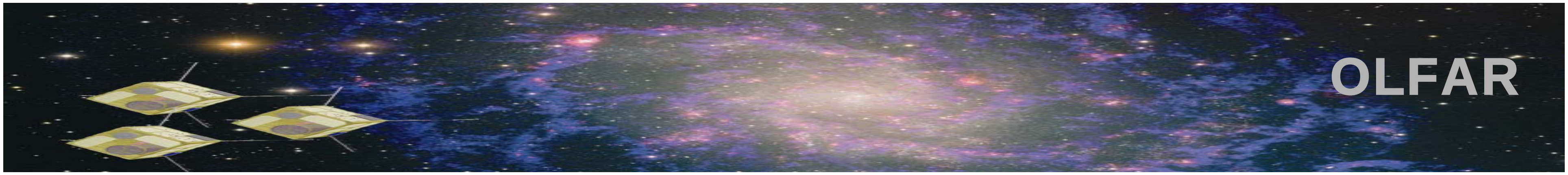
OLFAR – Orbiting Low-Frequency Antennas for Radio Astronomy

Mark Bentum

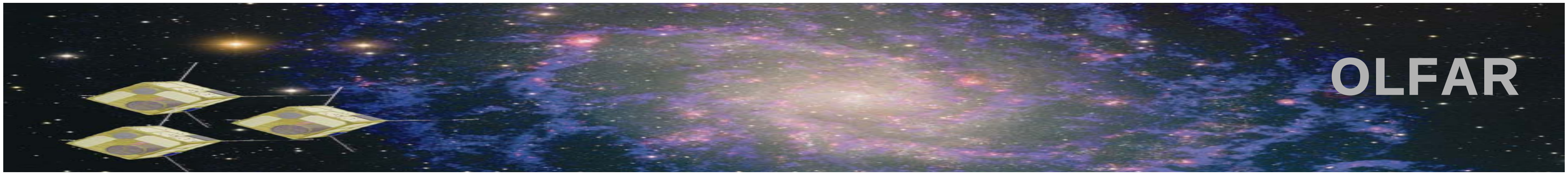
JENAM, April 22, 2009



Outline

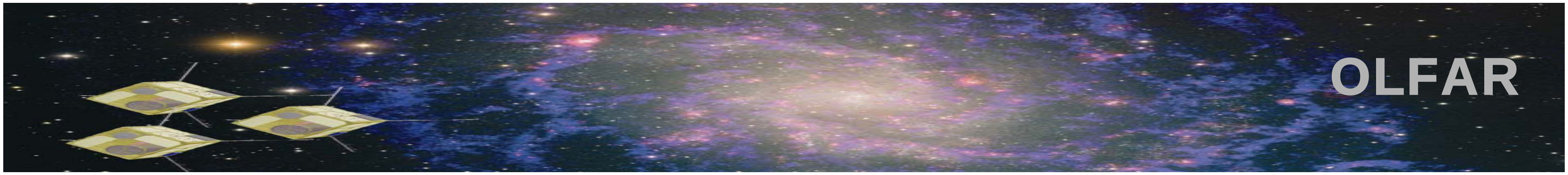
Presentation of a new concept for low frequency radio astronomy in space

- Why low frequencies?
- Why in space?
- Outline of the idea
- Issues



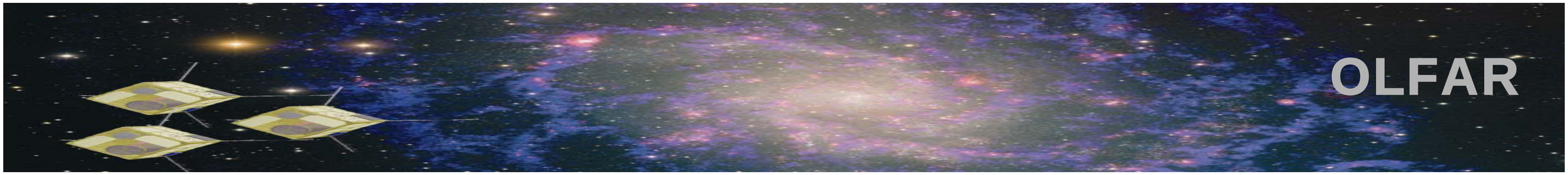
History of Low Frequency astronomy

- Karl Jansky's in 1932
  20.5 MHz (14.5 m) at Bell labs
- Grote Reber continued radio astronomy work at 160 MHz (1.9 m) and observed the Sun, IO, Cygnus-A



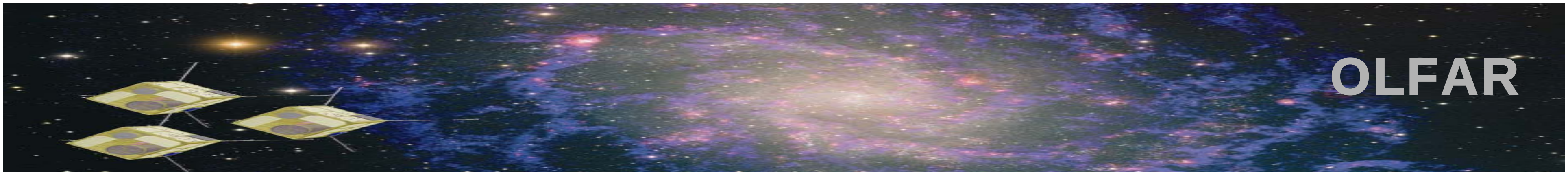
History of Low Frequency astronomy

- First radio telescopes operated at long wavelengths with low spatial resolution and very high system temperatures
- Radio astronomy quickly moved to higher frequencies with better spatial resolution $(\theta = \frac{\lambda}{D})$ and lower system temperatures



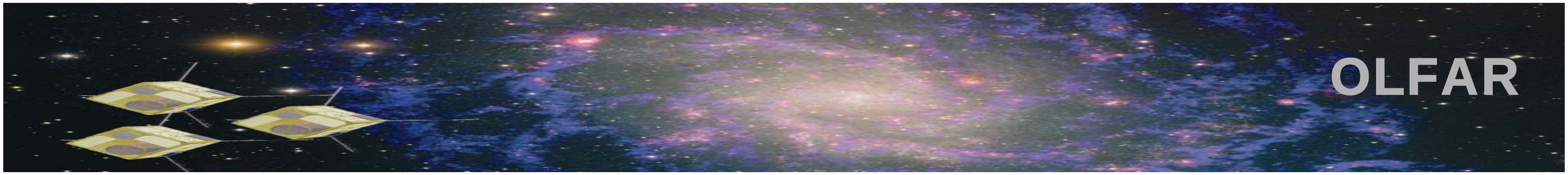
Low frequency Science

- One of the last unexplored frequency bands.
- Exploring the early cosmos at high hydrogen redshifts, the so-called dark-ages
- Discovery of planetary and solar bursts in other solar systems
- Tomographic view of space weather
- .. the unknown ..
- and for many other astronomical areas of interest



