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A Large Ultra-long Wavelength Radio Astronomy instrument in Space

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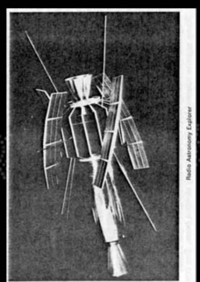
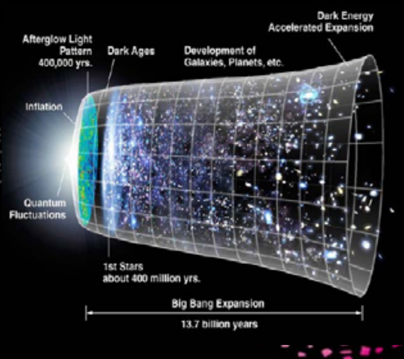
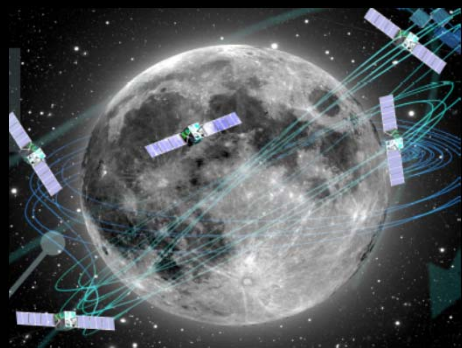






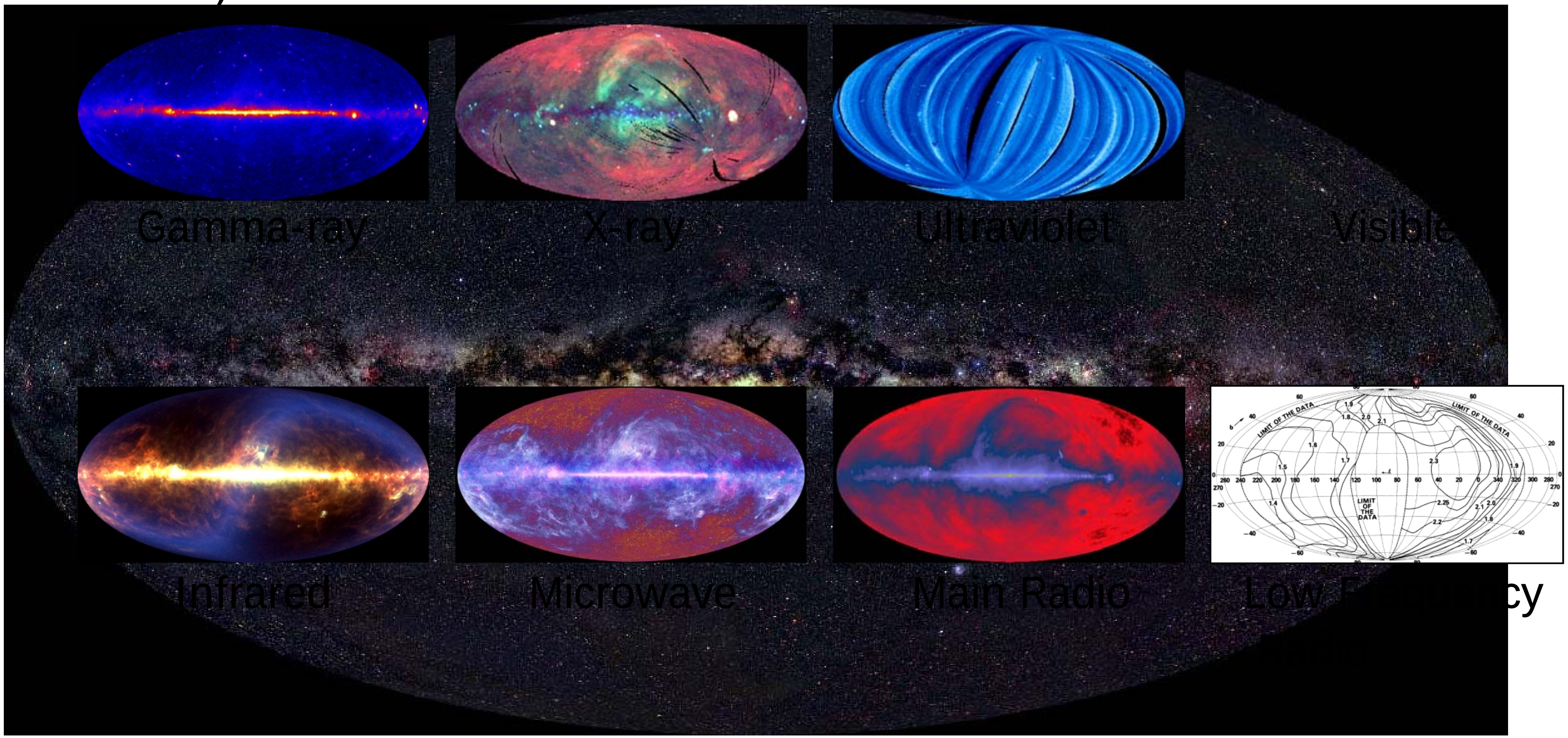
Content

Topic:
Orbitting Low Frequency Antennas for Radio Astronomy

- Background – need for a low frequency radio telescope
- Why in Space ?
- Why is it interesting ?
- Concept of OLFAR
- Requirements
- Selection of research results
  - Mission Analysis
  - Science antenna
  - Inter satellite link

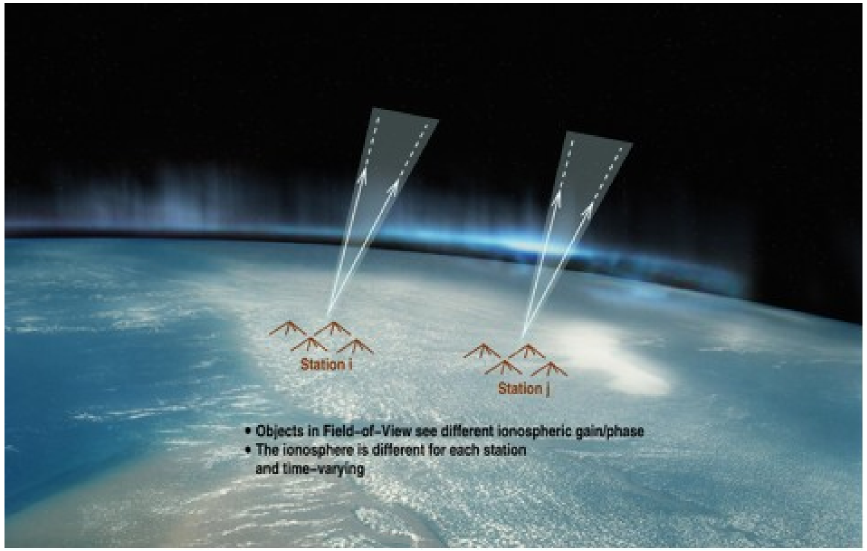
Introduction

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



Goal: an ultra long wavelength radio telescope

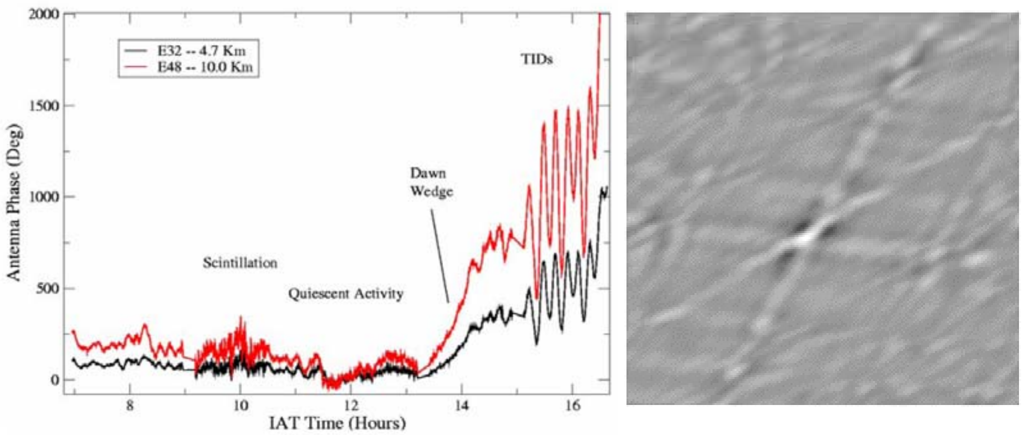
- Low frequency : below 30 MHz
- > ~30 MHz : LOFAR



