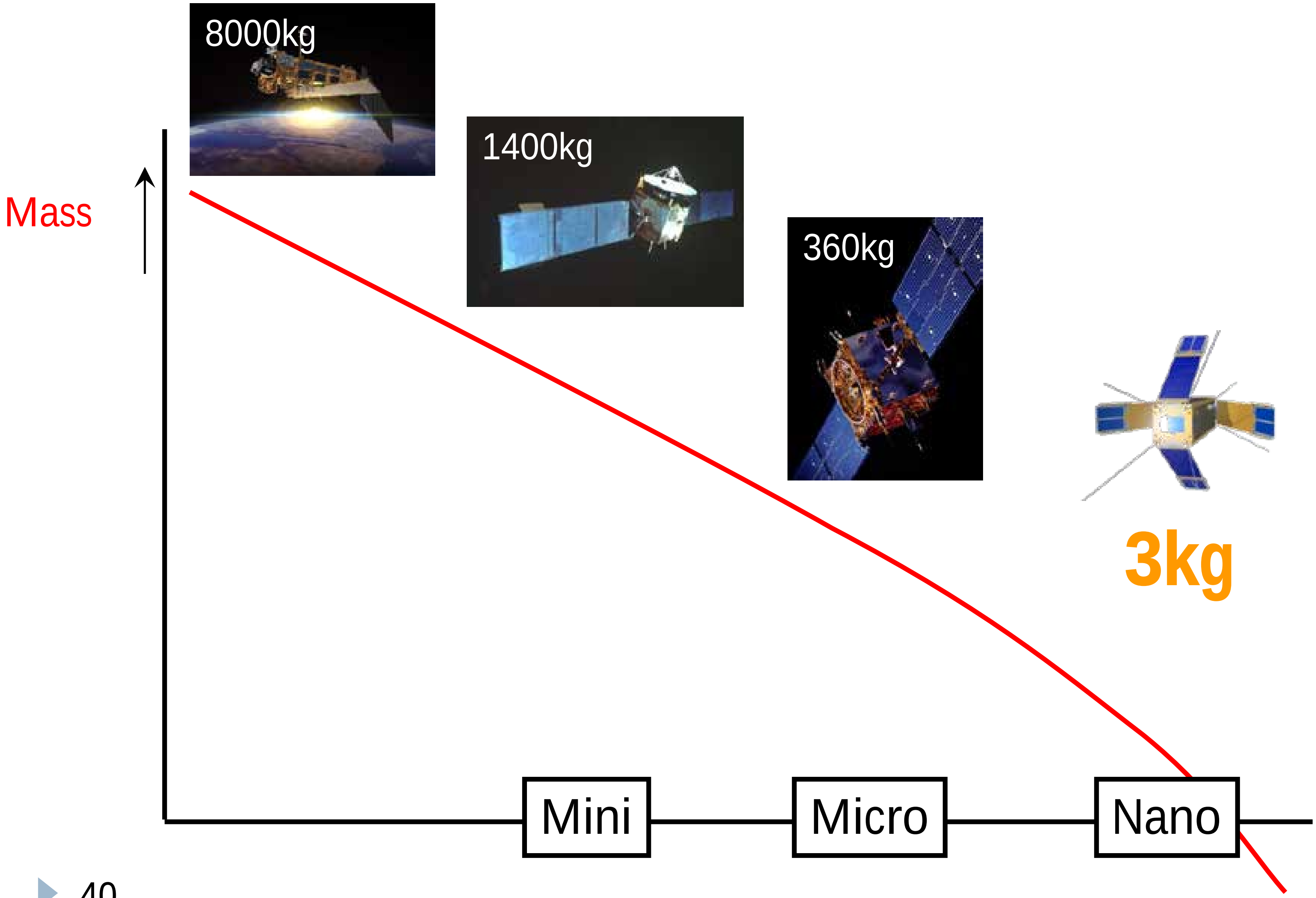
- Lander: deployment system (robots), comms/downlink, power, data processing
- Orbiter: comms/downlink
- Payload: thin-film sheets (ROLSS NASA concept)

