

# LOFAR

The Low-Frequency Array

(tri-talk franglais)



LOFAR = Interféromètre de Réseaux Phasés

$\Delta f = (10)30\text{-}240 \text{ MHz}$

$A_e \sim 200000 \text{ m}^2$ , Cœur + Stations (77 total)

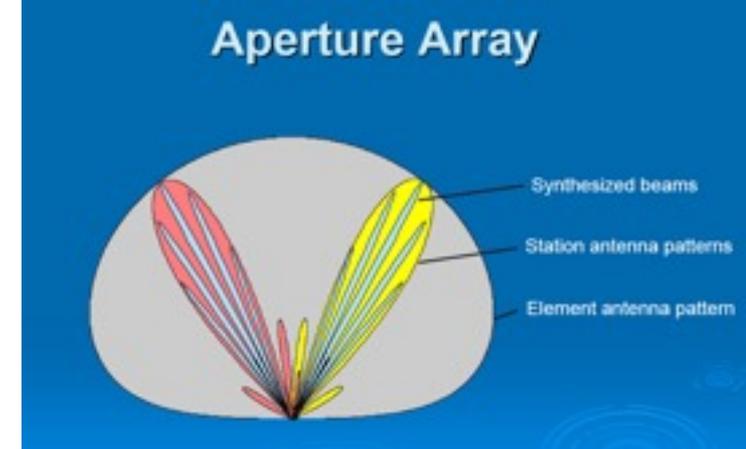
**Frequency dependent Array Performance (Initial array)**

Frequency	Point Source Sensitivity <sup>(b)</sup>		Effective Collecting Area		Beam Size	
	VC	Full Array	VC	Full Array	VC	Full Array
30 MHz	4.8 mJy	2.0 mJy	$7.9 \times 10^4 \text{ m}^2$	$1.9 \times 10^5 \text{ m}^2$	21'	25"
75 MHz	3.3 mJy	1.3 mJy	$1.2 \times 10^4 \text{ m}^2$	$3.0 \times 10^4 \text{ m}^2$	8.3'	10"
120 MHz	0.17 mJy	0.07 mJy	$7.9 \times 10^4 \text{ m}^2$	$1.9 \times 10^5 \text{ m}^2$	5.2'	6.0"
200 MHz	0.15 mJy	0.06 mJy	$2.9 \times 10^4 \text{ m}^2$	$6.9 \times 10^4 \text{ m}^2$	3.1'	3.5"

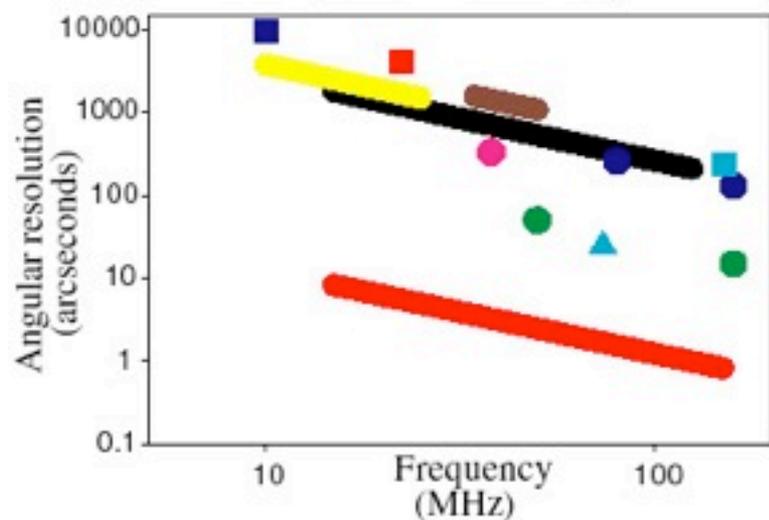
<sup>(b)</sup> Sensitivity quoted for 1 hour integration time, 2 polarizations and 4 MHz bandwidth

## Caractéristiques techniques :

- imagerie haute résolution ( $\sim 1-10''$ )
  - grand champ (plusieurs  $^\circ$ )
  - multi-fréquences / multi-faisceaux ( $8 \times 4$  MHz)
  - haute sensibilité (0.1-10 mJy),
  - polarisation complète (4 paramètres de Stokes)
  - résolutions 1 msec  $\times$  1 kHz
- gain de 1-2 ordres de grandeur en sensibilité & résolution / instruments existants
- 1<sup>er</sup> télescope BF généraliste et 1<sup>er</sup> spectro-imageur à  $f \leq 100$  MHz



LOFAR Angular Resolution  
( $\leq 500$  km baselines)

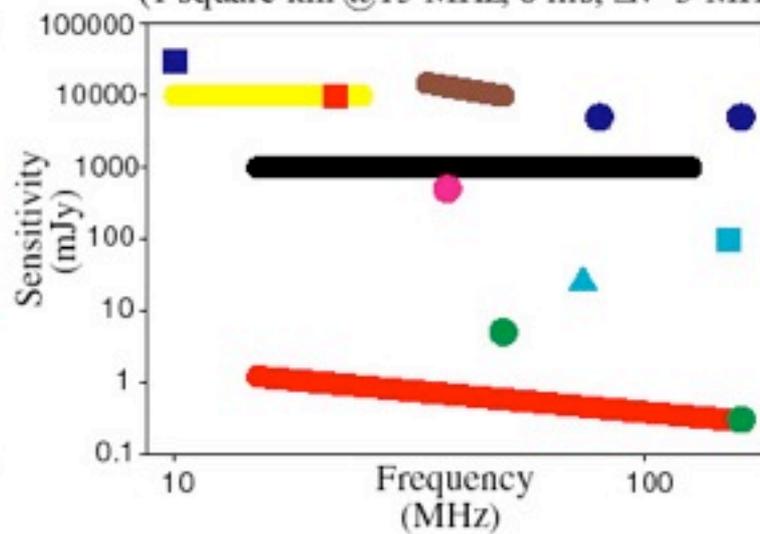


- CLRO
- Culgoora
- VLA
- UTR2
- Cambridge Polar cap

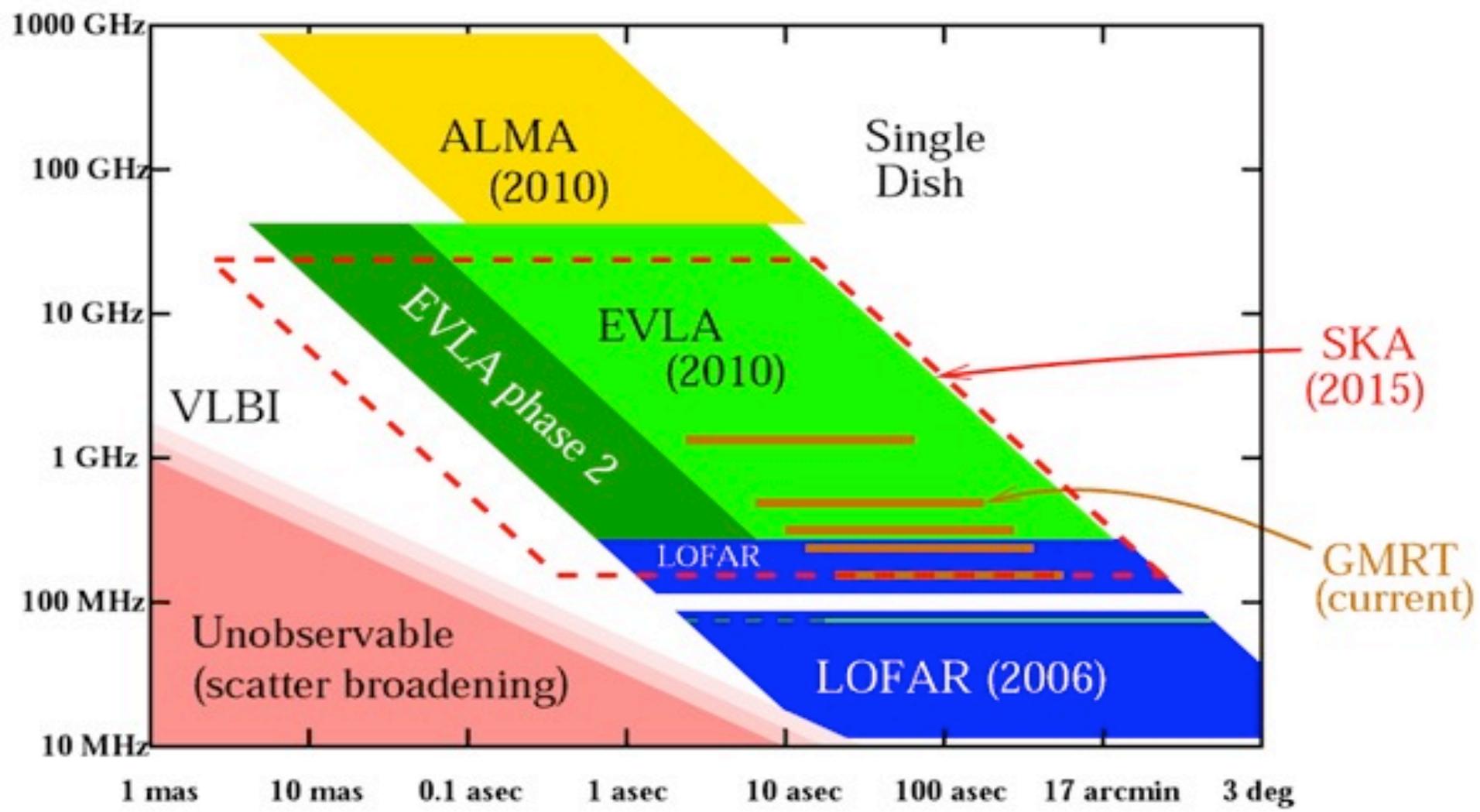
LOFAR

LOFAR Sensitivity

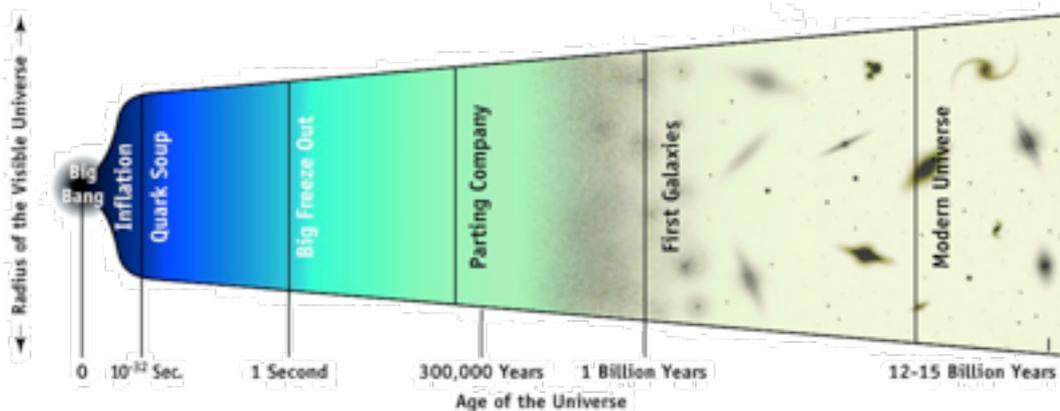
(1 square km @15 MHz, 8 hrs,  $\Delta\nu \sim 3$  MHz)



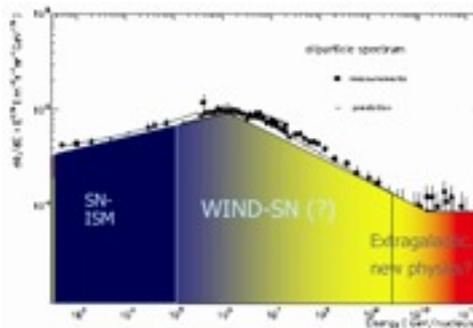
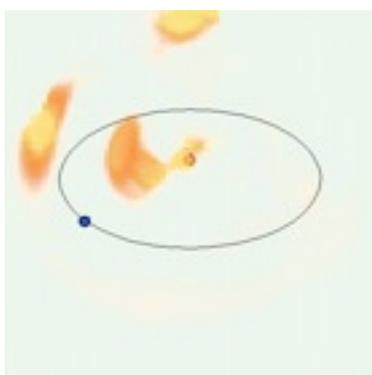
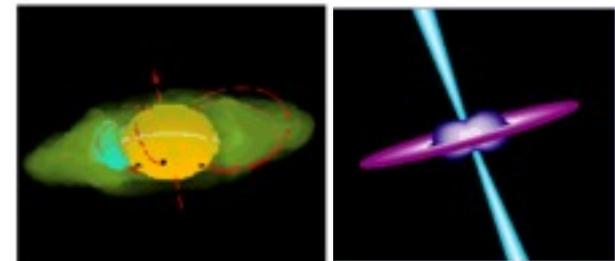
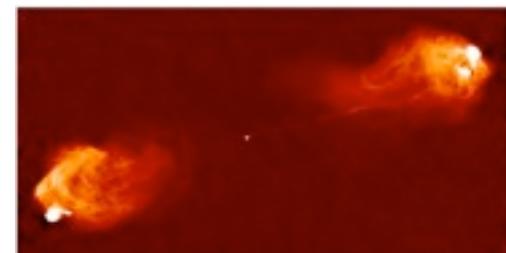
- DRAO-10
- DRAO-22
- Gauribidanur
- Mauritius
- GMRT



# Objectifs scientifiques :

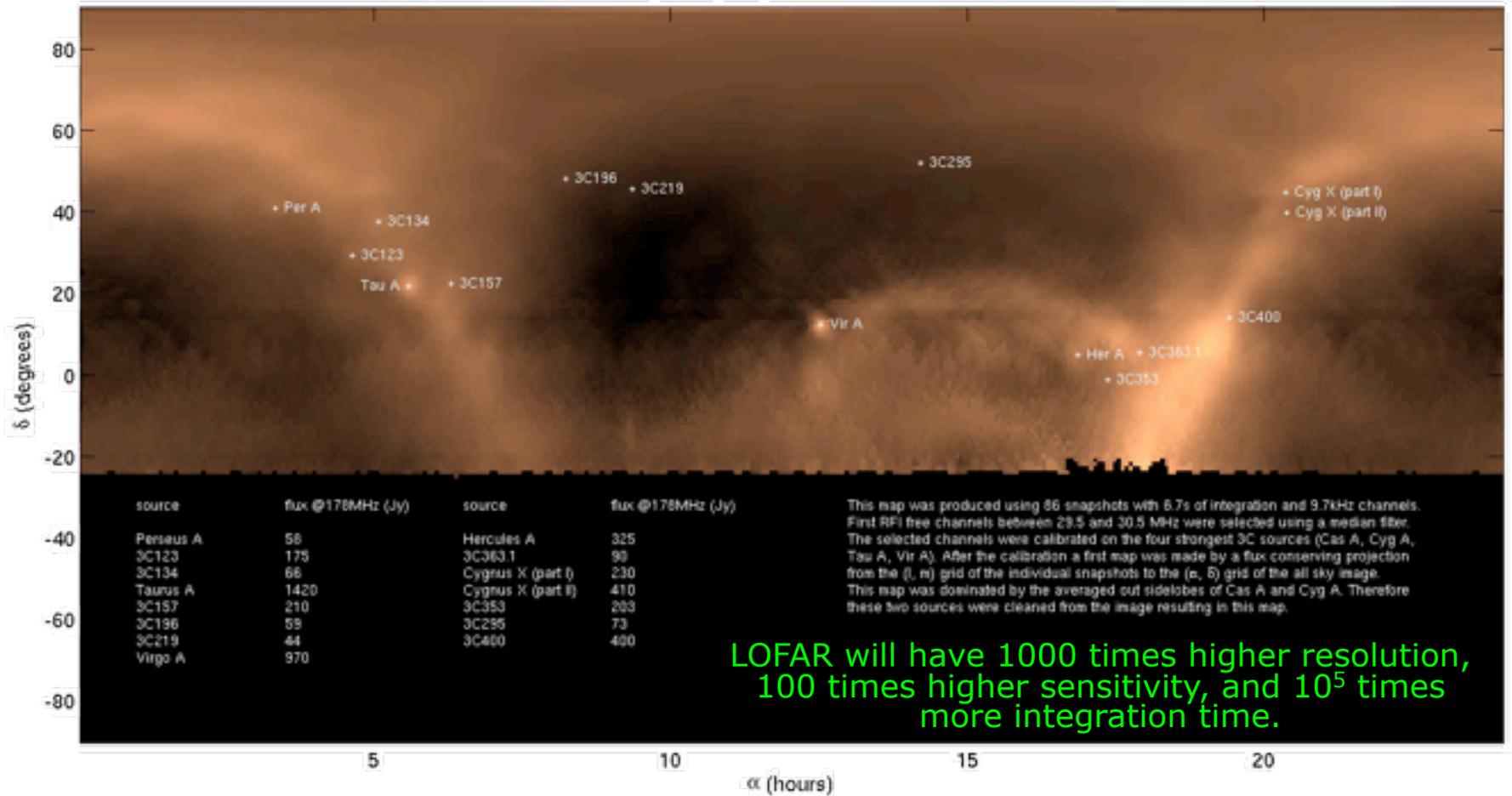


- Cosmologie / Réionisation (Groningen)
- Surveys profonds all-sky/galaxies (Leiden)
- Transients = Sources variables/sporadiques (Amsterdam)
- Rayons cosmiques (Nijmegen)
- Physique solaire & spatiale

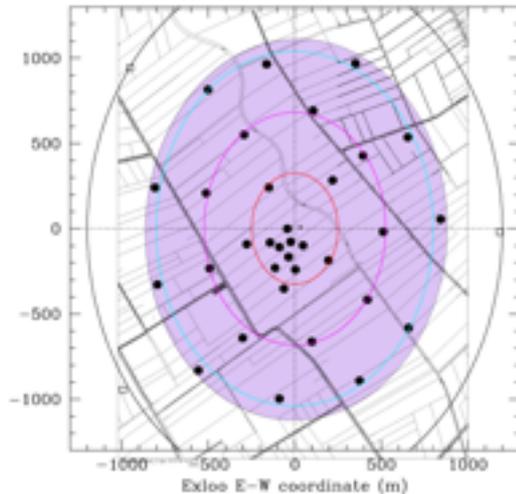


# LOFAR initial test station prototype (ITS) : 500 Second All-Sky Map

ITS all sky survey map with detected 3C sources



- Septembre 2006 : Core Station #1
- 2007 : début opérations
- 2008 : fonctionnement nominal



- Formation des SWG :

Transients Key Project :

(1) Jets

(2) Pulsars

(3) (exo)Planètes

(4) Étoiles/Flare stars

- Expansion Européenne : Allemagne (GLOW), Suède (LOIS), UK, France, Italie ?, Pologne ?



