Observation of low-frequency planetary radio emissions with an orbiting interferometer

Erwan Rouillé, Baptiste Cecconi, Boris Segret, Julien Girard, Alan Loh

Planetary, solar and heliospheric Radio Emissions X, 11 June 2025

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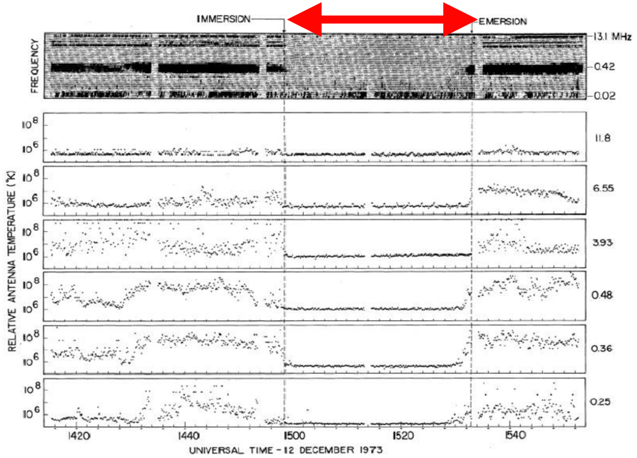
How to observe planetary radio emissions ?

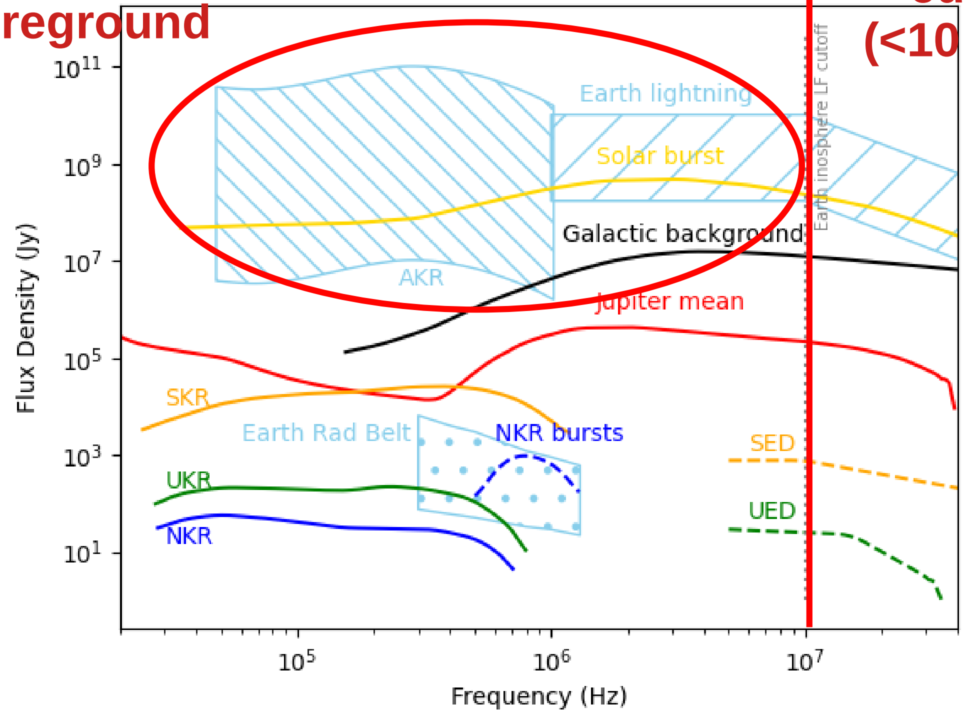
Observation constraints

Behind the Moon



Bright foreground

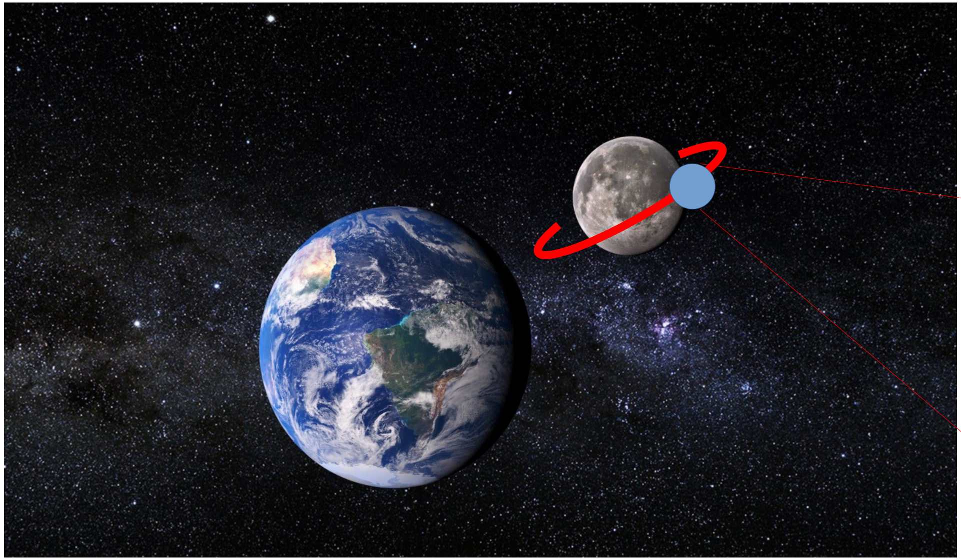
Ionospheric cutoff (<10 MHz)



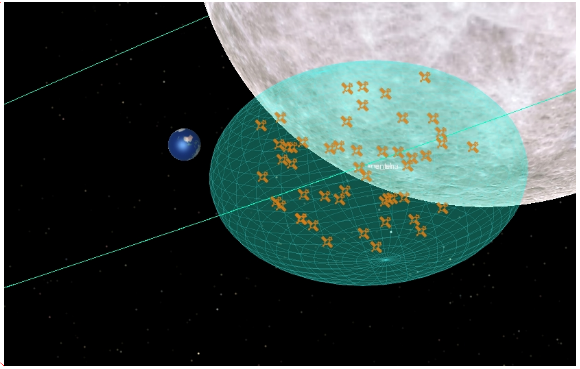
Derived from Zarka *et al* 2012

I] NOIRE concept study

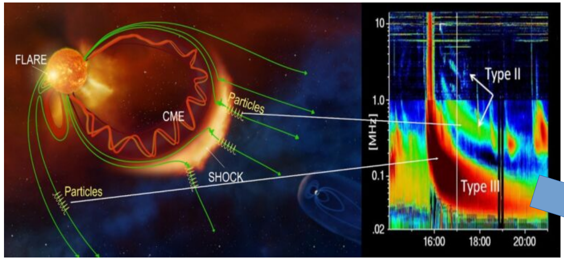
- NOIRE project



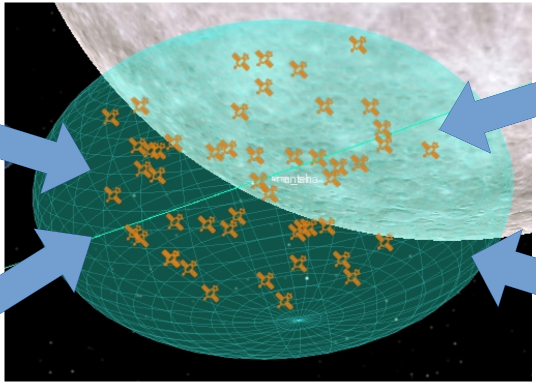
- Observatory
- Low frequency interferometer
- 30kHz – 100MHz
- > 50 Satellites
- scale: 100 km
- Lunar orbit



Science objectives

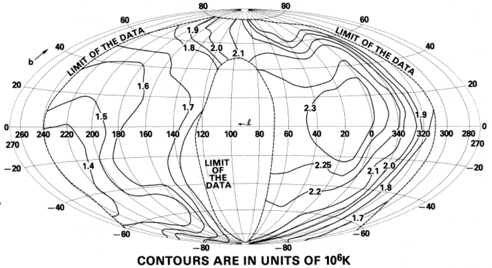


Solar burst propagation



And many more...

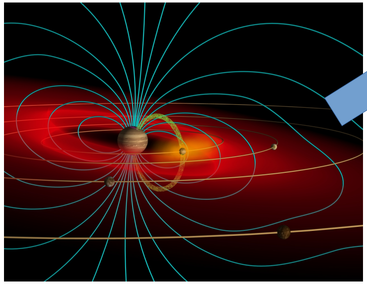
Skymap (<10MHz)

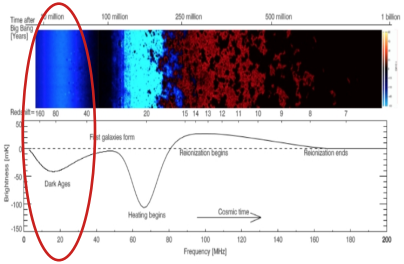


CONTOURS ARE IN UNITS OF 10^6K

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

Planetary emissions





Cosmology : Dark Ages

REFFFFFFFF

II] Observation of planetary radio emissions

With an interferometer or phased array

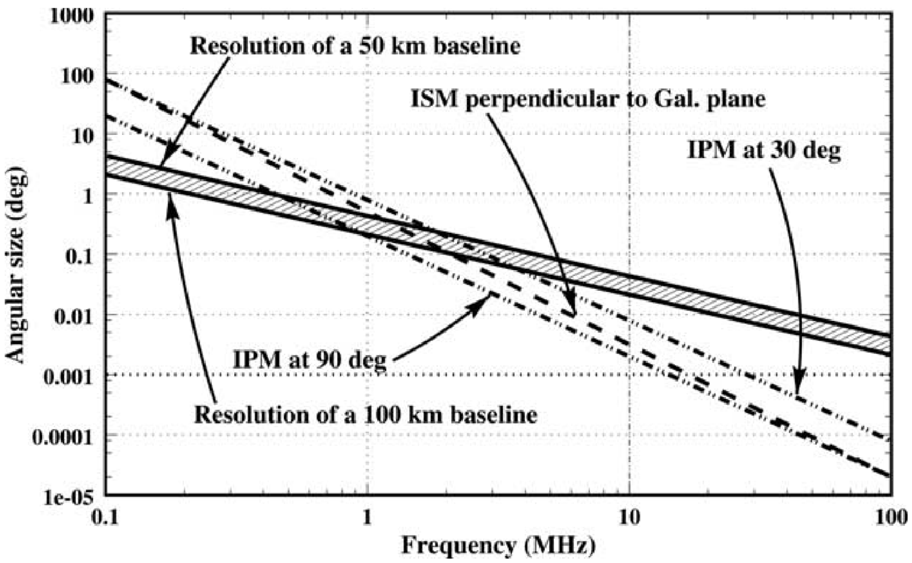
- Directional observation
  → can be performed from far away
- Digital pointing
  → Study multiple target at same time

→ Track solar burst from corona to outter planets and the auroral emissions it induces

II] Observation of planetary radio emissions

With a 100km wide interferometer, Planetary radio emissions cannot be spatially resolved

This distance was chosen for the observation of extrasolar sources

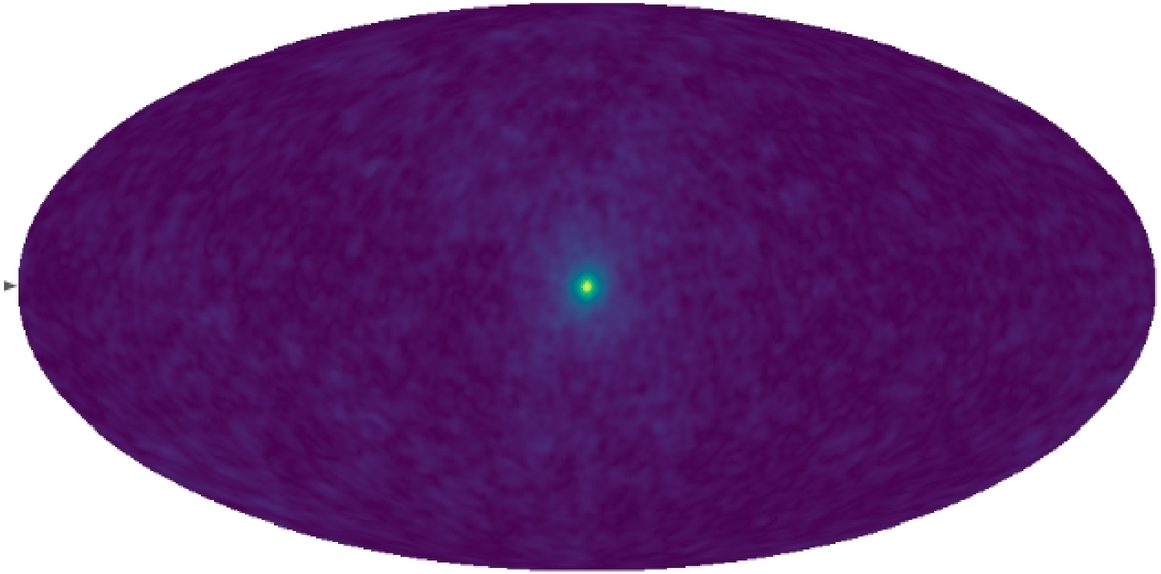


Observation can only be performed when the Earth is occulted with an altitude of 1200km we have :

- Orbital period 4h
- Occultation duration : 40min

III] Noises and bias

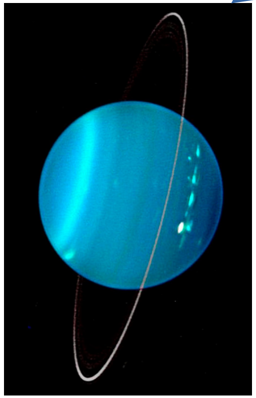
Beamform observation
= Integrate flux in synthesized beam (the PSF)

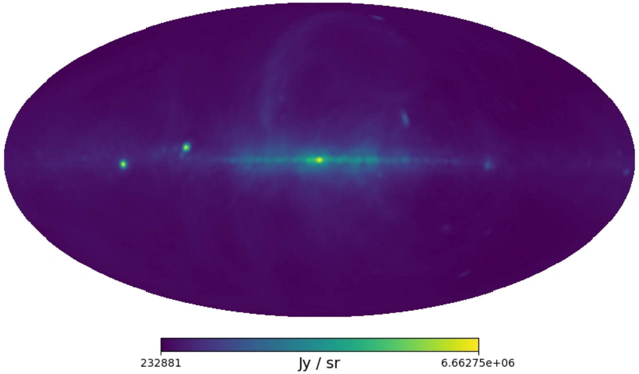


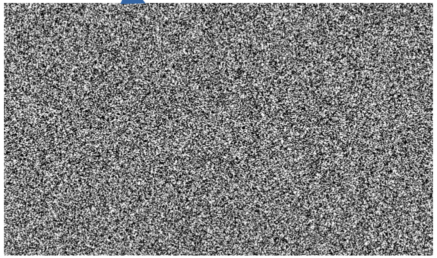
Exemple with NOIRE at 0.5MHz
(linear scale)

III] Noises and bias

$$S_{\mathrm{meas}} = S_{\mathrm{target}} + S_{\mathrm{bg}} + \mathcal{E}_{\mathrm{noise}}$$







III] Noises and bias

$$S_{\text{meas}} = S_{\text{target}} + S_{\text{bg}} + \mathcal{E}_{\text{noise}}$$

$$\widetilde{S}_{\text{target}} = S_{\text{meas}} - \widetilde{S}_{\text{bg}}$$

$$= S_{\text{target}} + \Delta S_{\text{bg}} + \mathcal{E}_{\text{noise}}$$

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$$\mathcal{E}_{\text{noise}} = \frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}}$$

