Instrumentation radio spatiale basse fréquence et la R&D STAR

B. Cecconi (LESIA), R. Mohellebi (LESIA, TelecomParis)
et l'équipe STAR (LESIA/TelecomParis)

Outline

- **Context**
- **Low frequency radio sources and spectrum**
- **Space radio instrumentation - Goniopolarimetry**
- **Future projects**

NB: Low frequency = a few kHz to 50 MHz

Context

- **Low Frequency radio instrumentation has been used on most of the solar system exploration missions since Voyager** (except missions to Mars and Venus).

- **The Plasma Group of LESIA has build many such receivers with very successful science return**. However, the team could not take the lead on recent projects (Solar Probe Plus and JUICE).
  An R&D on a new generation of radio receiver has then been started.

- In the last decade low frequency **radio astronomy interferometers** has changed dramatically our knowledge of the evolution of the Universe, with projects like LOFAR and LWA.

- In the same time access to space and small platforms are now changing the way we can think of space missions, with the **nanosatellite concepts**.

Galactic Background

Sensitivity Limitation: background temperature is high !

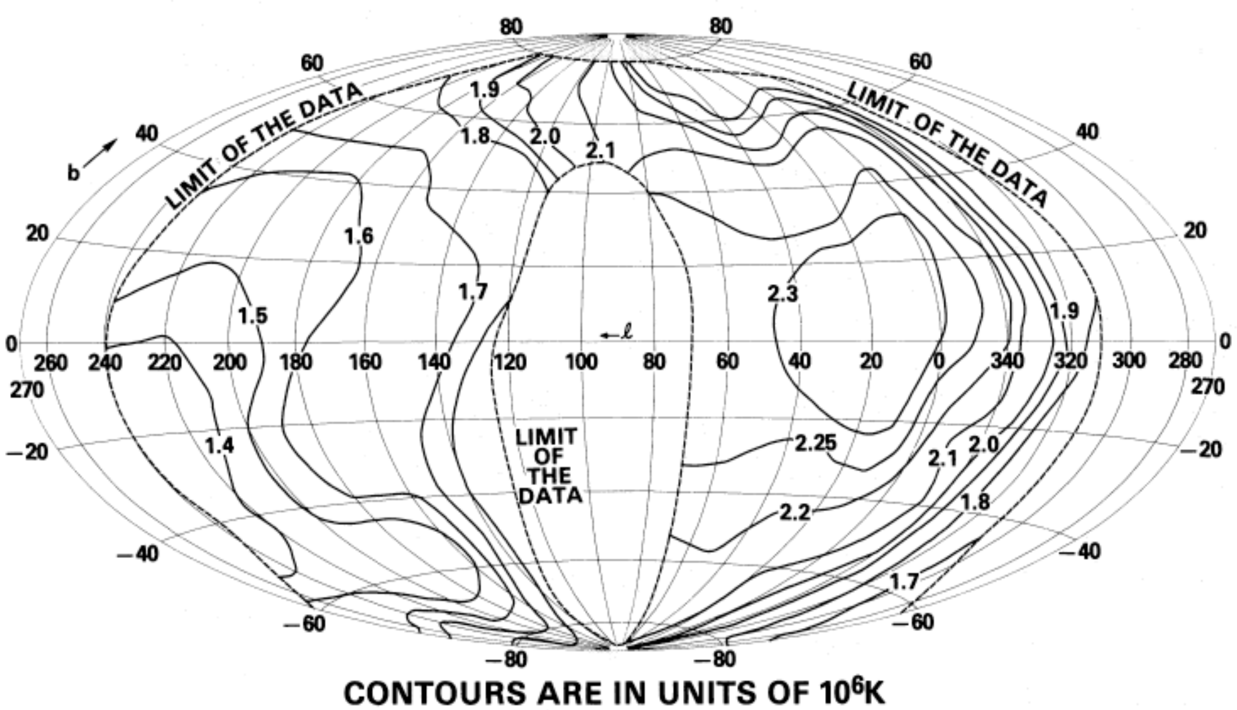


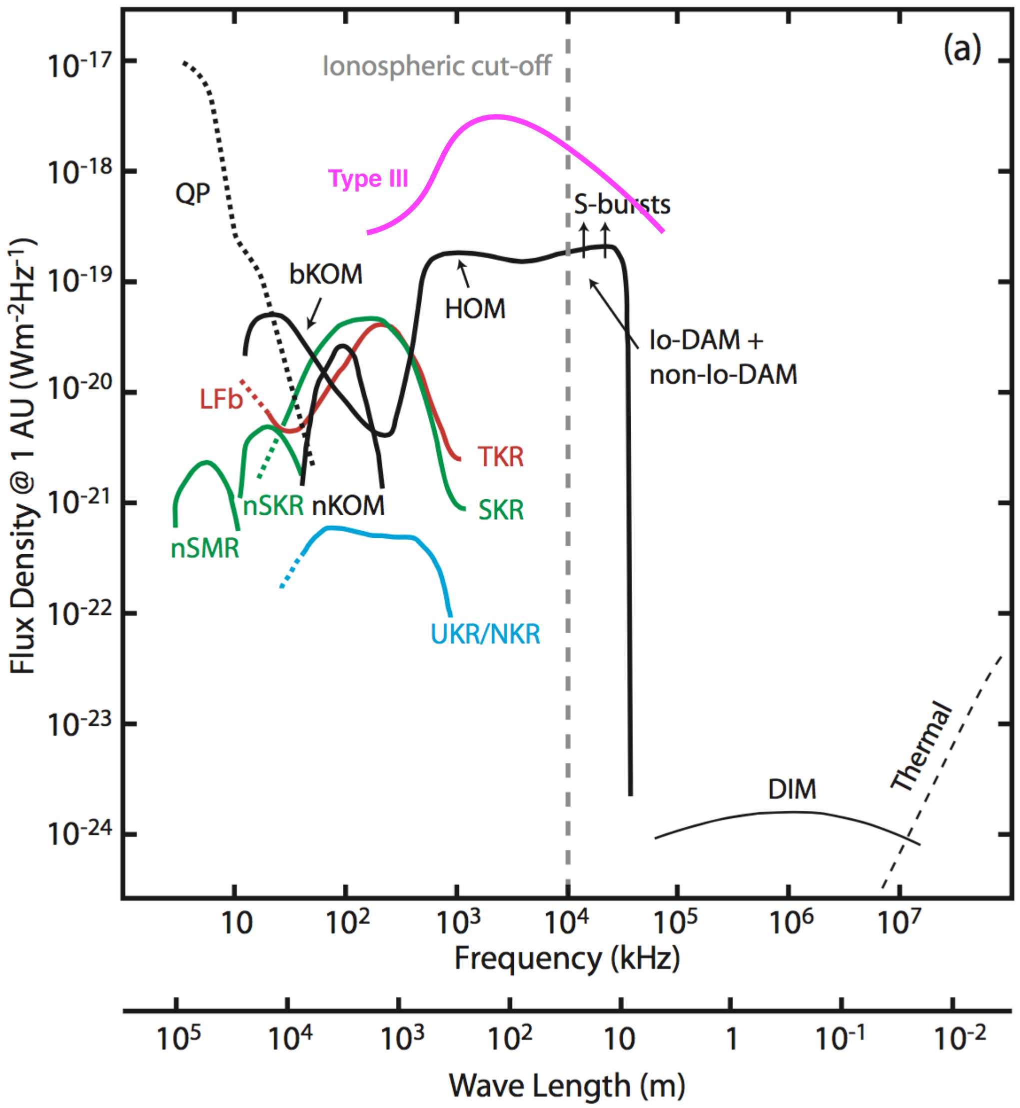
FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

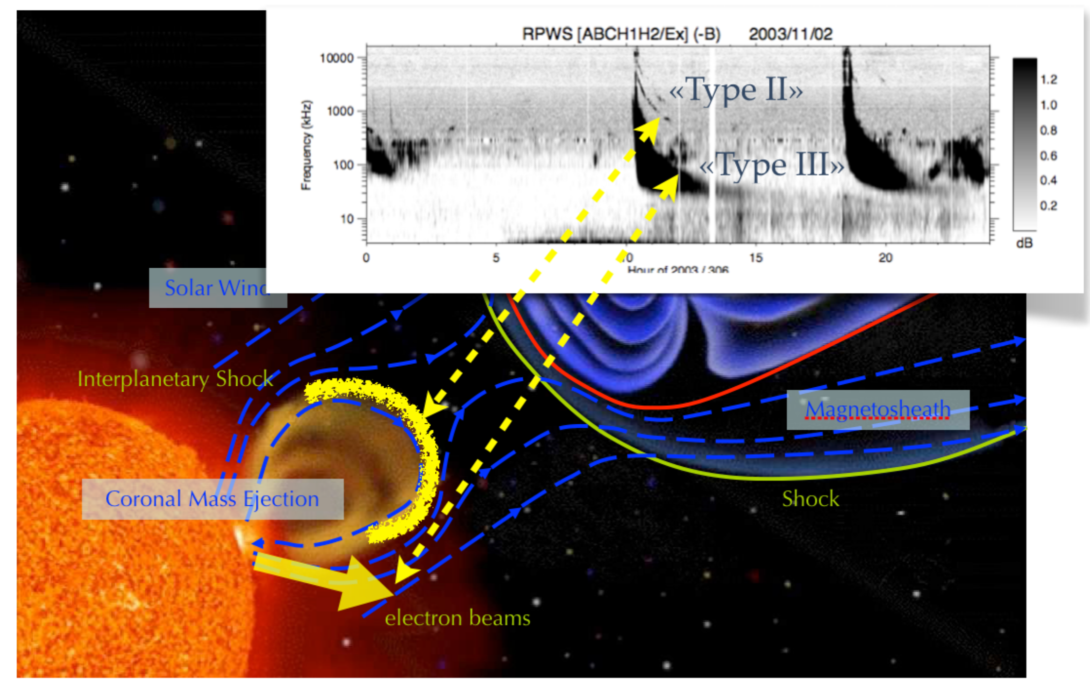
T_{sky}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

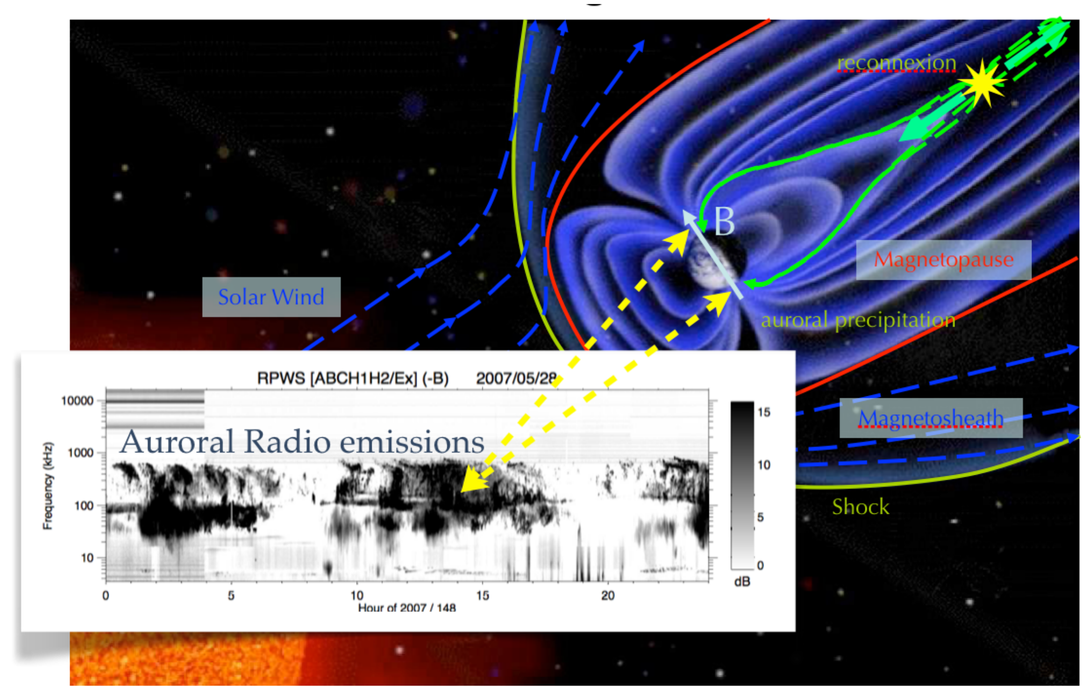
Galactic background flux density detected by a short dipole antenna :
S_{sky} ($Wm^{-2}Hz^{-1}$) = $2kT_{sky}/A_{eff} = 2kT_{sky}\lambda^2/\Omega$ with $\Omega=8\pi/3$, $A_{eff}=3\lambda^2/8\pi$

