Radioastronomy in Space with Cubesats

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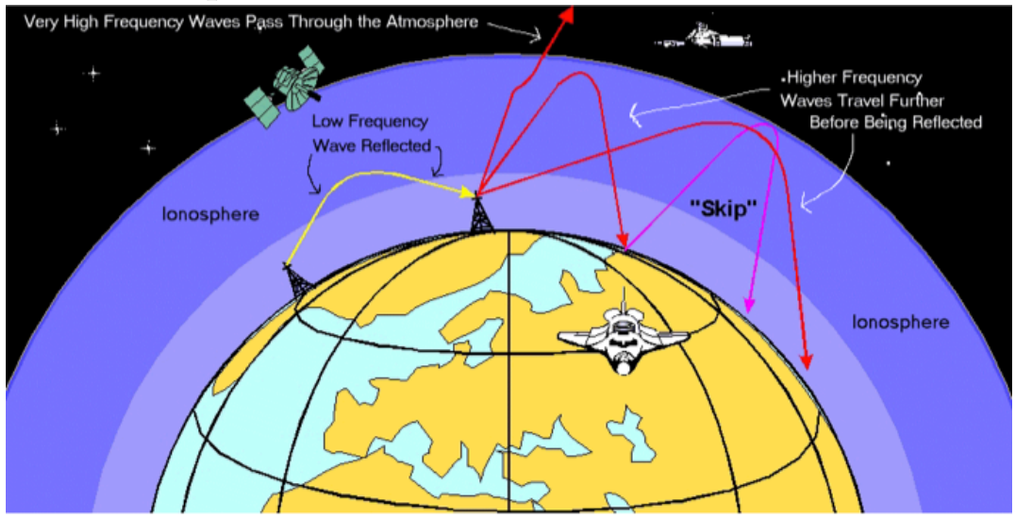
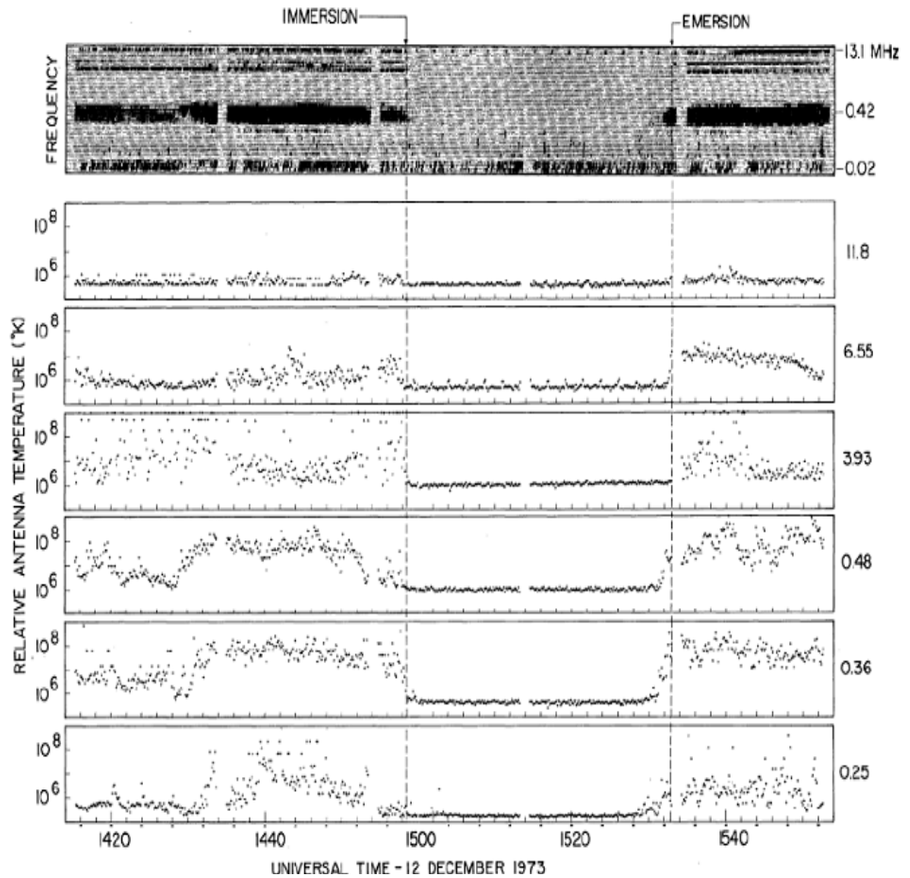
No place on/near Earth is Dark at Low Frequencies (LF radio "smog")