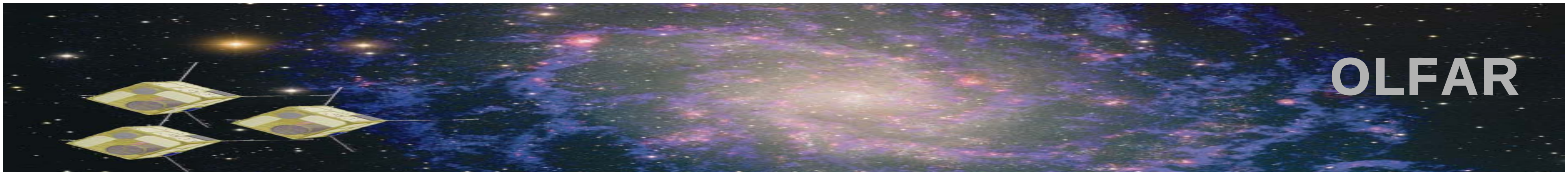
Current low frequency instruments

- VLA 74 MHz
- GMRT
- LOFAR
- LWA
- MWA
- … and more



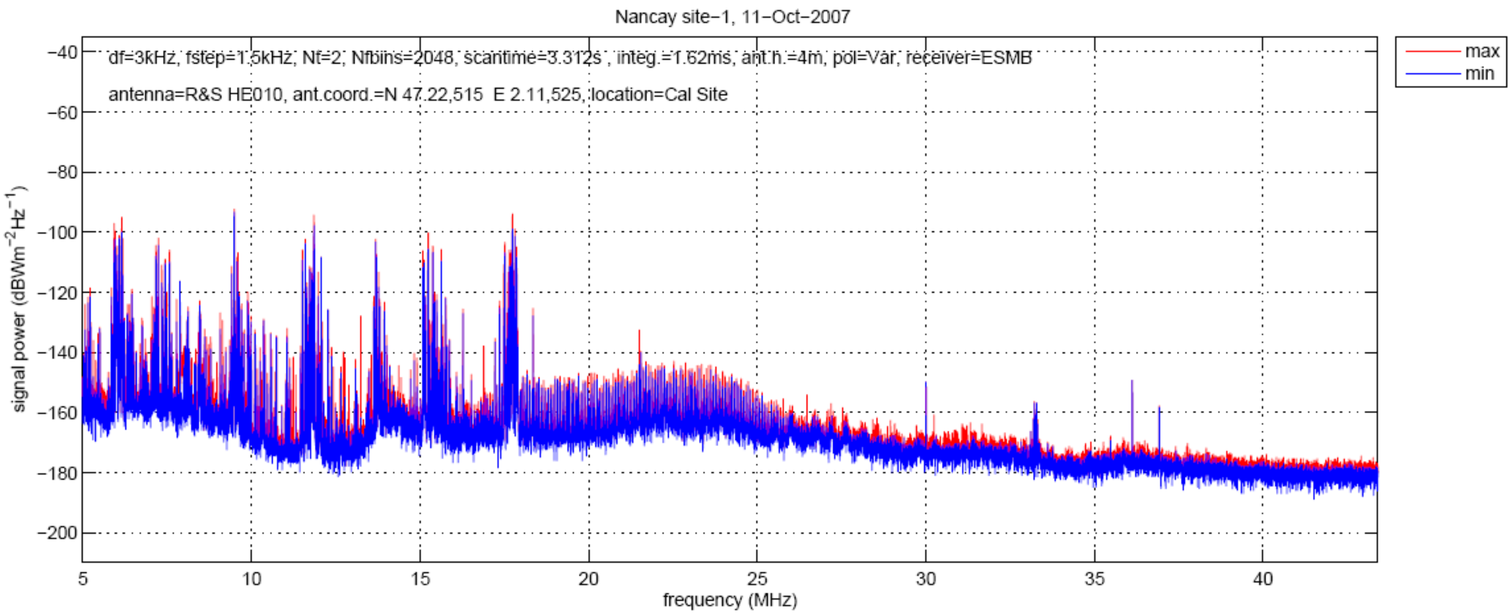
Difficulties with Low Frequency observations on Earth

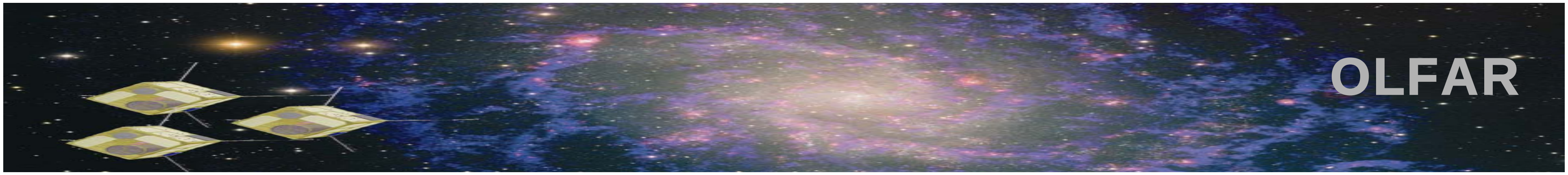
- Interference
  - Severe at low frequencies
- Phase coherence through ionosphere
  - Corruption of coherence of phase on longer baselines
  - Imperfect calibrator based gain calibration
- Isoplanatic Patch Problem:
  - Calibration changes as a function of position



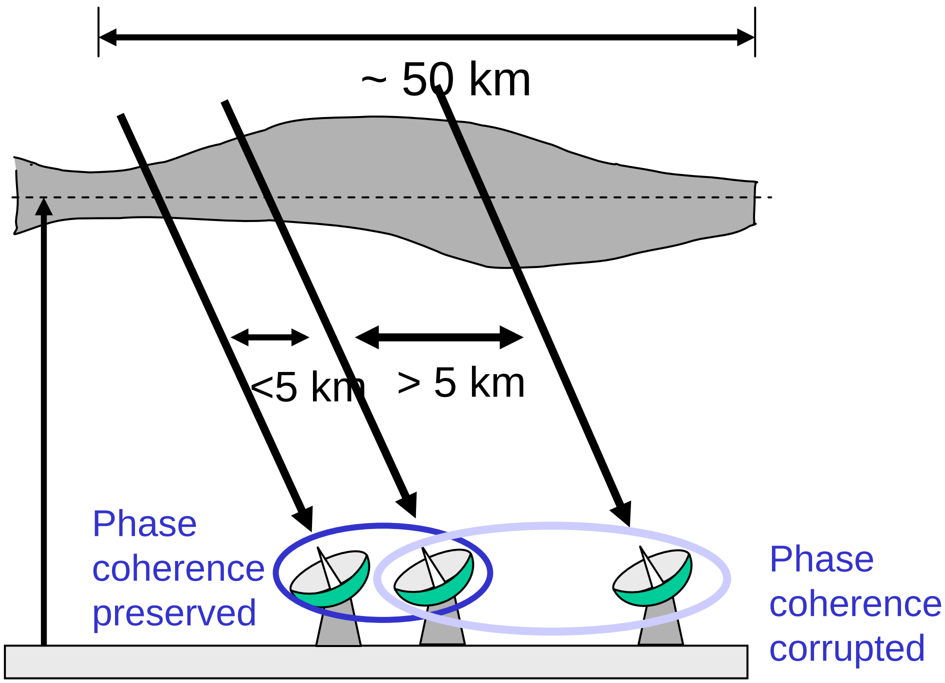
Interference

- Very “crowded” spectrum





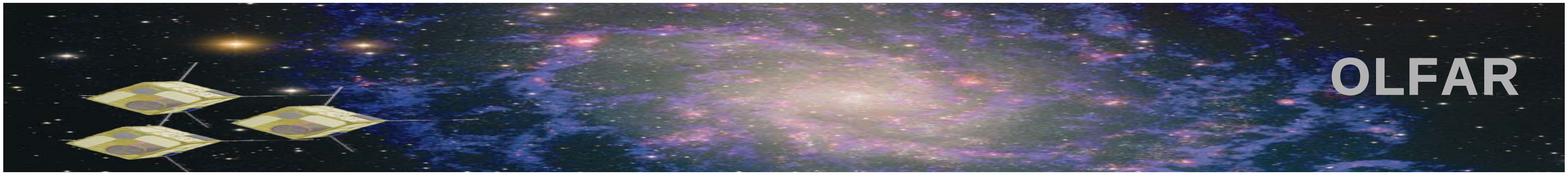
Ionospheric Structure



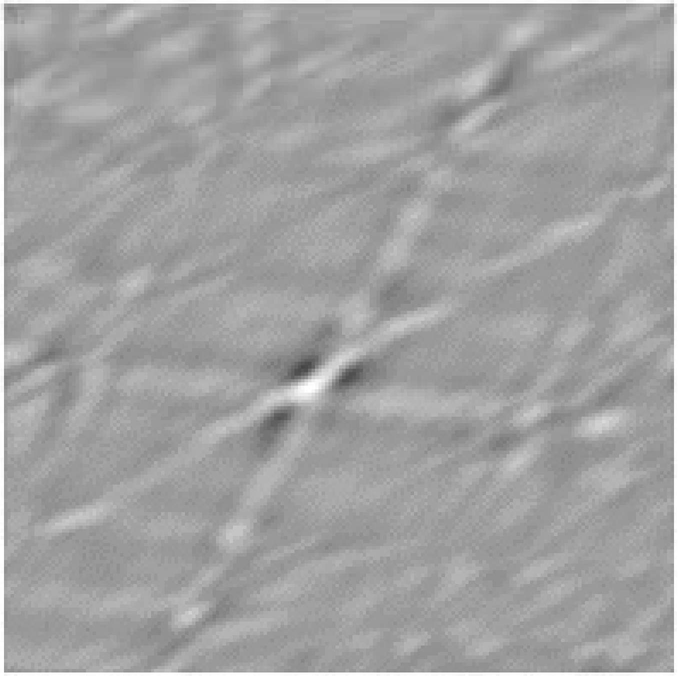
<u>Compared to shorter λ:</u>

Maximum antenna separation:
< 5 km (vs. >10^3 km)

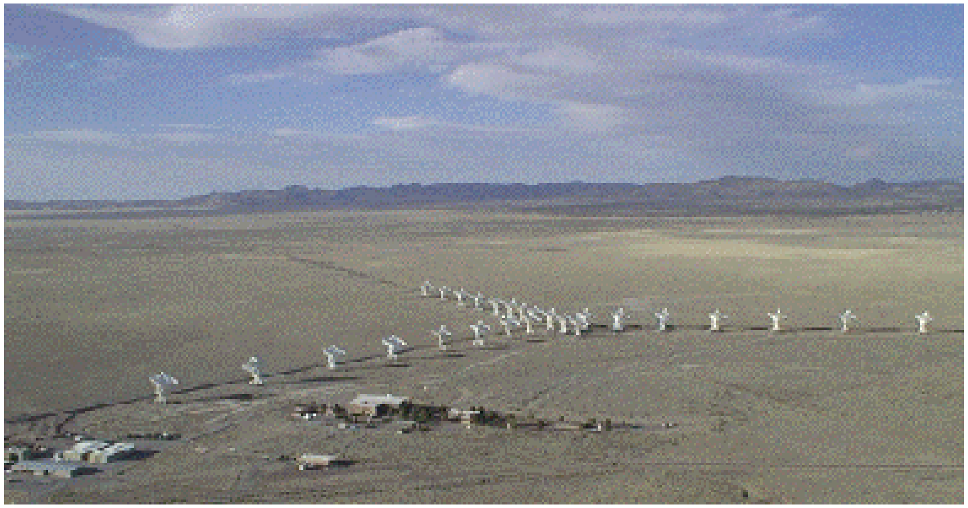
Angular resolution:
$\theta > 0.3°$ (vs. $< 10^{-3}$ °)

