Decameter Radioastronomy: from the Nançay Decameter Array to LOFAR

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- Jupiter's radiophysics unveiled by 2 decades of decameter observations in Nancay

- Fast LF radio imaging of Jupiter’s magnetosphere with arcsecond resolution

- Long baseline interferometry test on Jupiter with NDA and LOFAR

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- Discovery of Jovian Radio emissions (DAM) using Mills cross array at 22 MHz [Burke & Franklin, 1955], circularly polarized [Franklin & Burke, 1956]
  → cyclotron emission

- Synchrotron decimeter emission from radiation belts [Sloanaker, 1959]
  → magnetic field and magnetosphere

VARIABLE RADIO SOURCE ASSOCIATED WITH JUPITER 215

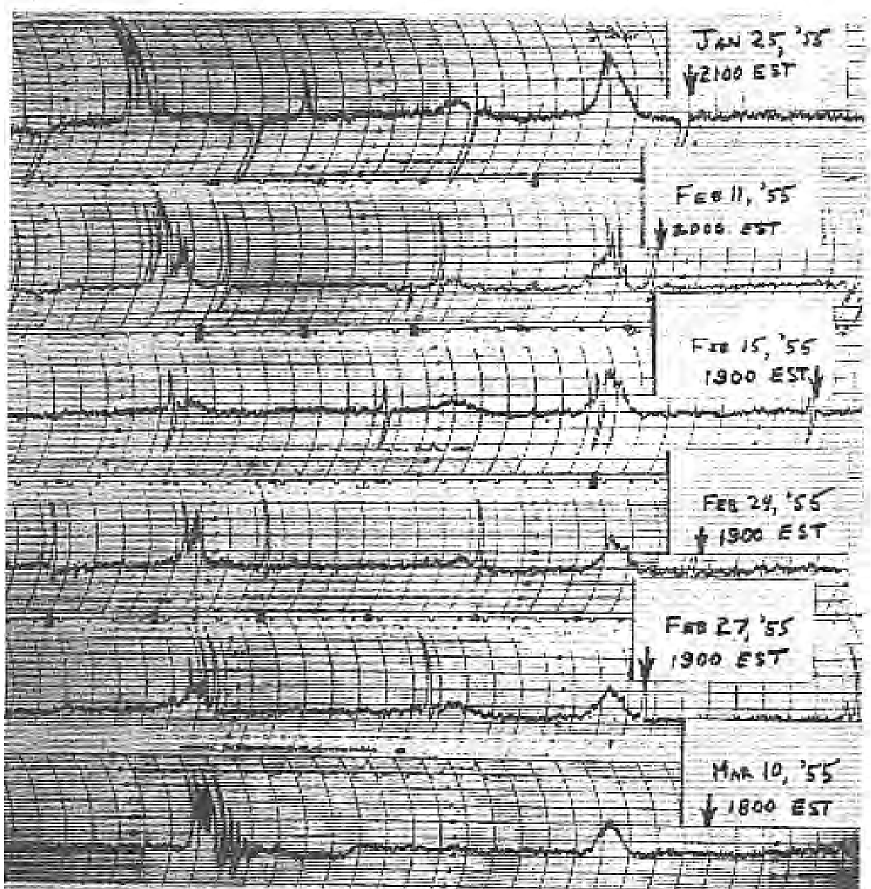
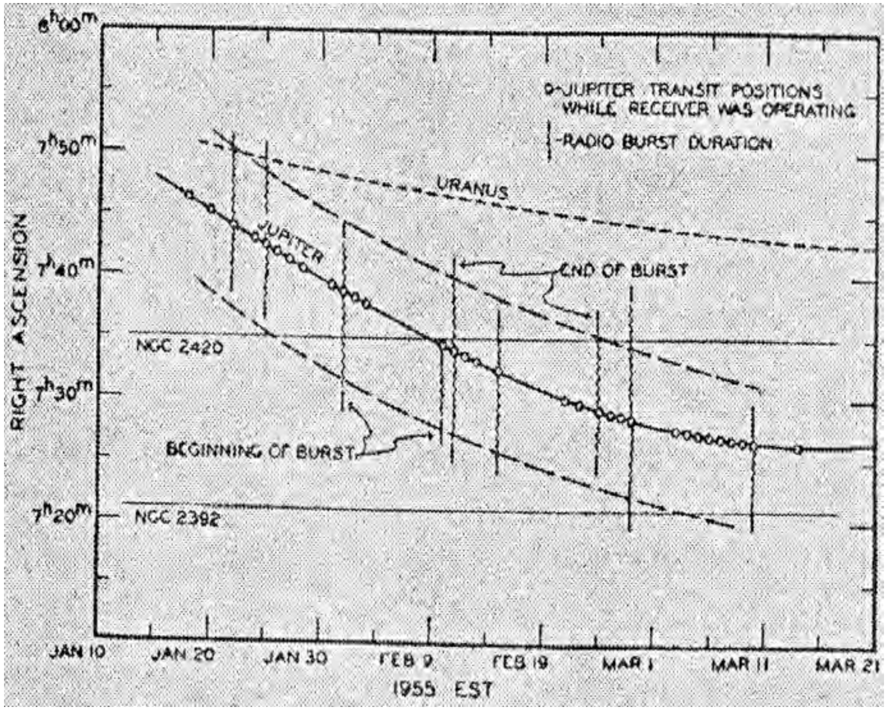
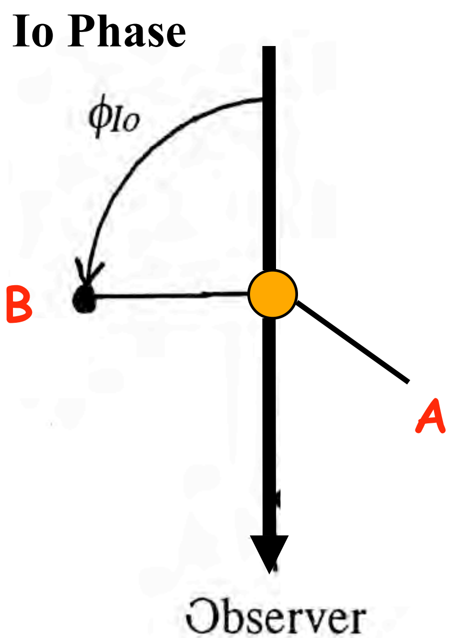


FIG. 2—Phase-switching records showing the appearance of the variable source



• Discovery of Io control [Bigg, 1964]



T_{Io}~42 hours

T_J ~10 hours

September 5, 1964 NATURE

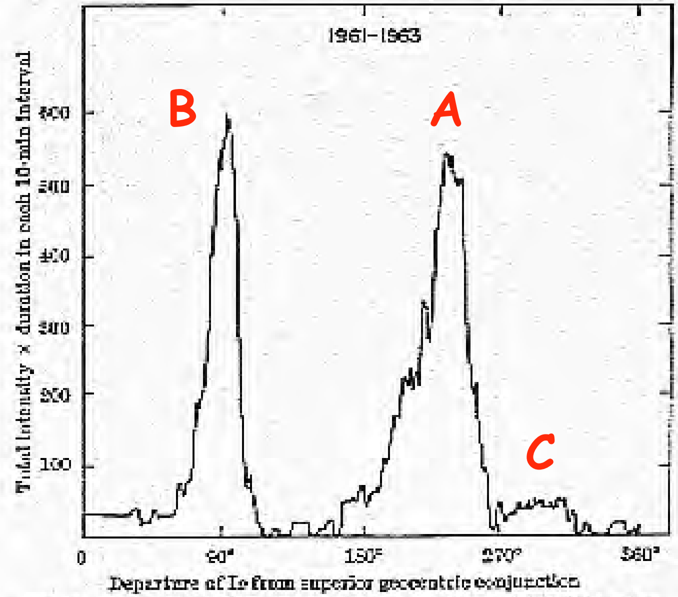


Fig. 4. Dependence of Jupiter's emission on the position of Io when only cases having top frequencies ≥30 Mc/s are considered

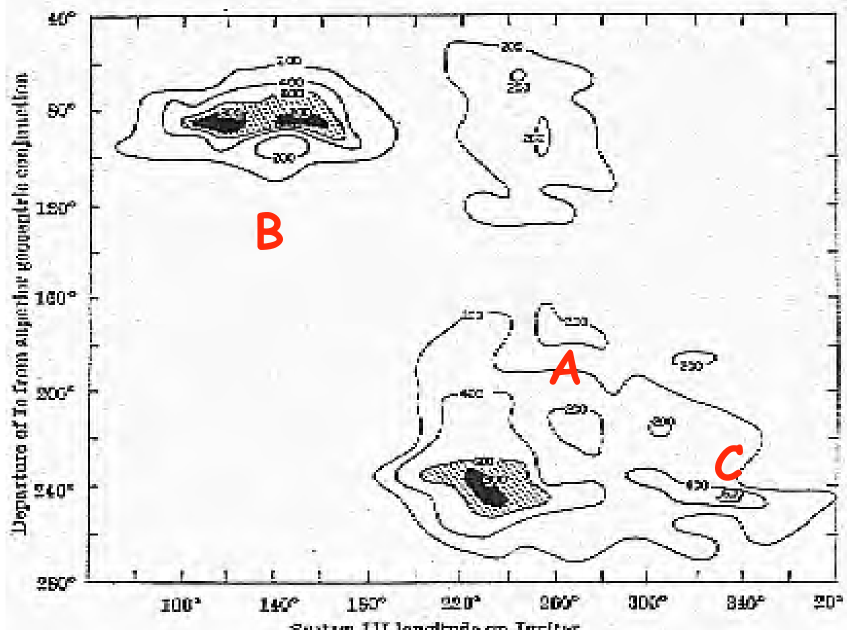
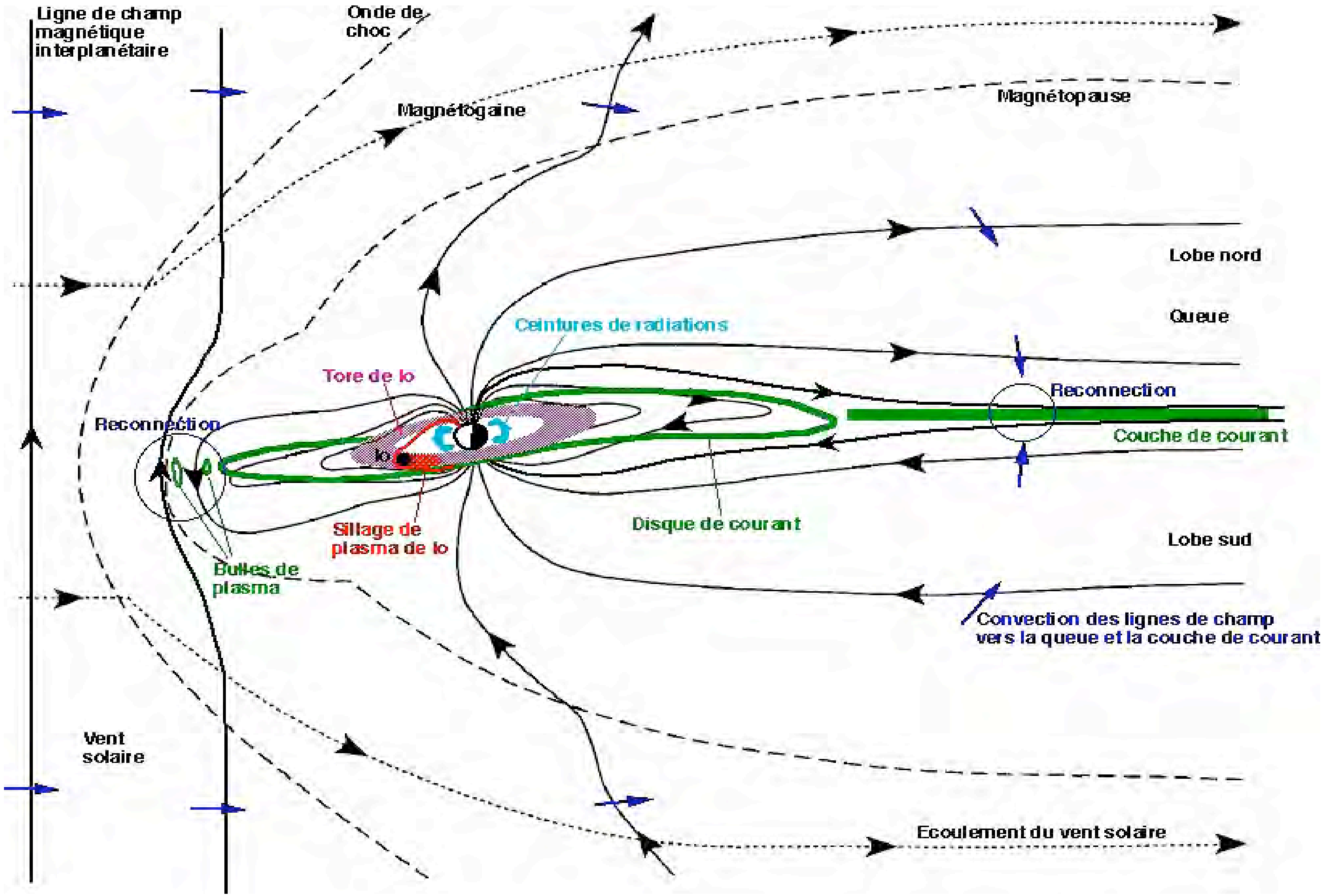
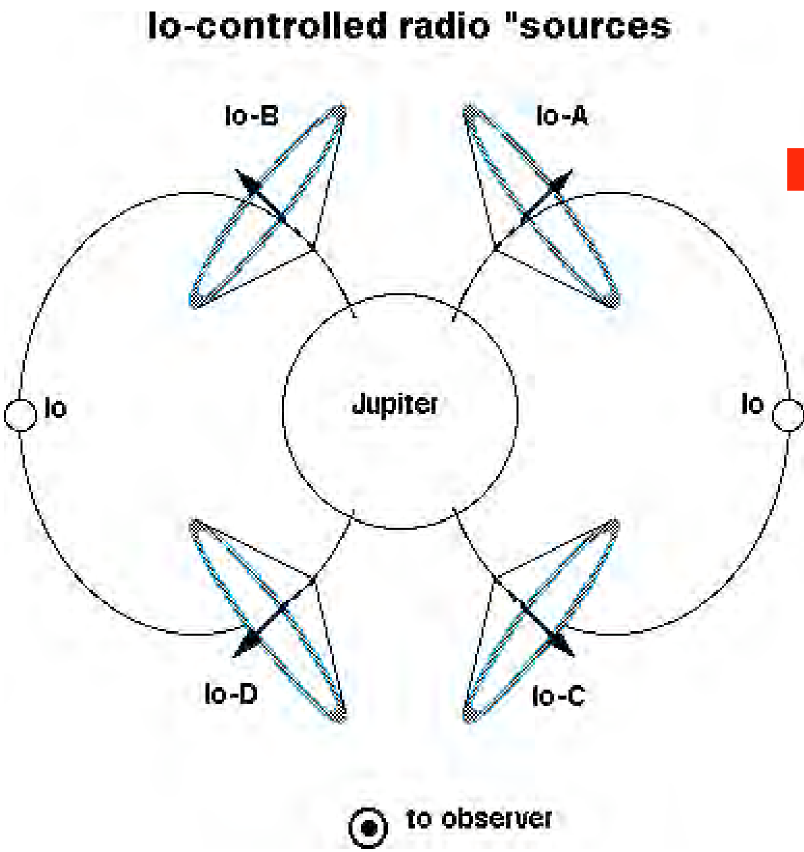


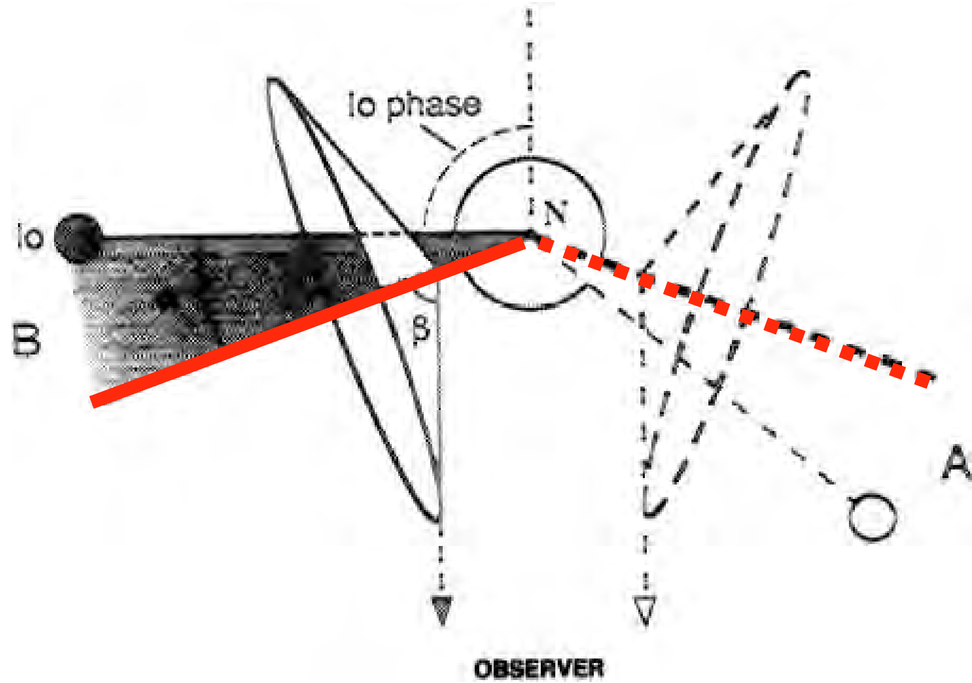
Fig. 5. The relationship between the position of Io and the orientation of Jupiter for the reception of decametric emission at the Earth

• Jupiter's magnetosphere



• Qualitative interpretation of Io « control »





- We focus here on DAM emission

  (there are also NRT studies of the synchrotron radiation)

- No angular resolution (λ/D)

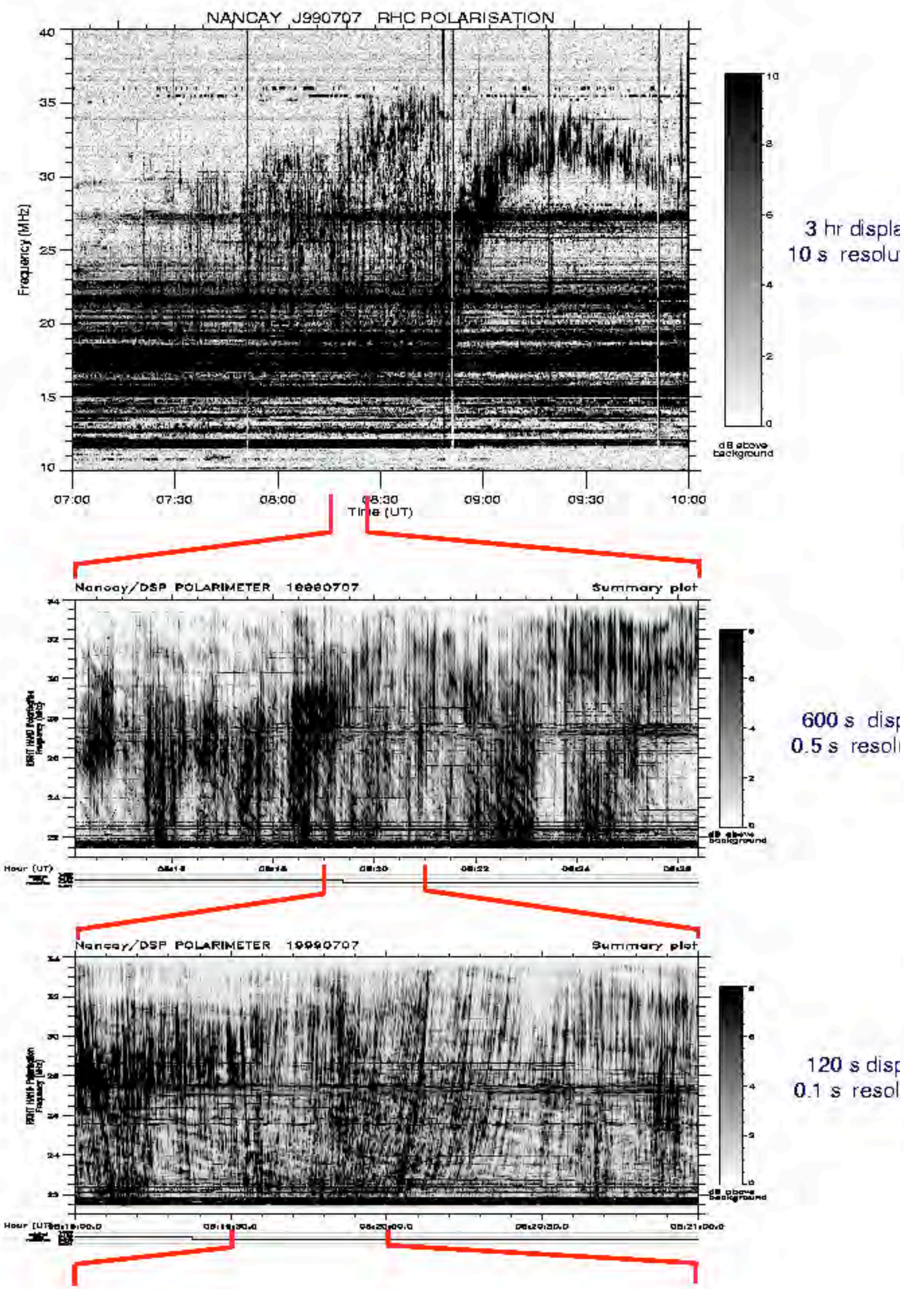
  → spectral studies

- Emission very sporadic, results from many superimposed modulations (seasonal, SW, Io, rotation, short term)