➔ Opening up the last unexplored frequency regime

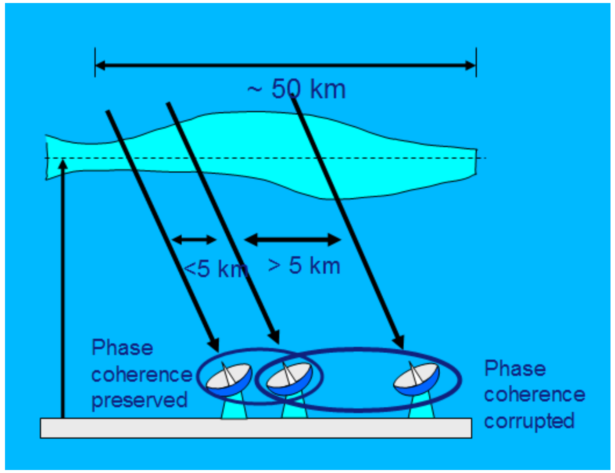
Why in space: ionospheric disturbance and cut-off

- 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

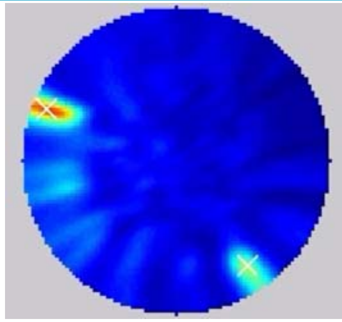


Maximum antenna separation:
< 5 km vs. >10^2 km
Angular resolution at 10 MHz:
$\theta > 0.3°$ vs. $< 10^{-2}$ °

Why in space: radio frequency interference

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

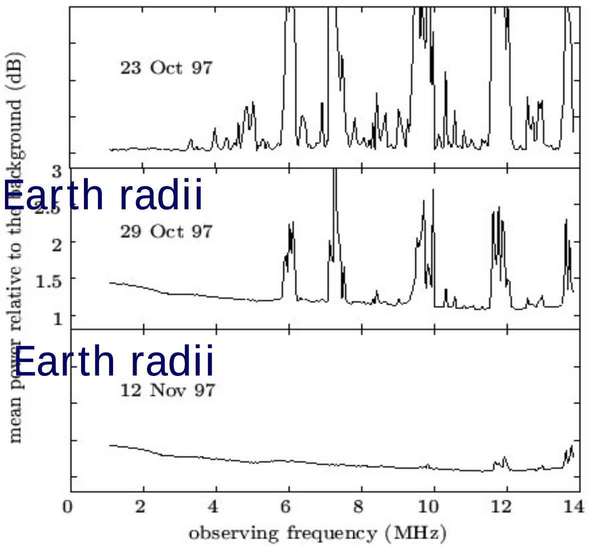
All-sky image
(movie)
of LOFAR ITS
at 15.004 MHz
(Moren, Boonstra, 2007)



40 Earth radii

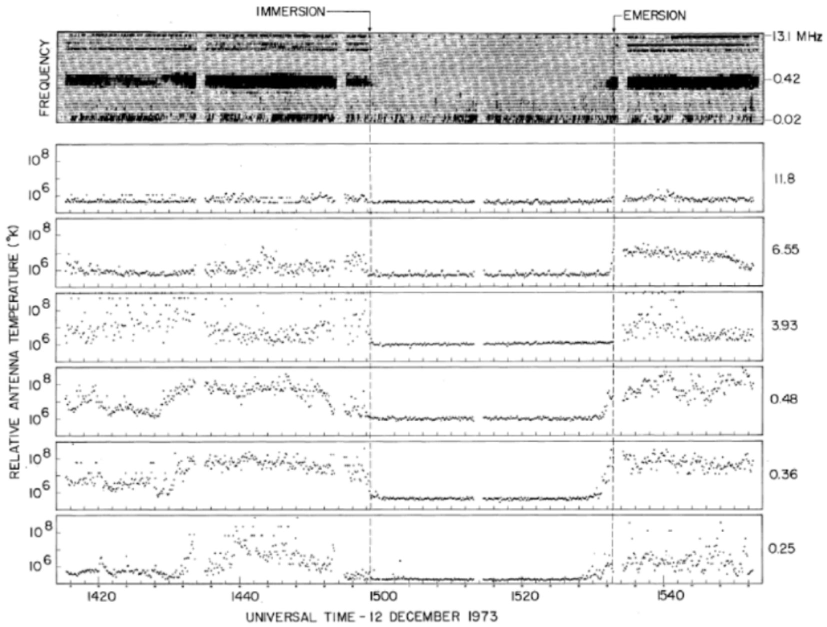
93 Earth radii

157 Earth radii

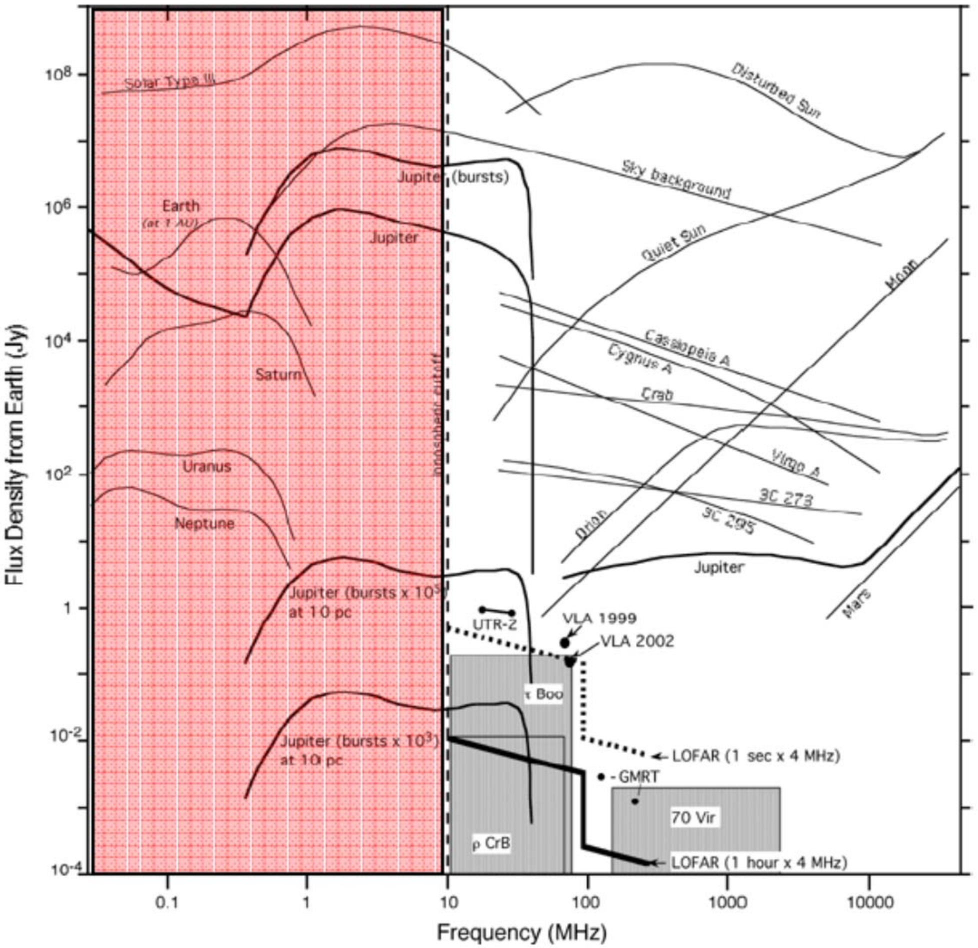


G. Woan from ESA study SCI(97)2

RAE B (1973) in Lunar orbit, Kaiser 1975



Why is it interesting: New frequency window

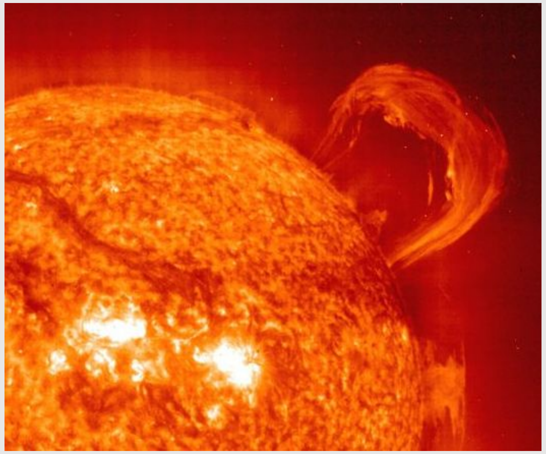


- At very low frequencies the universe is virtually unexplored
- The earth's ionosphere masks the key low frequencies
- Science cases:
  - Extra-galactic surveys
  - Transients (Jupiter-like flares, Crab-like pulses, extra-solar planetary burst, etc)
  - Solar activity and Space Weather
  - Coronal activity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