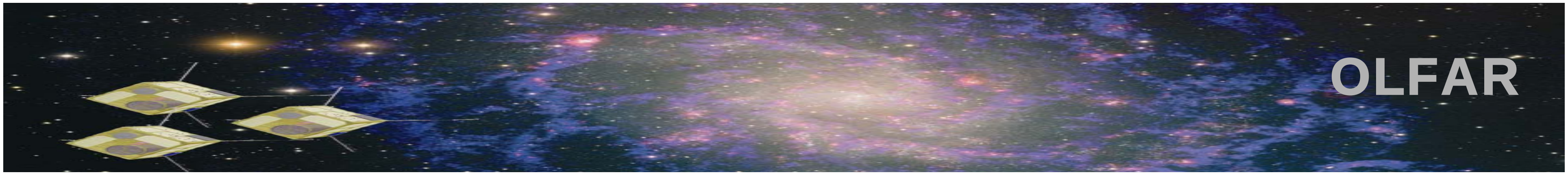


Example ionosphere



- VLA – 74 MHz



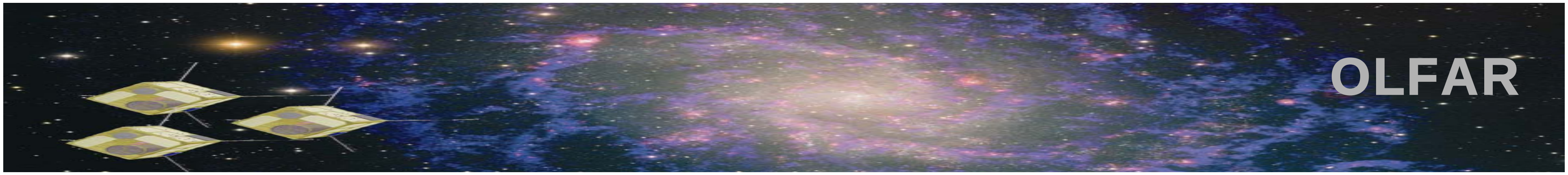


Isoplanatic Patch Problem

- Standard self-calibration assumes single ionospheric solution across FOV: **$\varphi i(t)$**
  - Problems: differential refraction, image distortion, reduced sensitivity
  - Solution: selfcal solutions with angular dependence

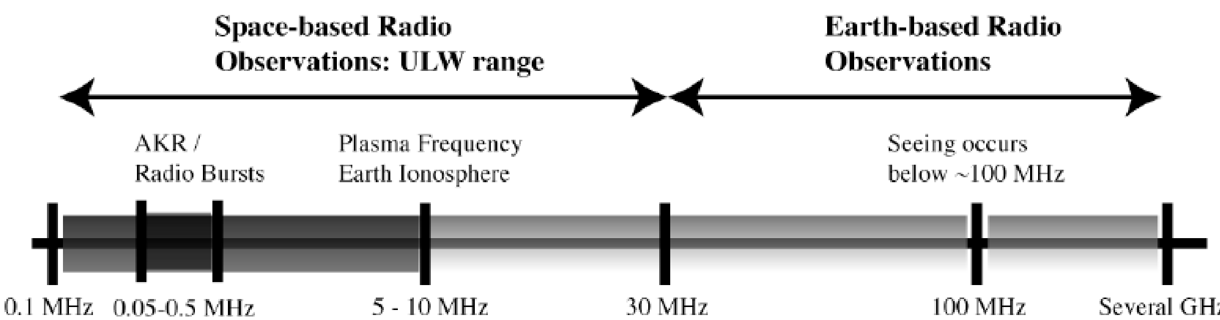
    $\varphi i(t) \rightarrow \varphi i(t, \alpha, \delta)$

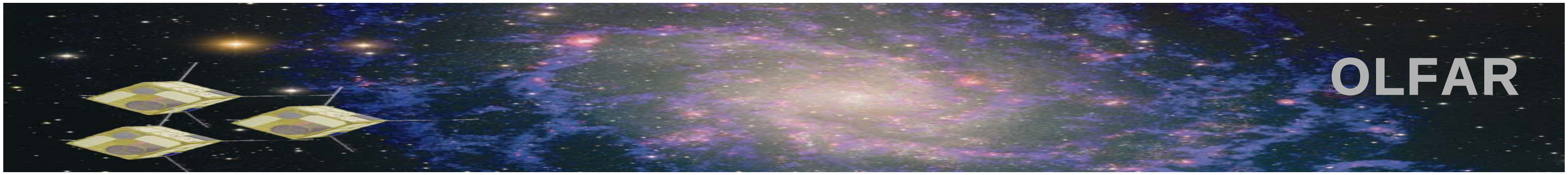
However: computational complex



OLFAR

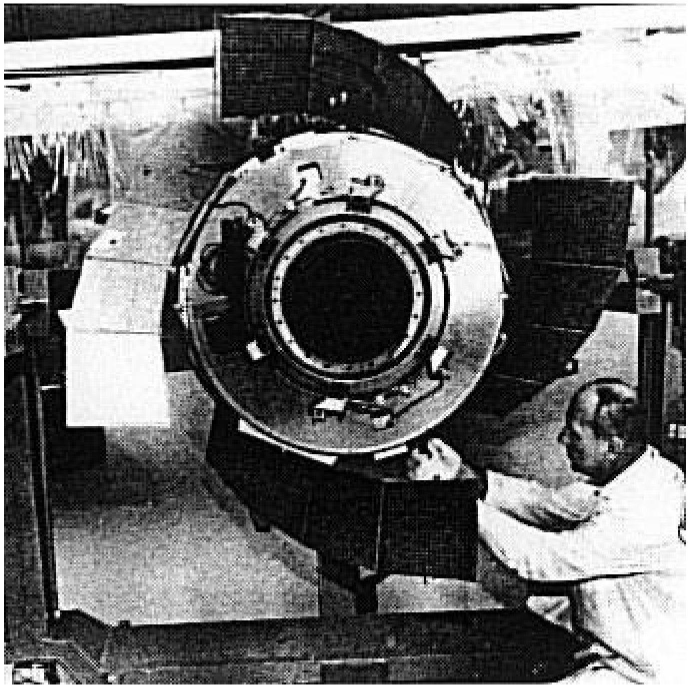
- Want to observe the 0.3 - 30 MHz band (unique)
- So, if the ionosphere is a problem ➔ Space mission
- Aperture diameter of 10 – 100 kilometer ➔ distributed aperture synthesis array (eg. Multiple satellites)
- Autonomous system
- Distributed processing system
- Possible locations: moon-orbit, Earth-Moon L2, L4/5, outer space ..