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Planetary and Space Science 52 (2004) 1455–1467

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[www.elsevier.com/locate/pss](http://www.elsevier.com/locate/pss)

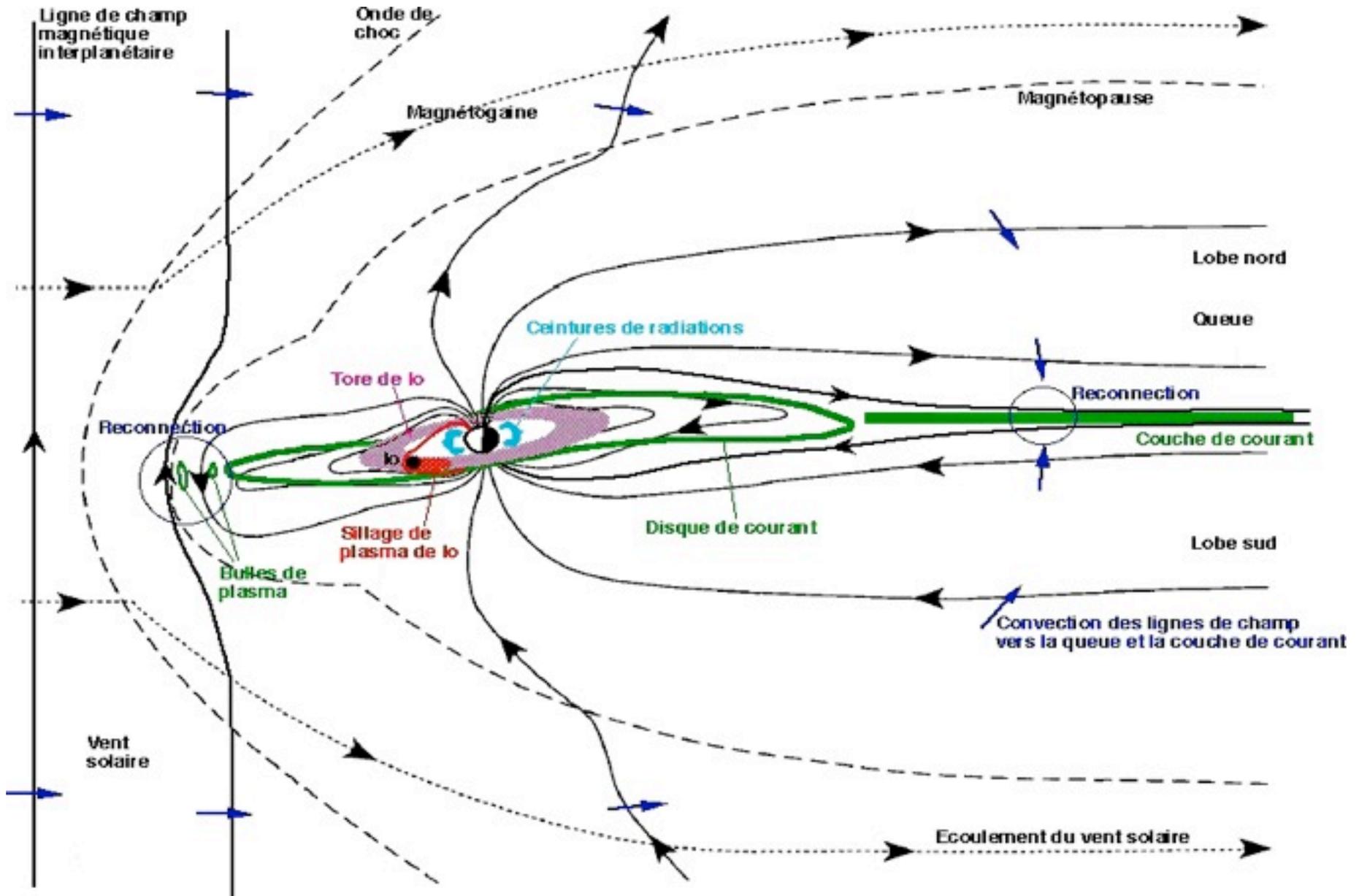
# Fast radio imaging of Jupiter's magnetosphere at low-frequencies with LOFAR

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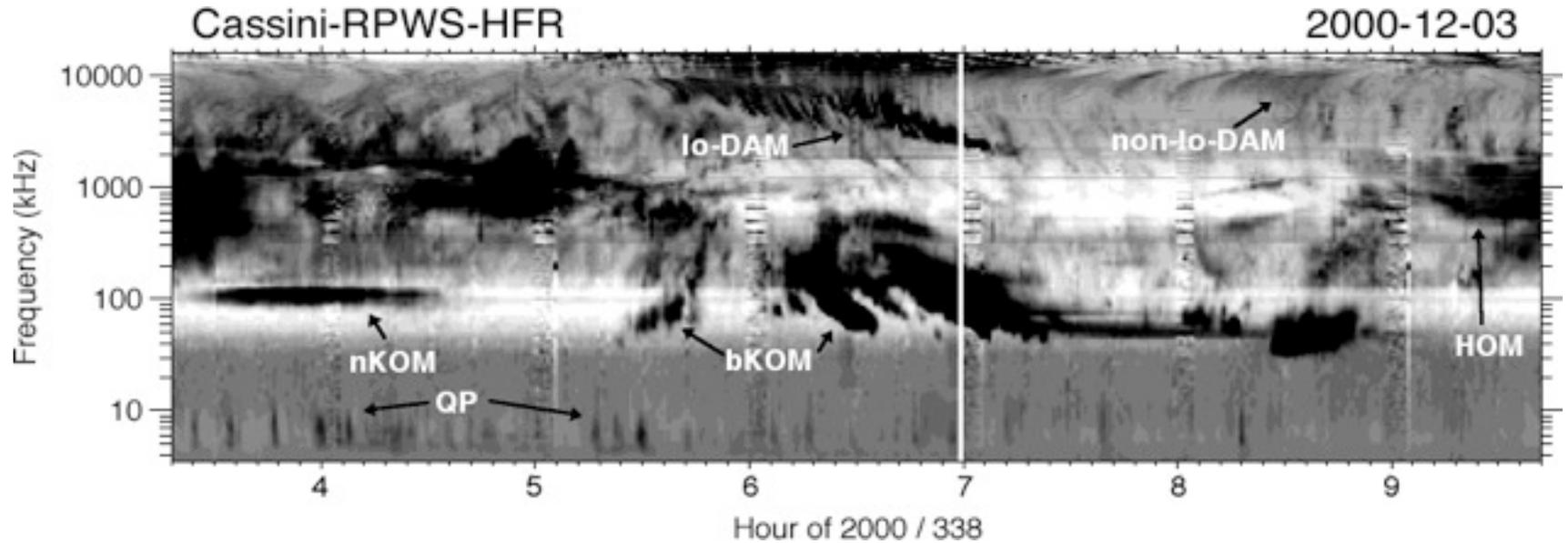
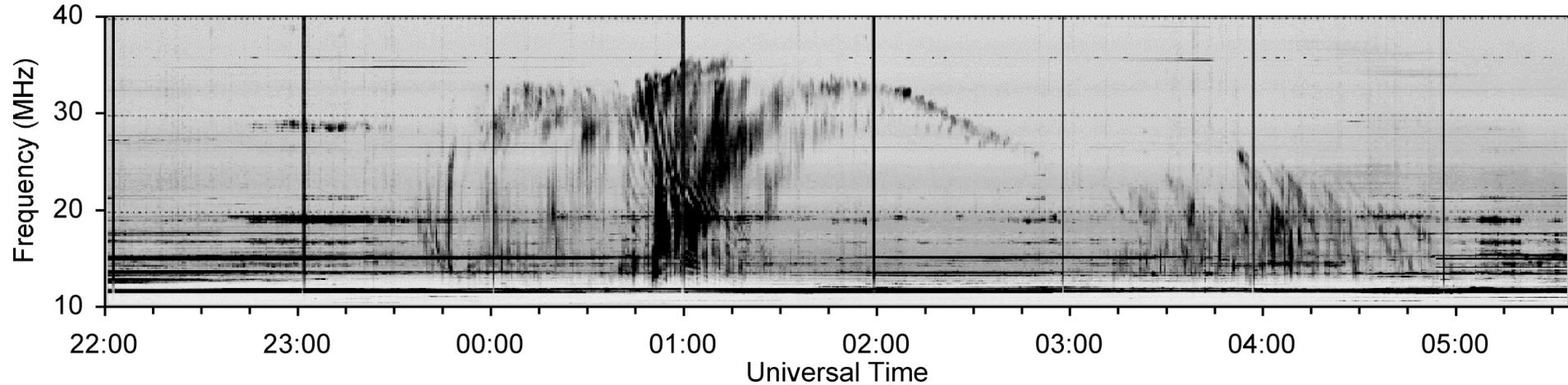
Accepted 3 September 2004

# Jupiter's magnetosphere

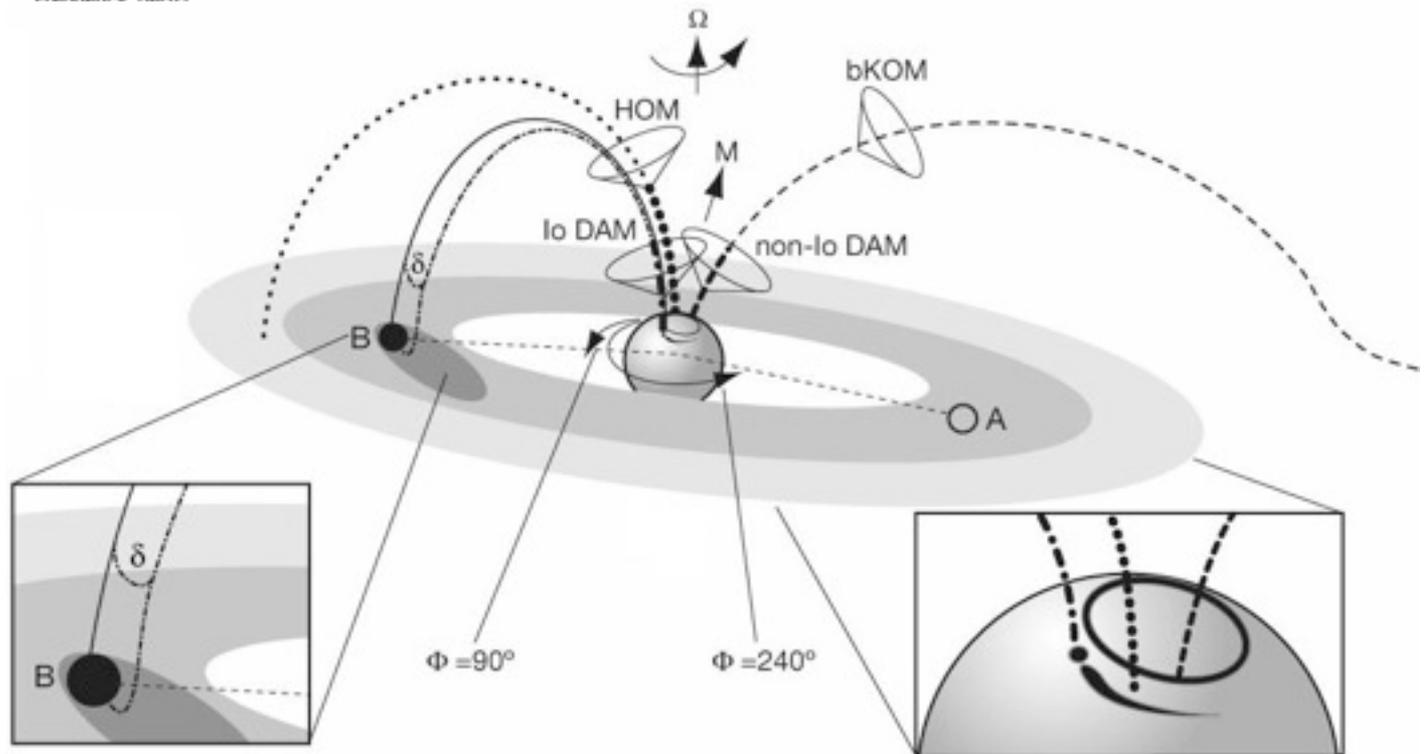
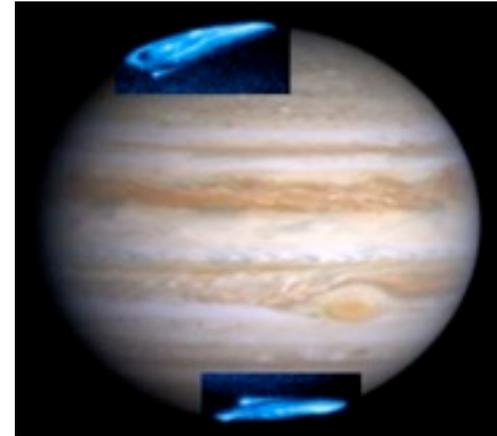
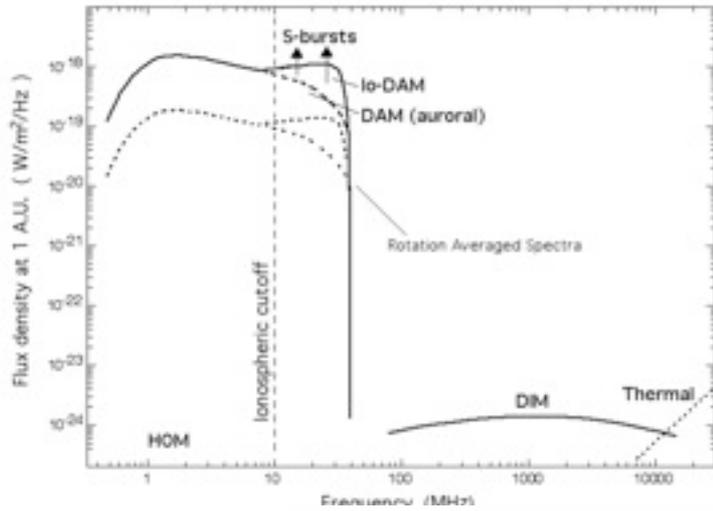


# Jovian high latitude radio emissions

JUPITER 1991 Jan1 (Ionospheric conditions : winter - early morning)

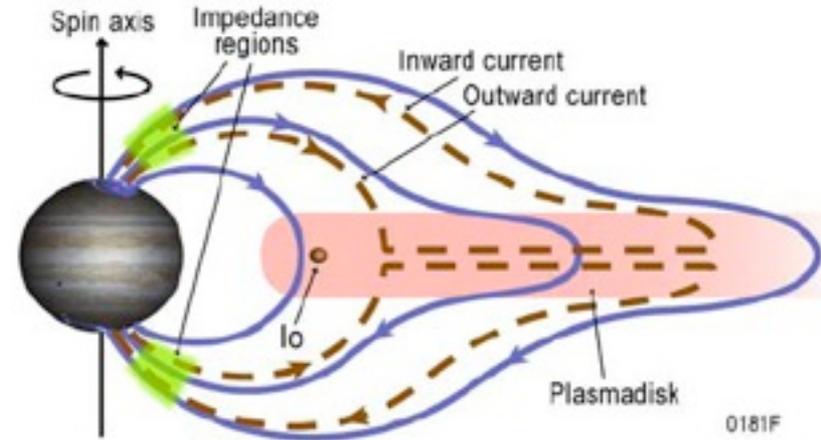
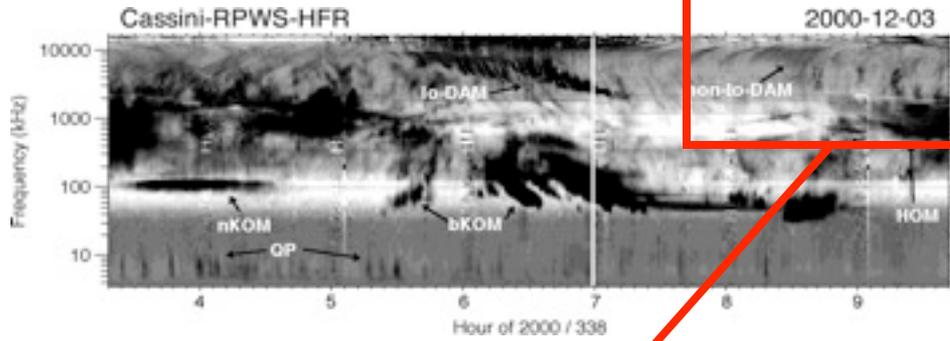
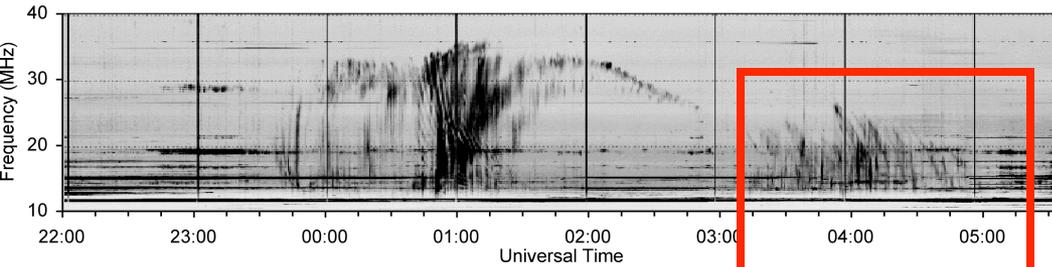


# Jovian high latitude radiosources



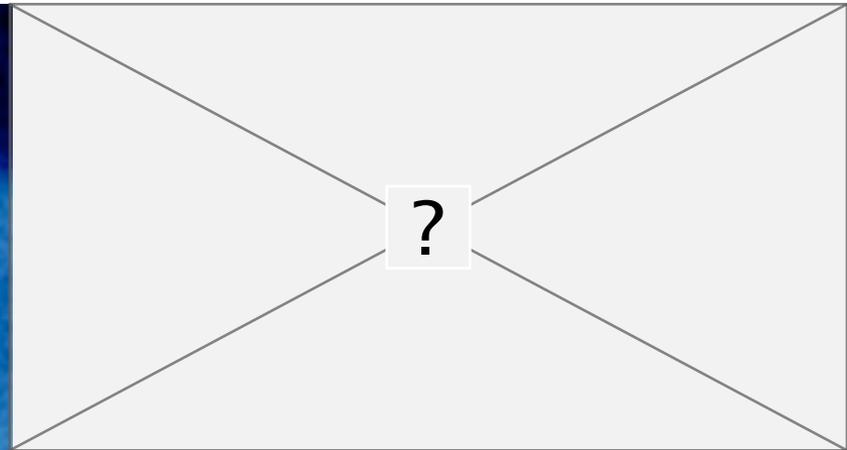
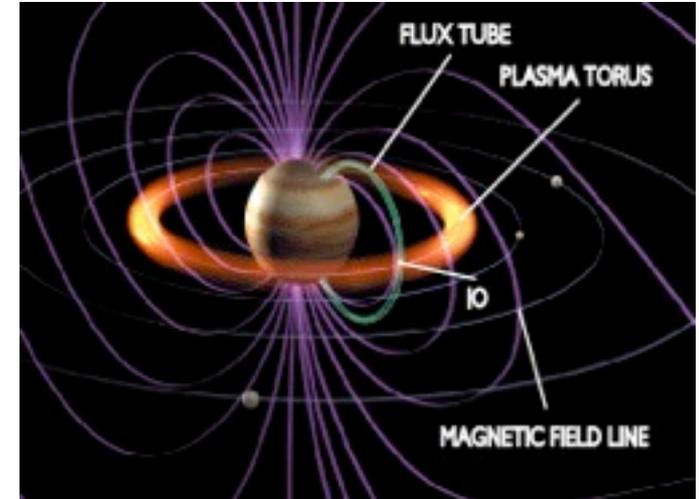
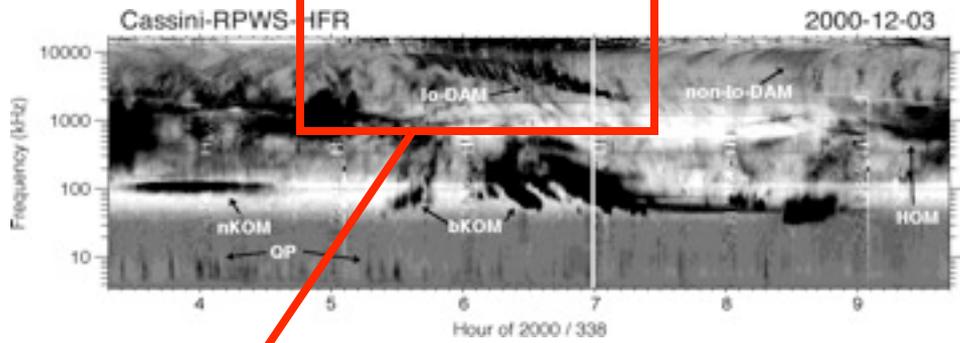
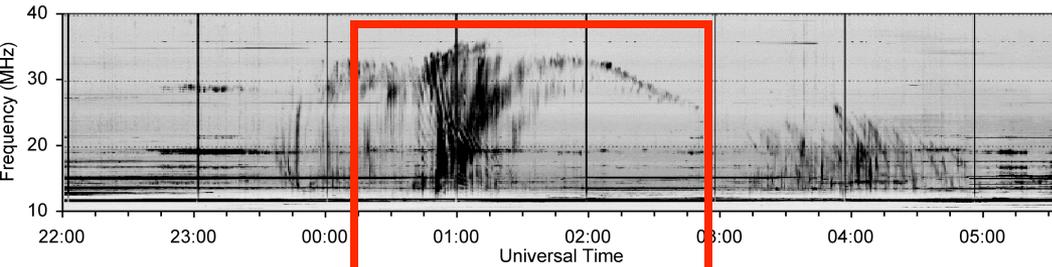
# Main aurora