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

Solar System Radio Sources



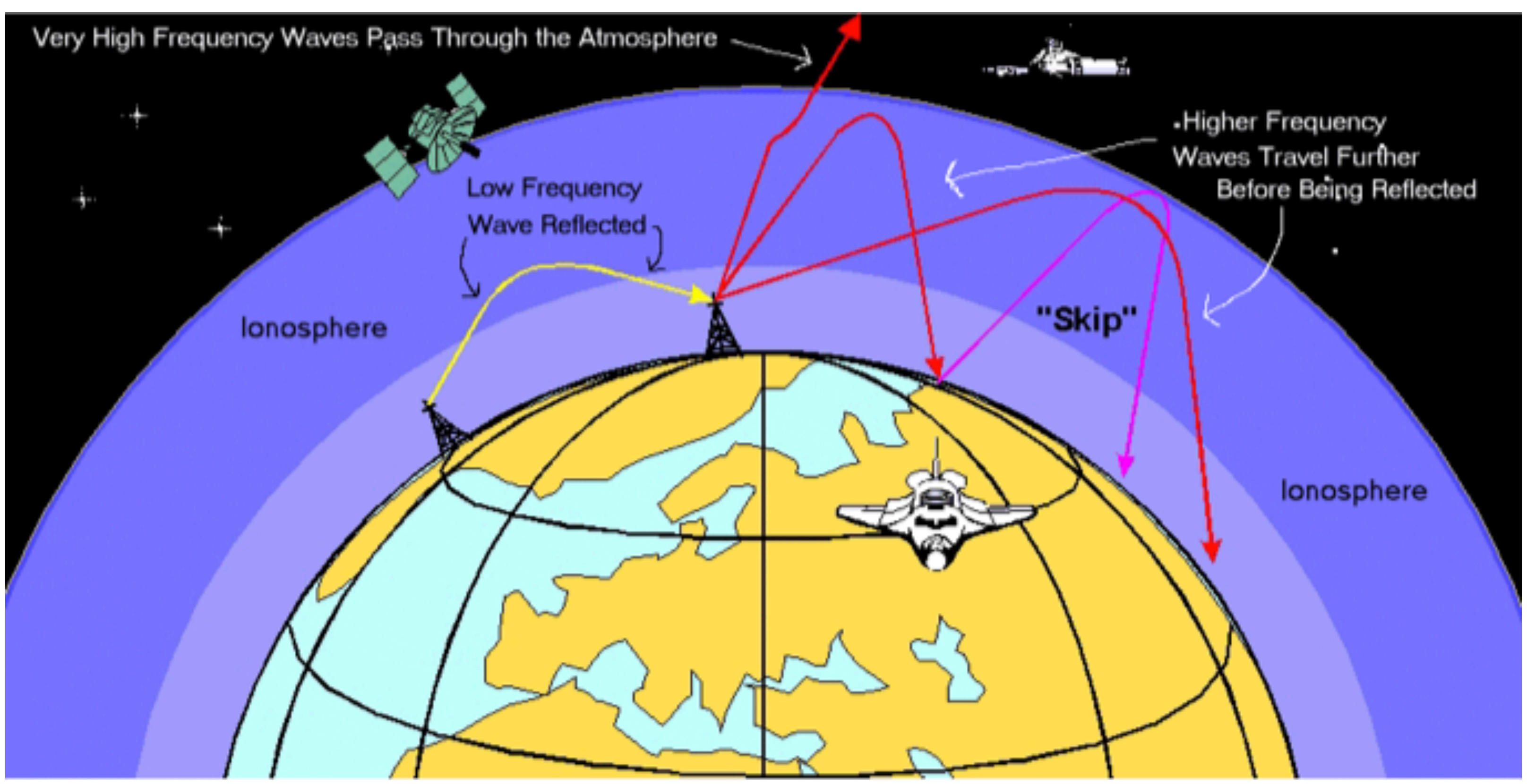


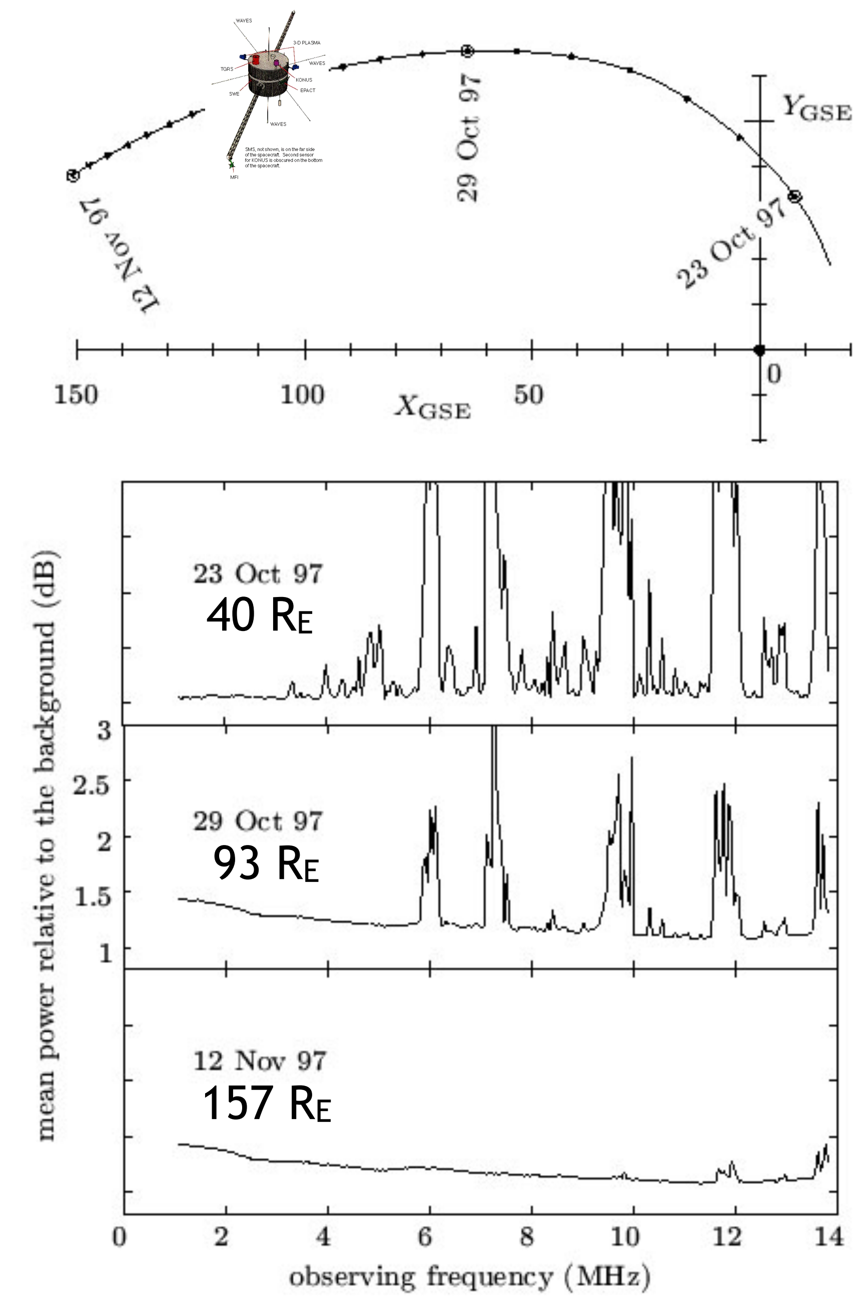


Very intense and sporadic

Near-Earth Radio Environment

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

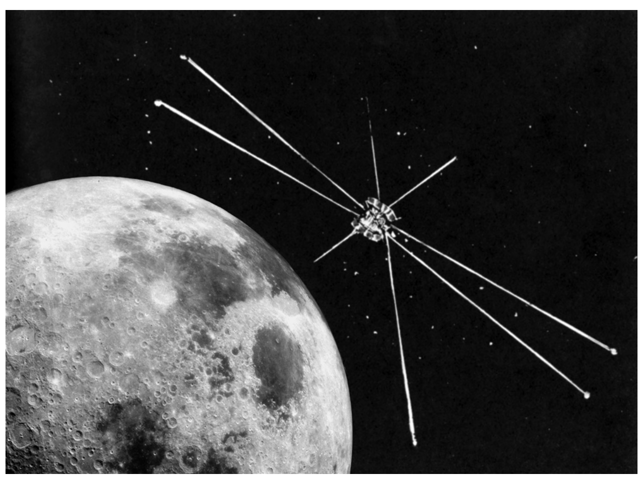


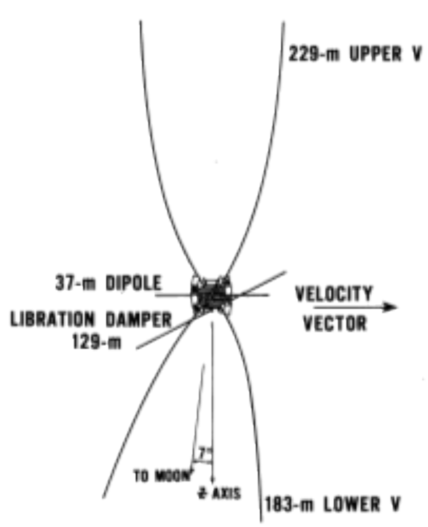


24h averages from Wind/WAVES

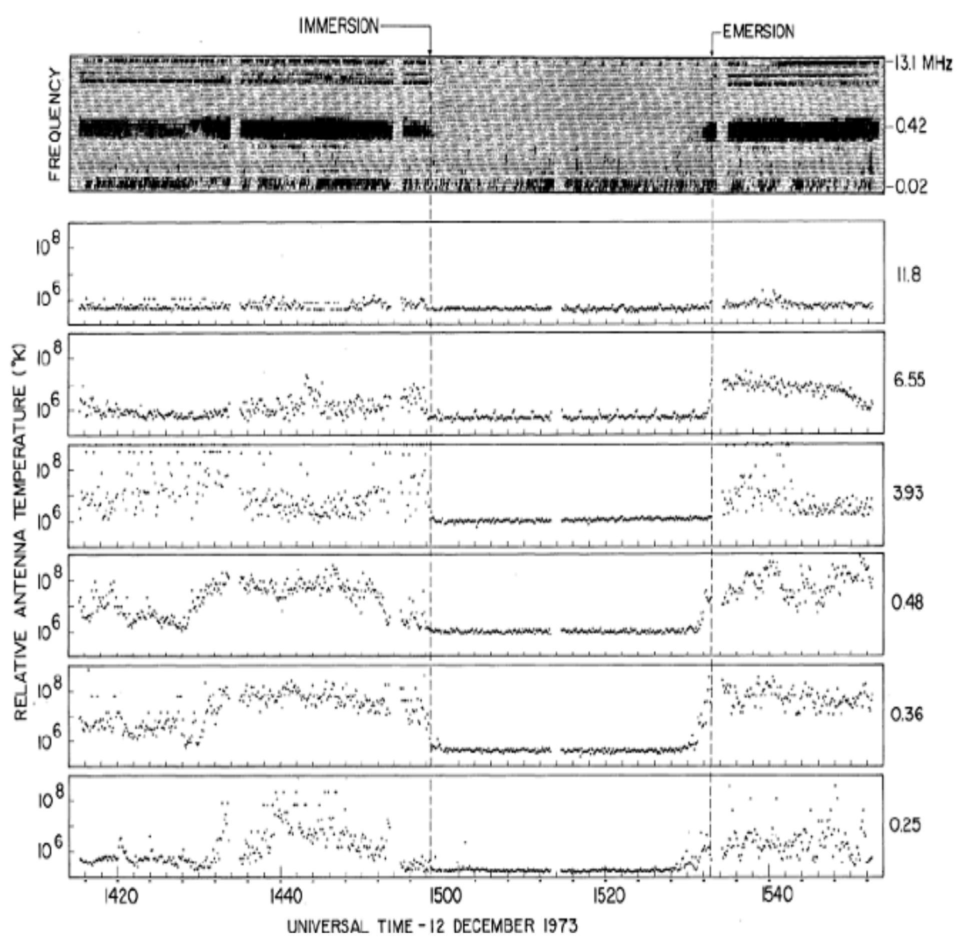
Except behind the moon

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

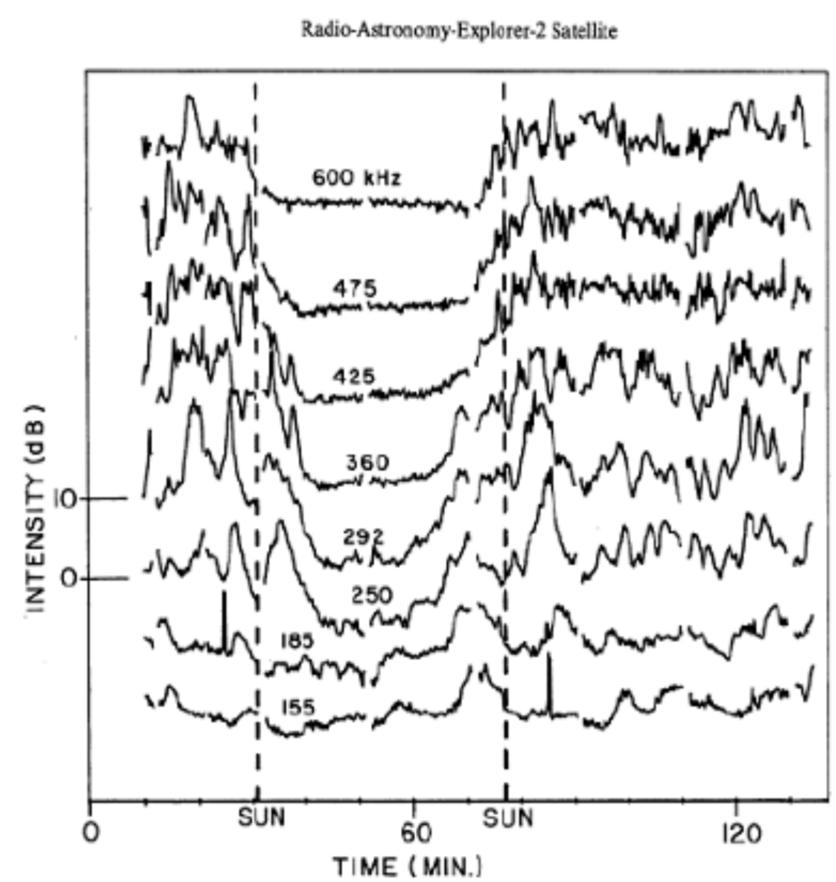




RAE-2 occultation of Earth (1973)

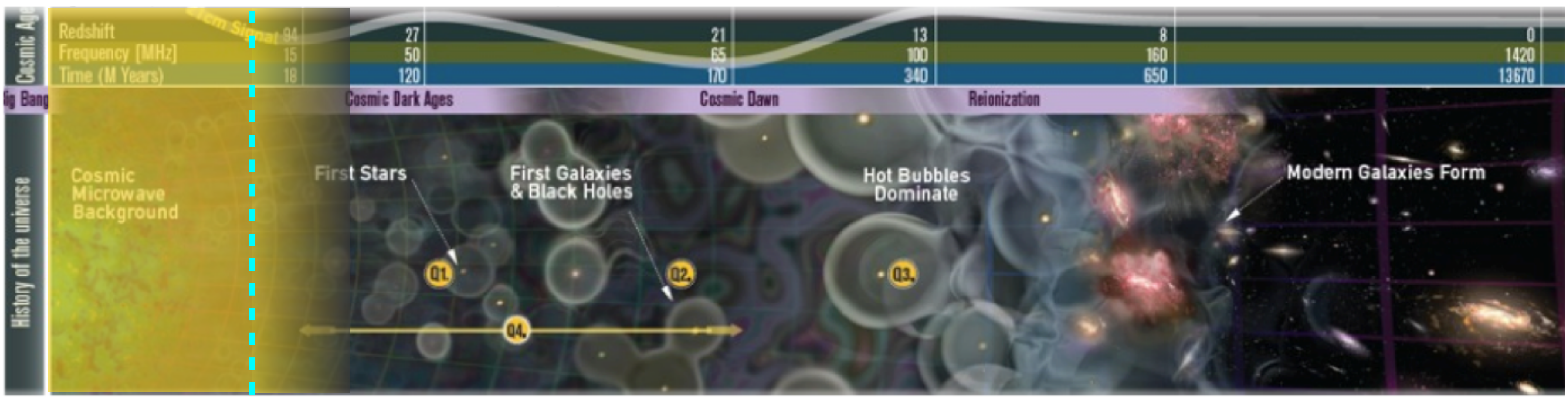


RAE-2 occultation of a solar storm



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

Science opportunities

- **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** … (Frequency range is almost unexplored !)

Science opportunities

ESEP!