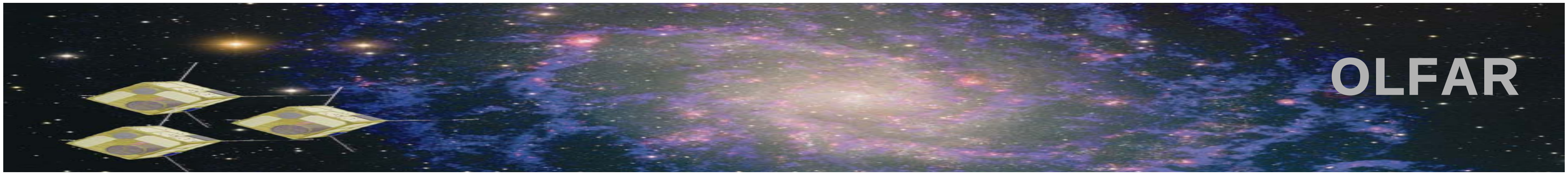




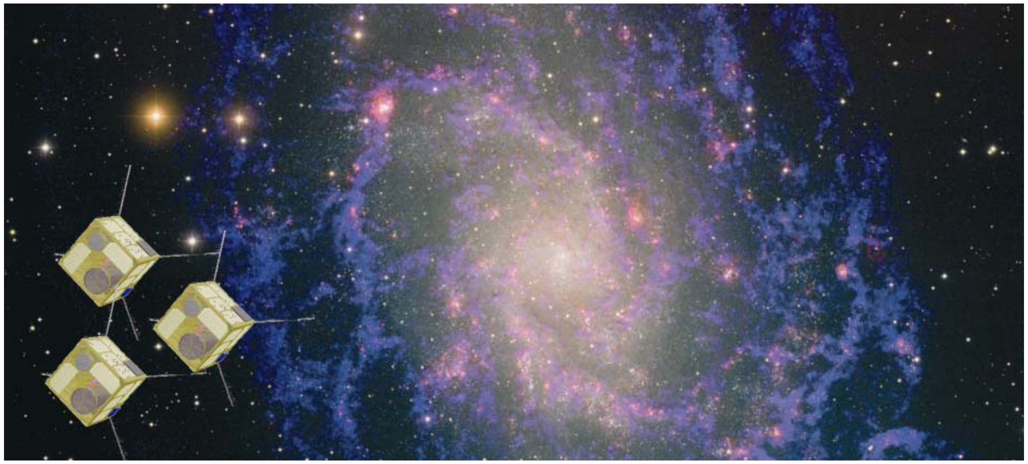
Previous low frequency missions

- 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

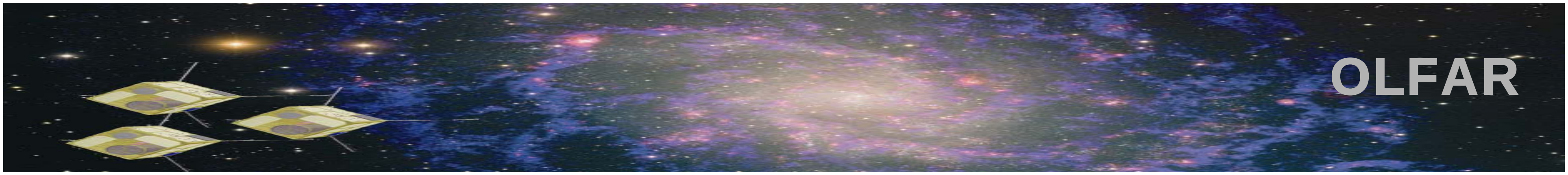




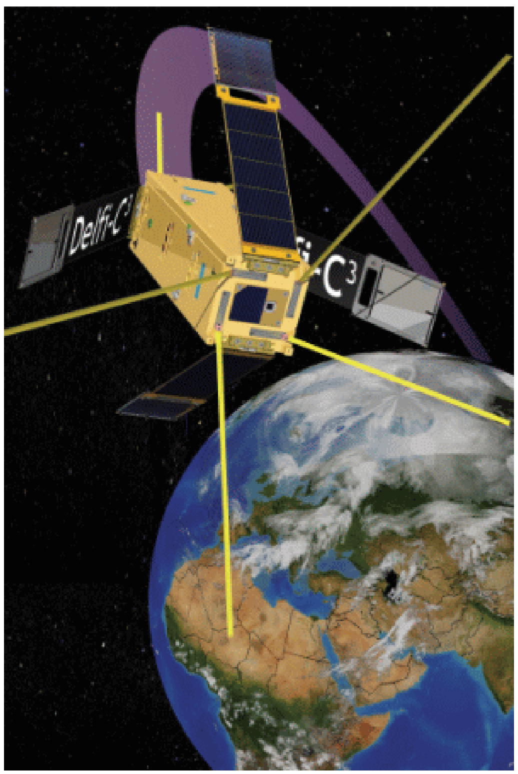
Basic idea

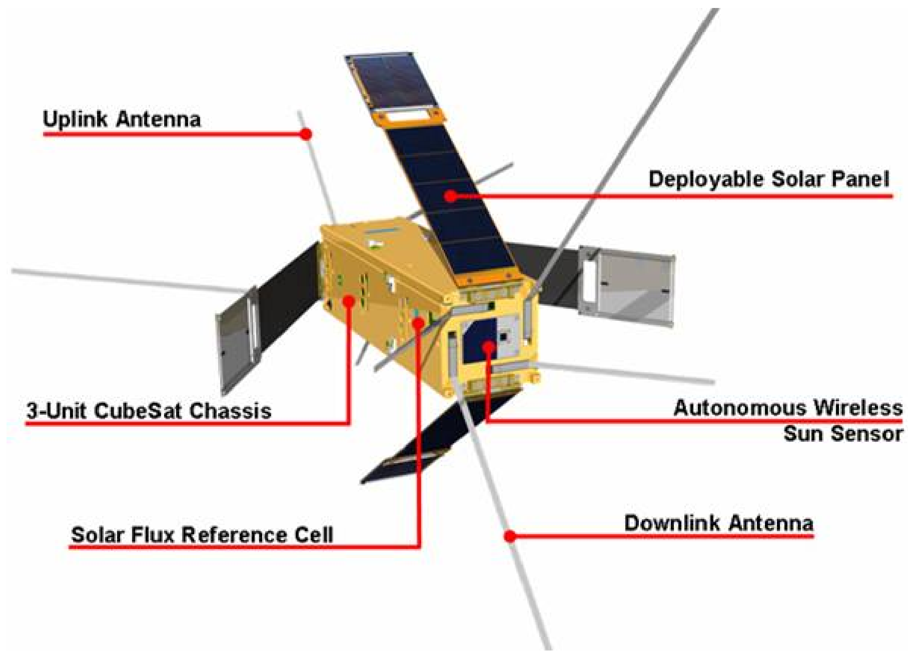


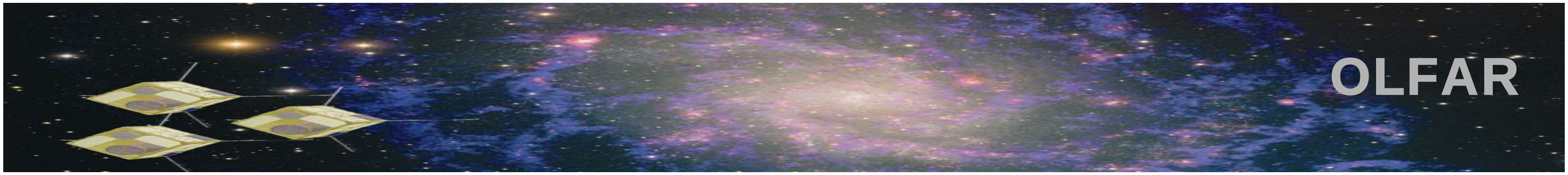
- Nano satellites
- Formation flying
- Deployable antenna for the frequency band between 1 and 30 MHz
- Ultra-low power receivers
- Intra-satellite communication
- Autonomous distributed processing
- Using diversity techniques for downlink



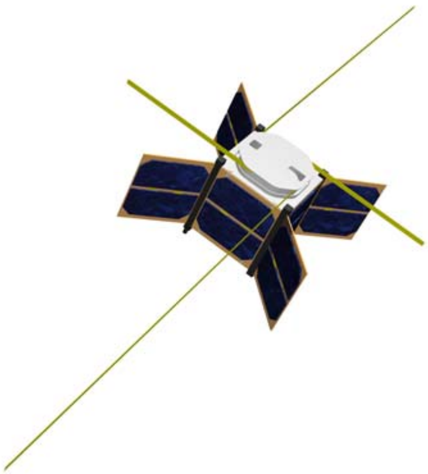
Example – Delfi-C3 Cubesats





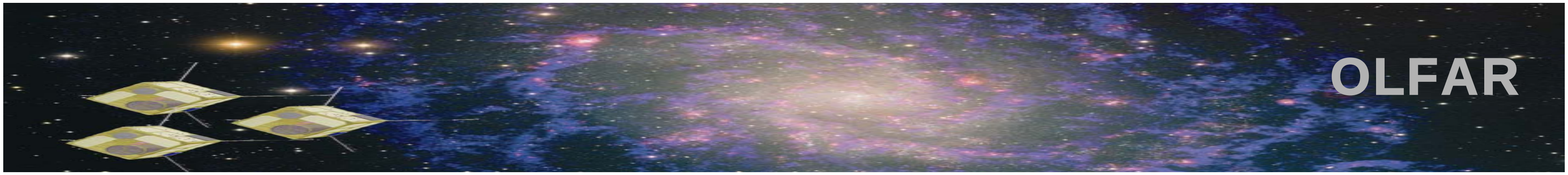


Cubesat



- Nanosatellite
- 1..3 kg
- 10x10x10 cm
- Approx. 1 ..3 W of power

- Payload for other missions

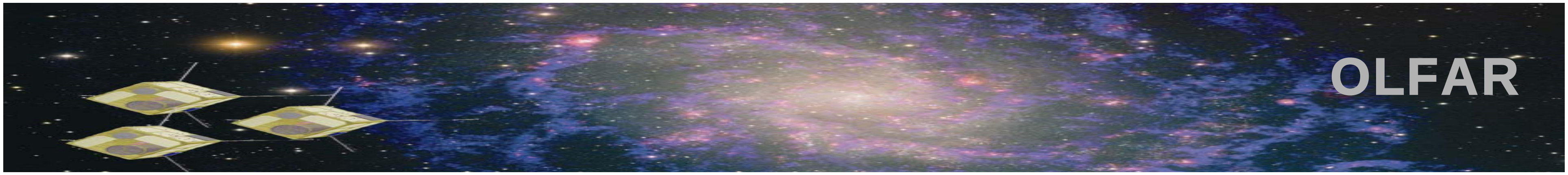


OLFAR system specifications

Preliminary OLFAR system specs	
Frequency range	at least 1-10 MHz, preferably 0.3 - 30 MHz
Antennas	dipole, tripole
Number of antennas / satellites	≥ 50
Maximum baseline	between 60 and 100 km
Configuration	Formation flying, investigate 2D and 3D
Spectral resolution	1 kHz
Processing bandwidth	t.b.d. 100 kHz?
Spatial resolution at 1 MHz	0.35 degrees for 60 km aperture
Snapshot integration time	1 to 1000 s, dependent on deployment location
Sensitivity	confusion limited
Instantaneous bandwidth	to be determined
Deployment location	Earth orbit, moon orbit, moon far side ?, L2 point