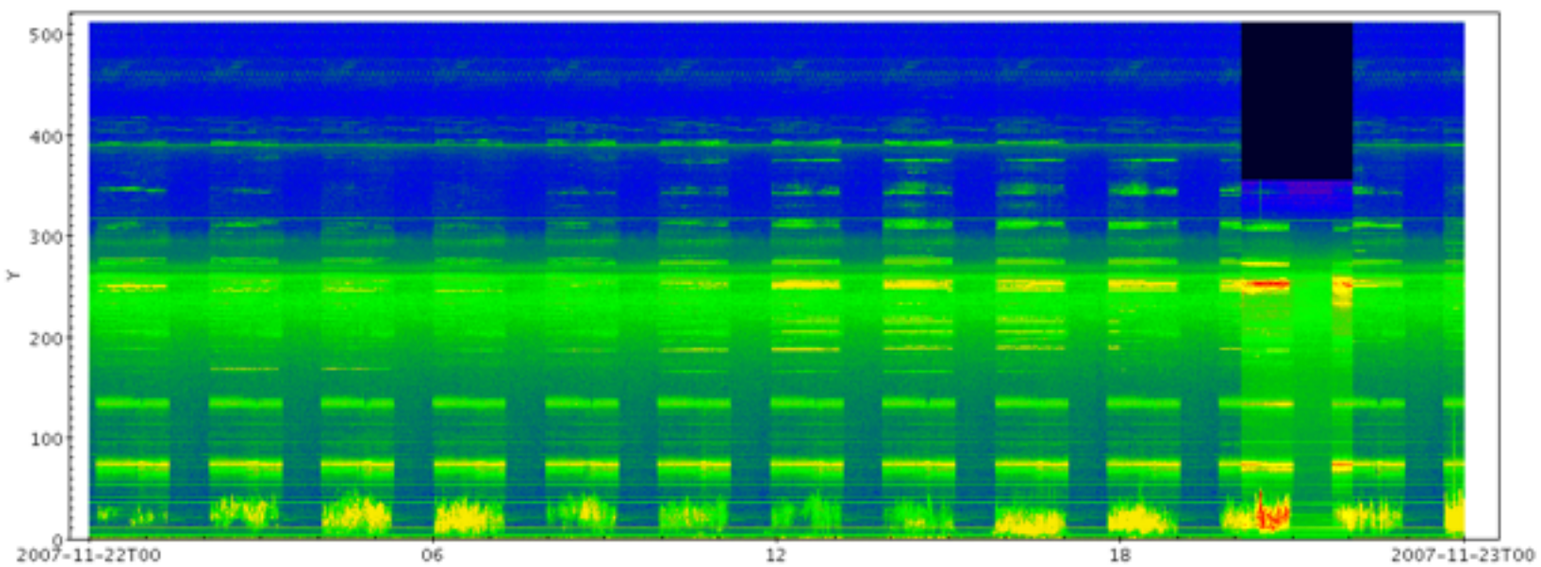
Ionospheric cutoff at ~10 MHz:



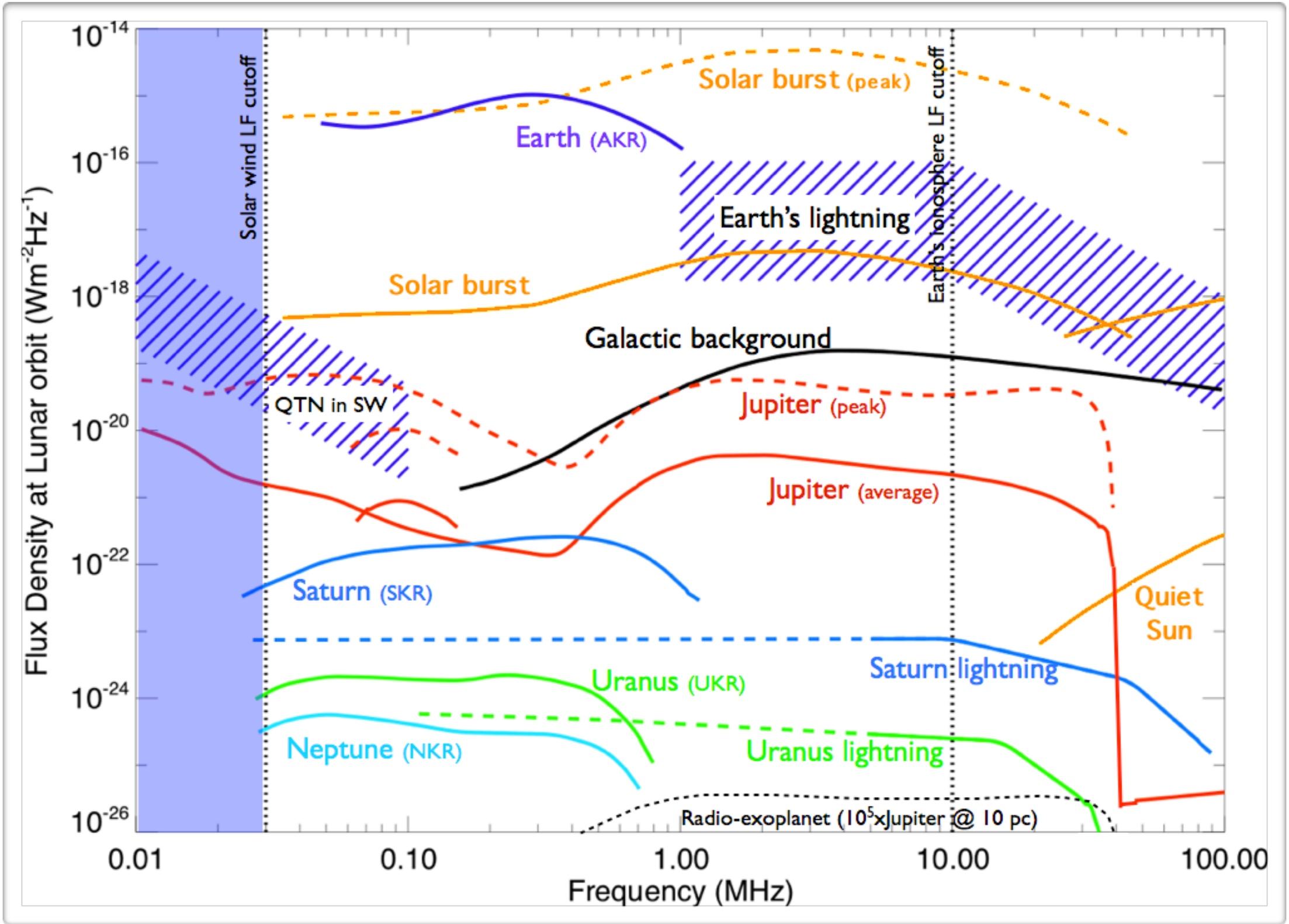
RAE-2 occultation of Earth (1973)



Kaguya-Selene LRS Occultations of Earth RFI and AKR (22-Nov-2007)



Natural radio environment around Earth



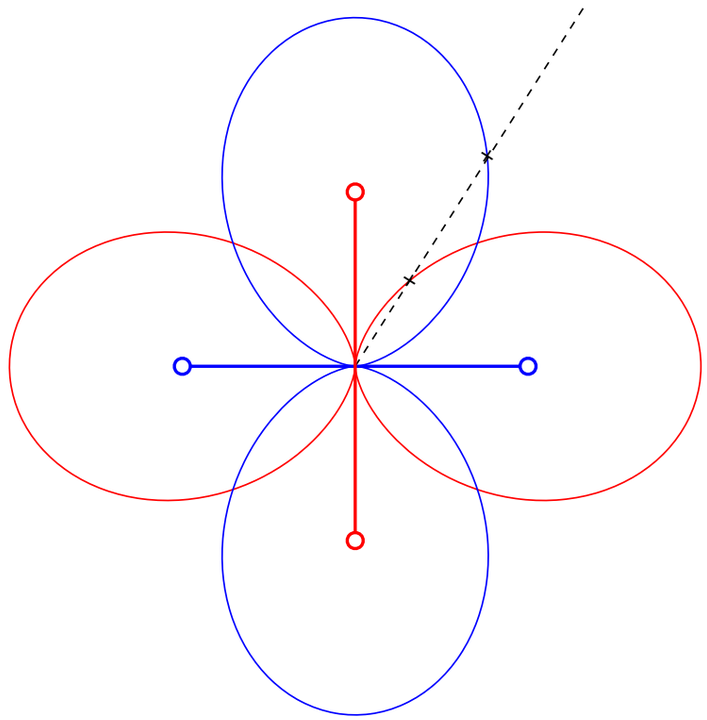
Space borne Radio Astronomy
Goniopolarimetry