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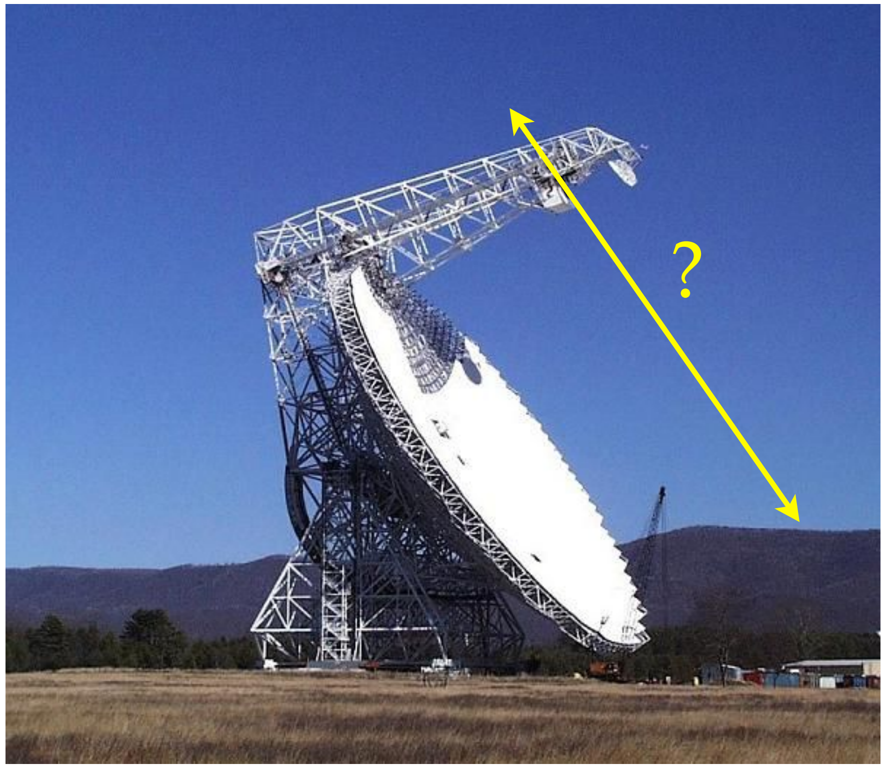
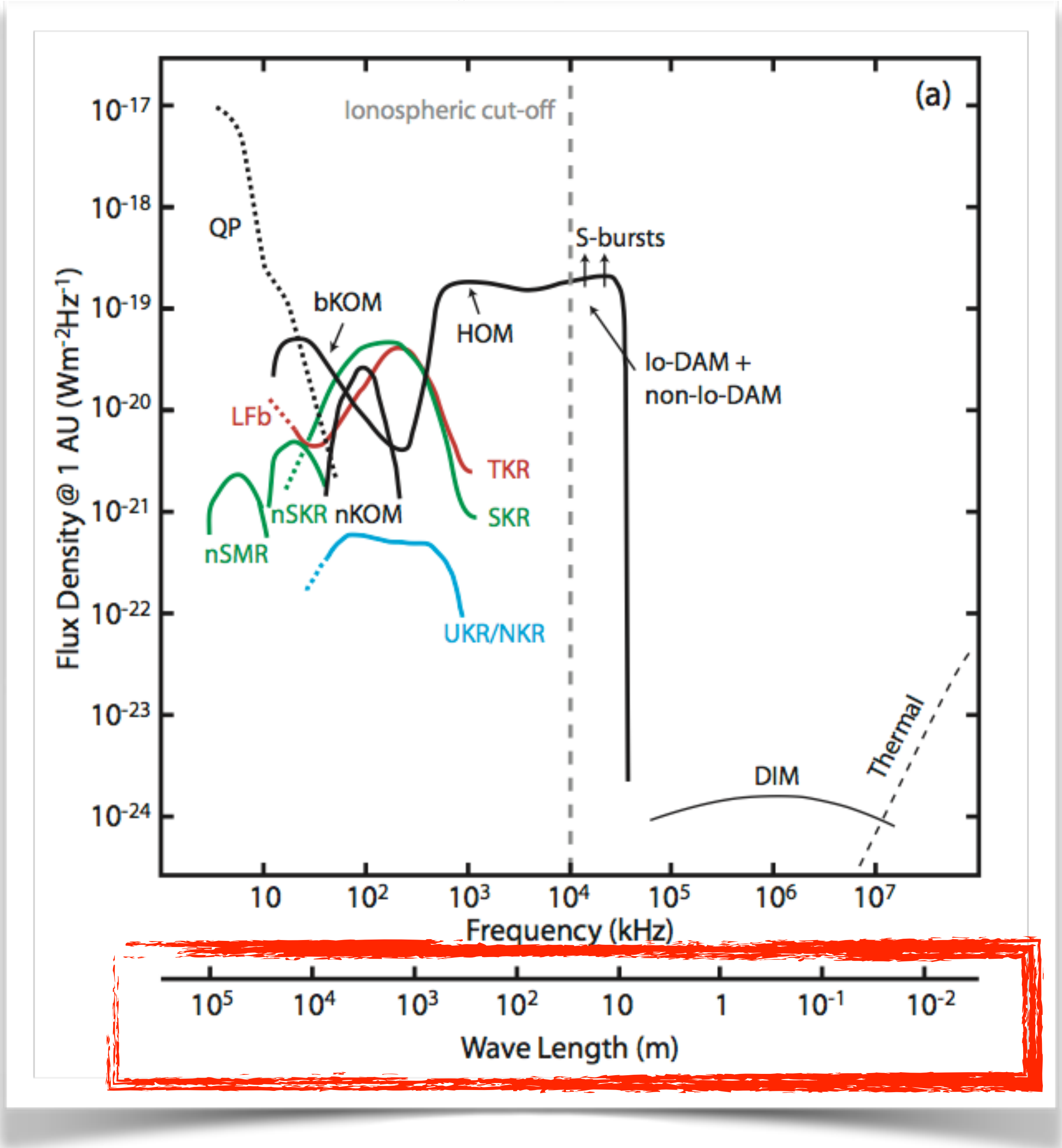
LF radio astronomy in space

Can we use a large dish ?



Greenbank Radio Telescope

Planetary radio emissions



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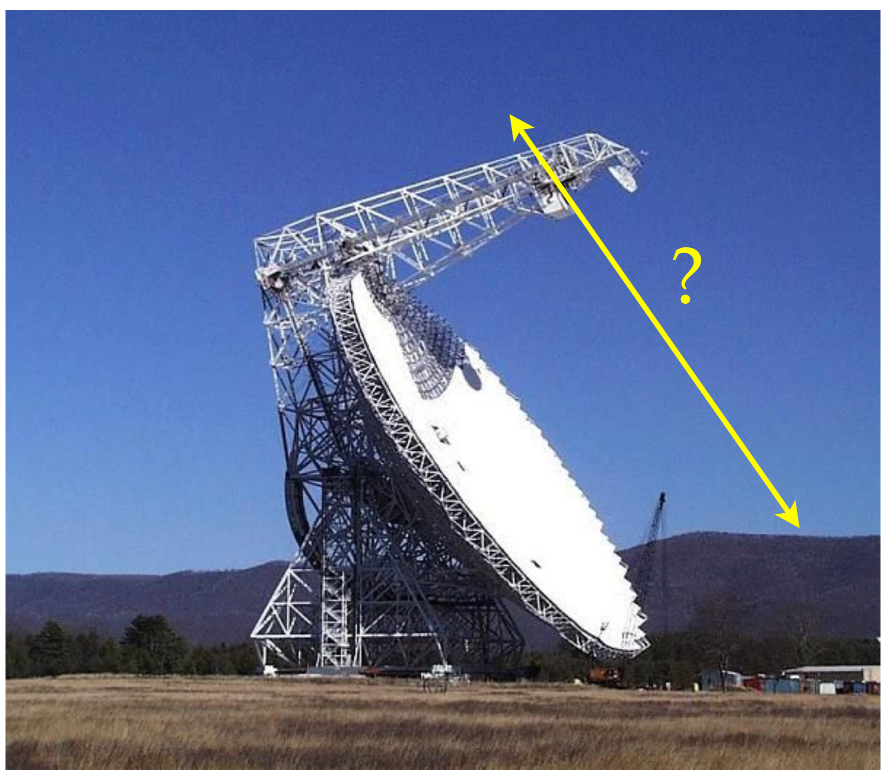

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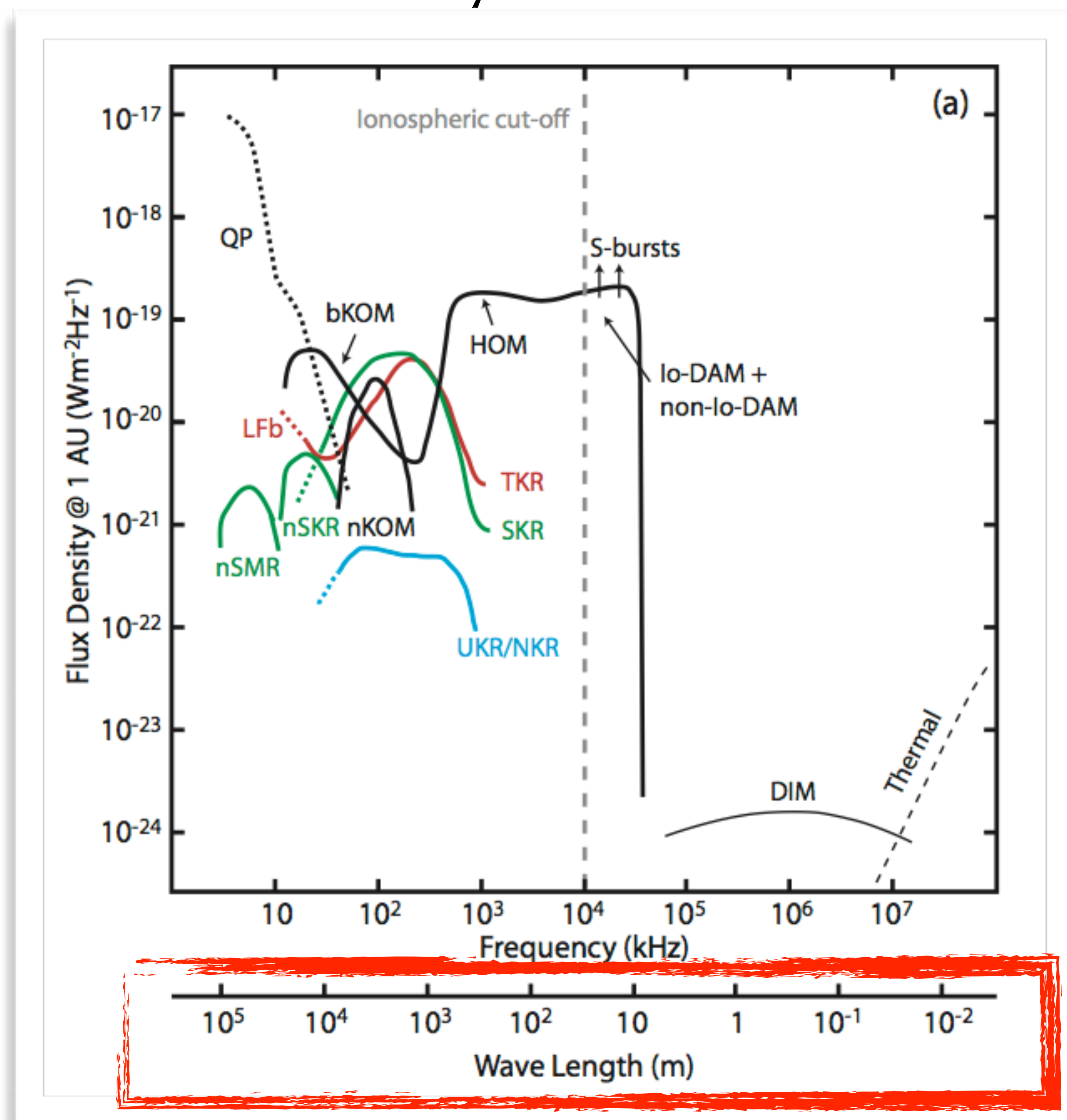

Angular resolution requires $\lambda / D << 1$
=> at 30 kHz, **D >> 100 km** !!

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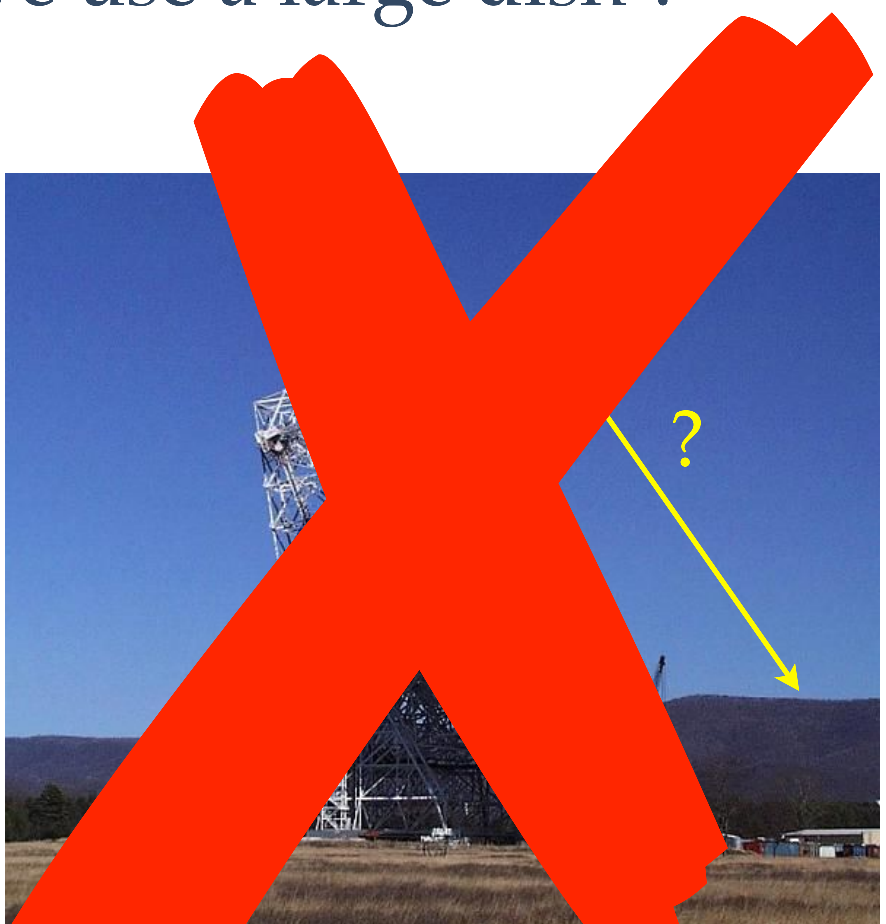

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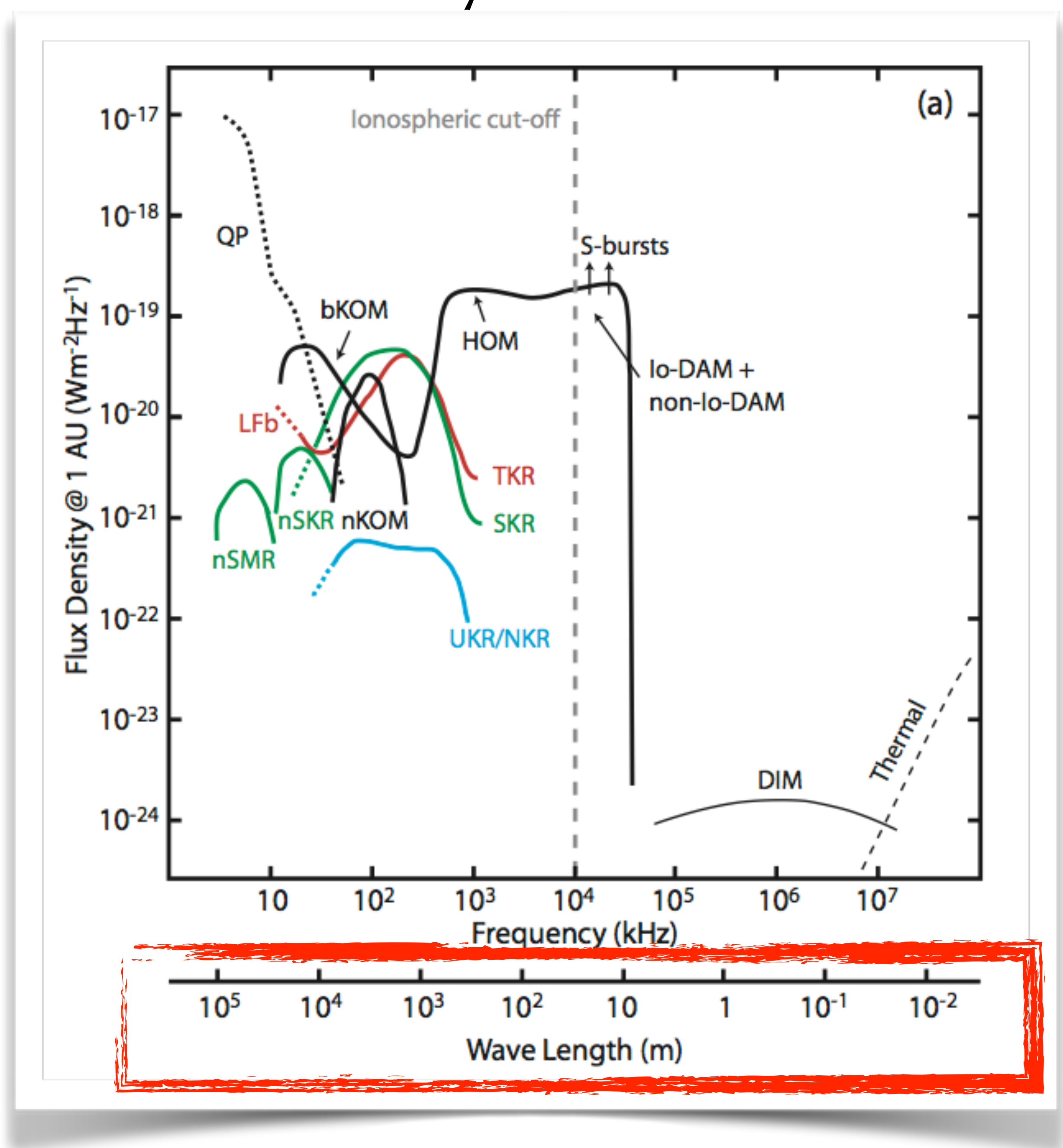
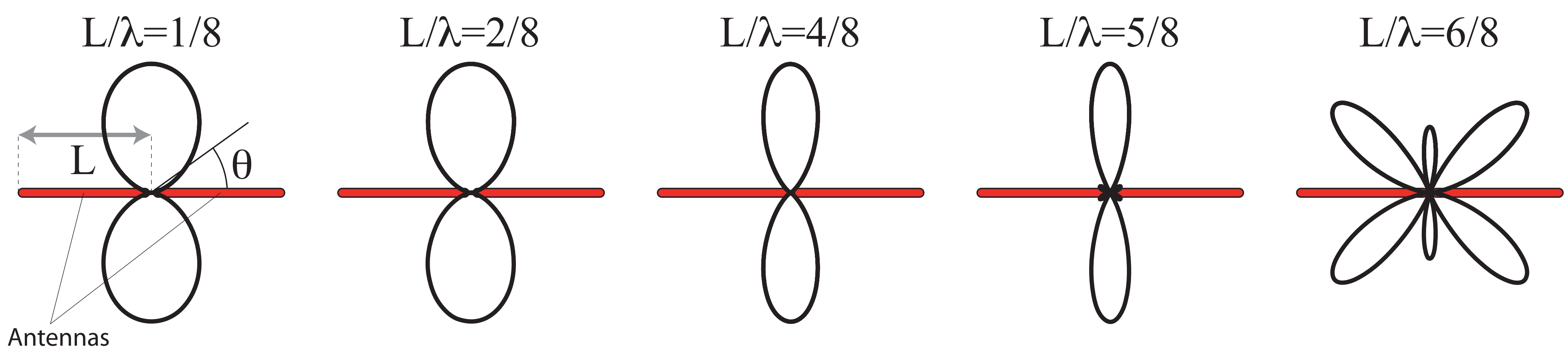