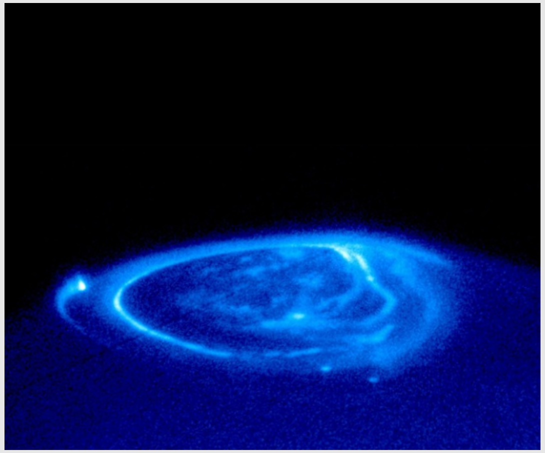
Why is it interesting: Radio sources

Astronomical radio sources

Radio galaxies
(static source)



Solar eruptions
(transient source)

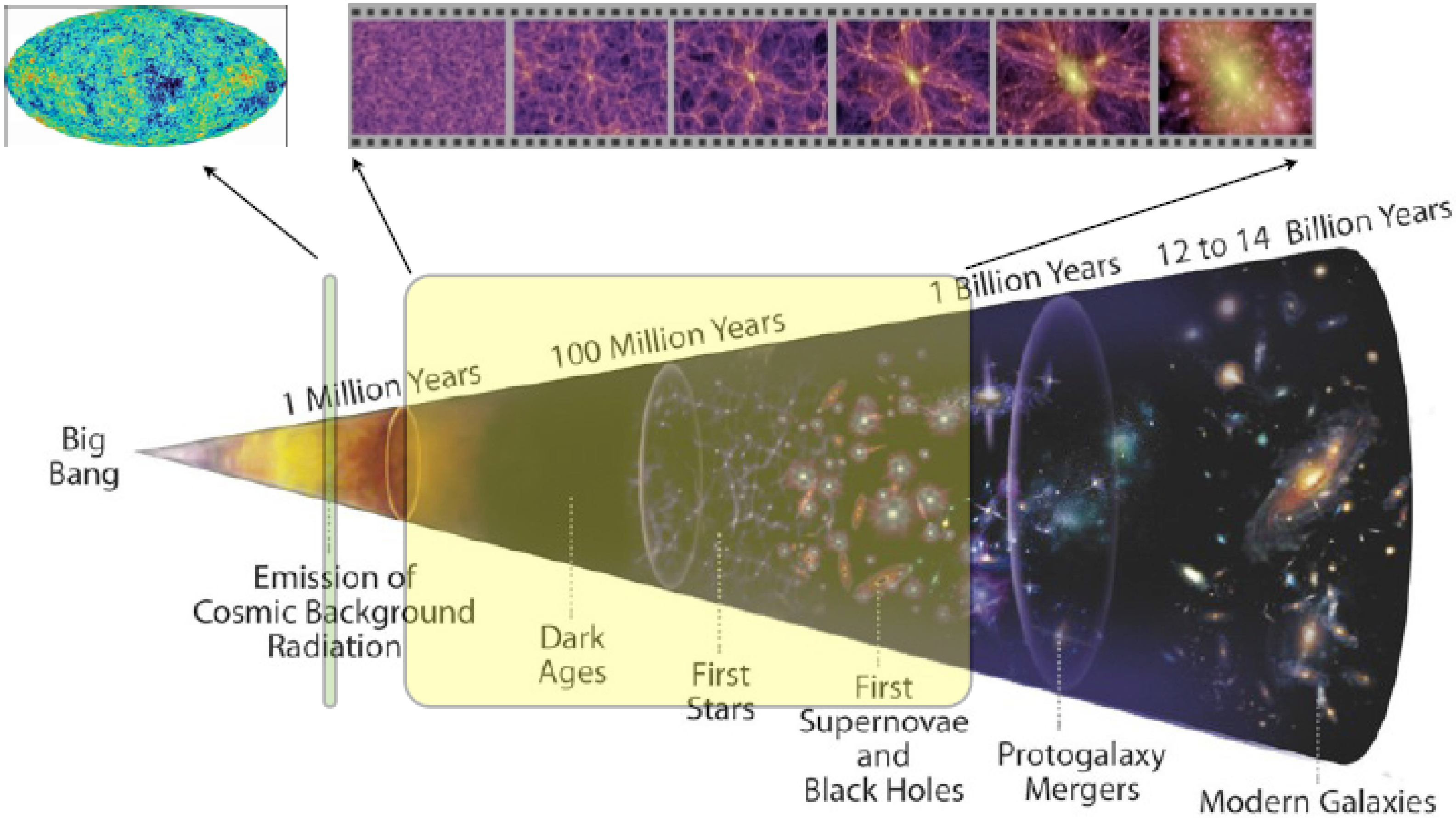


Aurora's of planets
(transient source)