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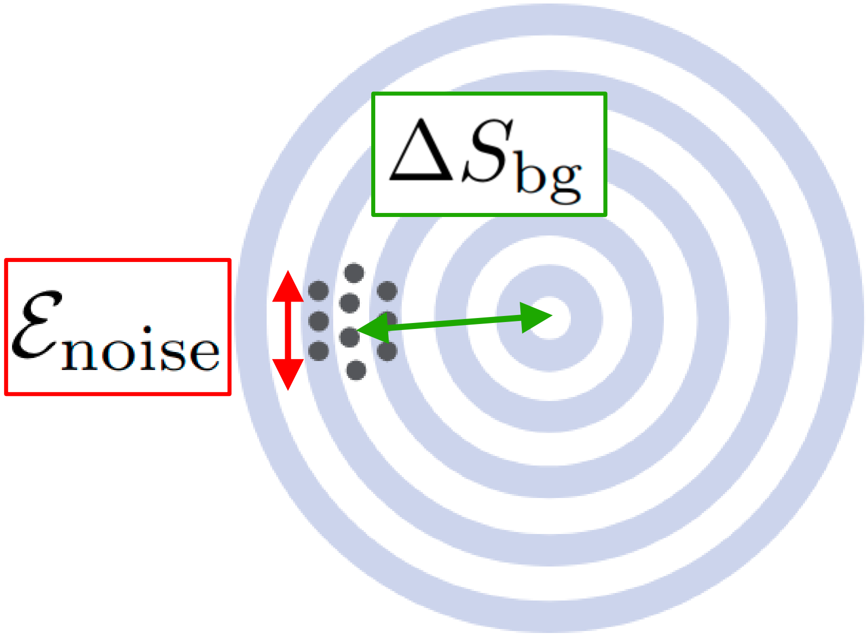
$$\text{SNR} = \frac{S_{\text{target}}}{\frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}} + \Delta S_{\text{bg}}}$$

III] Noises and bias



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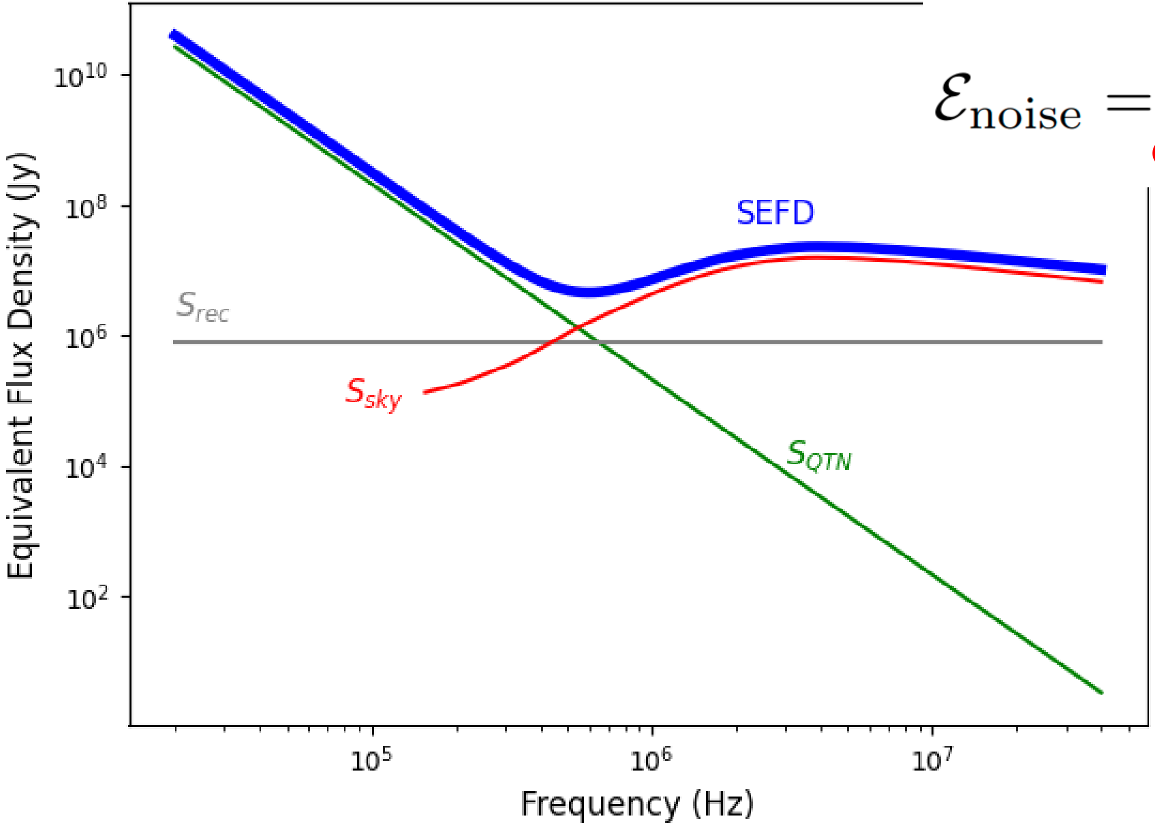
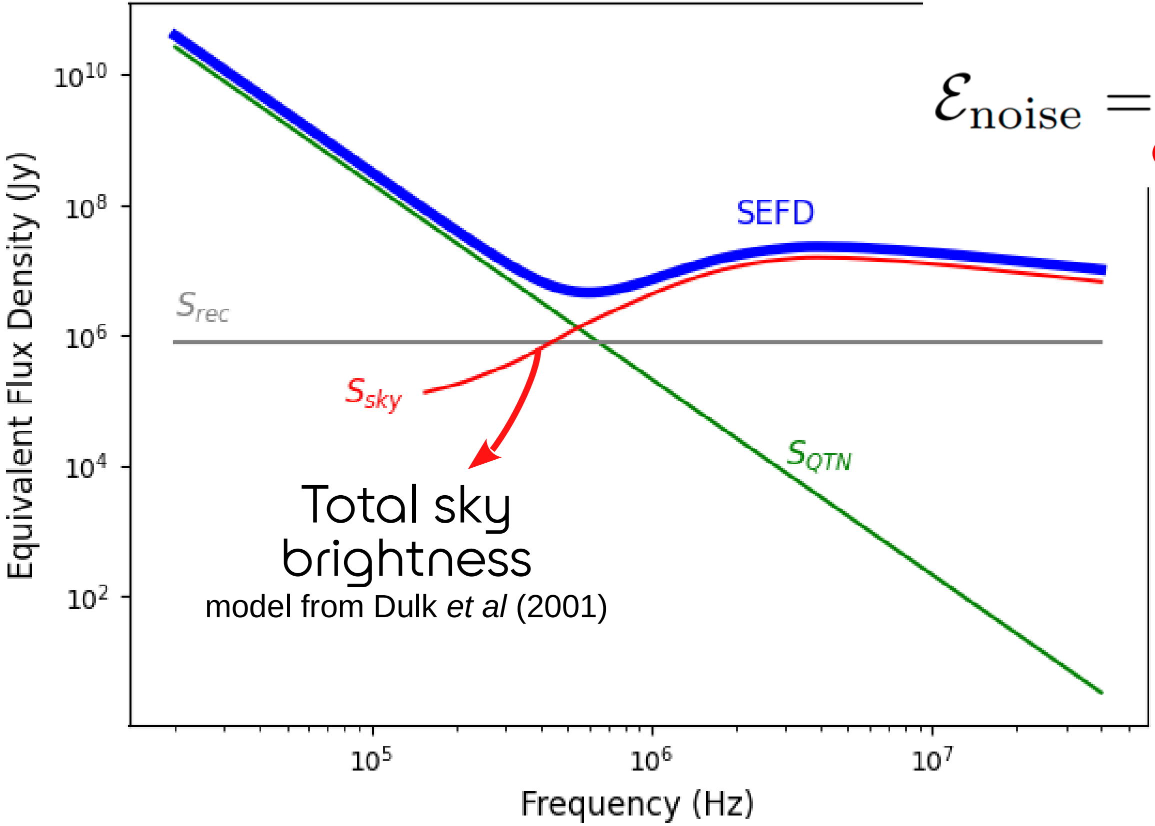
III] Noises and bias – Noises



$$\mathcal{E}_{\text{noise}} = \frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}}$$

= C

III] Noises and bias – Noises



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$$\mathcal{E}_{\text{noise}} = \frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}}$$

= C

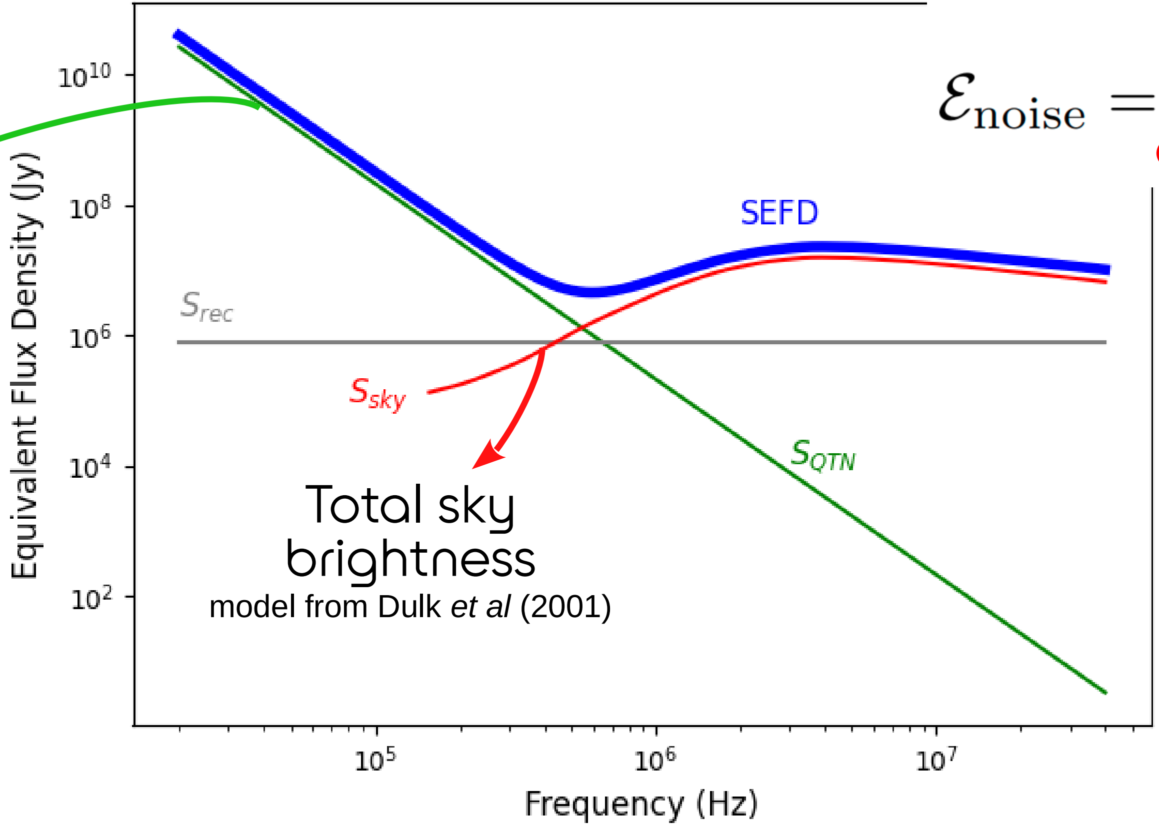
Quasi-thermal Noise (QTN)

$$S_{\text{QTN}} = \frac{2}{Z_0 L^2} V_{\text{QTN}}^2$$

$$\propto \nu^{-3} L^{-3}$$

Caused by the local plasma

=> only in space



Total sky brightness

model from Dulk *et al* (2001)

III] Noises and bias – Noises

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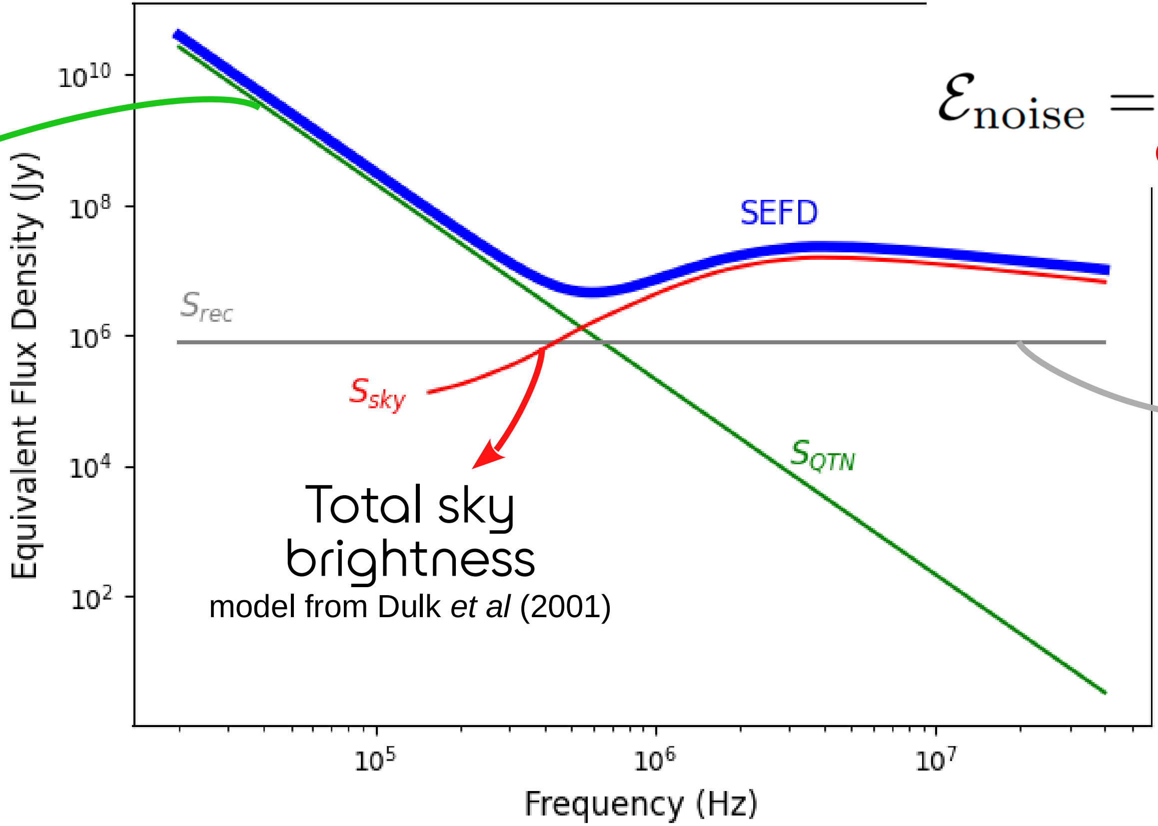