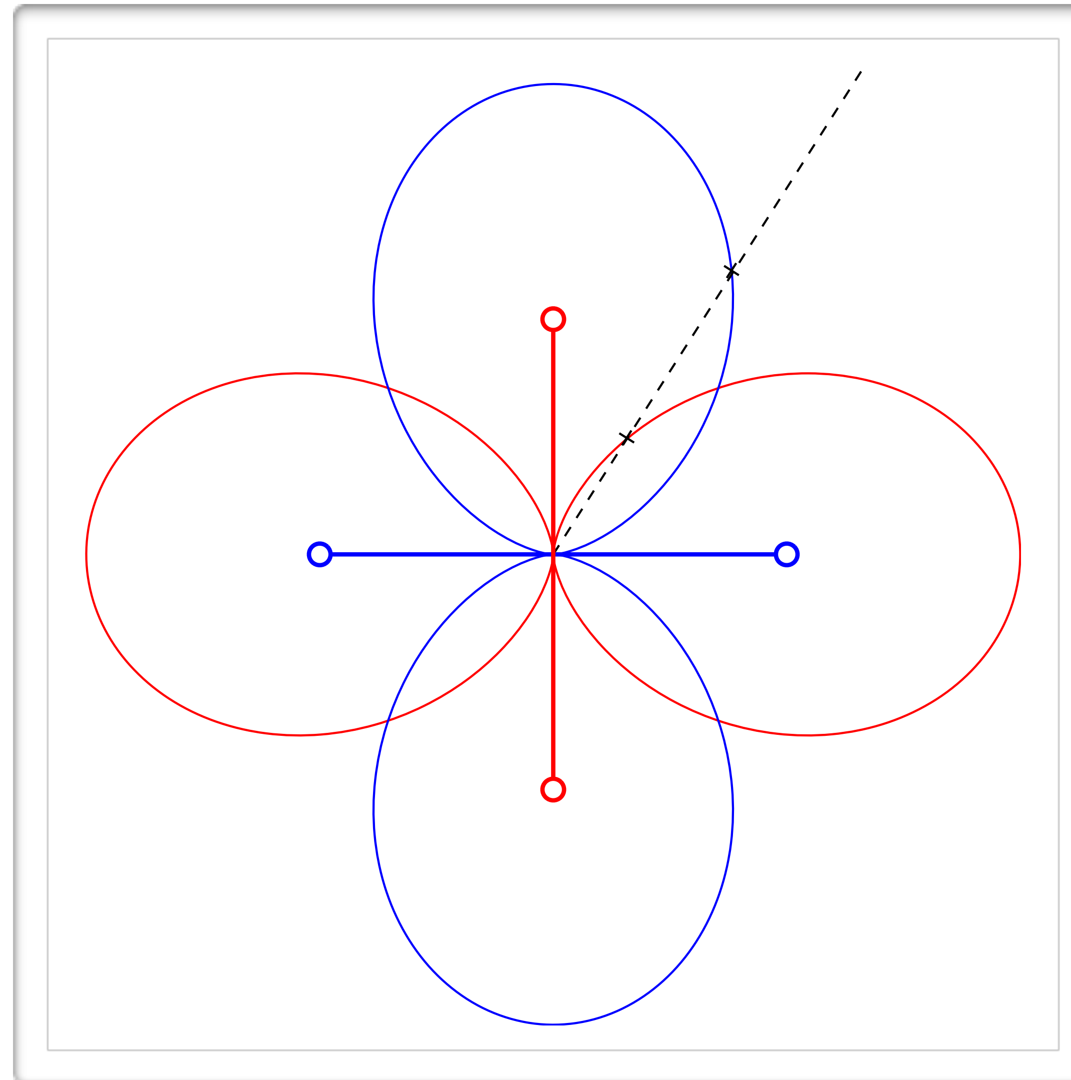
LF radio astronomy in space
Goniopolarimetry

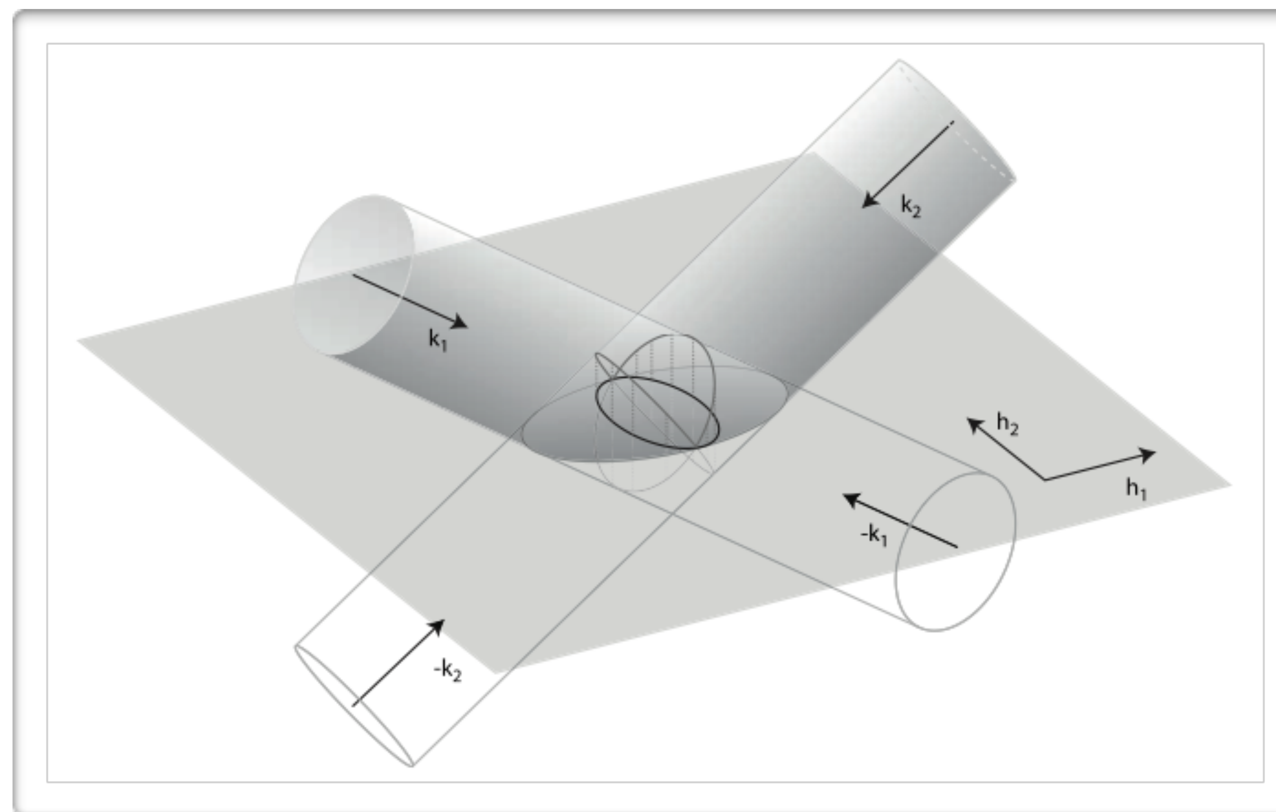
- Space based radio antennas: simple dipoles or monopoles with length L of a few meters
  (impossible to have a reflector large enough to have $\lambda/D << 1$)
- Short antenna range ($L << \lambda$) : monopole antenna + S/C body ~ effective dipole
- Antenna gain ~ $L^2 \sin^2\theta$ → null // antenna,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



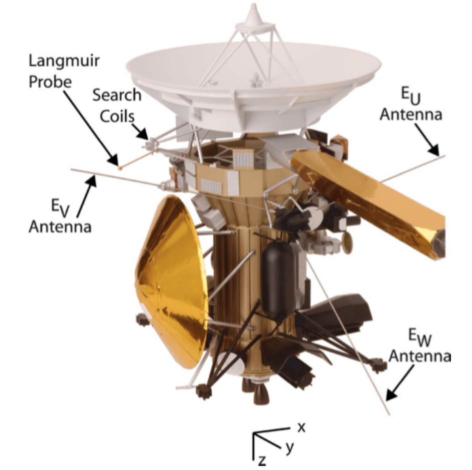
GonioPolarimetry

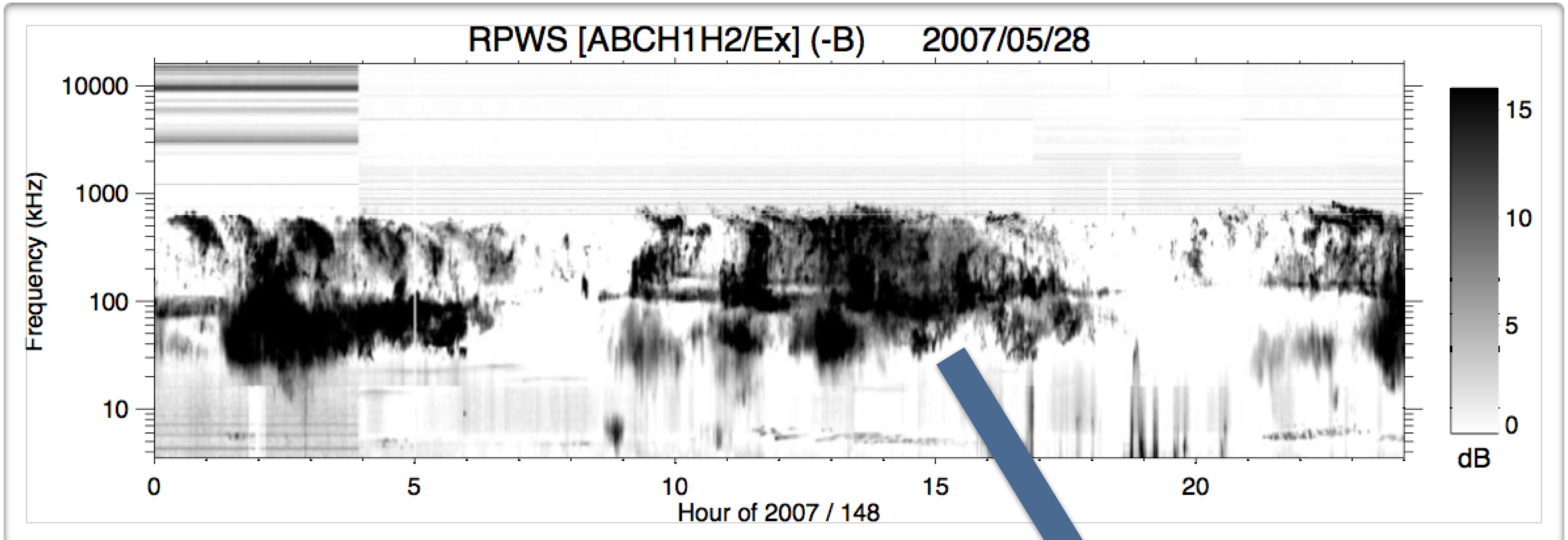
- Dipole has no angular resolution:
  ∫ antenna pattern = $8\pi/3$ sr
- Solution : Use 2 crossed dipoles connected to a dual-input receiver and correlate measurements on both antenna
- With 3 antennas + crosscorrelations : full wave parameters (flux S, polarization Q,U,V, and wave vector θ, φ)
- Angular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



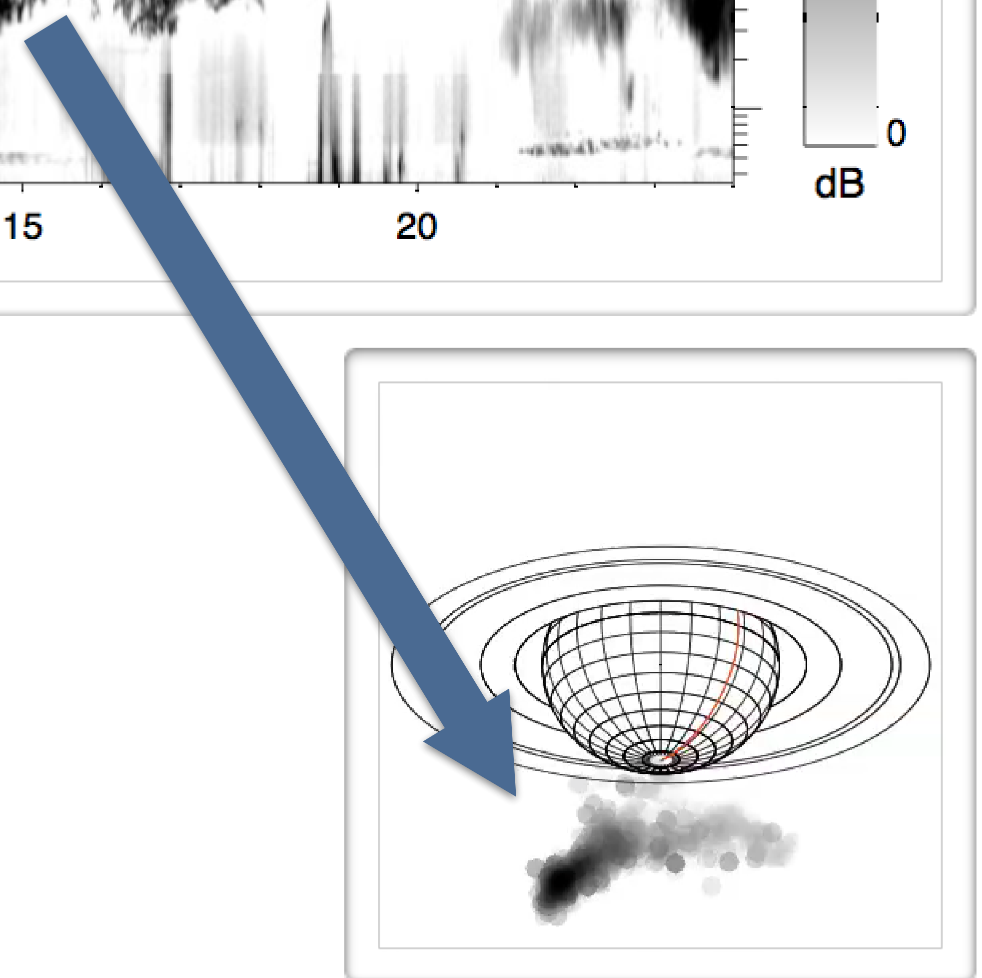


Goniopolarimetry illustrated (Cassini/RPWS @ Saturn)