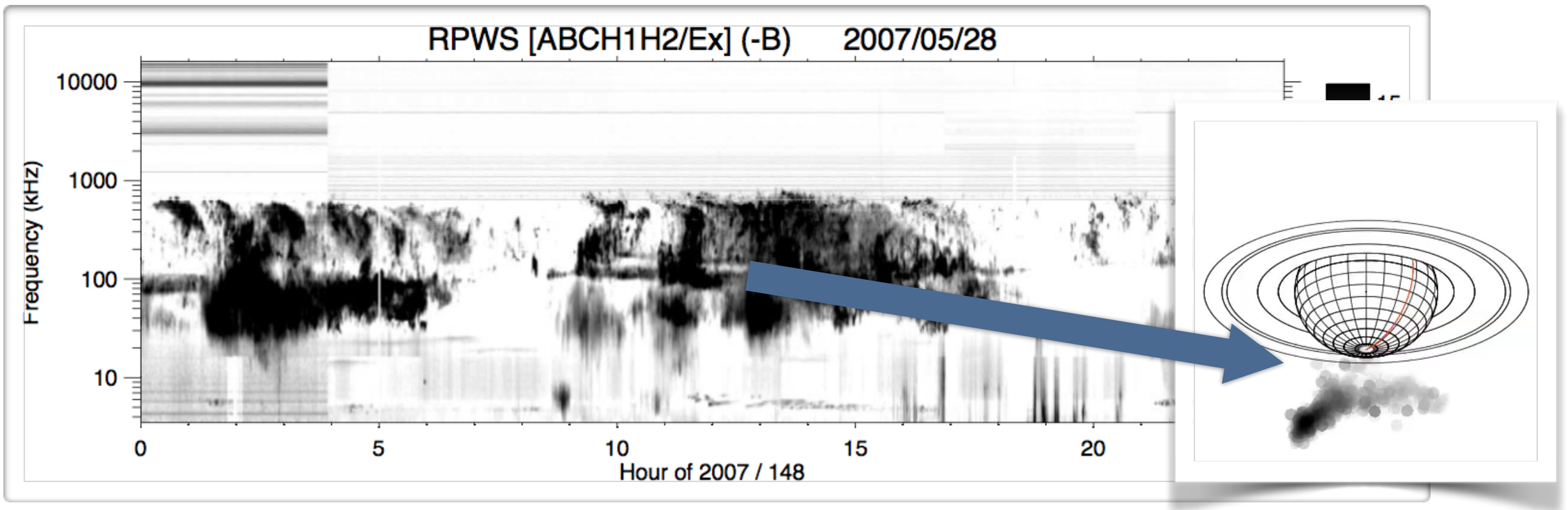
- Space based radio antennas: simple dipoles or monopoles with length L of a few meters (impossible to have a reflector large enough to have $\lambda/D << 1$)

- Short antenna range ($L << \lambda$) : monopole antenna + S/C body ~ effective dipole

- Antenna gain ~ $L^2\sin^2\theta$ → null // antenna, max ⊥ to antenna

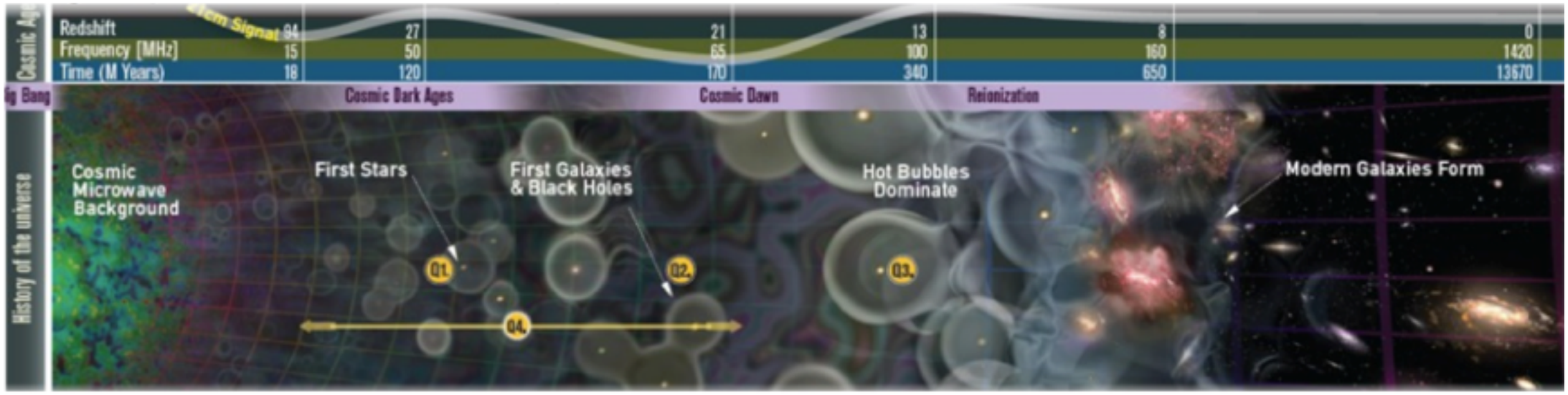
  => local measurement of the wave-front orientation:
  direction of arrival + polarization + flux (+ *wave front curvature*)