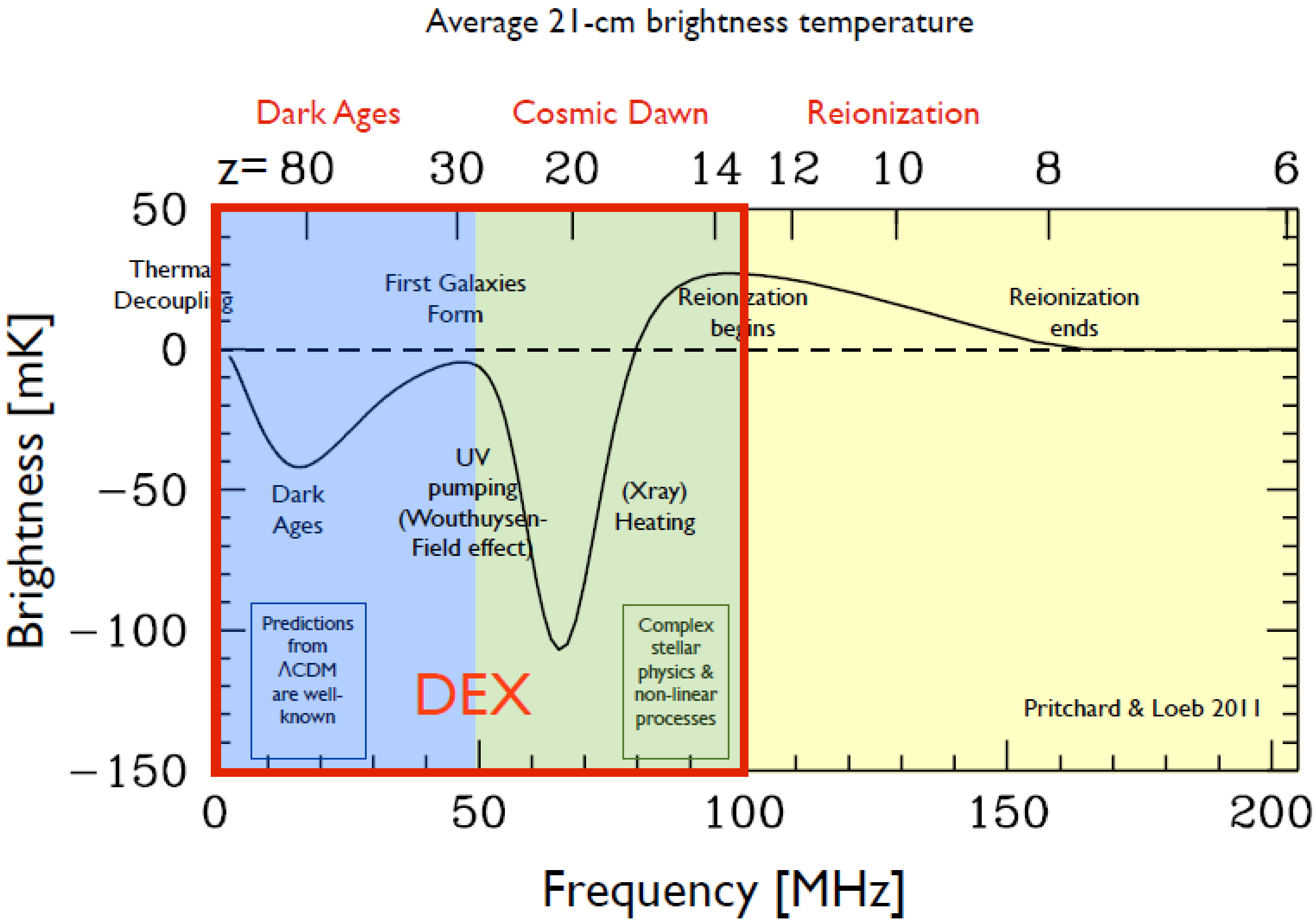
Why is it interesting: Dark ages

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)

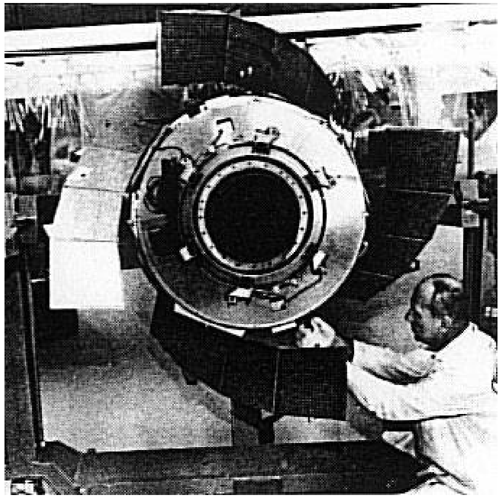


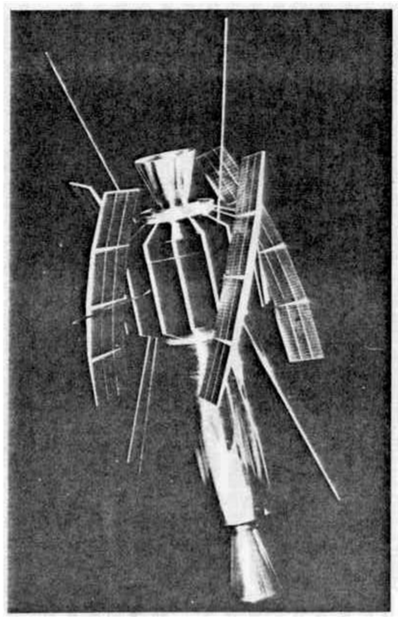
Dark ages explorer



Previous low frequency missions

- RAE-A (Explorer 38)
  - 1968 July 4
  - 190 kilogram
  - Earth orbit
- RAE- B (Explorer 49)
  - 1973 June 10
  - 328 kilogram
  - Moon orbit
  - 25 kHz to 13.1 MHz





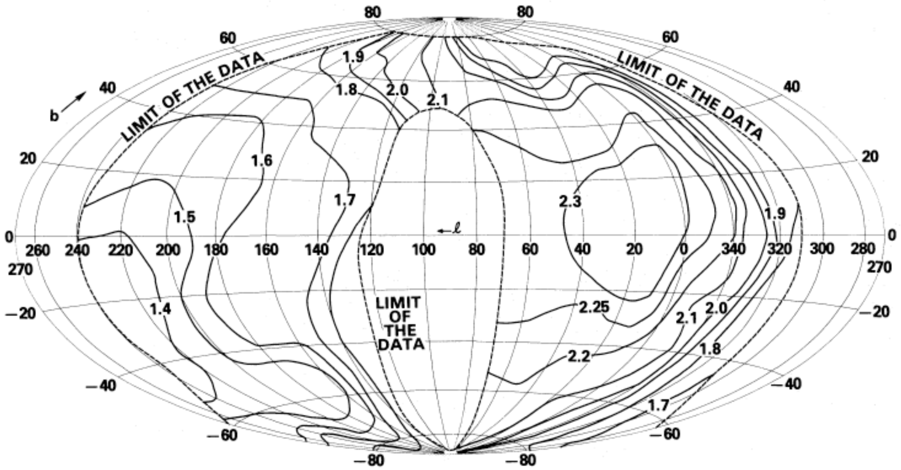
Radio Astronomy Explorer

Current Status at Long Wavelengths

Extremely poor resolution, strong diffuse Galactic emission

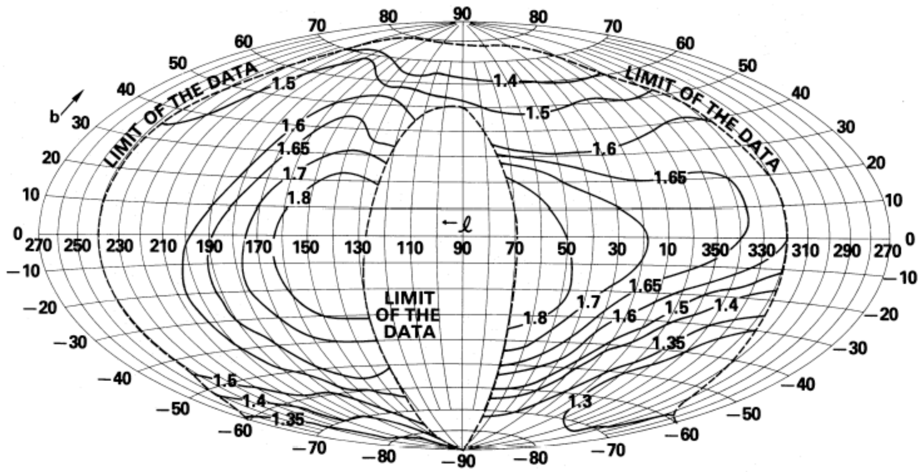
RAE-2 observations at
1.3 and 4.7 MHz, Novaco
& Brown 1978

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

- Aeff~10 km^2 collecting area for t_{int}=1yr
- Compact array: high sensitivity - good uvw coverage
- Angular scales: arcmins to degrees
- Field-of-View: (near) all-sky: 2-4π
- Frequency range: 1kHz-1MHz-100MHz
- Frequency resolution: <1KHz
- Integration times: 1+ year, nominal mission lifetime: 4years
- Time-resolution: sub-second

Strawman designs

Moon-based: Earth-RFI shielded

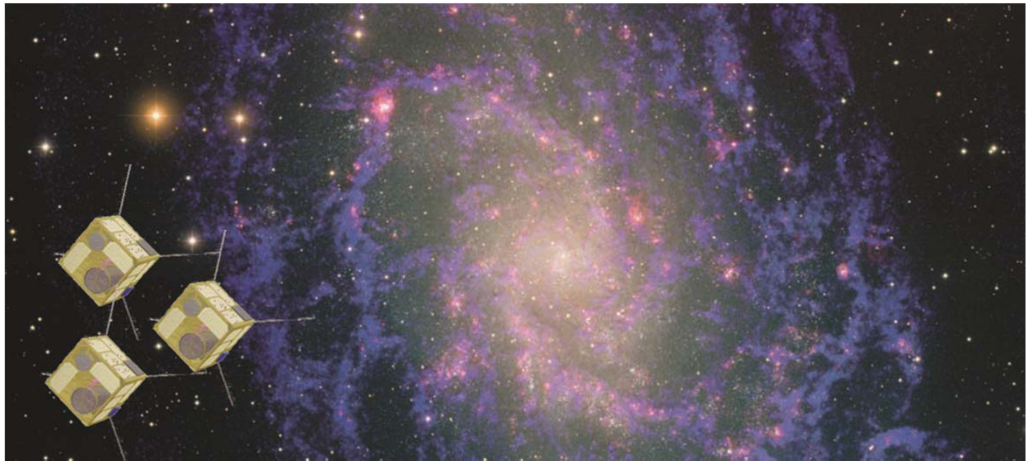
- Lander: deployment system (robots), comms/downlink, power, data processing
- Orbiter: comms/downlink
- Payload: thin-film sheets (ROLSS NASA concept)