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



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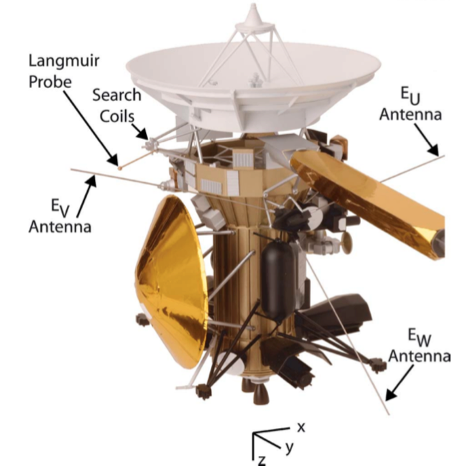
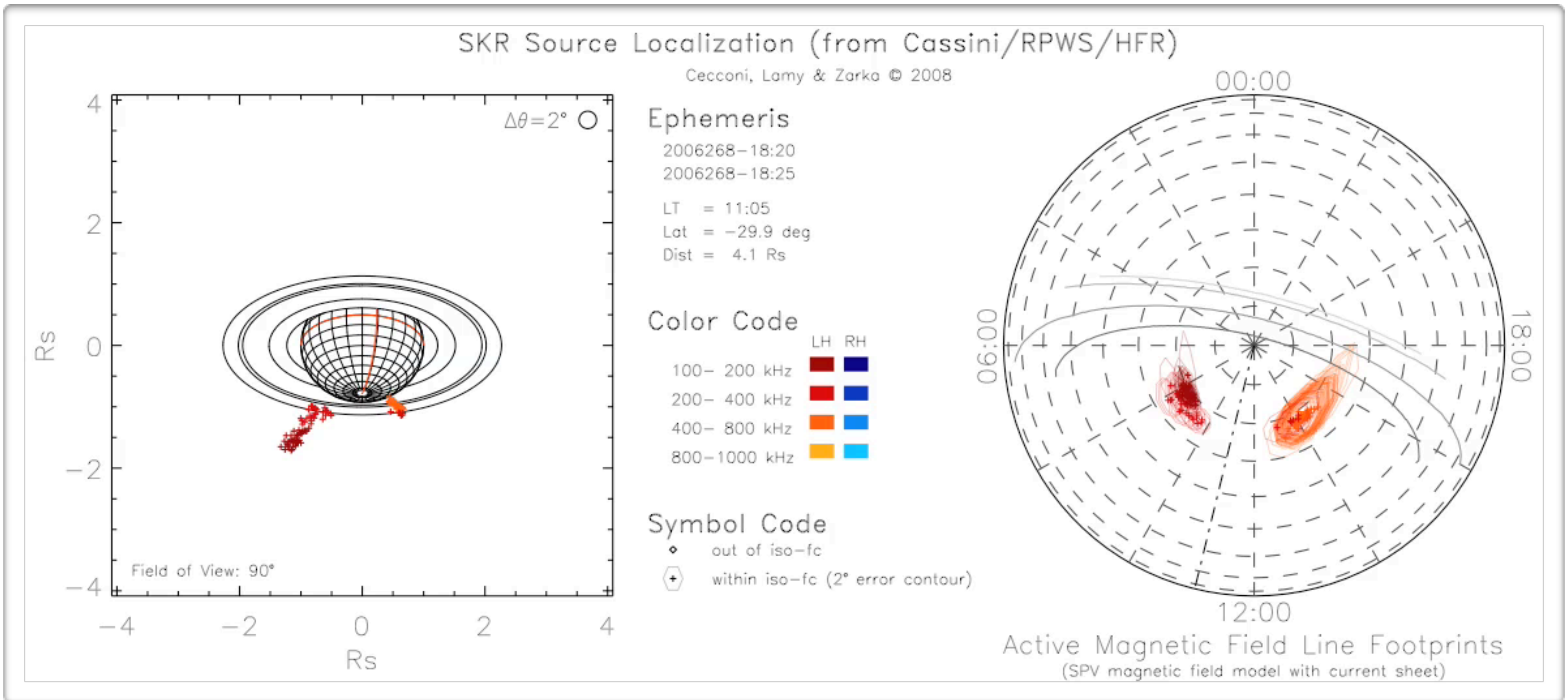
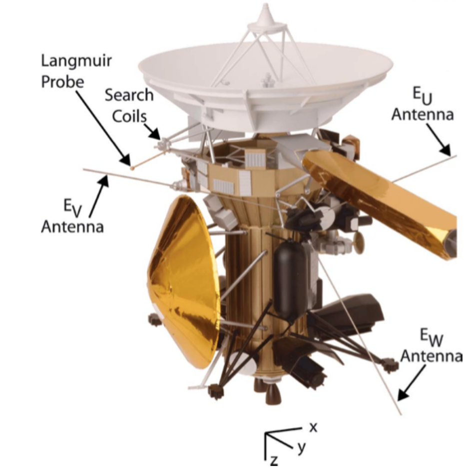


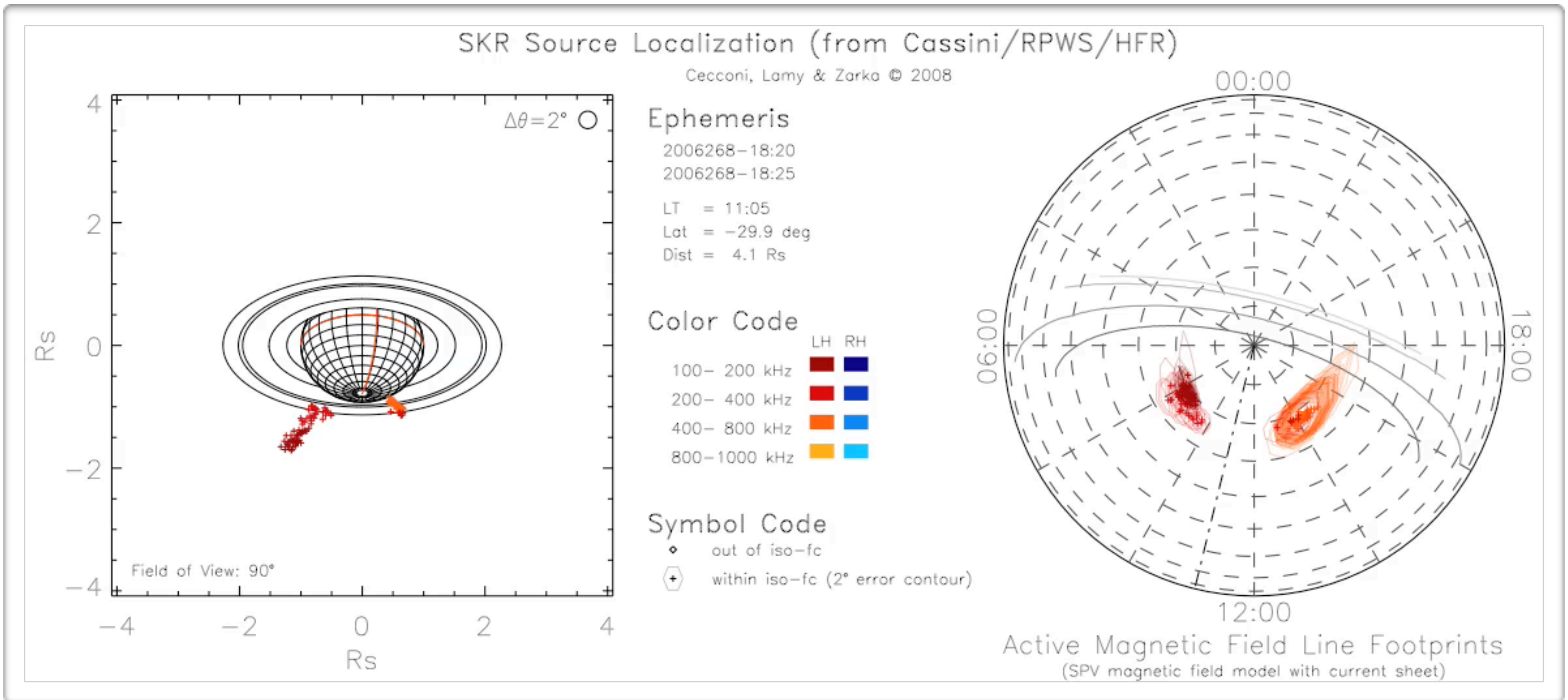


Saturn auroral kilometric radio source location from Cassini/RPWS data

(left: as seen from Cassini; right: projected on Saturn's poles along magnetic field lines)

Goniopolarimetry illustrated (Cassini/RPWS @ Saturn)



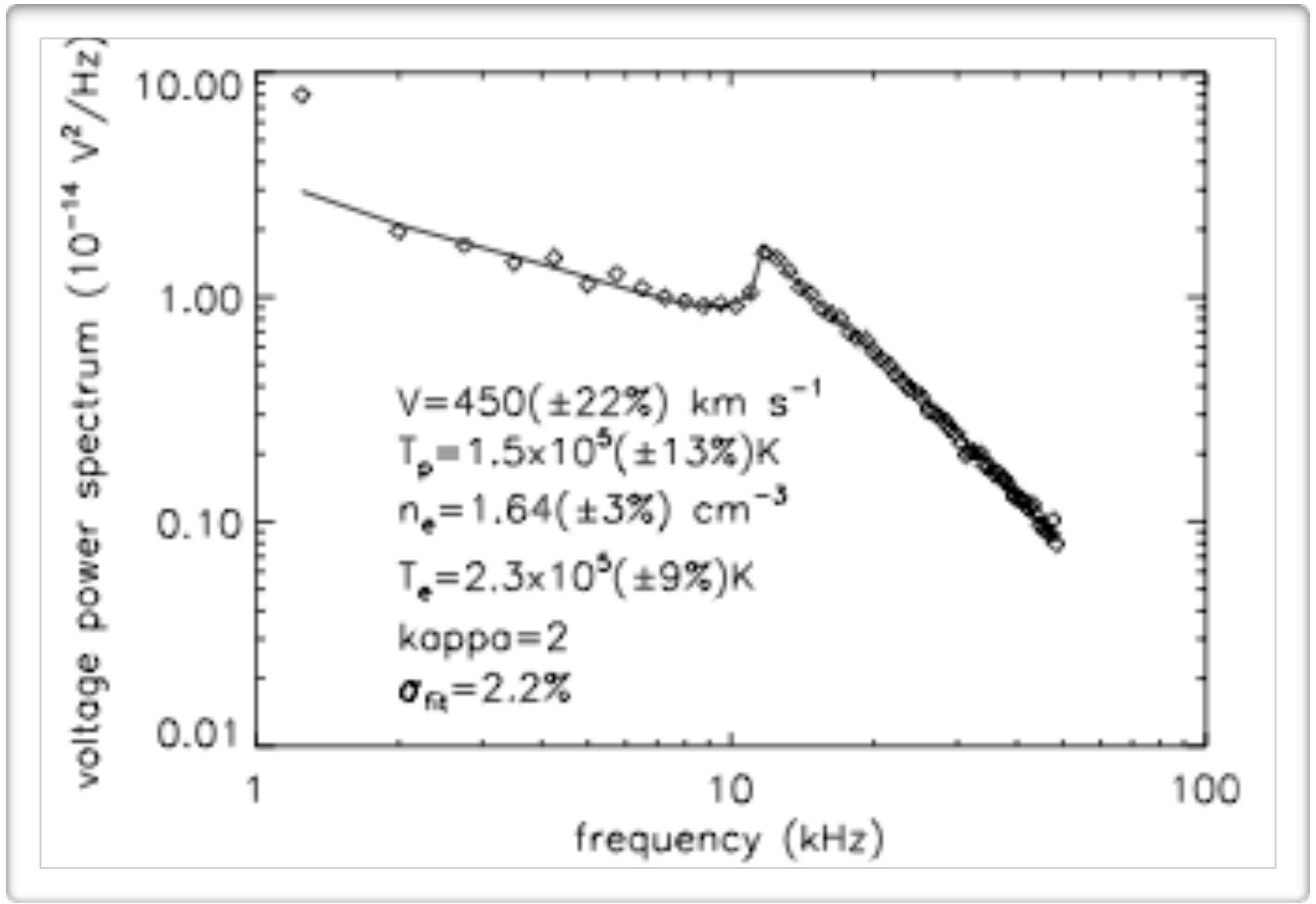


Saturn auroral kilometric radio source location from Cassini/RPWS data

(left: as seen from Cassini; right: projected on Saturn's poles along magnetic field lines)

Quasi Thermal Noise Spectroscopy

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

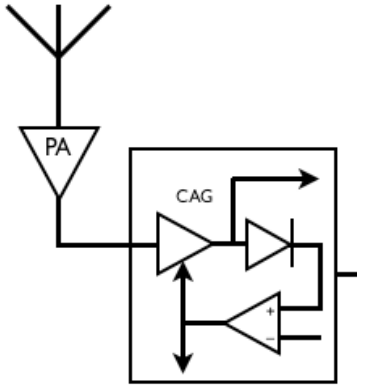


- Requires thin and long antennas (ok for spinning spacecraft, more difficult on stabilized spacecraft) and high spectral resolution radio receiver (Δf/f ~ 1%)

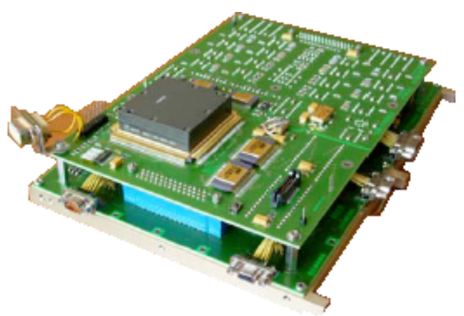
- Absolute determination of plasma parameters: complementary to active measurements (such as Langmuir probes)

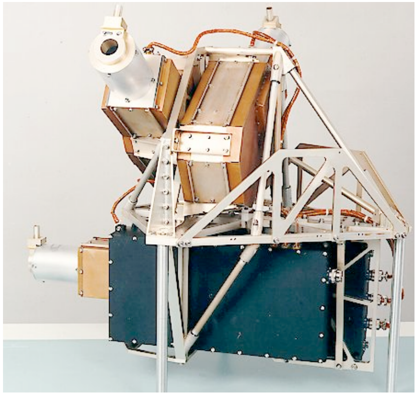
Space radio instrument characteristics

- **Current (Bepi Colombo, Solar Orbiter…)**
  - superheterodyne (base band: 1 to 3 MHz), sweeping frequency
  - receiver sensitivity 3-5 nV/√Hz,
  - need separate LF & HF due to 1/f spectrum,
  - dynamic range 80-100 dB (with or without Automatic Gain Control (AGC))
  - Resources: ~1 W, a few 100's g, A5 board
  (2 sensing channels + processing)
- **Near Future (Solar Probe Plus, JUICE…)**
  - base band (up to 100 Msample/s sampling)
  - digital filtering / processing to reduce bandwidth
  - 1W per sensing channel + processing.
- **Ongoing R&D in France (Observatoire de Paris / CNES / TelecomParis) for a new generation of digital radio receiver with high dynamic, low power and sampling up to 100 MHz.**