JUPITER 1991 Jan1 (Ionospheric conditions : winter - early morning)

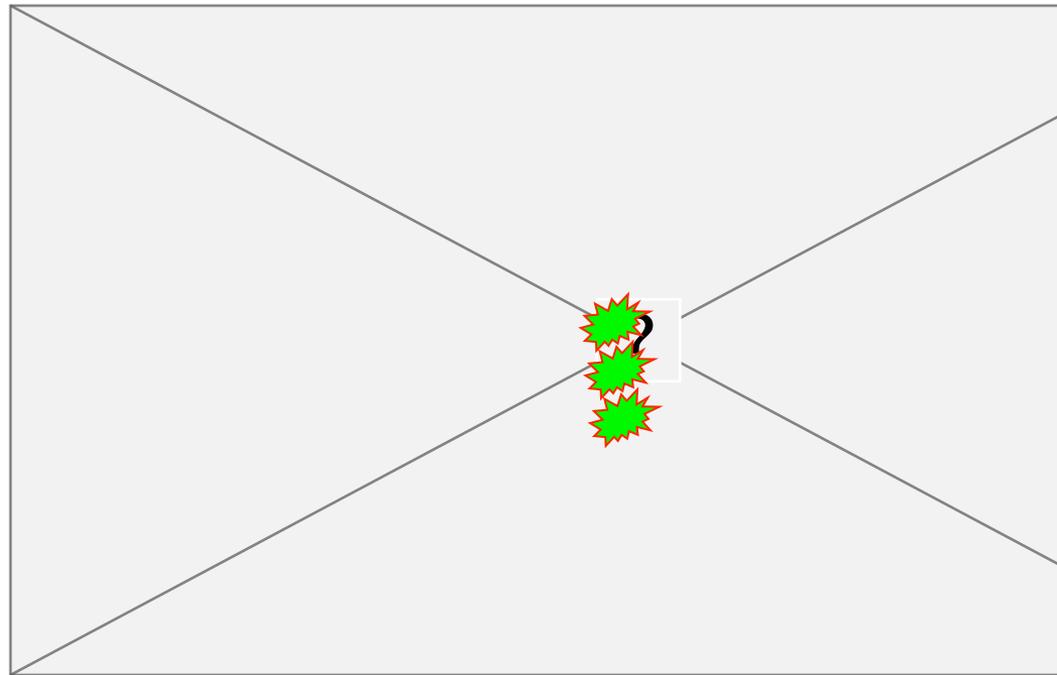
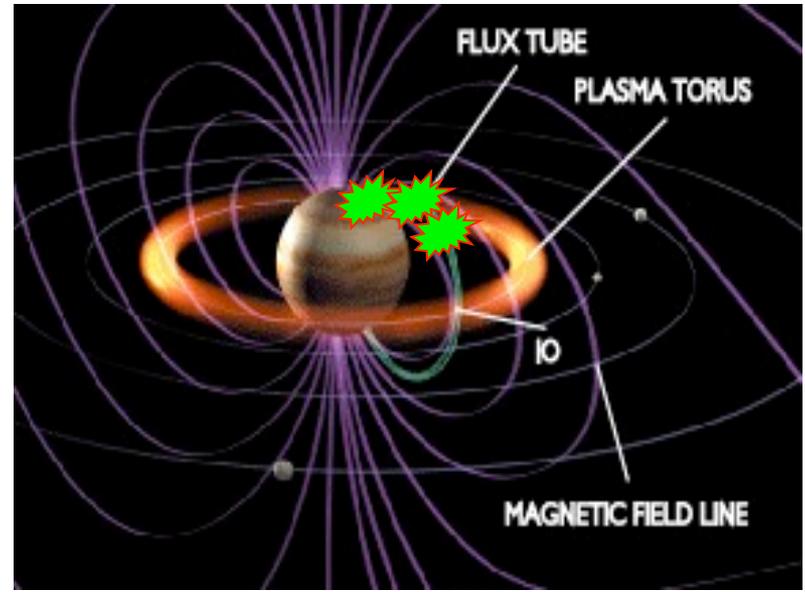
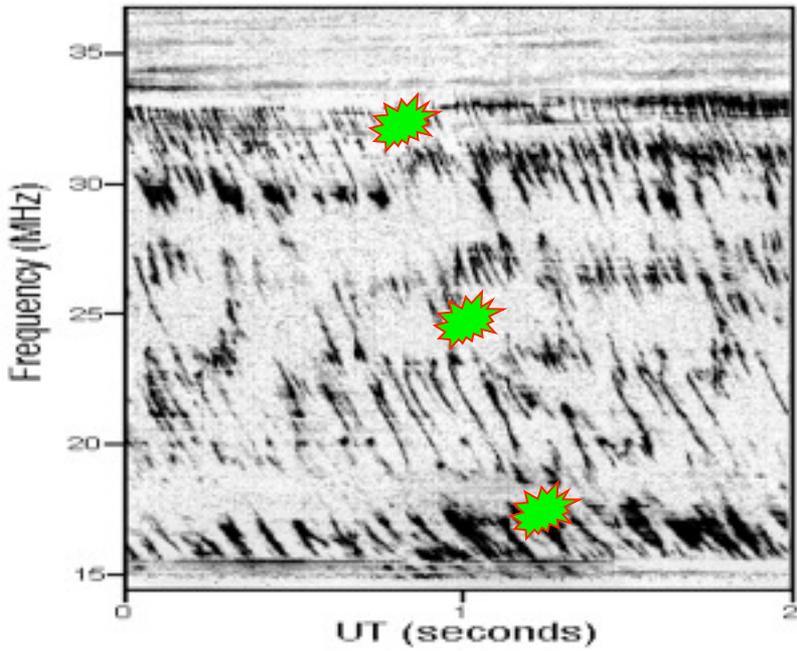


# Io-induced emissions

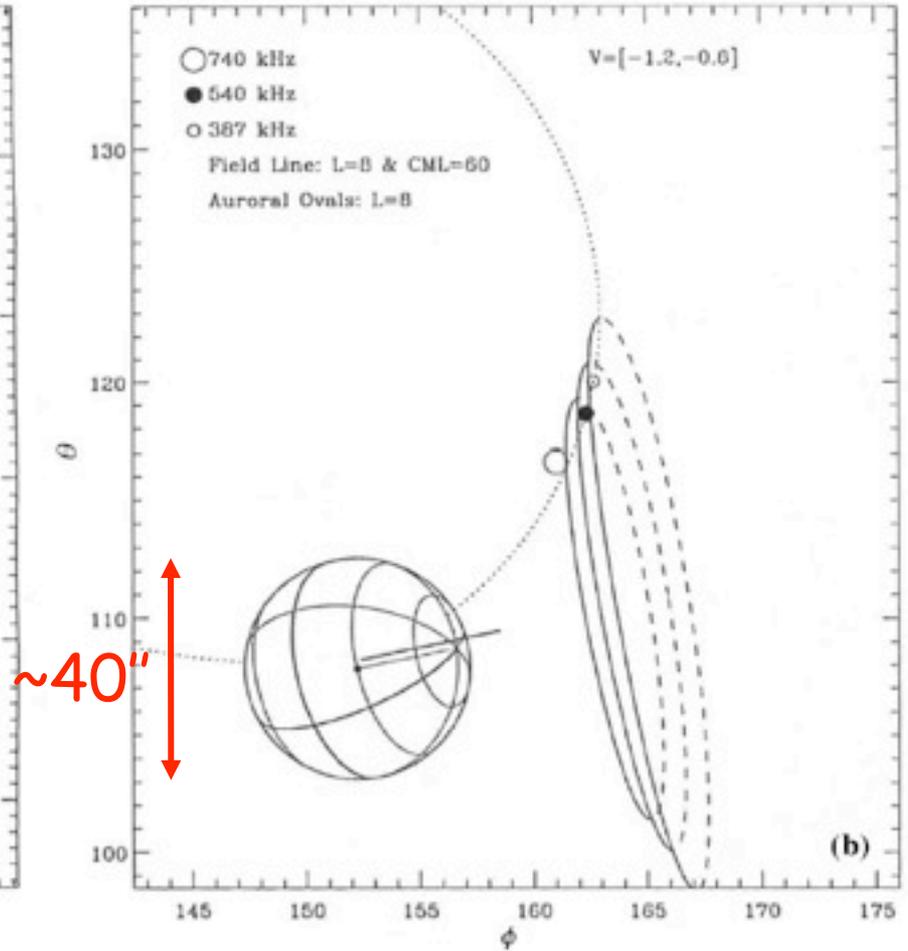
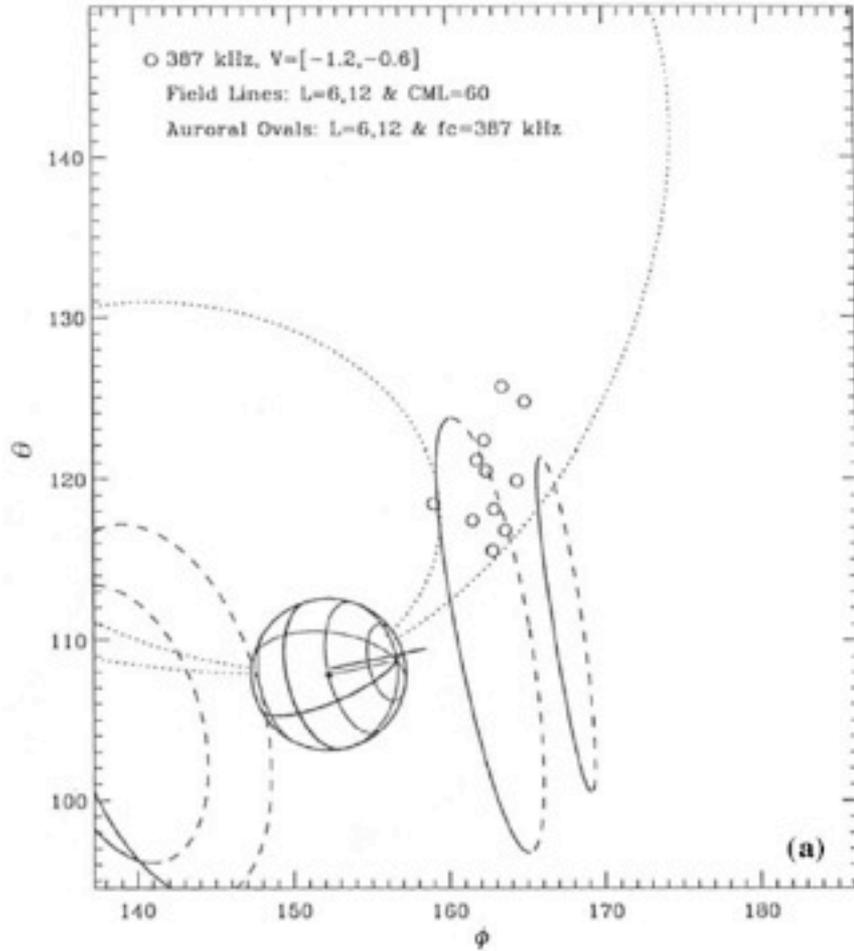
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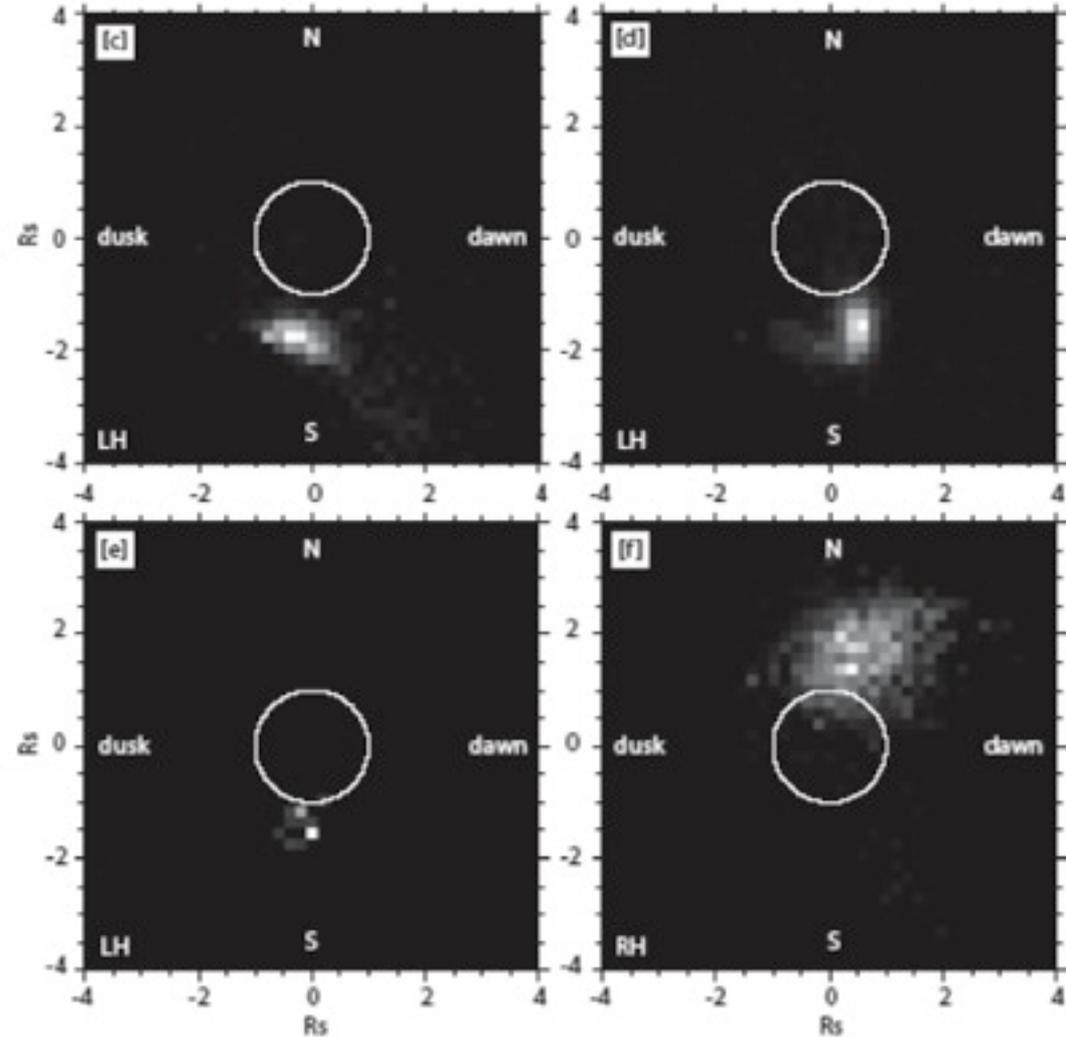
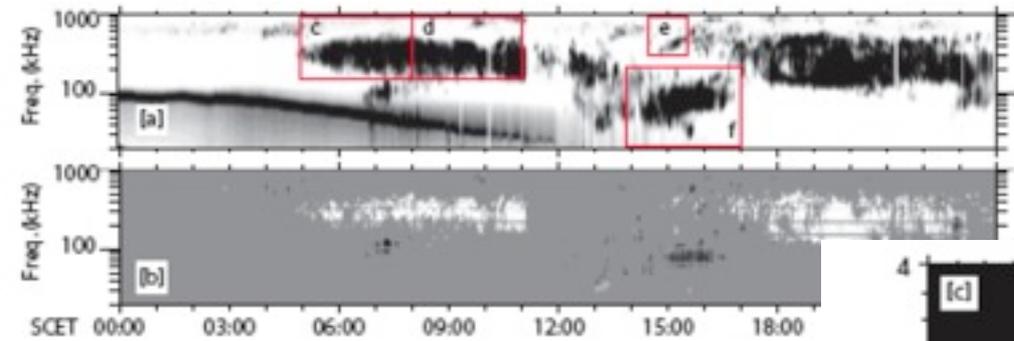
# Io-induced emissions



# Radio imaging of high latitude sources (Jupiter/Ulysses)



# Radio imaging of high latitude sources (Saturn/Cassini)



[Cecconi et al., 2006]

# Radio imaging of Jupiter with $\sim 1''$ resolution from Earth

- Surface magnetic field mapping (maximum cyclotron frequency)
- Lead angle (physics) of Io-Jupiter interaction
- Radio beaming angle  $\rightarrow$  physics of generation process
- Direct detection (& energetics) of Ganymede, Europe, Callisto-Jupiter radio emission
- Electron bunches & electric fields (potential drops) along Io flux tube
- torus  $J_N$  vs longitude via Faraday rotation
- « modulation lanes » due to diffraction by torus ?
- multi-wavelength correlations (Radio, UV, IR, X)

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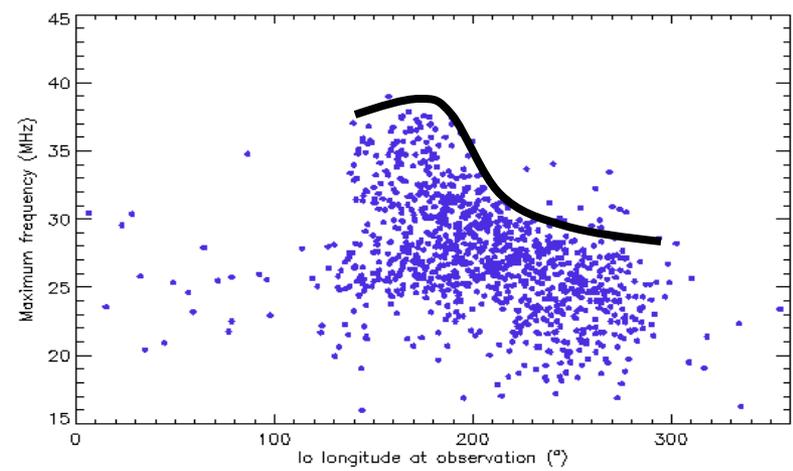
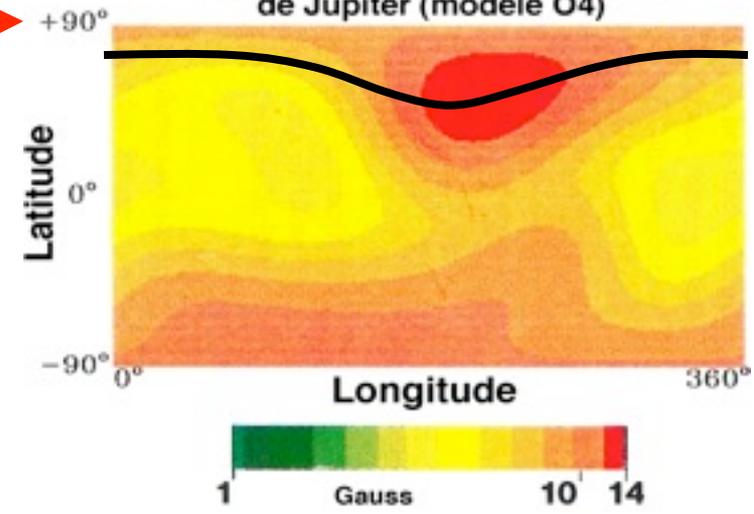
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dipole

	H4	VIP 4	Ulysses 17eV	O <sub>6</sub>	O <sub>4</sub>
$g_1^0$	4.30103	4.205	4.109	4.242	4.218
$g_1^1$	-0.69932	-0.659	-0.679	-0.659	-0.664
$h_1^1$	0.23753	0.250	0.229	0.241	0.264
$g_2^0$	-0.16931	-0.051	0.071	-0.022	-0.203
$g_2^1$	-0.60970	-0.619	-0.644	-0.711	-0.735
$g_2^2$	0.46864	0.497	0.464	0.487	0.513
$h_2^1$	-0.54471	-0.361	-0.309	-0.403	-0.469
$h_2^2$	0.28911	0.053	0.133	0.072	0.088
$g_3^0$	-0.08512	-0.016	-0.051	0.075	-0.233
$g_3^1$	-0.45039	-0.520	-0.157	-0.155	-0.076
$g_3^2$	0.18676	0.244	0.251	0.198	0.168
$g_3^3$	0.07755	-0.176	-0.043	-0.180	-0.231
$h_3^1$	-0.25561	-0.088	-0.150	-0.388	-0.580
$h_3^2$	0.59221	0.408	0.457	0.342	0.487
$h_3^3$	-0.25877	-0.316	-0.217	-0.224	-0.294
$g_4^0$	-0.34354	-0.168			
$g_4^1$	0.07479	0.222			
$g_4^2$	0.08283	-0.061			
$g_4^3$	-0.06446	-0.202			
$g_4^4$	-0.13662	0.066			
$h_4^1$	0.08630	0.076			
$h_4^2$	0.27332	0.404			
$h_4^3$	-0.27452	-0.166			
$h_4^4$	0.02801	0.039			