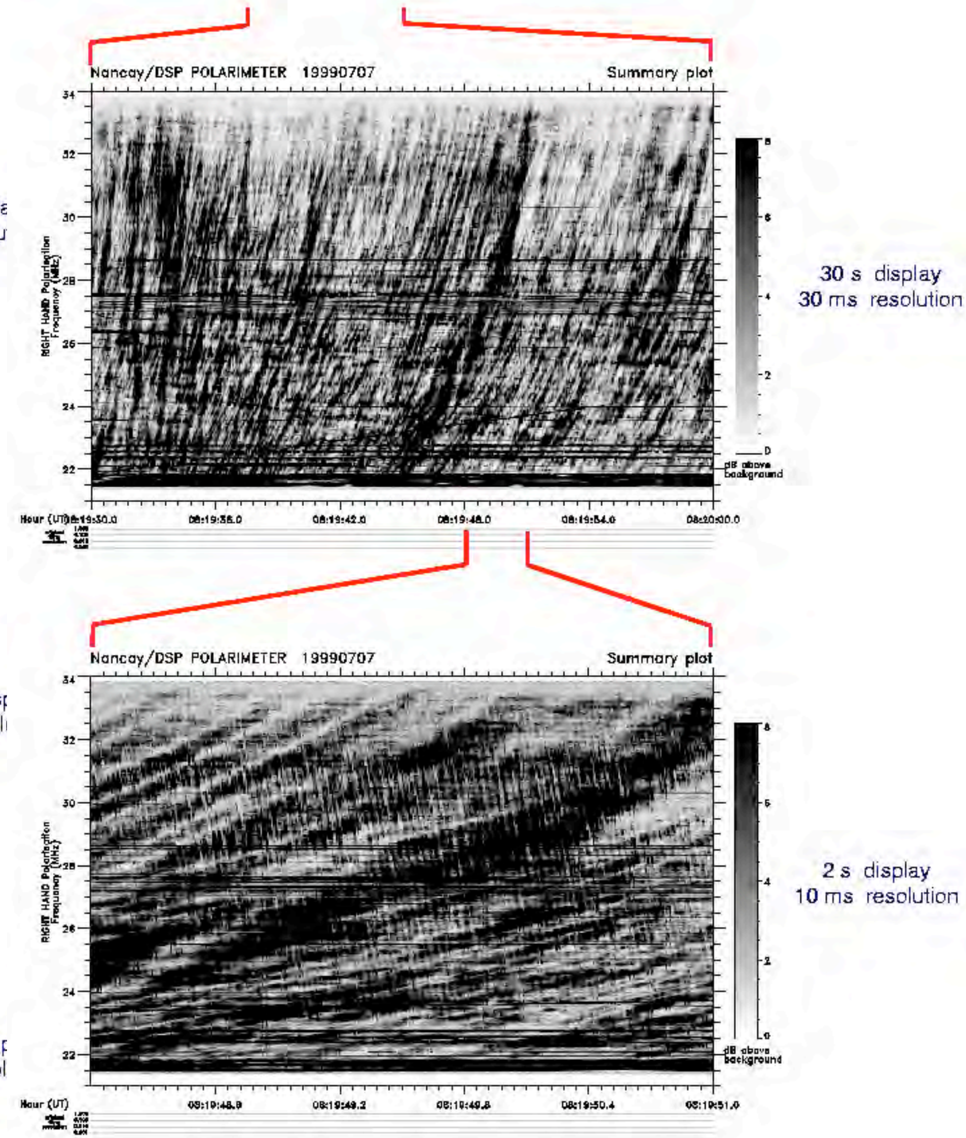
  \+ propagation effects

  → multi-scale dynamic spectral studies

Nested fringes modulations in Jovian DAM radiation



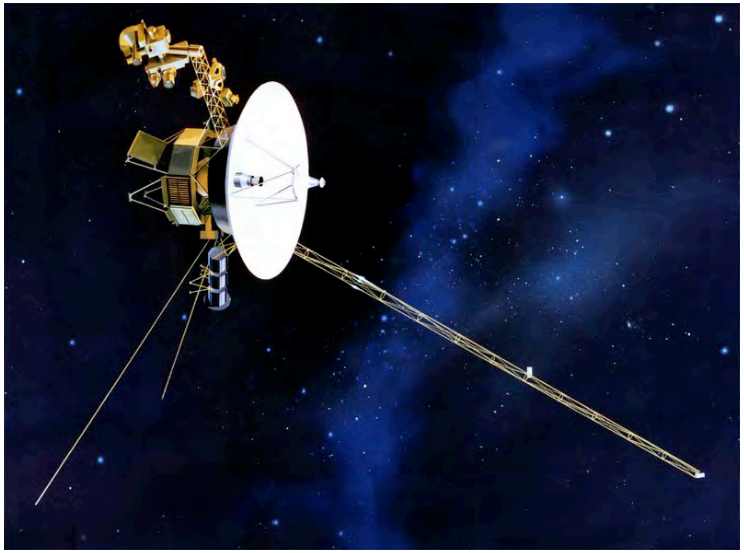
Nested fringes modulations in Jovian DAM radiation (continued)



[Lecacheux, 2004]

- 4 epochs and corresponding results

(1) Early studies (<1990) :



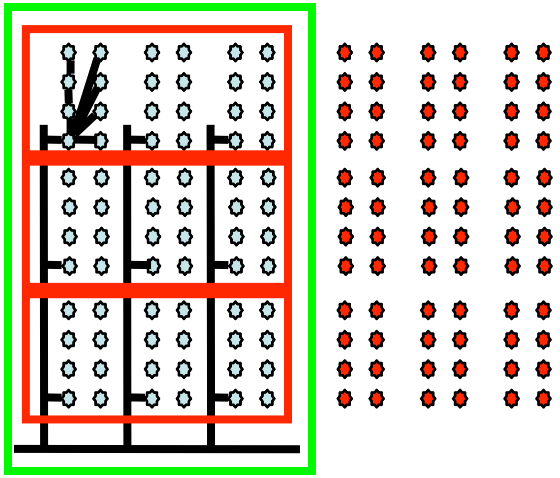
- Voyager launch : 1977
- Voyager @ Jupiter : 1978-79

[Warwick et al., 1979]

- Nançay Decameter Array : 1977+

[Boischot et al., 1980]

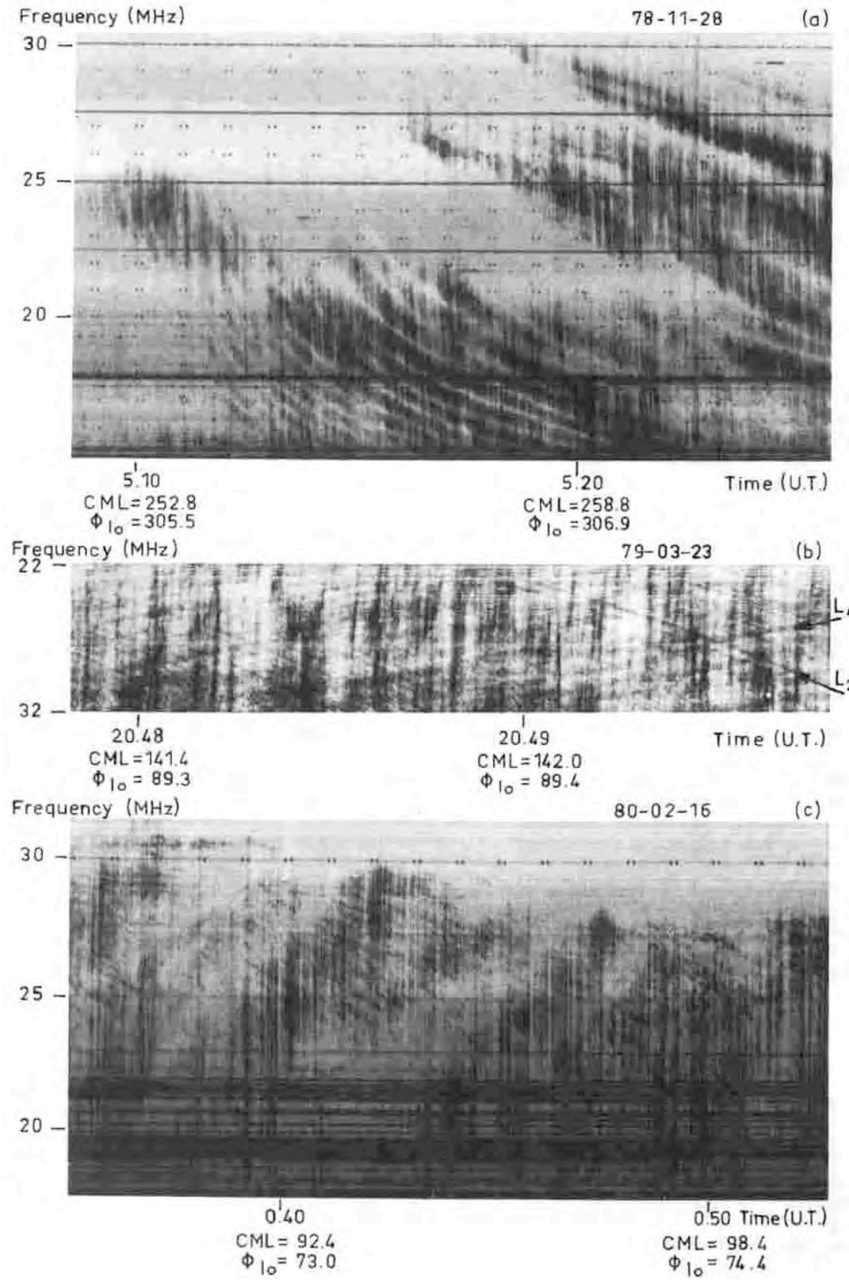
→ Nançay Decameter Array



- filled-aperture phased arrays allowing to derive calibrated fluxes
- 144 conical log-spiral antennas (~Clark-Lake) : 72 LHC, 72 RHC, over ~100m×100m field
- 10-120 MHz total band
- Beam of single antenna = 90° half power width
- Phasing scheme : analog beamforming through blocks of 8 antennas phased by 45° steps rotation + delay lines → Main beam ~6°×10°

  (beamforming optimized over ~1 octave)
- Gain = 25 dB (overall), 15 dB (1 block) , 6 dB (1 antenna)
- $A_e = 24\ \lambda^2 \leq 4000\ m^2$
- Computer-controlled electronic pointing, $-20° \leq \delta \leq +50°$, tracking time= meridian transit ±4h

→ « Routine » on facsimile



→ Catalogs and occurrence rates

[Leblanc & al.]

Y. Leblanc *et al.*

TABLE I. — *Catalogue.*

DATE	DOY	OBSERVATIONS TIME UT	CML III	IO PHASE	WIDTH	EMISSIONS TIME UT	CML III	IO PHASE	WIDTH
YY/MM/DD	333	HHMM - HHMM	(1965.0)		MHZ	HHMM - HHMM	(1965.0)		MHZ
78/ 1/ 3	3	1930 - 24 0	240 - 51	119 - 157	10 - 50	2054 - 2156	299 - 330	131 - 139	10 - 30
78/ 1/ 4	4	0 0 - 230	51 - 142	157 - 170	10 - 50				
78/ 1/ 4	4	1930 - 24 0	39 - 202	322 - 1	10 - 50				
78/ 1/ 5	5	0 0 - 230	202 - 293	1 - 22	10 - 50				
78/ 1/ 5	5	1930 - 24 0	189 - 353	166 - 204	10 - 30	1959 - 2320	207 - 329	170 - 190	10 - 20
78/ 1/ 6	6	0 0 - 146	353 - 57	204 - 219	10 - 30				
78/ 1/ 6	6	19 0 - 24 0	322 - 143	5 - 48	10 - 40	22 9 - 24 0	76 - 143	32 - 48	10 - 20
78/ 1/ 7	7	0 0 - 2 0	143 - 216	48 - 65	10 - 40	0 0 - 039	143 - 167	40 - 53	10 - 20
78/ 1/ 7	7	19 0 - 24 0	113 - 294	209 - 251	10 - 40	1941 - 2013	137 - 157	215 - 219	10 - 35
						2117 - 24 0	195 - 294	220 - 251	10 - 35
78/ 1/ 8	8	0 0 - 056	294 - 328	251 - 259	10 - 40	0 0 - 056	294 - 328	251 - 259	10 - 35
78/ 1/ 9	9	1930 - 24 0	72 - 235	260 - 299	10 - 50				
78/ 1/10	10	0 0 - 230	235 - 326	295 - 320	10 - 50	010 - 219	241 - 319	300 - 310	10 - 20
78/ 1/10	10	1930 - 24 0	223 - 26	104 - 142	10 - 50	20 6 - 20 8	244 - 246	109 - 109	10 - 13
						2036 - 2242	262 - 339	113 - 131	10 - 20
78/ 1/11	11	0 0 - 230	26 - 116	142 - 163	10 - 50				
78/ 1/11	11	1930 - 24 0	13 - 176	300 - 346	10 - 50	2320 - 2330	152 - 158	340 - 341	10 - 15
78/ 1/12	12	0 0 - 130	176 - 236	346 - 0	10 - 60				
78/ 1/12	12	1845 - 24 0	137 - 327	145 - 189	10 - 40	2037 - 24 0	204 - 327	161 - 189	10 - 20
78/ 1/13	13	0 0 - 2 0	327 - 40	189 - 206	10 - 40	0 0 - 036	327 - 349	189 - 194	10 - 20
78/ 1/13	13	19 0 - 24 0	296 - 110	351 - 33	10 - 40	1933 - 2010	310 - 343	355 - 2	12 - 15
						2240 - 23 9	74 - 87	23 - 26	10 - 15
						2325 - 24 0	96 - 110	20 - 33	10 - 30
78/ 1/14	14	0 0 - 1 0	110 - 154	33 - 41	10 - 40	0 0 - 057	110 - 152	33 - 41	10 - 30
78/ 1/14	14	1845 - 24 0	76 - 260	192 - 237	10 - 40				
78/ 1/15	15	0 0 - 2 0	260 - 341	237 - 253	10 - 40				
78/ 1/15	15	19 0 - 24 0	237 - 59	36 - 80	10 - 40				
78/ 1/16	16	0 0 - 1 0	59 - 96	80 - 89	10 - 40				
78/ 1/16	16	19 0 - 24 0	20 - 289	241 - 284	10 - 40				
78/ 1/17	17	0 0 - 2 0	289 - 292	284 - 301	10 - 40				
78/ 1/17	17	1745 - 2153	133 - 283	74 - 109	10 - 40	1930 - 2153	197 - 283	89 - 109	10 - 27
78/ 1/18	18	1745 - 24 0	204 - 151	278 - 331	10 - 40	18 8 - 1911	298 - 336	281 - 290	10 - 23
78/ 1/19	19	0 0 - 2 0	151 - 223	331 - 348	10 - 40				
78/ 1/19	19	1730 - 2255	65 - 262	119 - 165	10 - 40	1839 - 2020	107 - 173	129 - 144	10 - 22
						22 8 - 2253	234 - 261	159 - 165	10 - 27
78/ 1/20	20	1730 - 24 0	216 - 92	323 - 10	10 - 40	18 6 - 1949	238 - 264	320 - 334	15 - 20
						2318 - 24 0	66 - 92	12 - 18	10 - 25
78/ 1/21	21	0 0 - 2 0	92 - 164	18 - 35	10 - 40	0 0 - 152	92 - 160	18 - 34	10 - 25
78/ 1/21	21	1730 - 24 0	7 - 242	166 - 222	10 - 40				
78/ 1/22	22	0 0 - 2 0	242 - 315	222 - 239	10 - 40				
78/ 1/22	22	1715 - 24 0	140 - 33	8 - 65	10 - 40	1859 - 22 8	211 - 325	23 - 49	10 - 30
78/ 1/23	23	0 0 - 2 0	33 - 106	65 - 82	10 - 40	1 5 - 157	72 - 104	71 - 82	15 - 25
78/ 1/23	23	17 0 - 24 0	290 - 184	209 - 269	10 - 30	2129 - 2130	92 - 93	247 - 248	17 - 20
78/ 1/24	24	0 0 - 2 0	184 - 266	269 - 288	10 - 30	135 - 149	242 - 250	282 - 284	10 - 25
78/ 1/24	24	17 0 - 1910	80 - 159	53 - 71	20 - 40				
78/ 1/24	24	1910 - 24 0	159 - 334	71 - 112	13 - 33				
78/ 1/25	25	0 0 - 2 0	334 - 47	112 - 129	13 - 33				
78/ 1/25	25	17 0 - 24 0	231 - 125	266 - 316	10 - 40	17 1 - 1760	231 - 261	257 - 264	20 - 24
78/ 1/26	26	0 0 - 2 0	125 - 197	316 - 333	10 - 40				
78/ 1/26	26	17 0 - 24 0	21 - 275	100 - 159	10 - 40	1935 - 1940	115 - 123	122 - 124	15 - 30
						2059 - 2110	165 - 173	134 - 135	10 - 20
						2330 - 2339	262 - 263	156 - 155	14 - 17
78/ 1/27	27	0 0 - 2 0	275 - 348	159 - 176	10 - 40				
78/ 1/27	27	17 0 - 24 2	172 - 66	304 - 3	10 - 40	1827 - 20 0	225 - 286	316 - 330	10 - 25
						2119 - 2136	329 - 338	240 - 342	10 - 16
78/ 1/28	28	0 0 - 2 0	66 - 138	3 - 20	10 - 40	029 - 035	83 - 87	7 - 8	15 - 25
78/ 1/28	28	17 0 - 24 0	323 - 216	147 - 207	10 - 40	2040 - 21 5	100 - 111	179 - 182	15 - 25

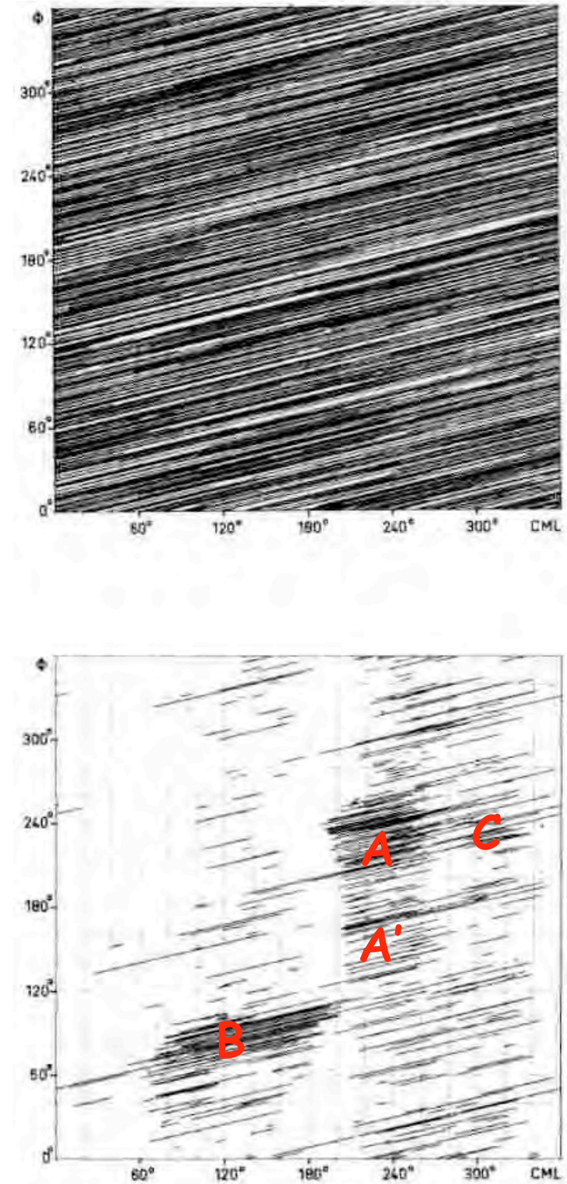
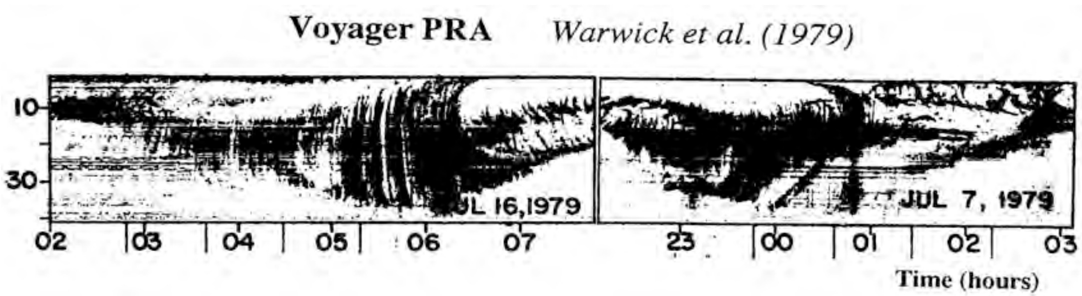
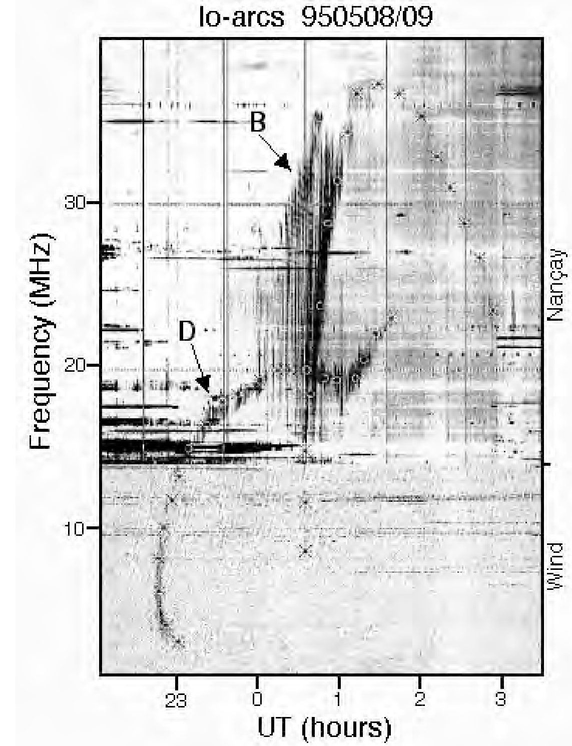


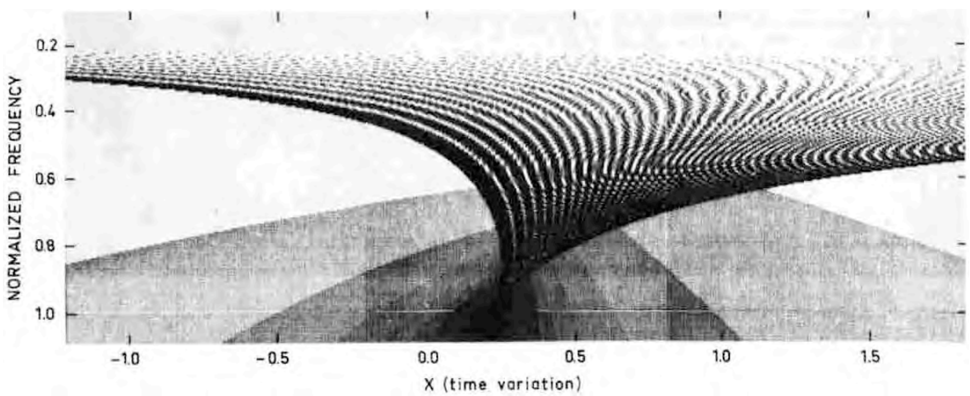
FIGURE 6. — The CML and Io-phase diagram for the period of January 1978 to December 1979. a) the observation tracks ; b) the emission tracks.