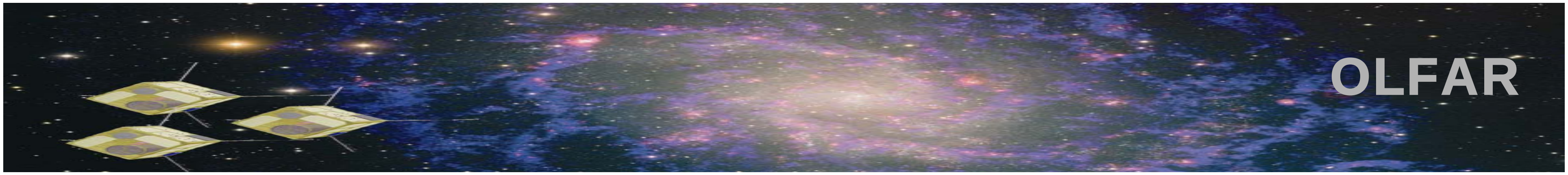
Program

- DARIS – Distributed Aperture Array for Radio Astronomy in Space (ESA/ESTEC funded project)
  - Concept study started
- OLFAR project – Funding for phase-A currently under review (Dutch Science and Technology Funds)

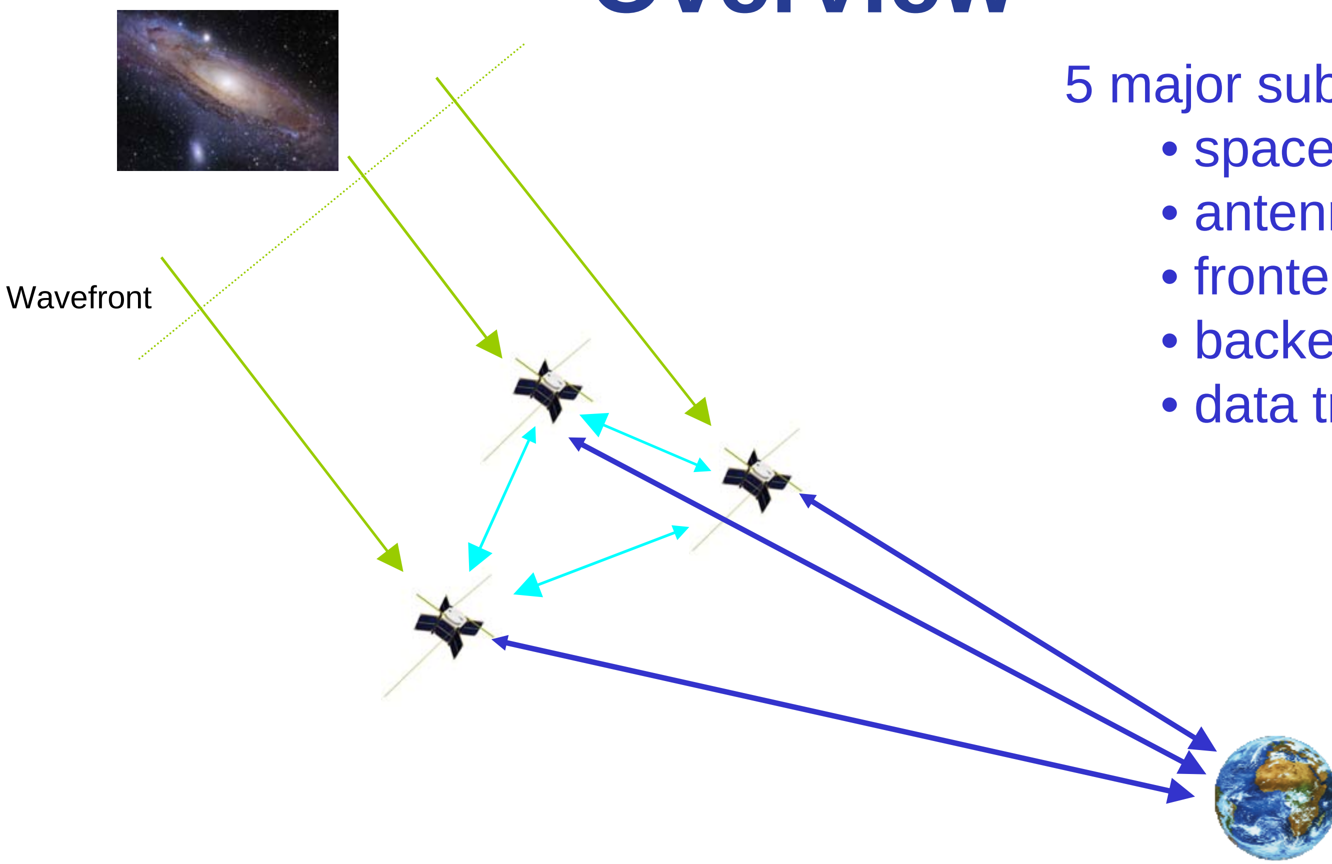


How many satellites?

Topic	Requirements					
	Freq. (MHz)	Res.	Baseline (km)	Expected signal	N (Antennas)	t_{exp} (5σ)
Extragalactic surveys	10	1’	0.1-100	≈ 65 mJy	300	2 yr
Galactic surveys						
Solar system	0.1-10	degrees	0.3-30	10 000 K	10-100	yr
Origin cosmic rays	0.1-30	1”	$(3\text{-}30)\times10^3$	155 000K	100 000	100 d
Transients						
Solar/Planetary bursts	0.1-30	degrees	0.5-200	MJy	1-100	min-hours
Extrasolar planets	0.5-30	$\lesssim$1’	$\gtrsim$35-1000	10 mJy	10^4-10^5	15 min
Ultra-high energy particles	10-100	N/A	0-5	100 MJy	1-00	N/A (Bursts)
Meteoritic impacts						

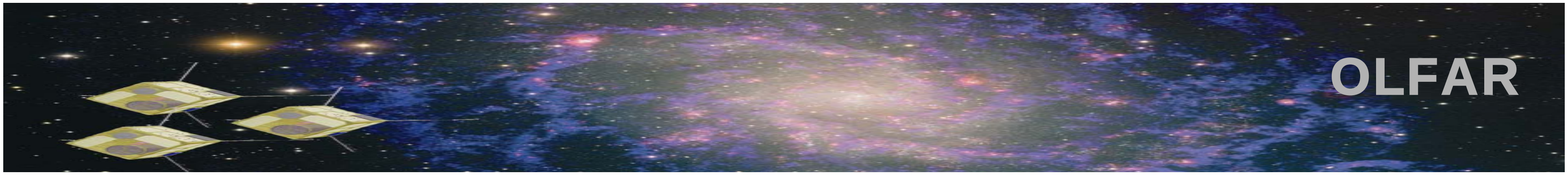


Overview

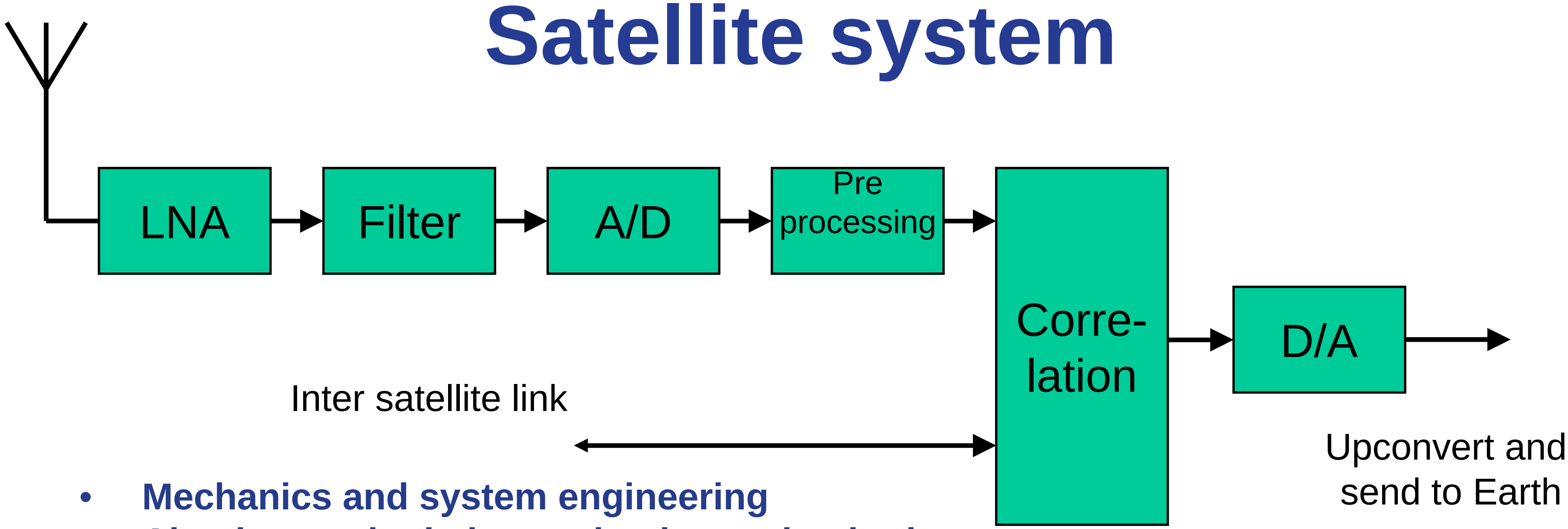


5 major subsystems:

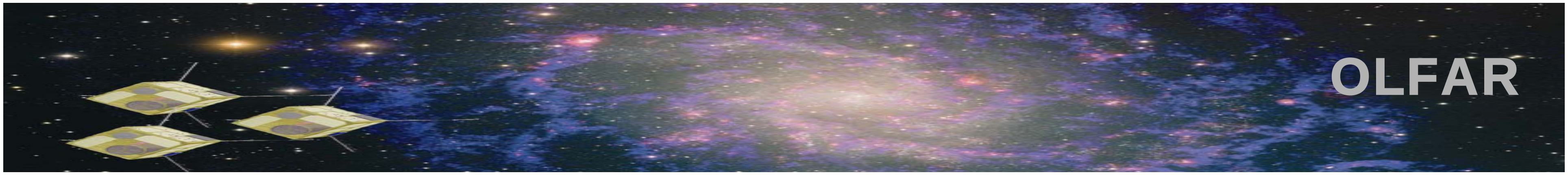
- spacecraft
- antenna design
- frontend
- backend
- data transport



Satellite system

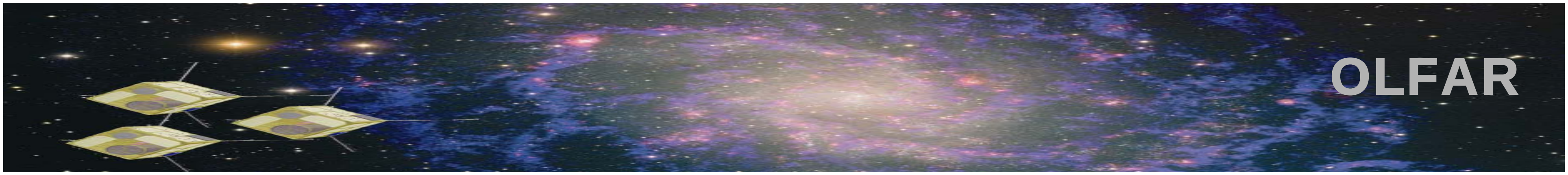


- Mechanics and system engineering
- Absolute and relative navigation and attitude
- Inter-satellite link
- Active antenna system for low-frequency radio astronomy
- Sensors for relative attitude determination
- Star trackers for absolute attitude determination
- Constellation maintenance
- Correlation software and hardware
- Overall observation control



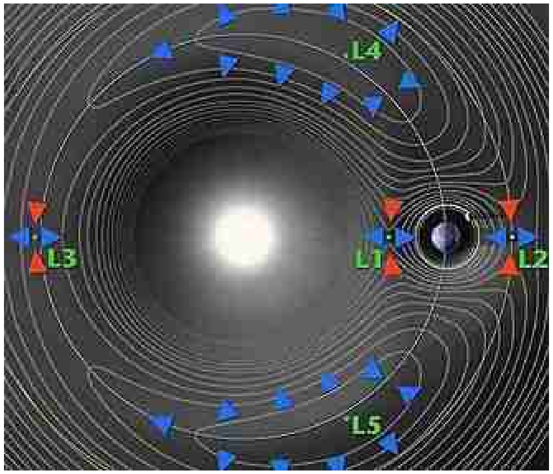
Some system aspects

- Antenna design for 1-30 MHz band
- Active LNA
- Receiver – filtering, sampling,
- Timing, clocking (local and global)
- Localization
- Digital signal processing
  - RFI mitigation
  - Filtering
  - Subband sampling
  - Distributed correlation, tied-array calculations
- Data transport
  - Between individual nodes
  - Corrrelated and/or tied array data to datacente
- Datahandling
  - LOFAR as receptor
  - Storage
  - Post-processing
  - Calibration

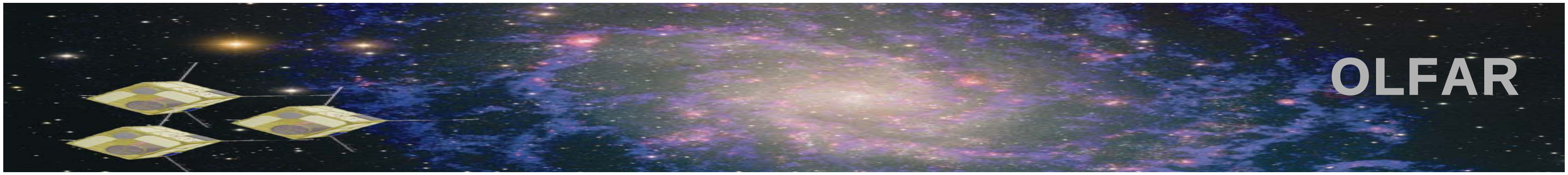


Locations

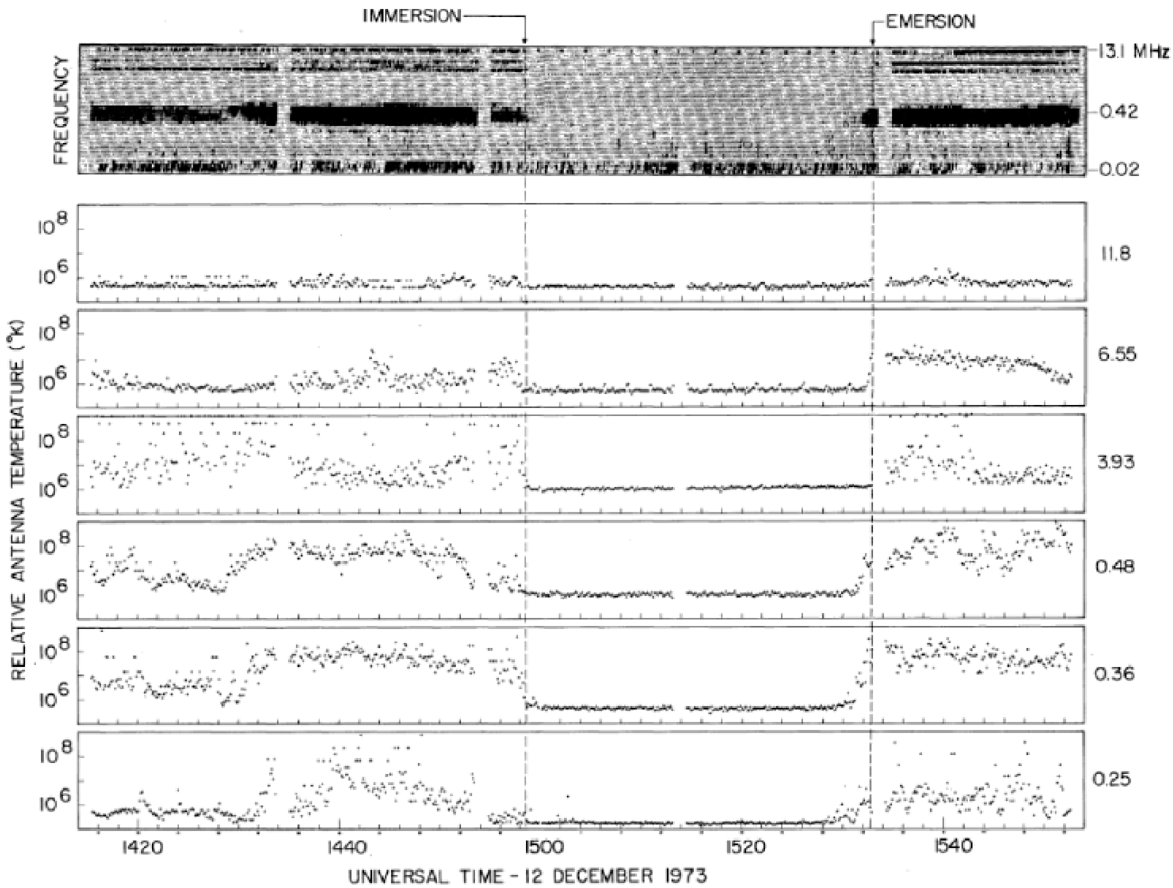
- Earth orbit
- Moon orbit
- L2
- Outer space

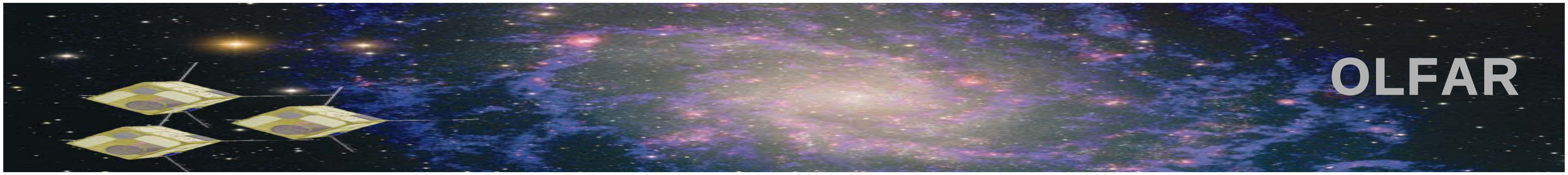


- Design considerations:
  - RFI from Earth
  - Constellation control (absolute and relative position)
  - Downlink to Earth
  - …