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= C

Receiver Noise

$$S_{\rm rec} = \frac{2}{Z_0 L^2 \Gamma^2} V_{\rm rec}^2$$

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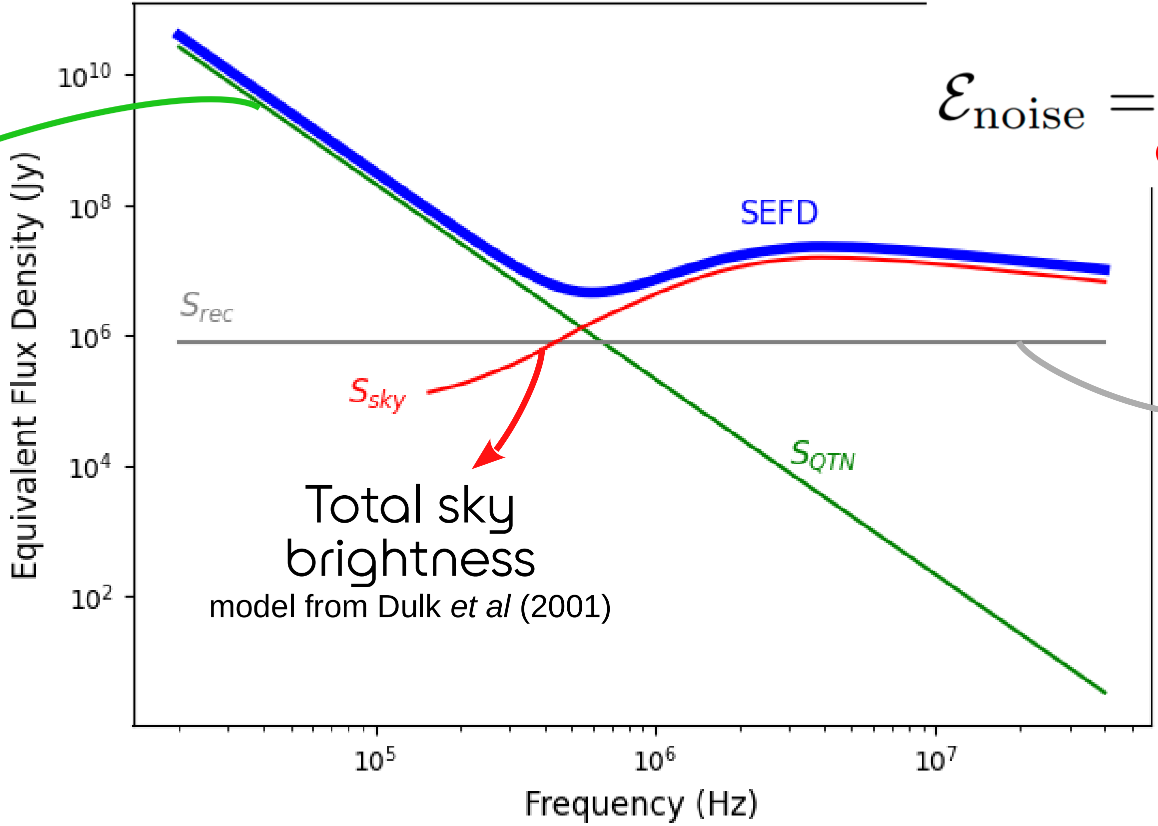

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= C

Receiver Noise

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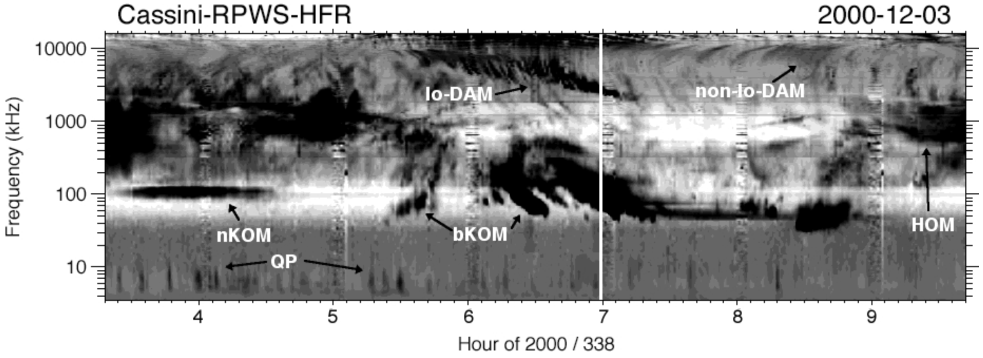
We take :

- **L = 5m**
- Γ = 1/3
- V_{rec} = 2 nV/√Hz

III] Noises and bias – Bias

How to estimate the background contribution ? $\widetilde{S}_{\mathrm{bg}}$

With good temporal resolution :
→ Selection of bins with background only



[1] Zarka *et al* 2004, [2] science.nrao.edu

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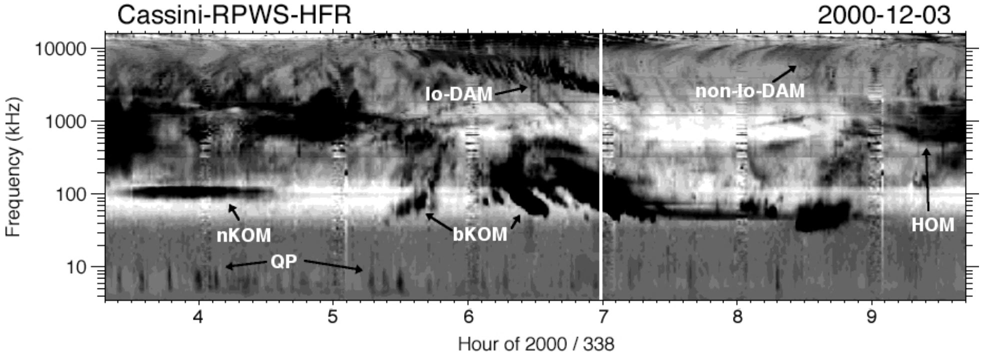
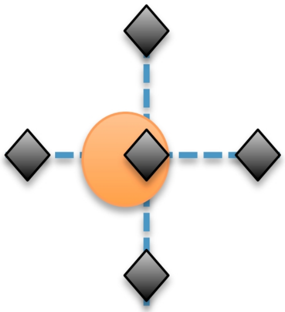


With good spatial resolution :
→ background in off-pointings



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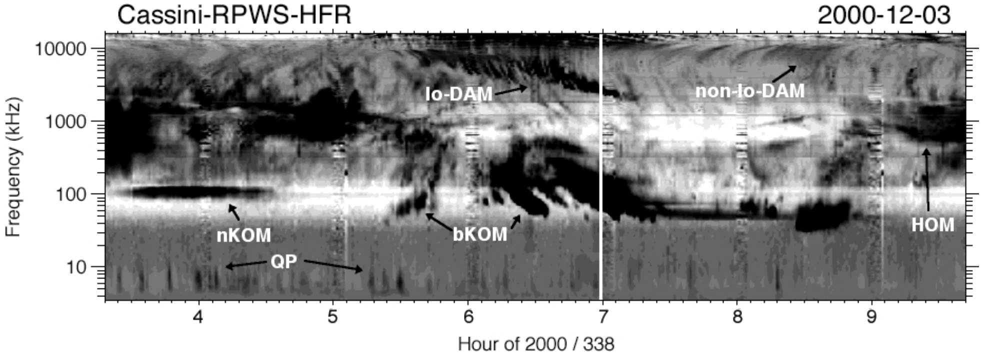

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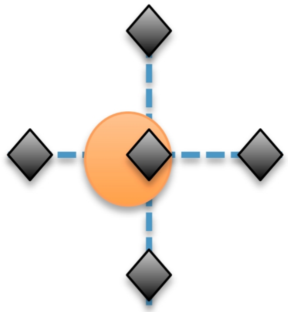
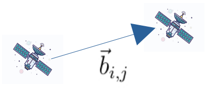


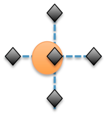
What if we have
- low spatial resolution
- low temporal resolution

[1] Zarka *et al* 2004, [2] science.nrao.edu

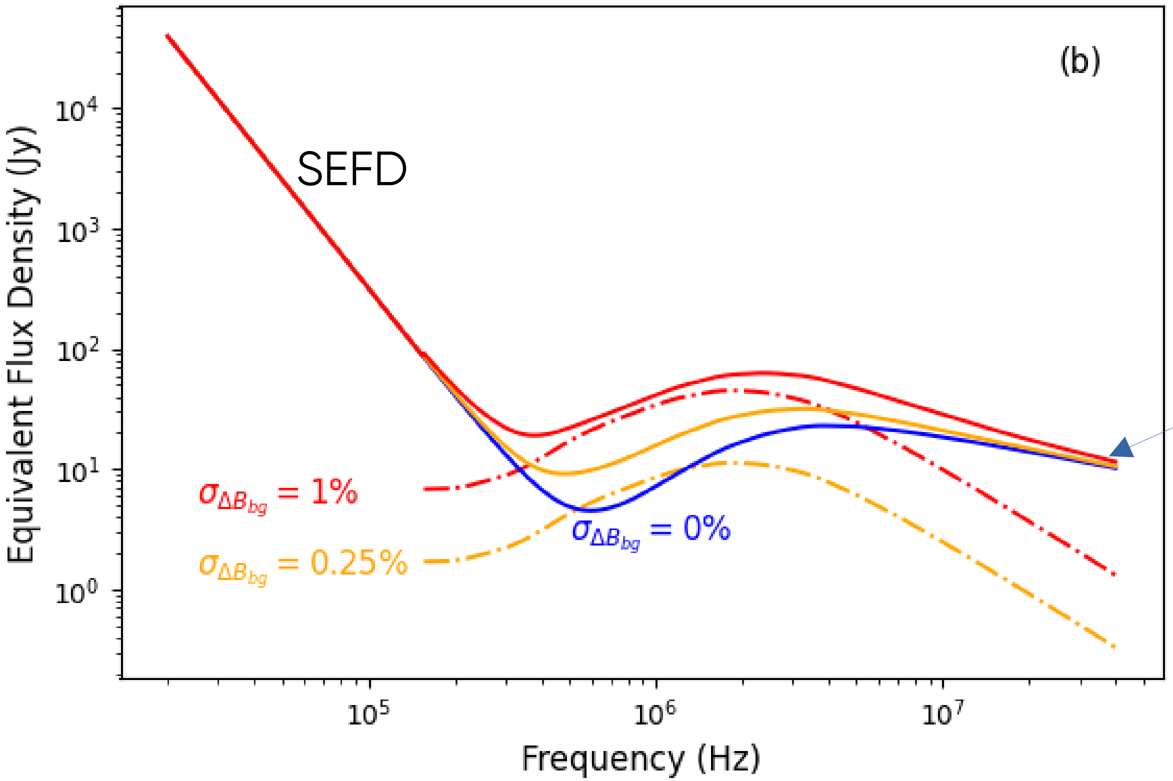
III] Noises and bias – Bias

Using a skymodel
We have systematic errors coming from

- Errors on the sky model
  - $\propto S_{sky}$ and PSF width
- Errors on the instruments parameters
  - Clock errors 
  - Baseline errors 

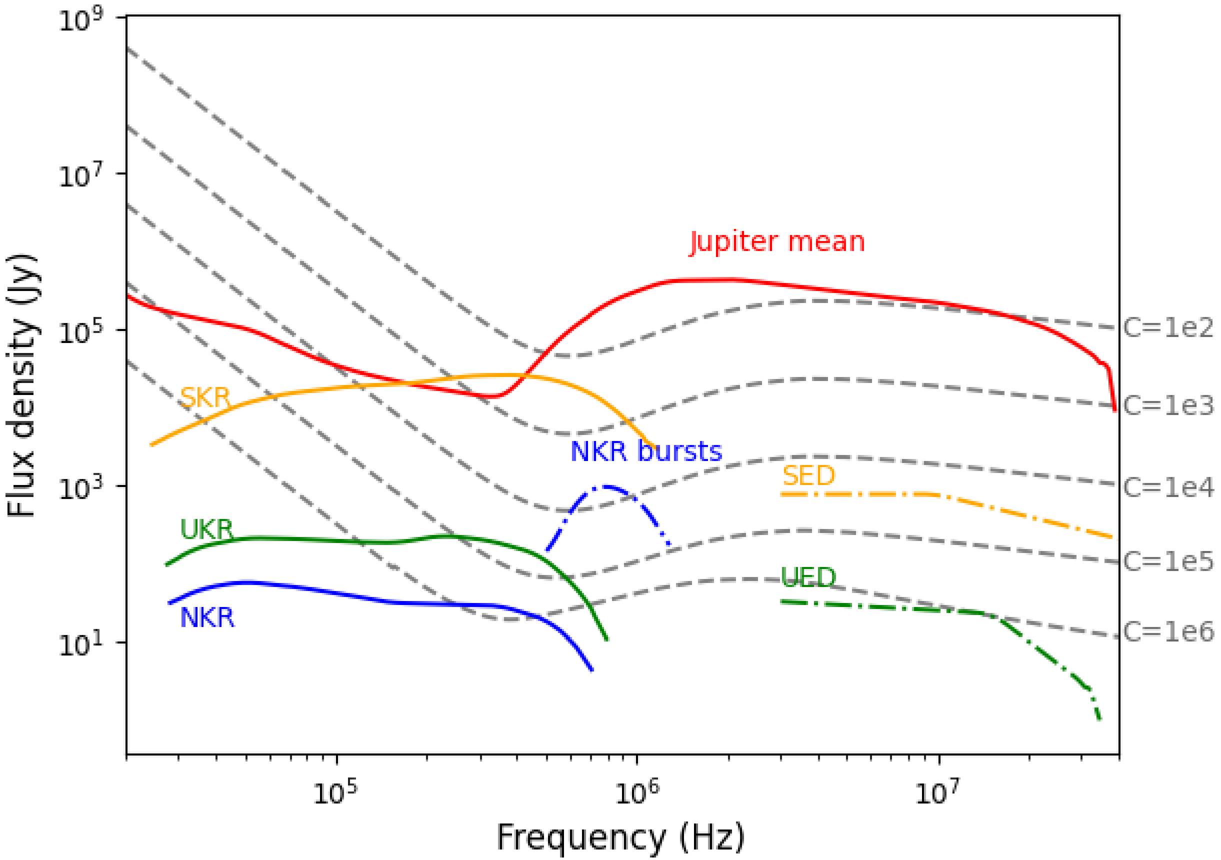
  - Pointing errors 

III] Noises and bias - Total



With C = 10^6

IV] Results – Sensitivity

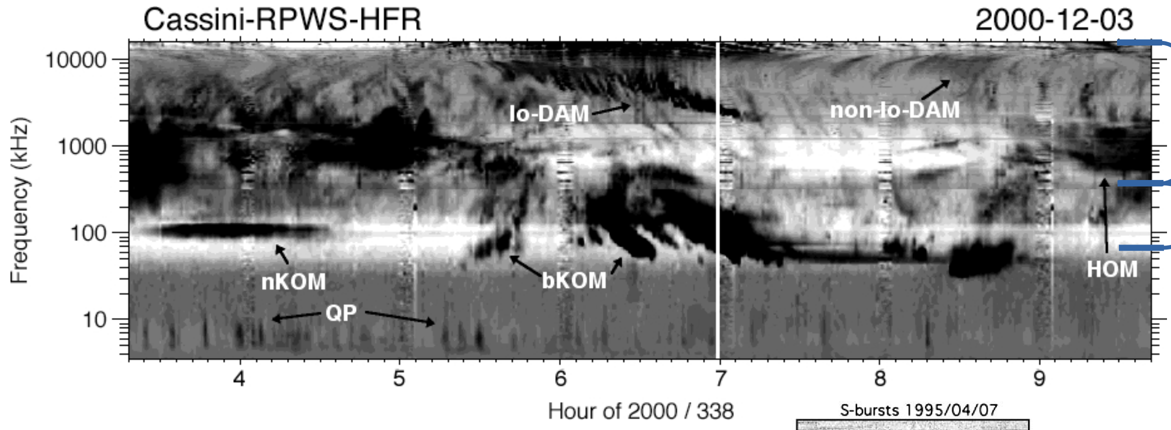


$\Delta\upsilon$ = 200kHz
τ = 40 min

IV] Results – Phenomenology

Radio Emission	C	τ	$\Delta\nu$ (kHz)	$\nu_{\min}$	$\nu_{\max}$	$\sigma_{\Delta B_{bg}}$	SNR
Jupiter (HOM, DAM)	10^3	100ms	5	300	$30\,.10^3$	1%	5
Jupiter (S-burst)	$1.5\,.10^2$	1ms	10	$0.6\,.10^3$	$26\,.10^3$	1%	3
Jupiter (nKOM, bKOM)	5.10^4	2min	10	70	300	1%	> 3
Saturn mean	10^4	10s	5	200	1000	1%	5
	10^5	80s	50	100	200	1%	5
Saturn SED	10^6	300ms	$15\,.10^3$	$5\,.10^3$	$20\,.10^3$	0	3
UKR b-smooth	$5\,.10^5$	40min	50	250	450	1%	5
	$2\,.10^5$	5min	50	300	550	0.25%	3
UKR n-smooth	10^7	-	-	-	-	-	3
UED	$5\,.10^6$	-	-	-	-	0	-
NKR	10^6	40min	200	300	500	0.25%	2
NKR bursts	$3.5\,10^4$	-	-	-	-	0	-