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

Basic idea of OLFAR

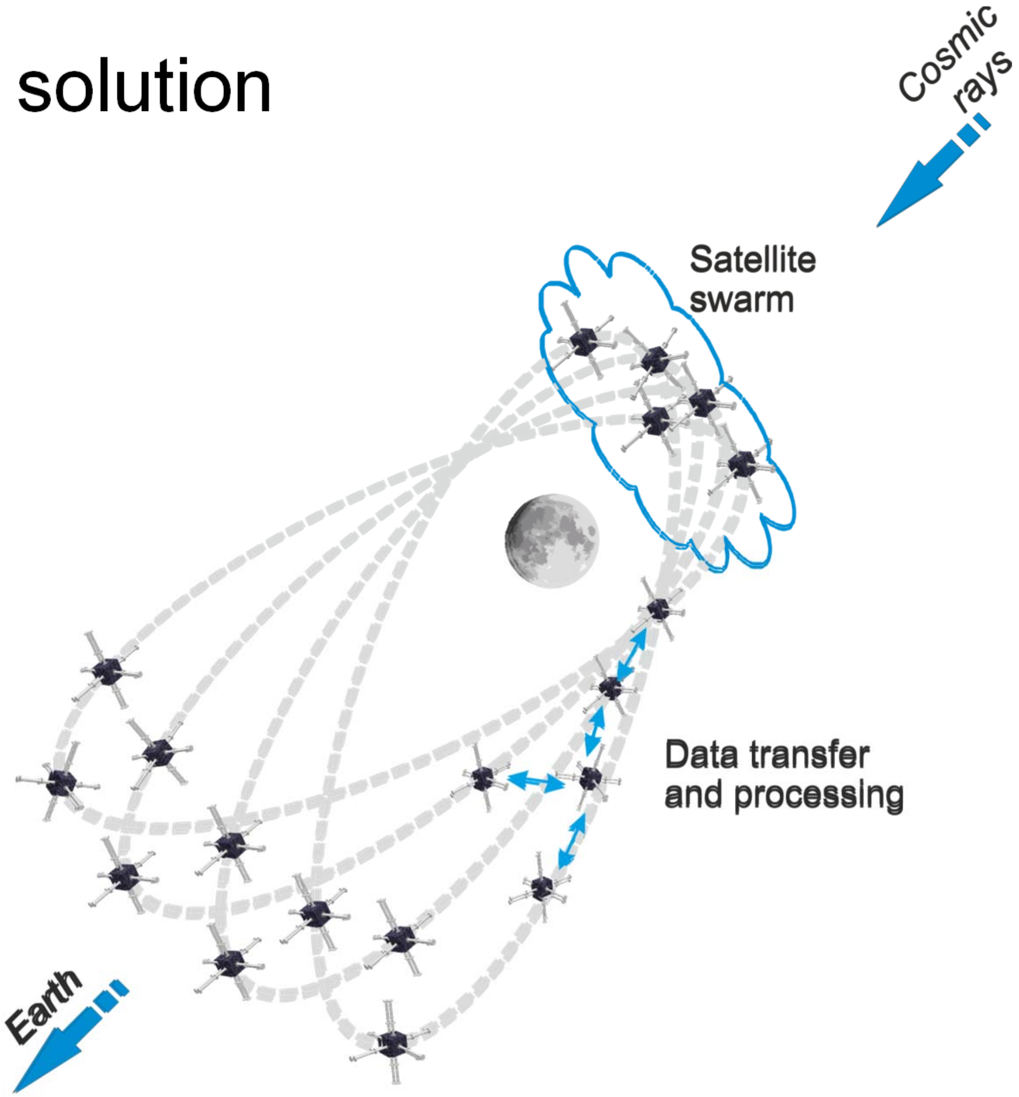


- Nano/small satellites
- Swarm
- Deployable antenna for the frequency band between 1 and 30 MHz
- Ultra-low power receivers
- Intra-satellite communication
- Autonomous distributed processing
- Using diversity techniques for downlink

OLFAR concept

- Efficient and robust solution
  - Low frequencies
    ➔ long wavelength
    ➔ large aperture
  - Feasible

- Swarm advantages
  - Robustness
  - Redundancy
  - Autonomy



OLFAR- requirements

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

Some results

- Team:
  - Four PhD students
  - One Postdoc
  - Lot's of MSc students
  - University of Twente / Delft University of Technology / ASTRON

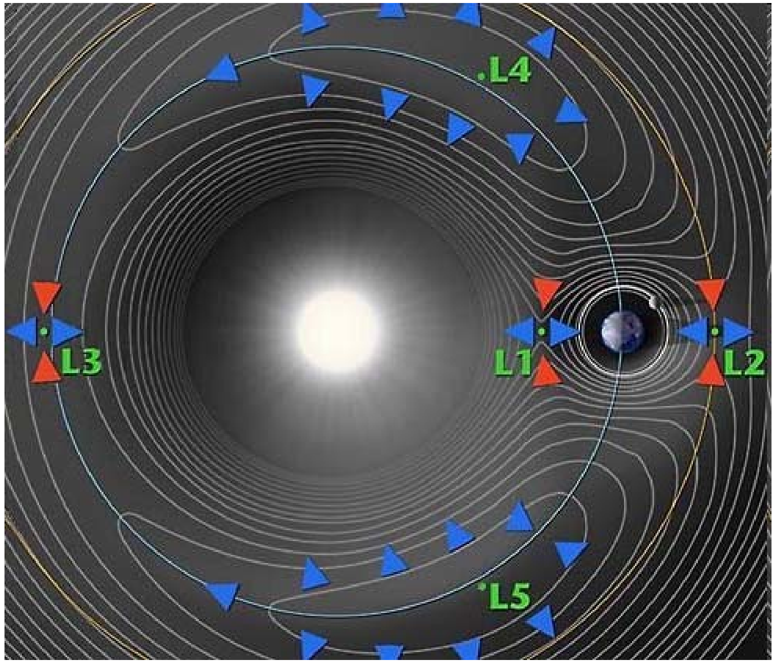
- Topics (selection)
  - Mission analysis
  - Science antenna
  - Intersatellite link
  - ….

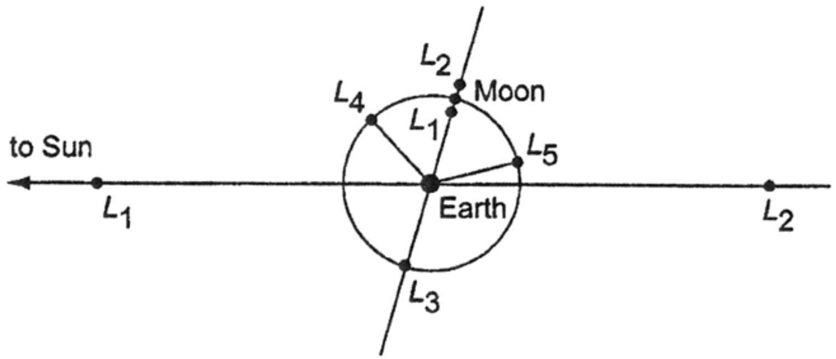
Mission analysis (orbits)