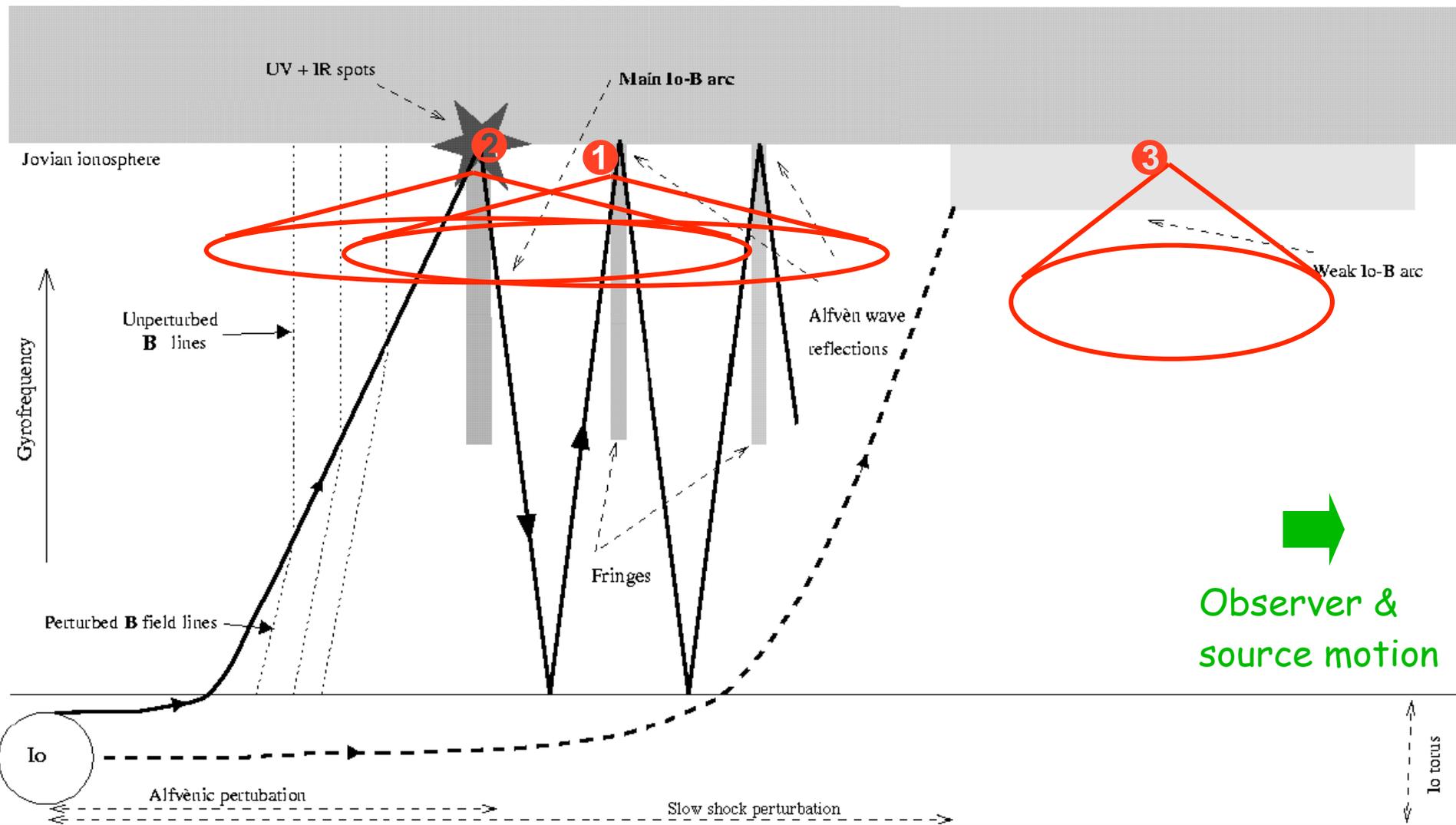
Champ magnétique à la surface de Jupiter (modèle O4)



# Radio imaging of Jupiter with $\sim 1''$ resolution from Earth

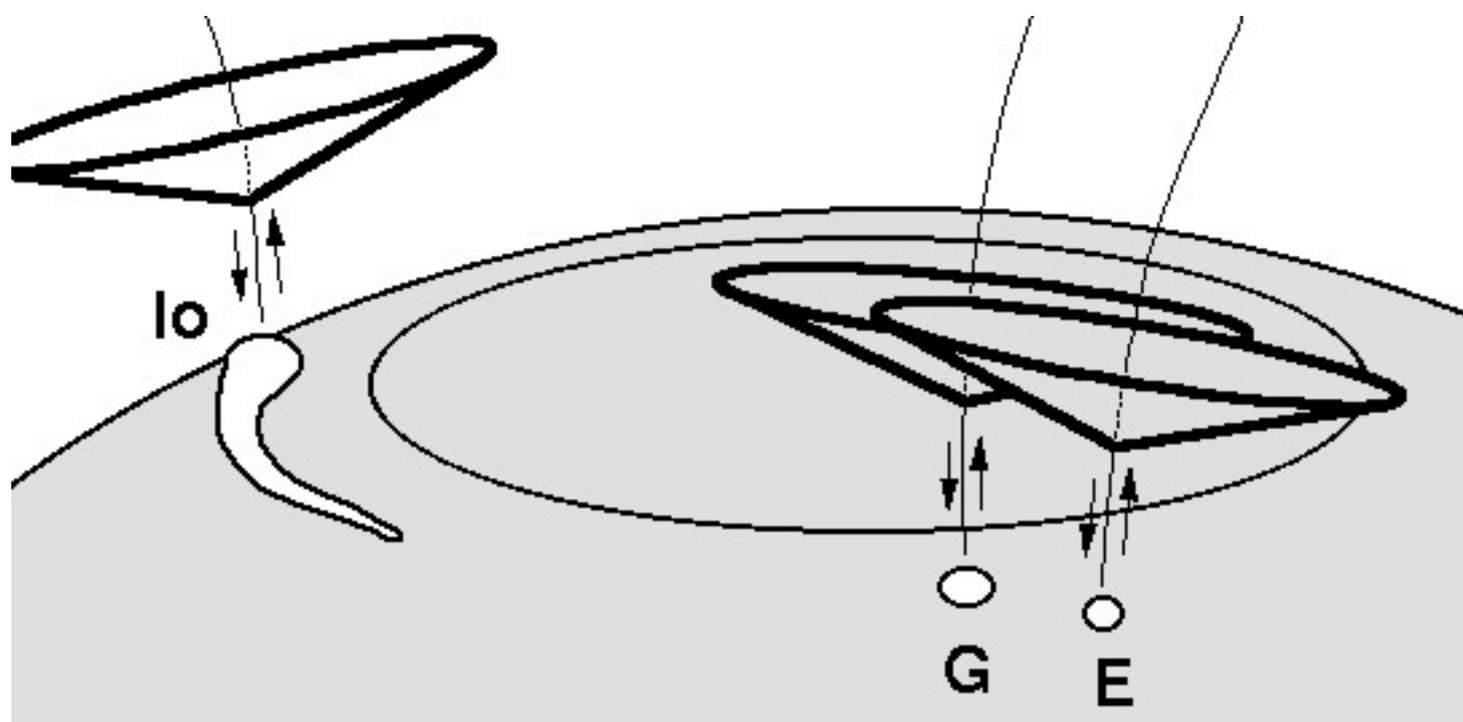
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# The Io-B scenario #2



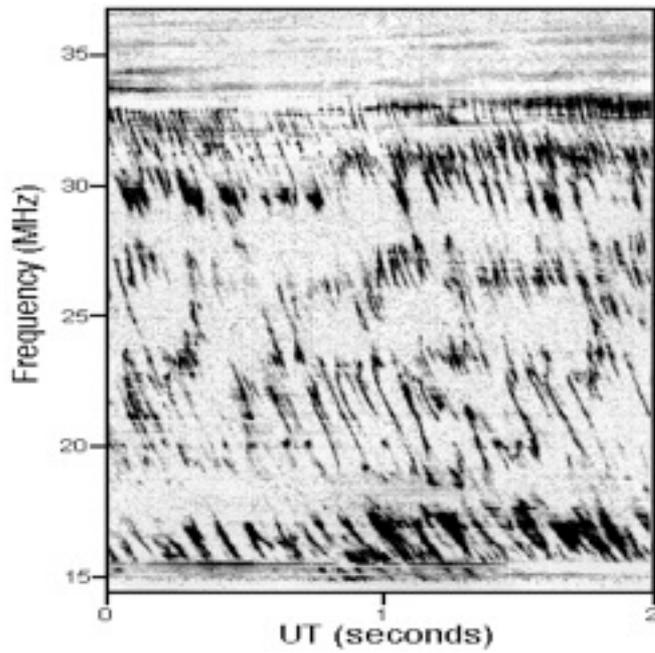
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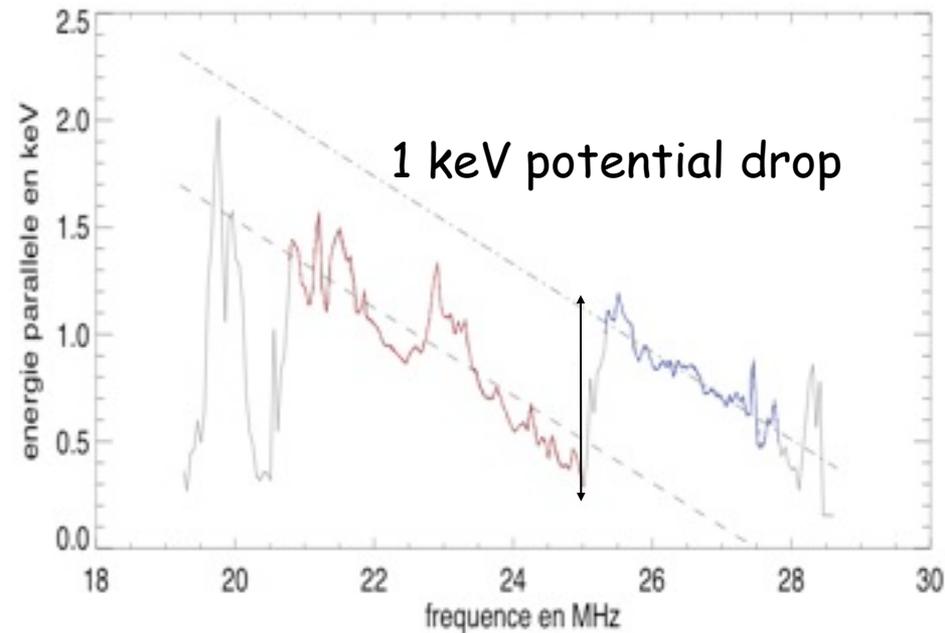
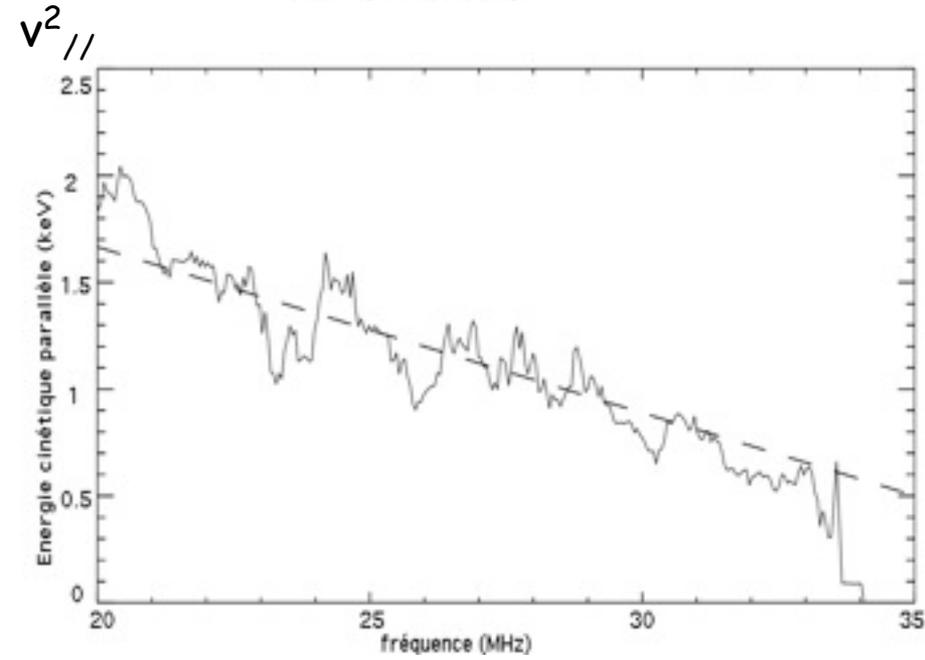
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adiabatic motion  $\rightarrow v_{//}^2 = v^2 - v_{\perp}^2 = v^2 - \mu \cdot f_{ce}$

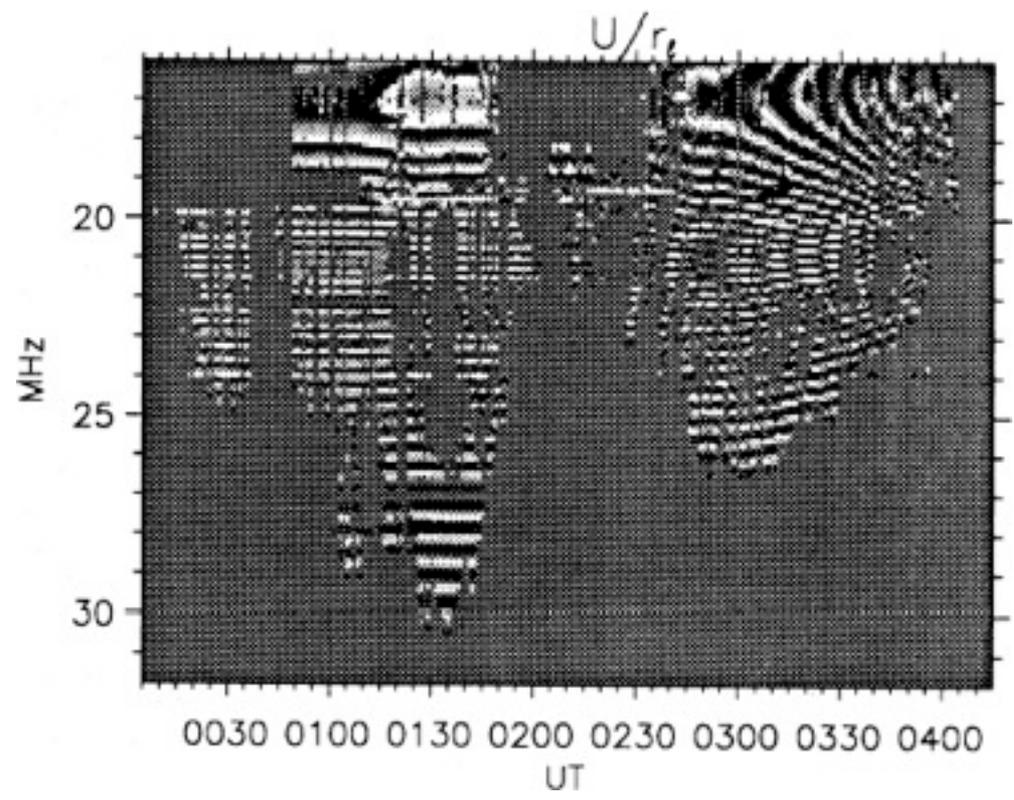
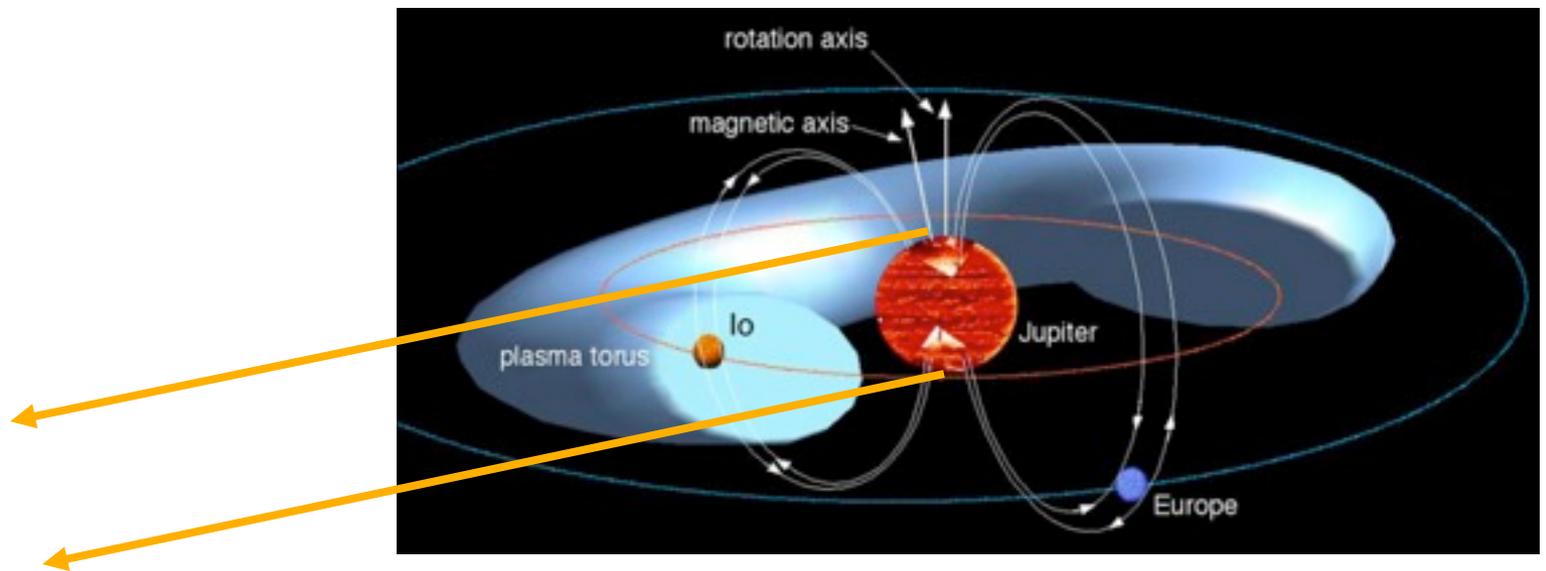
[Hess et al., 2006]



$f_{ce}$

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Frequency (MHz)

79-07-27

LH

20

30

20

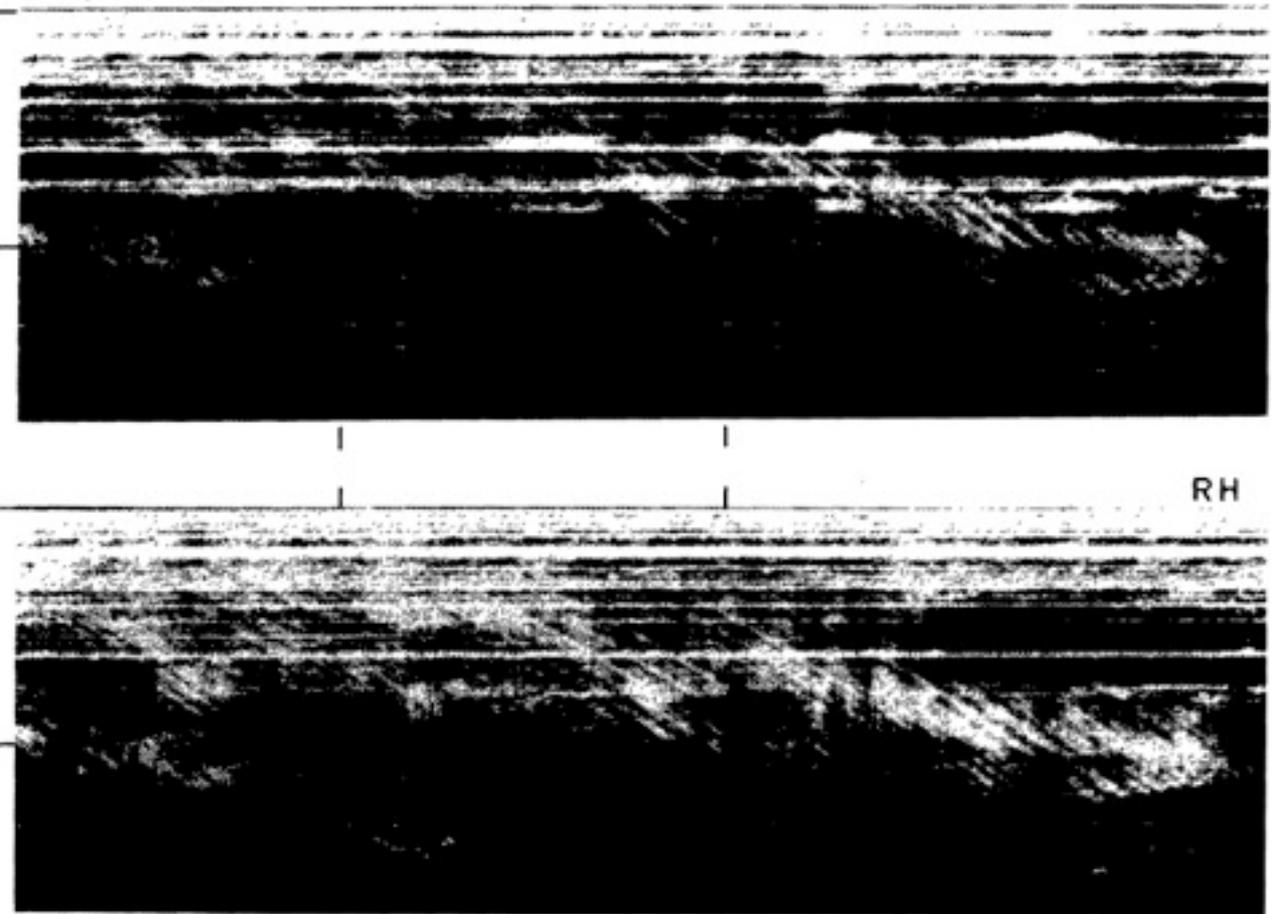
30

RH

14.25  
CML=132.4  
 $\Phi_{10} = 95.7$

14.26  
CML=133.0  
 $\Phi_{10} = 95.9$

Time (U.T.)