→ Radio « arcs » phenomenology :

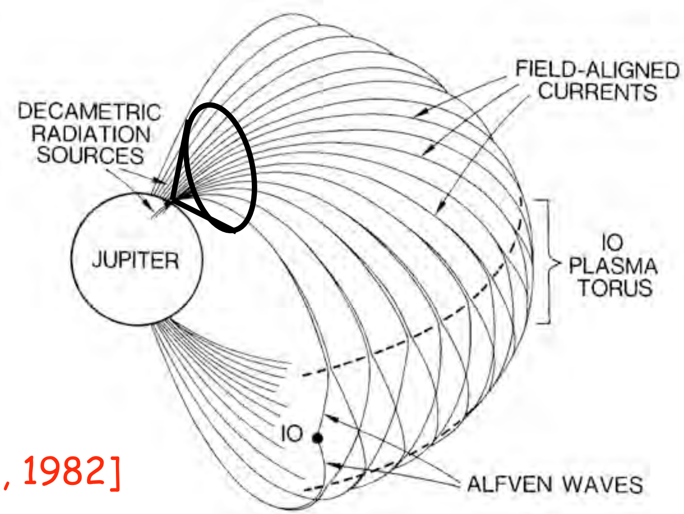




Diffraction caustics ? [Lecacheux & al., 1981]



Alfvèn waves ? [Gurnett & Goertz, 1982]



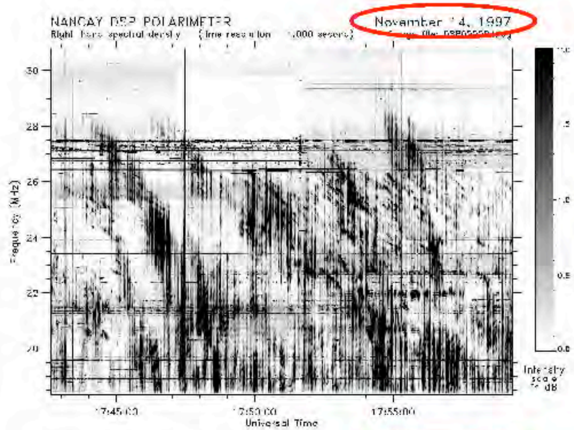
→ Interplanetary scintillation studies :

Source locations, distributed / f

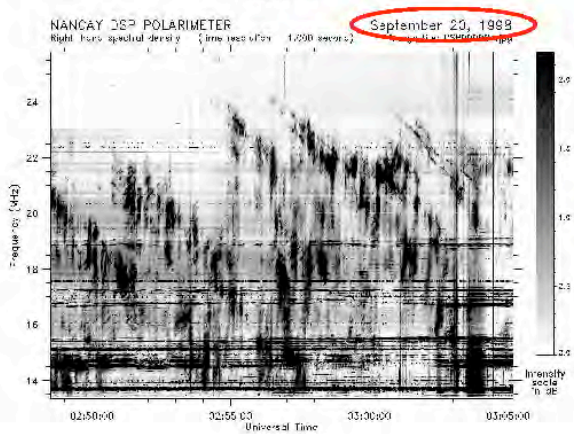
[Genova & Boischot 1981]

Interplanetary scintillations (IPS) of Jovian DAM radiation

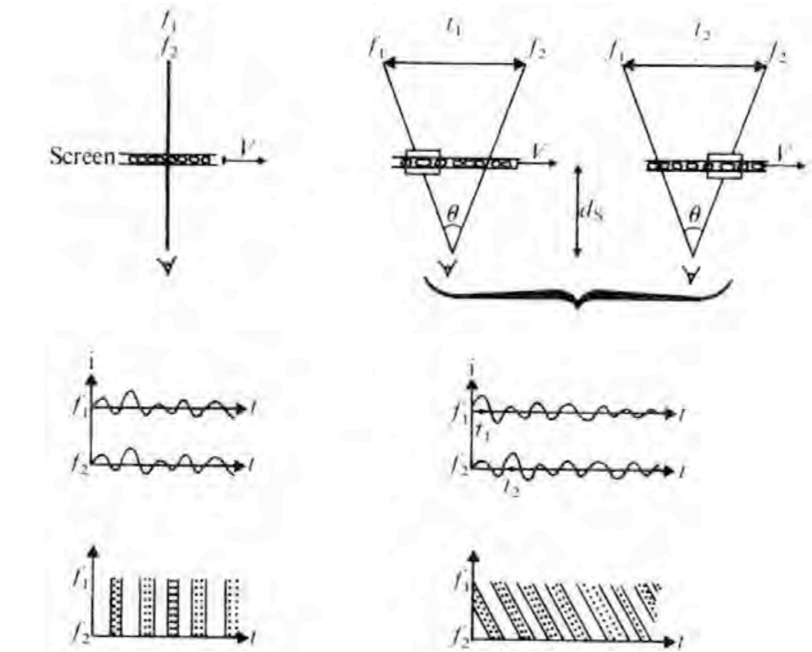
[Douglas and Smith (1967)
Slee and Higgins (1968)
Warwick (1967)
Genova and Leblanc (1981)]

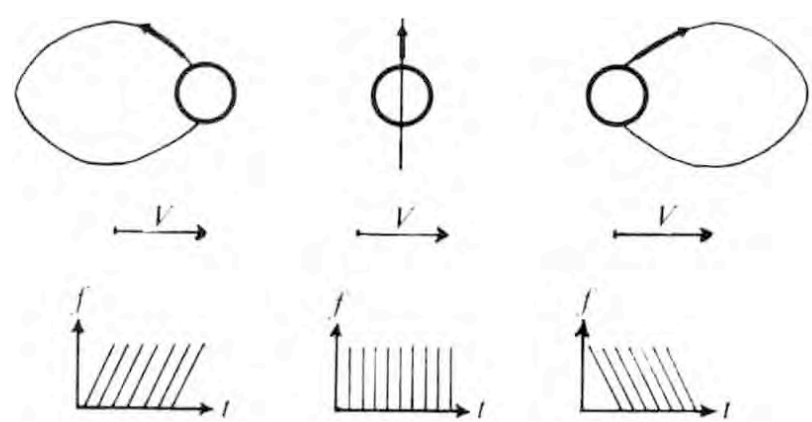


Jupiter
far from
opposition



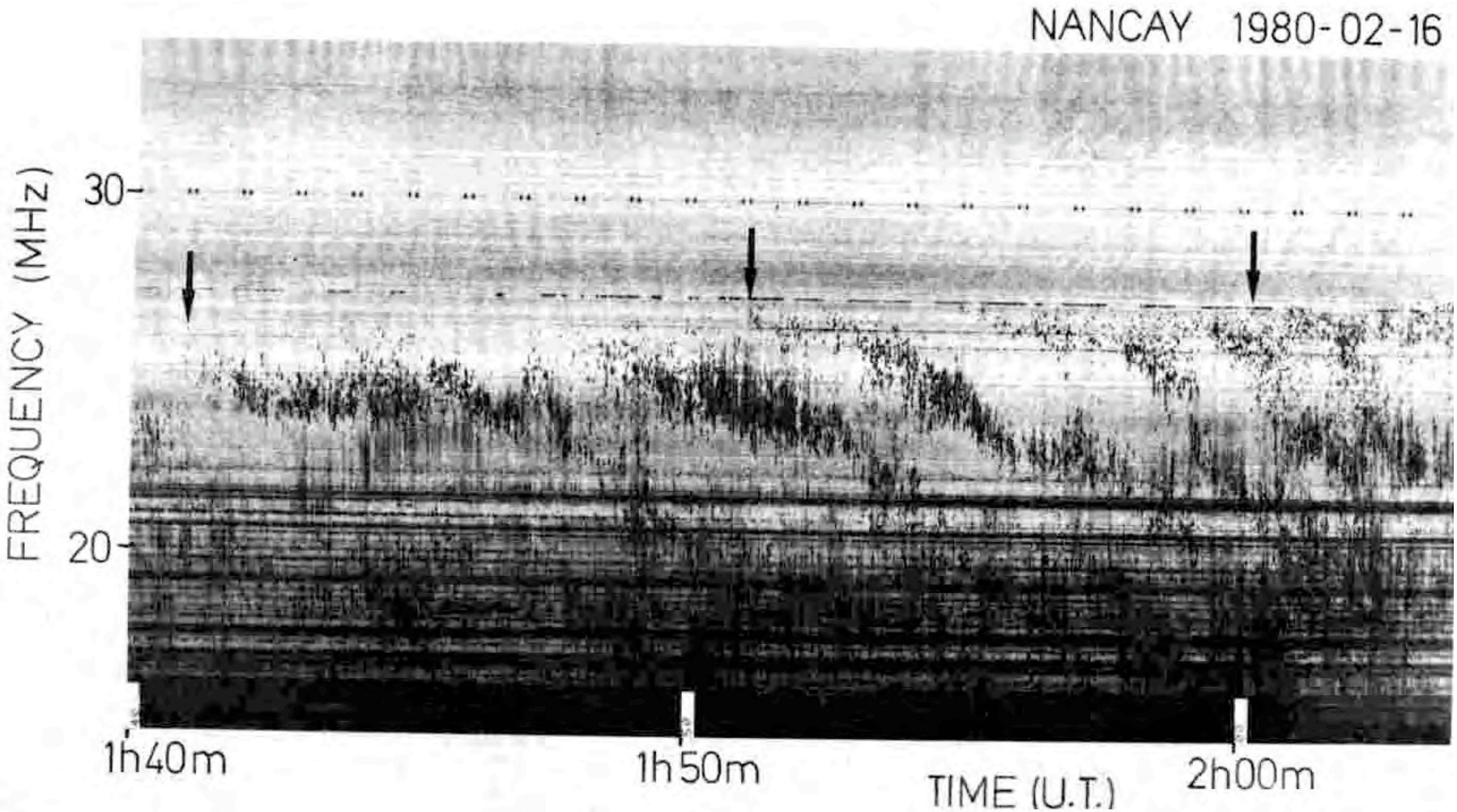
Jupiter
near
opposition





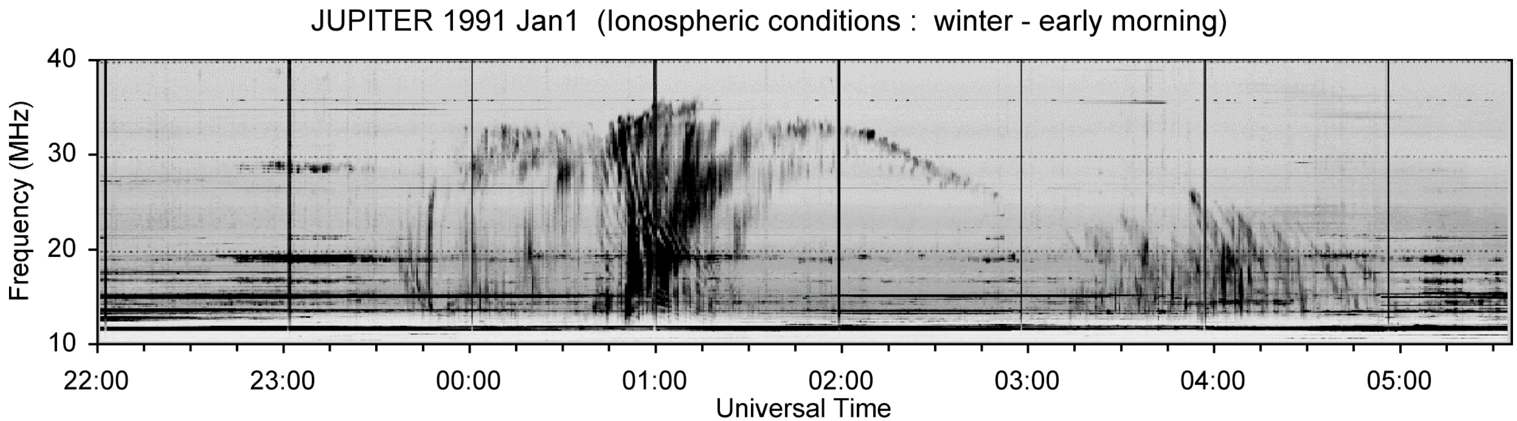
→ Short (« S ») bursts :

Energetic electron bunches ? [Genova, Leblanc & al.]

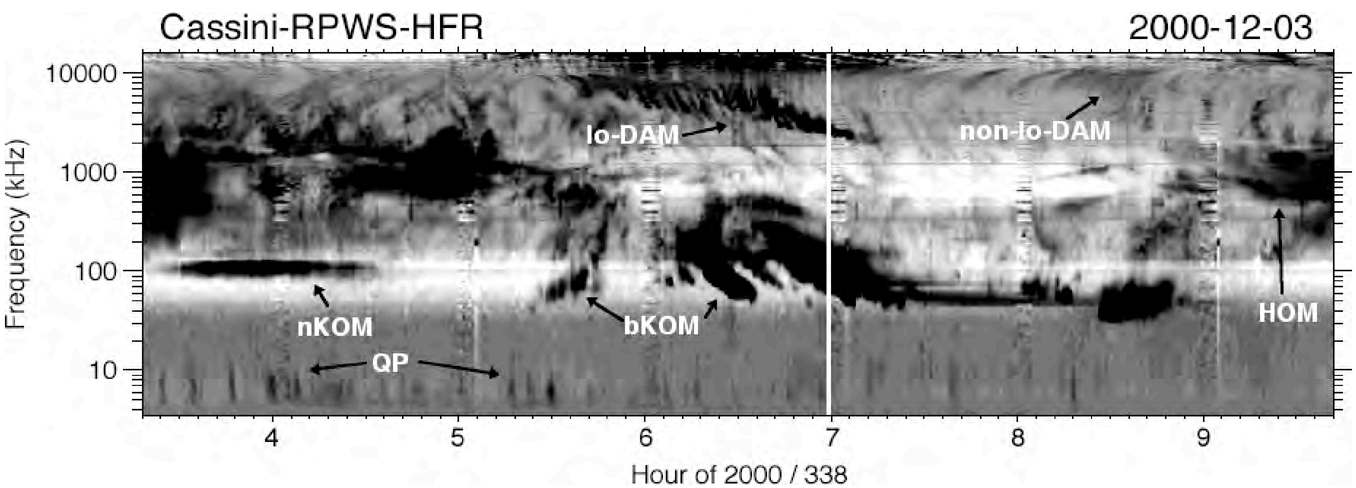


(2) Recent past (1990 - 2000) :

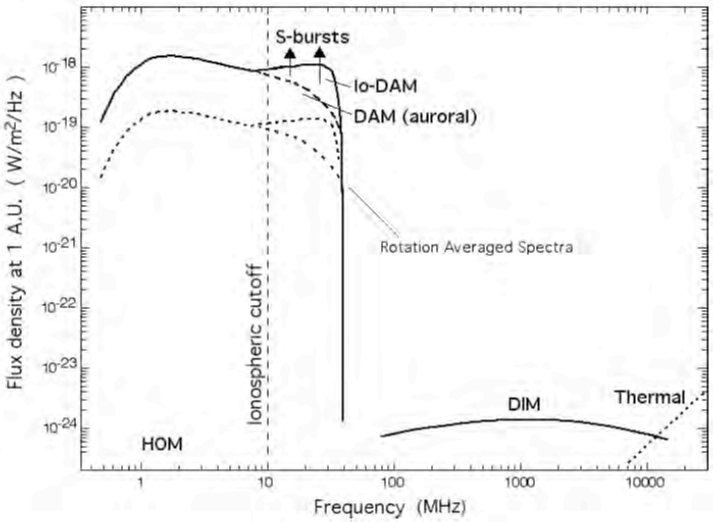
- Digital « Routine » (www.obs-nancay.fr → decameter array)
- Digital swept-frequency polarimeter
- Acousto-Optical spectrograph [Rosolen, Denis…]

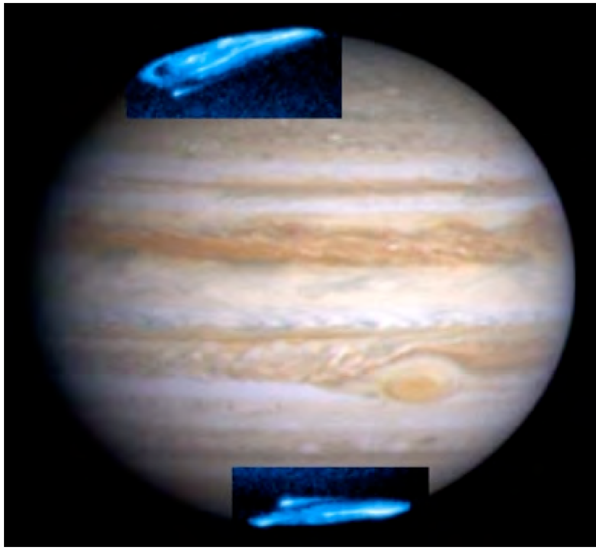


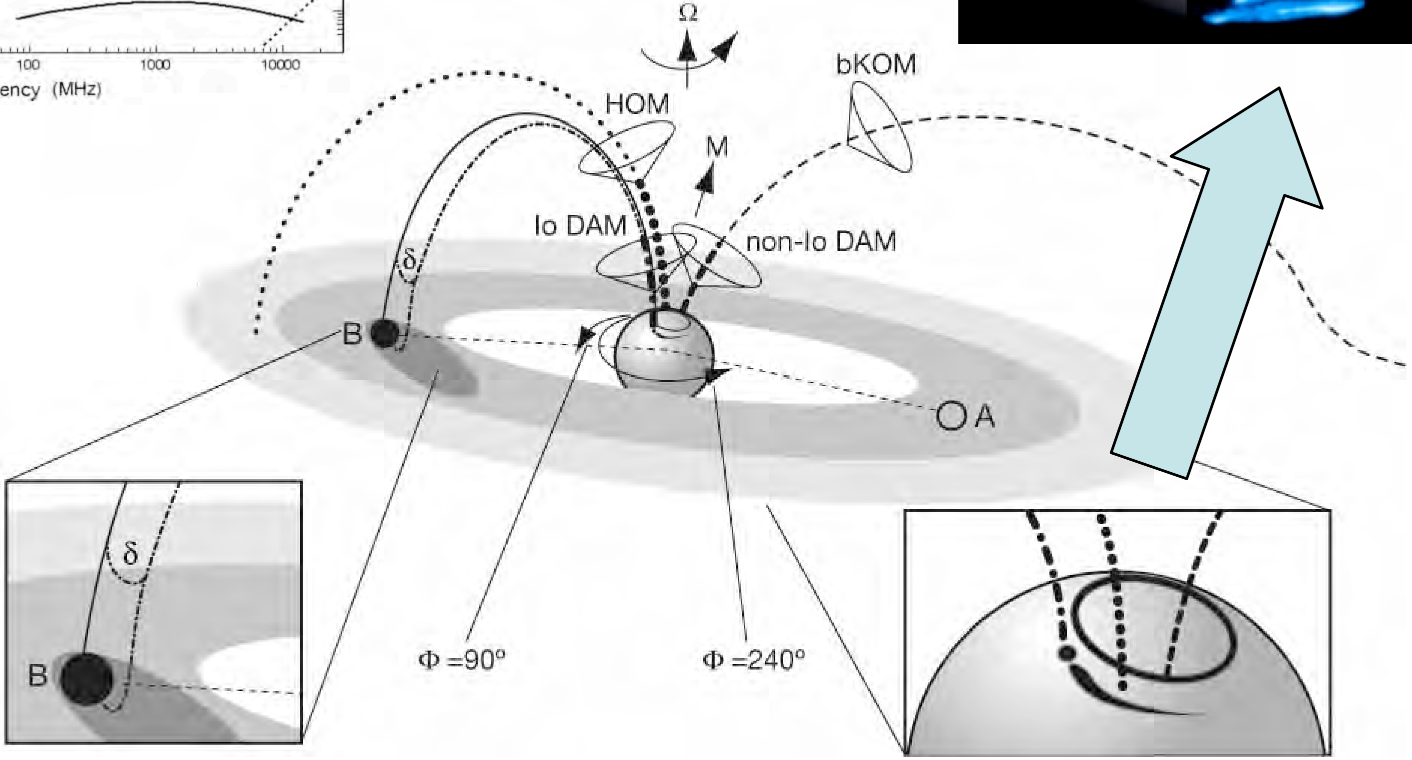
+ Ulysses, Galileo, Cassini



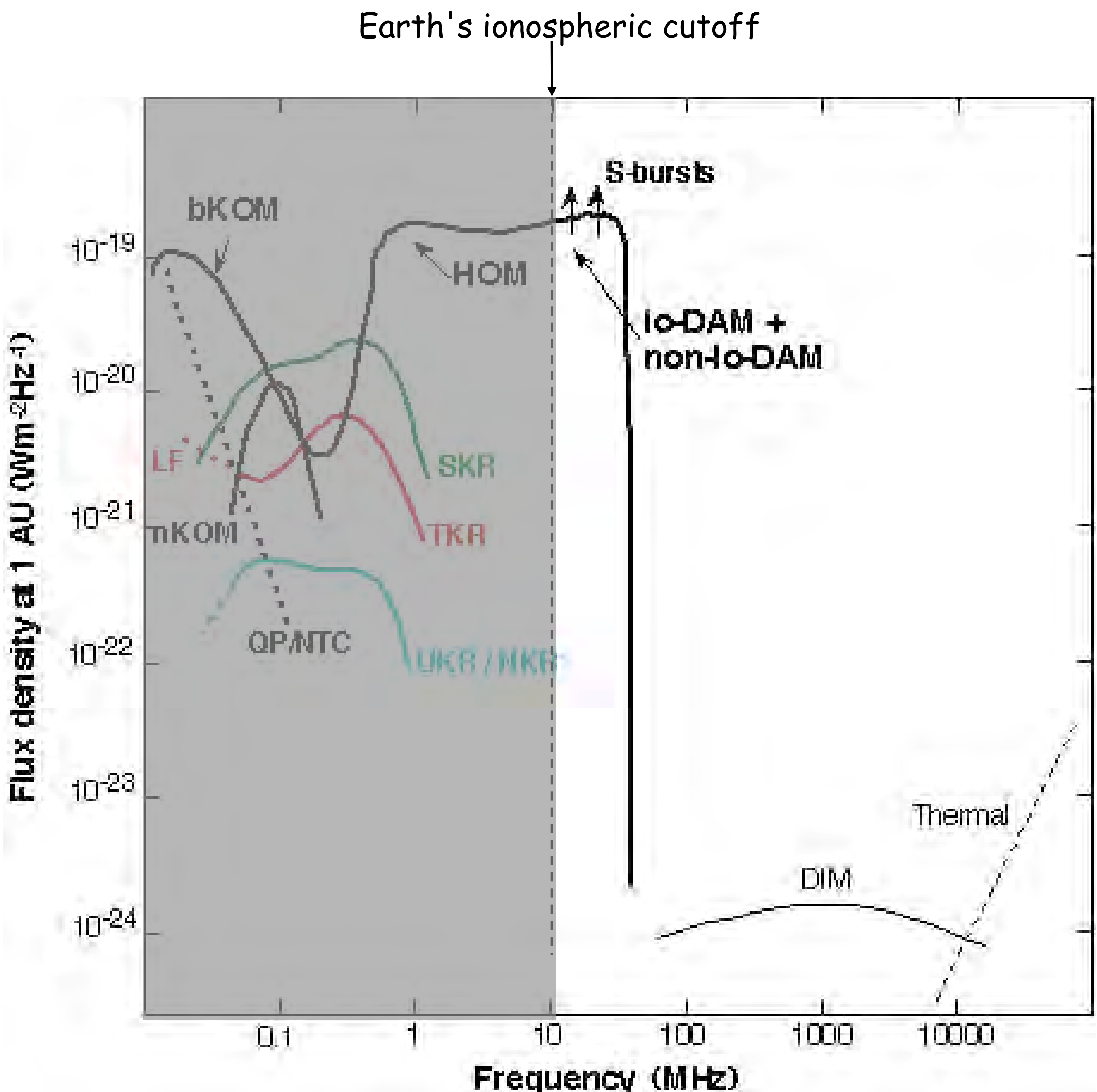
- Jovian Radiosources spectra, locations and beaming
- Multi-λ studies & ground-space complementarity