IV] Jupiter

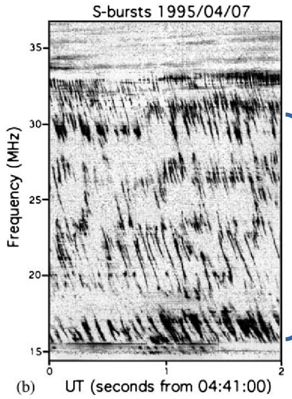


Δυ = 5 kHz
τ = 0.1 s

DAM, HOM

Δυ = 10 kHz
τ = 2 min

bKOM, nKOM

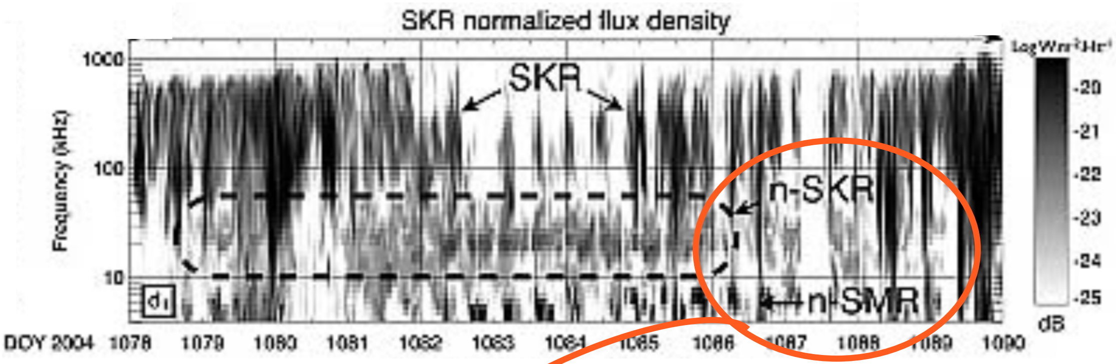


Δυ = 10 kHz
τ = 1 ms

S-burst

[1] Zarka *et al* 2004 (a), (b)

IV] Saturn

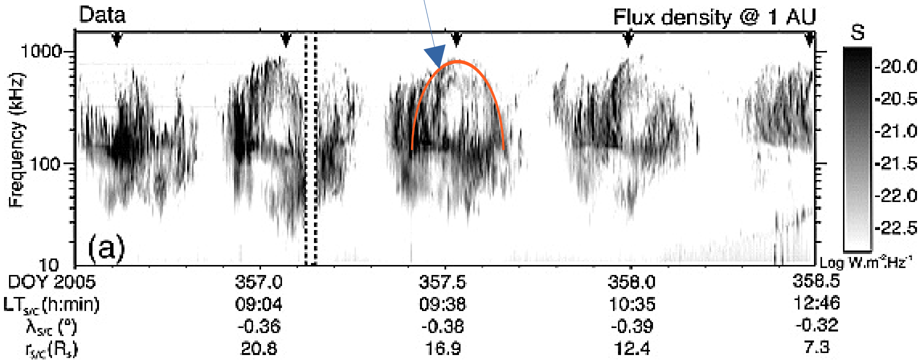


$\Delta\upsilon$ = 5 kHz
τ = 10 s

SKR

$\Delta\upsilon$ = 5 kHz
τ = 0.1 s

Arc structures identifiable



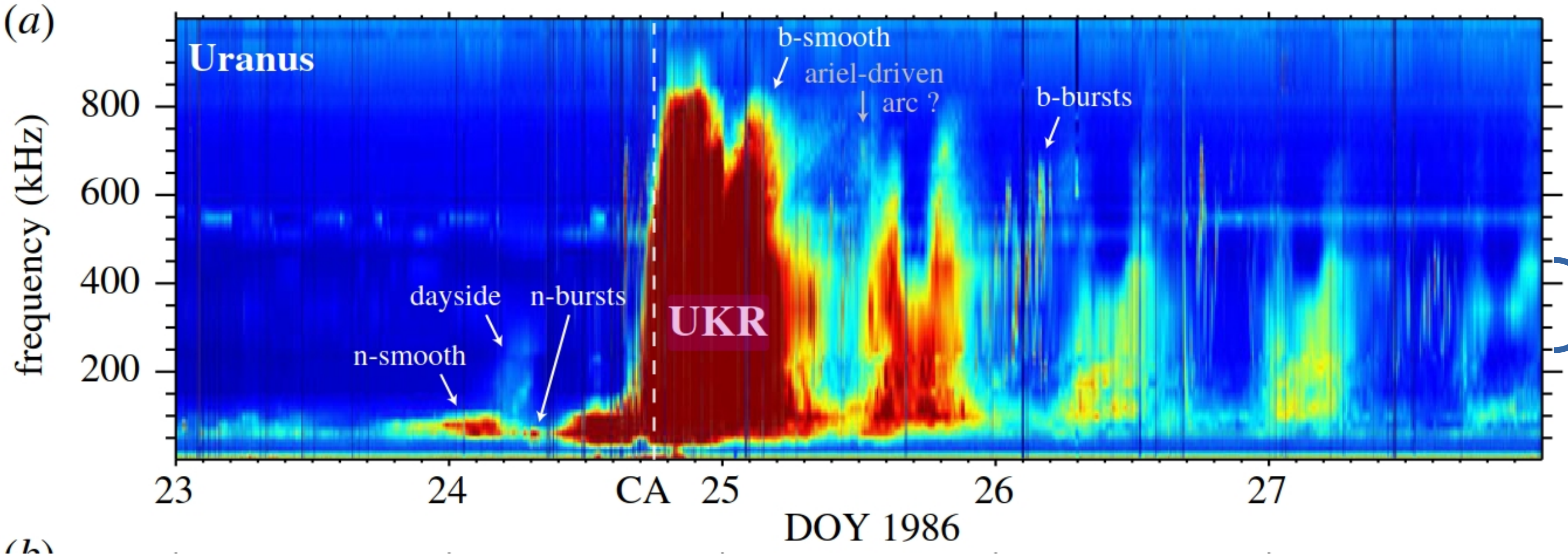
Not observable :
→ Plasma frequency cutoff
→ QTN

SED : maybe with dedicated mode but with τ = 300ms

[1] Lamy *et al* 2008 (a), (b)

IV] Uranus

Only observation we have is from Voyager 2 back in 1986



Δυ = 50 kHz
τ = 40 min

Once every 4h

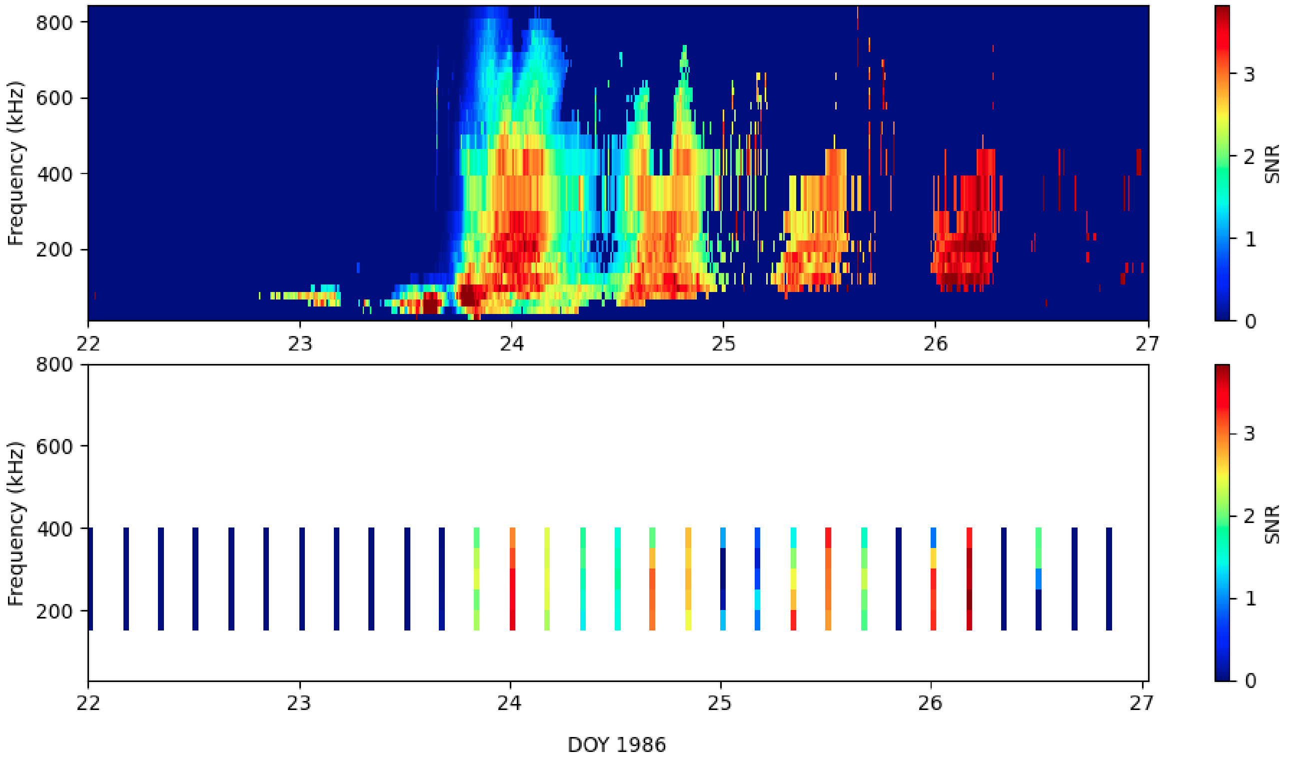
[1] Lamy *et al* 2020

IV] Uranus

Simulated acquisition based on Voyager 2 data scaled as seen from the Moon

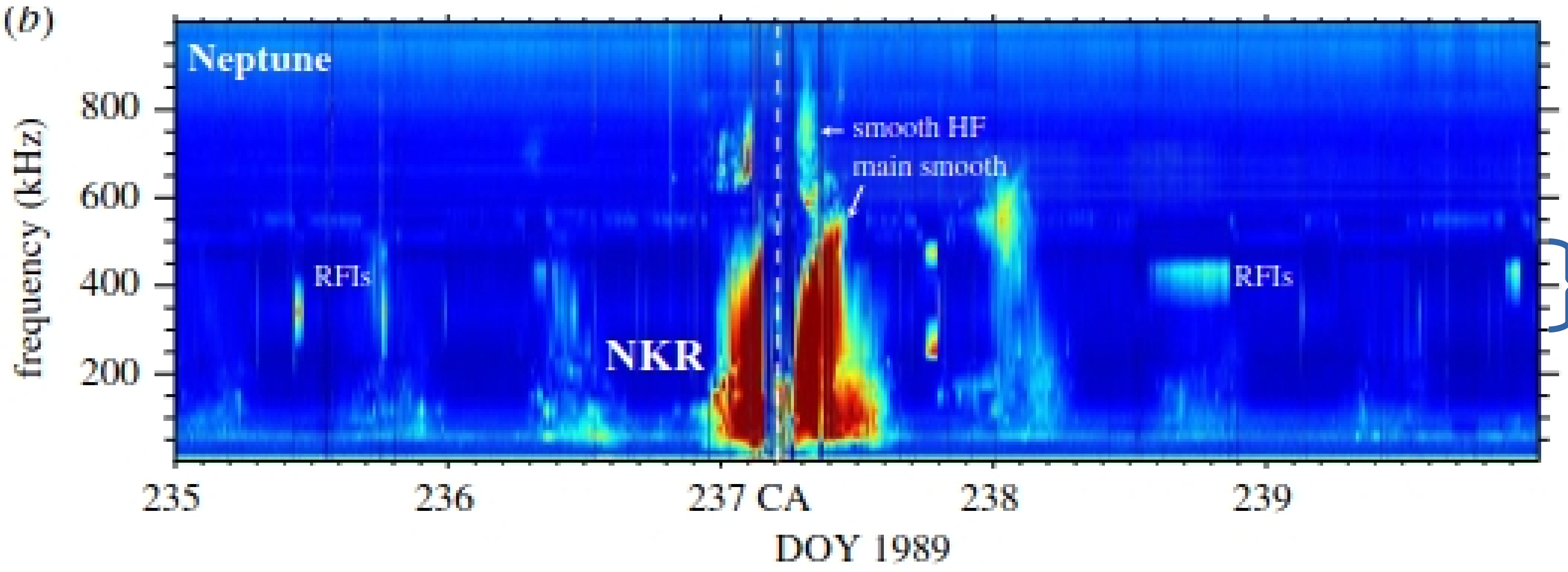
ok for long term study

/!\ dayside / nightside how different ? When ?