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

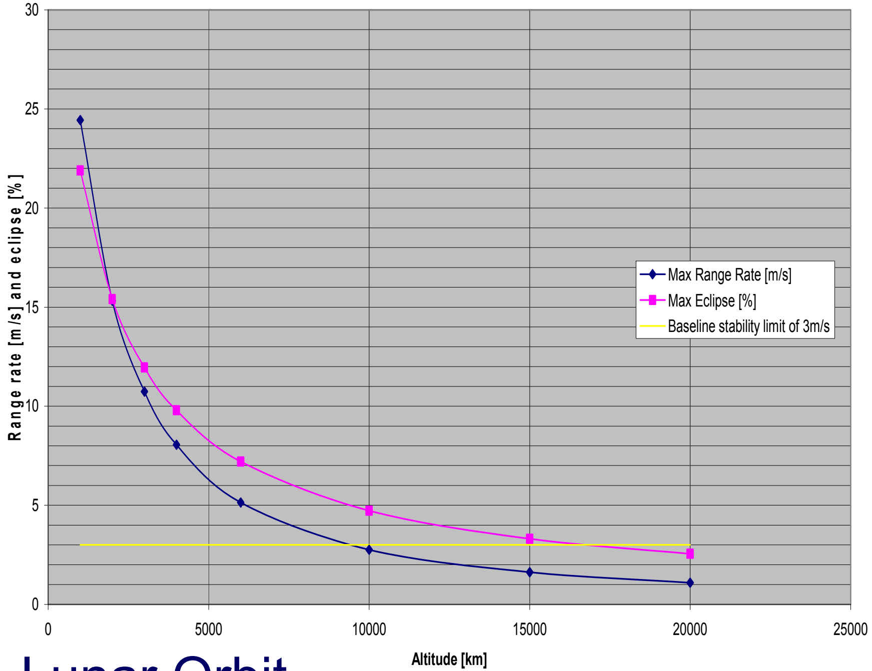
Possible orbits:

- 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**





Mission analysis (orbits)



Lunar Orbit

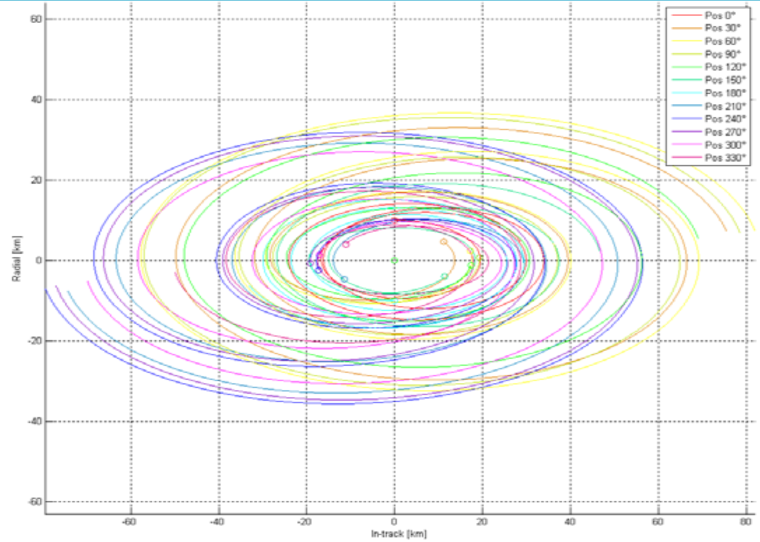
A circular orbit in the lunar equatorial plane

Advantages:

- Stable reference orbit
- Stable relative orbit

Disadvantages:

- Trade-off between eclipse time and range rates



Solar Orbit

An elliptical orbit at a distance of 4-10 million km to Earth

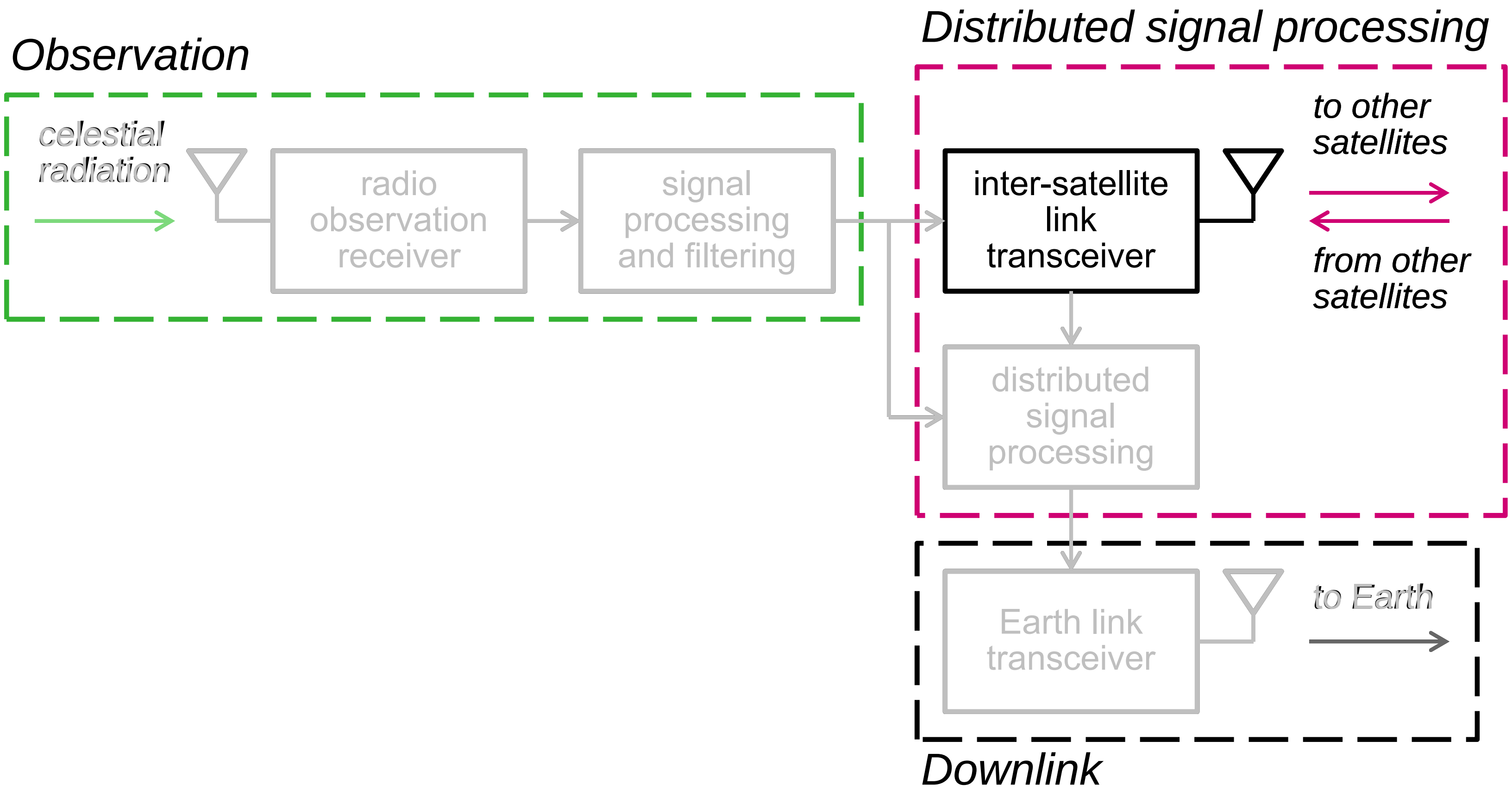
Advantages:

- Very low range rates
- Continuous observations possible
- Stable reference orbit over a very long time

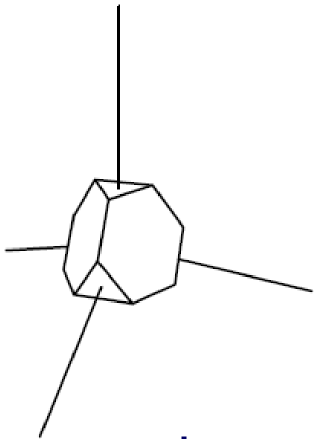
Disadvantages:

- Continuous drift of the satellites, so limited life time
- Very sensitive for velocity changes

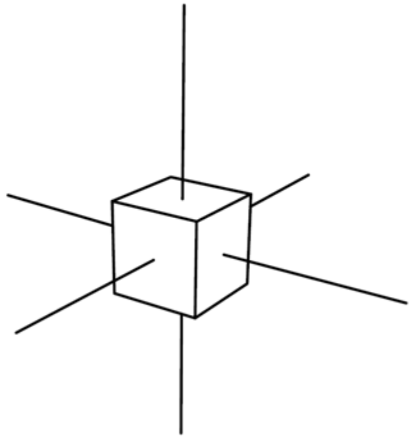
Radio architecture



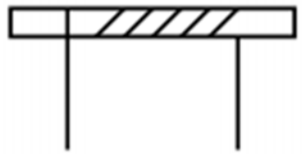
Science antenna



four monopoles on tetraeder



"tripole"