Very Low Frequency Radioastronomy Identified Science opportunities

- **LF sky mapping** + monitoring : radio galaxies, large scale structures (clusters with radio halos, cosmological filaments, …), including polarization, down to a few MHz
- **Cosmology** : pathfinder measurements of the red-shifted HI line that originates from before the formation of the first stars (dark ages, recombination)



- Interaction of **ultra-high energy cosmic rays and neutrinos** with the lunar surface
- **Low-frequency radio bursts** from the Sun, from 1.5 Rs to ~1 AU : Type II & III, CME, ...
  Space weather - Passive: through scintillation and Faraday rotation
  - Active: through radar scattering
- **Auroral emissions from the giant planets**' magnetospheres in our solar system: rotation periods, modulations by satellites & SW, MS dynamics, seasonal effects, ...
  First opportunity in decades to study Uranus and Neptune
- **Detection of pulsars down to VLF**, with implications for interstellar radio propagation : LF cutoff of temporal broadening in 1/f4.4 ?
  → largest scale of turbulence in ISS ? limit of transient observations ?
- **The unknown** …

What can we do further in terms of instrumentation ?

- **Current space-borne radio instrumentation:**
  set electric dipoles on a spacecraft + goniopolarimetry
  => only up to 9 instantaneous measurements
  => simple radio source modeling required

- **Future = Interferometry in space**
  electric dipoles on a series of spacecraft spread over a large range
  => Interferometry : angular resolution up to λ/B with B the longest baseline

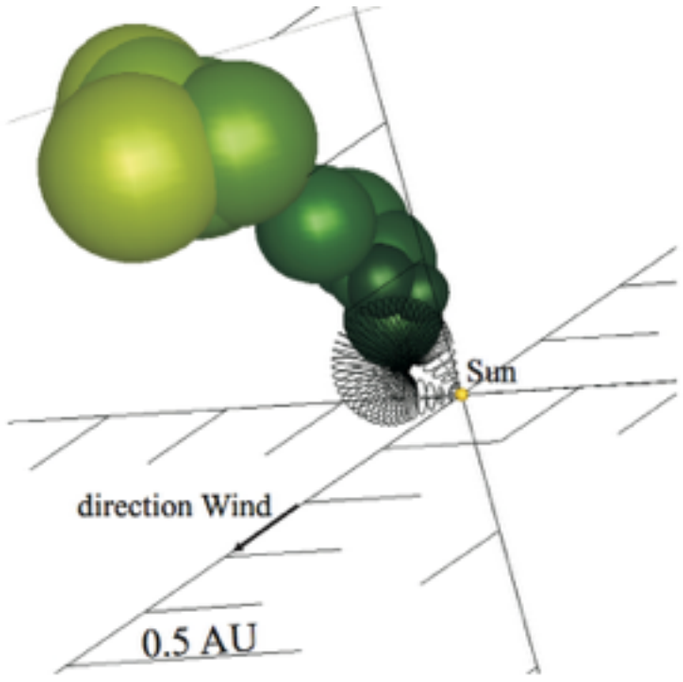
Frequency	Wavelength	θ @ 10 km	θ @ 100 km	θ @ 1000 km	θ @ 10,000 km
30 MHz	10 m	3.4′	20.63″	2.06″	0.2″
10 MHz	30 m	10.31′	1′	6.19″	0.62″
1 MHz	300 m	1.719°	10.31′	1′	6.19″
100 kHz	3000 m	17.19°	1.719°	10.31′	1′

Knapp et al. 2012

=> Radio Wavefront can be spatially sampled
=> Instantaneous Imaging capabilities !