IV] Neptune

Simulated acquisition



Δυ = 200 kHz
τ = 40 min

SNR ~ 2
with good skymodel

Once every 4h

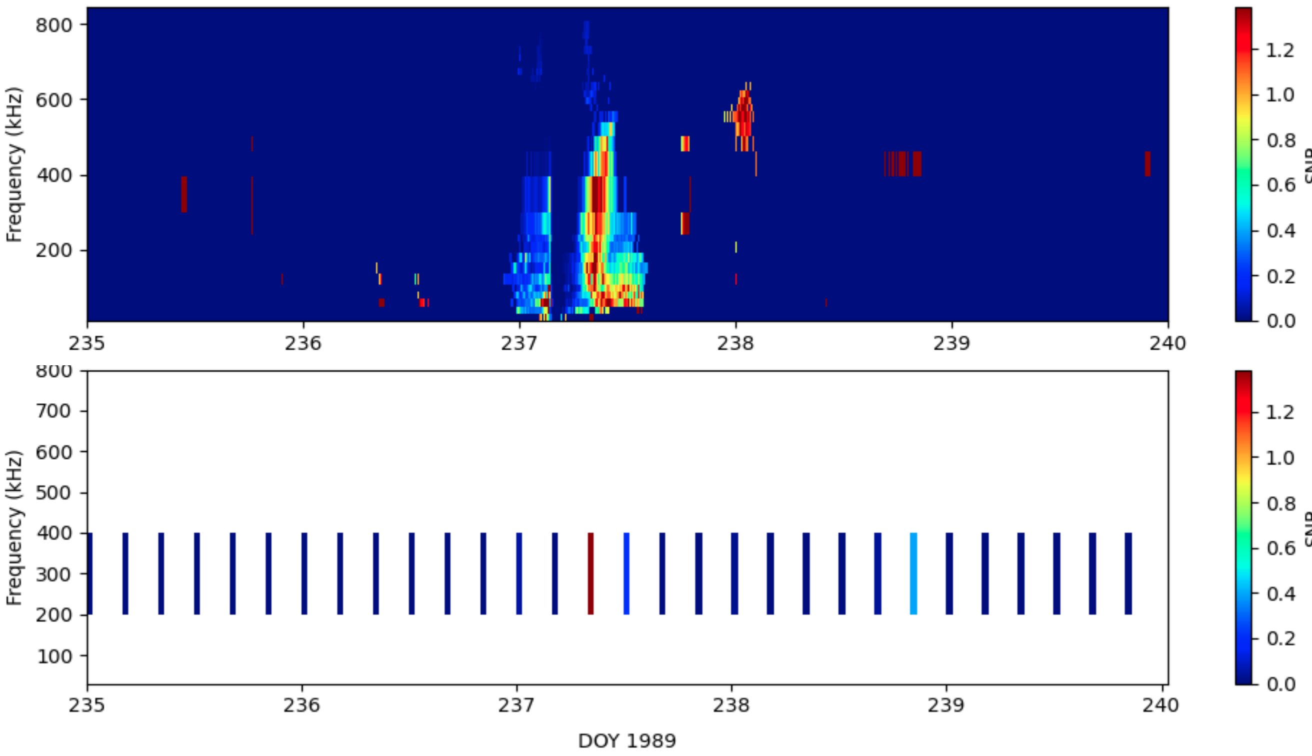
[1] Lamy *et al* 2020

IV] Neptune

Simulated acquisition based on Voyager 2 data scaled as seen from the Moon

Barely detectable

Enough to study the rotation period ?
(certainly with polarized observations



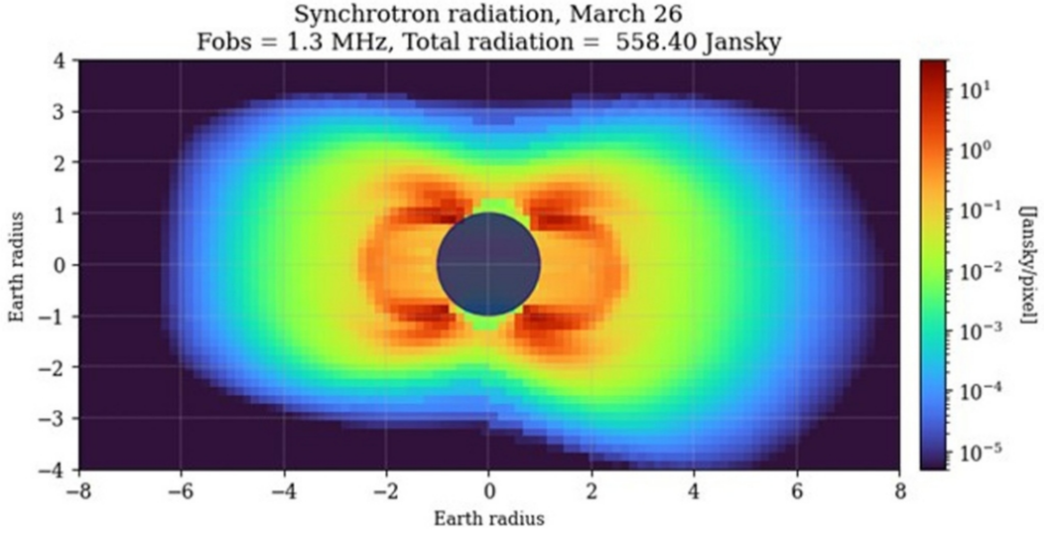
IV] What about Earth ?

NOIRE could map the Earth's radiation belts

The noise expression is very different :

- Spatial resolution required
- Earth auroral emissions
- RFI

→ Requires a dedicated study



Discussion

- Space-borne interferometers will offer new possibilities for the observation of planetary radio emissions and much more
- Systematic errors are the limiting factors for sensitive observations (Uranus, Neptune)
  → We need a good **sky model** (<10MHz)
- Only **Stokes I** was considered in this study
  - Background sky mostly unpolarized
    (Faraday rotation + Diffusion)
  - Better SNR with circular polar
  - But polarized Skymodel (1-10MHz) mostly unknown
    + QTN still limits at the lowest frequencies
    → should we use longer antennas

Thank you for your attention

Questions ?

Backup Slides

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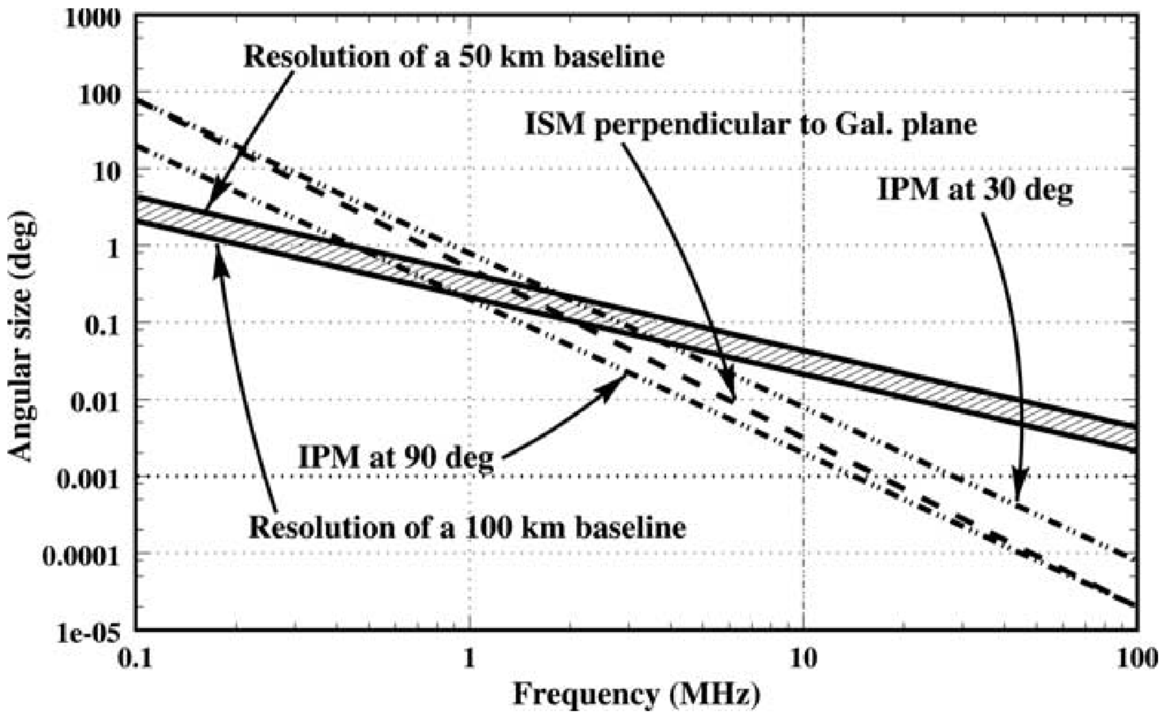
Université Paris Cité

PSL UNIVERSITÉ PARIS

Longer baselines ?

- Diffusion limit for sources outside the SolSys



III] Noises and bias

Interferometry

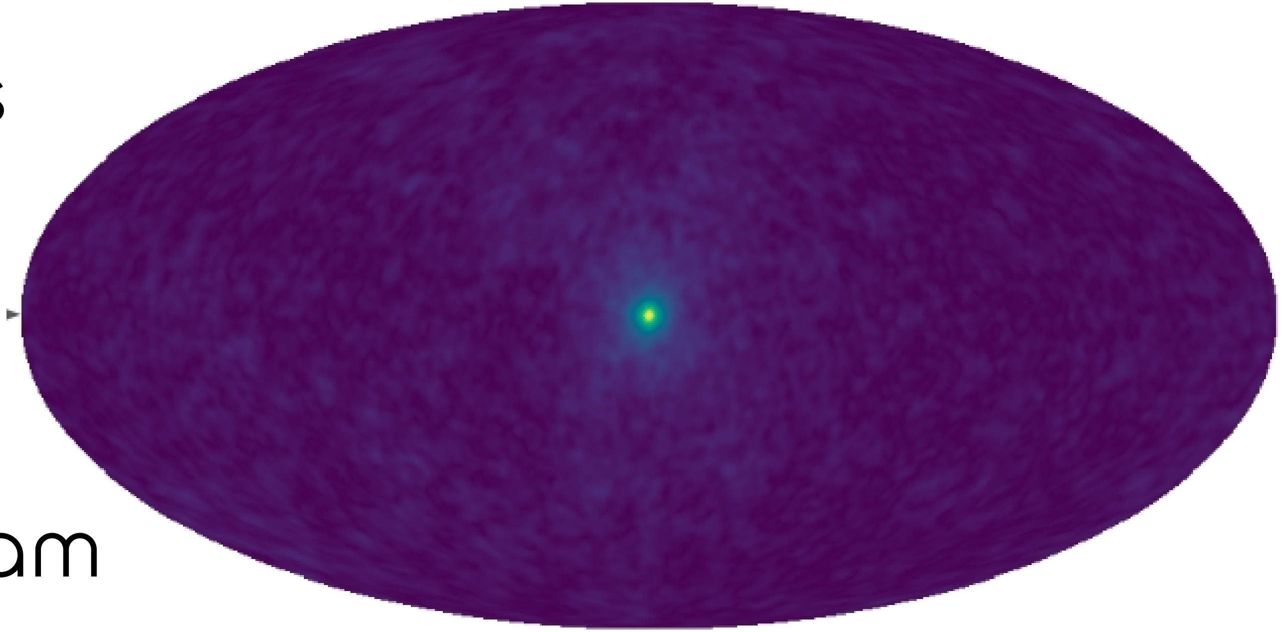
→ Set of visibilities

→ Phased sum

= Beamform

= Integrate flux
in synthesized beam

Synthetized beam = PSF



Exemple with NOIRE at 0.5MHz
(linear scale)

III] Noises and bias – Noises

$$\mathcal{E}_{\text{noise}} = \frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}}$$

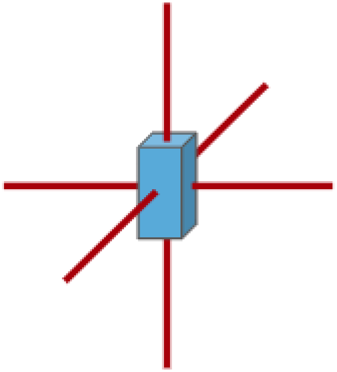
= C

III] Noises and bias – Noises

$$\mathcal{E}_{\text{noise}} = \frac{\text{SEFD}}{\sqrt{2 n_b \Delta\nu \Delta\tau}}$$

= C

Sum over the
3 dipoles



$$\text{SEFD}^2 = \frac{1}{4}\left(2S_{\text{sky}}^2 + 3N^2 + 4NS_{\text{sky}}\right)$$

Total Sky brightness

System Noise

III] Noises and bias – Noises

Receiver noise

$$S_{\mathrm{rec}} = \frac{2}{Z_0 L^2 \Gamma^2} V_{\mathrm{rec}}^2$$

Antenna length

Impedance coupling

$\Gamma = C_s/(C_a+C_s)$

We take :

- $L = 5$m
- $\Gamma = 1/3$
- $V_{rec} = 2$ nV/√Hz

Derived from Zaslavsky *et al* (2011)

III] Noises and bias – Noises

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Antenna length

Impedance coupling

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Quasi-thermal Noise

$$S_{\text{QTN}} = \frac{2}{Z_0 L^2} V_{\text{QTN}}^2$$

$$\propto \nu^{-3} L^{-3}$$

Caused by the local plasma

=> only in space

We take :

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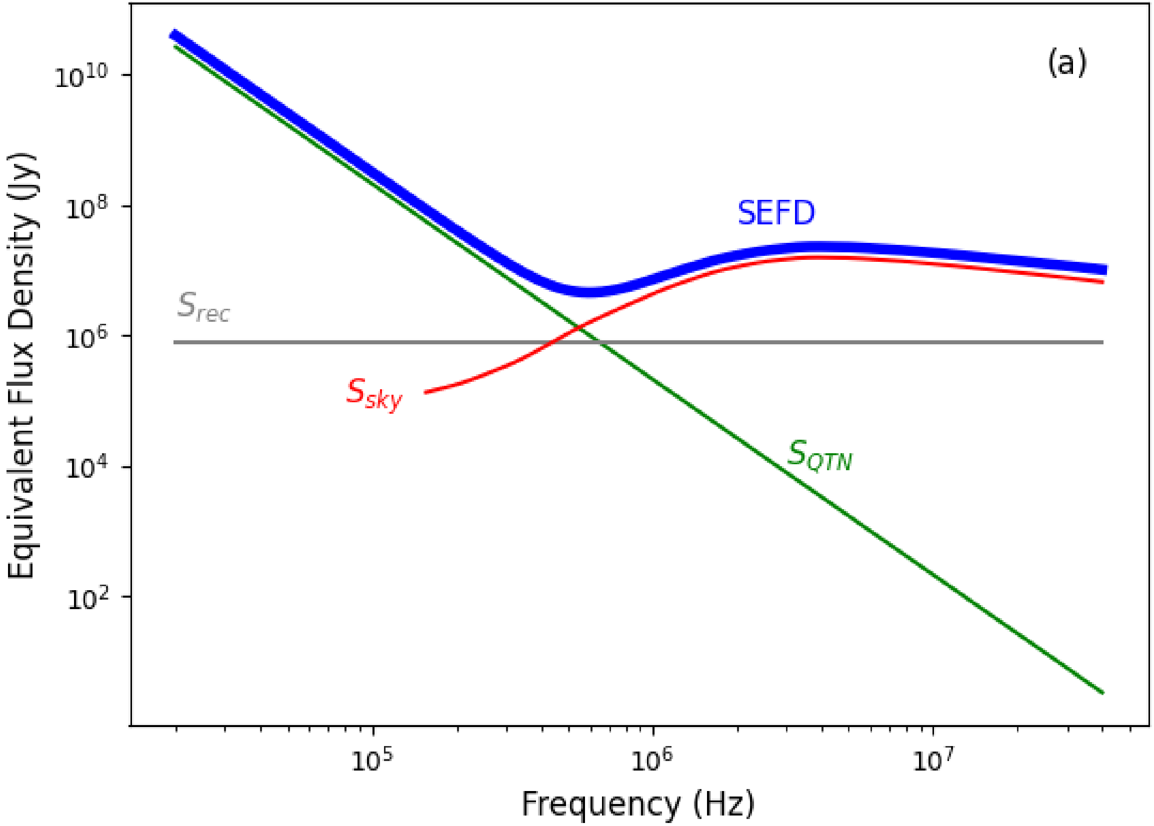


S_{sky} derived from Dulk *et al* (2001)

Using a skymodel

We need to estimate the PSF using the measured baselines

$$\Delta S = S_{\rm bg} - \widetilde{S}_{\rm bg}$$
$$= \oiint I(\vec{s})\mathrm{PSF}(\vec{s})d\Omega_s - \oiint \widetilde{I}(\vec{s})\widetilde{\mathrm{PSF}}(\vec{s})d\Omega_s$$

III] Noises and bias – Bias

Using a skymodel

We need to estimate the PSF using the measured baselines

$$\Delta S = S_{\mathrm{bg}} - \widetilde{S}_{\mathrm{bg}}$$

$$= \iint I(\vec{s})\mathrm{PSF}(\vec{s})d\Omega_s - \iint \widetilde{I}(\vec{s})\widetilde{\mathrm{PSF}}(\vec{s})d\Omega_s$$

$$\simeq \iint \Delta I(\vec{s})\mathrm{PSF}(\vec{s})d\Omega_s + \iint I(\vec{s})\Delta\mathrm{PSF}(\vec{s})d\Omega_s$$

Errors of the Sky Model

Errors of the Instrument Parameters

III] Noises and bias – Bias

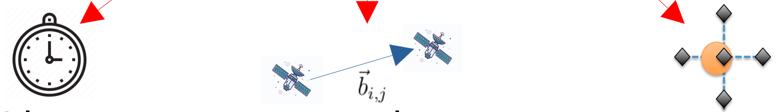
Using a skymodel

We need to estimate the PSF using the measured baselines

$$\Delta S \simeq \oiint \Delta I(\vec{s})\mathrm{PSF}(\vec{s})d\Omega_s + \oiint I(\vec{s})\Delta\mathrm{PSF}(\vec{s})d\Omega_s$$

Errors of the Sky Model — Errors of the Instrument Parameters

$$\Delta I / I \quad >> \quad k(c\Delta T + \Delta b + \vec{b}\cdot\vec{\Delta s_0})$$



Clock errors — Baseline errors — Pointing errors

III] Noises and bias – Bias

Using a skymodel

We need to estimate the PSF using the measured baselines

$$\Delta S \simeq \oiint \Delta I(\vec{s})\mathrm{PSF}(\vec{s})d\Omega_s + \oiint I(\vec{s})\Delta\mathrm{PSF}(\vec{s})d\Omega_s$$

