Low Frequency Radio Observations From Space: Now and Next

B. Cecconi[1], P. Zarka[1], M. Klein Wolt[2], S.L.G. Hess[1], J. Bergman[3]

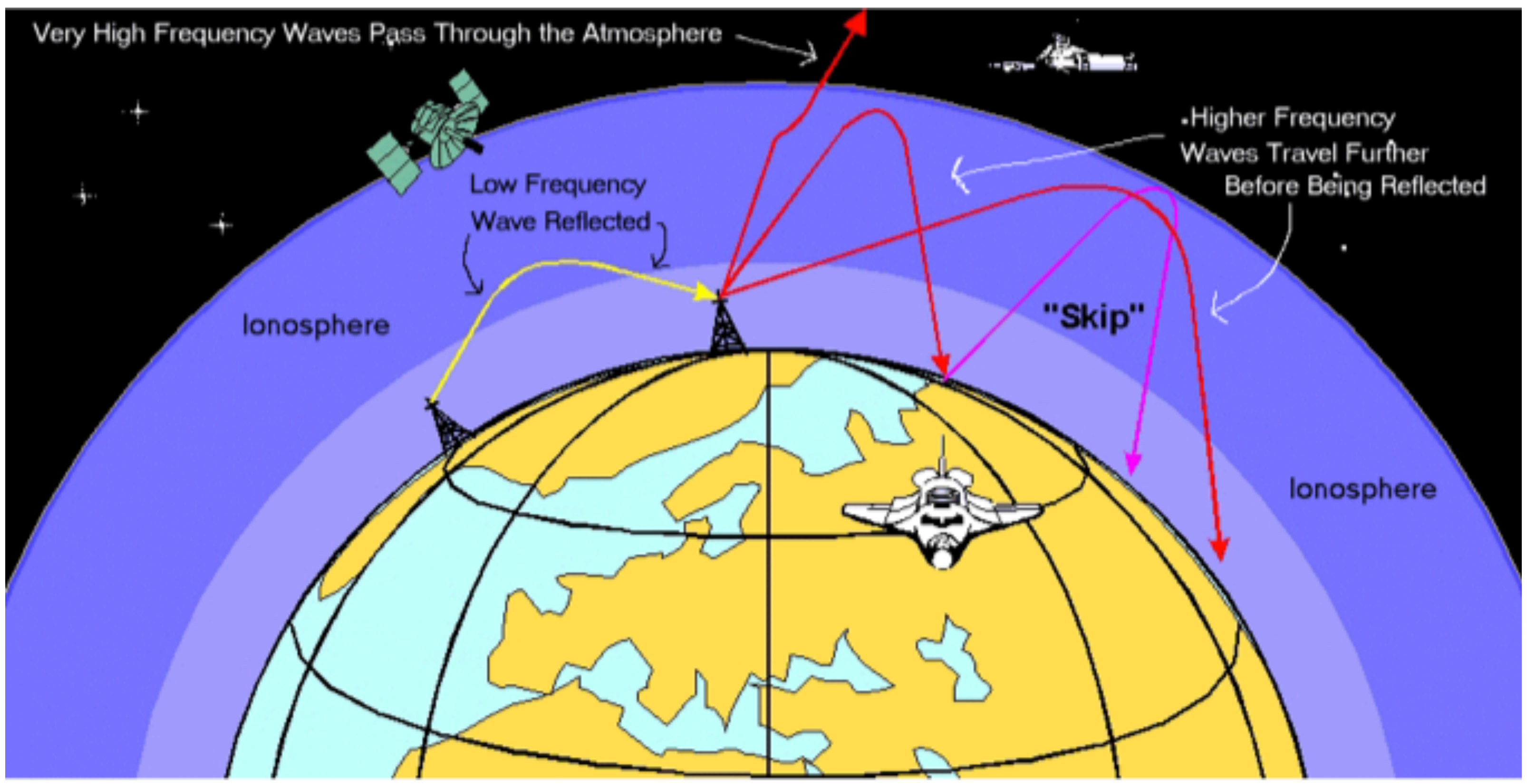
[1] *LESIA, Observatoire de Paris, CNRS, UPMC, Univ. Paris Diderot, Meudon, France*
[2] *Department of Physics, Radboud University Nijmegen, Netherlands.*
[3] *IRFU, Uppsala, Sweden.*

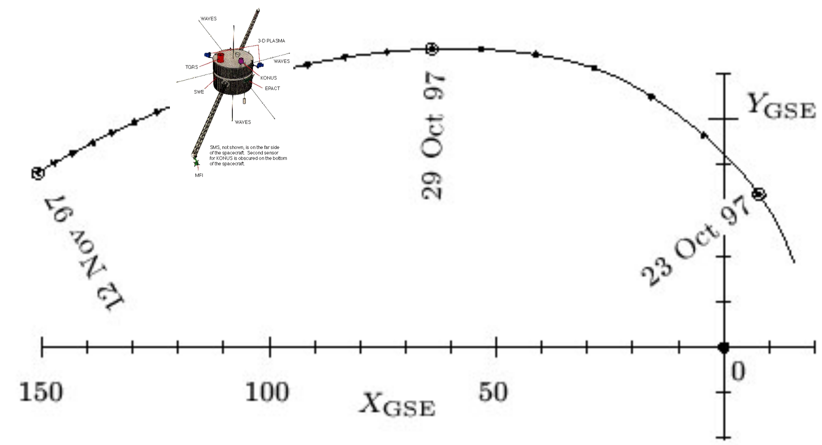
Outline

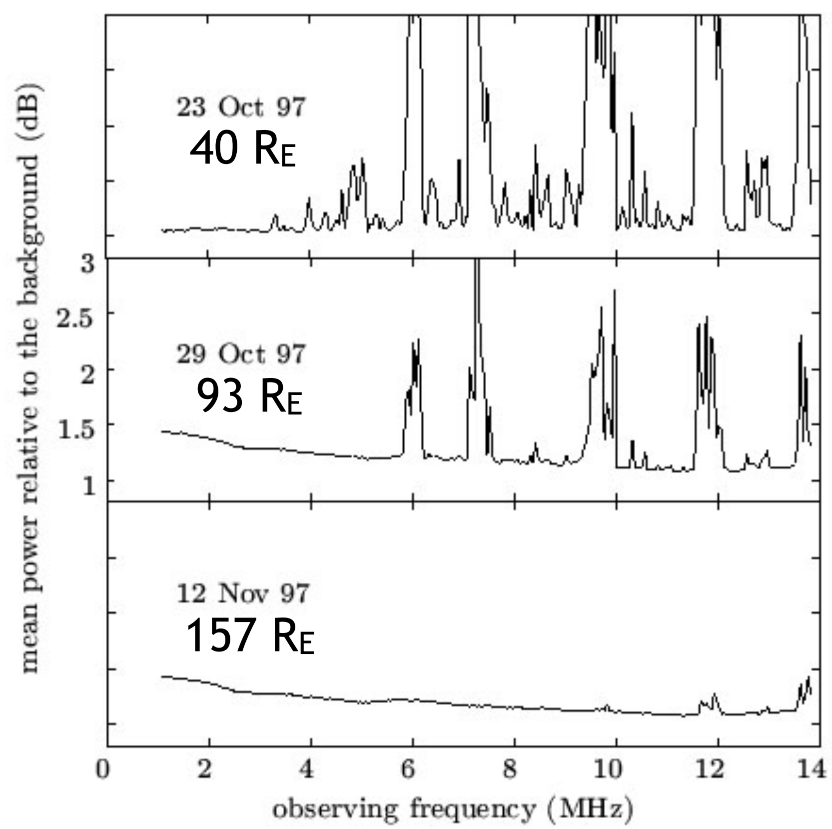
- **Near Earth low frequency radio environment**
- **Case for Radio observation from the Moon**
- **Space radio instrumentation - Goniopolarimetry**
- **Future projects**

NB: Low frequency = a few kHz to 50 MHz

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







24h averages from Wind/WAVES

Sensitivity Limitation: background temperature is high !