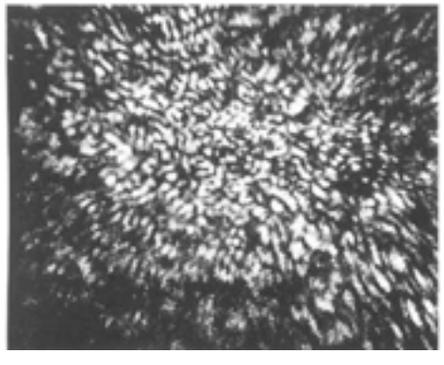
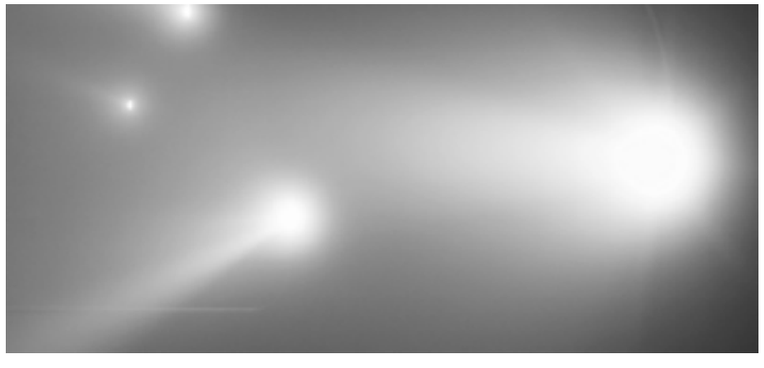
Solar Radio Emissions

- **What do we see now**:
  using simple a model for extended source (*on left figure, each «bubble» is a frequency step)*
  Each record: *1 location and 1 radius*



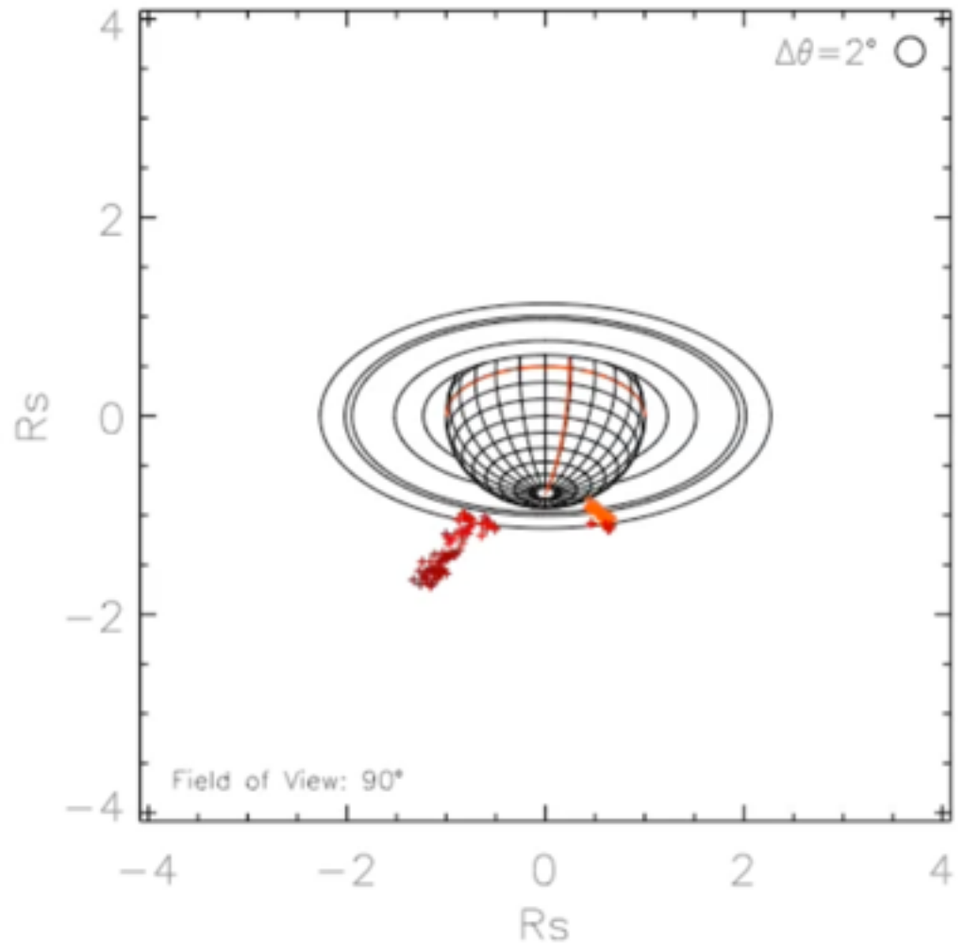
Magdalenic et al, 2014

- **What to expect**:
  each record = 1 image (= flux map)

  Will we see  or  ?