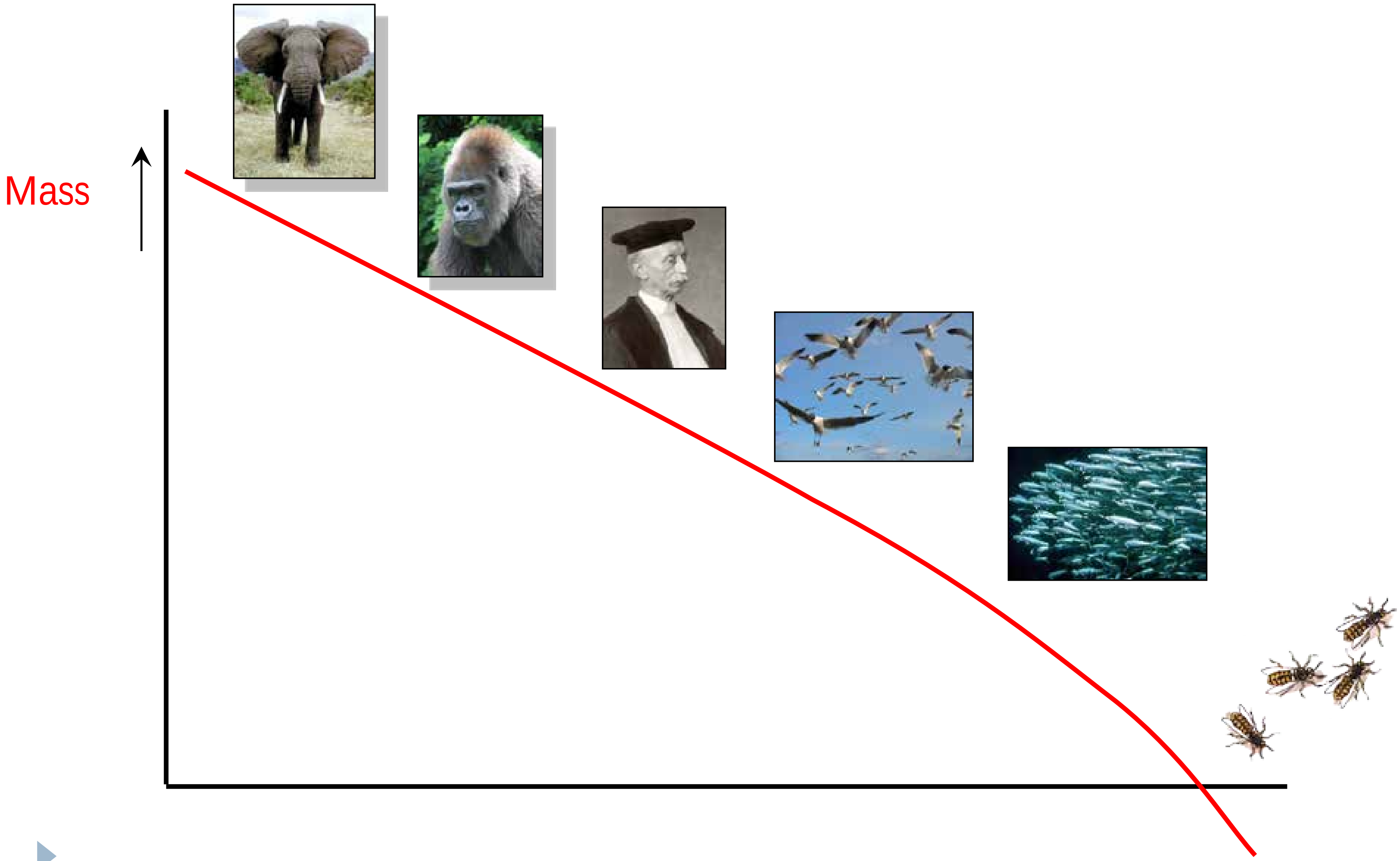
Space-based Lagrange points

- Mothership: deployment inflatable structures, comms/downlink, power, data processing
- Payload: light-weight structures, balloons, solar-sail-like

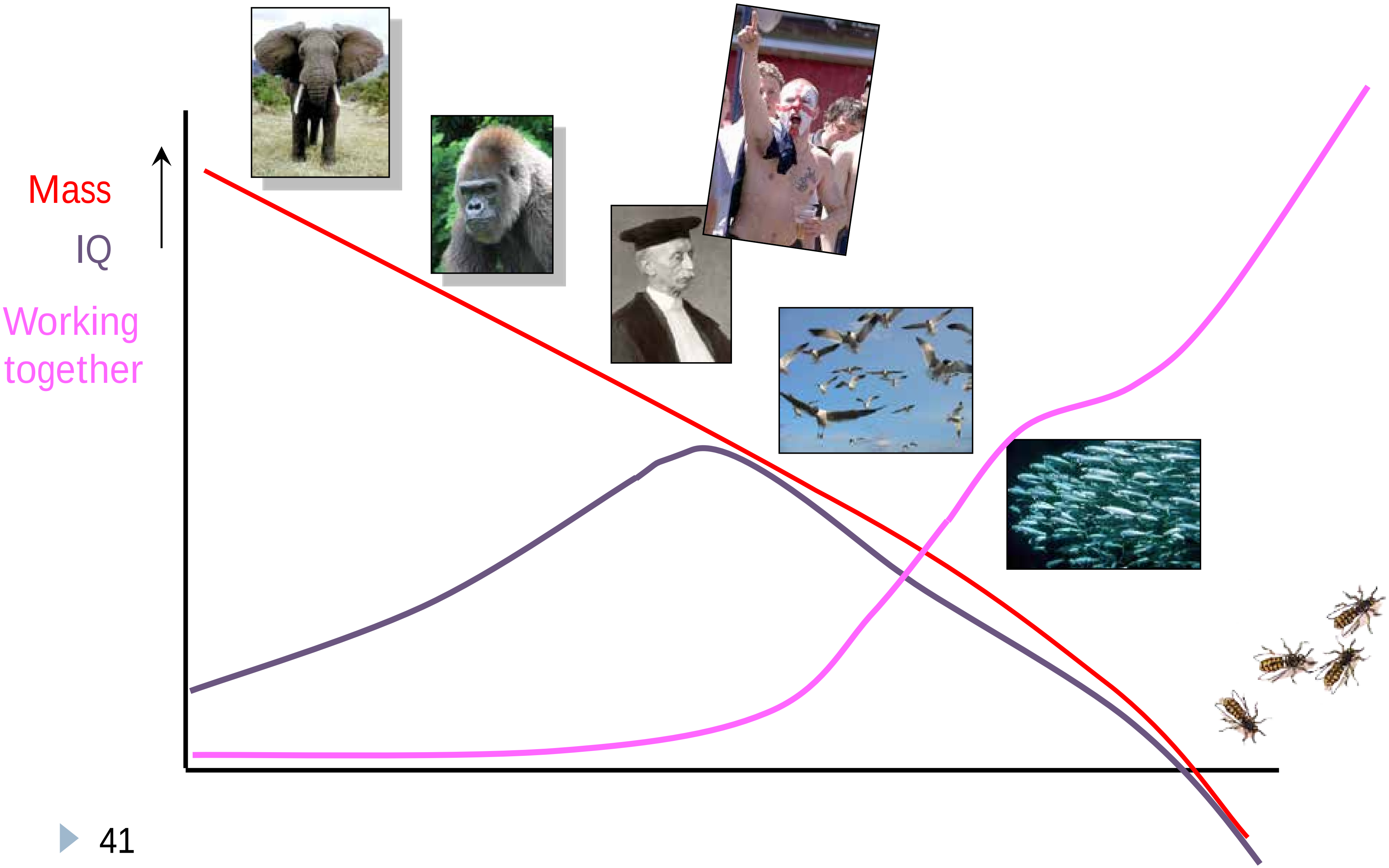
Launcher: future heavy launchers (100+ tons), e.g. Falcon Heavy (SpaceX), SLS (NASA), i.e. cheaper and larger commercial space flight opportunities