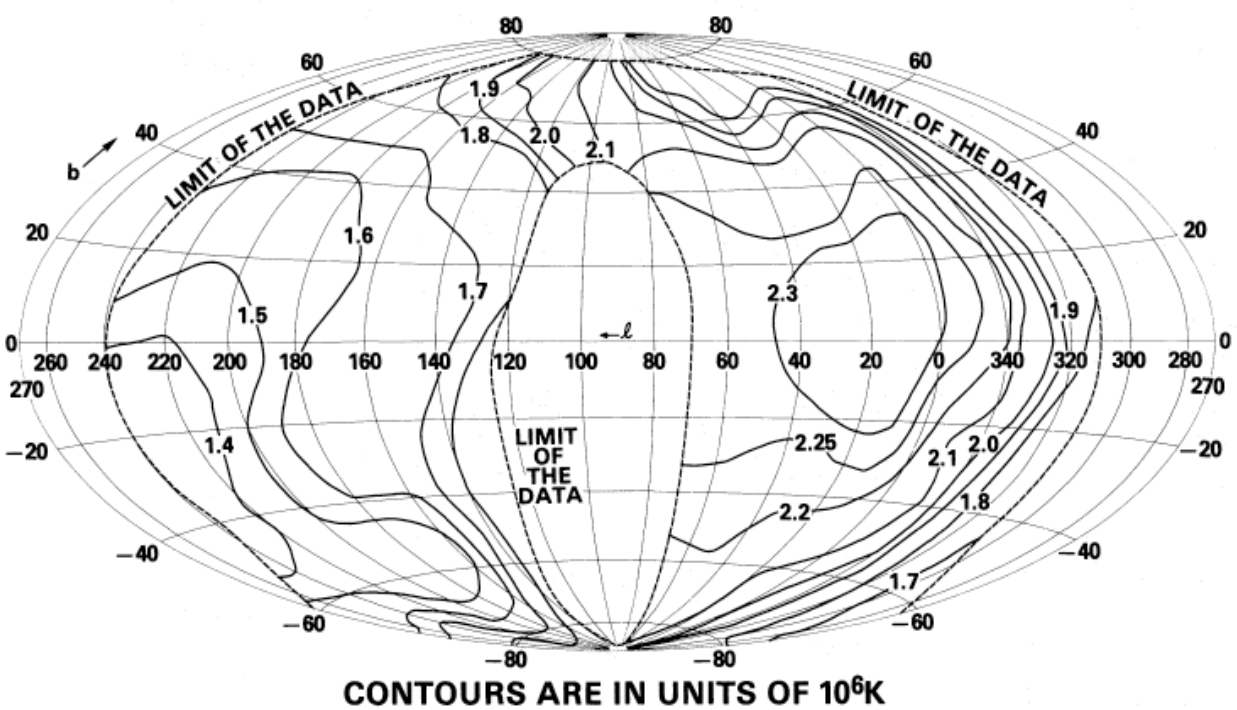


FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

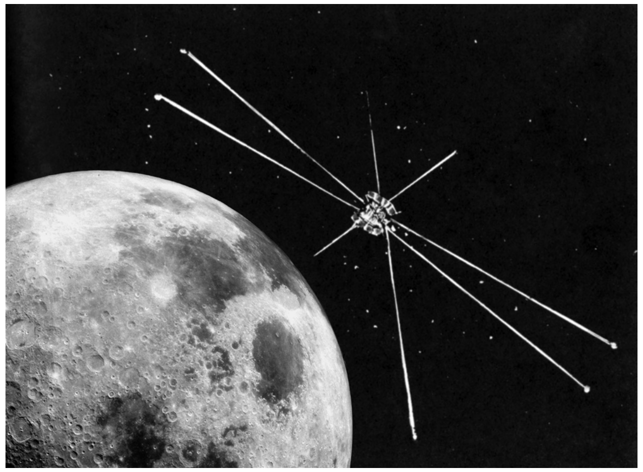
T_{sky}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

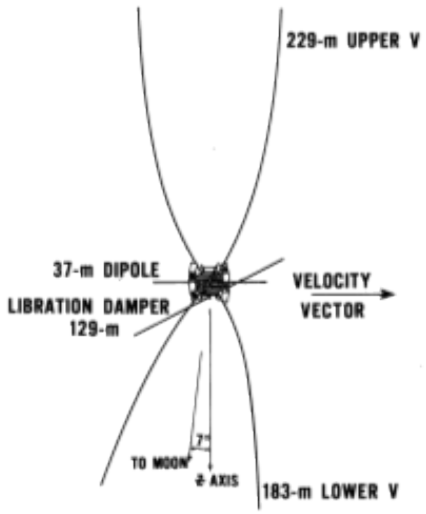
Galactic background flux density detected by a short dipole antenna :
S_{sky} ($Wm^{-2}Hz^{-1}$) = $2kT_{sky}/A_{eff} = 2kT_{sky}\lambda^2/\Omega$ with $\Omega=8\pi/3$, $A_{eff}=3\lambda^2/8\pi$

→ sensitivity with N dipoles, bandwidth b, integration time τ :
$S_{min} = S_{sky}{}^1/C$ with $C = N(b\tau)^{1/2}$

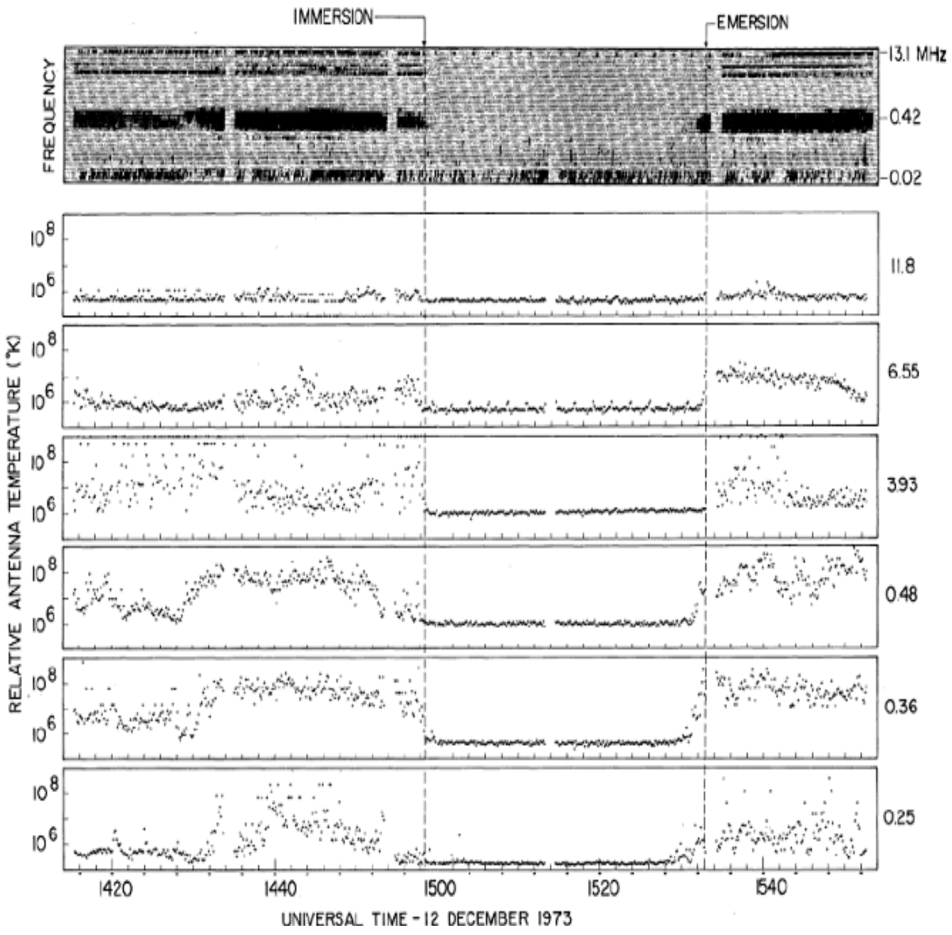
Except behind the moon:

RAE-2 : 1100 km circular orbit
inclined by 59° / lunar equator

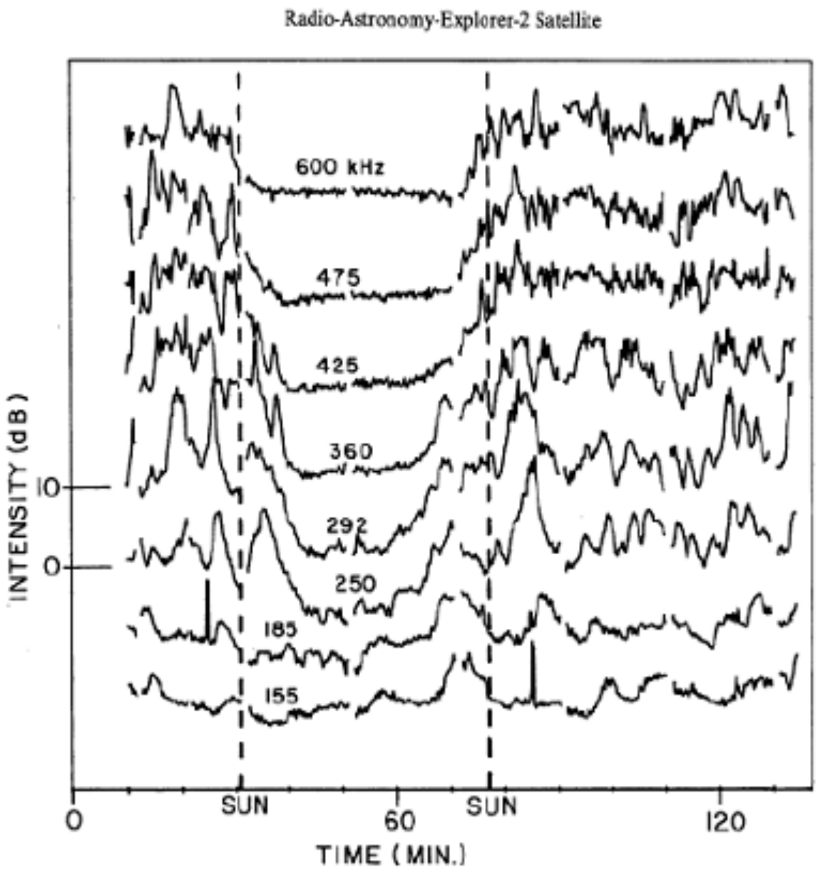




RAE-2 occultation of Earth (1973)