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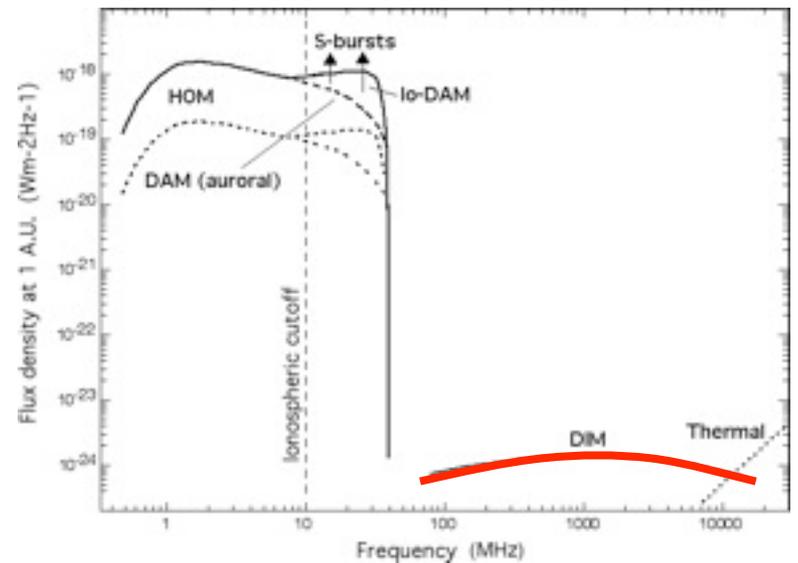
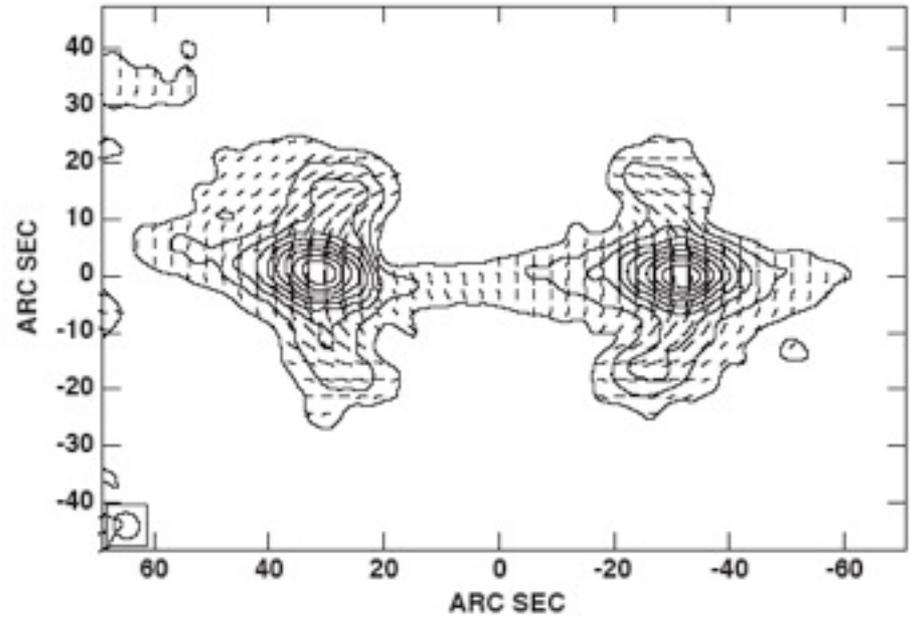
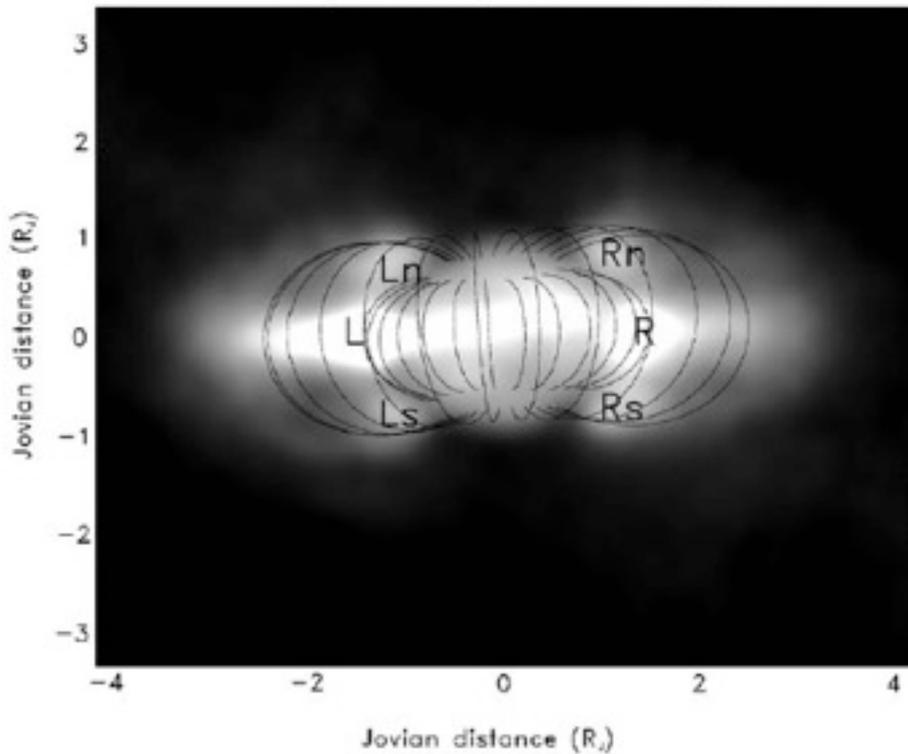
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- $\rightarrow$  LOFAR fast imaging should provide NEW information about Jupiter's magnetospheric structure and dynamics**

# Radio imaging of Jupiter Radiation Belts

[de Pater, P&SS, 2004]

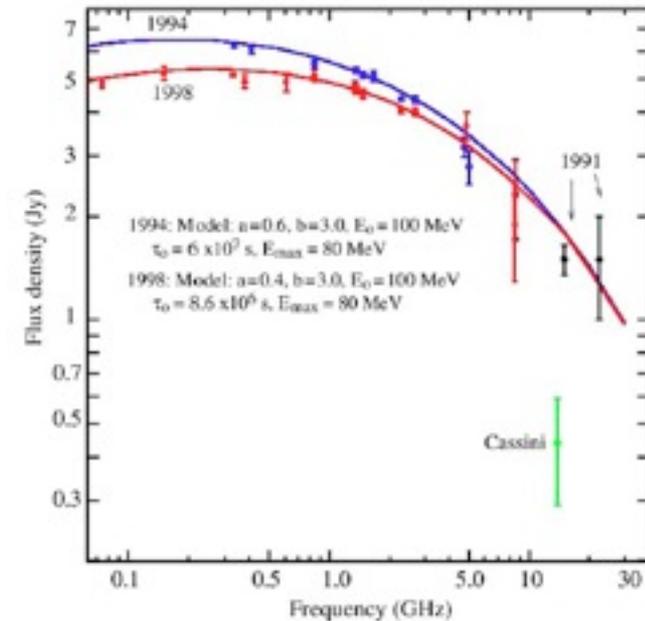
Jupiter, longitude 312 deg.



# Radio imaging of Jupiter Radiation Belts

[de Pater, P&SS, 2004]

- high spatial resolution imaging  $\leq 240$  MHz (« low » energy  $e^-$ ) over a large relative bandwidth
- variation with time and solar wind parameters
- origin and transport of energetic  $e^-$  in Jupiter's inner radiation belts : pitch-angle scattering by PW, coulomb scattering, interaction with dust ?
- + emission from Saturn, Uranus, Neptune ?



## Instrumental constraints (for magnetospheric radio emissions)

- ❑ Arcsec (1"-4") resolution imaging of planetary disk environment (~10', including Io's plasma torus).
- ❑ Frequency range = 10-40+ MHz (instantaneous).
- ❑ Spectral resolution = 10-50 kHz.
- ❑ Time integration ~ 1-1000 msec (typical Jovian burst duration).
- ❑ Full polarization.
- ❑ Emission intense, with bursts up to  $10^{5-6}$  Jy, dynamic range 20-30 dB.
- ❑ Observation sequences of minutes to tens of minutes (Jovian radio « storm » duration, source tracking), at intervals of days/weeks.
- ❑ Partial predictability of Jovian radio emission.
- ❑ RFI mitigation required + quiet ionosphere better.

# **Feasibility of LF (20-25 MHz) VLBI measurements with a ~800 km baseline**

P. Zarka, A. Nigl, L. Denis, L. Bahren, H. Falcke et al.,  
(+ acknowledgements to S. Hess for help with observations)

*25 September 2006*

## • Radio decameter VLBI tests

- ❑ Target resolution :  $\sim 1''$ , 1 msec, 1 kHz @ 30 MHz
- ❑ Aim: LF radioastronomy with high angular resolution

## • Influence of ionosphere :

- ❑ Loss of phase coherency, dispersion in frequency, Faraday rotation, refraction
- ❑ Limitation of coherence time, usable spectral band, self-cal capabilities

## • Previous studies

- ❑ Jupiter @ 34 MHz, baseline 4300 km [Dulk, *Astrophys. J.*, 1970]
- ❑ Radiosources @ 81.5 MHz, baselines  $\leq 1500$  km [Hartas et al., *MNRAS*, 1983]
- ❑ Radiosources @ 20 & 25 MHz, baseline 900 km [Megn et al., *Radio Phys. and Radio Astron.*, 1997]

## • Problematic : % de feasibility as a function of $f$ , $t$ ... ?

## • Observation of Jupiter's "millisecond" radio bursts

❑ LOFAR-ITS [H. Falcke, A. Nigl, et al.] + NDA [P. Zarka, L. Denis, et al.] (11/2005)



❑ 10-40 MHz, baseline ~750 km, remote control ITS, synchro GPS/crystal, "snapshots" of 6.7 sec

❑ radiosource ~point-like,  $10^{5-6}$  Jy, sporadic, wave packets ~0.1 msec

❑ cross-correlation of dynamic spectra → data time-stamping

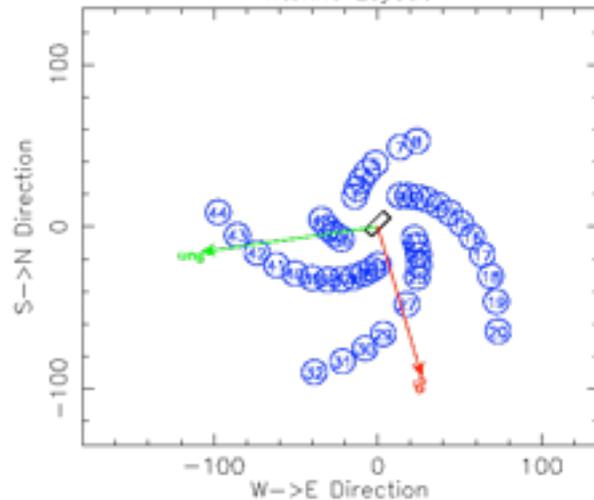
❑ waveforms cross-correlation → OK!

[http://www.astron.nl/~bahren/wiki/doku.php?id=research:nda-its\\_observations\\_of\\_jupiter](http://www.astron.nl/~bahren/wiki/doku.php?id=research:nda-its_observations_of_jupiter)

# Instruments: ITS



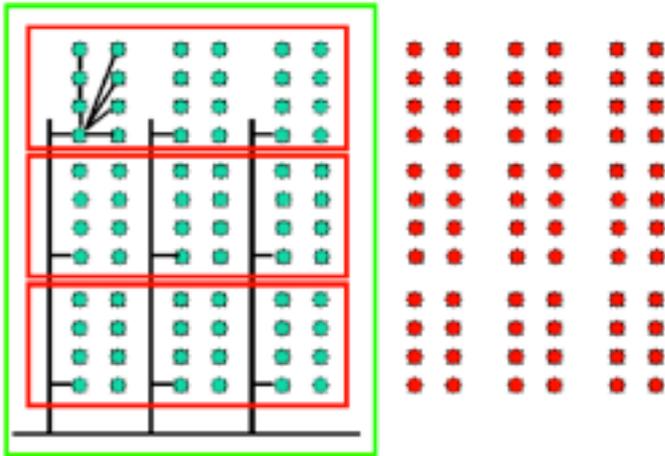
Antenna Layout



## LOFAR Initial Test Station

- 60 (30x2) dipoles
- < 40 MHz
- digitization (80 Msamples)
- storage (1GB = 6.7s)
- offline time-beam-forming

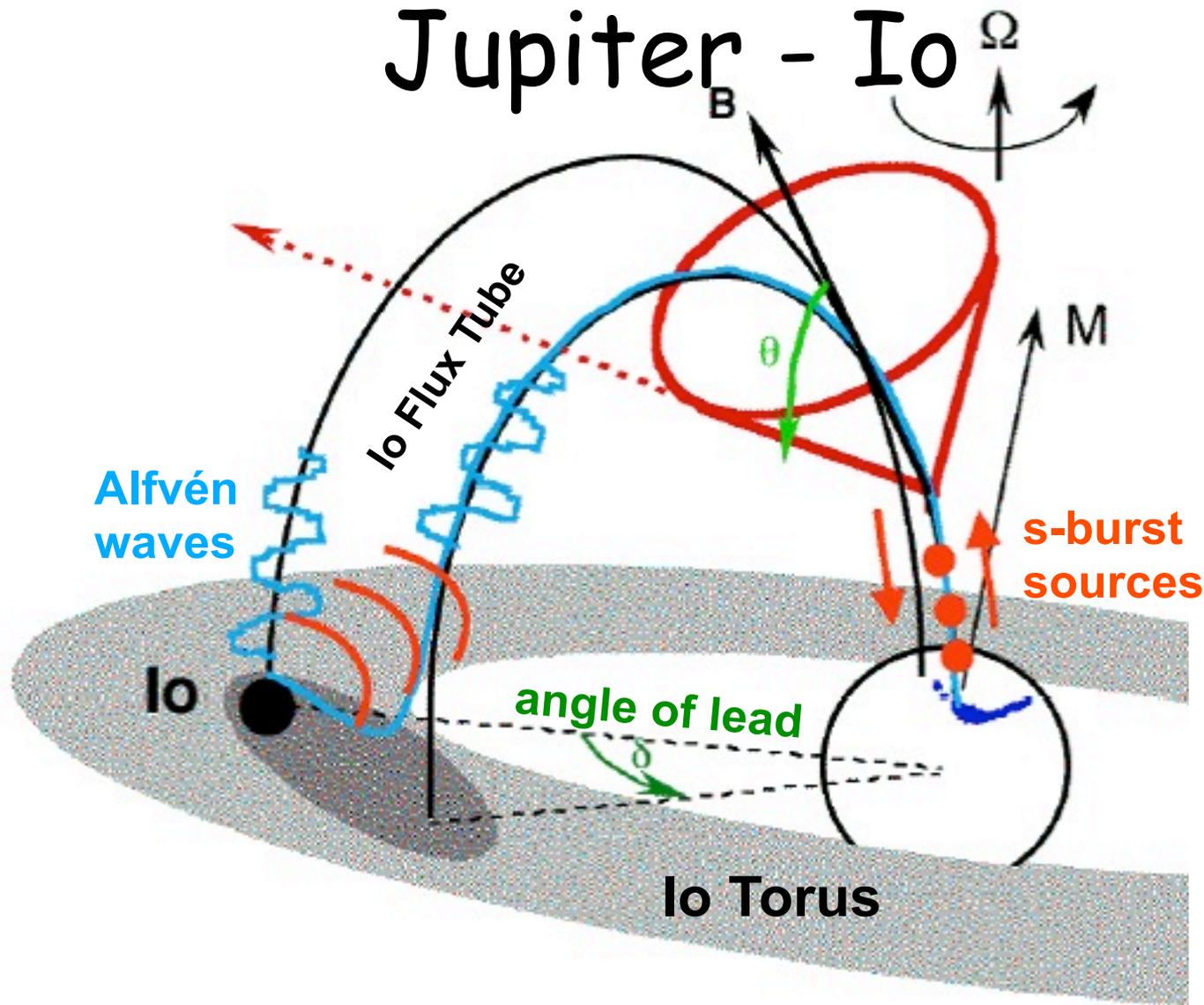
# Instruments: NDA



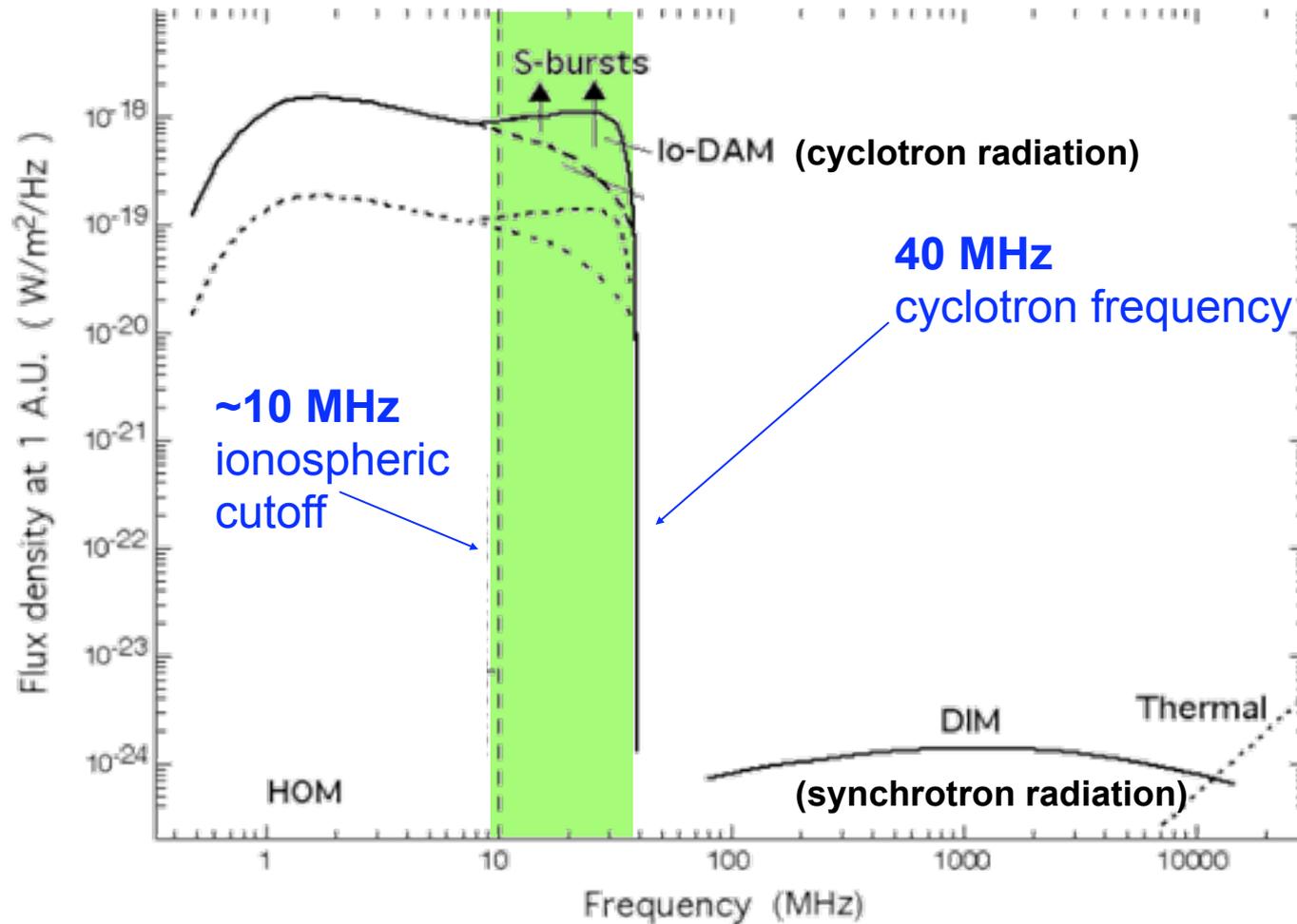
## Nancay Decametric Array

- 72 spirals (RH wounded)
- < 40 MHz
- analog beamforming
- digitization (80 Msamples)
- storage