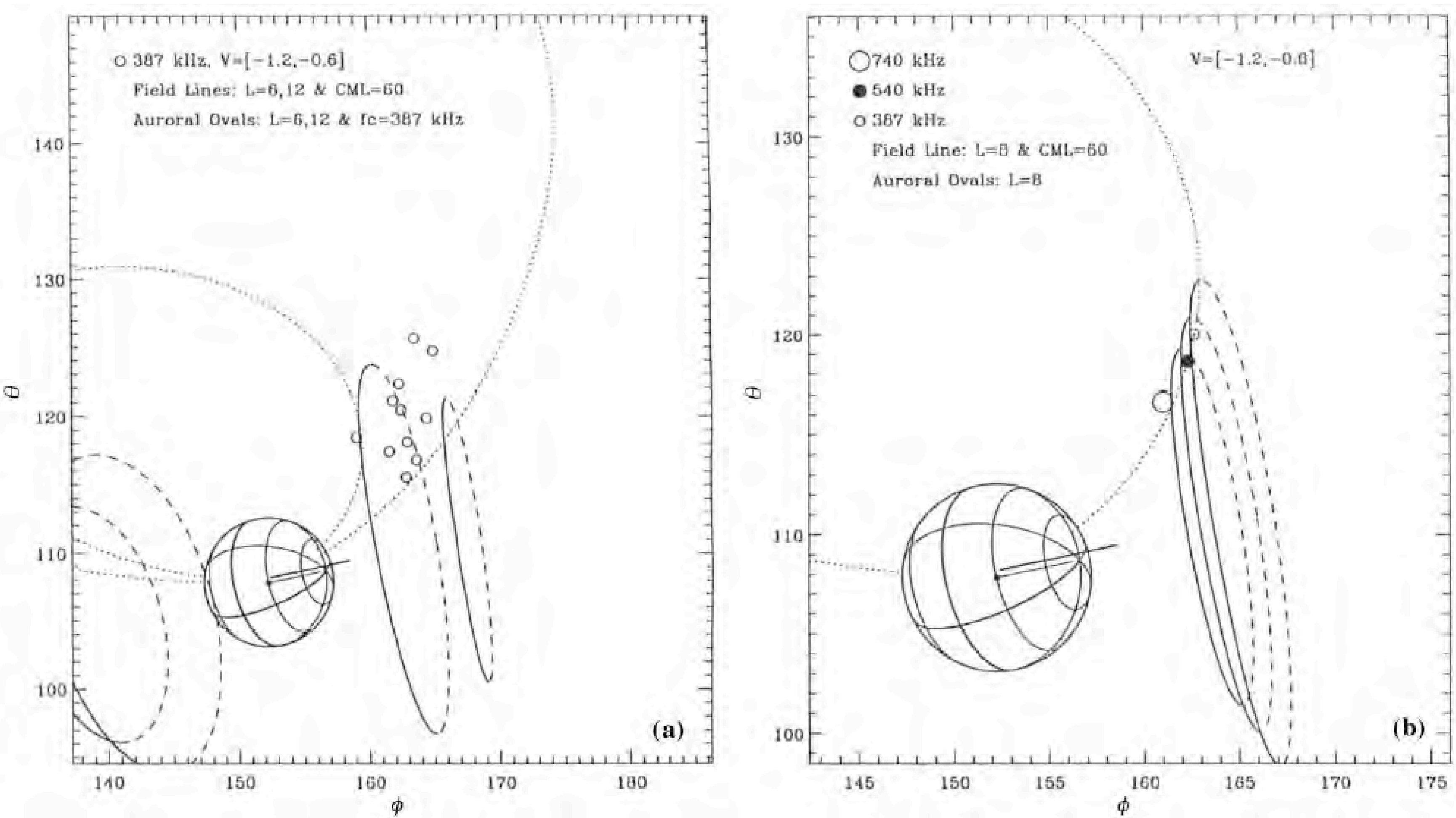
• Planetary radio emissions spectra



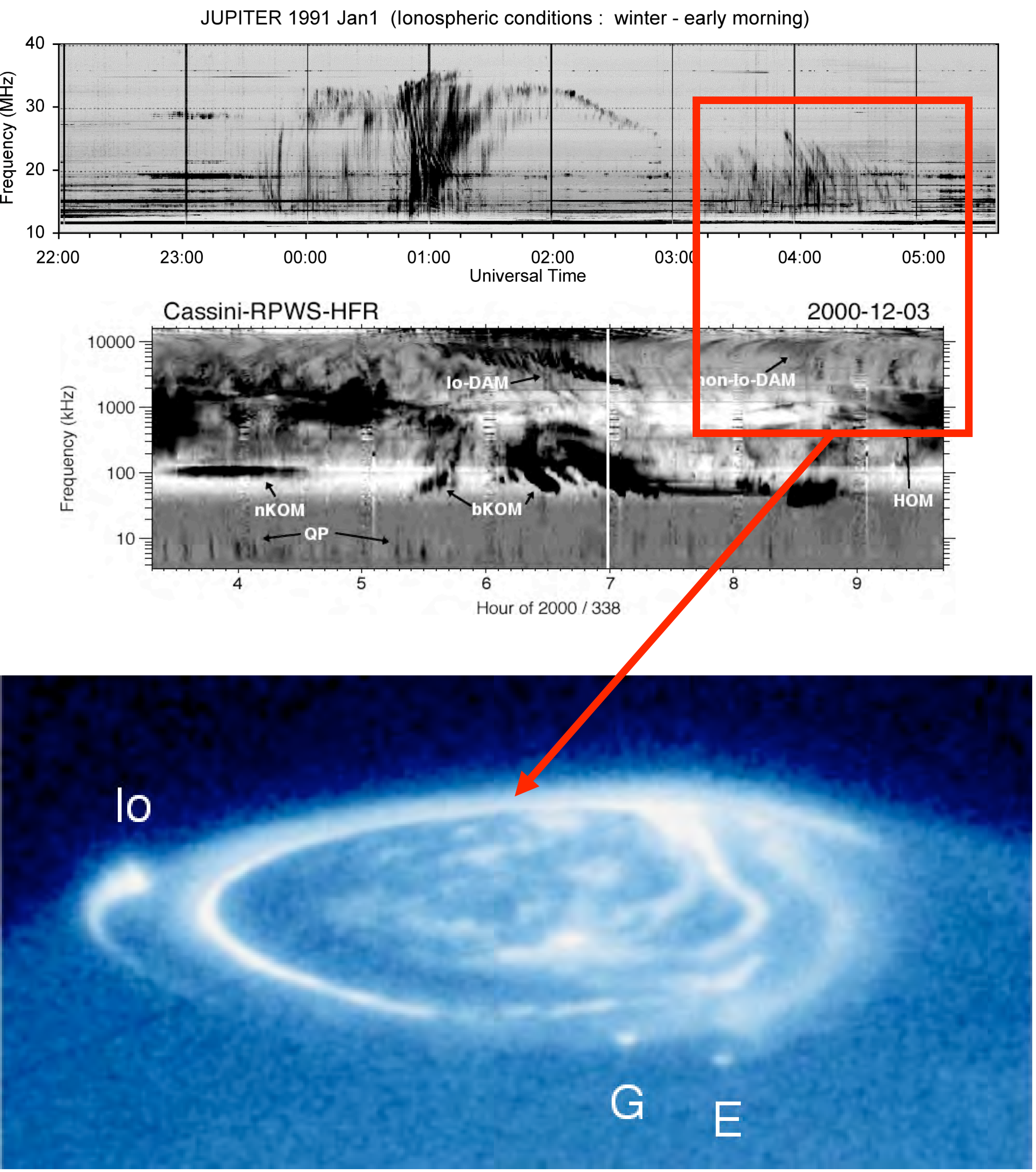
[Zarka, 2000]

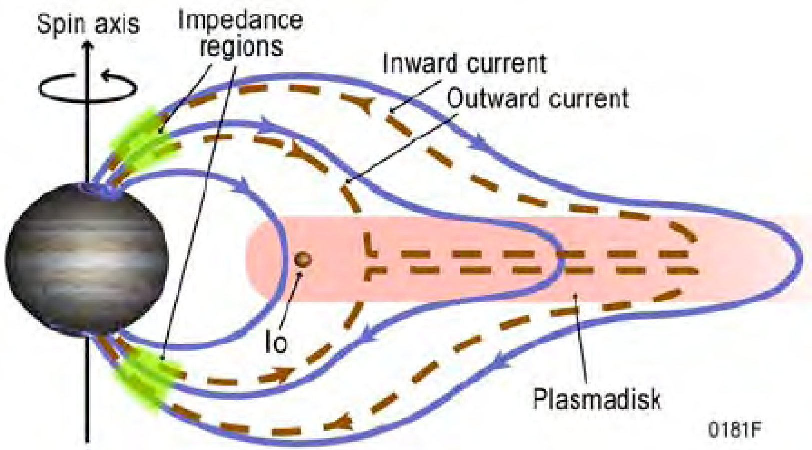
→ Gonio-Polarimetry of Jovian high-latitude radiosources

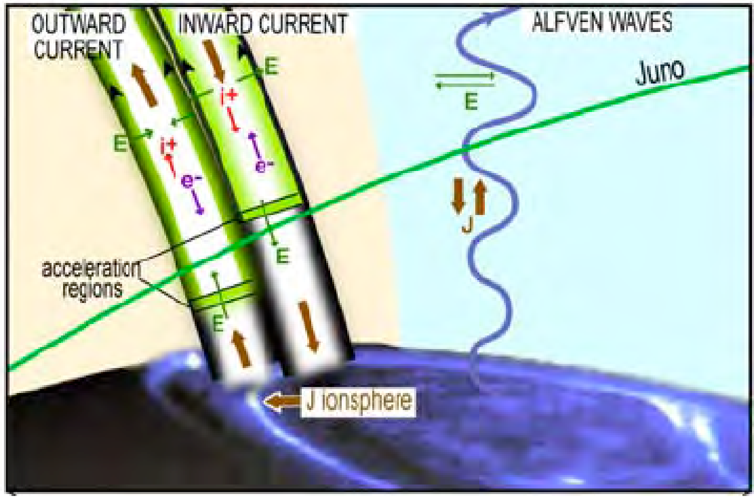
→ $f=f_{ce}$ (cyclotron-maser emission)



→ Main aurora

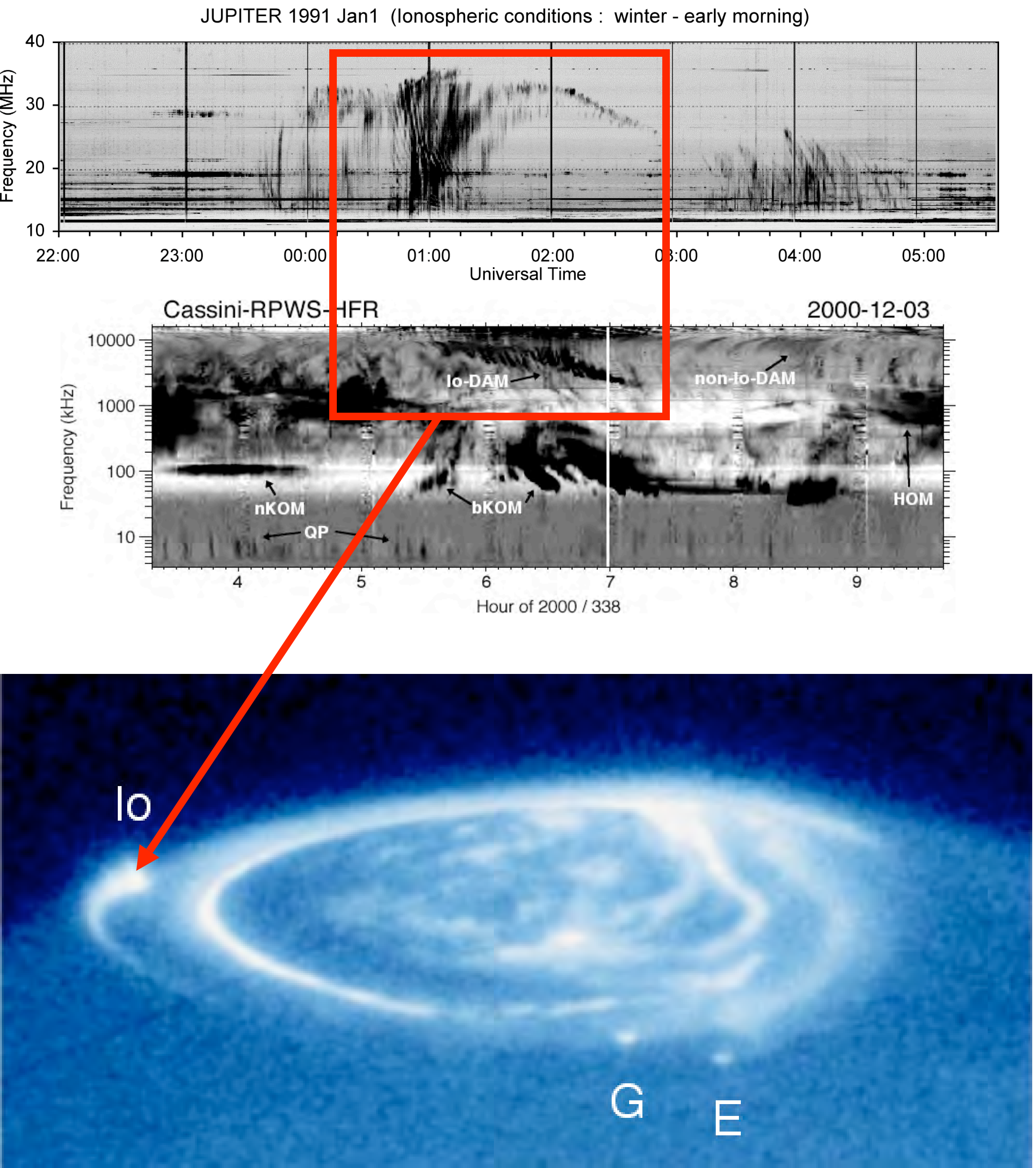

JUPITER 1991 Jan1 (Ionospheric conditions : winter - early morning)
Frequency (MHz)
40
30
20
10
22:00
23:00
00:00
01:00
02:00
03:00
04:00
05:00
Universal Time
Cassini-RPWS-HFR
2000-12-03
Frequency (kHz)
10000
1000
100
10
Io-DAM
non-Io-DAM
nKOM
bKOM
QP
HOM
4
5
6
7
8
9
Hour of 2000 / 338
Io
G
E

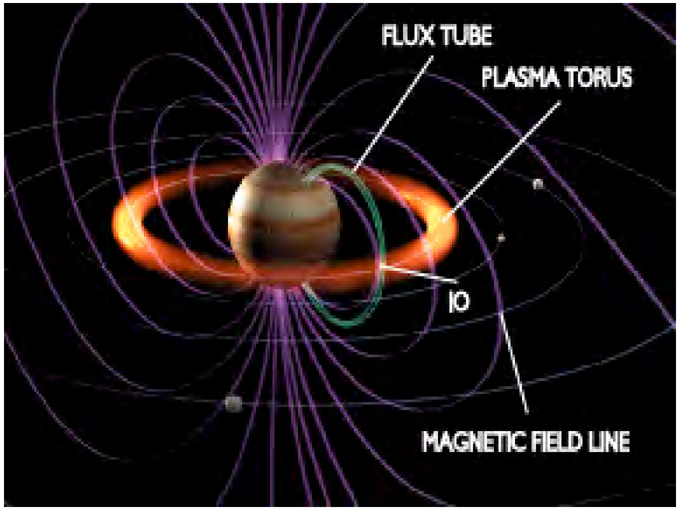

Spin axis
Impedance regions
Inward current
Outward current
Io
Plasmadisk
0181F

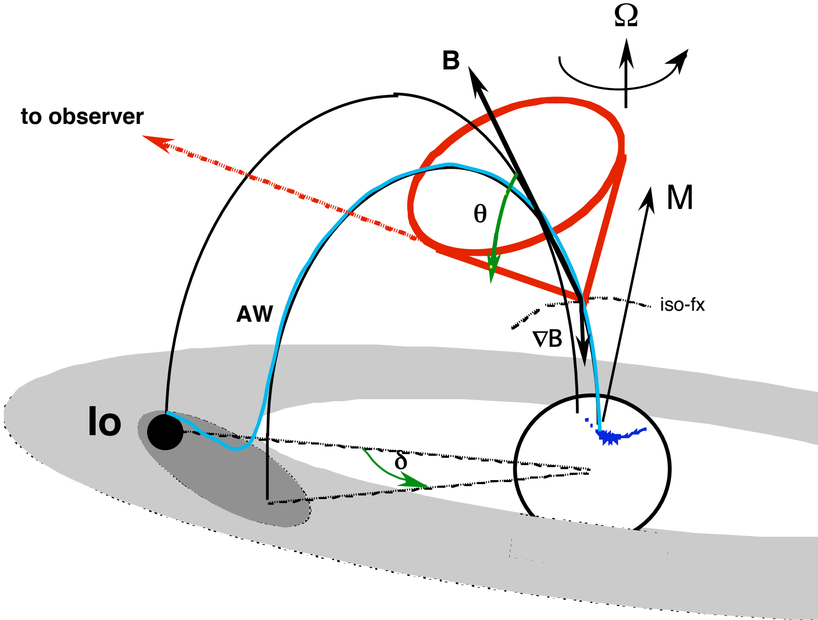

OUTWARD CURRENT
INWARD CURRENT
ALFVEN WAVES
Juno
E
i+
e-
J
acceleration regions
J ionsphere

→ Io-induced emissions

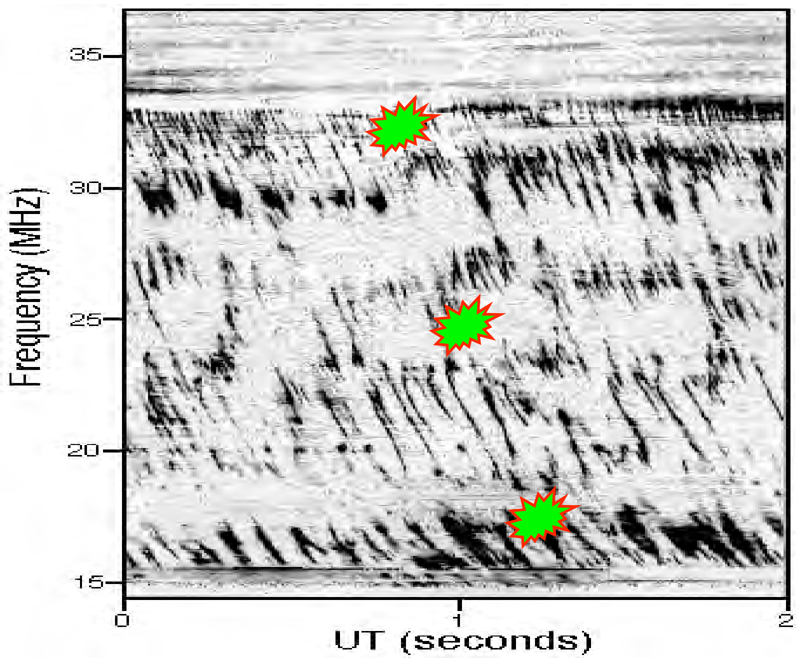
→ Alfvén waves produced « at » Io, accelerate electrons