RAE-2 occultation of a solar storm



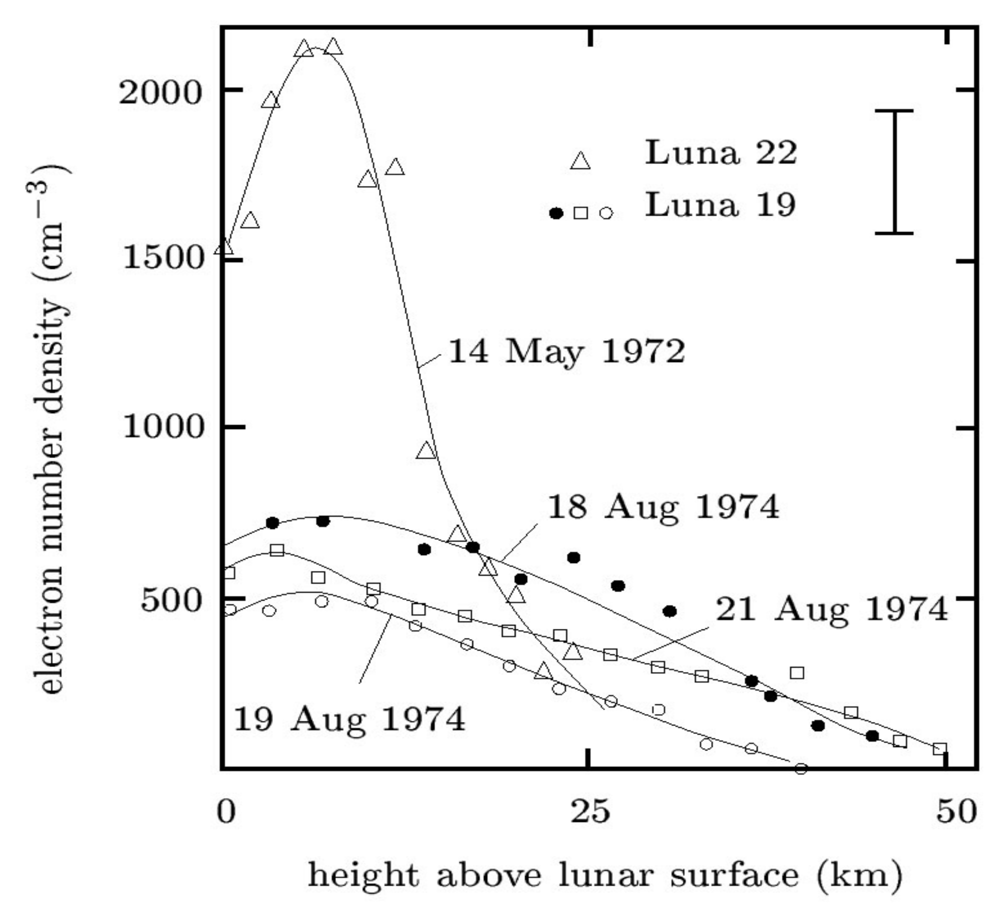
Radioastronomy on the Moon is an Old idea. First proposals pre-date Apollo missions !

- **1964** Gorgolewski identifies the far side of the Moon as a good site for VLF radio interferometry (Lunar International Laboratory Panel)
- **1966** Research Program on Radio Astronomy and Plasma for Apollo Applications Program Lunar Surface Missions (Report from North American Aviation Inc.)
- **1967** Utilization of Crater Reflectors for Lunar Radio Astronomy (J.M. Greiner, WG on Extraterrestrial Resources)
- **1968** RAE-1 VLF Earth satellite (0.2-9.2 MHz)
- **1973** RAE-2 VLF Moon satellite (0.02-13.1 MHz, 1100 km, 59°inclination/lunar equator)
- **1983** VLF radio observatory on the Moon proposed by Douglas & Smith in Lunar Bases and Space Activities of the 21 Century
- **1988** Workshop: Burns et al., A Lunar Far-Side Very Low Frequency array (NASA)
- **1992** Design study: Astronomical Lunar Low Frequency Array (Hughes Aircraft Co.)
- **1993** Design study: Mendell et al., International Lunar Farside Observatory and Science Station (ISU)
- **1997** Design study: Bely et al., Very Low Frequency Array on the Lunar Far Side (ESA)
- **1998** MIDEX proposal: Jones et al., Astronomical Low Frequency Array (ALFA), JPL, NRL, GSFC,…
- **2003** GSFC workshop for the Solar Imaging Radio Array (SIRA)
- **2005-8** Conferences Moon&Beyond, Joint statement to ESA, LIFE & MoonNext projects
- **2009+** ESA Lunar Lander project
- **2010** Farside Explorer (response to M3 call)

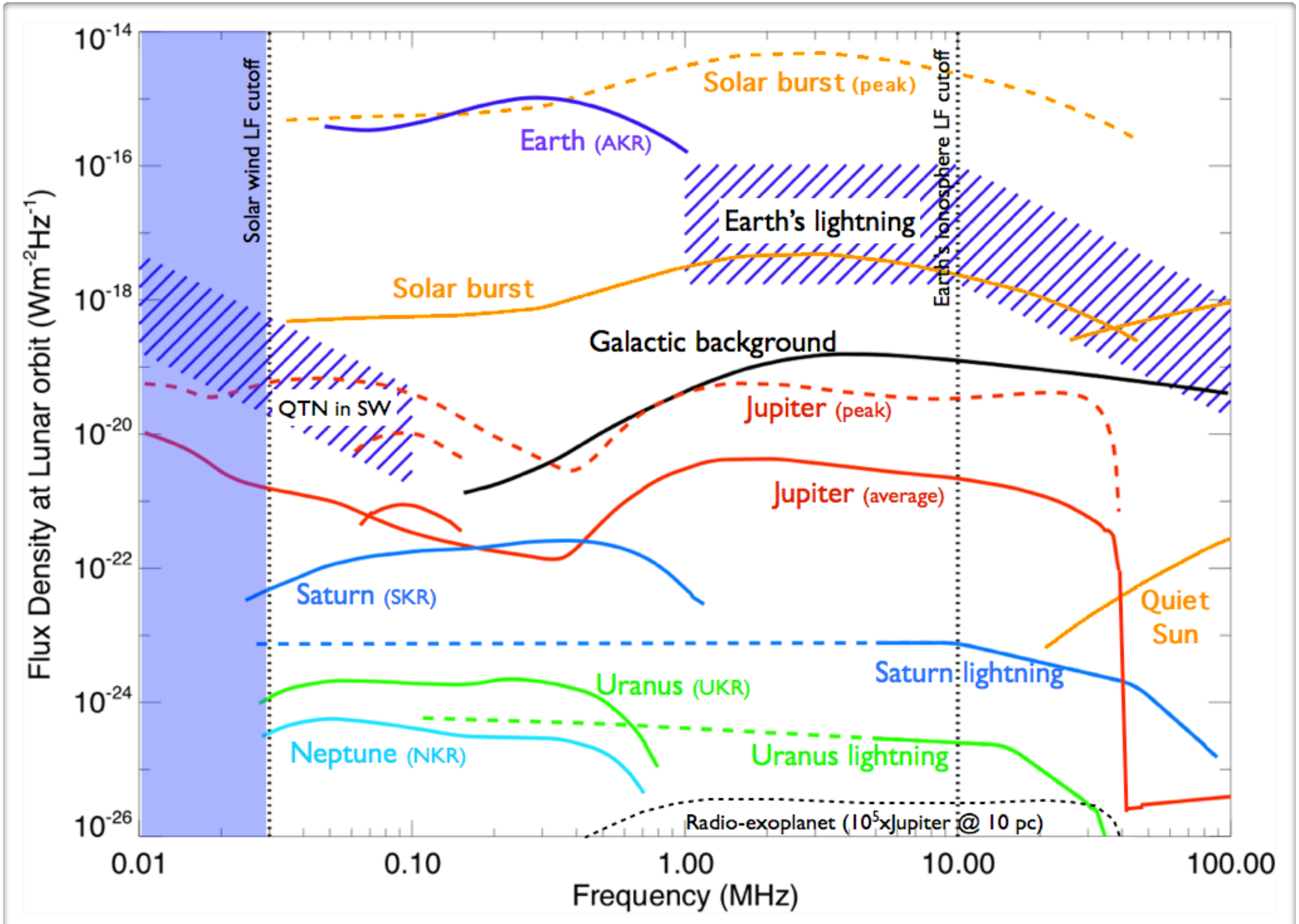
The Moon (Far side especially) has been long recognized as unique astronomical platform, and a radio quiet zone by International Telecommunications Union

Lunar ionosphere is very thin
low frequency cut-off near 100 kHz

- Lunar ionosphere is very thin. Dual-frequency Luna spacecraft measurements suggest that an ionised layer, several km thick, builds up on the illuminated side of the Moon, with $f_{pe\text{-}max}$ ~0.5 MHz (Vyshlov 1976). No layer seen during the lunar night.