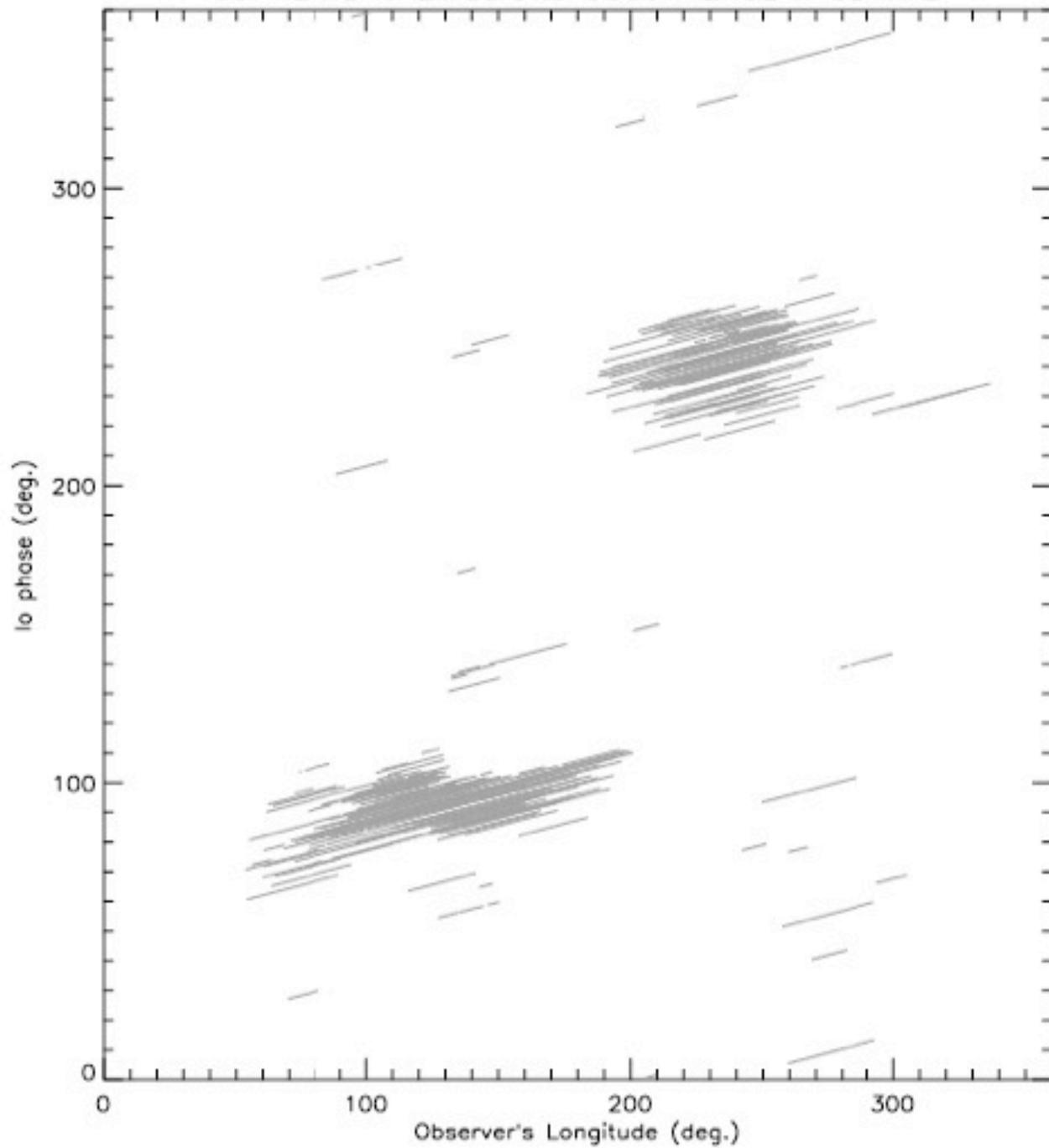
# Jupiter - Io



# Jupiter - Io: Frequency Window

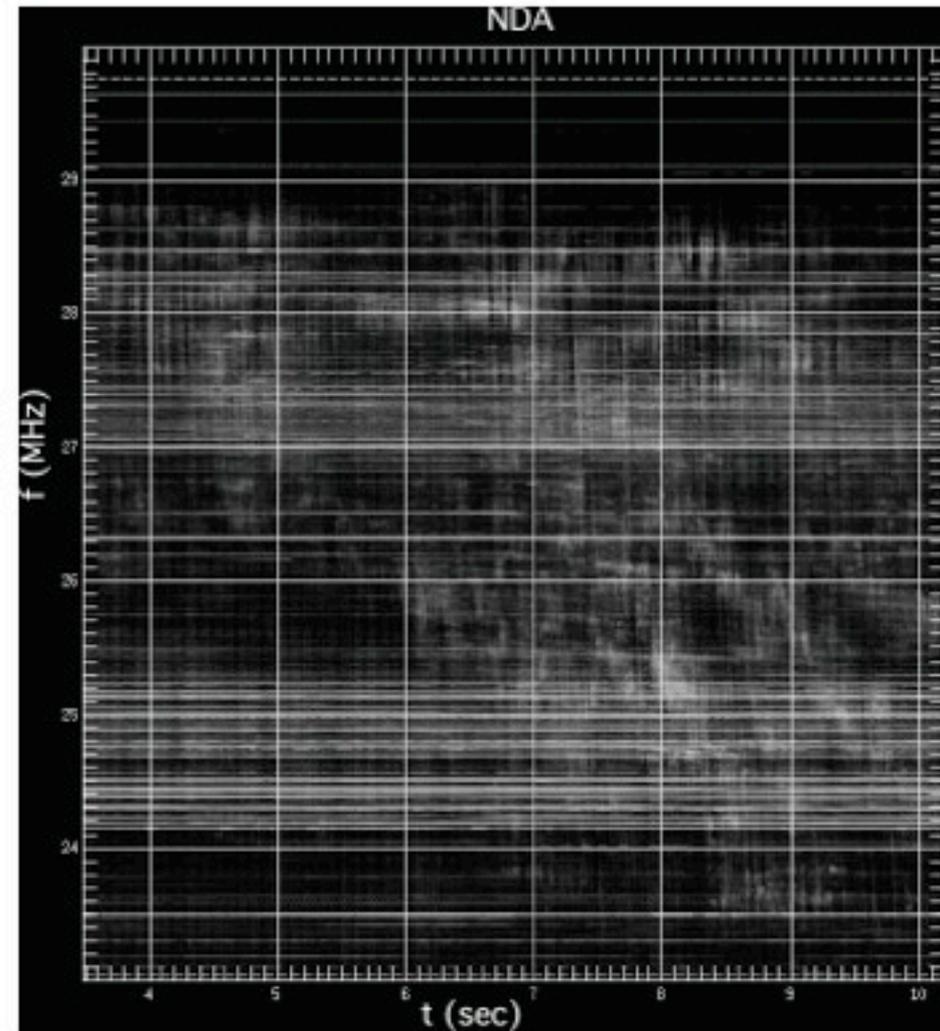


JUPITER DAM EMISSIONS OCCURRENCE > 32 MHz

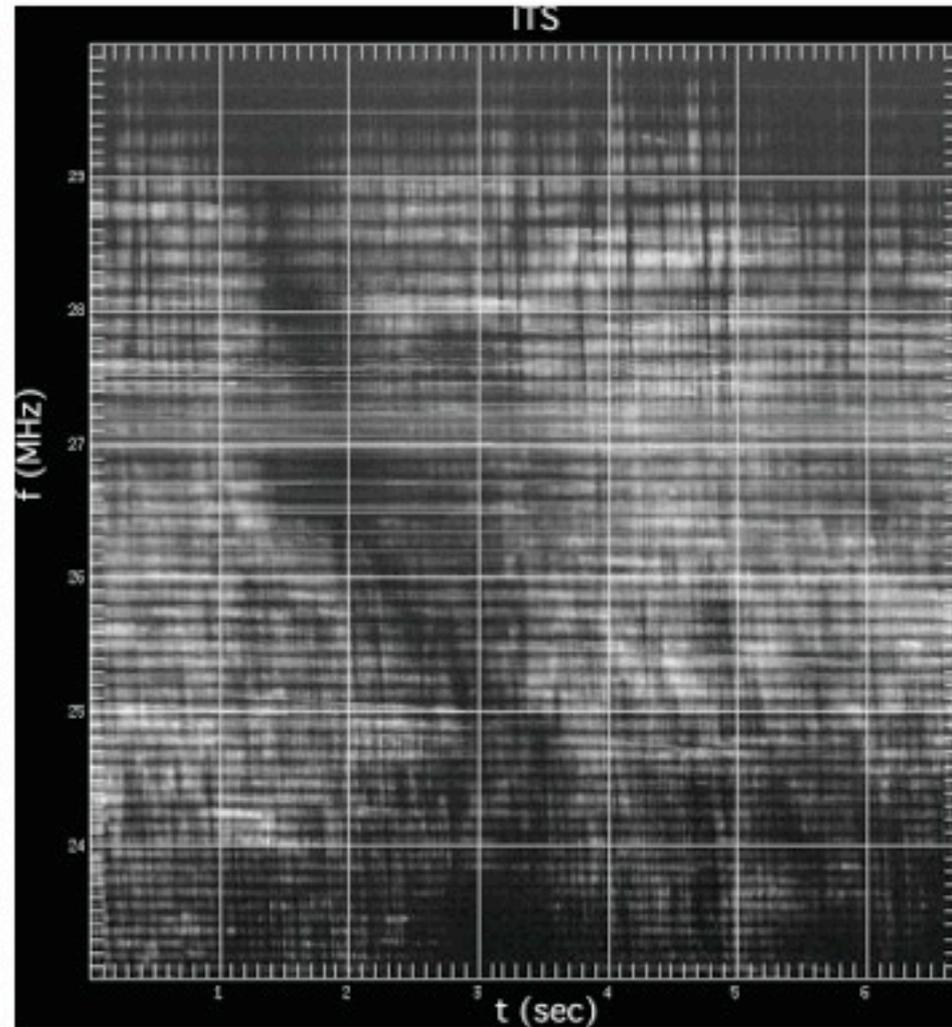


22/6/2004

NDA



IIS



30/11/2005

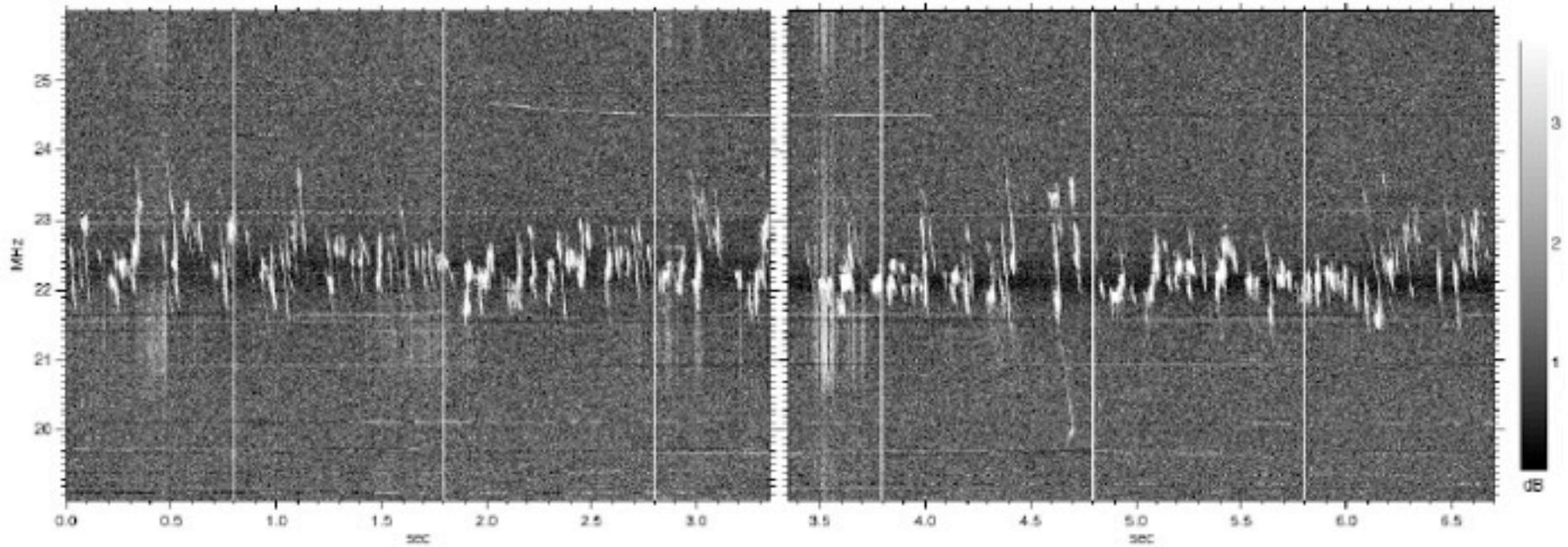
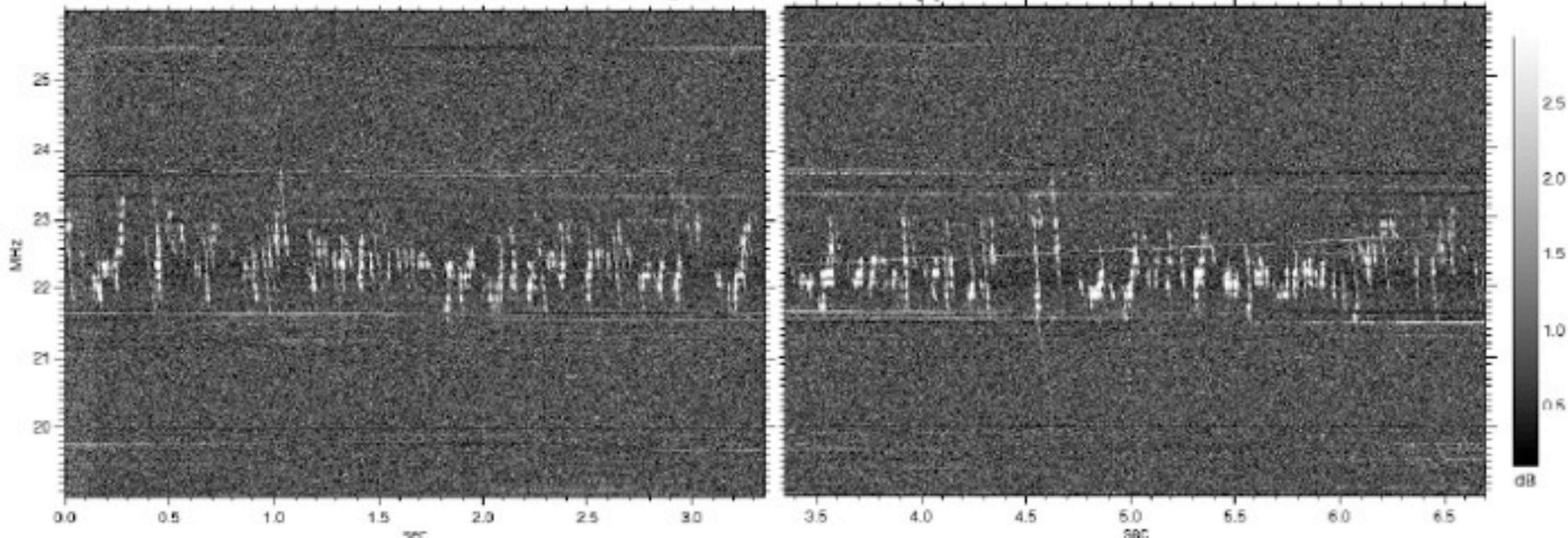
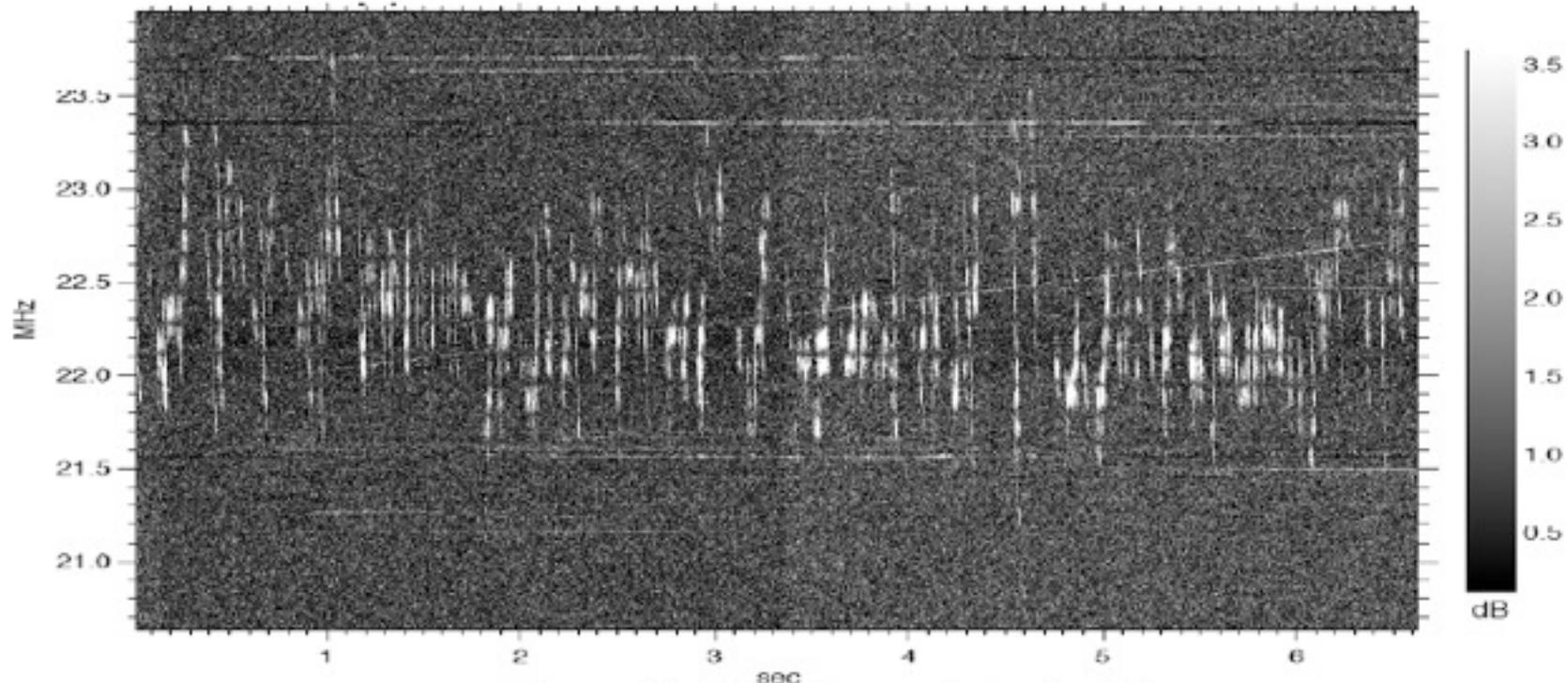