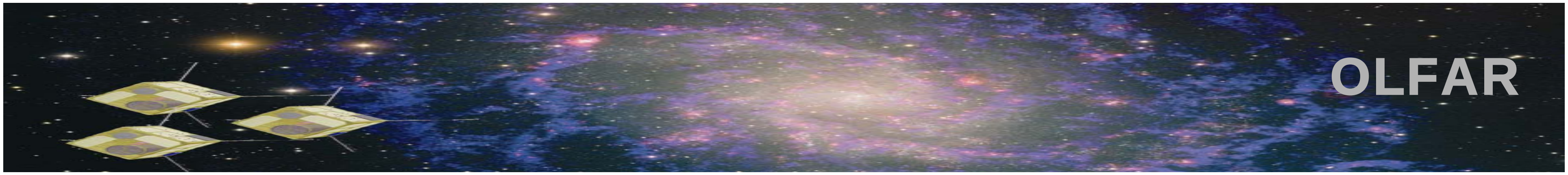
Shielding by the moon





Antenna systems

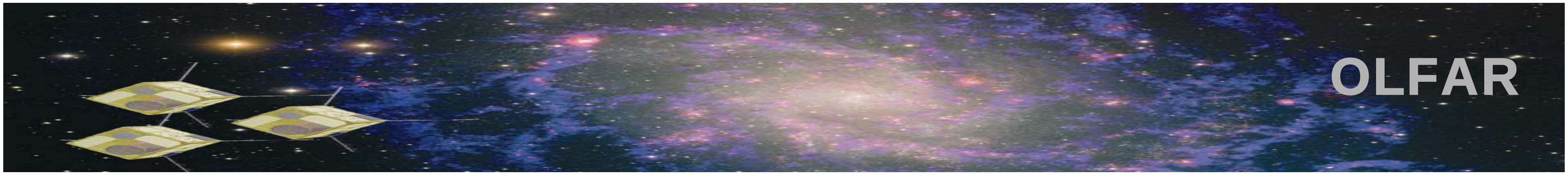
- Astronomical observing antenna
  - 0.3 – 30 MHz ➔ Wavelengths: 10 - 1000 meter !
  - Aperture
- Inter satellite link
  - Data rates (raw data – bandwidth of 100 kHz with 8 bits and all-to-all satellites is ~200 Mbps per satellite)
- Down link
  - Data rate is ~ 20 Mbps in case of correlation in space.
  - Possible use of diversity techniques



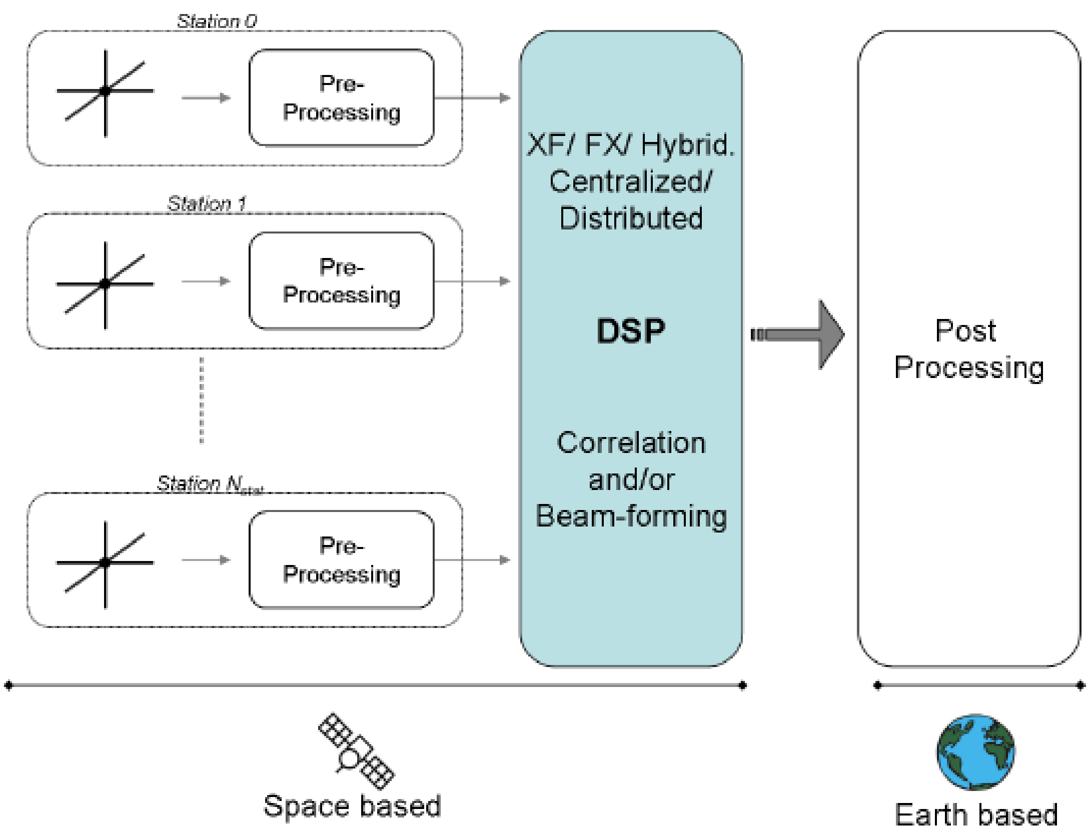
Formation flying

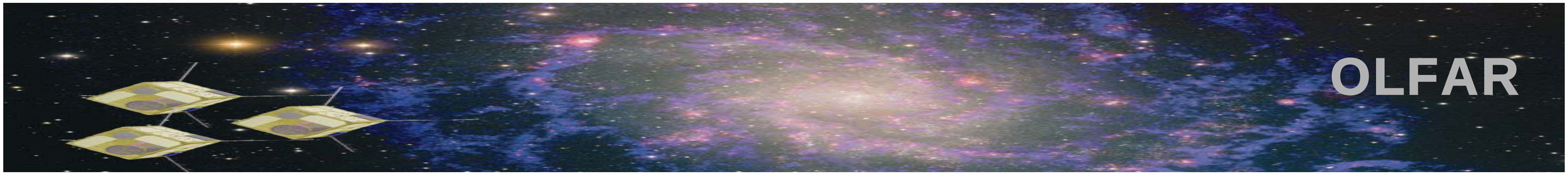
- Constellation must be limited to approx. 100 kilometers.
- Individual satellites can move slowly (as long as stable within integration time).
  - Constraint: given the integration time and the accuracy of 1/20th of the wavelength within the integration time.
- 5 years of operation

- This is currently under research (we consider L2 and moon orbit at this moment).

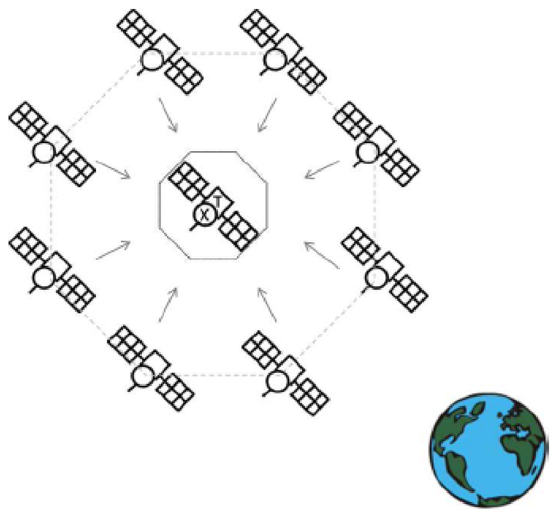


Data processing



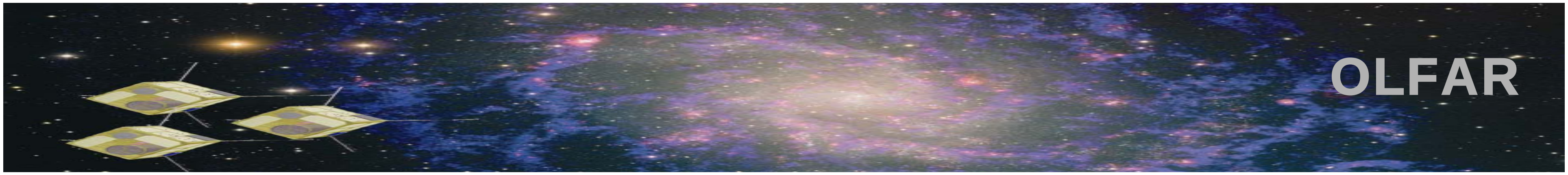


Signal processing

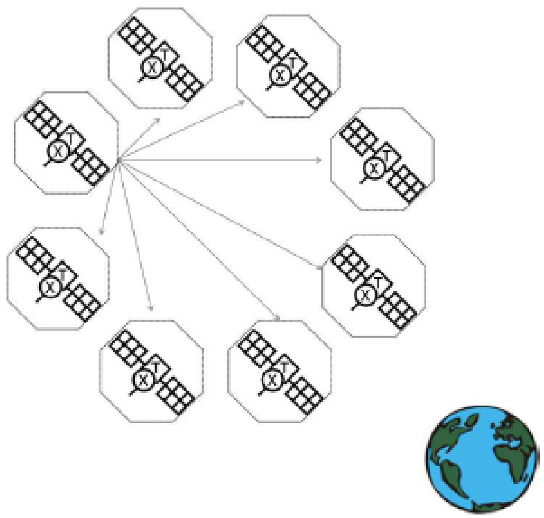


Centralized correlation, centralized downlink

- Correlation:
  - Distributed
  - Centralized
- Downlink
  - Distributed
  - Centralized