Satellites

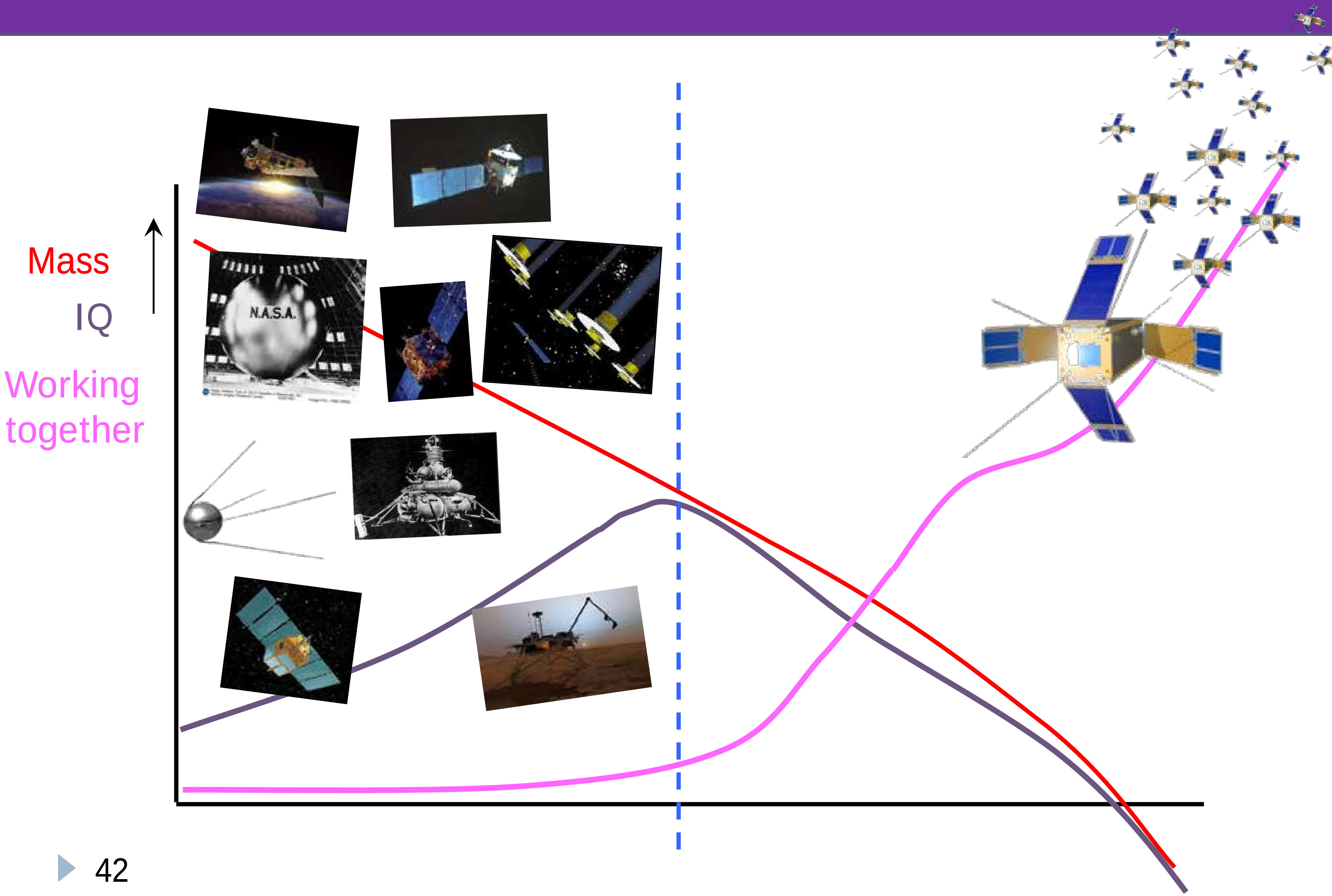




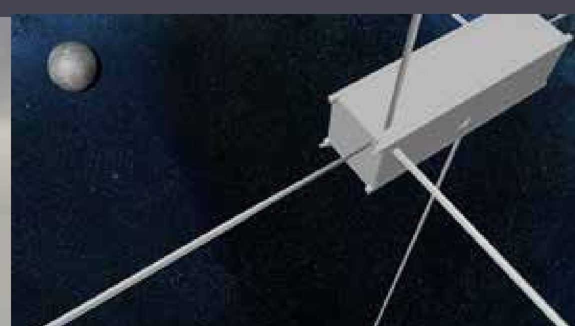
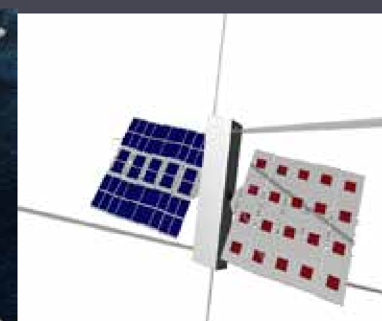
Mass



Mass
IQ
Working together


Mass
IQ
Working together
N.A.S.A.

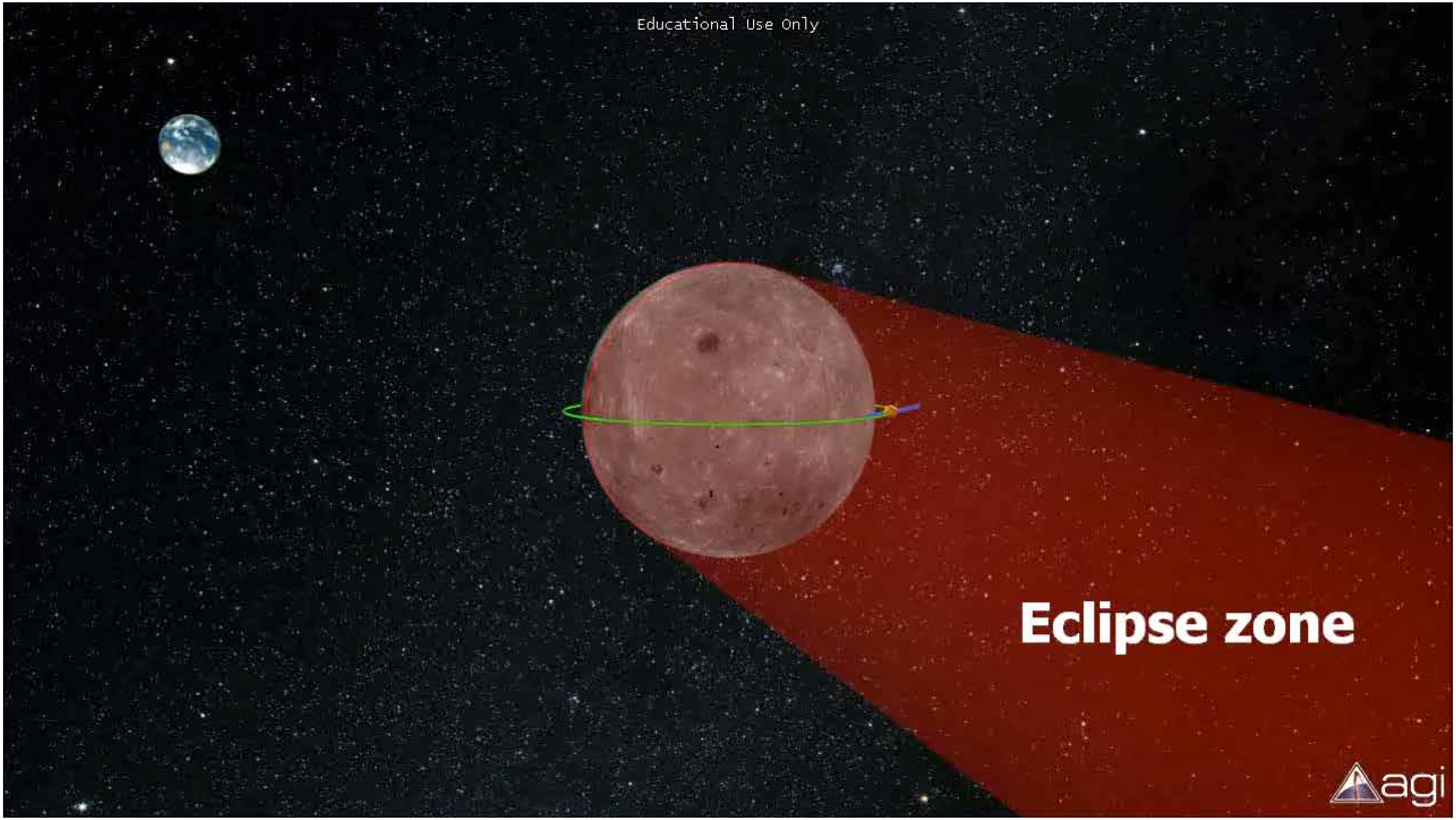
Orbiting Low frequency antennas for radio astronomy