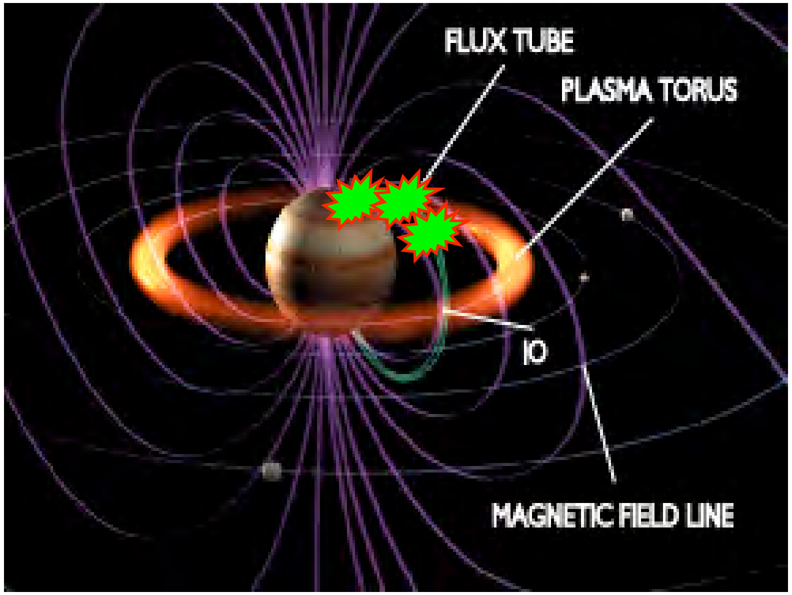


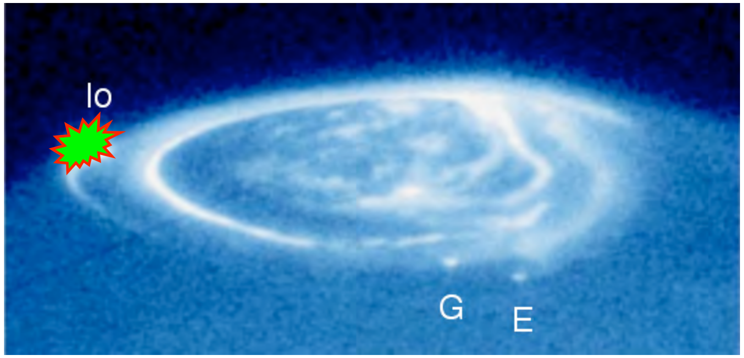


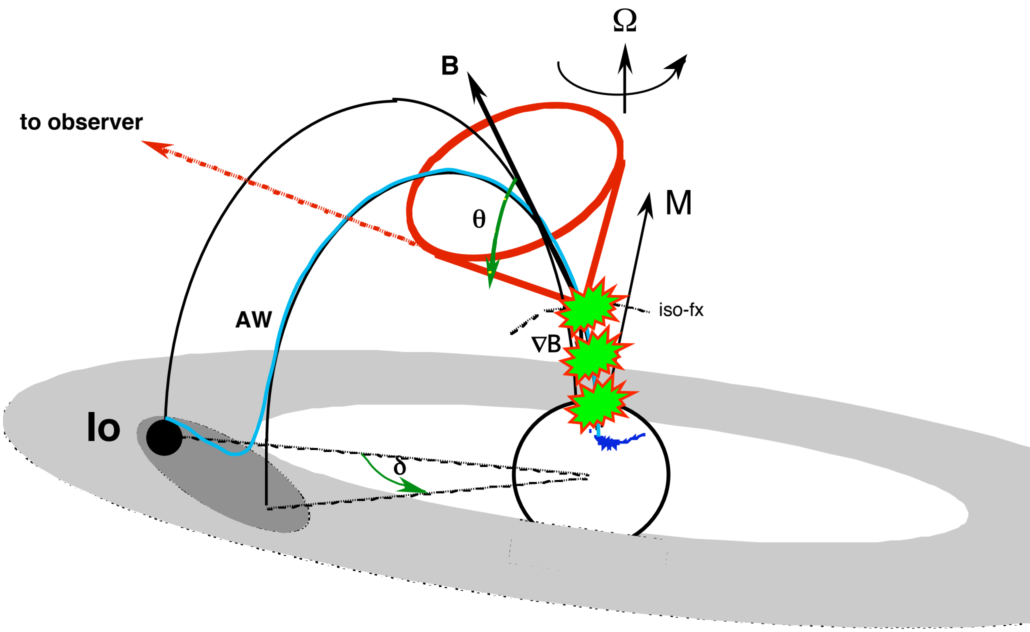


→ Io-induced emissions

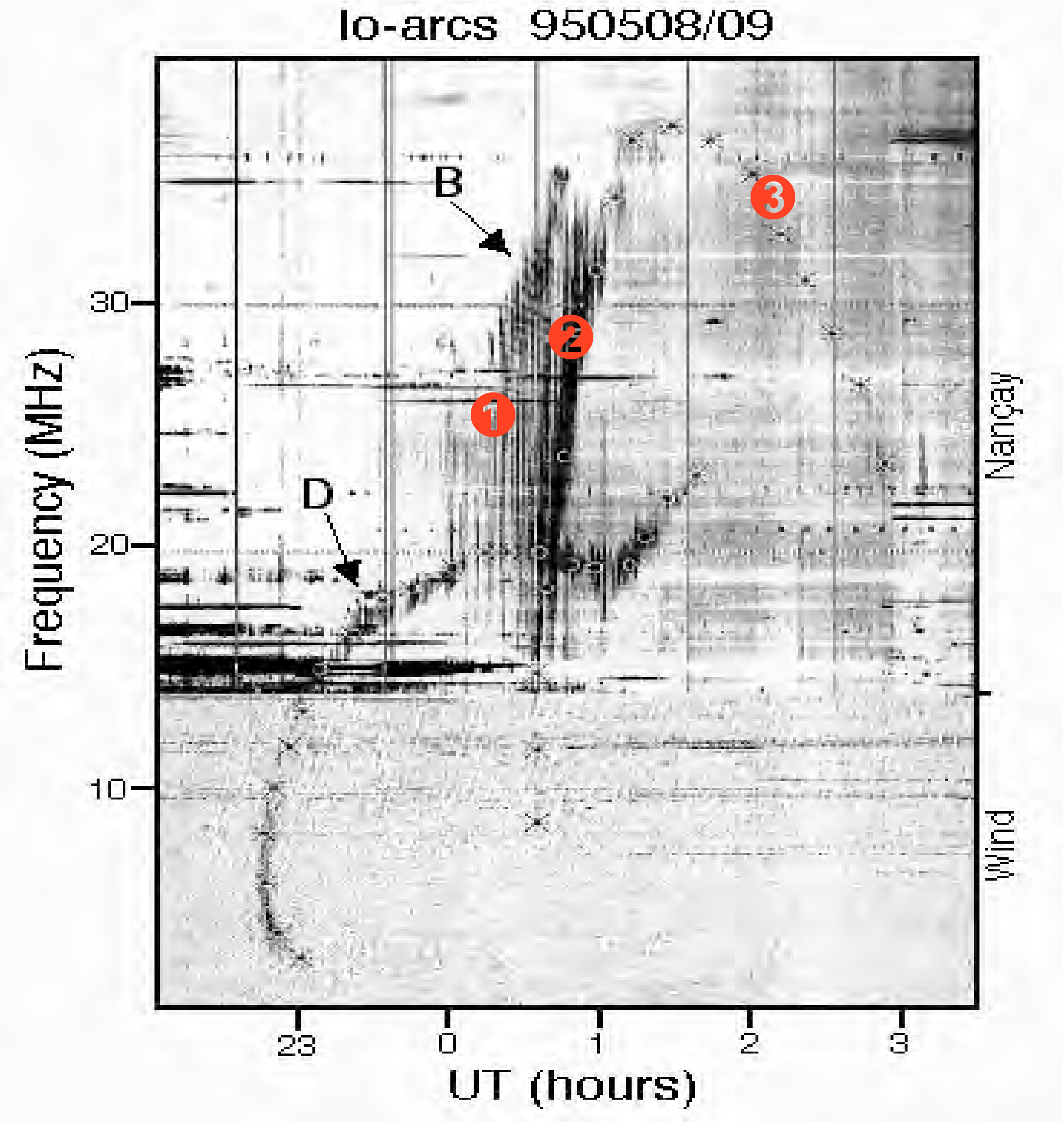








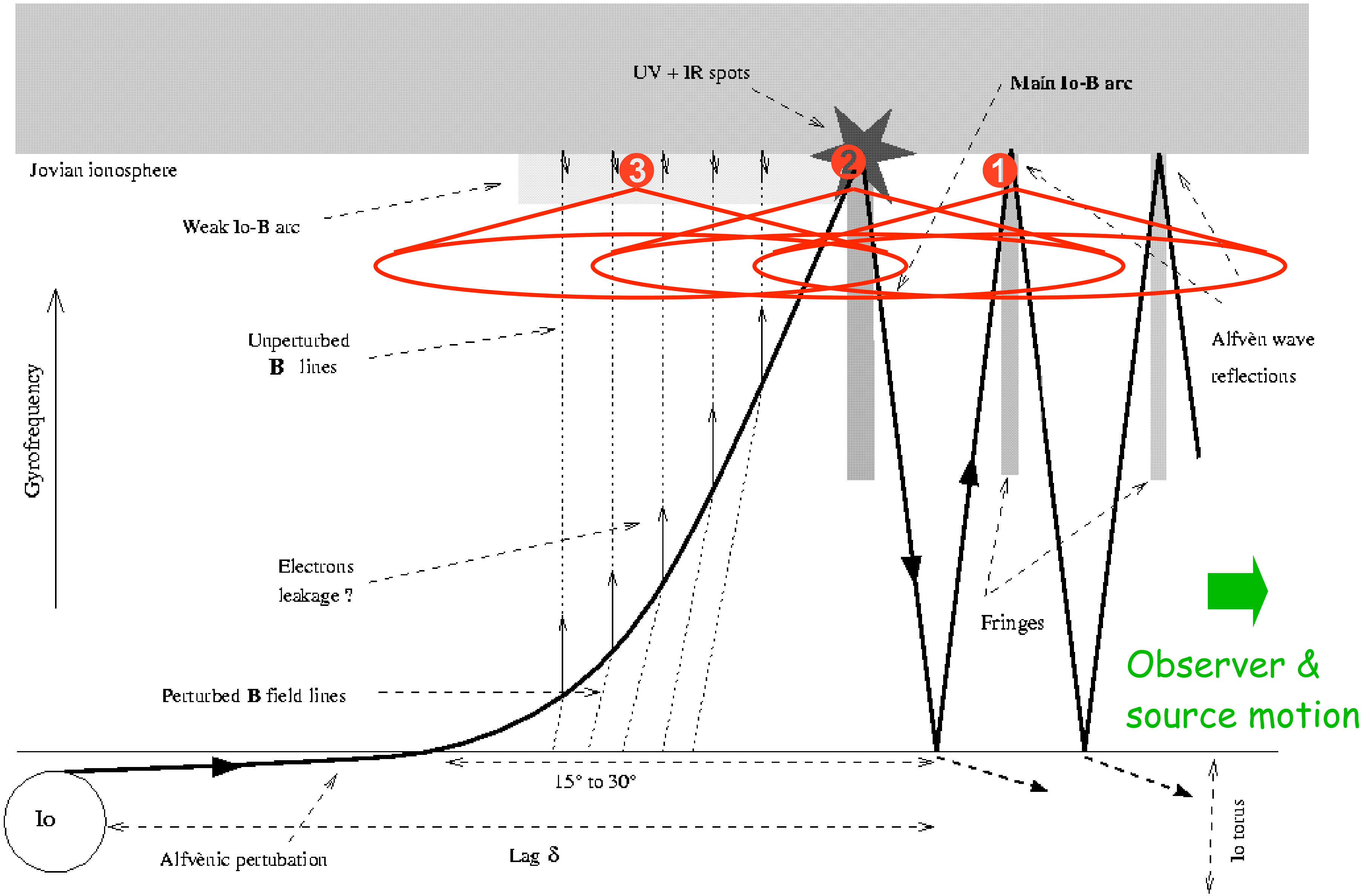
→ Radio Arcs shape : Magnetic field topology + beaming



→ Radio Arcs shape

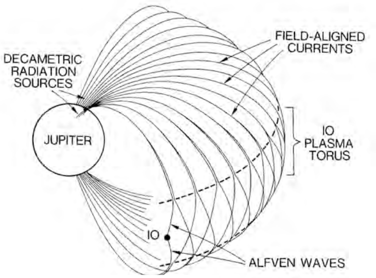
[Queinnec & Zarka, 1998]

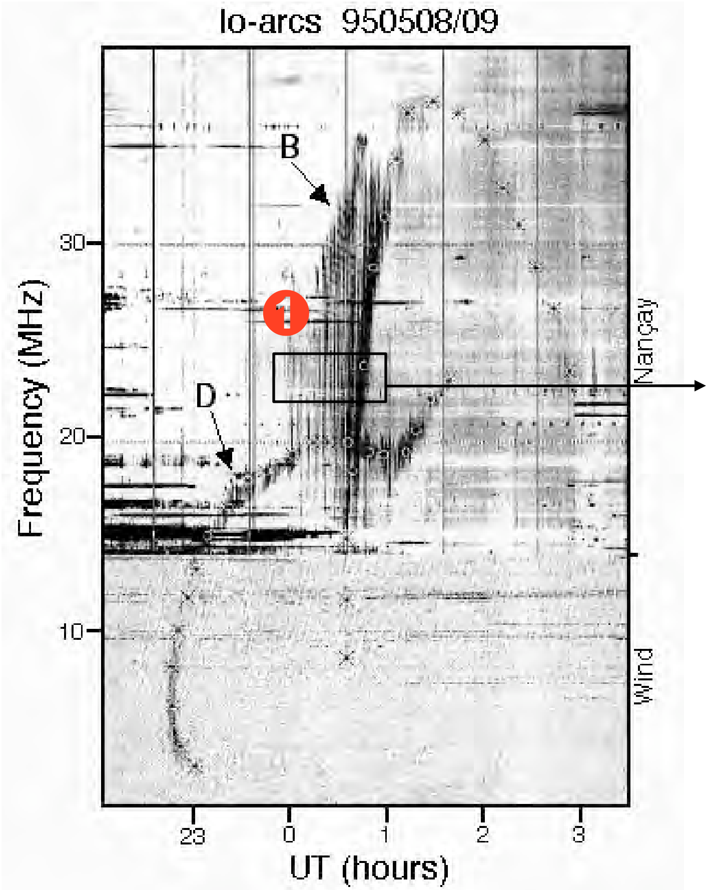
scenario #1

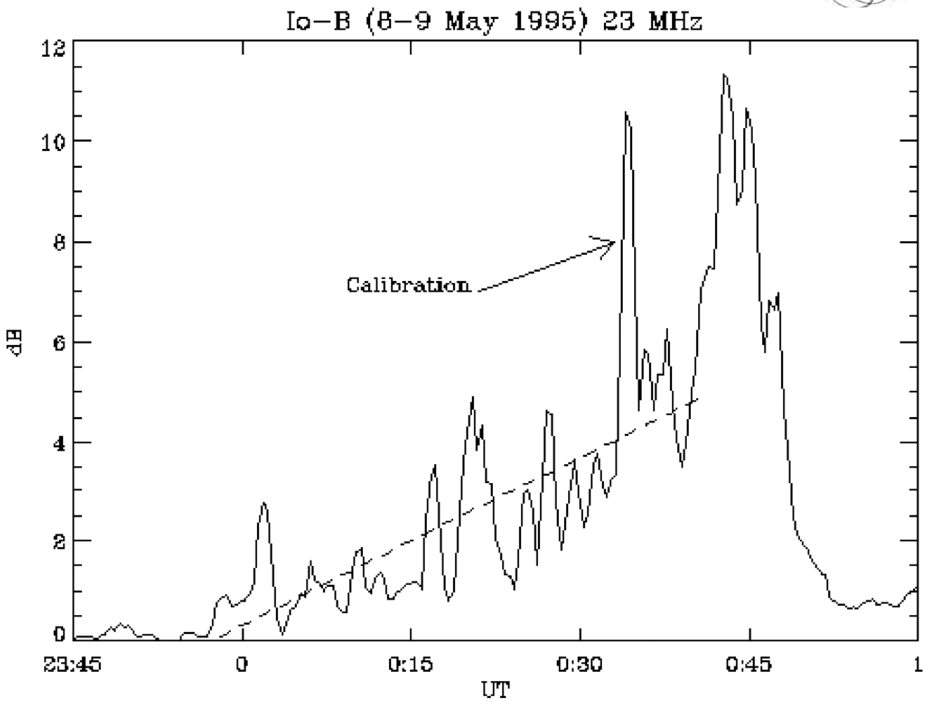


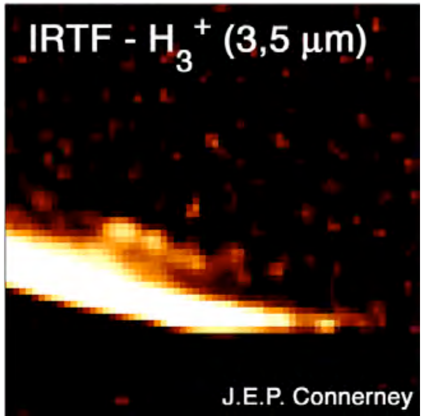
→ Arcs fringes : Alfvèn bouncing torus-ionosphere

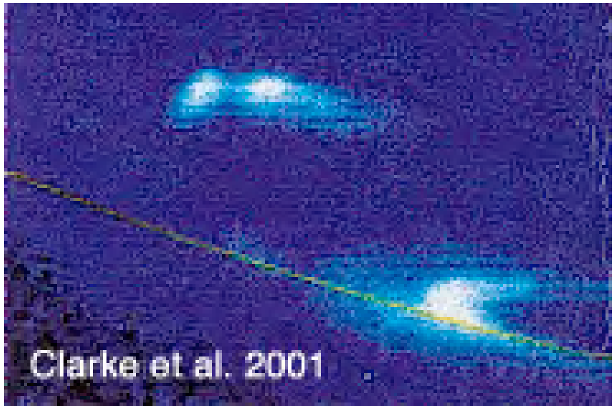
[Queinnec & Zarka, 1998]





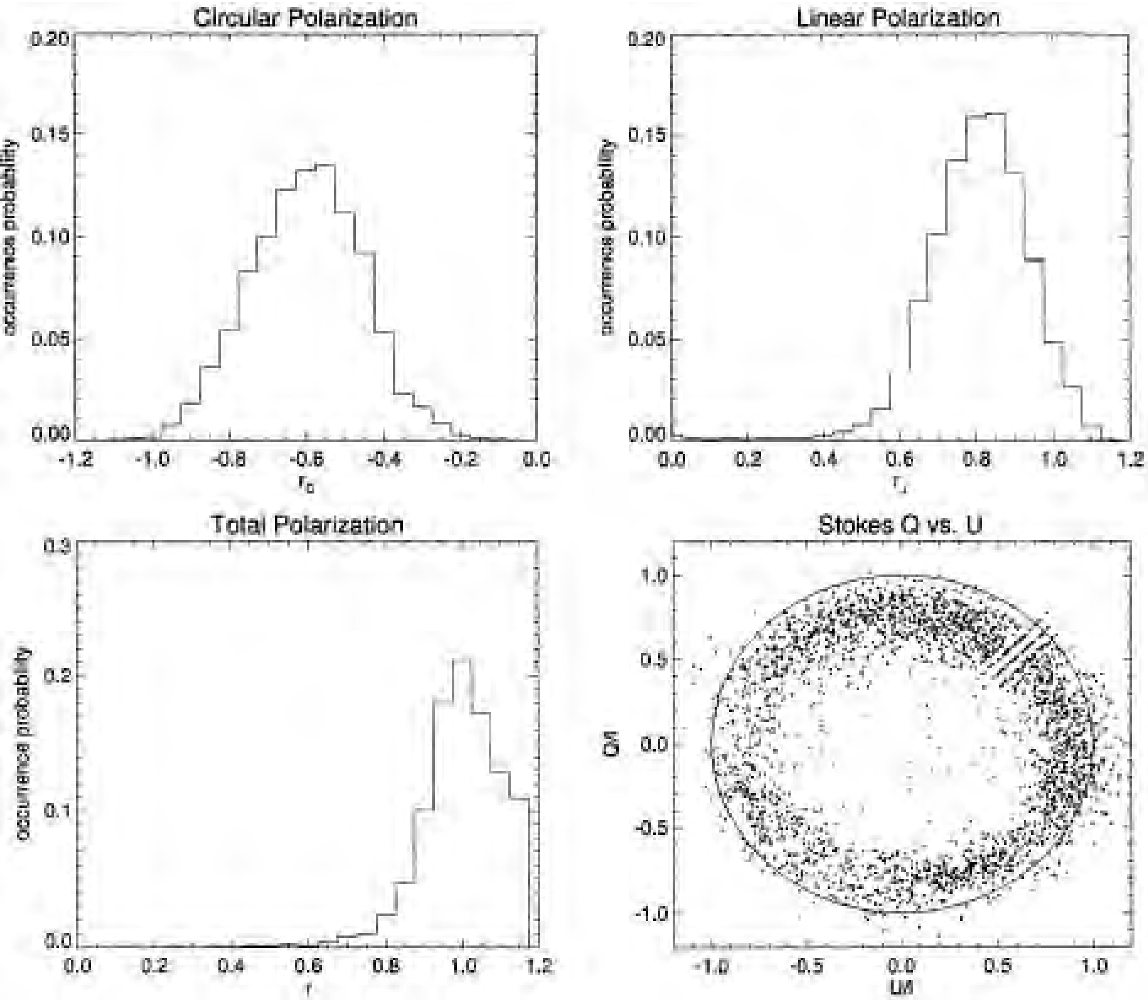


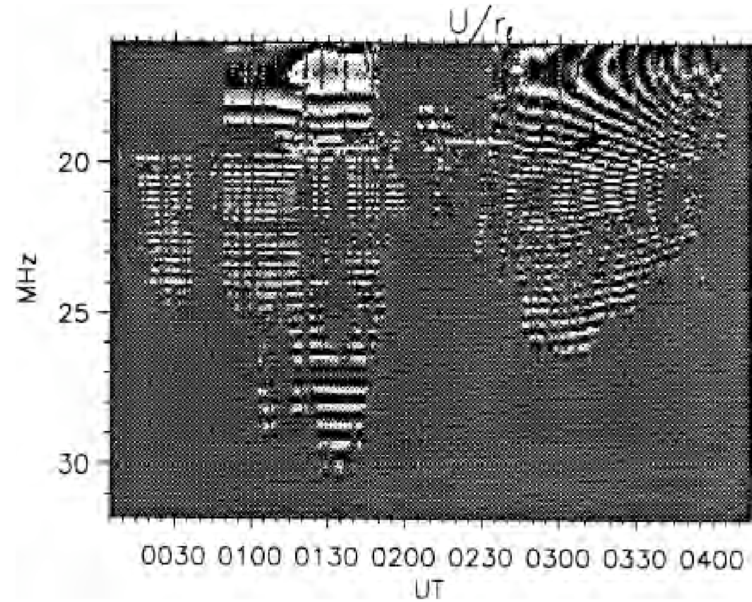


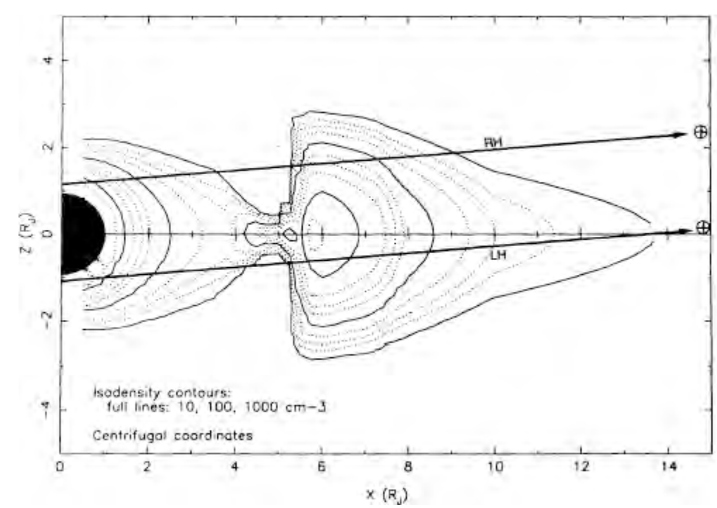


→ 100% elliptical polarization of DAM [Dulk & al., 1992, 1994]

→ implies plasma depleted ($N_e \leq 5\ cm^{-3}$) source regions [Lecacheux, 1988]