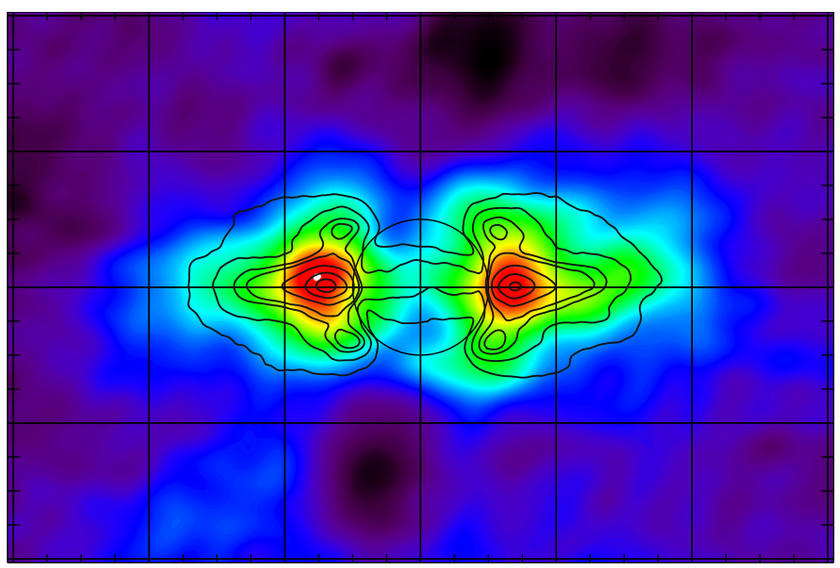
Planetary Radio Emissions

- **What do we see now**:
  for each time-frequency step:
  1 location, 1 flux, 1 polarization
  (a posteriori reconstruction with a lot a records, i.e., time/freq averaging)