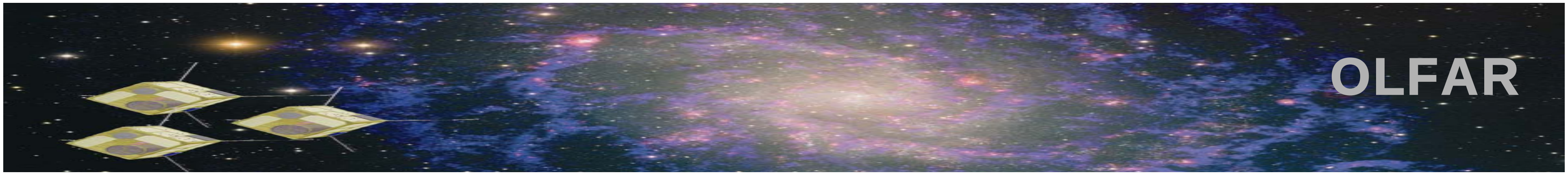


Signal processing

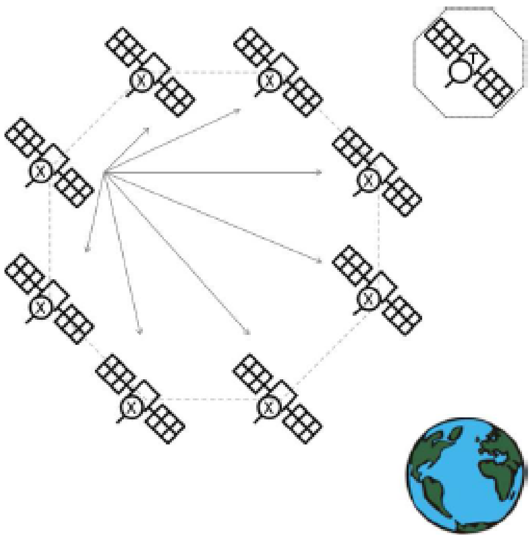


Distributed correlation,
Distributed downlink

- Correlation:
  - Distributed
  - Centralized
- Downlink
  - Distributed
  - Centralized



Signal processing



Distributed correlation,
Centralized downlink

- Correlation:
  - Distributed
  - Centralized
- Downlink
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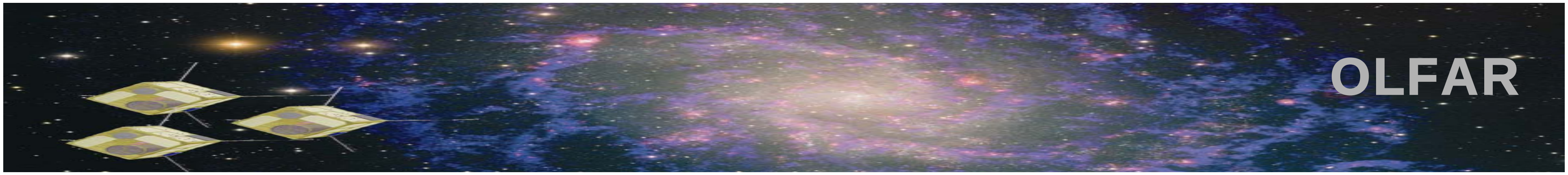
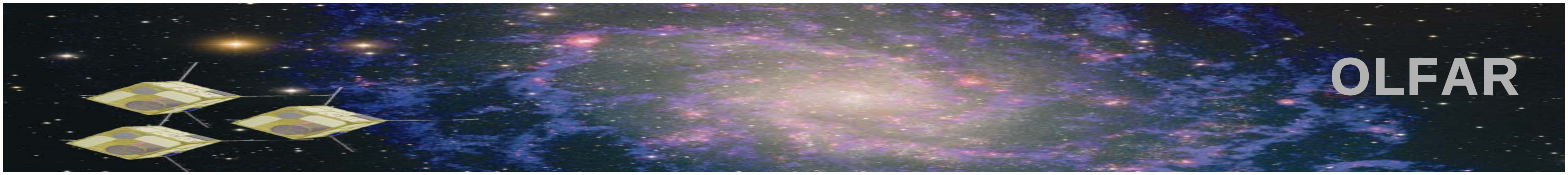


Example

- If case of 50 satellites
- 8 bit sampling
- Bandwidth of 10 MHz
- Integration time of 1 second

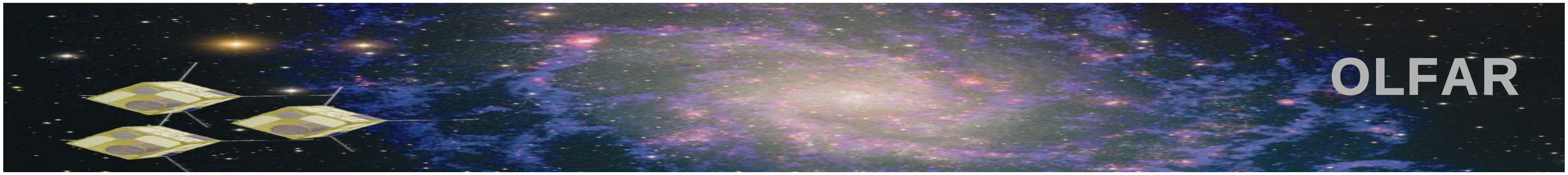
➔ Communicaton in bits/sec:

	Intersatellite	***Downlink***
Distributed correlation		
Distributed Transmission	235,2E+6	359,99E+3
Centralized Transmission	235,2E+6	18,0E+6



Planning

- 2009: concept study, start
- After that – detailed system design with focus on main issues:
  - Virtual distributed system and nano satellite architecture
  - Radio architectures for the communication in distributed arrays in space
  - distributed autonomous signal processing
- 2010/11: astronomical receiver in Delfi-N3xt
- 2013: flightunits available

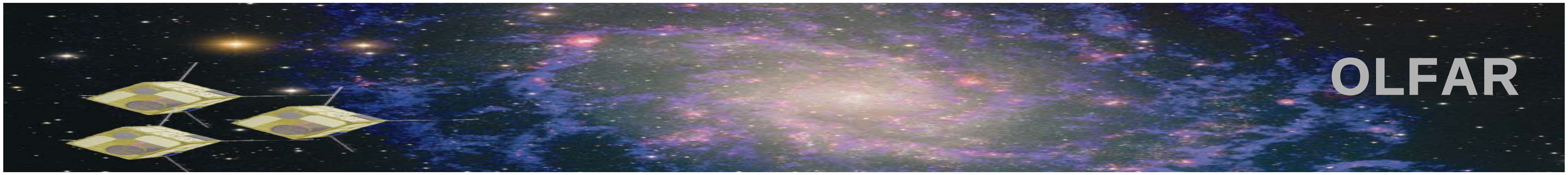


Conclusions and future work

- OLFAR is a new concept of a low frequency radio telescope in space using small satellites.
- Correlation must be done in space.
- Distributed processing with centralized downlink transmission is the preferable option.
- Inter satellite link is the communication challenge.
- In 2010/2011 experiments with Delfi-N3xt.

Future work:

- Simulate the constellations in Moon Orbit en L2
- Virtual distributed system and nano satellite architecture
- Radio architectures for the communication in distributed arrays in space
- Distributed autonomous signal processing



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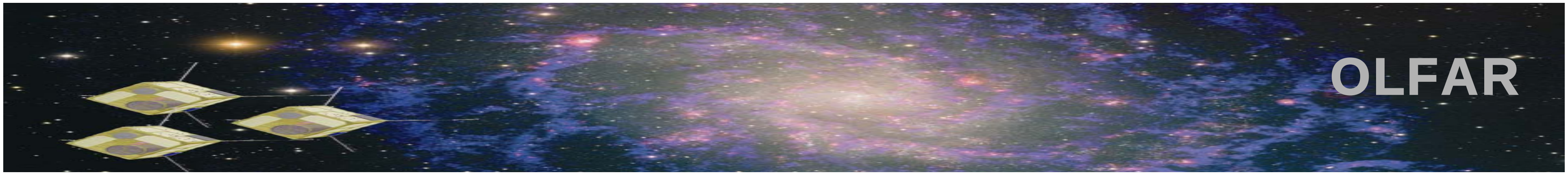

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