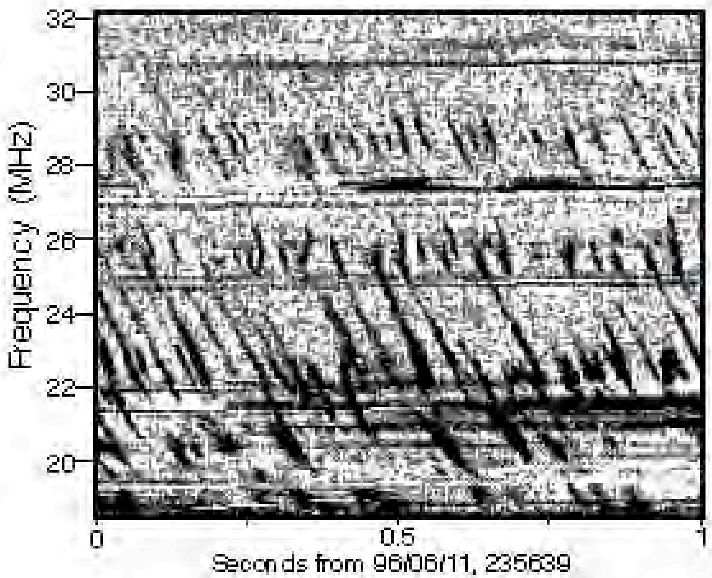


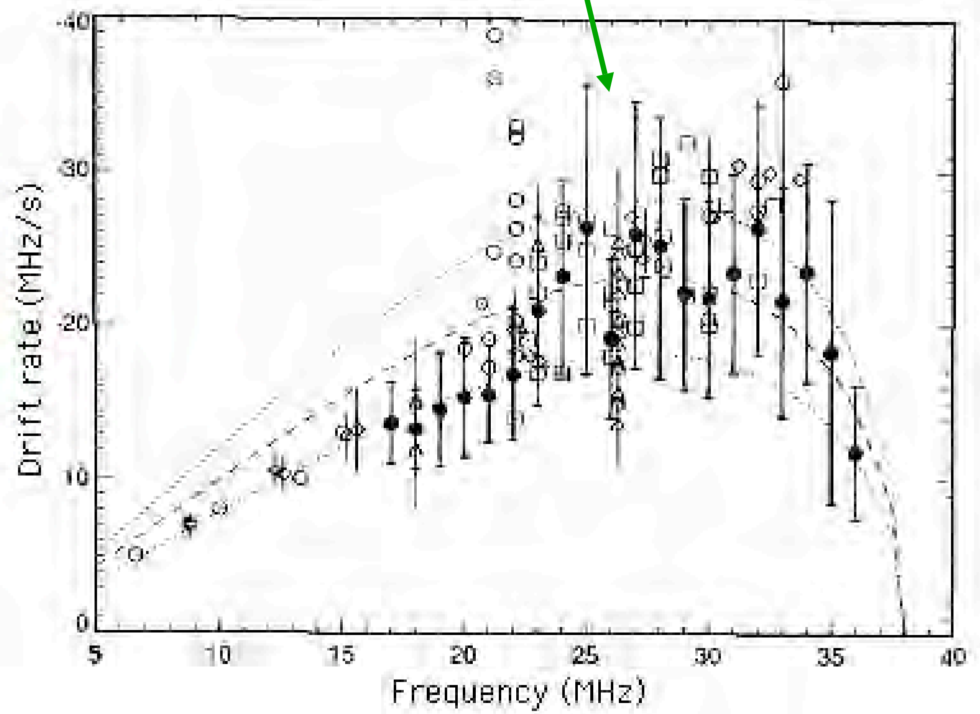


→ Massive measurements of S-bursts drift rates df/df(f)

5±2 keV electron bunches in adiabatic motion

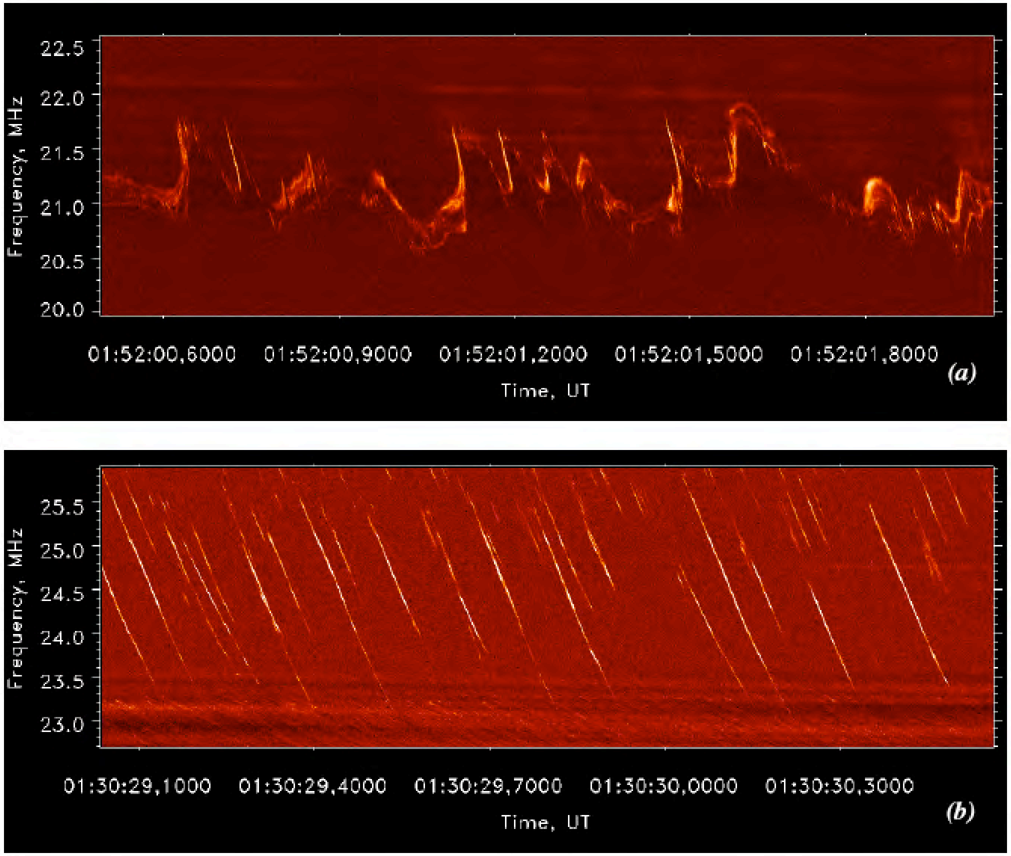
[Zarka & al., 1996]





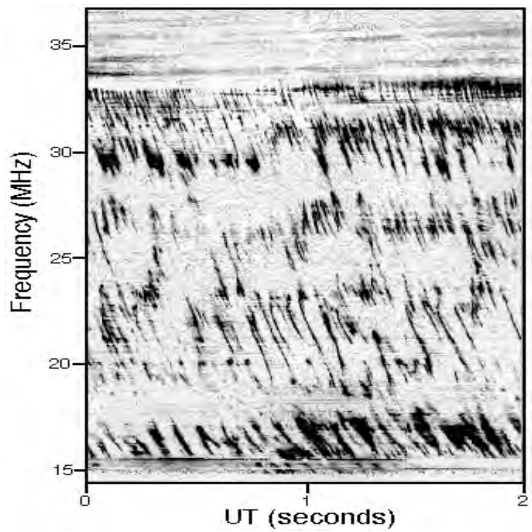
(3) Present :

- Digital DSP/FFT spectrograph (I) [Rosolen, Lecacheux…]
- Waveform capture (ROBIN)
- Digital DSP/FFT spectrograph (II) = « Reconquête » [Denis…]
- DRAFTA/UTR-2 [Ryabov et al.]



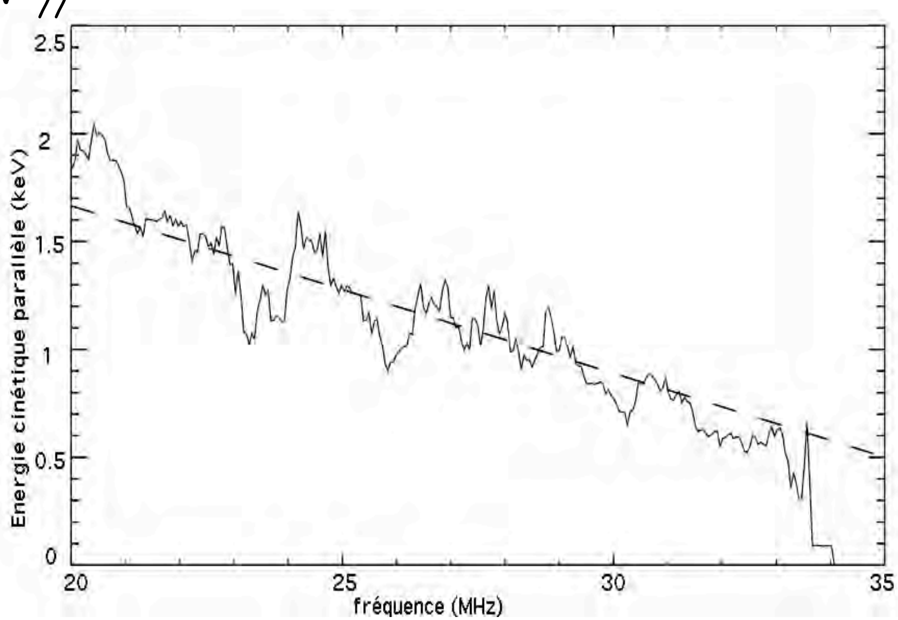
+ theoretical modelling

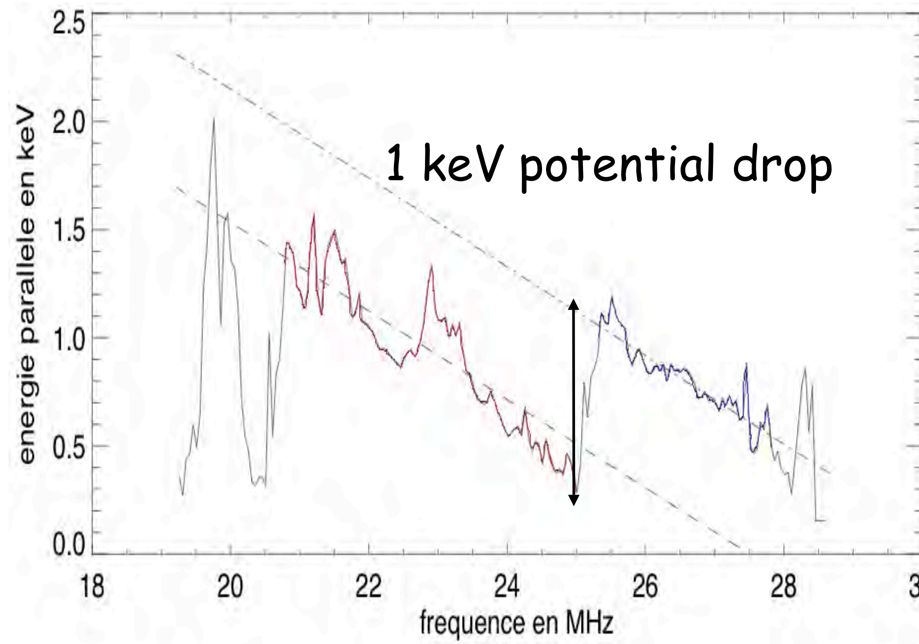
→ Potential drops & accelerations along Io flux tube ? [Hess & al., 2007a]



adiabatic motion → $v^2_{//} = v^2 - v^2_{\perp} = v^2 - \mu . f_{ce}$

$v^2_{//}$

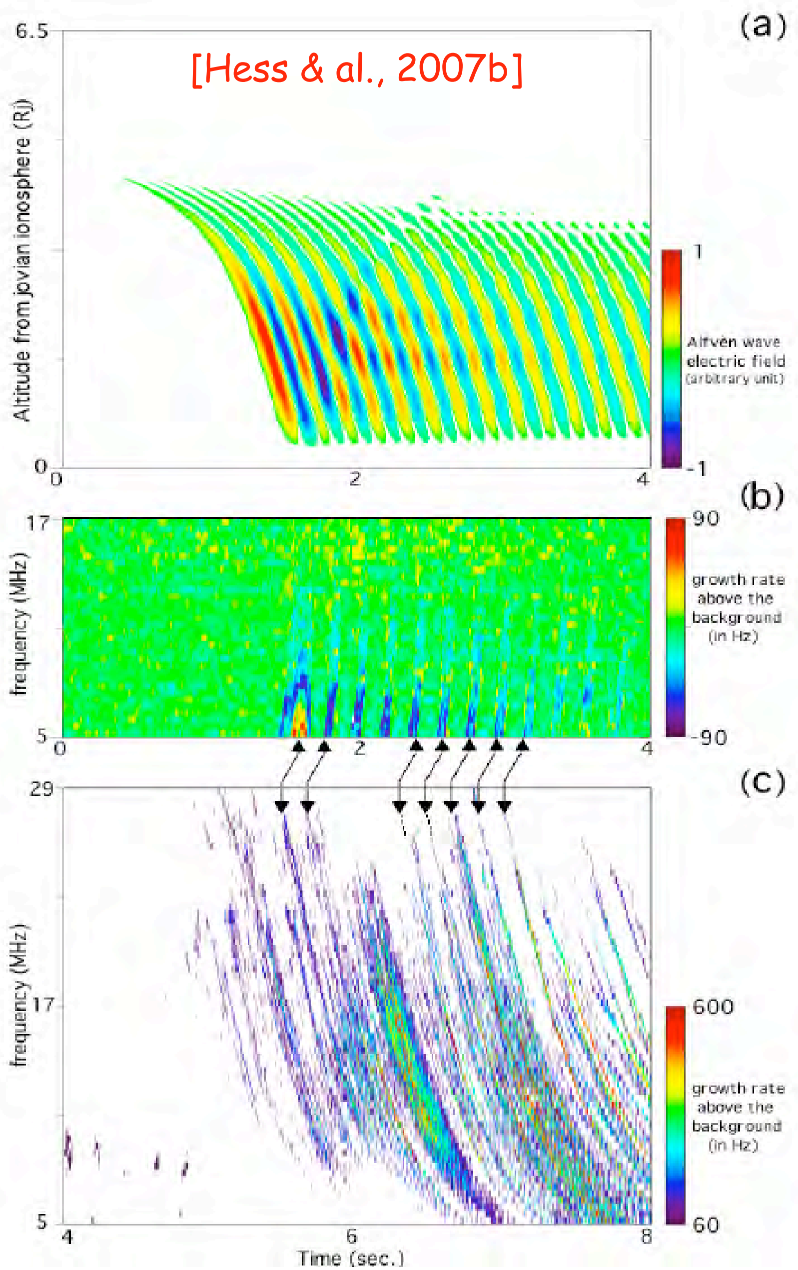


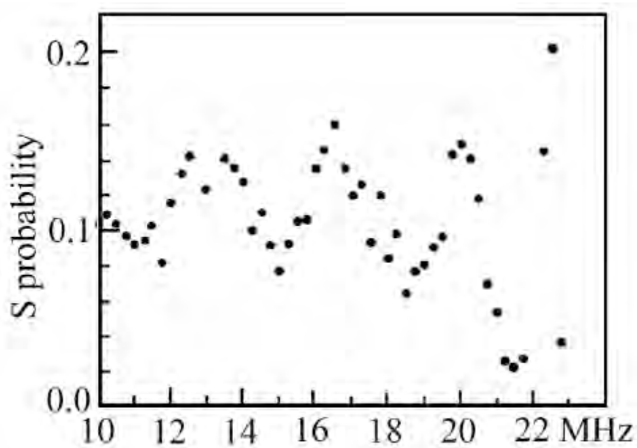


1 keV potential drop

f_{ce}

→ Electrons acceleration by Alfvén waves ?



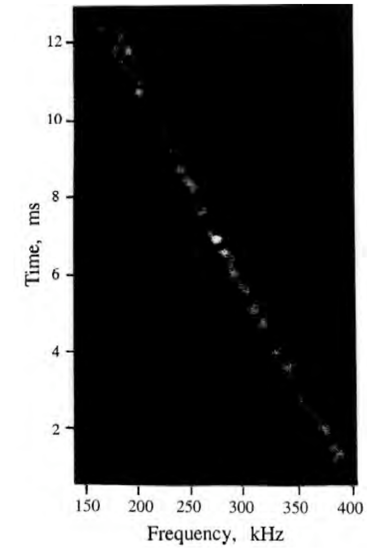


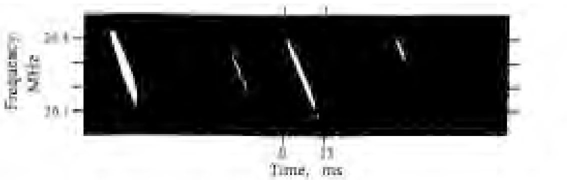
[Ryabov et al., 1985 ;
Ergun et al., 2005 ;
Arkhipov et al., 2006]

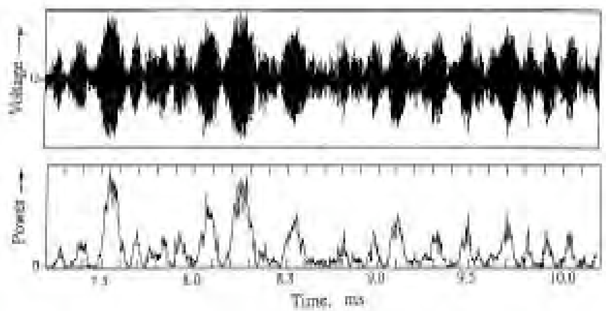
→ Waveform analysis on S-burst emission :

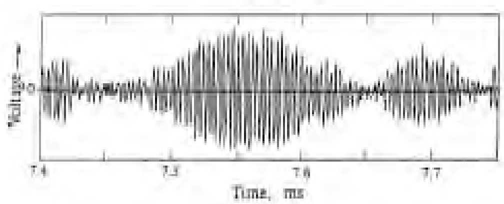
→ monochromatic time segments ? [Carr & Reyes, 1999]

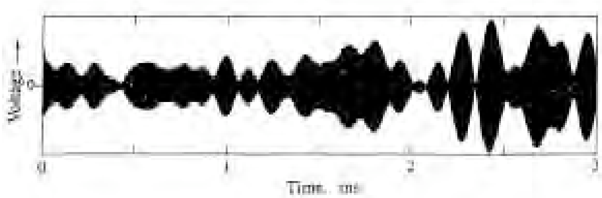
→ narrow-band amplifier ? [Ryabov et al., 2007]

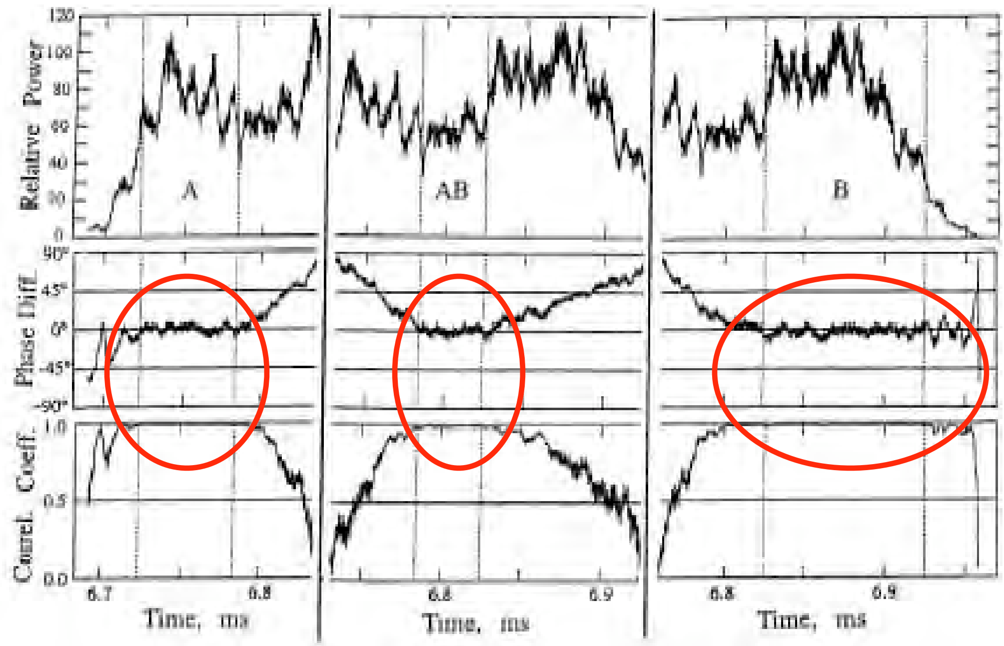






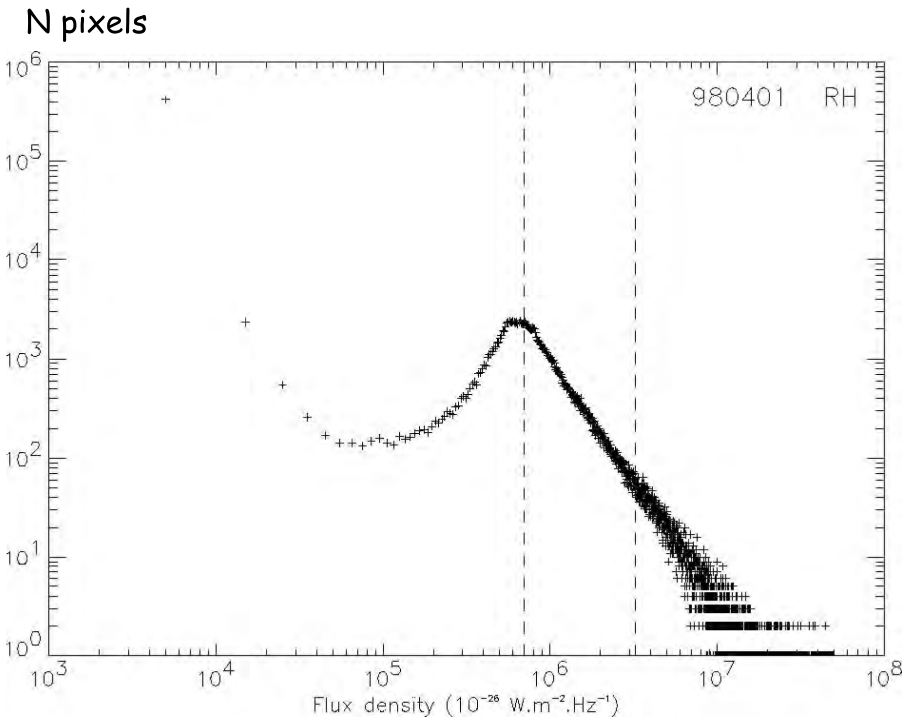


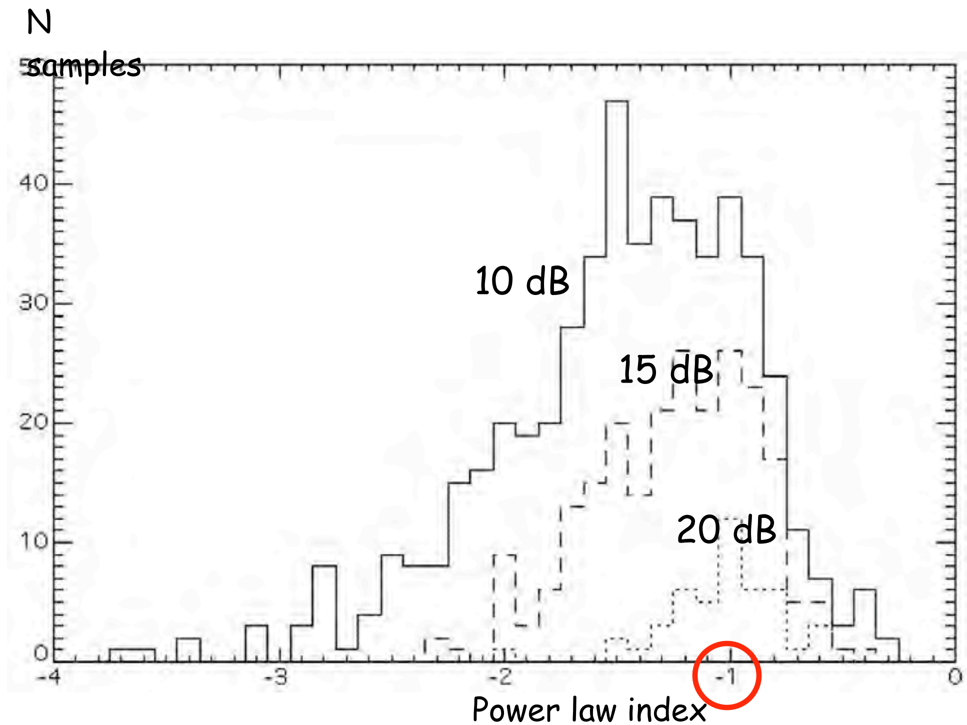




→ Power law distributions for S-burst intensities :