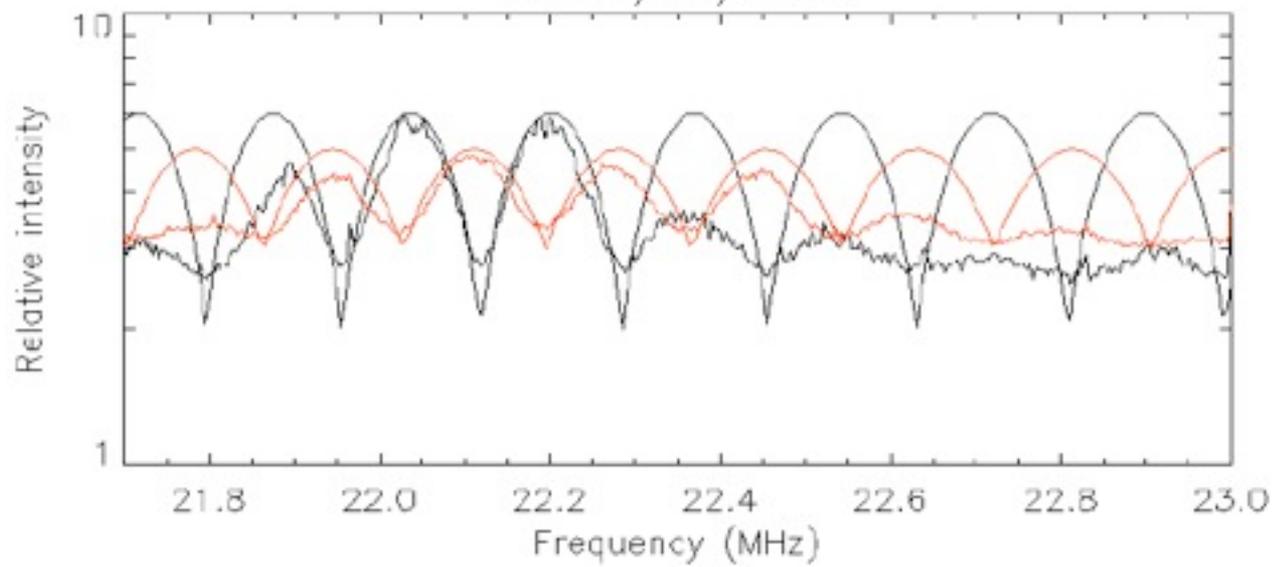
Figure 3a (Nançay)





**Figure 4b (ITS : linear polarization E)**

ITS 30/11/2005



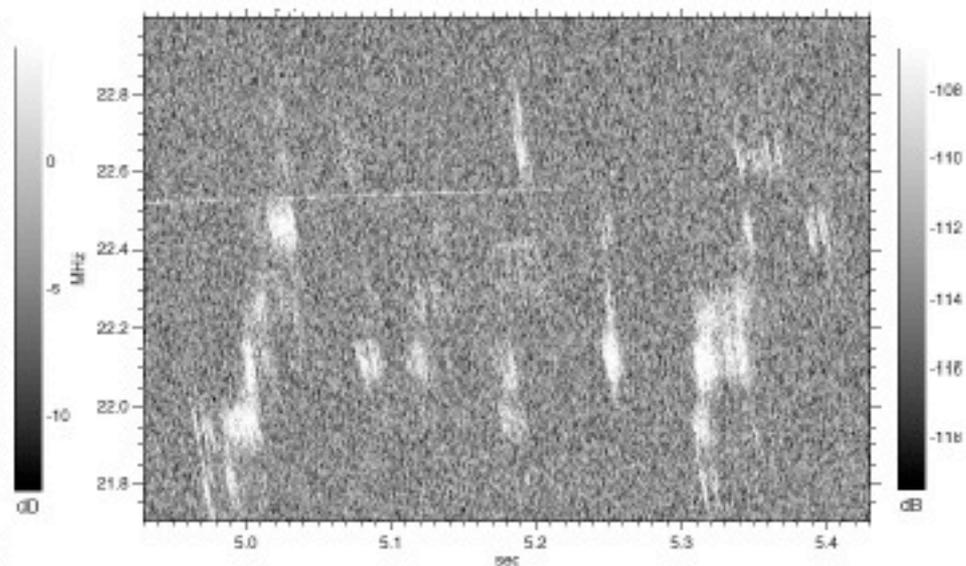
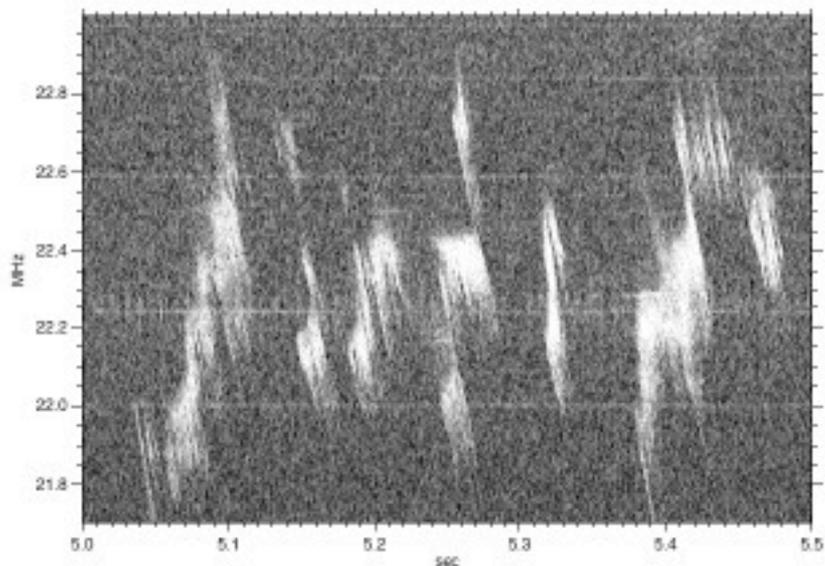
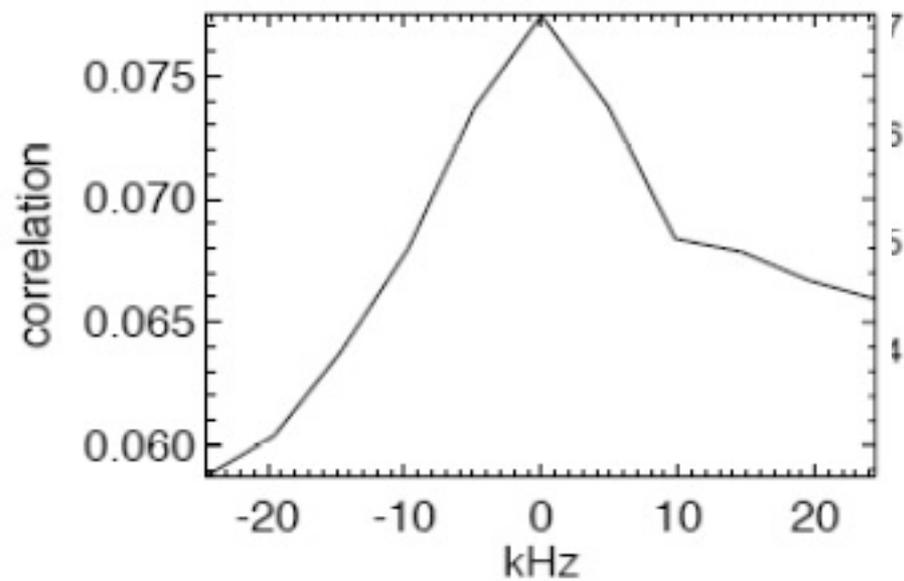
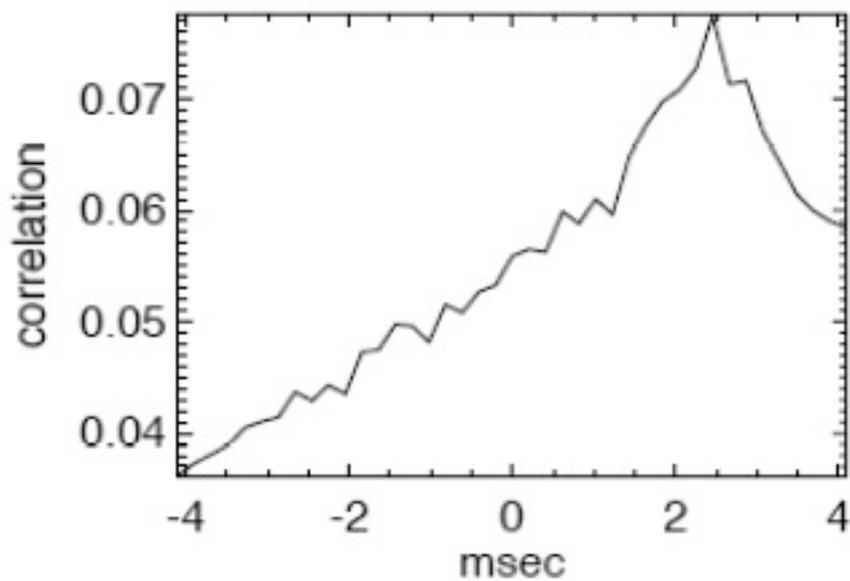
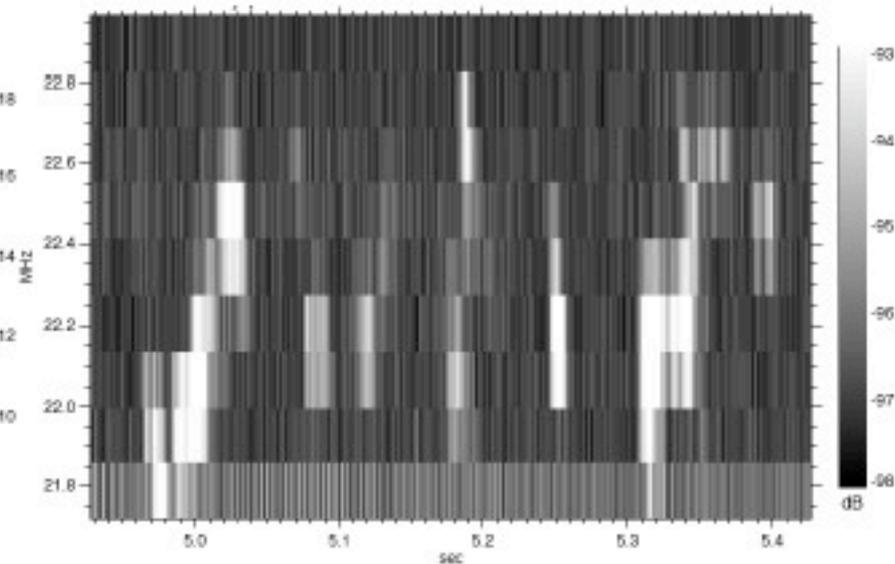
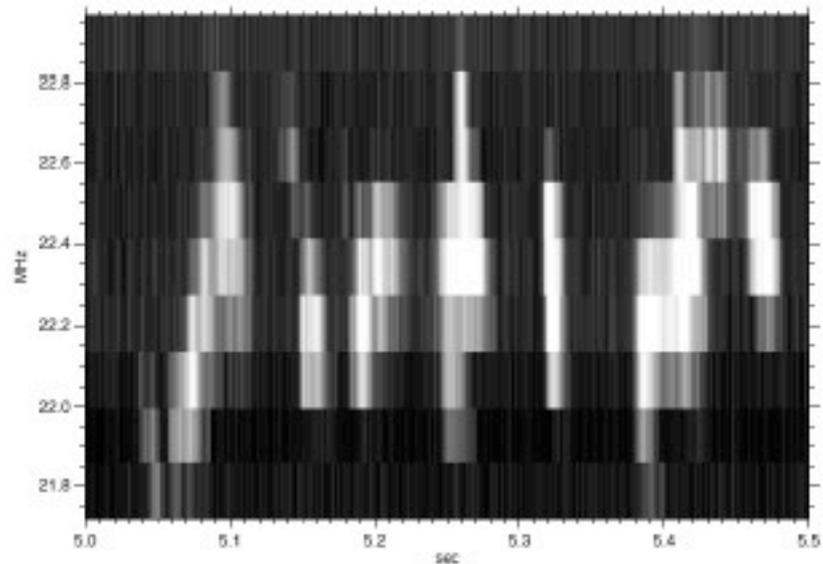
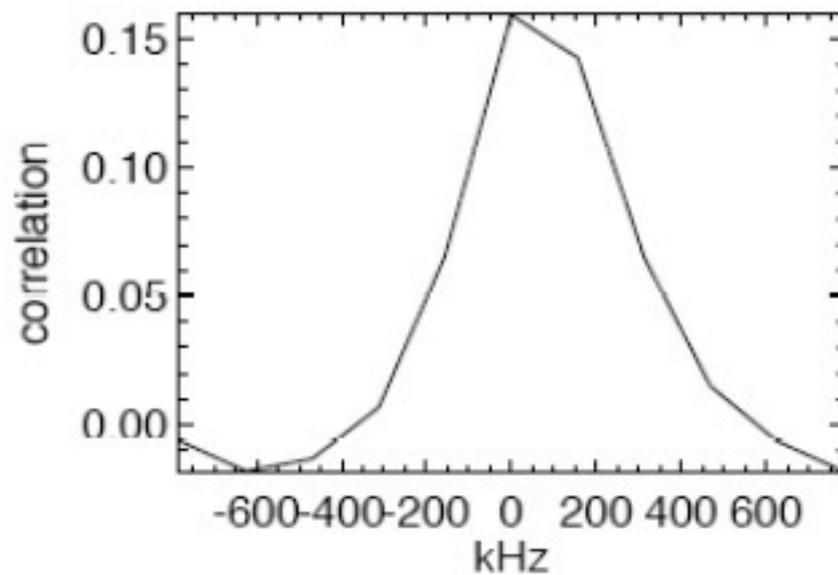
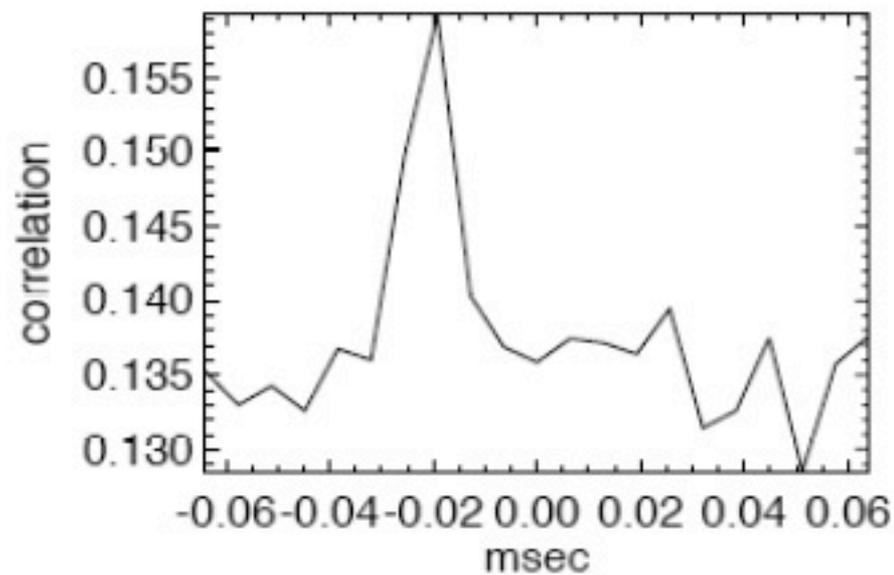