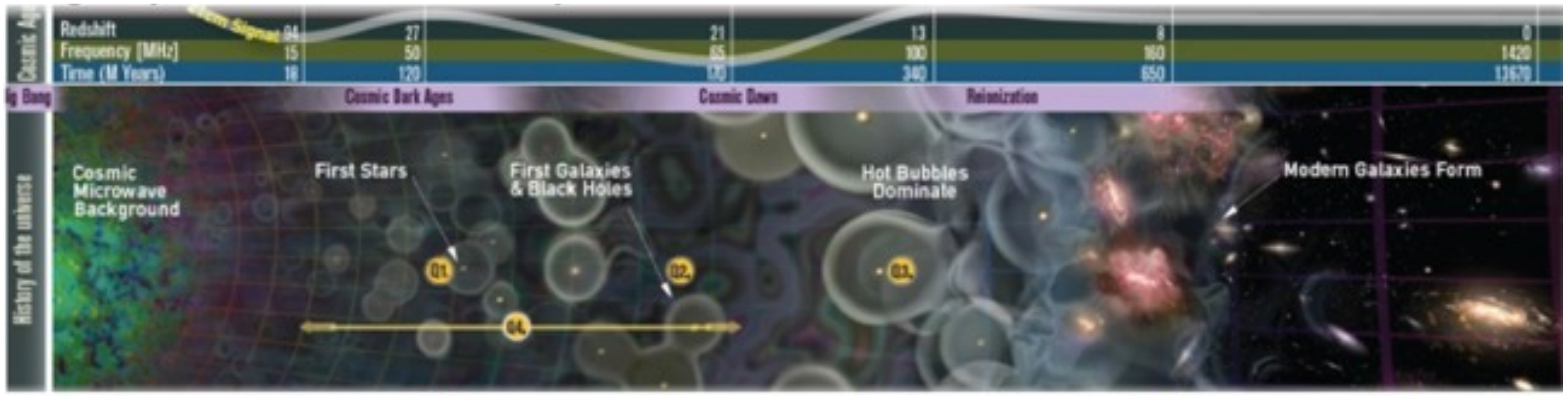


Local radio environment



Very Low Frequency Radioastronomy Identified Science opportunities

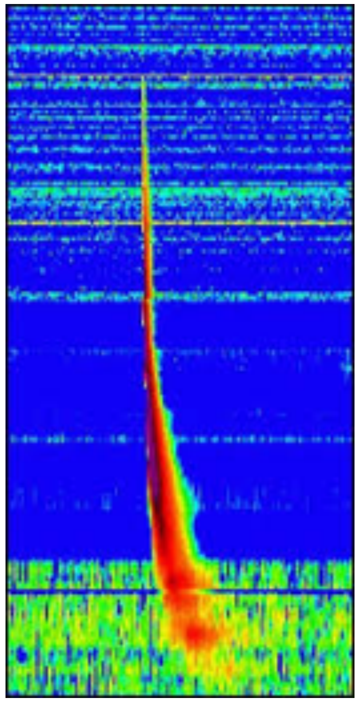
- **LF sky mapping** + monitoring : radio galaxies, large scale structures (clusters with radio halos, cosmological filaments, …), including polarization, down to a few MHz
- **Cosmology** : pathfinder measurements of the red-shifted HI line that originates from before the formation of the first stars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

Very Low frequency Radio Interferometry
What to do better ?

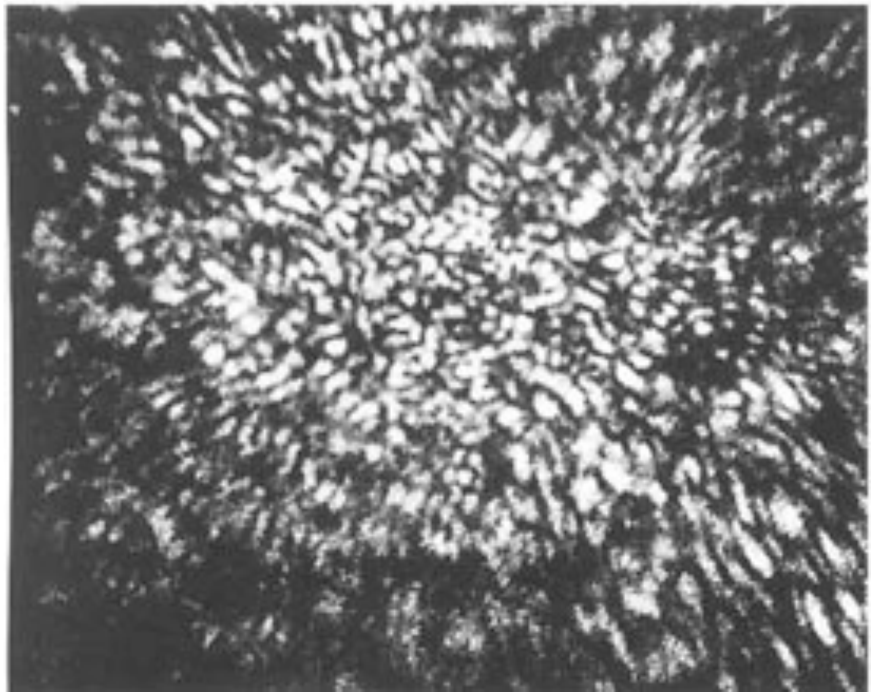
- Solar radio observations (type II, type III)
  Now: *measurements at 1 point (centroid + apparent source size)*
  source spatial extension due to scattering along propagation
  Next: *full imaging => parameters on the source and on scattering*



Solar Type III burst

=>

or

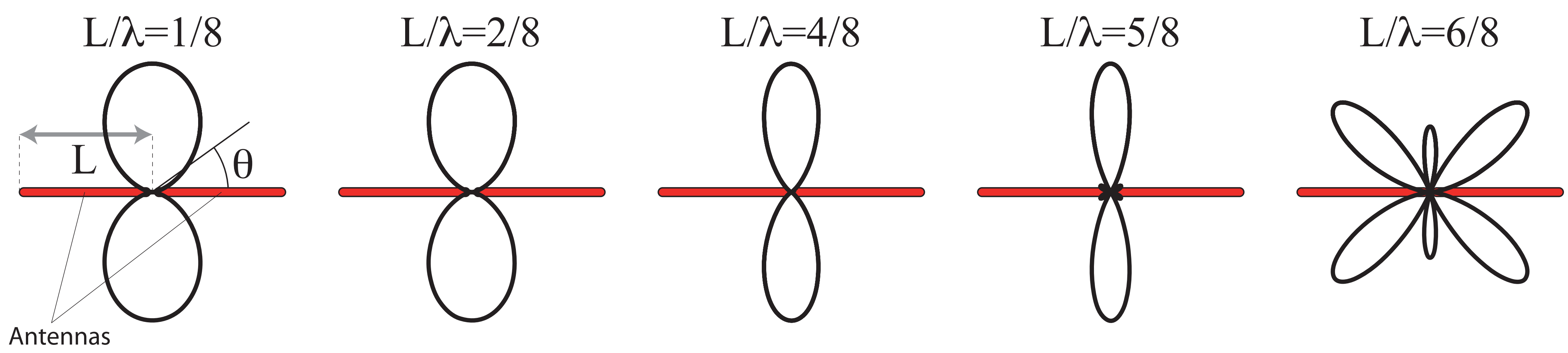


?