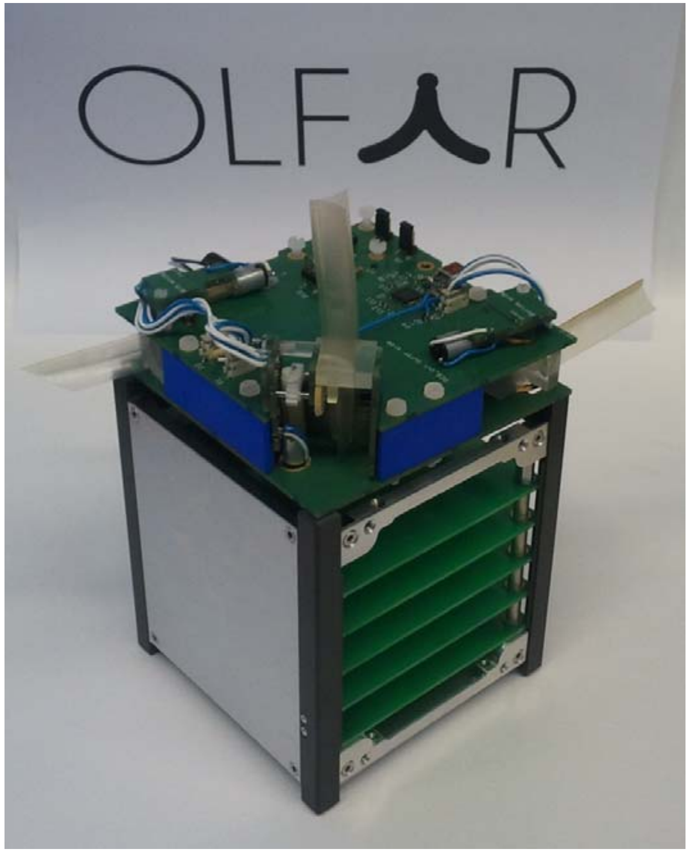
magnetic loop antenna

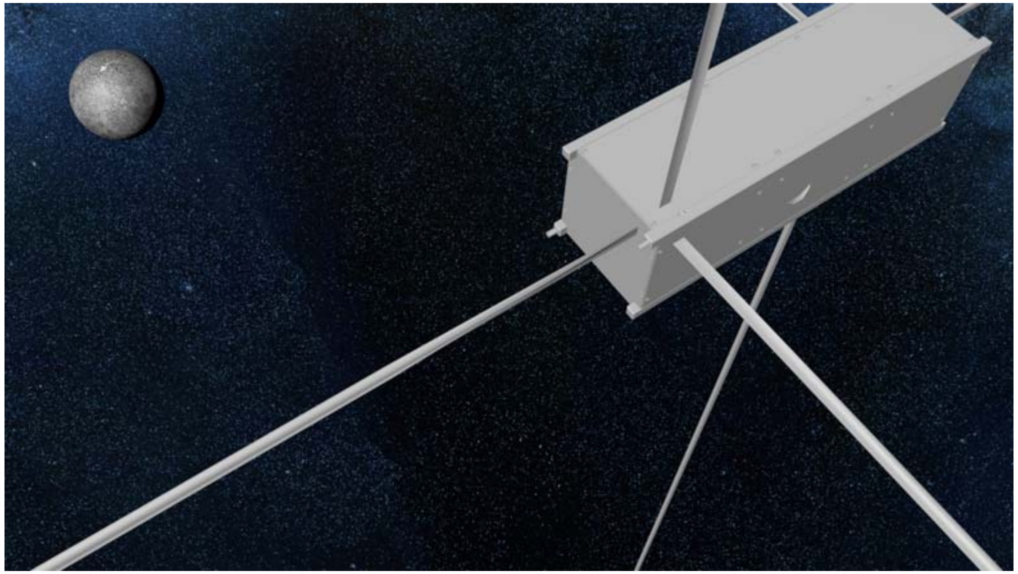
Requirements:

- system needs to be sky noise limited
- Trec<0.1Tsky
- operational bandwidth 1-10 MHz
- instantaneous bandwidth at least 1 MHz
- Small form factor
- Lightweight

Science antenna

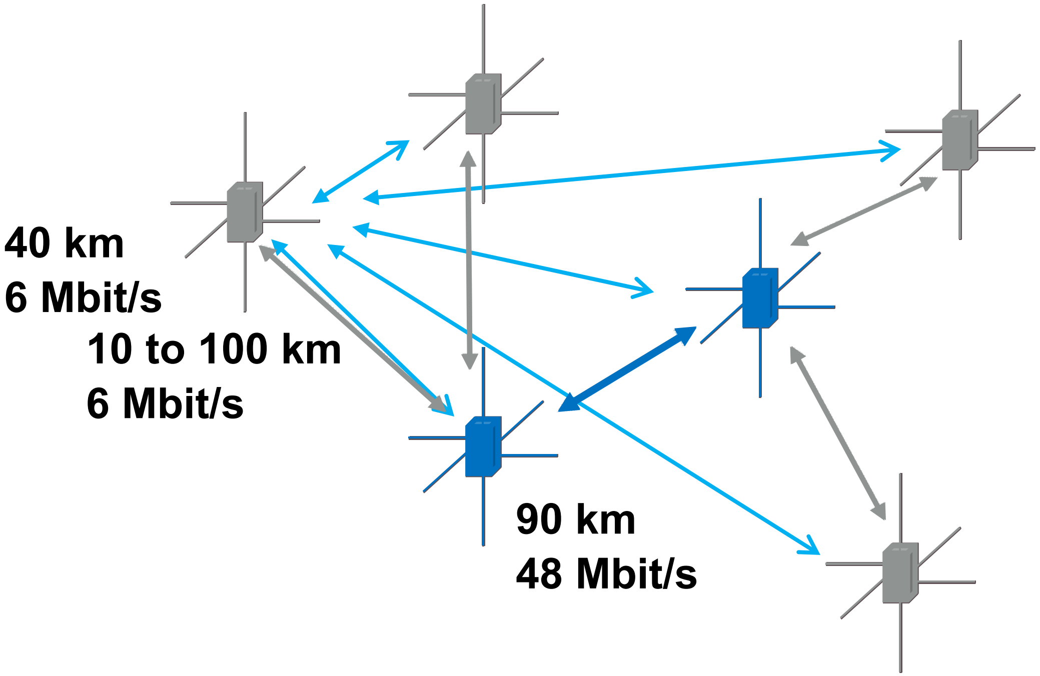
- 3 orthogonally placed dipoles consisting of 6 monopoles, each with a length of 4.9m
- 2 units