A channel of Cassini/RPWS/HFR

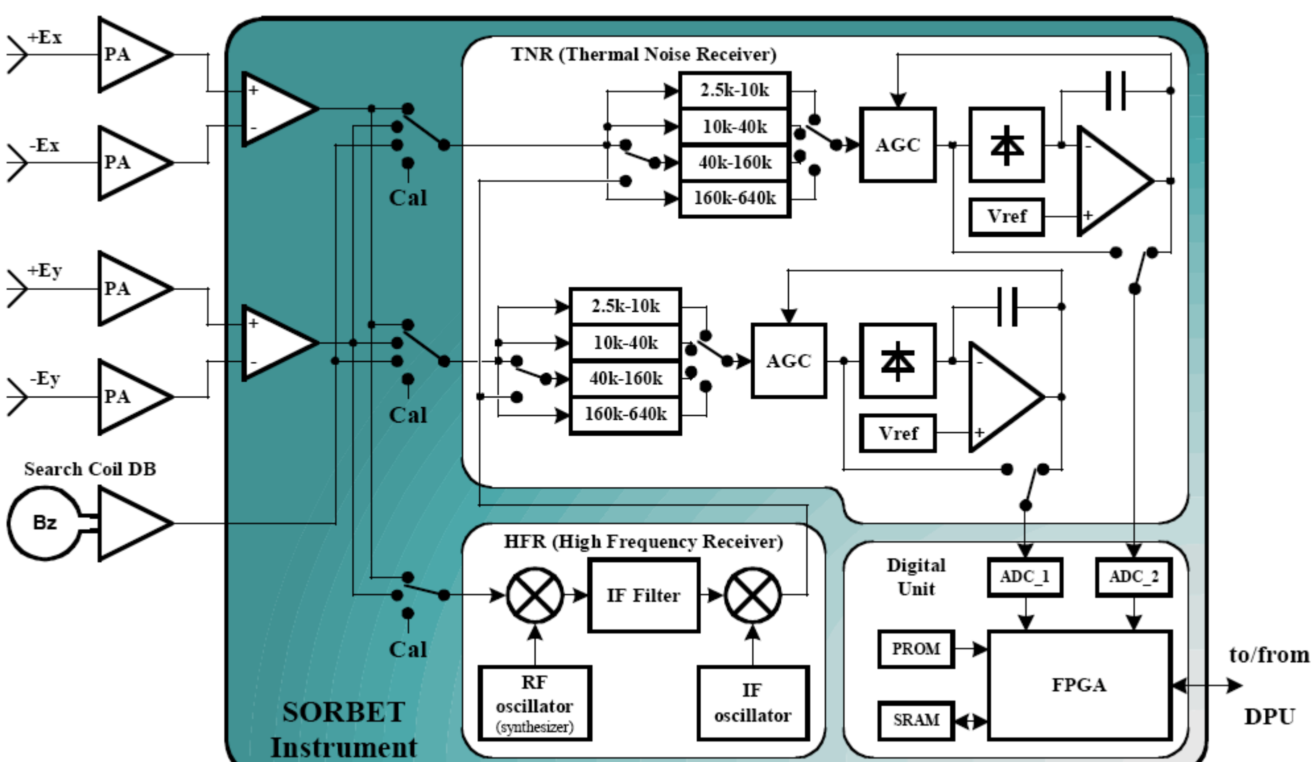

BepiColombo/MMO/RPW/Sorbet


Cassini/RPWS antennas (stowed)

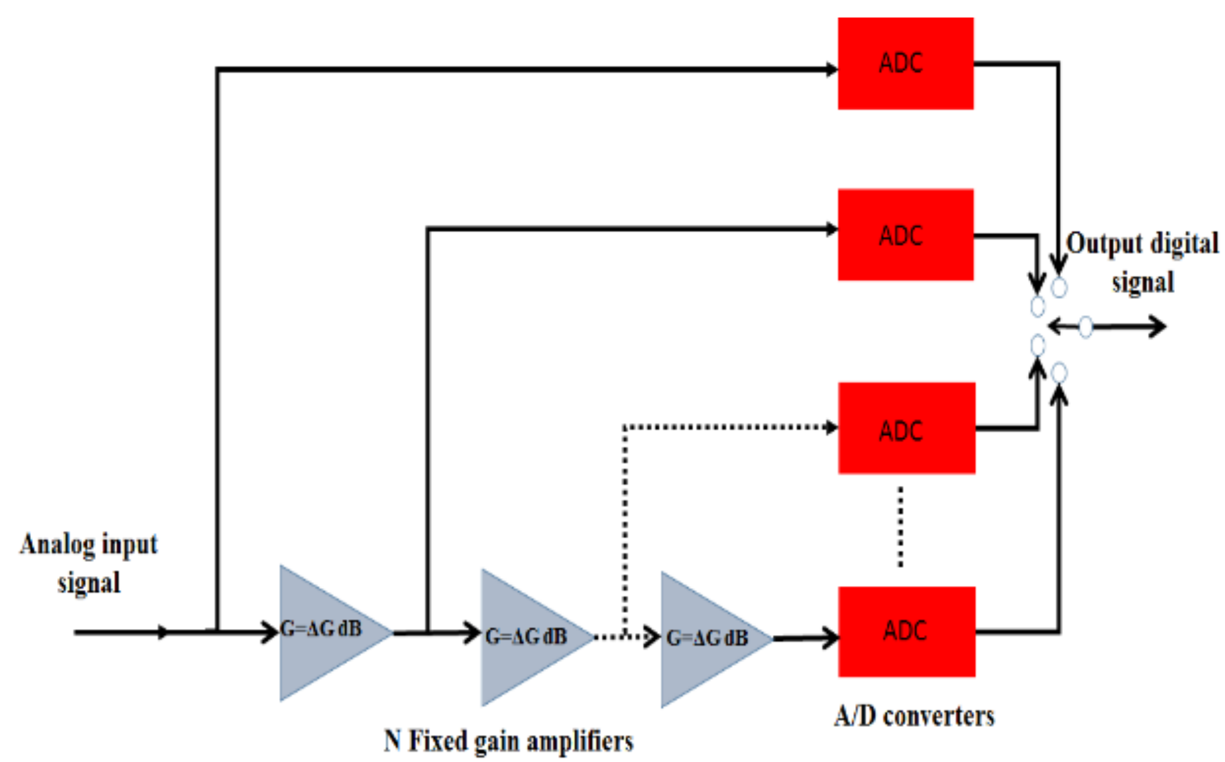
R&D STAR (Stacked ADC Receiver)

- Collaboration : LESIA + TelecomParis
- Support from : CNES (R&T) + ESEP (CDD)

Current Architecture (BepiColombo/SORBET)



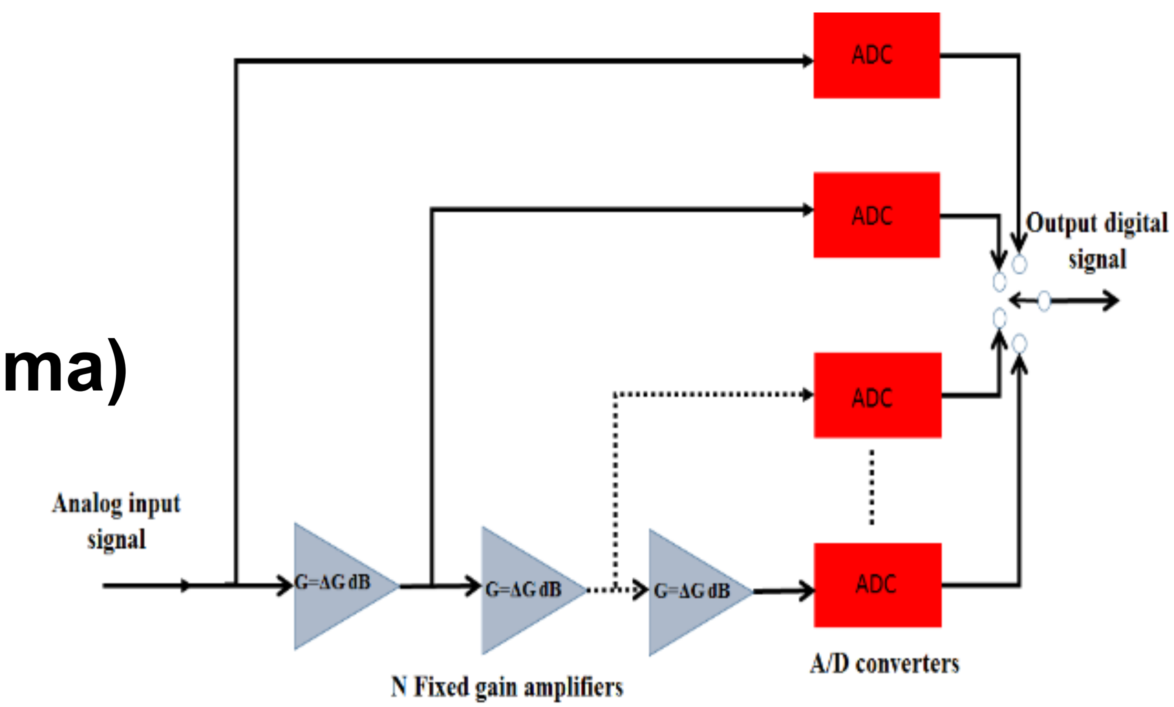
Studied Architecture (STAR)



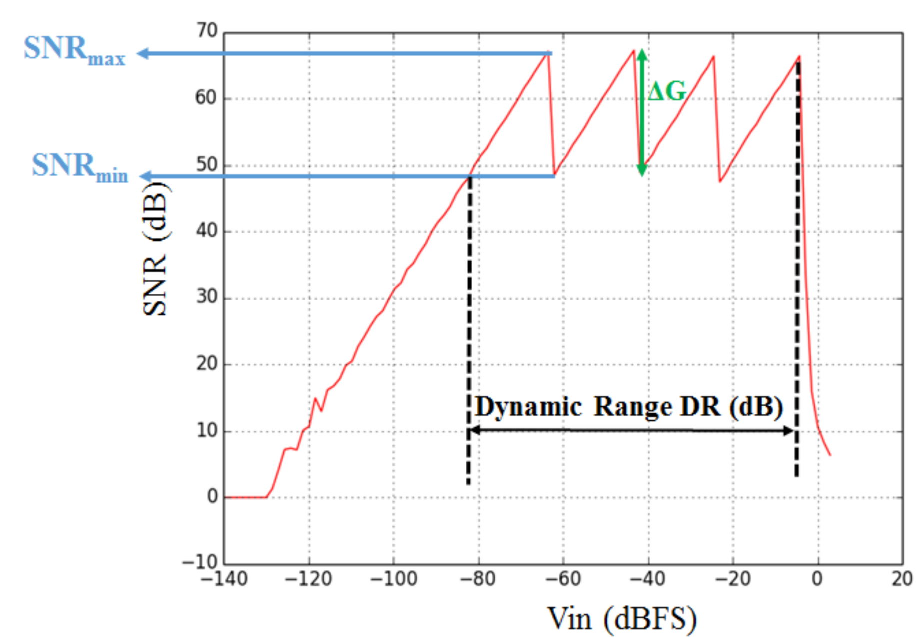
R&D STAR (Stacked ADC Receiver)

- Spécifications scientifiques du récepteur STAR:

- **Dynamique de mesure~ 120 dB**
- **Bande passante: 100 MHz**
- **Résolution spectrale: ~5%**
  (1% pour le tracking de la raie plasma)
- **Résolution temporelle : < 1s**



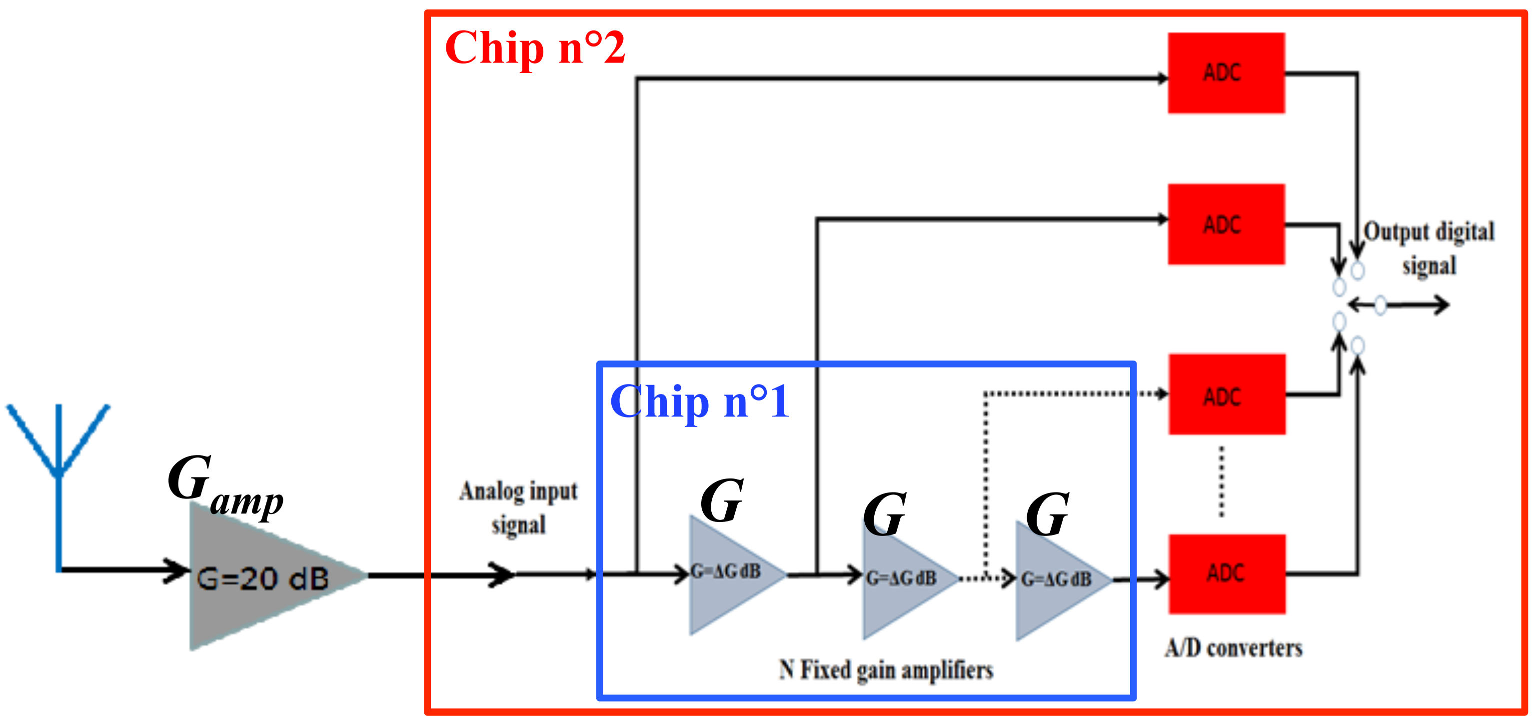
STAR: Récepteur à 4 voie avec des ADCs de 10 bits (SNR>60 dB) et des amplificateurs de 30 dB



Travail de Reda Mohellebi (CDD ESEP)

R&D STAR (Stacked ADC Receiver)

- Spécifications électriques pour le récepteur STAR :



ADC :
- 10 Bits
- SNDR = 60 dB
- BW = 100 MHz
- Fs = (200,100, 40)MHz
- Vref = 1 V
- Cin ~ 1pF
- P< 20 mW

Amplificateur 1 :
- **BW = 100MHz**
- **DC gain > 56 dB (5% sur le gain)**
- G = 30 dB
- **Noise (@1KHz) = 200 nV/Hz**
- SFDR >90 dB
- Output Swing= 1V
- Slew Rate > 1300 V/us
- **P< 40 mW**
- **DC offset <140 uV**

Amplificateurs 2 and 3 :
- BW = 100 MHz
- DC gain > 56 dB (5% sur le Gain)
- G = 30 dB
- Noise (@1KHz) = 1 uV/Hz
- SFDR >60 dB
- Output Swing= 1V
- Slew Rate > 1300 V/us
- P< 10 mW
- DC offset < 140 uV

La technologie CMOS 65 nm de STMicroelectronics à été choisie pour le design de STAR

Layout de l'ASIC n°1 en conception (fonderie en 2016)

New onboard processing capabilities

- Miniaturization + full digital receivers => new capabilities for onboard processing.

- Several ongoing developments:
  - onboard “Smart Averaging”:*separate noise from signal, opposite polarizations, at high resolution, before integration*
  - RFI mitigation: *similar to “smart averaging”: blank outliers on high resolution, before integration*
  - Polyphase filtering on FPGA (M. Dupard, 2015)
  - Plasma line detection at high cadence (CIRCUS)
  - Compressed Sampling (CNES PhD LESIA/TelecomParis)

Radio instrumentation in space

- **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 !