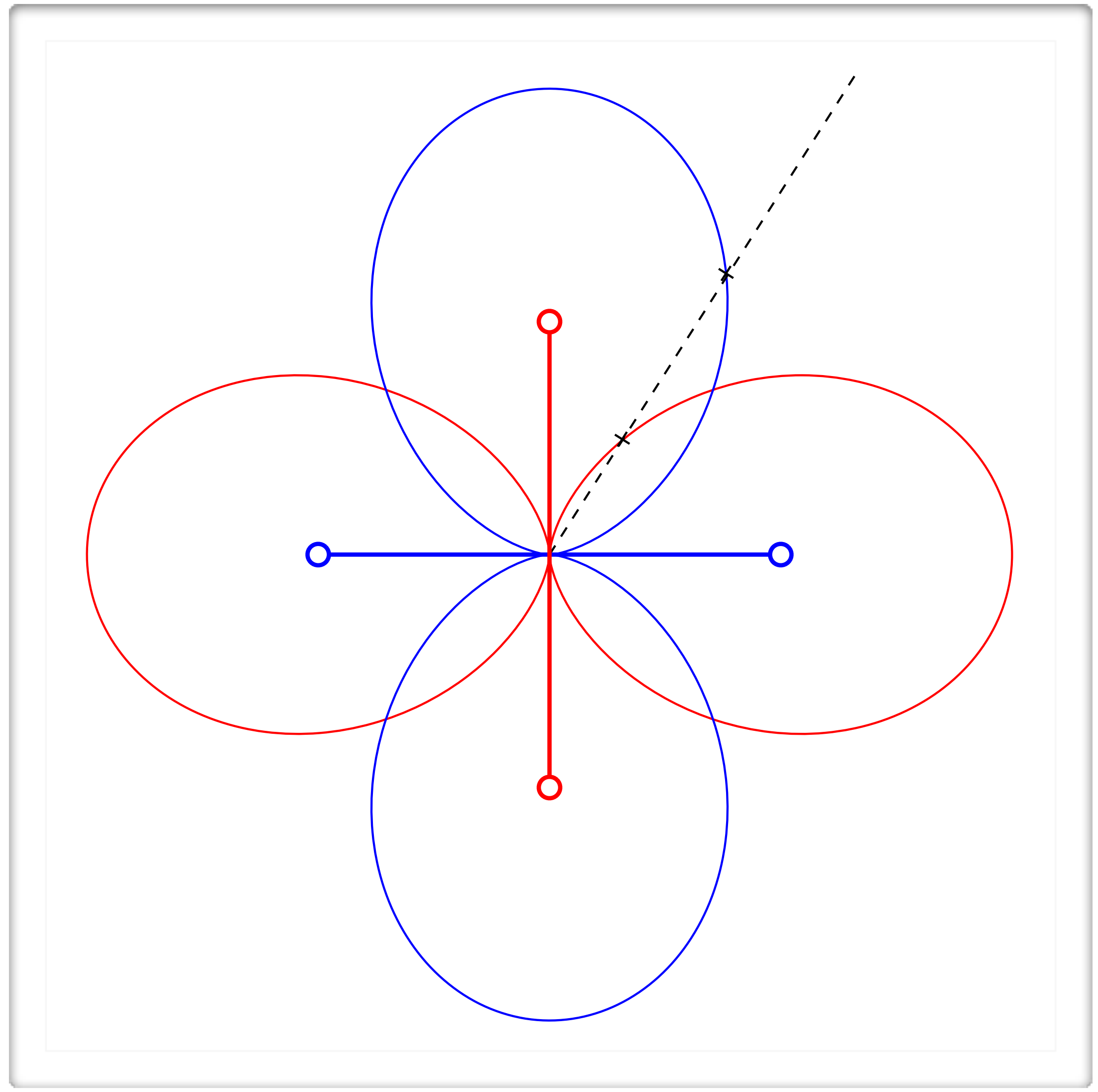
- Planetary radio emissions:
  Now: *only Jupiter is visible from Earth, or you go «on site»*
  Next: *Jupiter, Saturne, Uranus, Neptune...*

Space Radio Astronomy
Goniopolarimetry

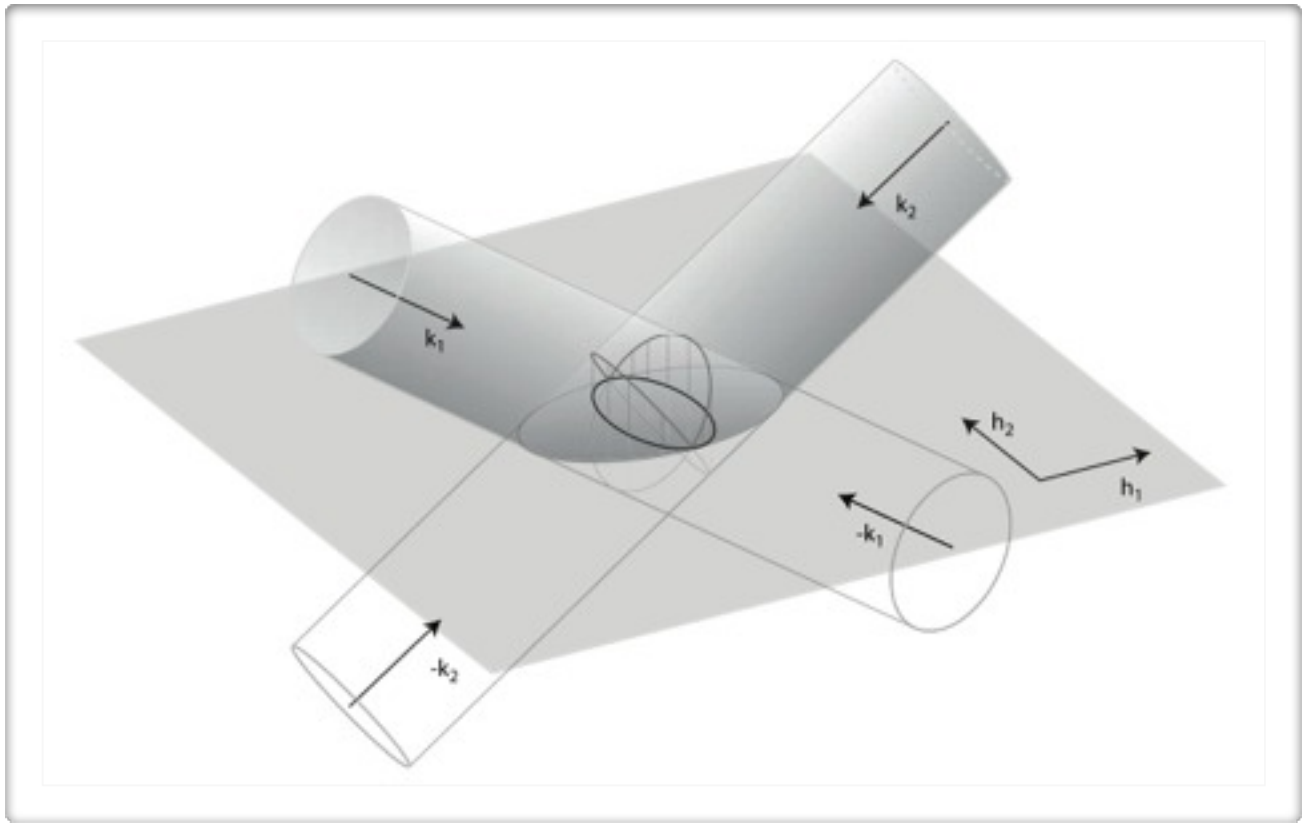
- Space based radio antennas: simple dipoles or monopoles with length L of a few meters
  (impossible to have a reflector large enough to have $\lambda/D \ll 1$)
- Short antenna range ($L \ll \lambda$) : monopole antenna + S/C body ~ effective dipole
- Antenna gain ~ $L^2 \sin^2\theta$ → null // antenna, max ⊥ to antenna
- Resonance at L ~ $\lambda/2$ (*multi-lobed, complex gain depending on direction*)