Cecconi et al, 2009
Cassini/RPWS

- **What to expect**:
  each time-frequency:
  1 flux map,
  1 polarization map

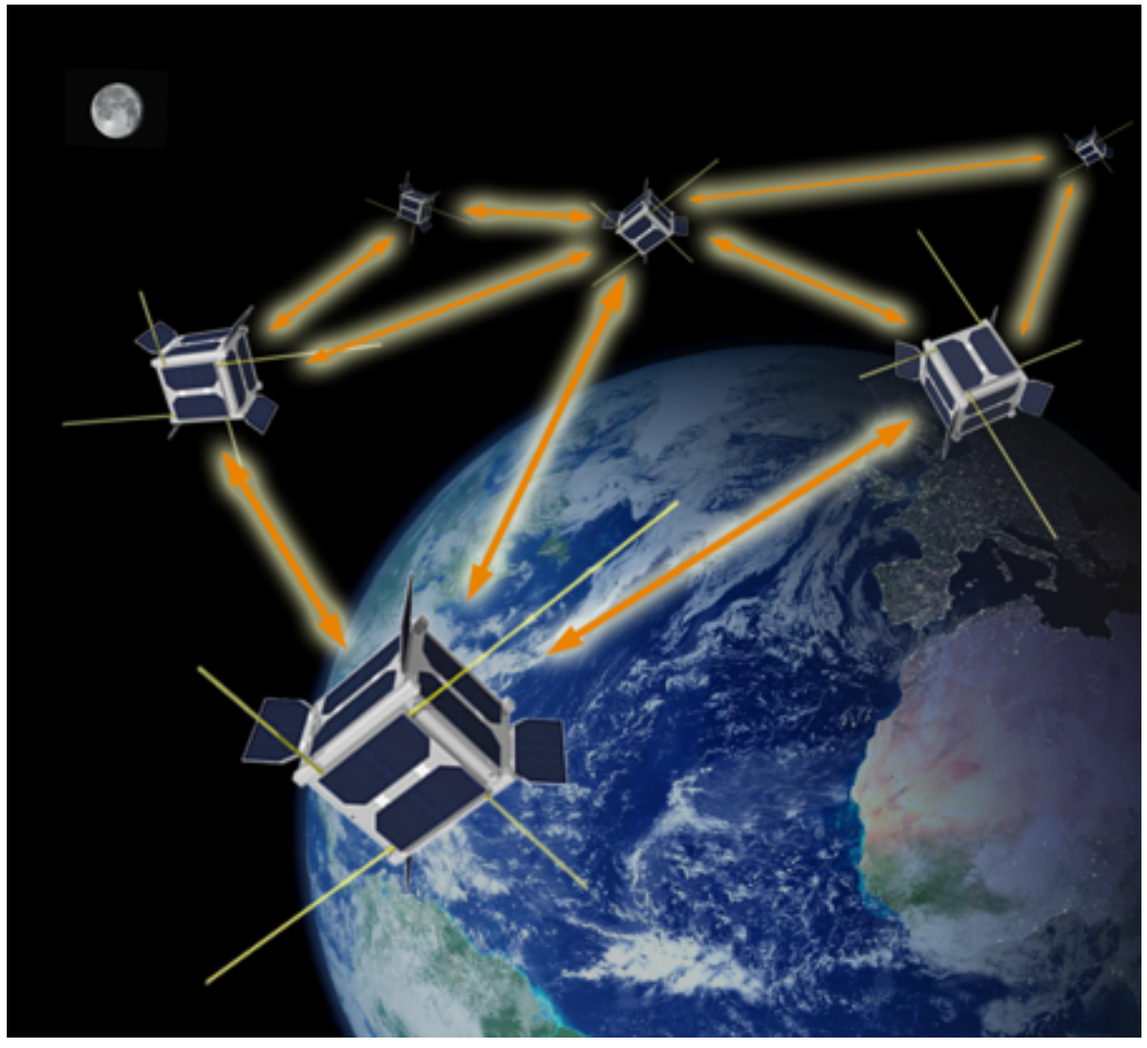

Girard et al, 2014
LOFAR

Past and present projects

- **Low Frequency radio interferometer** has already been proposed several times, here **in the USA**:
  - SIRA project (MacDowall et al, GSFC)
  - SOLARA/SARA project (Knapp et al, MIT)
- **in Europe**, with the LOFAR team:
  - OLFAR project (Bentum et al., NL)
  + other emerging projects in NL, Sweden and France (DEX, SURO, DARIS, FOAM...)
- **ESA-CAS** proposal:
  - DSL: Discover the Sky at Long wavelengths
  (Astron NL + SHAO China, et al)

OLFAR
Teams involved: NL, FR, SE
+ many other interested

- **OLFAR: Orbiting low Frequency Antennas for Radio Astronomy**
- **Science objectives**:
  - «Dark Ages» (cosmology < 10MHz, redshift ~100, EoR [*Epoch of Recombination*])
  - Sun-Earth (space weather), Planets (outer planets: Uranus...)
  - In situ measurements (Thermal Noise).
- **Technology objectives**:
  - Passive formation flying (swarm configuration); inter-satellite distance < 100 km
  - Inter-satellite communication with GSM, shared computing power (distributed computing)
  - Radio antennas: 3 electric dipoles axes (6 x 5 m); frequency range: 30 kHz-30 MHz
- **Schedule**: 2020 ?
  Orbitography: lunar orbit (or L4-L5 Earth Lagrange Points)



Past and present projects including cubesats

	freq. range	baseline	nb of S/C	location
SIRA	30 kHz – 15 MHz	>10 km	12 – 16	Sun-Earth L1 halo
SOLARA/ SARA	100 kHz – 10 MHz	<10,000 km	20	Earth-Moon L1
OLFAR*	30 kHz – 30 MHz	~100 km	50	Lunar orbit or Sun-Earth L4-L5
DSL	1 MHz – 100 MHz	< 30 km	12	Sun-Earth L2

* OLFAR = 50 nanosat "sensor nodes" with 3D radio sensors, including distributed computing power, beam formed downlink capabilities, ranging capabilities, inter-node communication, swarm configuration…
  Add a few "computing nodes" with GPUs ? (to be studied…)

Summary

- **Current very low frequency radio astronomy (below 20 MHz) is very limited (although very successful for solar and planetary sciences).**
- **The future of Very Low Frequency Radio Astronomy is in space (probably around the moon).**
- **Various projects have been proposed in the last few years, with CubeSats formation flying swarms, with 10 to 50 nano-satellites.**
- **There is ongoing R&D for future radio instrumentation on cubesats (antennas, receivers, correlators…)**
- **Final notes**
  - *Specific need for radio astronomy: EMC clean platform !!*
    (not easy to have no RFI lines in the observed frequency range 10 khz - 100 MHz)
  - *Radio receiver based on STAR developments (e.g., on Circus) is designed for nanosats*