Space radio instrument constraints

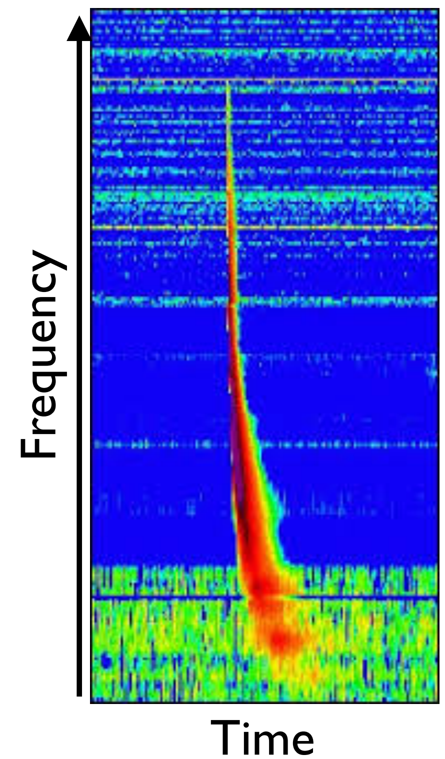
- Specific need for radio astronomy
  EMC clean platform !!
  no RFI lines in the observed frequency range 10 khz - 100 MHz (not easy) or automated RFI-mitigation

- Sensitivity
  - best low noise amplifier sensitivity is now ~3-5 $nV/Hz^{1/2}$
  - variability of gain in temperature and radiation must be studied carefully for cosmology (controlled cooling required?)

- Interferometry:
  - Pointing, node location knowledge, node position control
  - 3D imaging to be developed

Solar Radio Emissions

- **What we can do now**:
  using simple a model
  for extended source
  (*on left figure, each «bubble» is a frequency step)*
  STEREO, Solar Orbiter…



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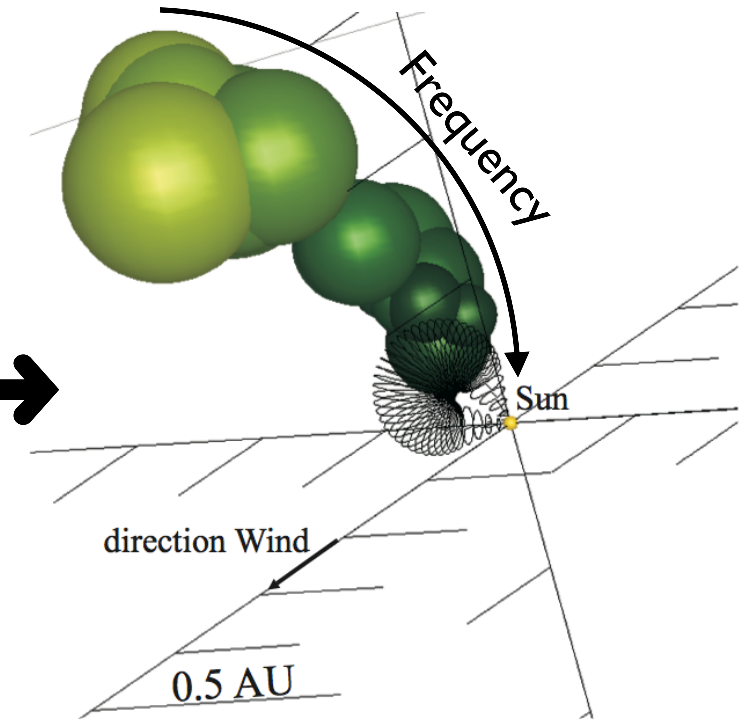
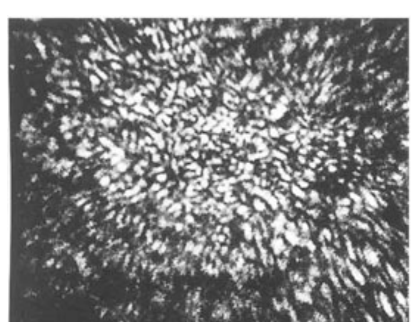


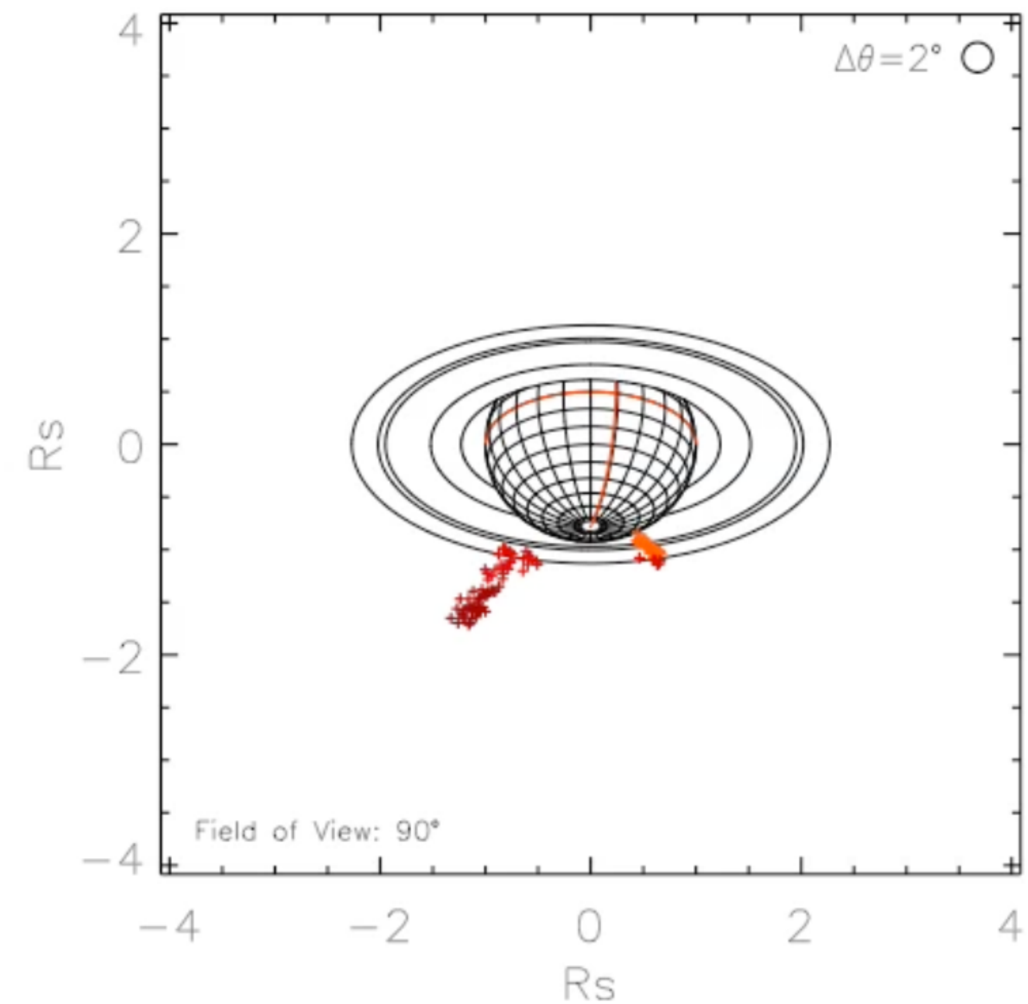
Magdalenic et al, 2014

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

Will we see  or  ?

Planetary Radio Emissions

- **What we can do now**:
  for each time-frequency step:
  1 location, 1 flux,1 polarization
  (a posteriori reconstruction with a lot a records)
  Cassini, JUICE…



Cecconi et al, 2009
Cassini/RPWS

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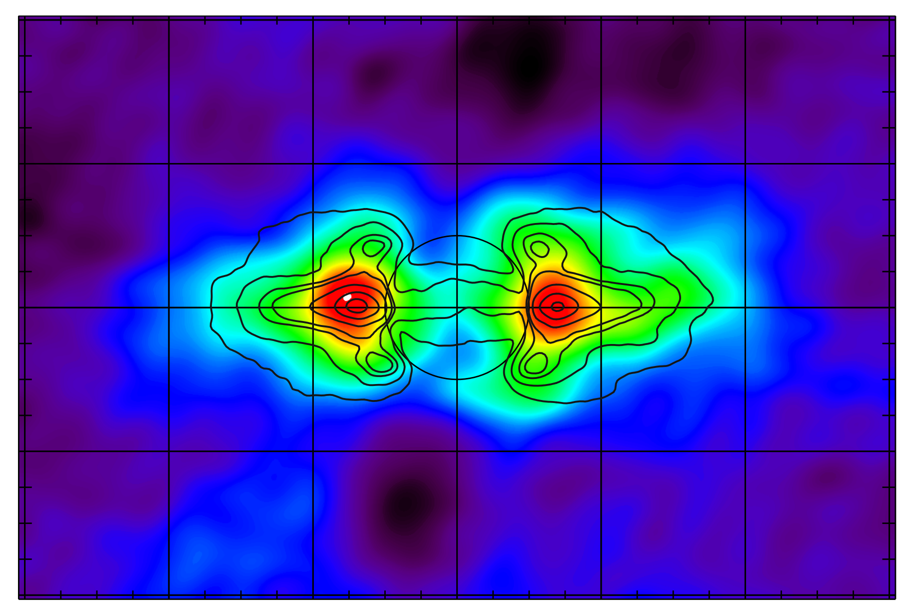
  1 polarization map



Girard et al, 2014
LOFAR

A few space radio interferometer projects on nanosats

Name	Frequency range	baseline	nb of S/C	Location	Team / Country
SIRA	30 kHz – 15 MHz	>10 km	12 – 16	Sun-Earth L1 halo	NASA/GSFC [2004]
SOLARA/ SARA	100 kHz – 10 MHz	<10,000 km	20	Earth-Moon L1	NASA/JPL - MIT [2012]
OLFAR	30 kHz – 30 MHz	~100 km	50	Lunar orbit or Sun-Earth L4-L5	ASTRON/Delft (NL) [2009]
DARIS	1 MHz – 10 MHZ	< 100 km	9	Dynamic Solar Orbit	ASTRON/Nijmegen (NL)
DEx	100 kHz – 80 MHz	~1 km	10^5	Sun-Earth L2	ESA-L2/L3 call
SURO	100 kHz – 30 MHz	~30 km	8	Sun-Earth L2	ESA M3 call
SULFRO	1 MHz – 100 MHz	< 30 km	12	Sun-Earth L2	NL-FR-Shangai [2012]
DSL	100 Khz – 50 MHz	<100 km	8	Lunar Orbit (linear array)	ESA-S2 [2015]

Possible Roadmap

- **Step 0: first light**
  Low Earth orbit, 1 nanosat: 3 dipoles, waveform output (correlator, ranging and communication).
  Test of radioastronomy capabilities, sensitivity, computing…

- **Step 1: first fringes**
  Low earth orbit, 2 nanosats, same hardware on both: 3 dipoles, waveform output, correlator, ranging and communication.
  Test of ranging and communication capabilities with increasing distance.
  Possible natural source = Jupiter ?

- **Step 2: first beam**
  Low earth orbit, 4+ nanosats, same hardware on each: 3 dipoles, waveform output, correlator, ranging and communication (may be same nanosats as for 1st step).
  Test of beam forming, in a non planar configuration.
  Nulling of Earth RFI ? Mapping of sky at low resolution ? Solar bursts tracking ?

NOIRE Study in short

- NOIRE: Nanosats pour un Observatoire Interférométrique Radio dans l'Espace
  Nanosats for the space-based interferometric radio observatory

- **Selected by CNES** (*national french space agency*) for a **feasibility study** mid-2015.

- Frequency band within: **1 kHz to 100 MHz**.

- Question to be addressed:
  Can we use nanosats for a low frequency space based radio interferometer ?

- Current steps:
  - Building science case
  - Gather a large community behind this concept in France.

- Future steps:
  - Science Measurement Requirements,
  - Instrument, System and Platform Requirements,
  - Roadmap including studies, pathfinders, science objectives
  - Studies, Pathfinders…

NOIRE Team

Core Labs

- **LESIA, Obs. Paris, France** :
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- **APC, Univ. Paris 7 Denis Diderot, France** :
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  Patanchon, A. Petiteau, A. Tartari
- **LUPM, Univ. Montpellier, France** :
  D. Puy, E. Nuss, G. Vasileiadis

Other Labs

- **CEA/SAp/IRFU, Saclay, France** : J. Girard;
- **ONERA/Toulouse, France** : A. Sicard-Piet;
- **IRAP, Toulouse, France** : M. Giard;
- **GEPI, CNRS-Obs. de Paris, France**:
  C. Tasse;
- **LPC2E, CNRS-Univ. d'Orléans, France** :
  J.-L. Pinçon, T. Dudok de Wit,
  J.-M. Griessmeier ;
- **C2S/TelecomParis, France** :
  P. Loumeau, H. Petit,
  T. Graba, P. Desgreys, Y. Gargouri

Space Campuses (University nanosat groups)

- Centre Spatial Universitaire de Montpellier-Nîmes, Université de Montpellier : L. Dusseau ;
- Fondation Van Allen, Institut d'Électronique du Sud, Université de Montpellier : F. Saigné ;
- Campus Spatial Diderot, UnivEarthS, Sorbonne Paris Cité : M. Agnan ;
- CERES, ESEP/PSL : B. Mosser, B. Segret

International partners

- OLFAR group in NL (Delft, Nijmegen, ASTRON).
- *Your team?*

Summary

- **Current very low frequency radio astronomy (below 20 MHz) is very limited (<u>although very successful for solar and planetary sciences</u>).**
- **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 (up to 10^5!).**
- **There is ongoing R&D for future radio instrumentation on cubesats (antennas, <u>receivers</u>, correlators…)**
- **Many projects are regularly proposed or currently studied: Farside Explorer, DARE, DEx, OLFAR…**

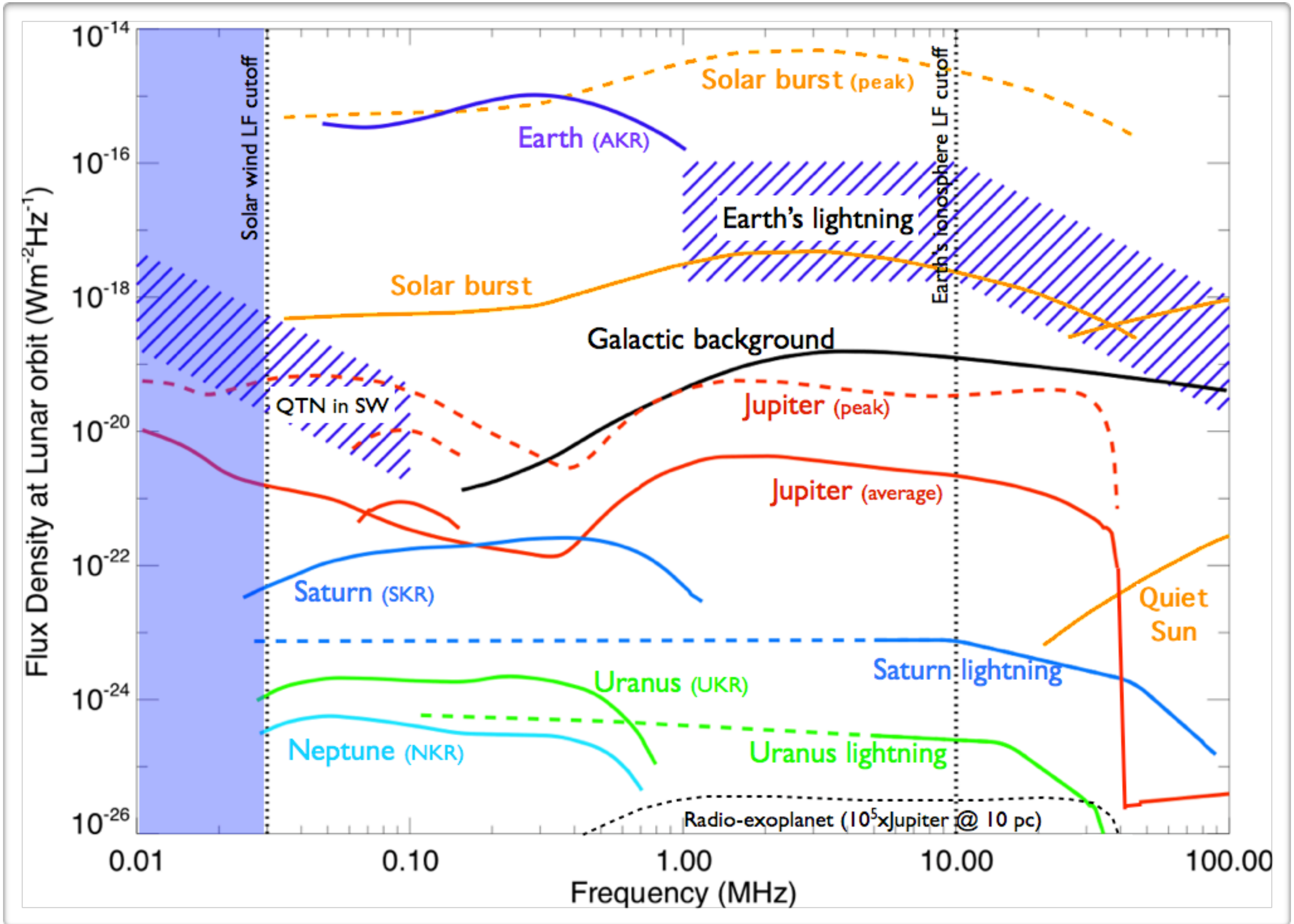
Radio on the Moon?