Figure 6a





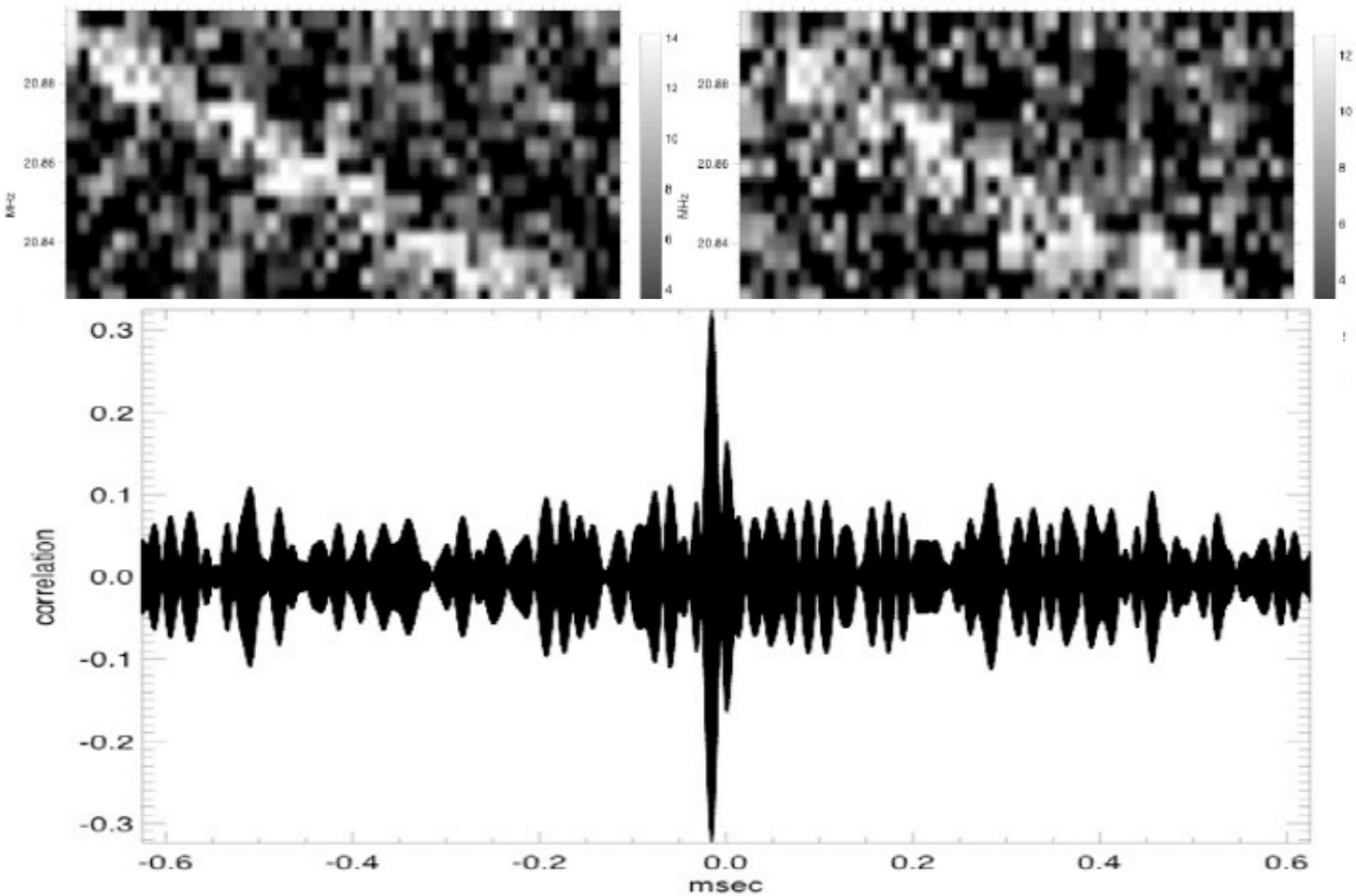
**Figure 6d**

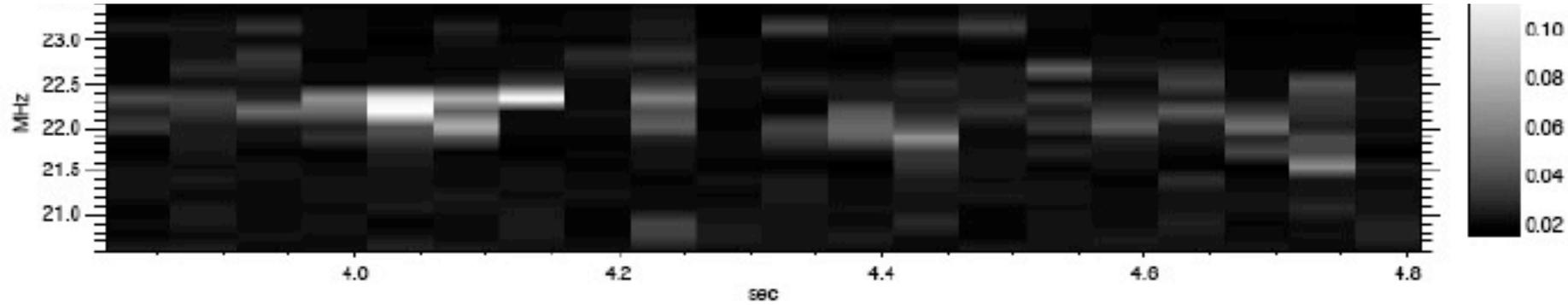
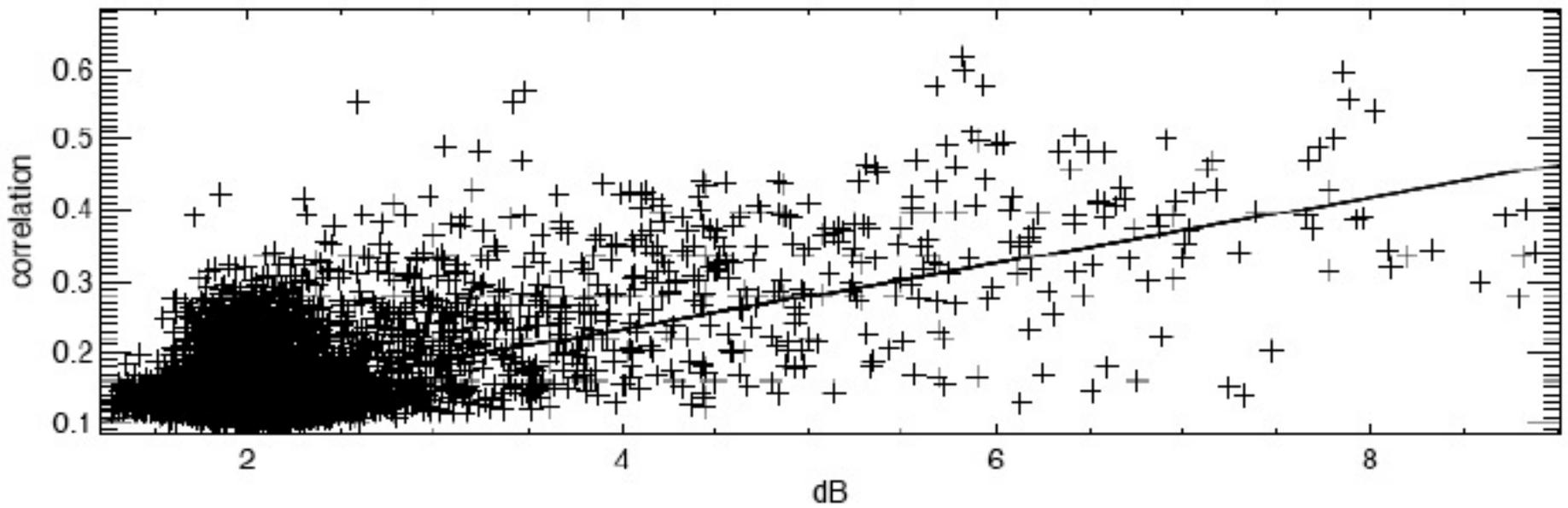
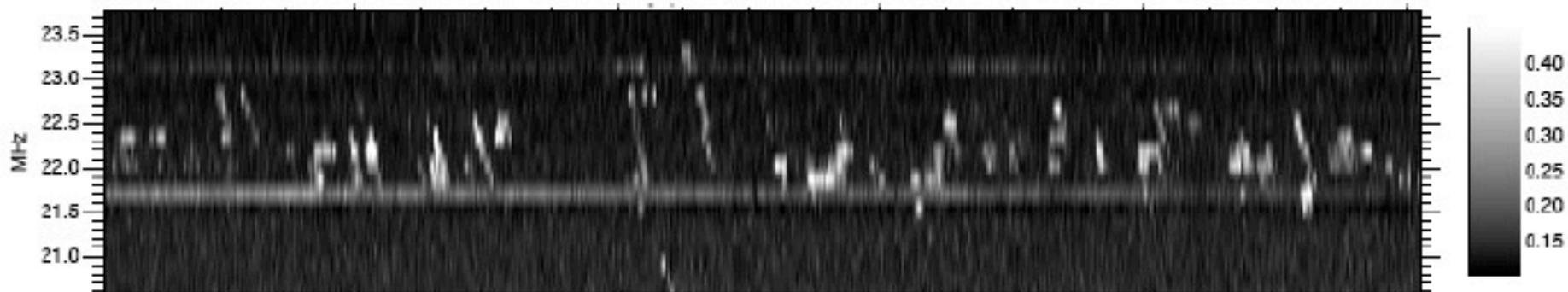


**Figure 6e**

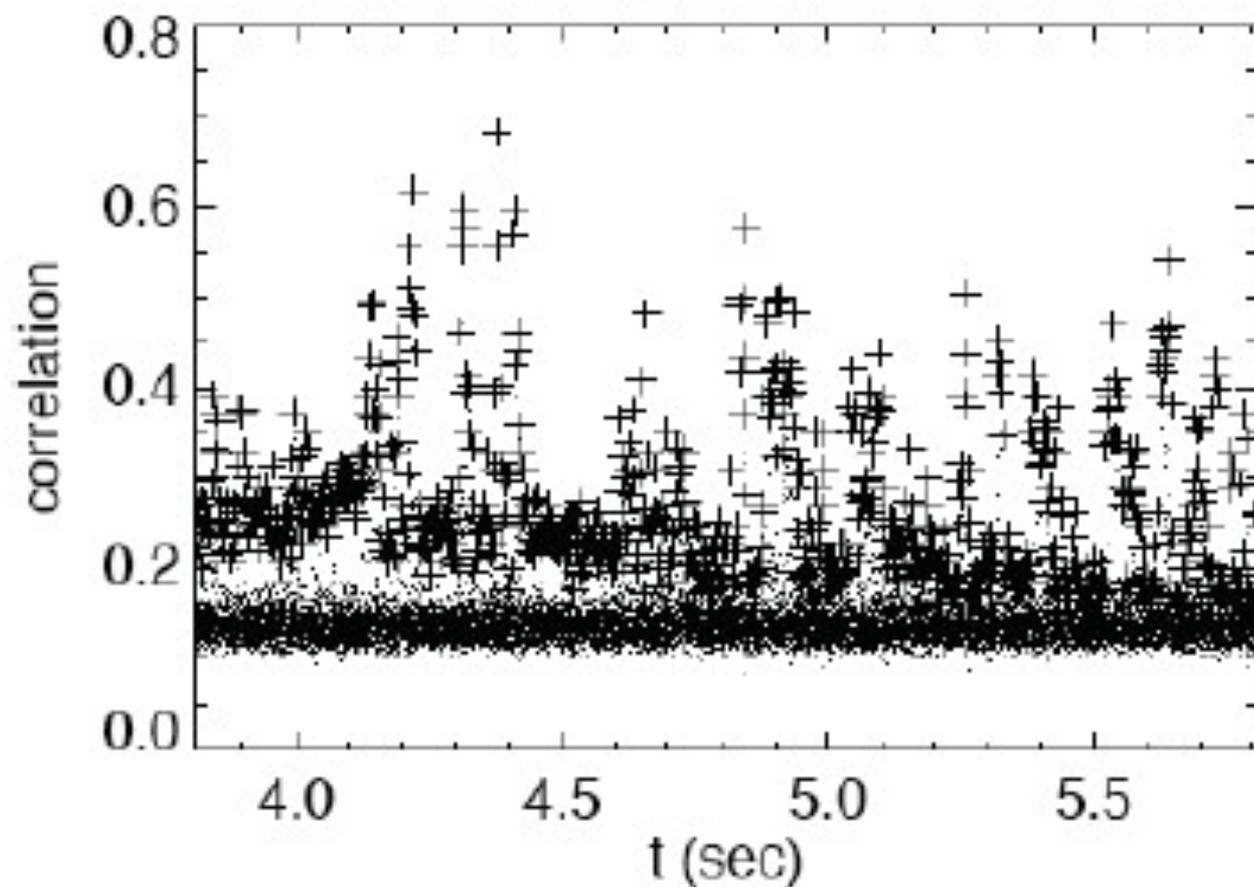
$$t_{\text{Nançay}} - t_{\text{ITS}} = 0.072379 \text{ sec.}$$

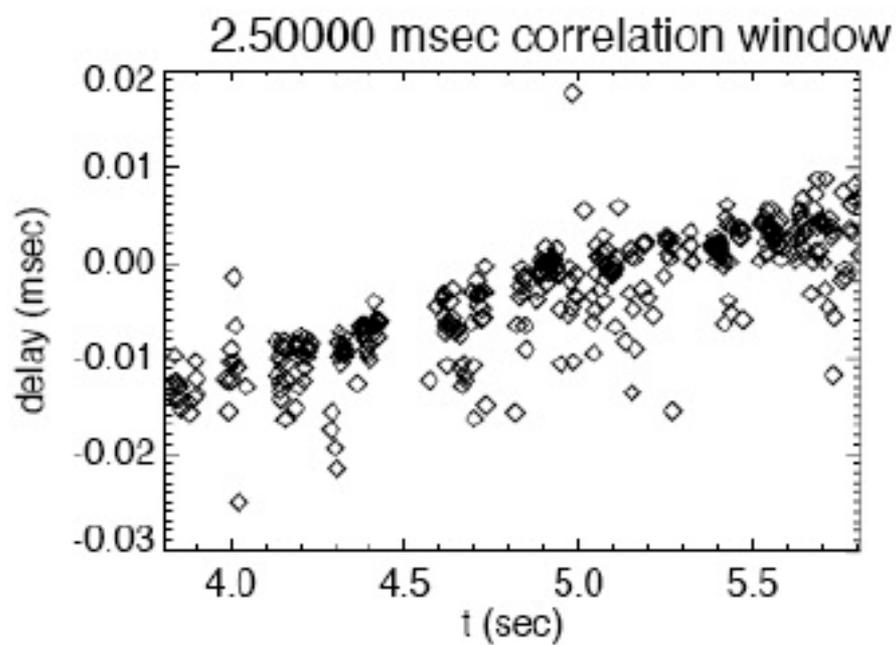
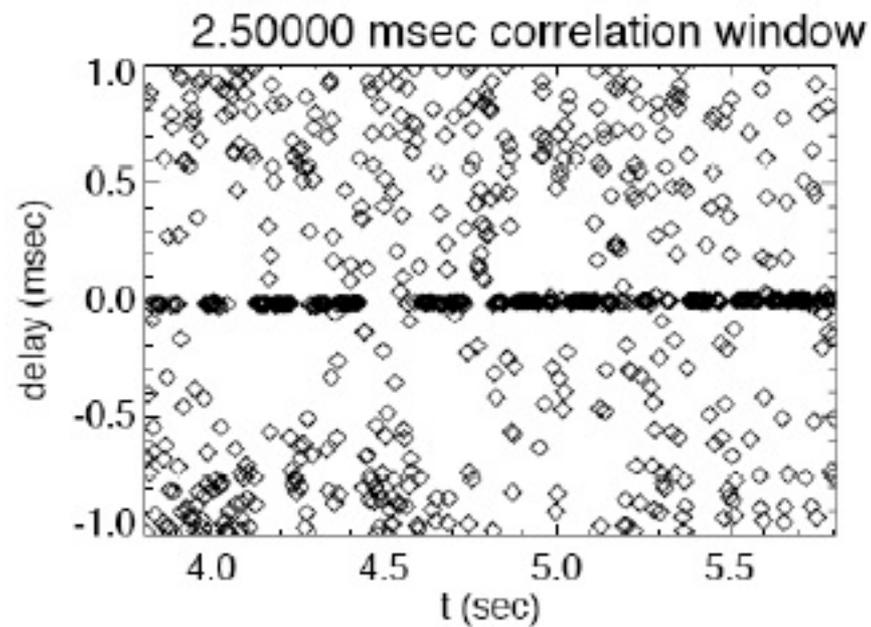
$$C = FT^{-1}[FT(W_N) \times FT(W_I)^*] / (\sigma_{W_N} \cdot \sigma_{W_I})$$





### 2.50000 msec correlation window





## Conclusions

This work demonstrates the feasibility of phase interferometry at 800 km distance at  $\sim 22$  MHz ( $\sim 60000 \lambda$ ), confirming earlier studies (cf. related bibliography below). Phase shifts and variations introduced by ionospheric propagation do not destroy phase coherency between Nançay and ITS over 10's to 100's msec. It is the first time that VLBI-type observations are performed over a broad relative bandwidth with baseband digitization, and direct correlation over the 12- or 14- bit signals. The results support the european extension of LOFAR to baselines of several 100 km, and in particular a LOFAR station in Nançay.

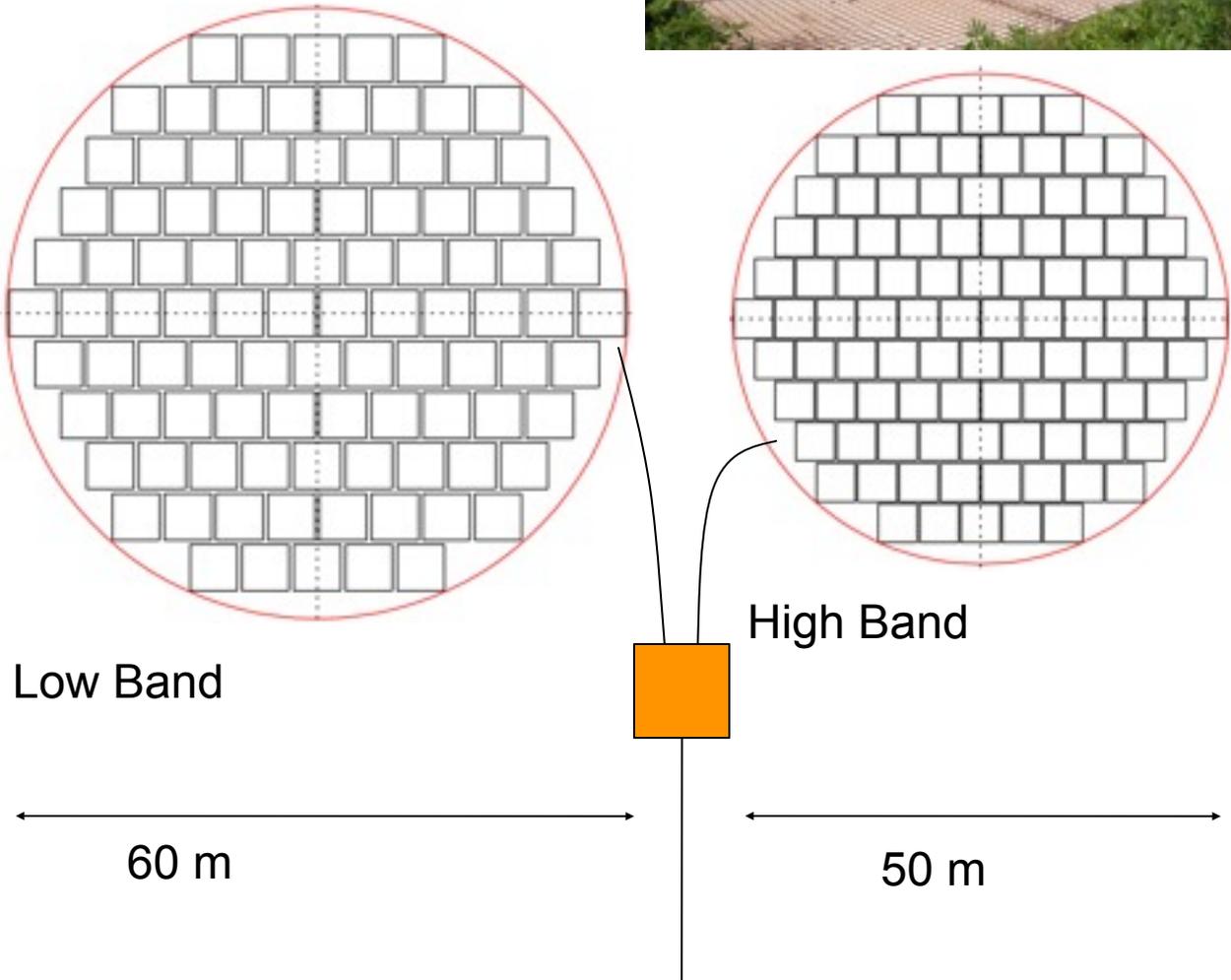
Work remaining TBD :

- Compute fringe visibilities, infer upper limit on source size at 22 MHz. →  $\sim 1$
- Interpret observed variations (of correlation coefficient and delay). → ITS time base  
(can be corrected)
- Synthesize RHC polarization with ITS and redo correlation.
- Compute visibilities over much narrower frequency intervals.
- Redo regular observations (with NDA and LOFAR core station CS#1) to quantify what % of the time phase coherency is preserved, as a function of time and frequency. → submitted
- Use weaker radiosources (e.g. Cas A or Tau A which have a core source size of resp. 3" and 1.5").
- ...

# Conclusions

- Prospective en France depuis 2002
- Atelier fondateur au CIAS-Meudon, 3/2006 : « LOFAR : Radioastronomie basses fréquences à une résolution de quelques secondes d'arc (Astrophysique, Cosmologie et Astroparticules) Vers une participation française ... »  
<http://www.lesia.obspm.fr/plasma/LOFAR2006/>  
→ ~40 participants
- Argumentaire scientifique FLOW (M. Tagger & al.) 
- Demande INSU 10/2006 pour 1 station à Nançay (M. Tagger & PZ)
- Études à venir pour une « super-station »
- TKP : (exo-)Planets SWG :  
PZ, G. Woan, J.-M. Griessmeier, D. Stam, H. Spreeuw, T. Bastian, I. de Pater  
.... 
- Observations VLBI CS-1 / Nançay (soumises)

Station : cost ~600 k€ +  
optical fiber link 3 Gbps



## European Expansion ...

A map of Europe with a dark blue background. Numerous glowing yellow dots are scattered across the continent, representing stations. Dotted lines connect these dots, showing various routes and connections between them. The dots are more densely packed in the central and western parts of Europe, with lines extending towards the north, south, and east.

Current discussions:  
Germany ~12 stations  
UK ~2-3 stations  
Italy ~2 stations  
France ~1 station?  
Poland ~1 station?