Errors of the Sky Model

Errors of the Instrument Parameters

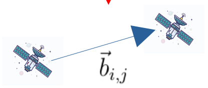
Hyp :
PSF = Gaussian

$$\Delta I / I \quad >> \quad k(c\Delta T + \Delta b + \vec{b}\cdot\vec{\Delta s_0})$$

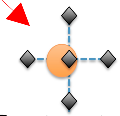
$$\Delta S_m \sim \Omega_\nu S_{\mathrm{sky}} \underbrace{\sigma_{\Delta I}}$$

= 1 % or 0.25 %

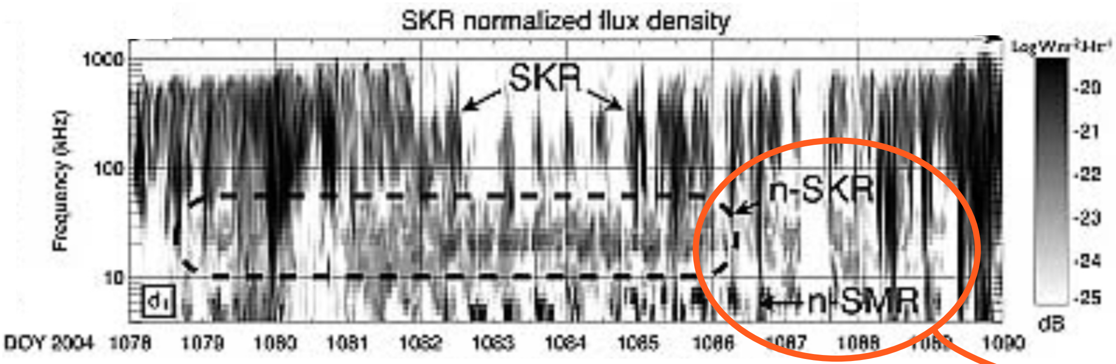

Clock errors

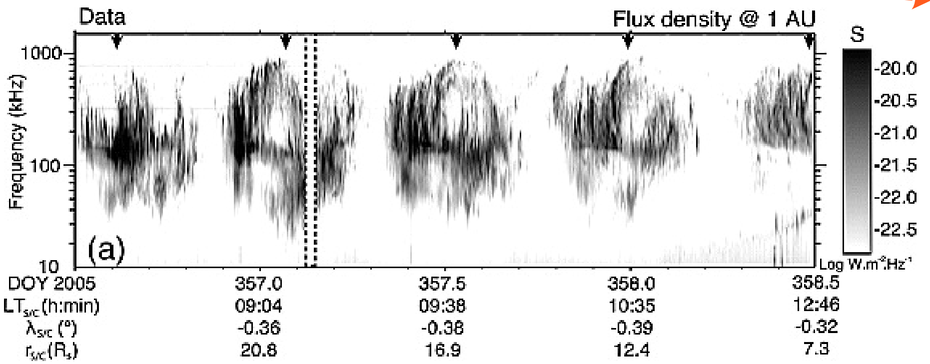


Baseline errors


Pointing errors

IV] Saturn





$\Delta\upsilon$ = 5 kHz
τ = 10 s

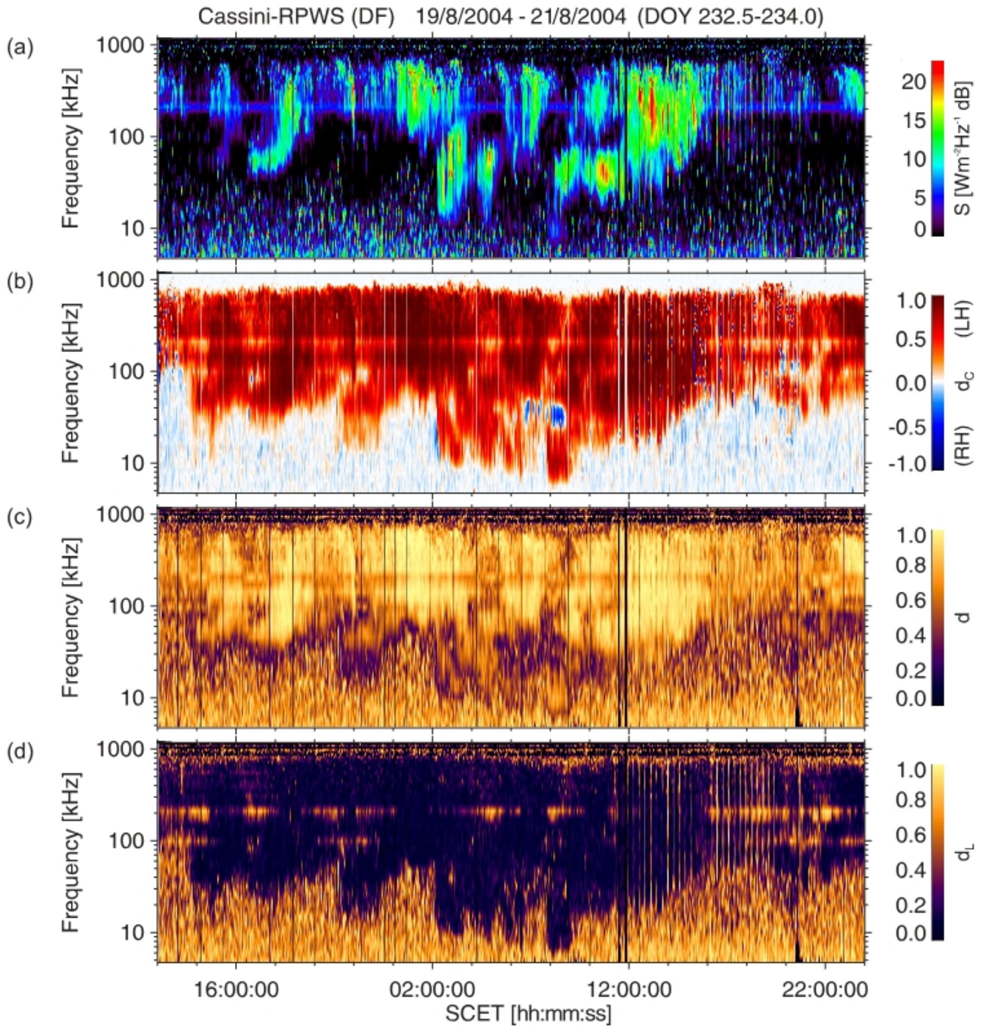
SKR

$\Delta\upsilon$ = 5 kHz
τ = 0.1 s

Lower part ?

Not observable :
→ Plasma frequency cutoff
→ QTN

[1] Lamy *et al* 2008 (a), (b)



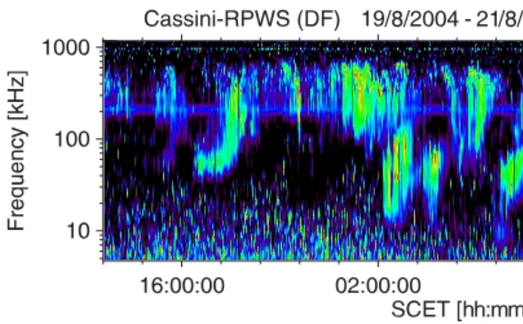
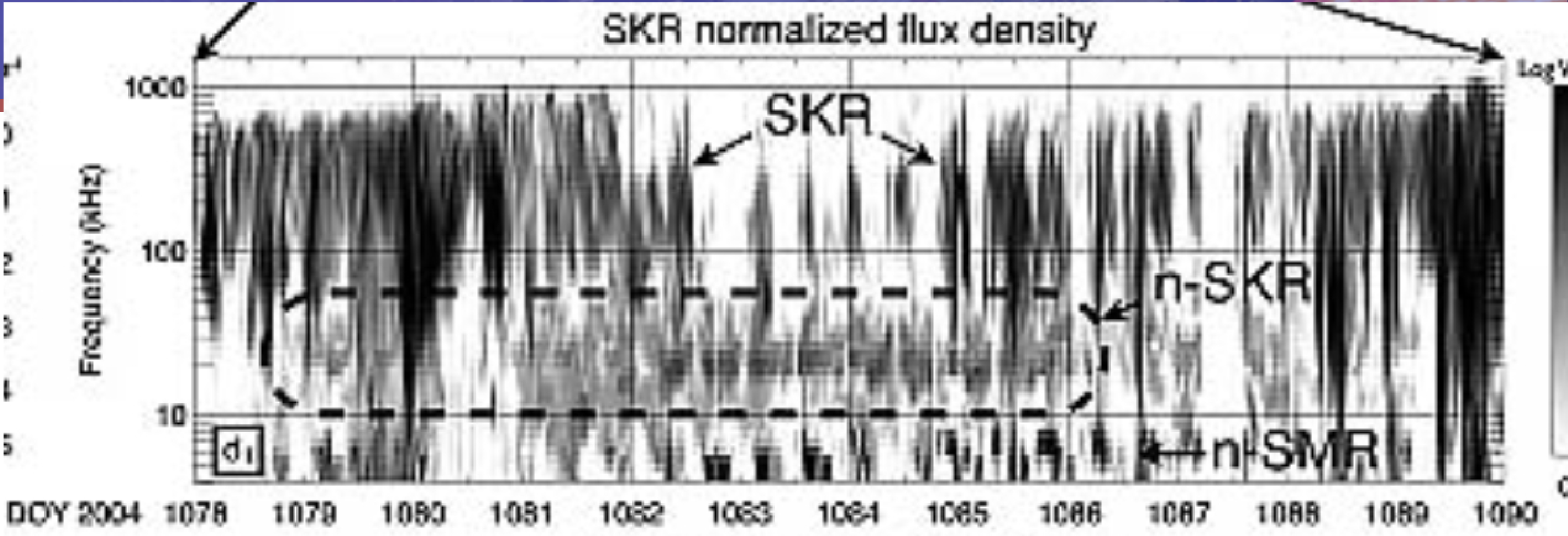
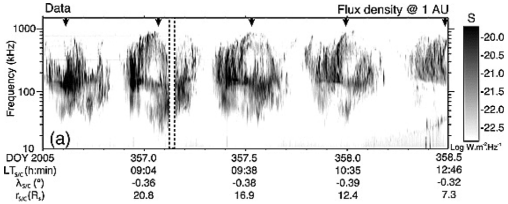
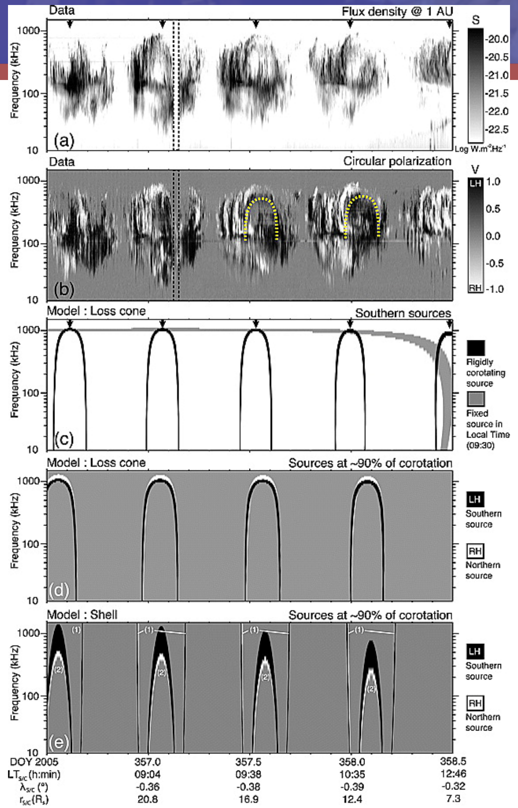


Fig. 2. Cassini-RPWS dynamic spectra for **(a)** the Stokes parameter S (= total intensity), **(b)** the degree of circular polarization d_c, **(c)** the


SKR normalized flux density
1000
100
10
Frequency (kHz)
SKR
n-SKR
n-SMR
DOY 2004
1078
1079
1080
1081
1082
1083
1084
1085
1086
1087
1088
1089
1090





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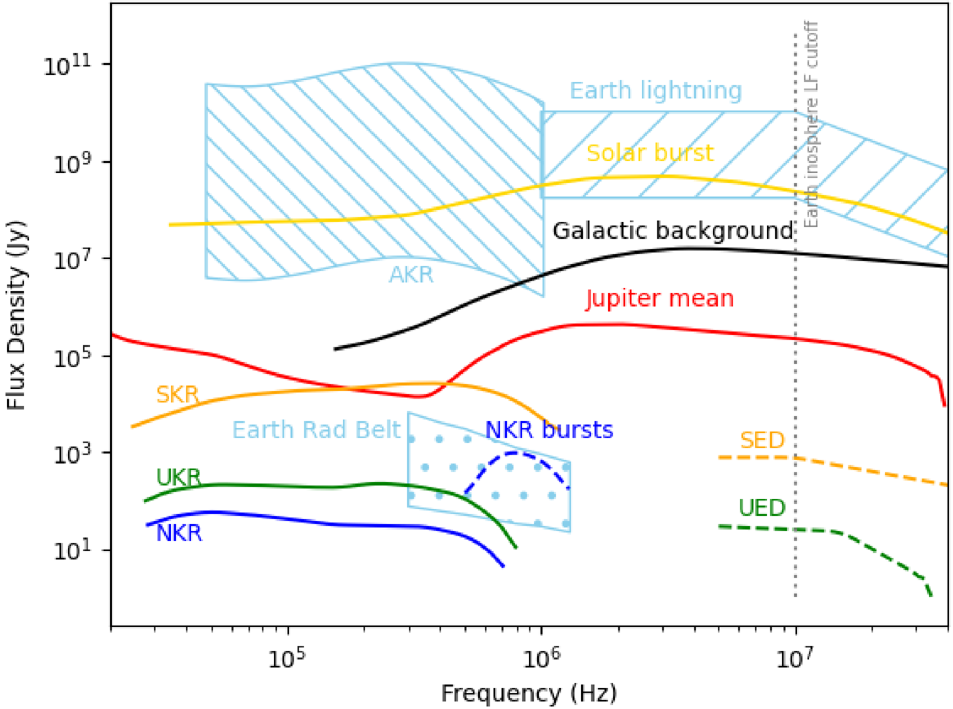
I] Planetary Radio Emissions - Spectra

- Magnetised planets emit coherent low frequency radio waves (<1MHz)
- They are :
  - Auroral (CMI)
  - Radiation belts
  - Ligthning
- They reveal information on the magnetic topology and dynamic

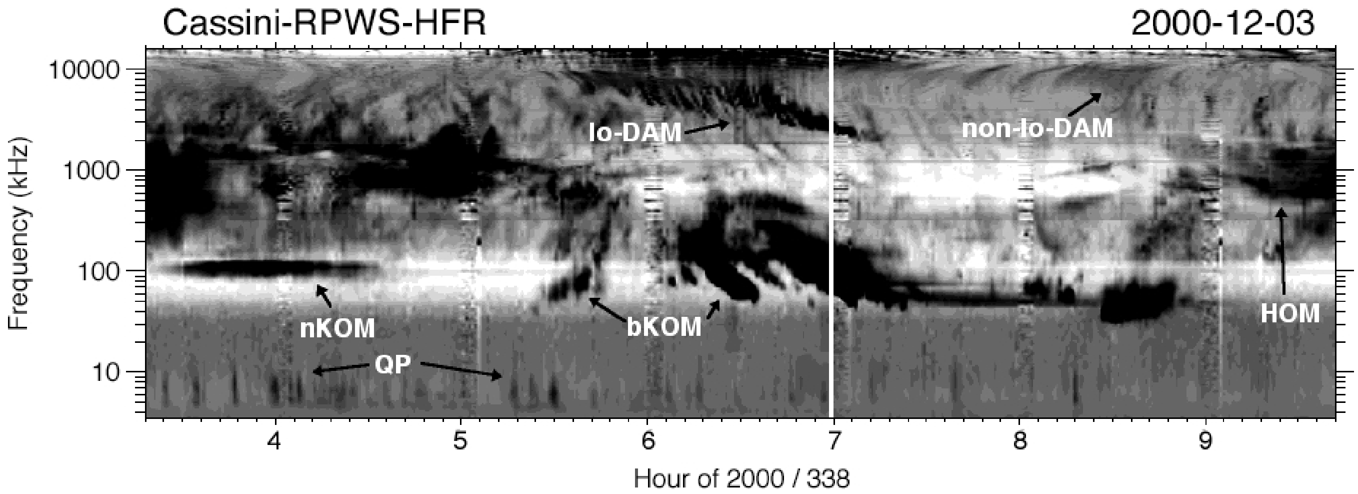


Zarka *et al* 2012

I] Planetary Radio Emissions – Spectra

Dynamic spectra reveal a wide varaiety of structures

Each structure = a given emission process
= another information on the magnetic field