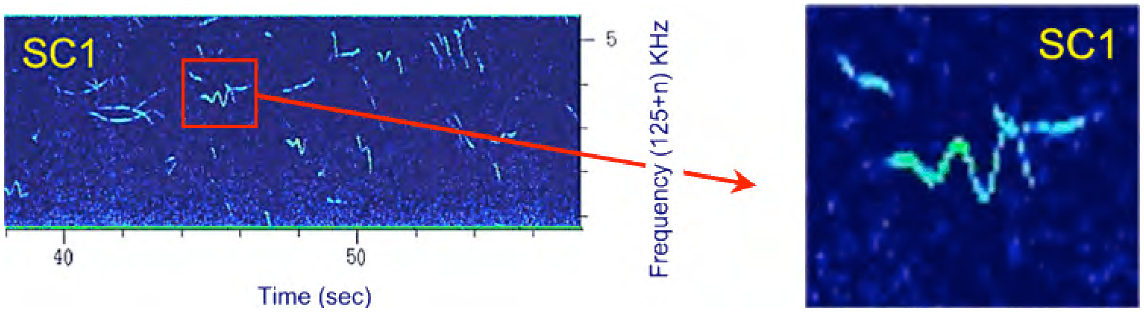
→ SOC ? [Queinnec & Zarka, 2001; Cohier, 2003]



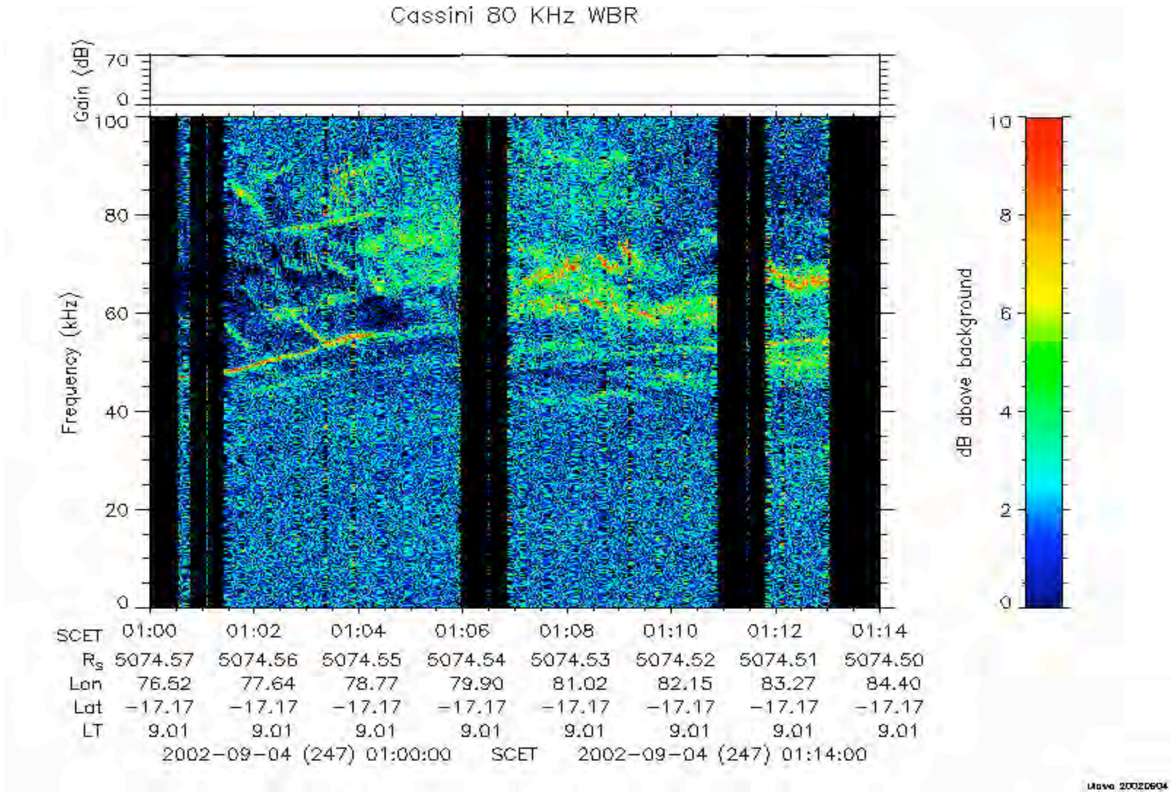


→ Fine structures of other planetary radio emissions

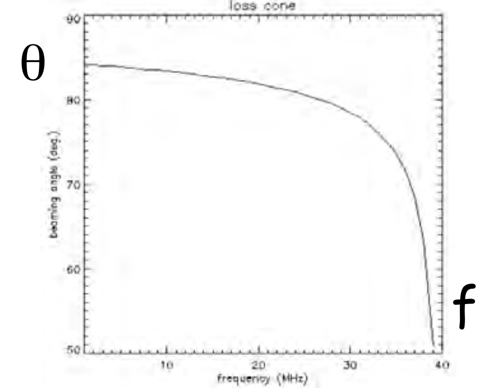
Earth: Cluster [Mutel & al.]

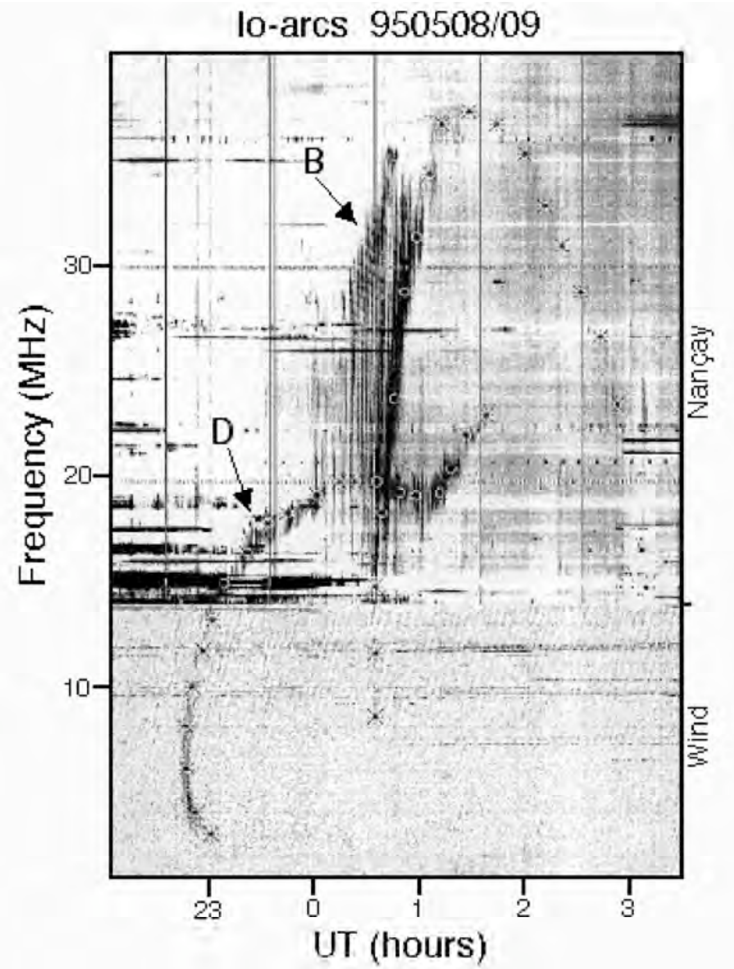


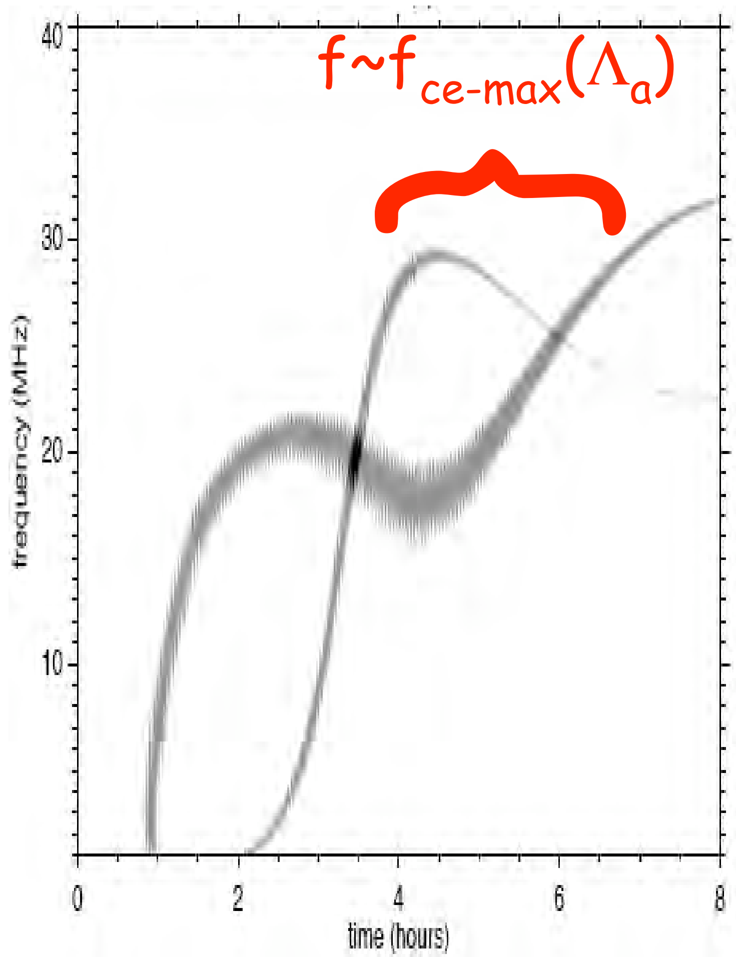
Saturn : Cassini [Kurth & al.]



→ Physical simulation of radio arcs

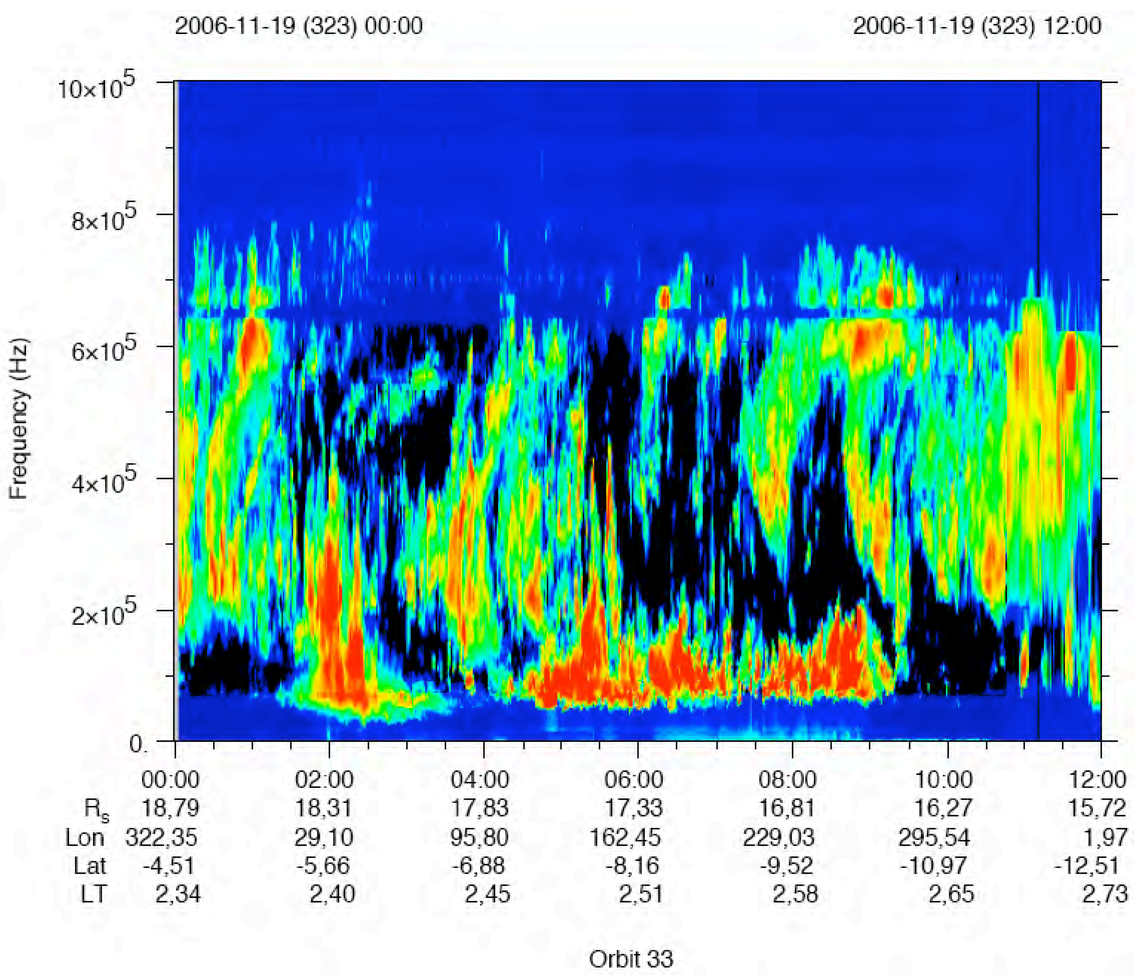






Io-B (N) and -D (S) arcs, Fixed equatorial observer, $\theta_{LC}(f) \rightarrow 70°$, $\delta\theta=1°$, CML=351°, $\Lambda°_{Io}=105°$, $\delta=30°$

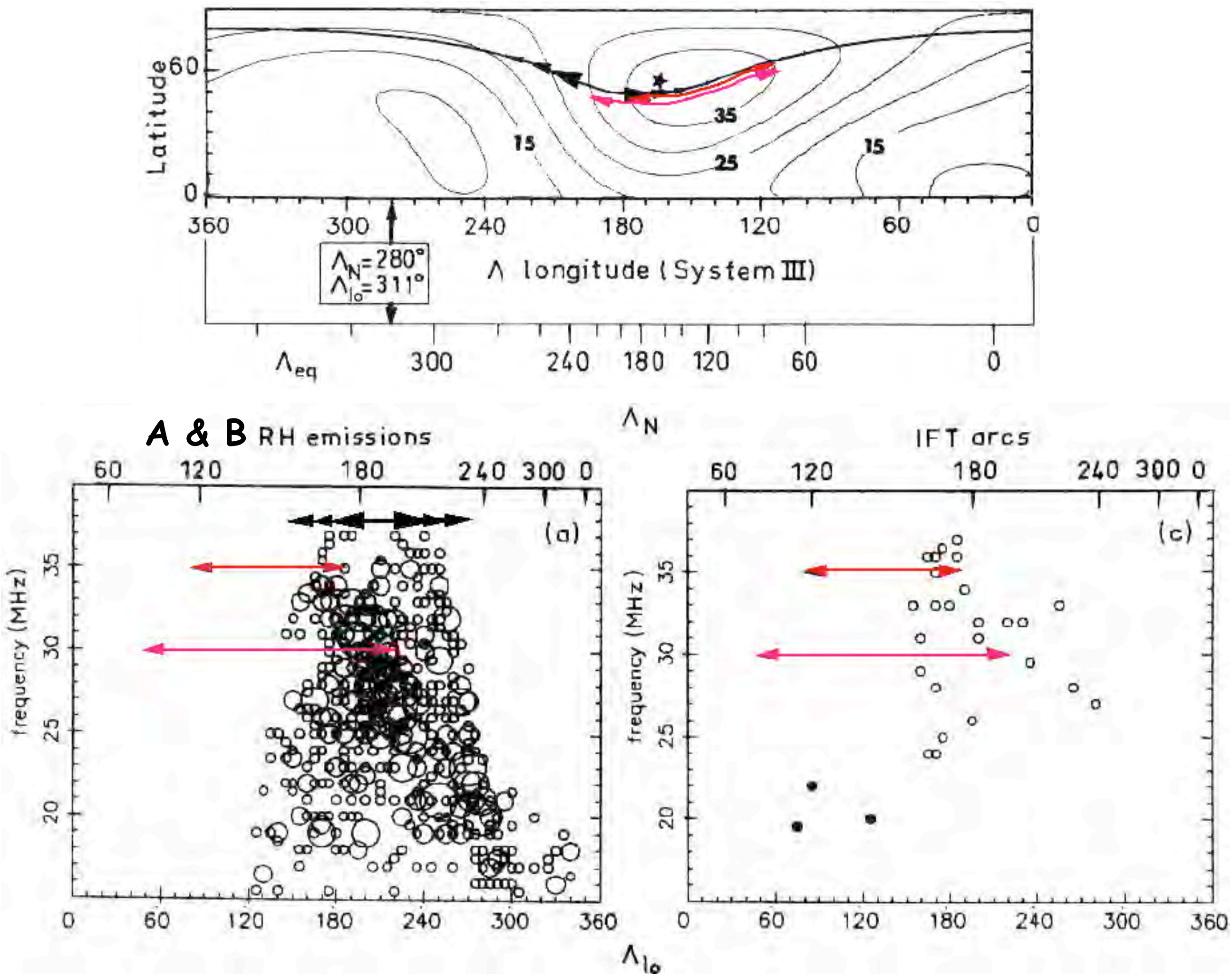
→ Saturn radio arcs



→ Comparison f_{max}(DAM) - magnetic field models

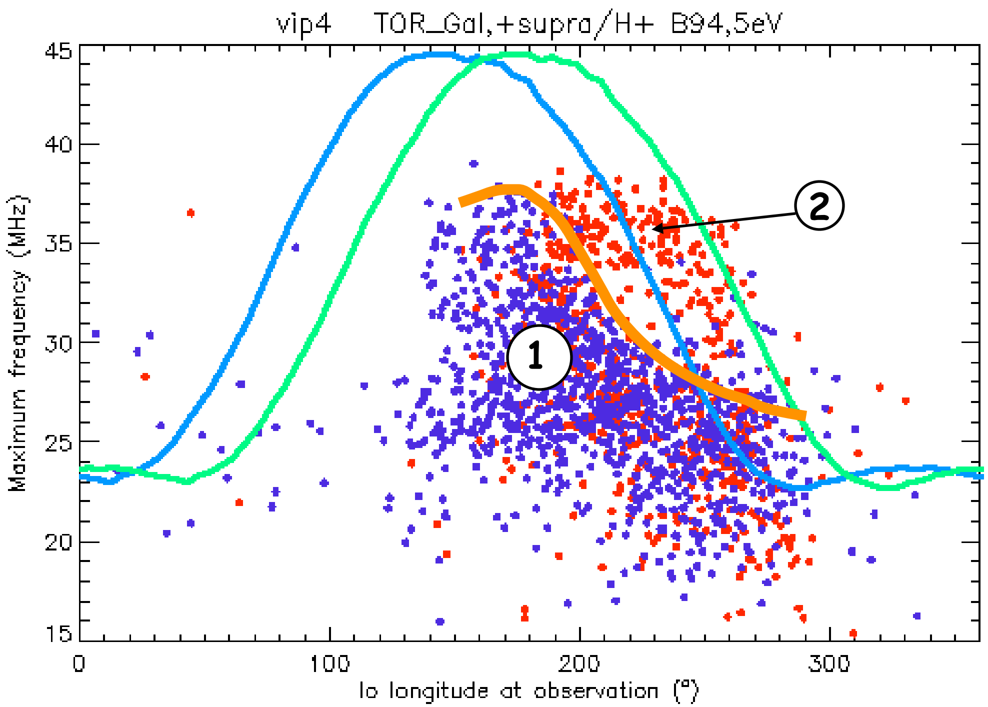
→ Inconsistency

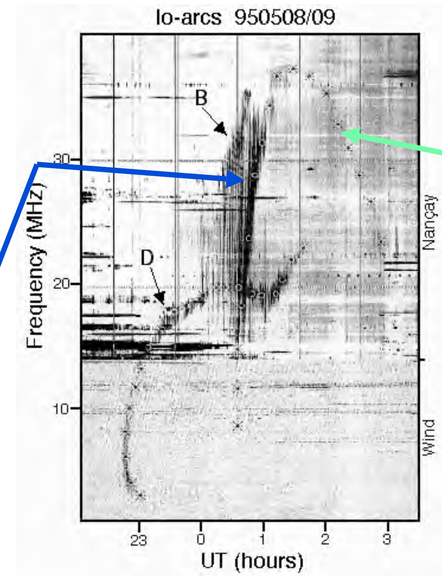
[Genova & Aubier, 1985]

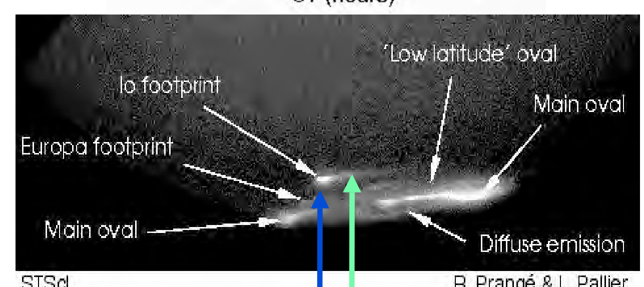


→ Inconsistency f_{max}(DAM) - magnetic field models [Genova & Aubier, 1985]

→ Solved as 2 radio emission populations, excited by Alfvén waves and slow shock / wake reacceleration currents [Zarka, Gerbault & al., 2002]







1 Alfvèn waves → several keV electrons → intense radio arcs + UV/IR spot

2 slow shock / wake reacc. J → ~1 keV electrons → radio & UV/IR "trails"

→ Strong constraints on Jovian magnetic field model

- Jupiter's radiophysics unveiled by 2 decades of decameter observations in Nancay