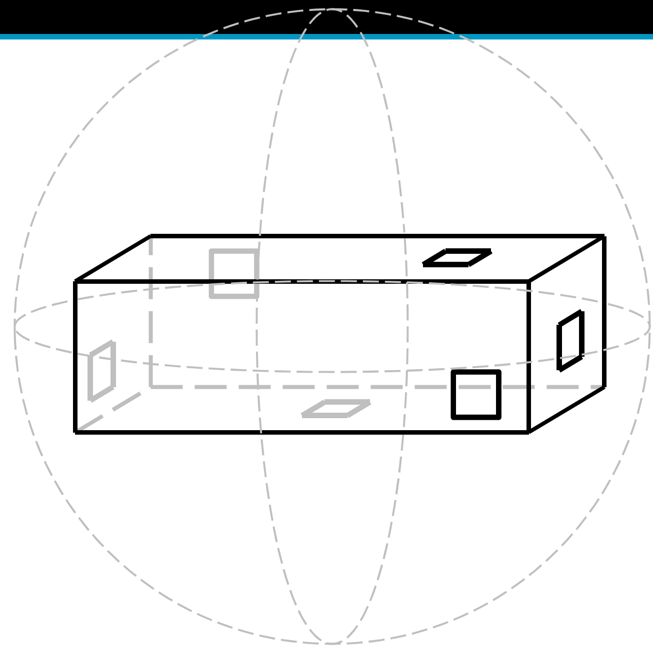
Inter satellite link

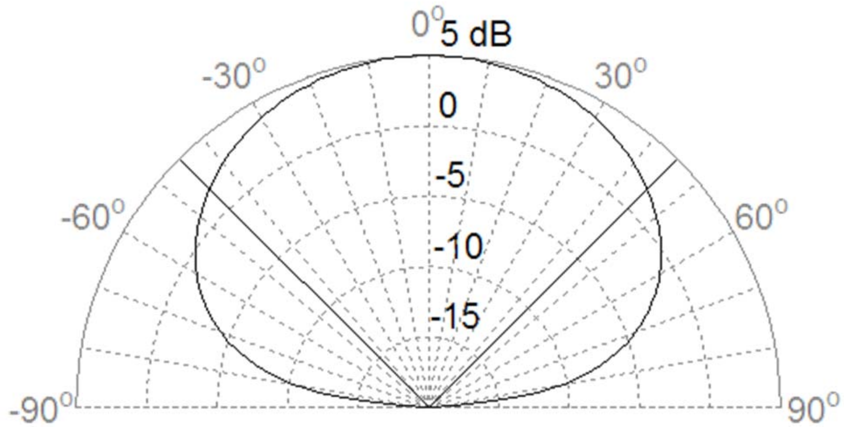
- Adaptive clustering for satellite swarms
  - Hierarchical topology
  - Power efficiency



Antenna configuration

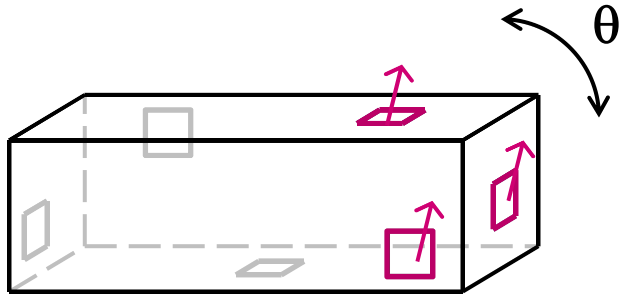
- 4π sr range
- Minimum number of antennas
- One antenna per face
- Radiation pattern
  - 90° 3-dB beamwidth
  - 5 dBi gain



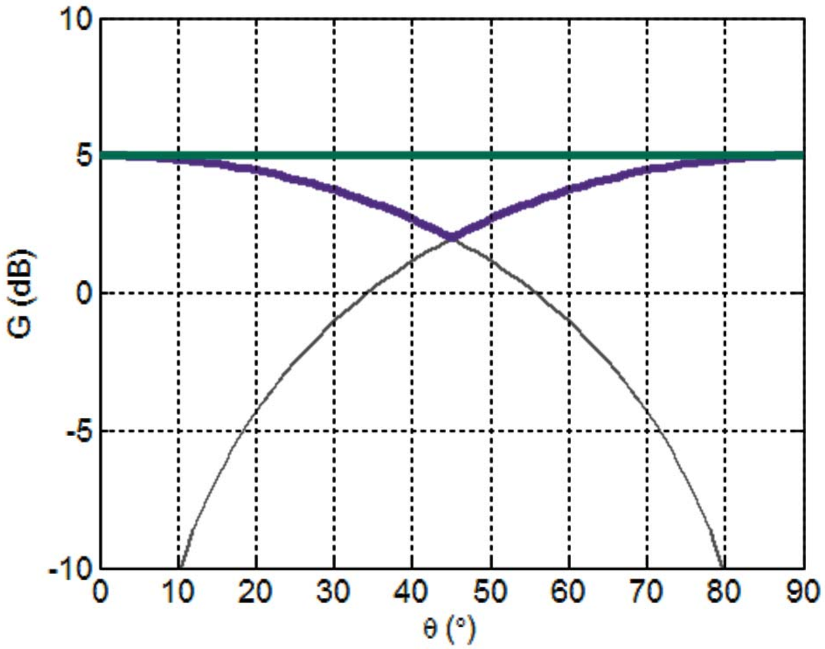


Antenna system control

- Smart antenna system
  - Selection
  - Beamforming

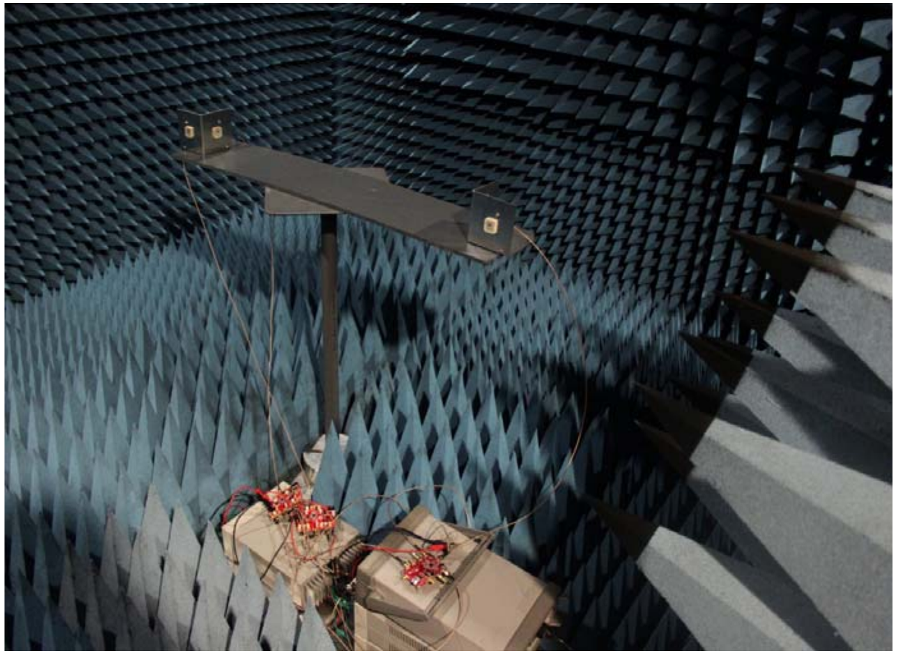


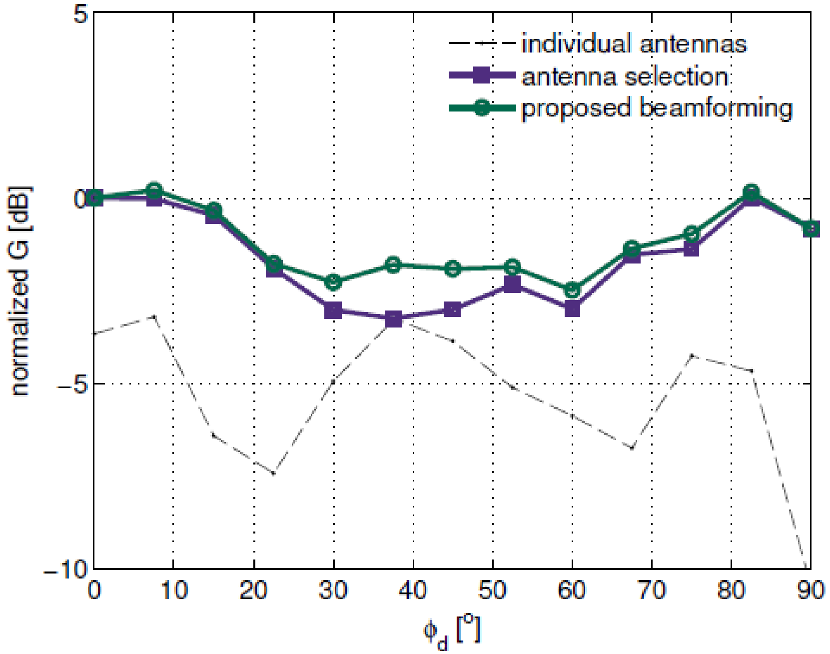
- 3 antennas for each direction



- Maximal gain for any direction
- DOA estimation
- Link tracking

Experiments





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

Conclusions

- Ultra long wavelength astronomy below 30 MHz is the last unexplored frequency range.
- Due to ionospheric and RFI reasons the best place to be is in space.
- Today's technology makes a satellite array (swarm) possible.
- A novel antenna system is presented.
- Inter satellite communication is perhaps the most challenging part of OLFAR.

Partners