[1] Lamy *et al* 2020, [2] Zarka *et al* 2004

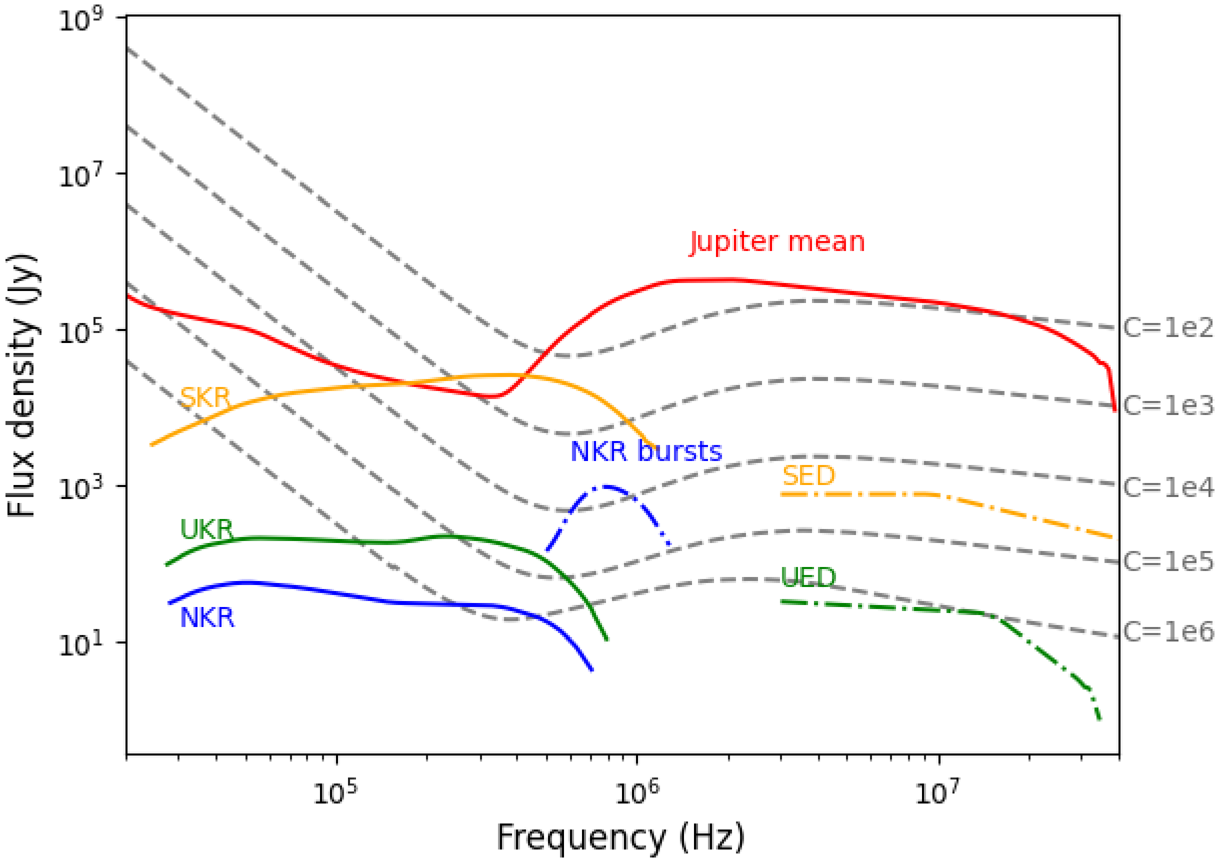
I] Planetary Radio Emissions - Measure

Contraints

- Earth ionosphere → measure in space
- Earth emissions & RFI → far away or shielding

- Send a probe nearby
(Voyager, …, JUICE)
- Directional observations
→ requires a large instrument: $10^2 – 10^3$ km
→ synthesize antenna = interferometry

IV] Results – Sensitivity



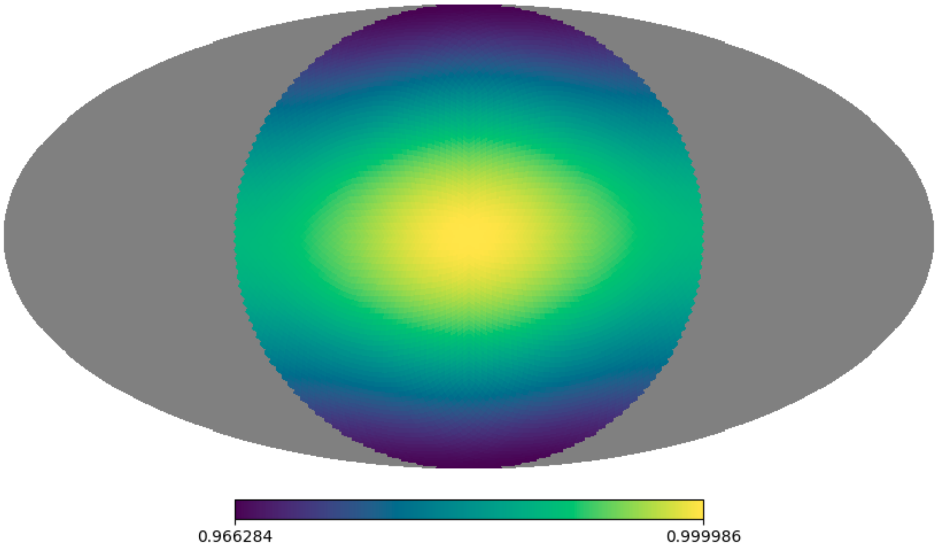
$\Delta\upsilon$ = 200kHz
τ = 40 min

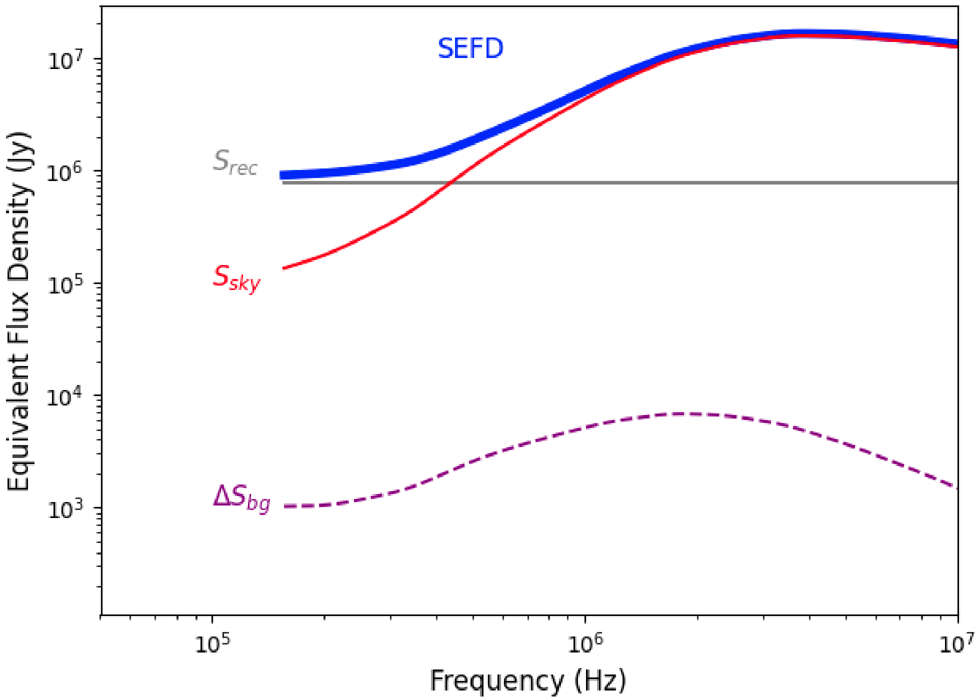
IV] Results – Phenomenology

Radio Emission	C	τ	$\Delta\nu$ (kHz)	ν_{min}	ν_{max}	$\sigma_{\Delta B_{\text{bg}}}$	SNR
Jupiter (HOM, DAM)	10^3	100ms	5	300	$30\,.10^3$	1%	5
Jupiter (S-burst)	$1.5\,.10^2$	1ms	10	$0.6\,.10^3$	$26\,.10^3$	1%	3
Jupiter (nKOM, bKOM)	5.10^4	2min	10	70	300	1%	> 3
Saturn mean	10^4	10s	5	200	1000	1%	5
	10^5	80s	50	100	200	1%	5
Saturn SED	10^6	300ms	$15\,.10^3$	$5\,.10^3$	$20\,.10^3$	0	3
UKR b-smooth	$5\,.10^5$	40min	50	250	450	1%	5
	$2\,.10^5$	5min	50	300	550	0.25%	3
UKR n-smooth	10^7	-	-	-	-	-	3
UED	$5\,.10^6$	-	-	-	-	0	-
NKR	10^6	40min	200	300	500	0.25%	2
NKR bursts	$3.5\,10^4$	-	-	-	-	0	-

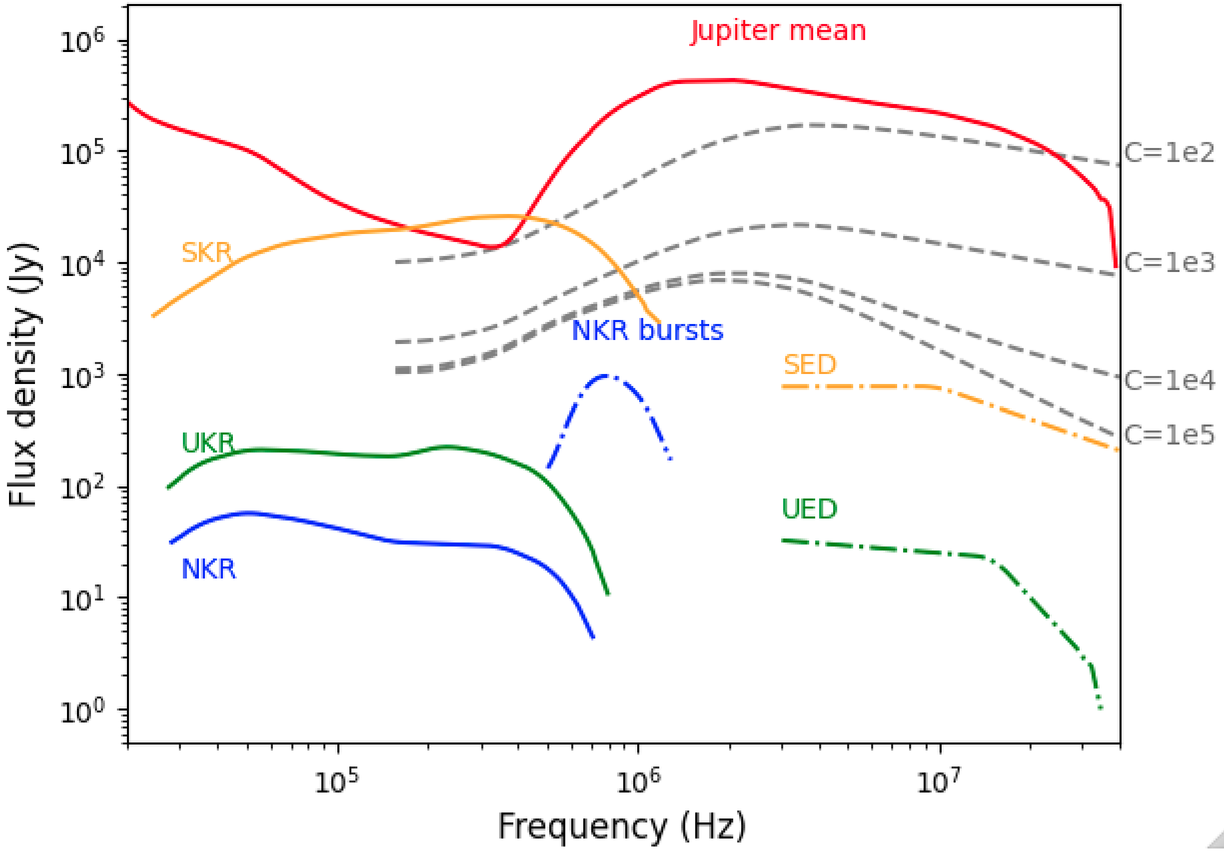
IV] Results – DEX

- DEX @ 1MHz
  → half sky





IV] Results – DEX



Conclusion – take home message

- Background subtraction is not straightforward with very low resolutions
- Systematic errors induced by the inaccuracies of the system parameters have to be considered
- We need a good background sky model (foreground for cosmology)

Thank you for your attention

I am looking for a PostDoc position

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Backup Slides

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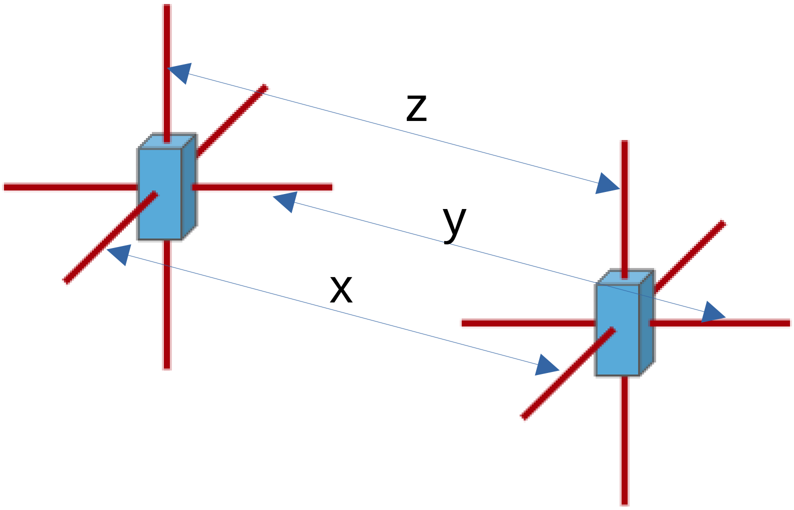
Université Paris Cité