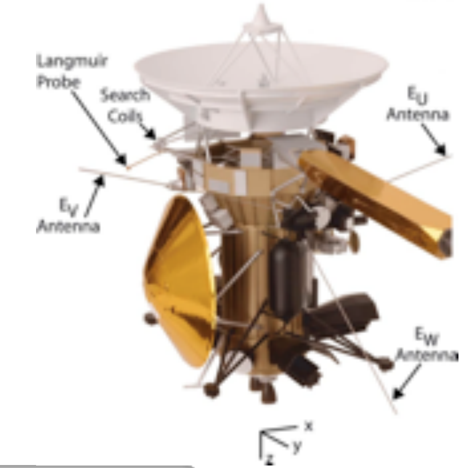
GonioPolarimetry

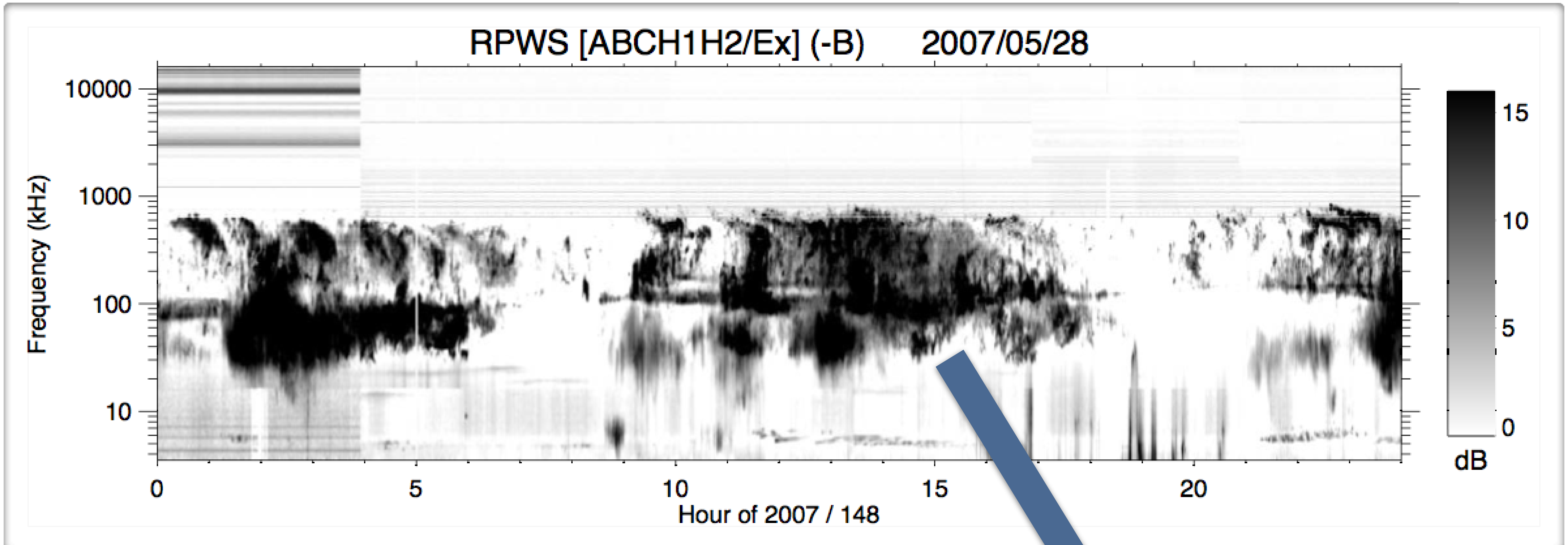


- Dipole has no angular resolution:
  ∫ antenna pattern = $8\pi/3$ sr
- Solution : Use 2 crossed dipoles connected to a dual-input receiver and correlate measurements on both antenna
- With 3 antennas + crosscorrelations : full wave parameters (flux S, polarization Q,U,V, and wave vector θ, φ)
- Angular resolution depends on phase calibration of receiver + effective antenna calibration (typically ~ 1°, instead of ~90°)



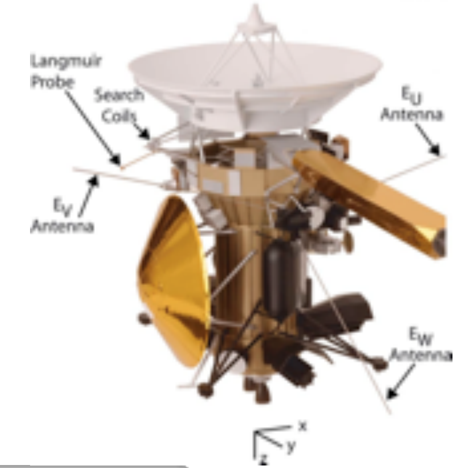
Goniopolarimetry illustrated (Cassini/RPWS @ Saturn)

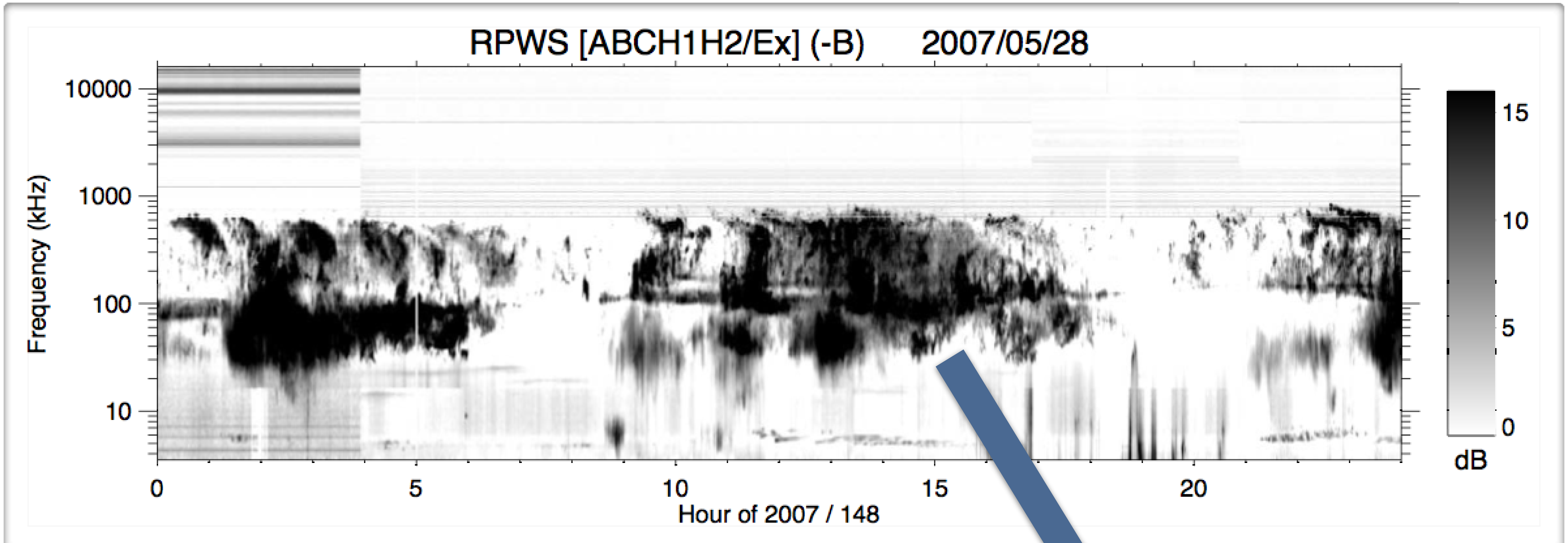




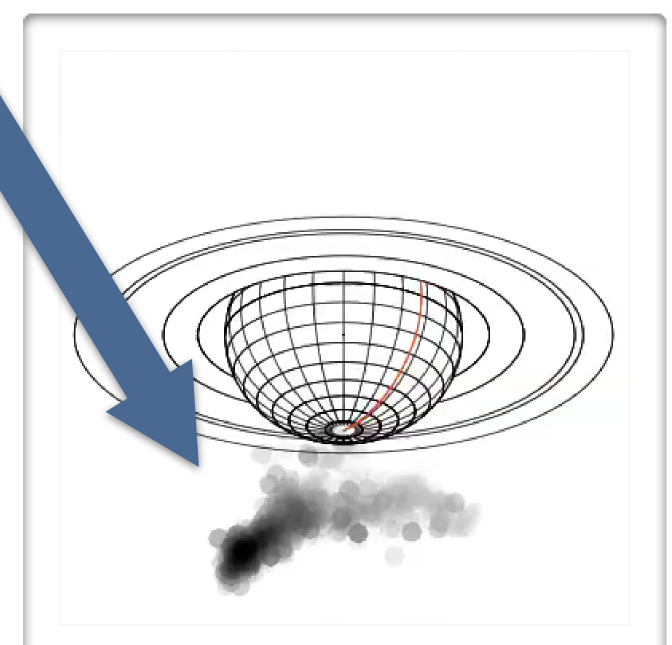
Cassini/RPWS dynamic spectrum of Saturn auroral kilometric radiation (classical radio data format)

Goniopolarimetry illustrated (Cassini/RPWS @ Saturn)