Basic idea of OLFAR

- Nano/small satellites
- Swarm of > 50 satellites
- Deployable antenna for the frequency band between 1 and 30 MHz
- Ultra-low power receivers
- Intra-satellite communication
- Autonomous distributed processing
- Using diversity techniques for downlink

OLFAR concept



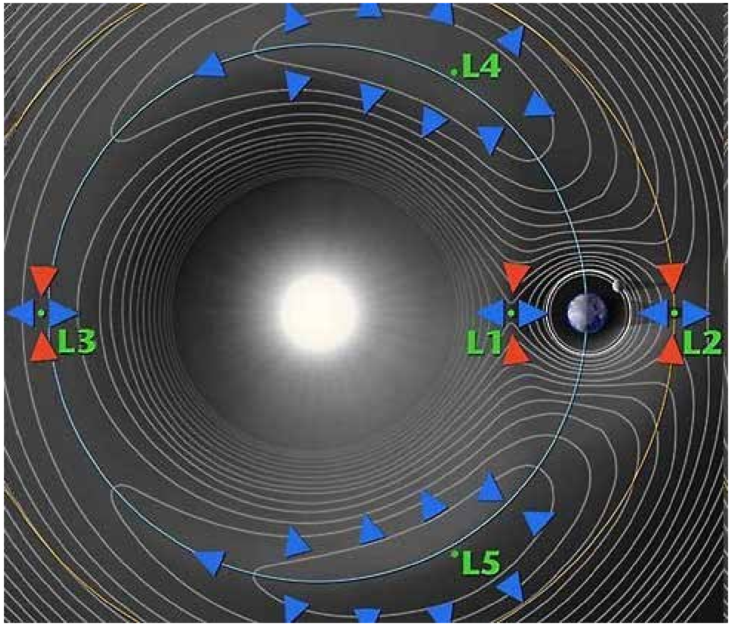
Mission analysis (orbits)

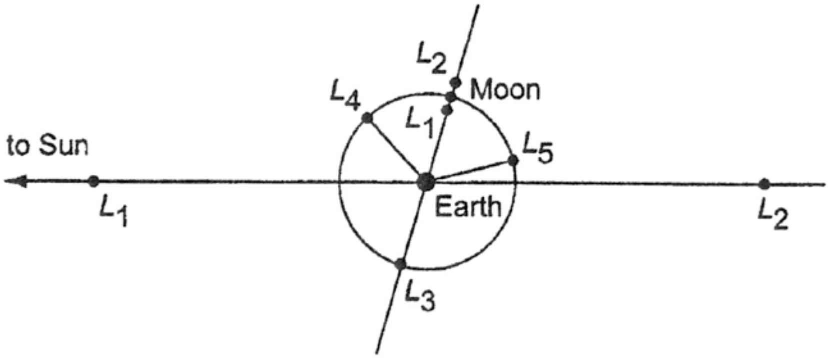
Design considerations

- Astronomical science
- RFI from Earth
- Intergration time, range rate
- Constellation control
  (abs. and rel. position)
- Downlink to Earth

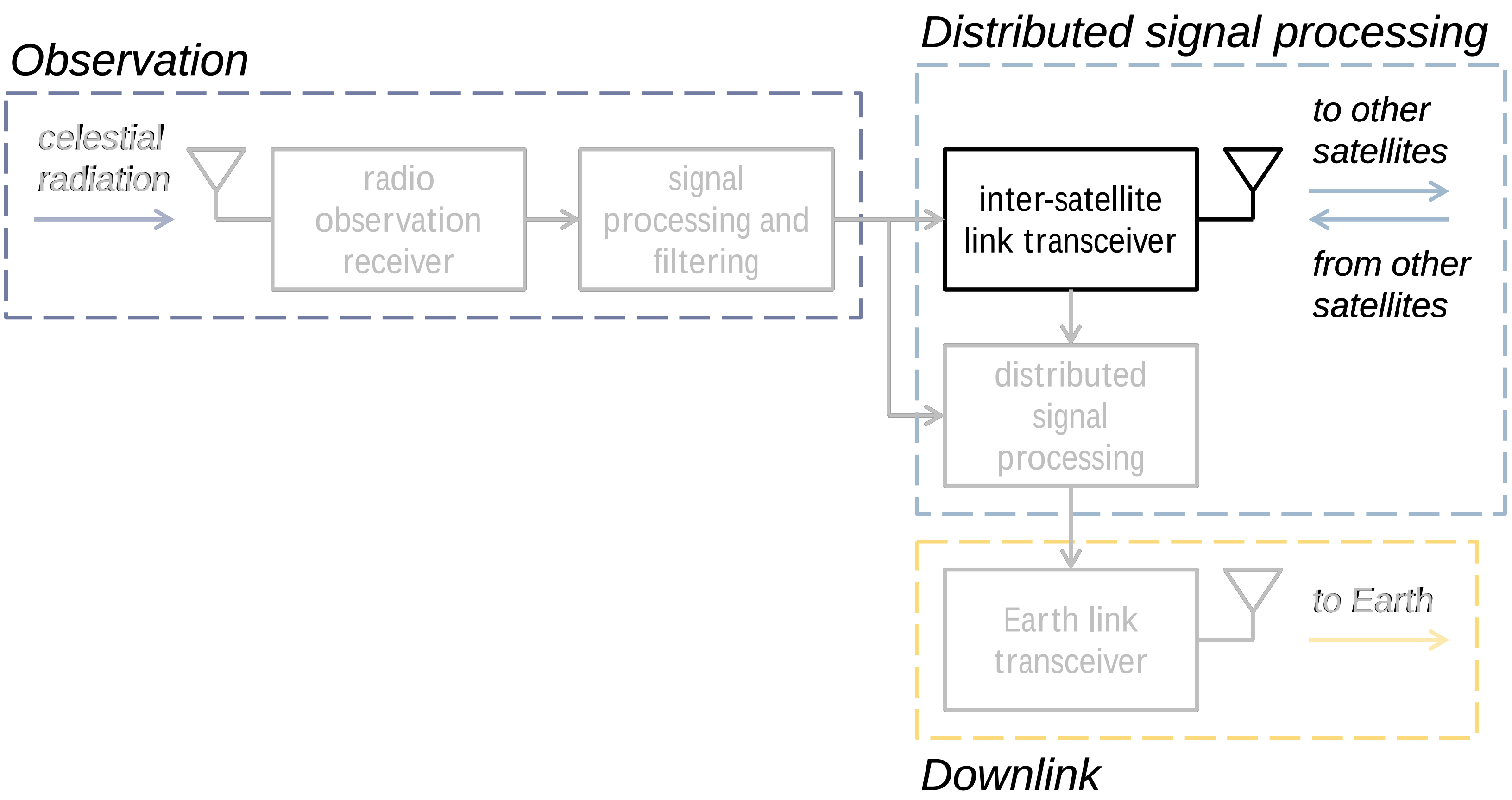
Possible orbits:

- Earth orbit
- **Moon orbit**
- Earth-Moon L2 (saddle point)
- Sun-Earth L4/L5
- Sun-Earth leading/trailing orbit
- **Dynamic solar orbit**
- Sun-Earth L2 (saddle point)
- **Moon surface - far side**



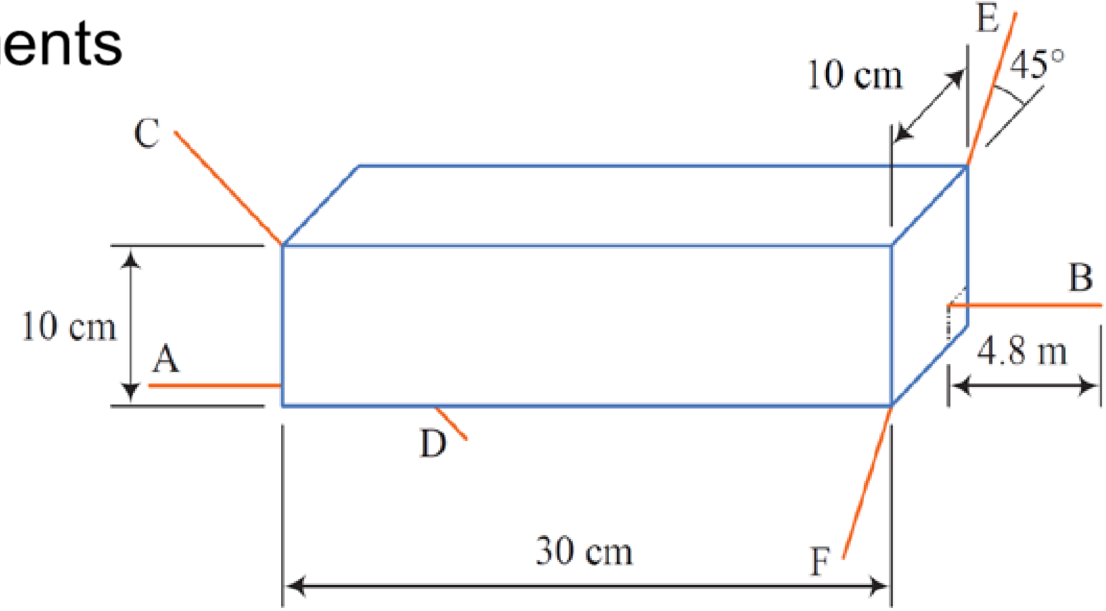


Radio architecture

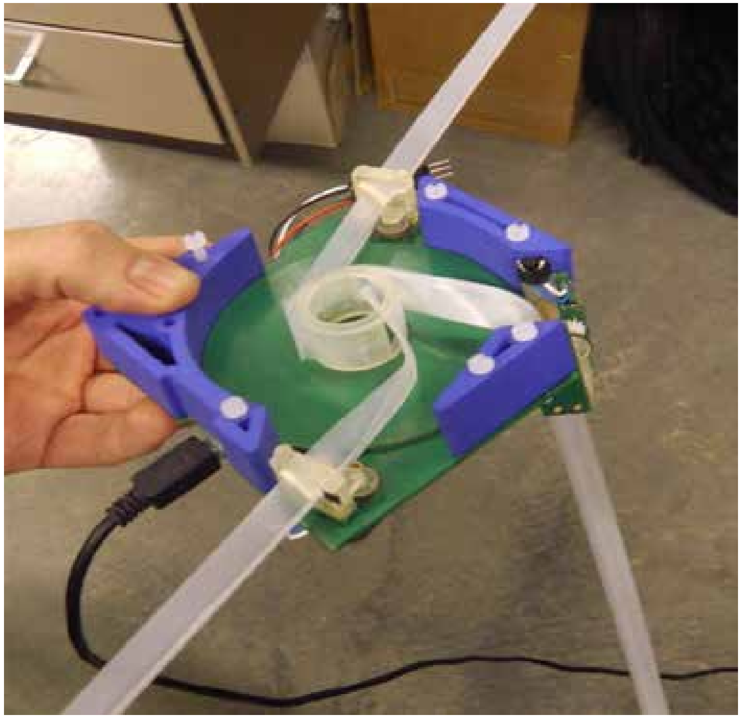


Science antenna

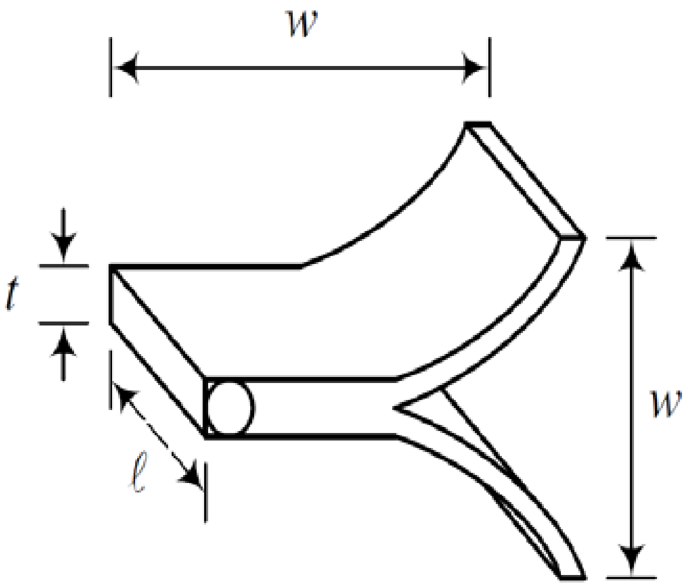
- Frequency band 0.3 – 30 MHz
  - Wavelength 10 m – 1 km
- Platform limitations
  - Wire antennas
- Field of view requirements
  - 3D array
  - 4π sr coverage