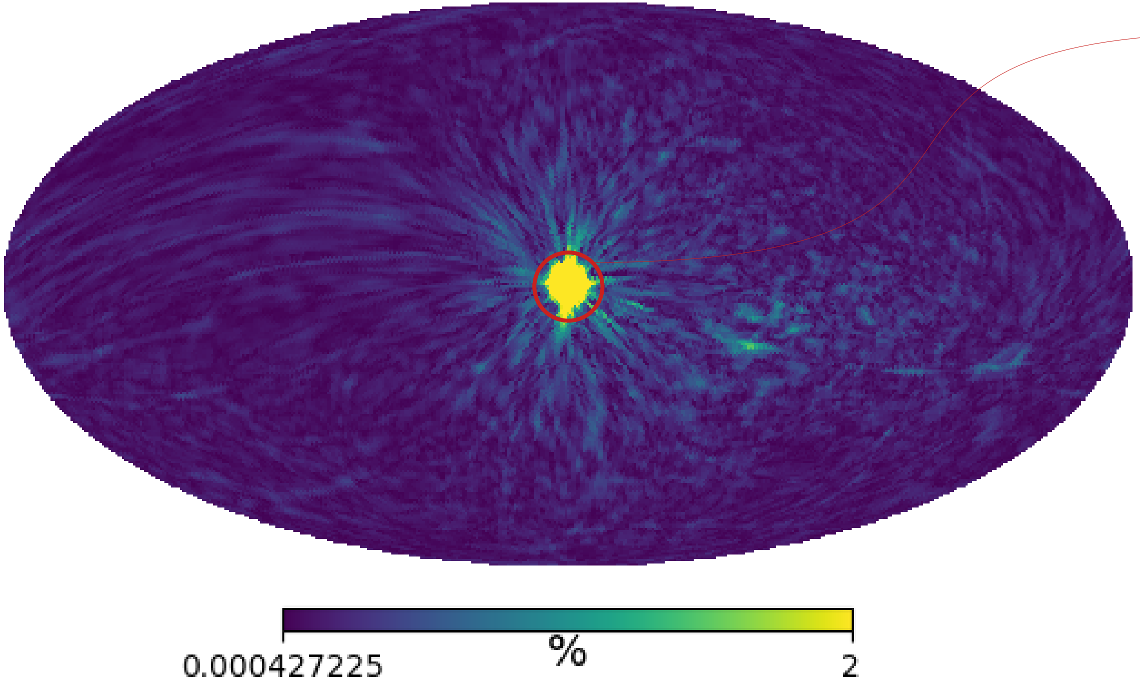
PSL UNIVERSITÉ PARIS

- Explication sum 3 dipôle = isotrope gain 2



$$\mathcal{V}_{p,q} = \frac{1}{2}(\mathcal{V}^x_{p,q} + \mathcal{V}^y_{p,q} + \mathcal{V}^z_{p,q})$$

PSF(τ=30’, Δυ=50kHz)

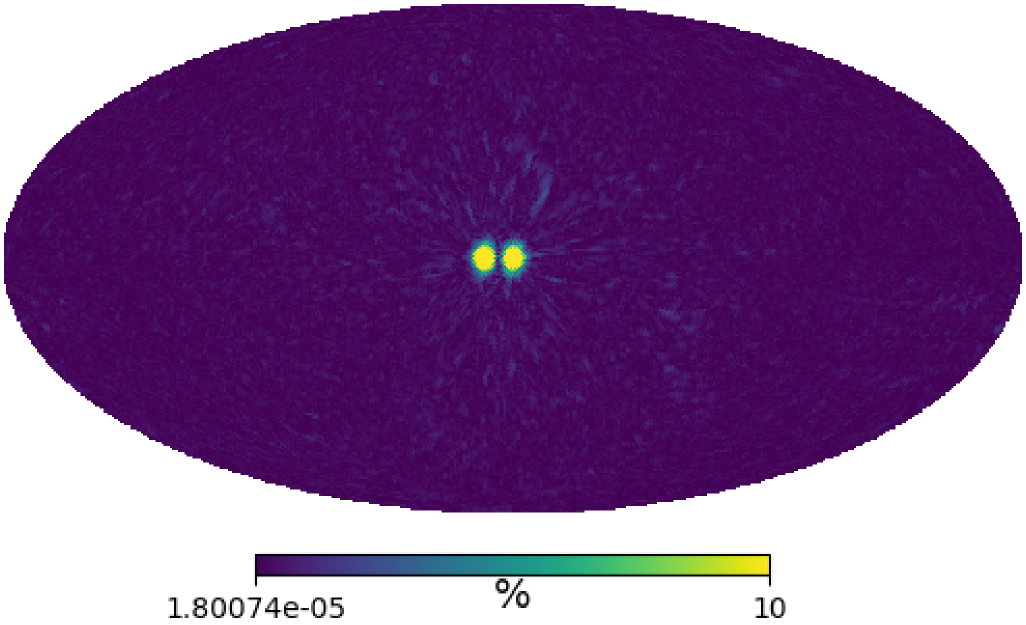


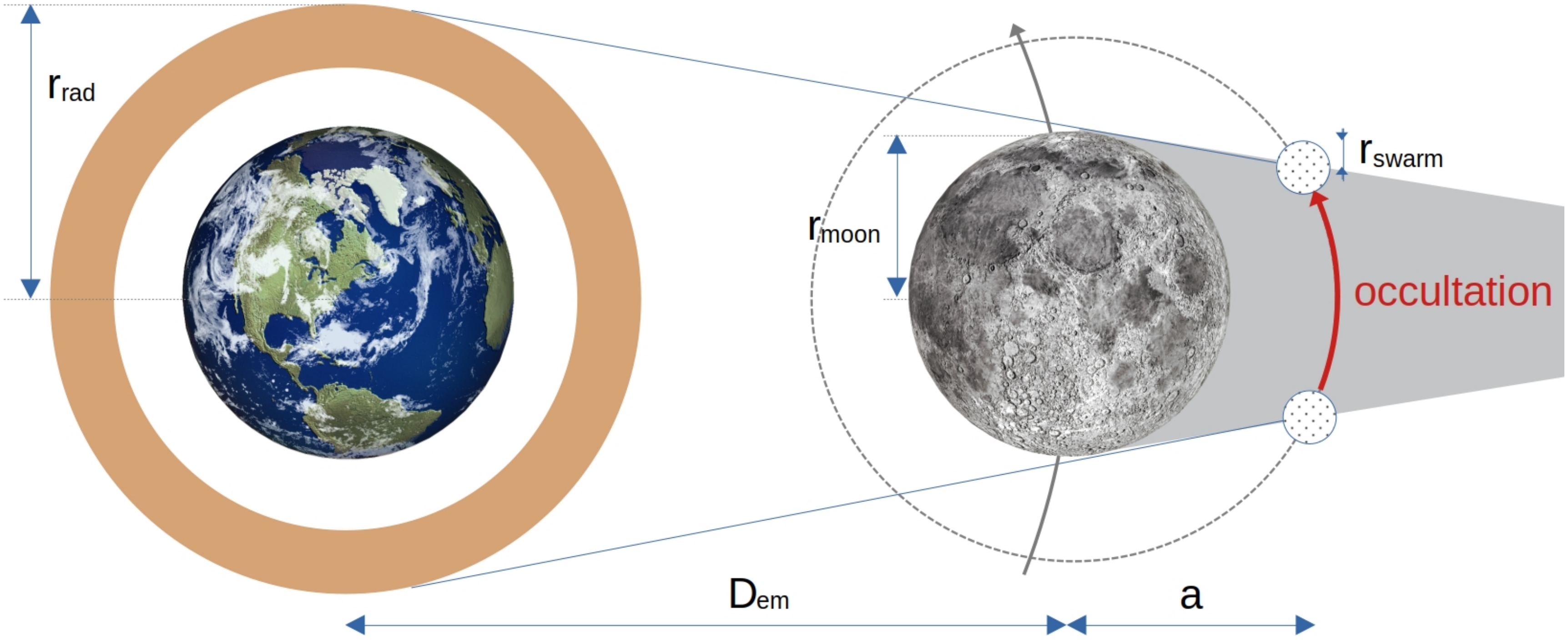
~20 % of total

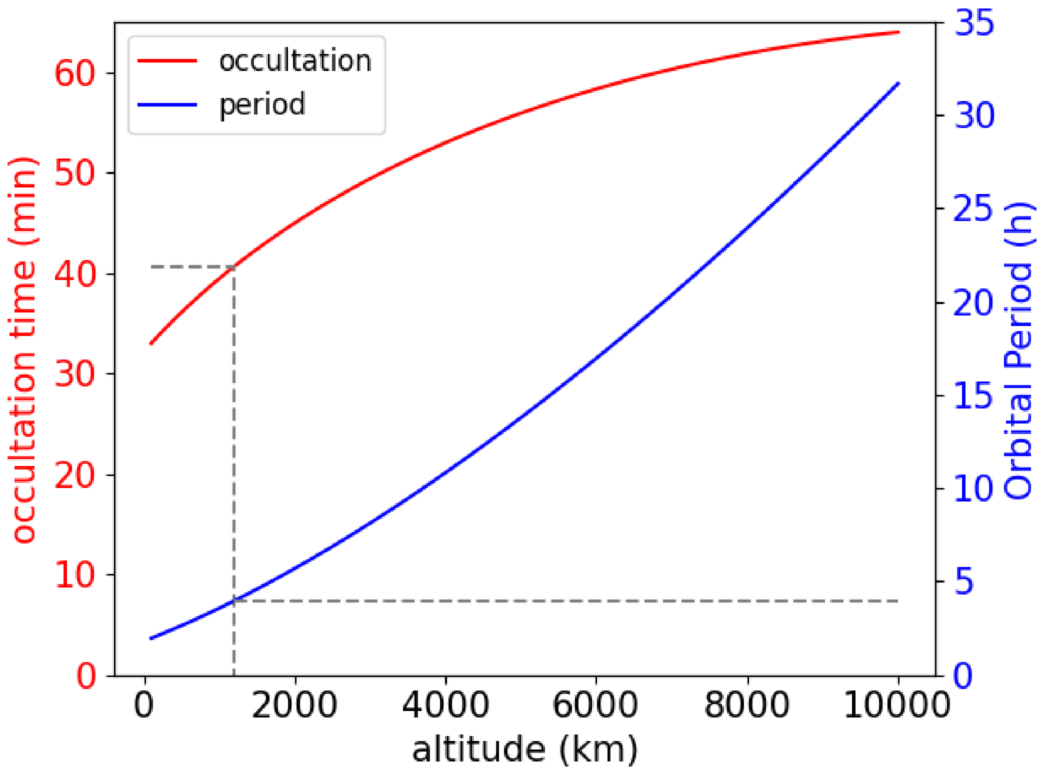
80 % are side lobes

So ΔS depends on the side lobes

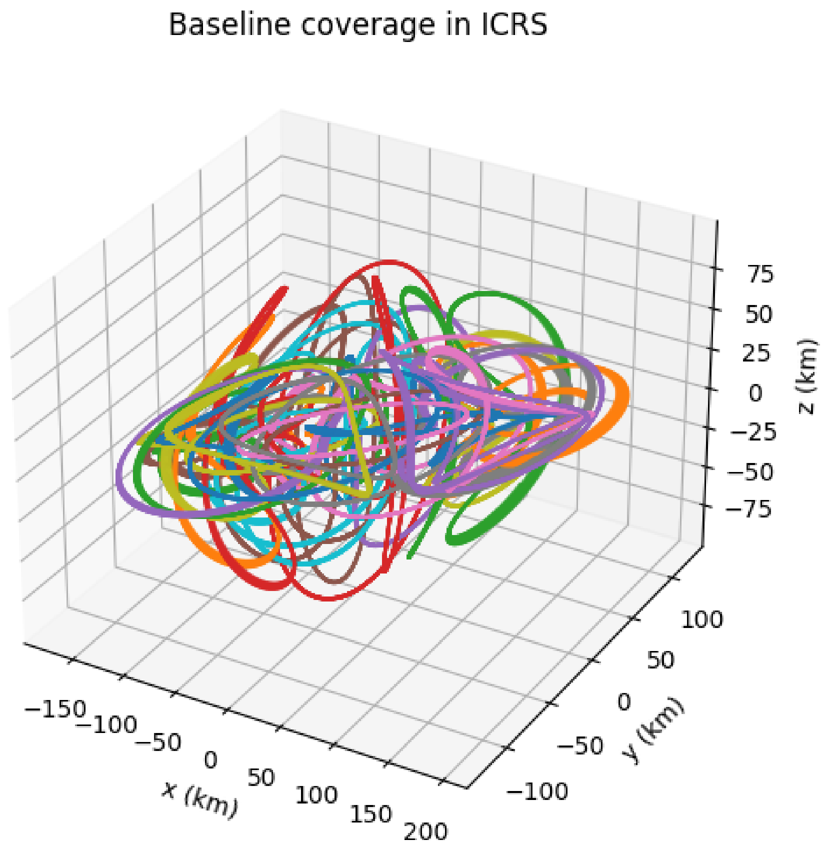
Side lobes are different from one phasing to another


1.80074e-05
%
10

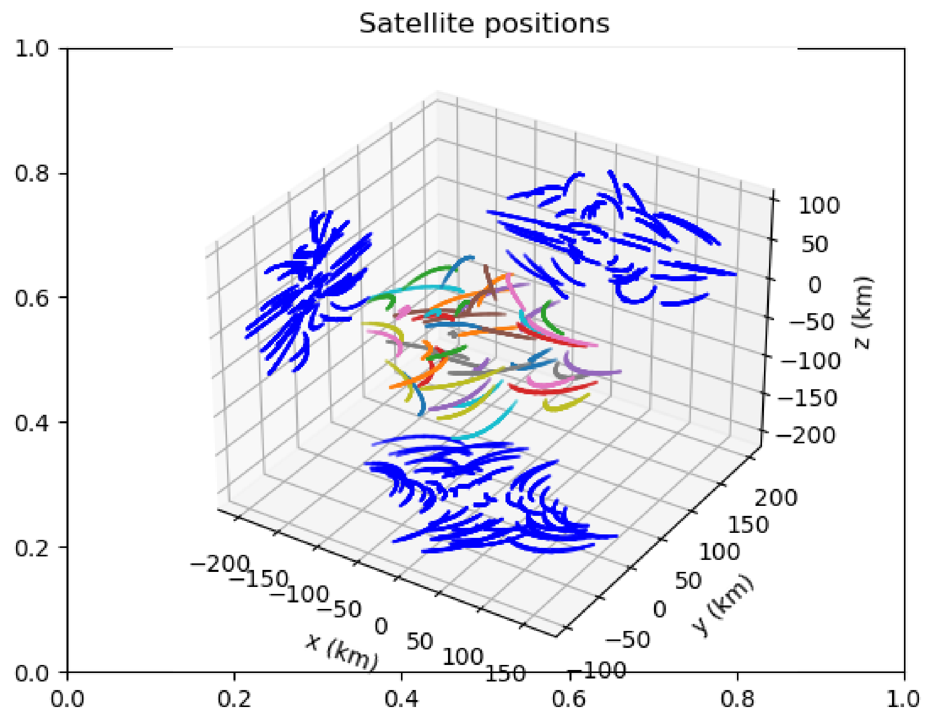

r_{rad}
r_{moon}
r_{swarm}
occultation
D_{em}
a



occultation
period
occultation time (min)
Orbital Period (h)
altitude (km)
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
0
2000
4000
6000
8000
10000



Baseline coverage in ICRS
x (km)
y (km)
z (km)



Satellite positions
x (km)
y (km)
z (km)

III] Noises and bias – Bias

Using a skymodel

We need to estimate the PSF using the measured baselines

$$\Delta S = S_{\text{bg}} - \widetilde{S}_{\text{bg}}$$

$$= \oiint I(\vec{s})\text{PSF}(\vec{s})d\Omega_s - \oiint \widetilde{I}(\vec{s})\widetilde{\text{PSF}}(\vec{s})d\Omega_s$$

$$\simeq \oiint \Delta I(\vec{s})\text{PSF}(\vec{s})d\Omega_s + \oiint I(\vec{s})\Delta\text{PSF}(\vec{s})d\Omega_s$$

Errors of the Sky Model

Errors of the Instrument Parameters

$\Delta I / I$ >> $\propto k(c\Delta T + \Delta b + \vec{b} \cdot \vec{\Delta s_0})$

- Intro planeto/instru ?
- On doit aller dans l'espace pour les mesurer
- NOIRE ou DEX ou autre projets de la conf devrait permettre de mesurer ces ondes mais est ce qu'on mesure les planètes ????
- Le concept NOIRE
- Bruits
- Biais : erreurs sur le niveau de fond
  - Modèle de ciel
  - Paramètres instrumentaux
- Sensitivity plot : NOIRE
  DEX
- Phenomenology pour NOIRE