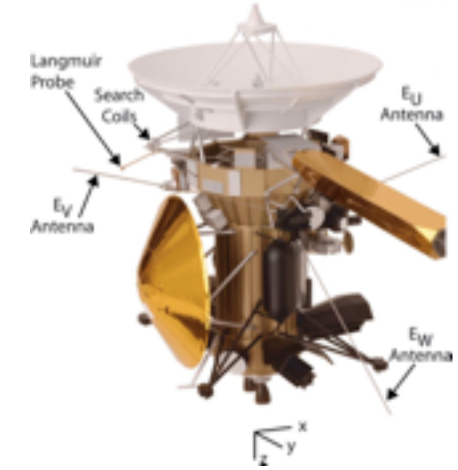


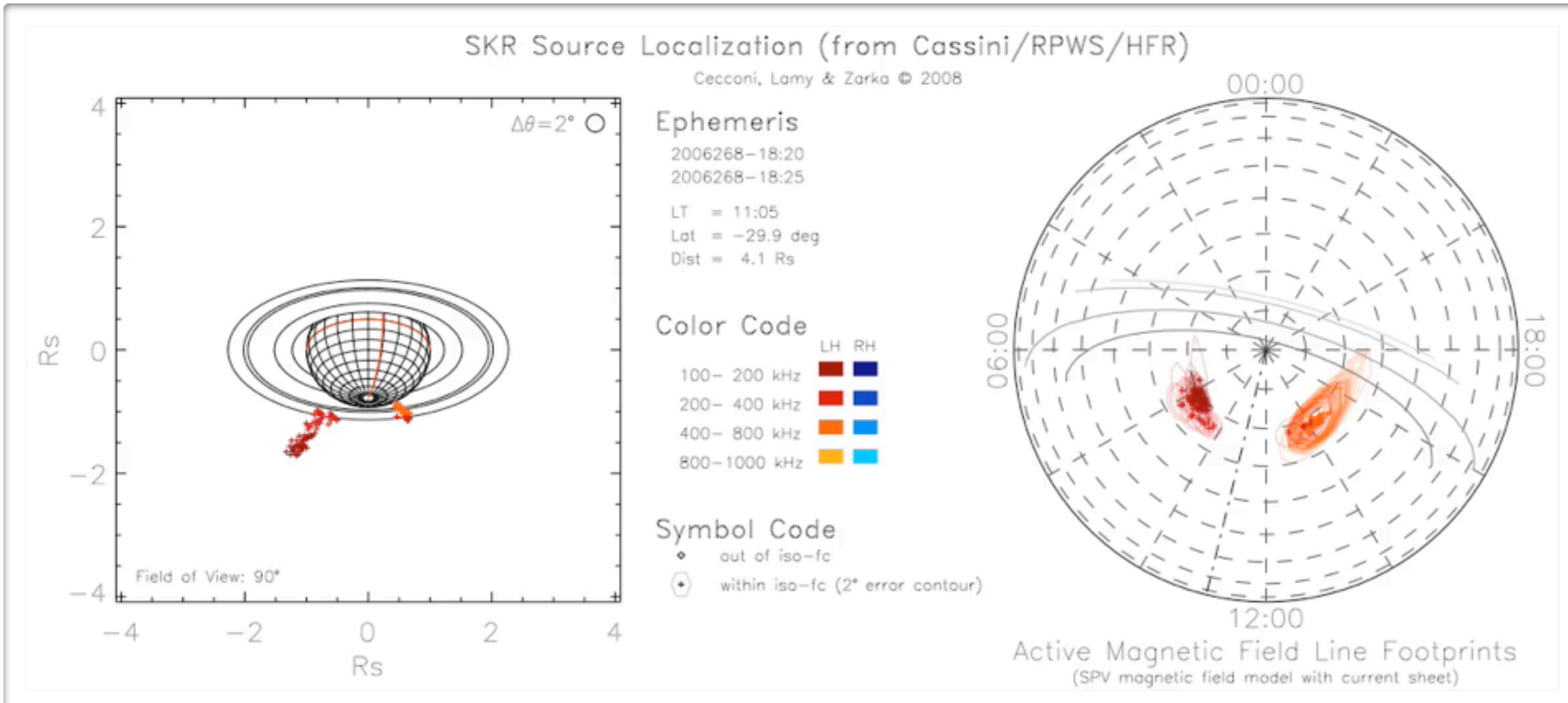


Cassini/RPWS dynamic spectrum of Saturn auroral kilometric radiation (classical radio data format)



Goniopolarimetry illustrated (Cassini/RPWS @ Saturn)





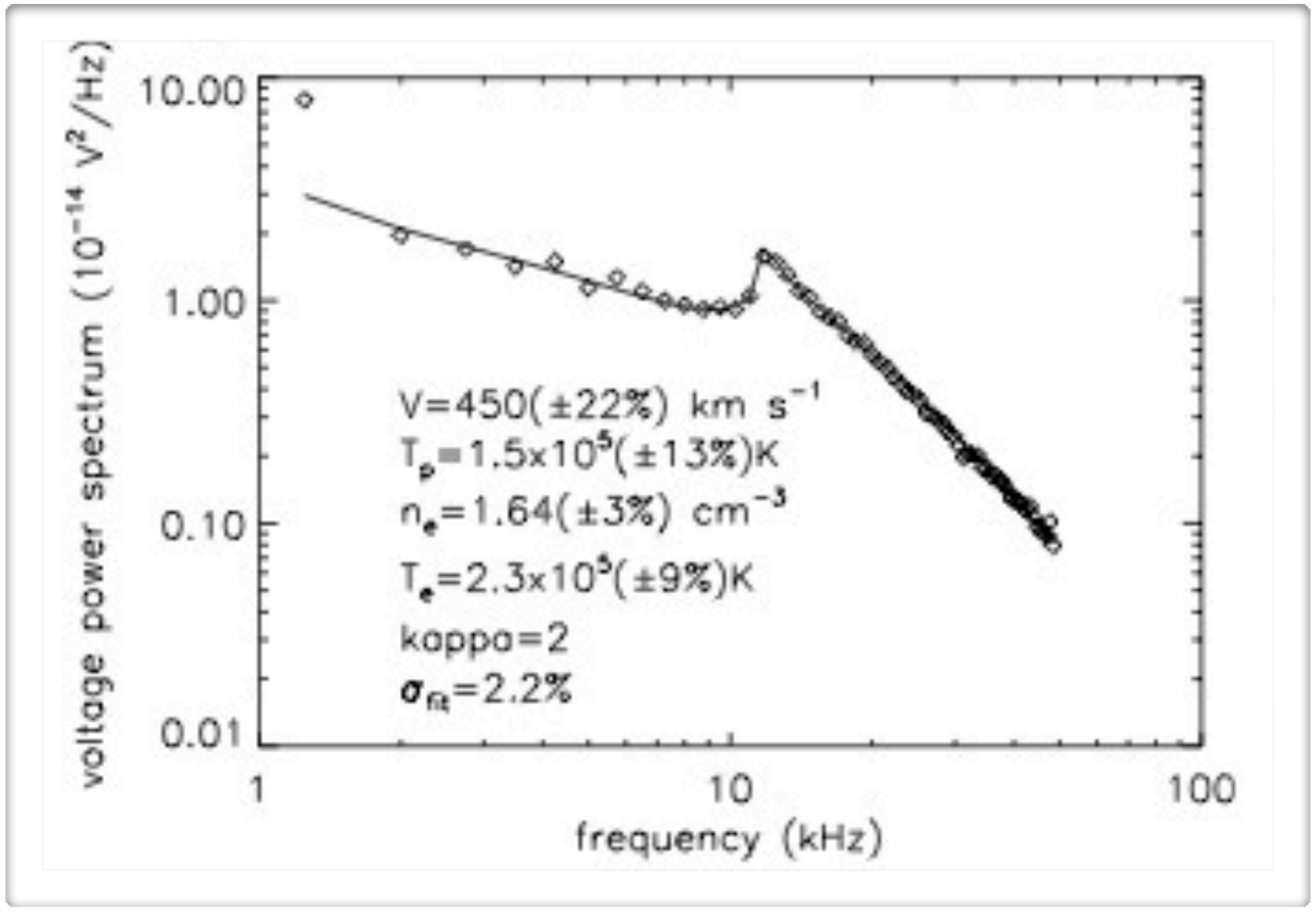
Saturn auroral kilometric radio source location from Cassini/RPWS data

Goniopolarimetric inversions

- **Point source**: Inversions solves for (S, Q, U, V, θ, φ)
  Auroral sources (Earth, Jupiter, Saturne)
  Cassini/RPWS (with 2 or 3 antennas), INTERBAL/Polrad (3 antennas)
  [Lecacheux, 1978; Ladreiter, 1995; Cecconi, 2010]
- **Extended source**: Inversions solves for (S, Q, U, V, θ, φ, γ)
  Solar radio bursts
  STEREO/Waves (with 3 antennas), Wind/Waves (spinning antennas)
  [Manning & Fainberg, 1980; Cecconi et al., 2008; Krupar et al., 2012]
- **Linearly-shaped source**: Inversions solves for (S, Q, U, V, θ, φ, γ) and brightness profile.
  [Hess, 2011]
- **Full sky source**: solves for sky brightness distribution
  Galactic background mapping
  Cassini/RPWS, STEREO/Waves, Ulysses/URAP
  [work in progress]
- **Compressed sensing**: not explored yet at all, but probably worth trying !