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
- …

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

Local radio environment



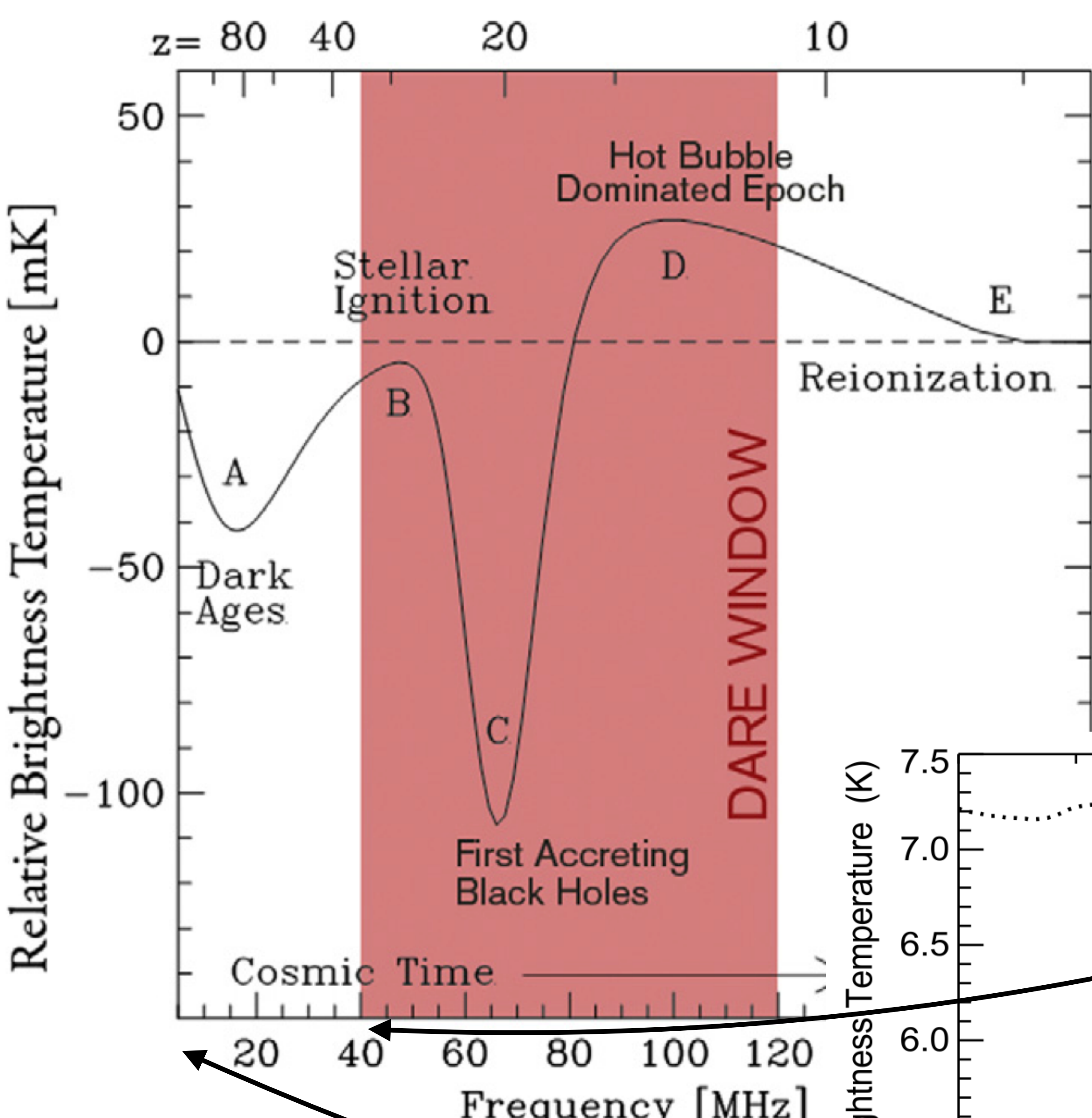
Goniopolarimetric inversions

- **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 ! 😀

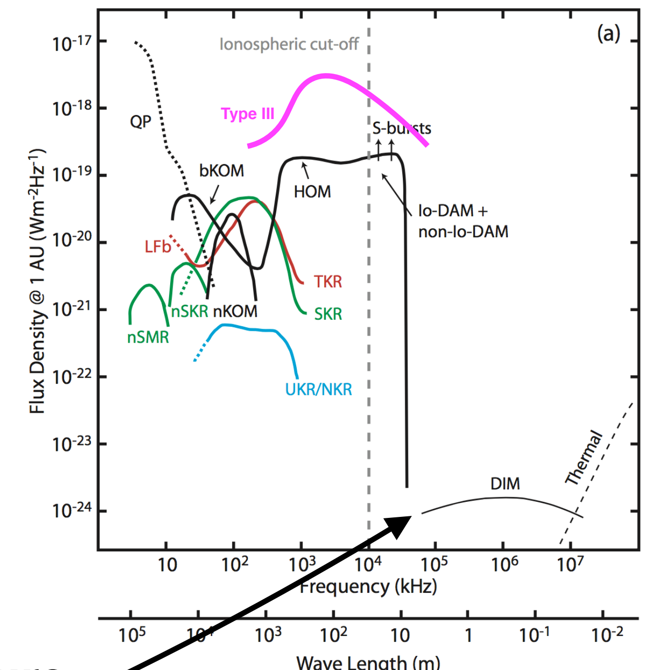
Dark Ages, Cosmic Dawn

Spectral Fluctuations (~50 mK)
on top of 10^5K background, and intense sporadic foregrounds (that are not power laws)!

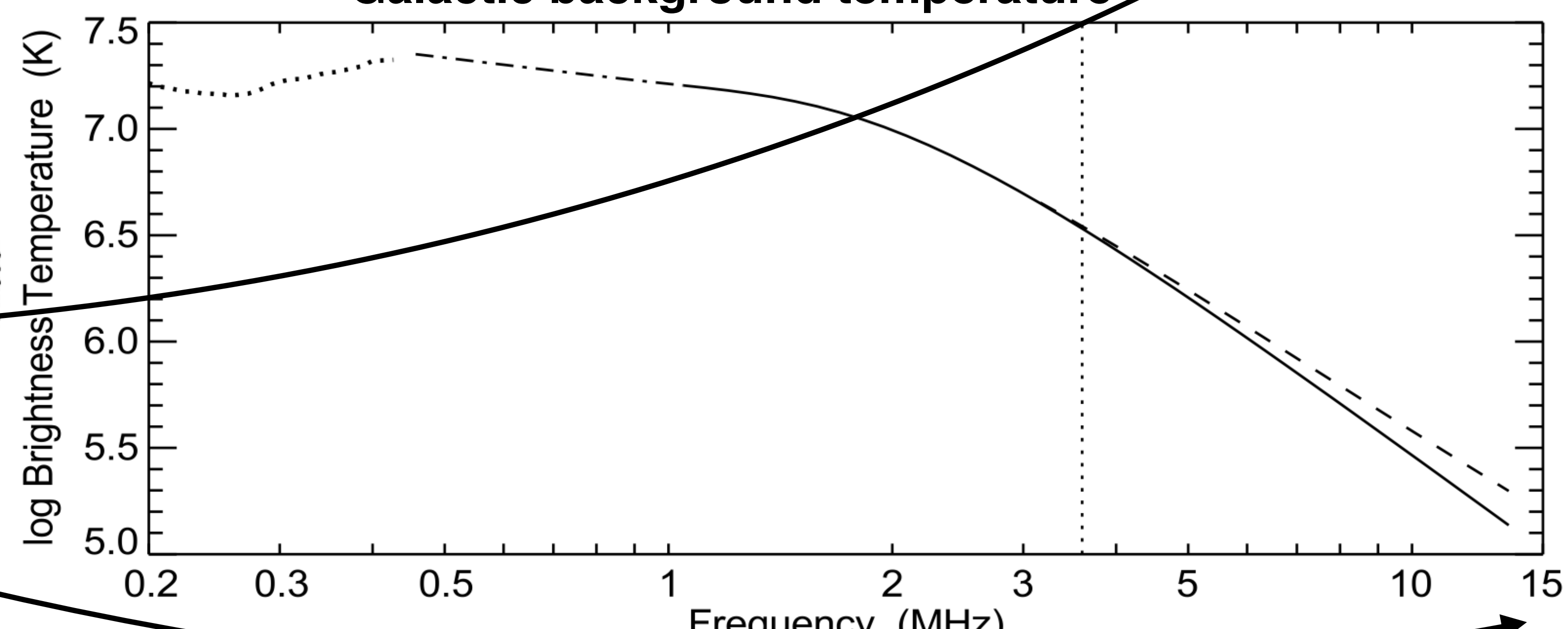
Cosmic Dawn predicted signals



Burns et al 2011



Galactic background temperature



Manning & Dulk 2001

Interferometric imaging

- **Interferometric on ground**
  - 2D imaging of Sky, with a 2D (plane or spherical portion) set of antenna + a reflecting ground.
  - FFT is working well in 2D.

- **With a swarm of antenna in space**:
  - no ground: we see 4π steradians all the time
  - swarm is 3D
  - efficient imaging inversion is not done yet
  - tessellation VS Full 3D imaging
  - beam-forming is possible (with 3D directivity)

- **Temporal and Spectral Smearing**
  - Orbital antennas: high velocity => more smearing (compared to antennas placed on ground)

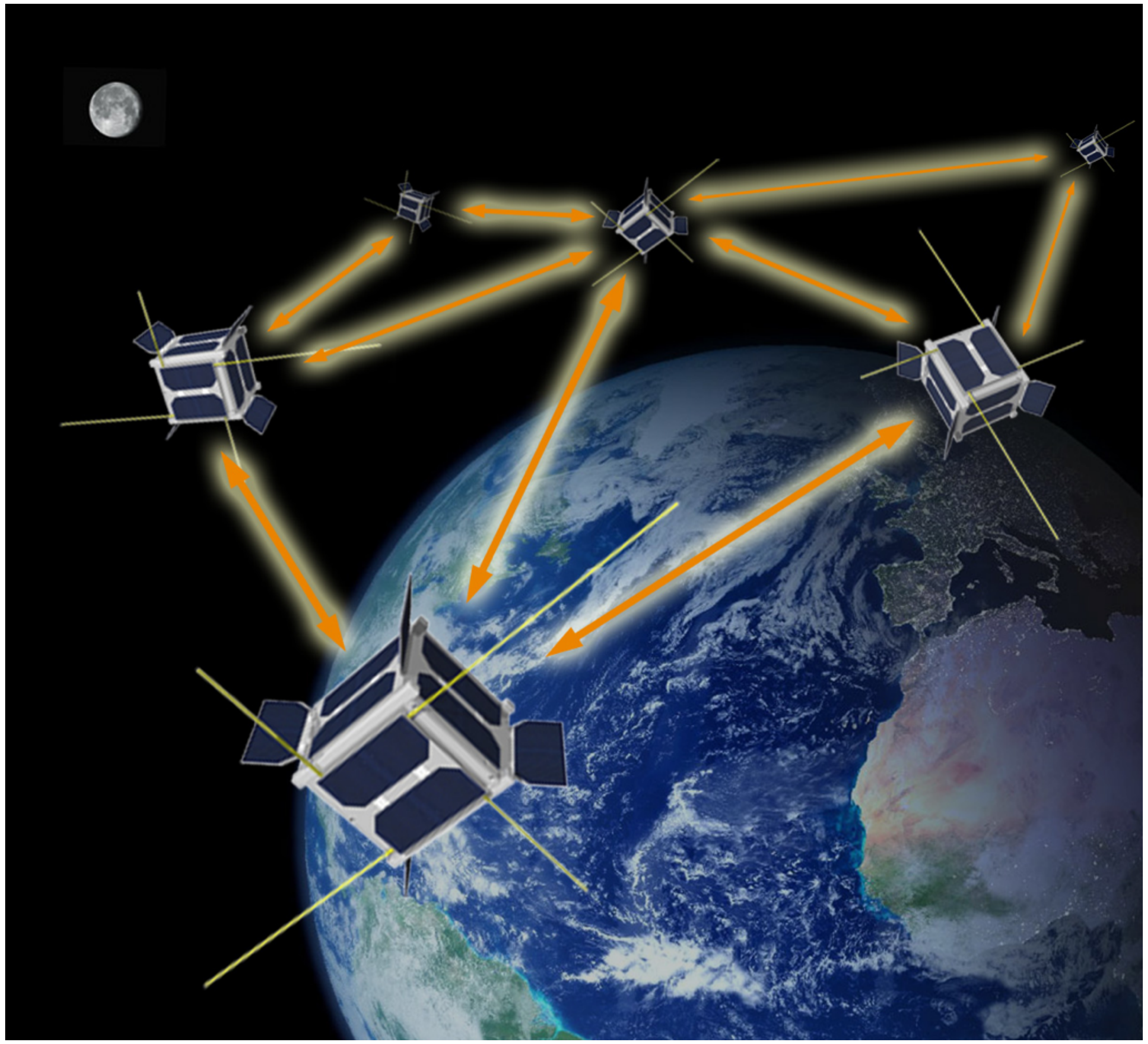
Projects [50 cubesats] OLFAR (NL, et al.)

- Example of developments in the roadmap of Univ. Delft (Delfi)
  - Delfi-C^3 :
    - launched in april 2008, still operating
    - attitude control
    - wireless communication with «solar sensor» module
  - Delfi-n3Xt
    - launched in november 2013
    - solar sensor coupled with attitude control
    - successful tests of micropropulsion (solid state)
  - DelFFI
    - launch planned for 2015
    - formation flying test
- more info: http://www.delfispace.nl

OLFAR

Teams involved: mainly NL.
But also FR, SE + many other interested

- **OLFAR: Orbiting low Frequency Antennas for Radio Astronomy**
- **Science objectives**:
  - «Dark Ages» (cosmology < 10MHz, redshift ~100, EoR)
  - 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)



SULFRO (presented at ESA-CAS meeting)

- SULFRO (*Space Ultra Low Frequency Radio Observatory*)
  - 12+ nanosats
  - coupled with a larger mothership spacecraft
  - low frequency interferometry
  - Frequency Range = ~1kHz - 100MHz
  - Science = «Dark Ages» (but could do many thing else)
  - Candidate for S2 ESA/China mission

DSL (submitted for ESA-CAS S2)

- DSL (*Discovering the Sky at the Longest wavelengths)*
  - 8 nanosats (~27 U)
  - coupled with a larger mothership spacecraft
  - low frequency interferometry
  - Frequency Range = ~30kHz - 30MHz
  - Science = «Dark Ages»
  - Submitted for S2 ESA/China S2