Observation antennas



Storage and deployment mechanism



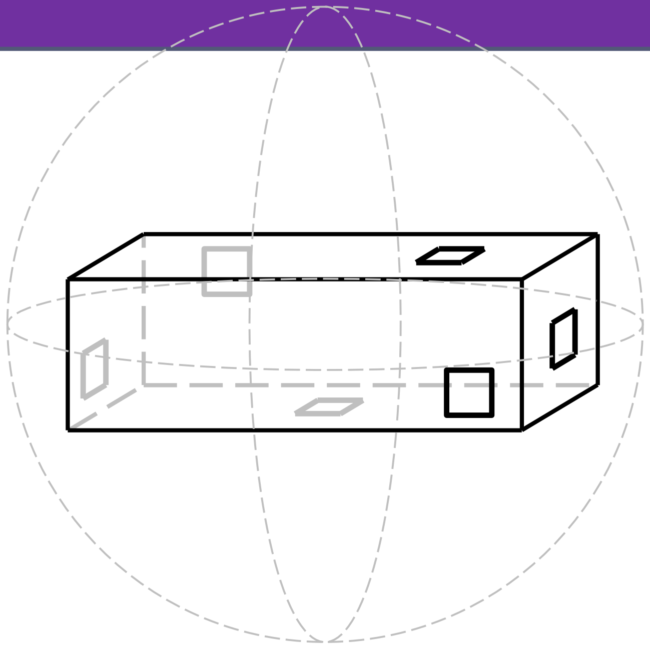
Antenna profile

Inter satellite link

§ ISL requirements
- Ø Data rate
- Ø Range
- Ø Coverage
  - Ø 4p sr range

§ Nano-satellite limitations

§ Implementation
- Ø One CP patch antenna on each face

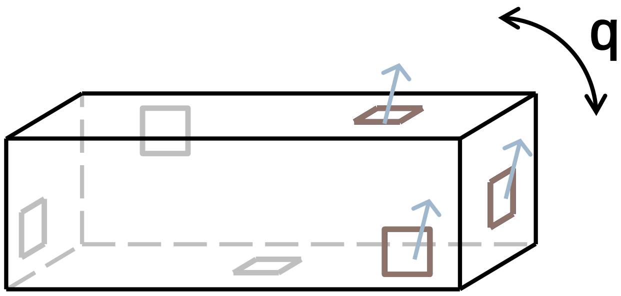


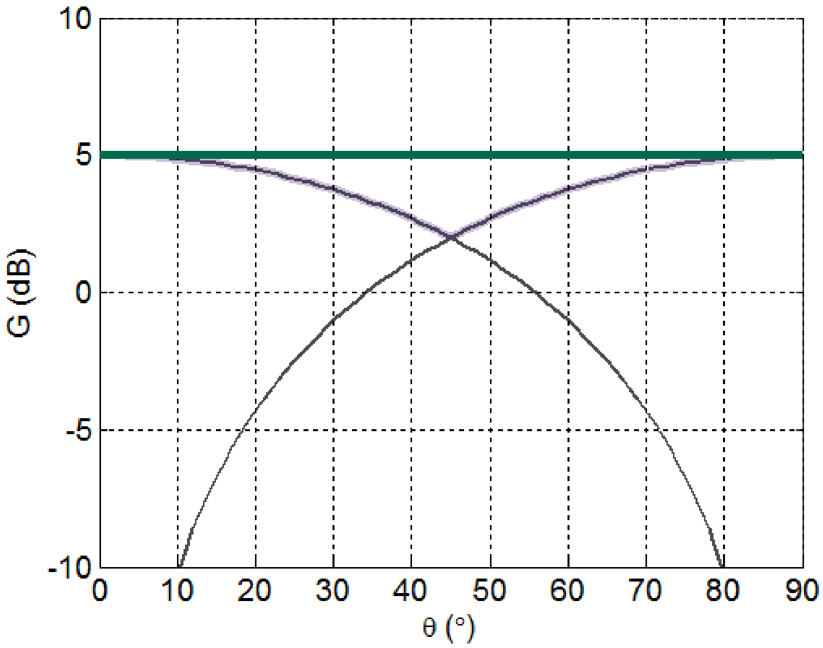
Inter satellite link

- ISL requirements
  - Data rate
  - Range
  - Coverage
    - 4p sr range

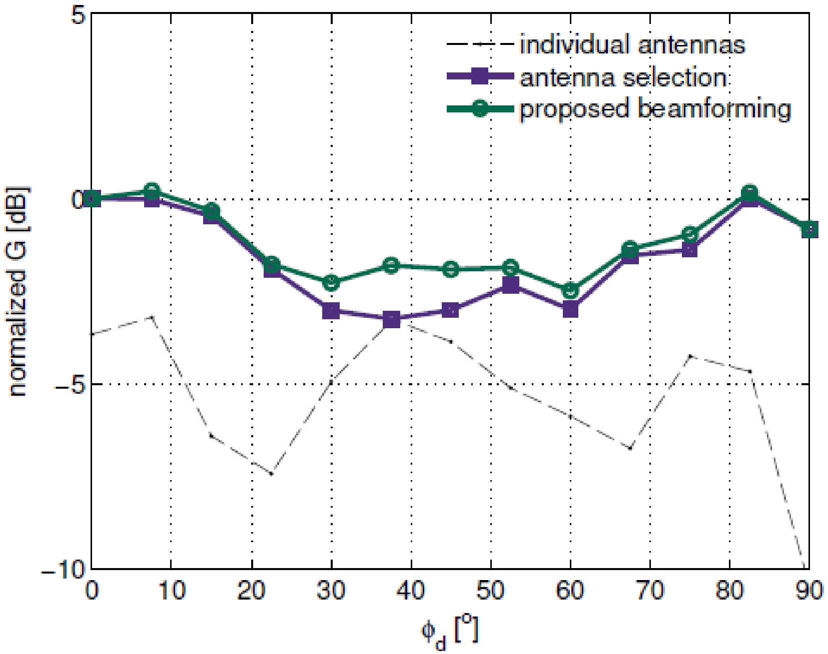
- Nano-satellite limitations

- Implementation
  - One CP patch antenna on each
  - **Beamforming**

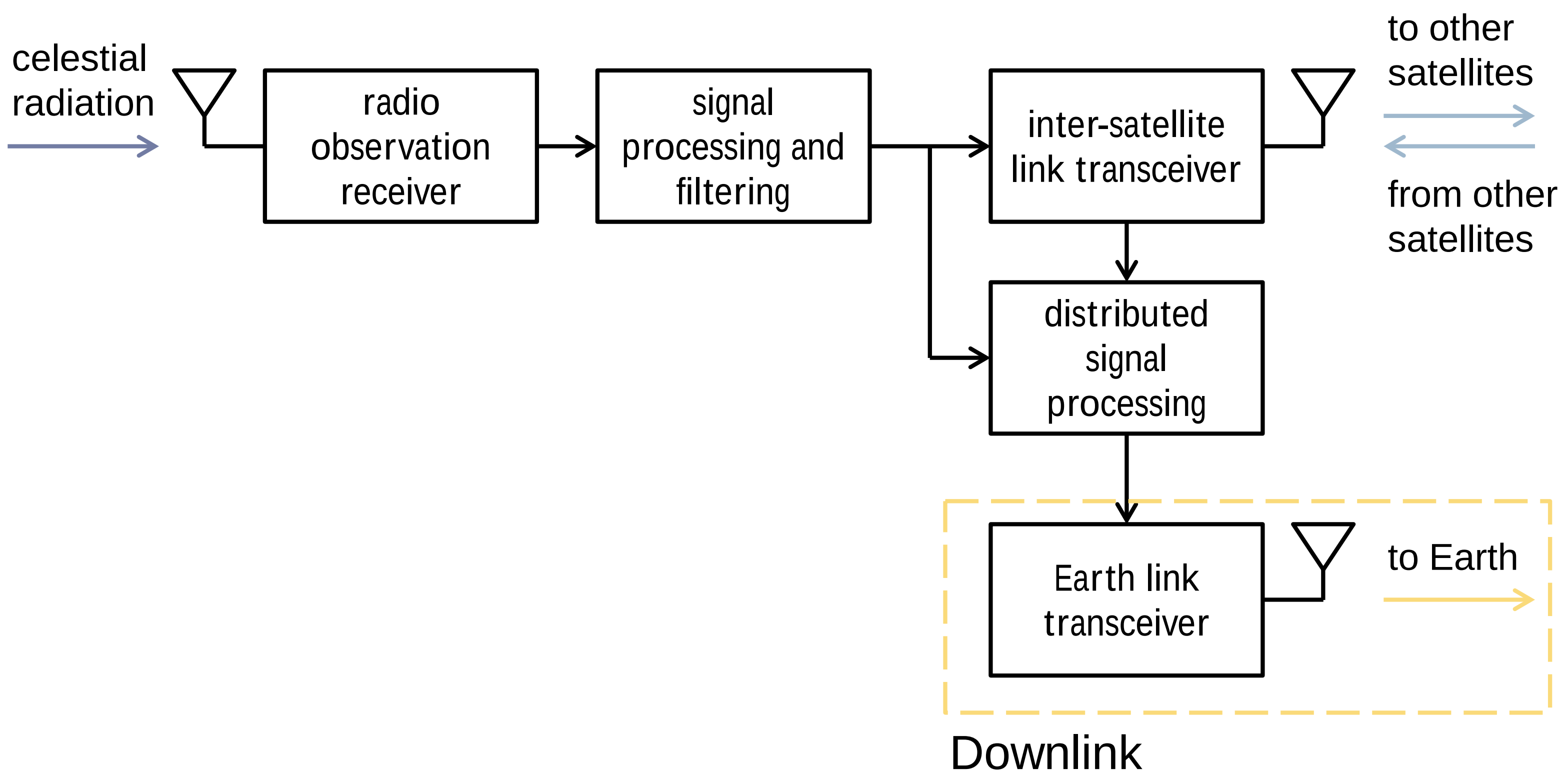




Experiments

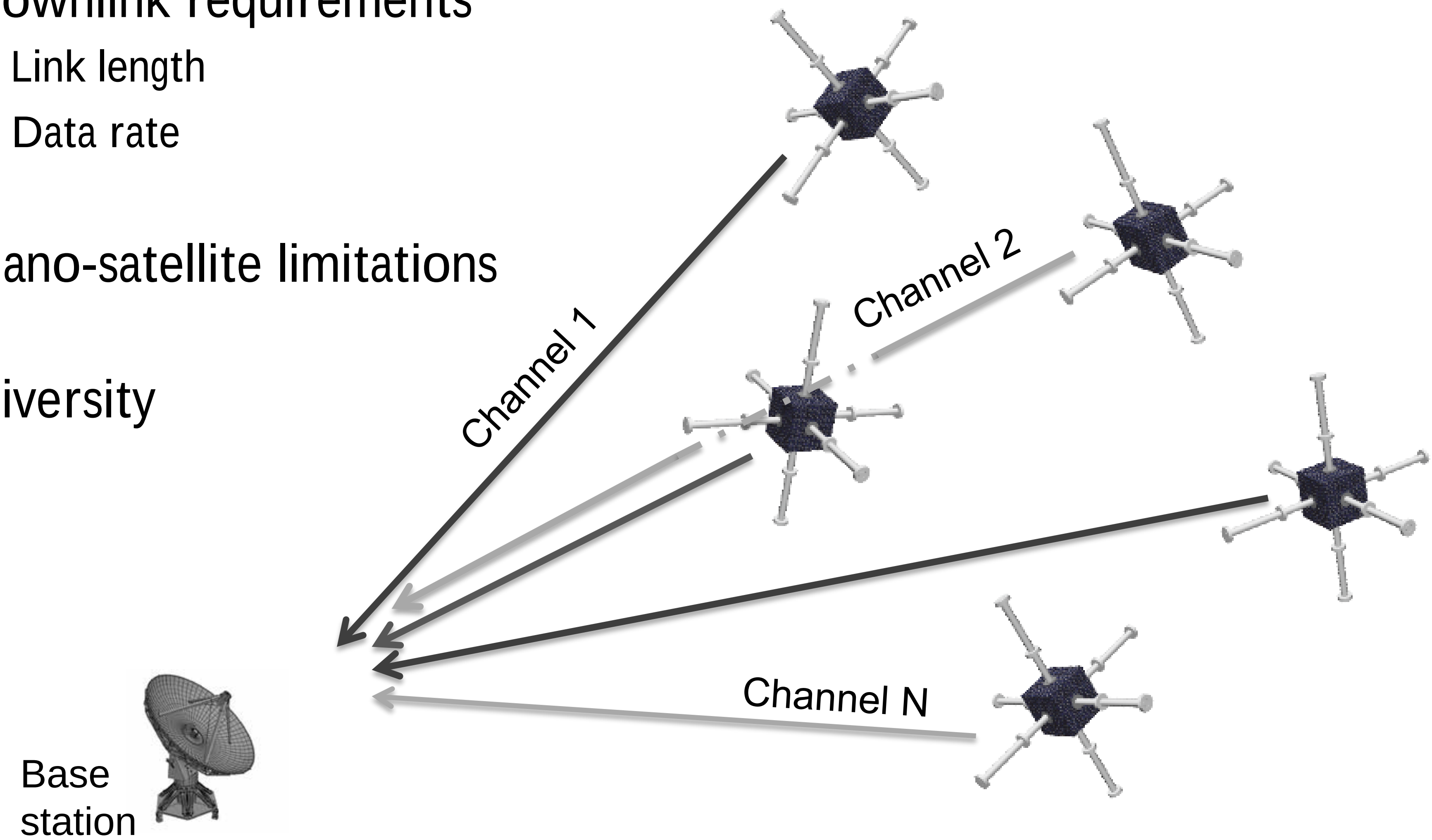


Architecture



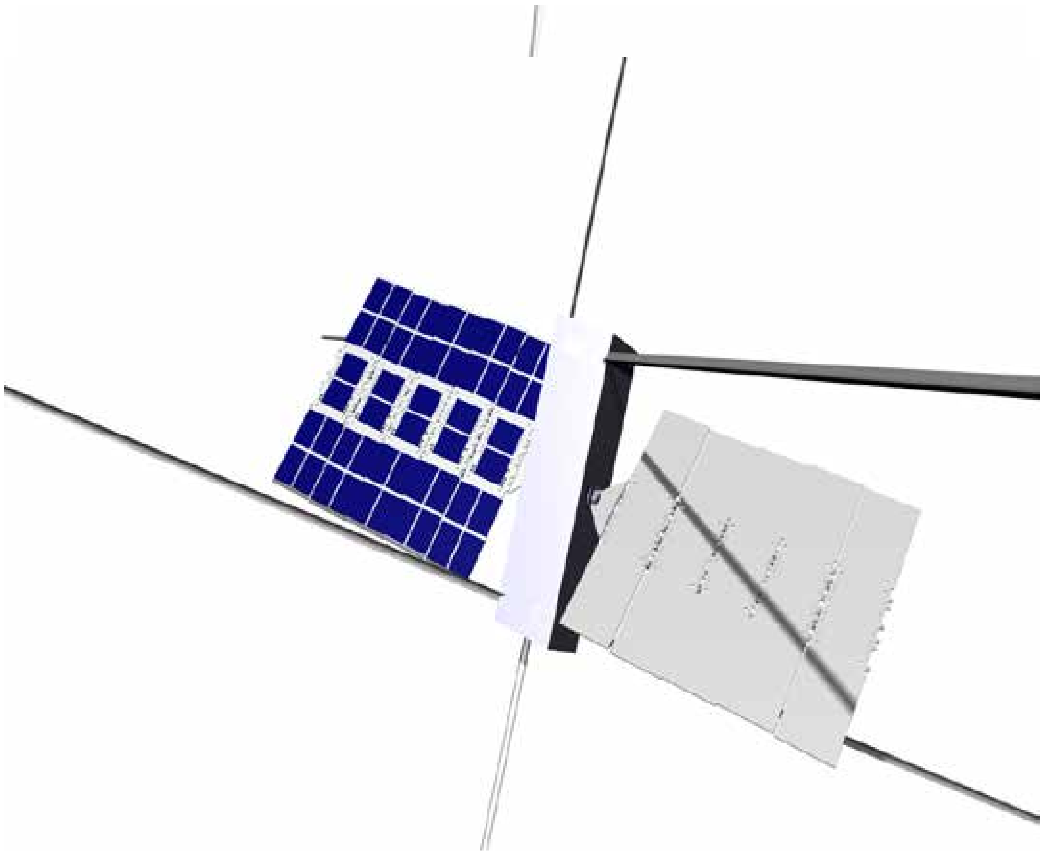
Downlink

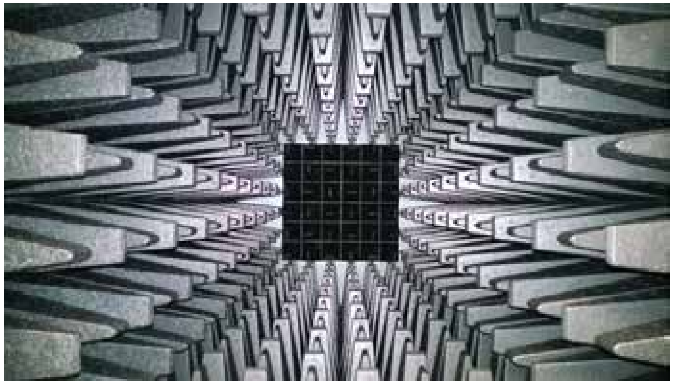