Quasi Thermal Noise Spectroscopy

- Plasma resonance with antenna, spectral analysis provides *plasma density, temperature and magnetic field strength*

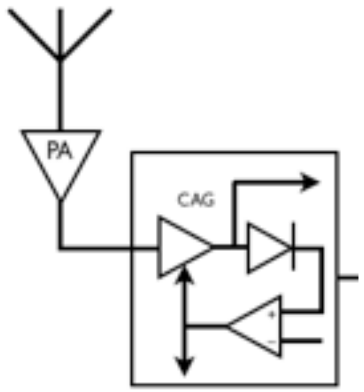


- Requires thin and long antennas (ok for spinning spacecraft, more difficult on stabilized spacecraft) and high spectral resolution radio receiver (Δf/f ~ 1%)

- Absolute determination of plasma parameters: complementary to active measurements (such as Langmuir probes)

Space radio instrument characteristics

- Performances: receiver sensitivity 3-5 nV/Hz$^{1/2}$, need separate LF & HF due to 1/f spectrum, dynamic range 80-100 dB (without/with Automatic Gain Control (AGC) circuit)
  - → ≤a few MHz : local conditions, Sun & Planets
  - → a few to 100 MHz : all other science measurements

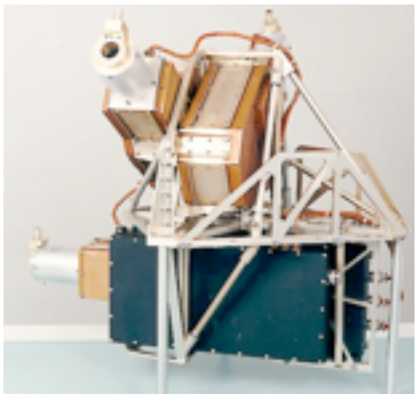


A channel of Cassini/RPWS/HFR

- Resources: ~1 W, a few 100's g, A5 board


BepiColombo/MMO/RPW/Sorbet

- Interfaces: booms, antennas, deployment, EMC (crucial for exploiting the quiet site)


Cassini/RPWS antennas (stowed)

- **New R&D action is starting in France between Radioastronomy and Telecom labs for a new generation of digital radio receiver with high dynamic, low power and sampling up to 100 MHz.**

Prospective in Europe
Projects of various size

- First: 1-2 sets of electric dipole/ monopole antennas, a few meters long (2 landers or lander+rover)
    - *ESA Lunar Lander, Farside Explorer = Pathfinder technology demonstration for a future radio array on the Moon's surface.*
- ~100 antennas (Aeff = ~3×10^4 m^2 @ 10 MHz, λ~30 m)
    - Near or Far side (OLFAR)
- ~1000-10000 antennas = LOFAR-on-the-Moon
    - Far side Lunar Radio Array

- **Cubesats Projects:**
    - CIRCUS:
      - 1 cubesat
      - ionosphere of Earth
    - FOAM:
      - 2-4 cubesats
      - auroral radio emissions of Earth
    - OLFAR:
      - 50 cubesats
      - very low frequency radio astronomy interferometer

CIRCUS
Teams involved: UPMC+ESEP+LESIA+TelecomParis

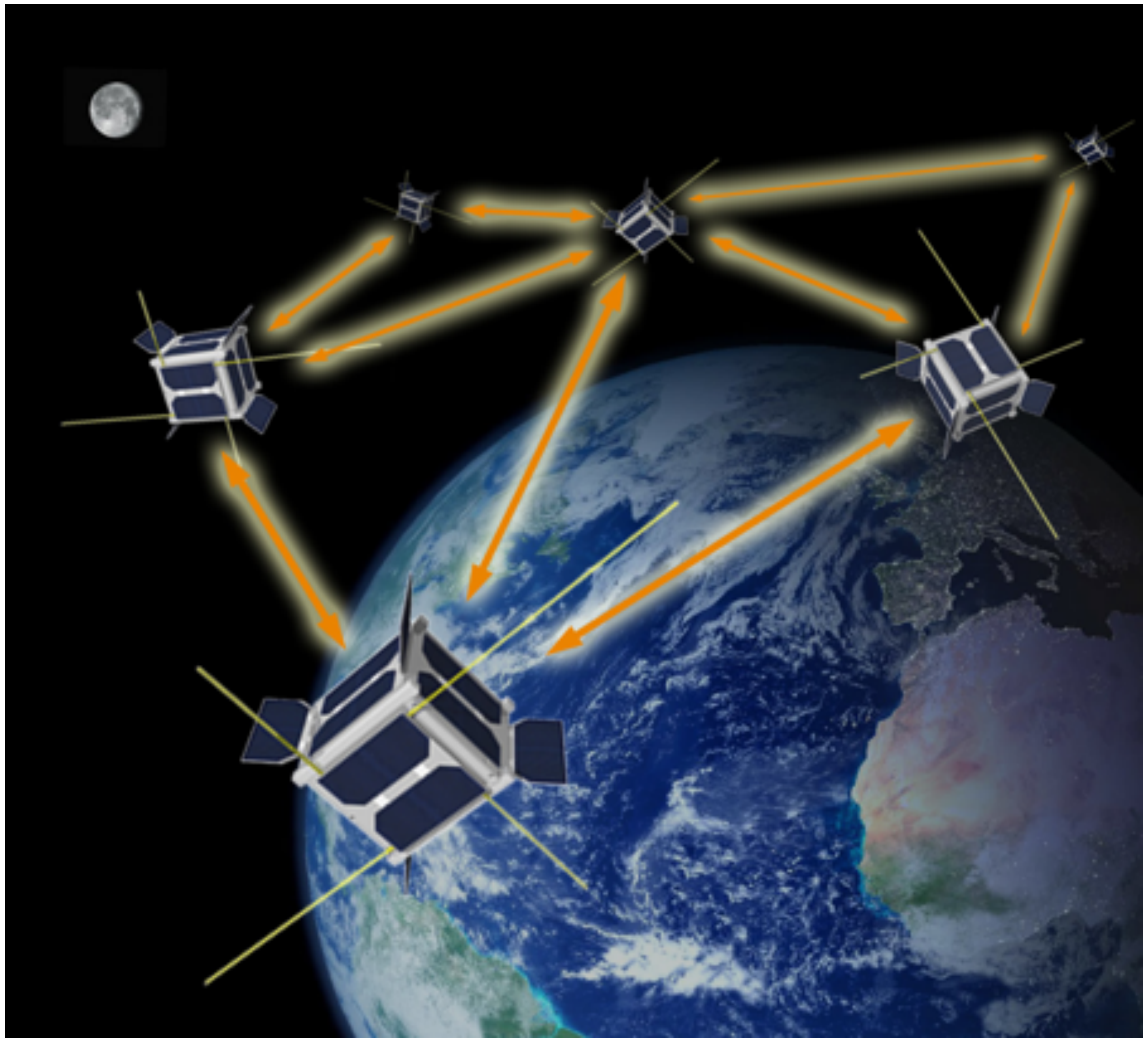
- **CIRCUS: Characterization of the Ionosphere using a Radio receiver on a CUbe Sat**
- **Science objectives**:
  - Quasi thermal noise spectroscopy in the ionosphere of Earth
  - High temporal cadence: turbulence and microscopic strucuture
- **Technology objectives**:
  - Higher TRL for new digital radio receiver under study (LESIA-TelecomParisTech)
  - Sampling: temporal = 10 ms; spectral = up to 100 Hz (over 50kHz-50MHz)
- **Selected technical solution** :
  - 1 cubesat (< 3U), no attitude control
  - short (10-20 cm) and thin (~1mm) antennas
- **Schedule**: in 4-5 years ?
  Orbitography: Low Earth Orbit: ~100 km

FOAM
Teams involved: IRFU (SE) + LESIA (FR) + many

- **FOAM: FOrmation-flying Auroral Mission**
- **Science Objectives**:
  - Imaging/mapping of AKR (Auroral Kilometric Radiation of Earth)
  - Do better than the Cluster mission for AKR (up to 1 MHz)
  - Measurements inside the radio sources and remote observations
  - Flux and polarization measurements
- **Technology objectives**:
  - Testing passive formation flying (swarm configuration)
- **Selected technical solution**:
  - 2 to 4 CubeSat-6U, swarm configuration
  - Electric tripoles, short antennas (AKR is very intense)
- **Schedule**: TBD.
  Orbitography: polar orbit, altitude up to ~5000 km required in auroral zone.

OLFAR
Teams involved: NL + 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, non-space qualified industry components
  - 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)

OLFAR
Teams involved: NL + many other interested

- Example of developments in the Delft Univ. roadmap (Delfi)
  - Delfi-C^3 :
    - launched in April 2008, still functionning
    - Attitude control
    - wireless communication between modules, Solar sensor
  - Delfi-n3Xt :
    - Launched in November 2013
    - coupled solar sensor and attitude control
    - neutral gaz micropropulsion
  - DelFFI
    - Launch planned in 2015
    - formation flying test
- More info: http://www.delfispace.nl

Conclusions

- Space instrumentation is required below 10 MHz
- Huge interest for all astronomy communities (from cosmology to planetary sciences)
- Large scale interferometer is the goal
- Pathfinder experiments:
  Lunar surface (far side) or lunar orbit
- Many projects on the roadmap (Farside Explorer, DARE, DEx, FOAM, OLFAR...)
- If you are interested participate to NLAP.
  Netherlands Low-frequency radio Astronomy Platform
  http://www.astron.nl/nlap/index.php