- Downlink requirements
  - Link length
  - Data rate
- Nano-satellite limitations
- Diversity

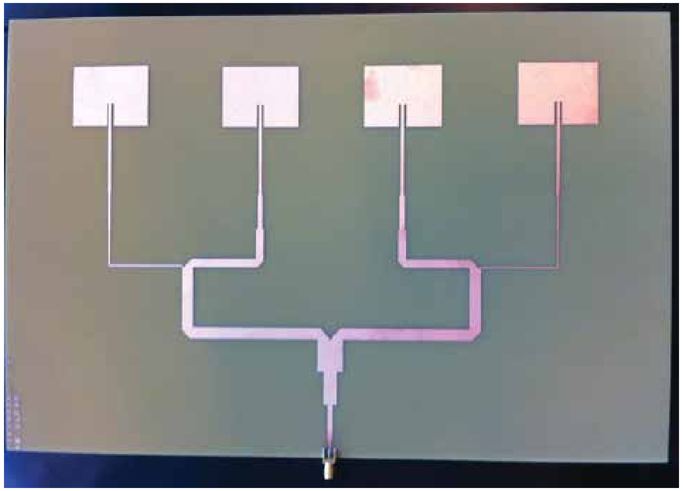


Downlink

- Downlink requirements
  - Link length
  - Data rate
- Nano-satellite limitations
- Diversity
- Implementation
  - 2D array of patches
  - Feeding network







Current OLFAR research topics

- Down link
- Solar arrays with integrated phased array transceivers
- Propulsion (see “EPFL - A Couple Drops of Fuel to Get to the Moon with MicroThrust” - http://www.youtube.com/watch?v=YJlSI_l5g4M)
- System design
- On Board Computer with swarm control algorithms
- High accuracy clock/timing
- Clock synchronisation and ranging algorithms
- Antenna deployment mechanisms
- Low power, high bandwidth high sensitivity receiver (i.e. payload package)
- Navigation systems (either pulsar based, or sun/star-sensor based, perhaps using optical navigation techniques)
- Attitude determination systems (star trackers, fine sun-sensors)
- Imaging
- Calibration

Advances in Radio Astronomy

- New era for radio astronomy … from multiple dishes to huge aperture arrays… both on Earth and in Space
- Only possible because of the ICT
  - direct sampling & digitisation
  - high speed data transport
  - super-computing
  - archive capacity
  - data mining
- Will lead to new discoveries … answering the five main questions about the Universe

Conclusions

- Radio Astronomy has started a new era ..Aperture array based observatories.
- Both on Earth, as well as in Space.
- Major technological breakthroughs are needed to realize this.
- It will help in answering the main questions about the formation and composition of the Universe