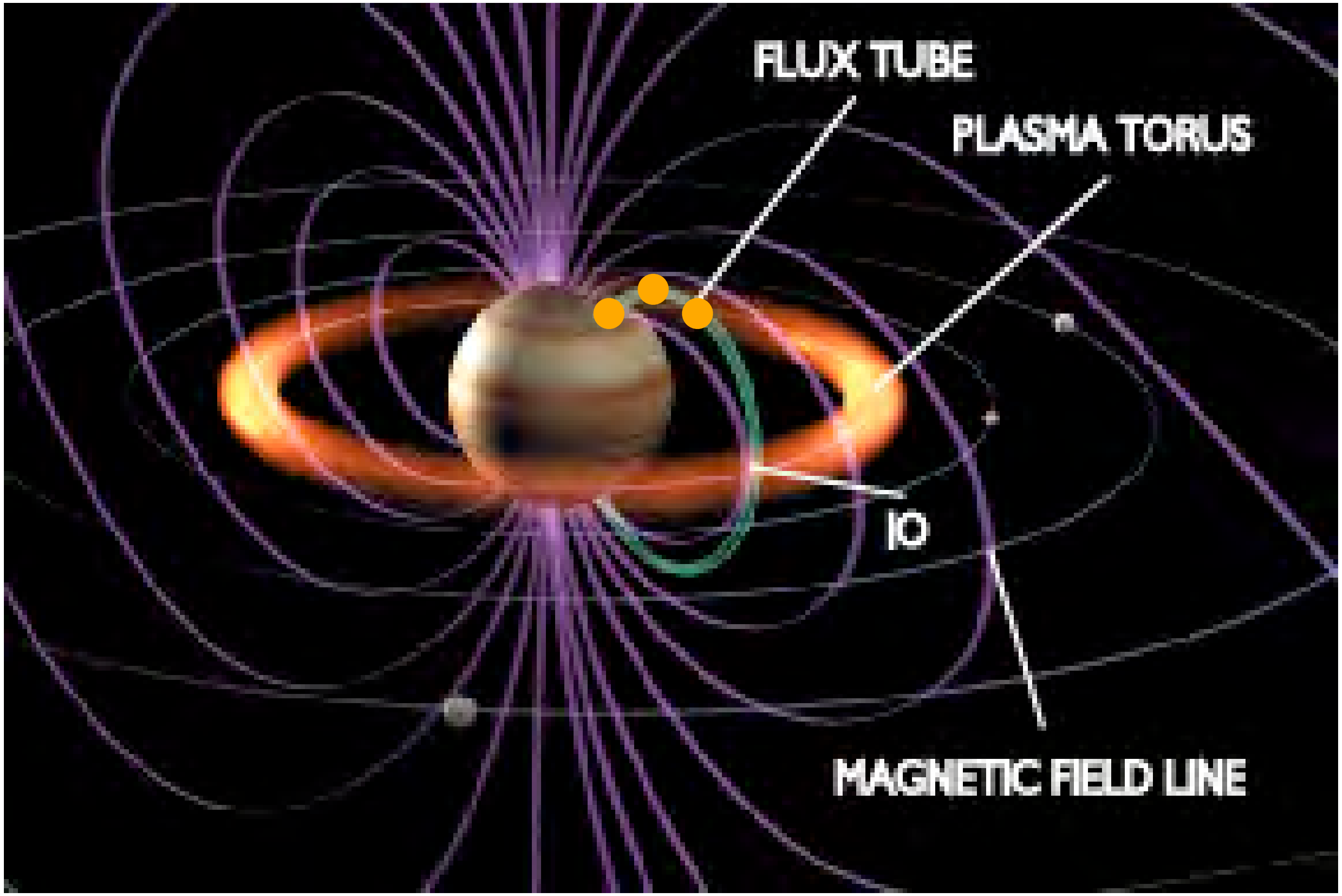
- Fast LF radio imaging of Jupiter's magnetosphere with arcsecond resolution

- Long baseline interferometry test on Jupiter with NDA and LOFAR

- LOFAR = future giant LF interferometer (of phased arrays) in construction in The Netherlands
- Diameter ~100 km
- Frequency range = (10)30-80 & 110-240 MHz
- Resolution = 20" at 30 MHz, decreases as λ (3" at 200 MHz)

• Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

→ Imaging of electron bunches (and potential drops) along B field lines

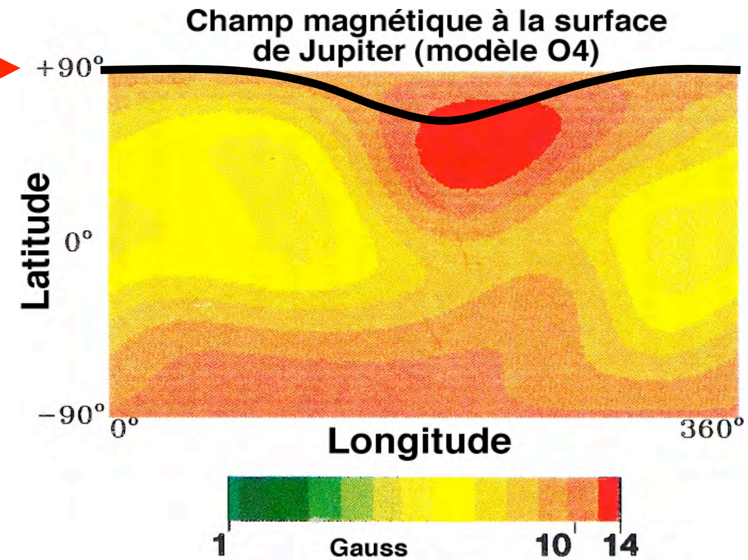


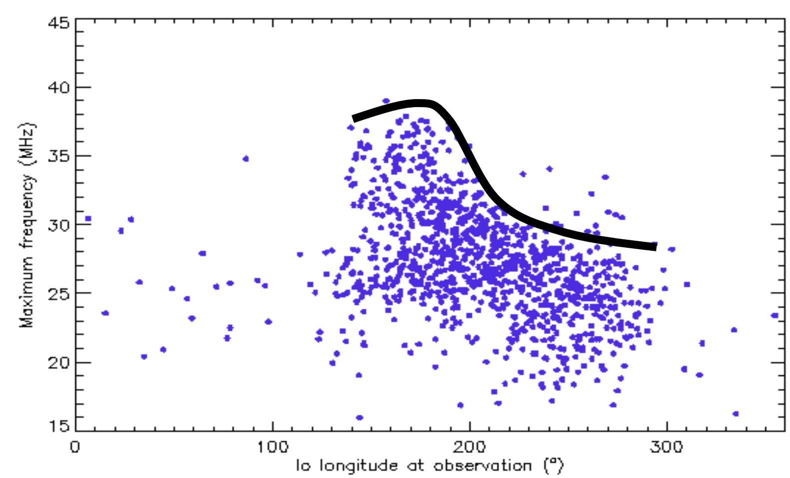
40”

• Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

→ Mapping of surface magnetic field ($f_{ce\text{-}max}$ (Λ))

	H4	VIP 4	Ulysses 17eV	O_6	O_4
dipole 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			



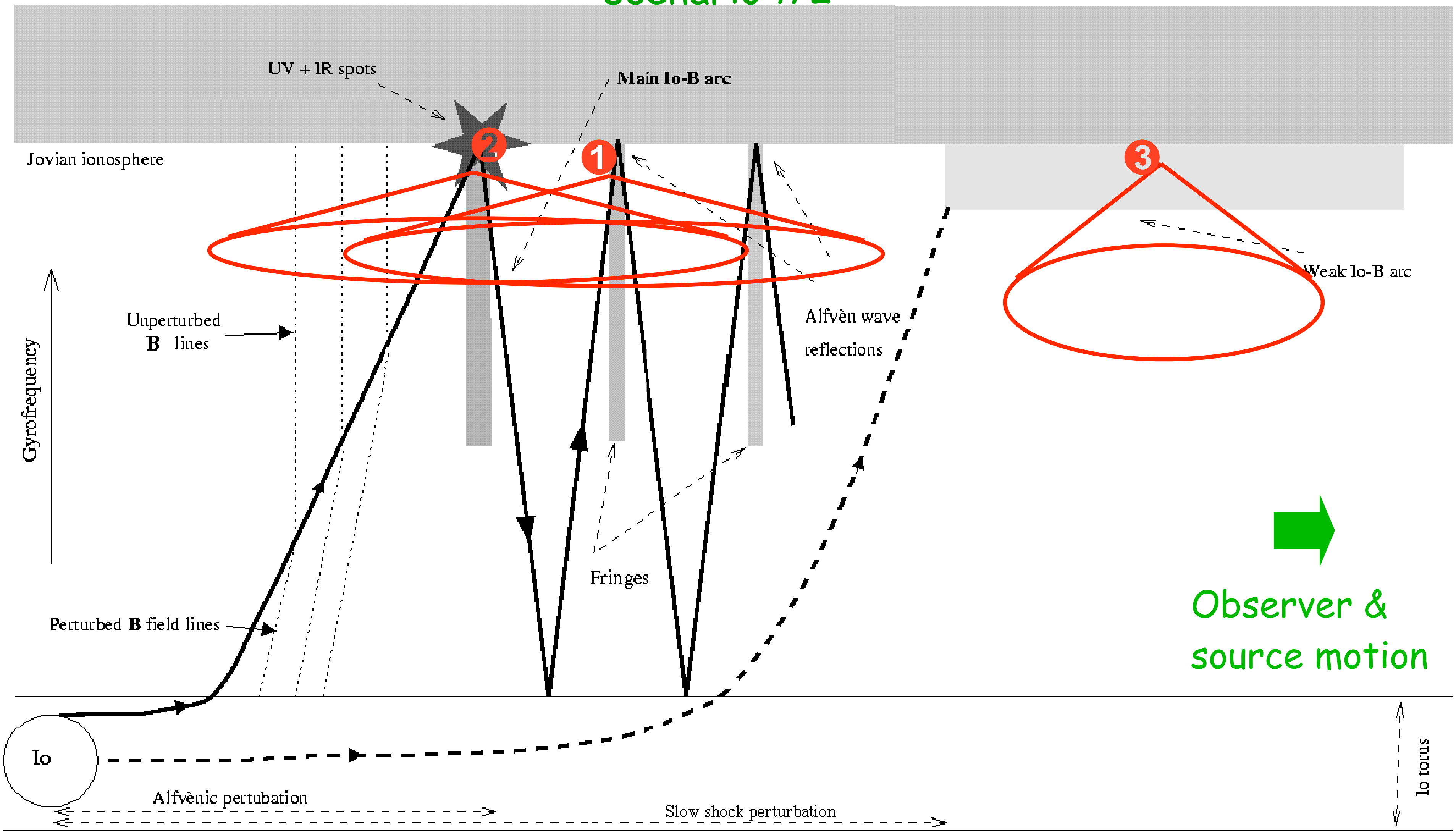


- Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

→ direct measurement of radio beaming angles

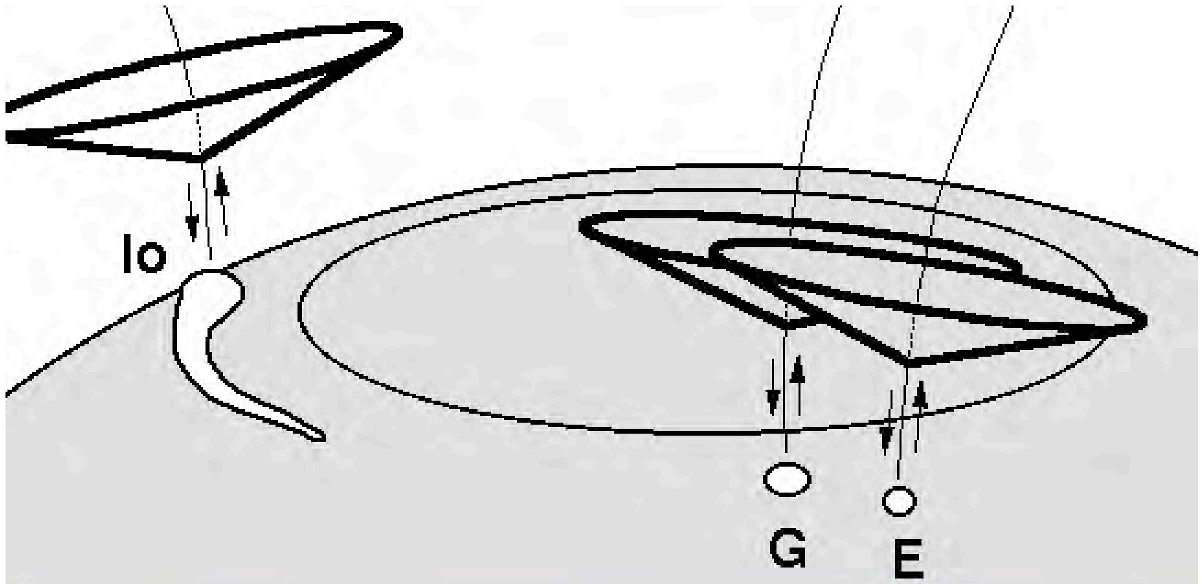
→ physics of generation process

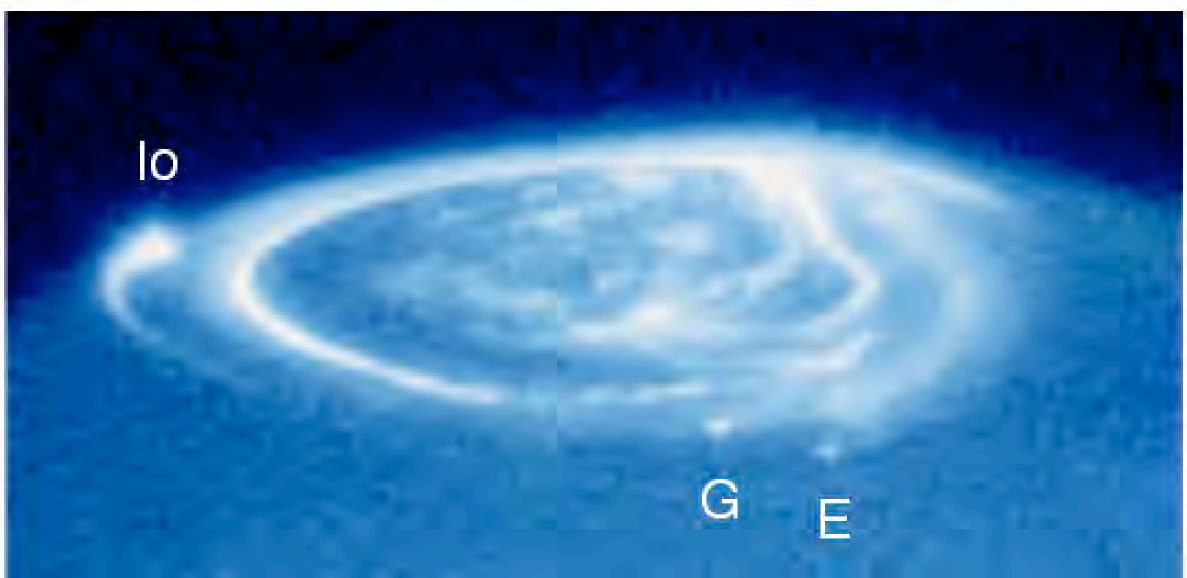
scenario #2



• Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

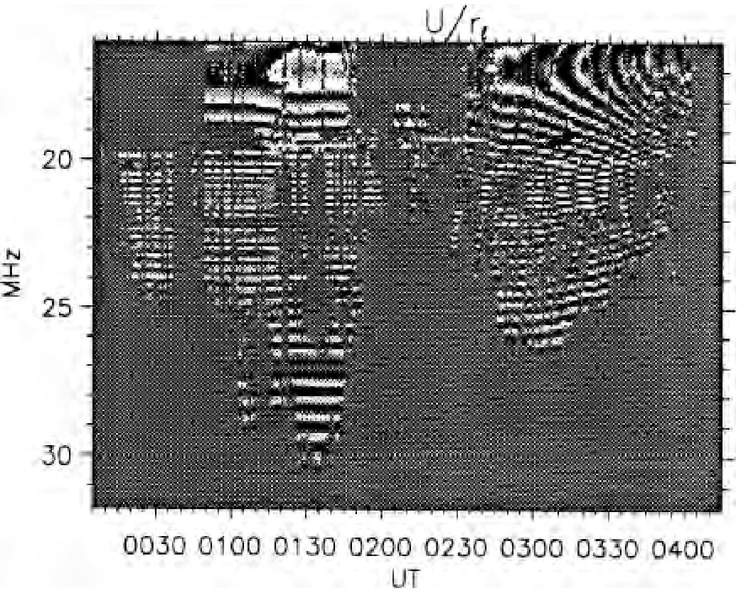
→ direct detection (& energetics) of Ganymede, Europe, Callisto-Jupiter radio emission

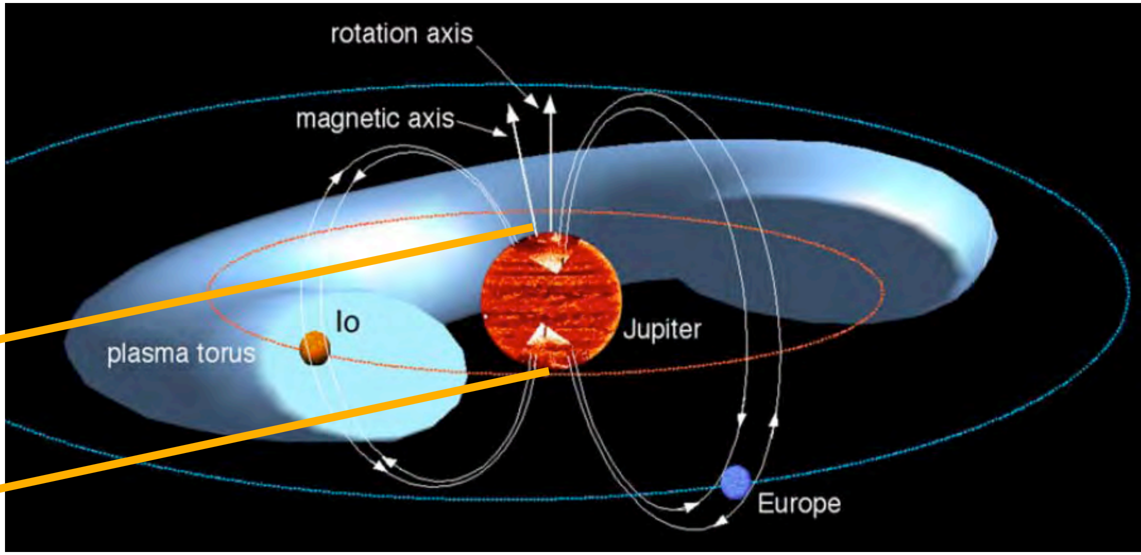




• Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

→ torus ∫Ne versus longitude via Faraday rotation

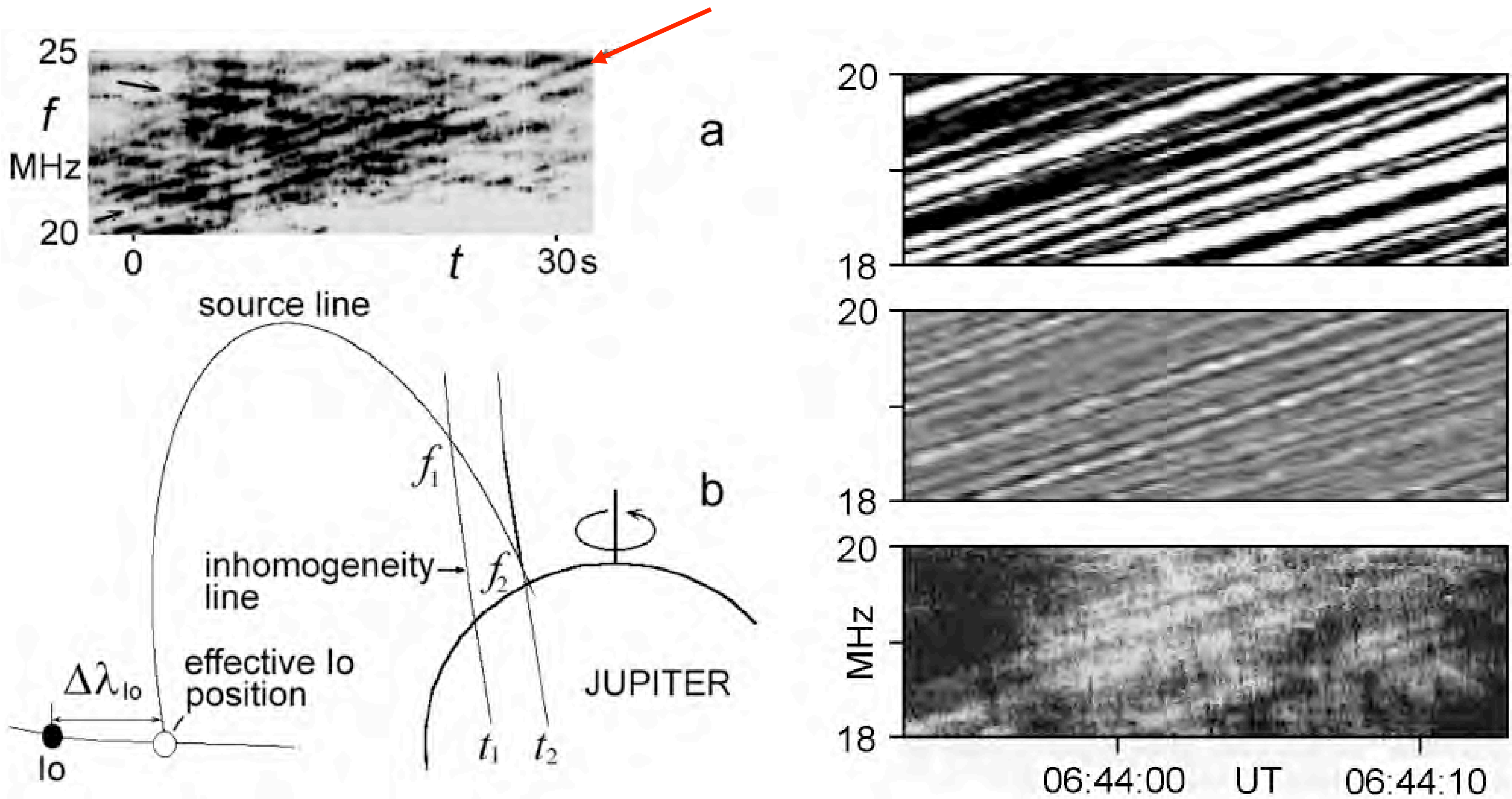




• Interest of 1" - 2" resolution (at 40 MHz), with high time resolution

→ probing of inner magnetosphere with « modulation lanes »

(diffraction by plasma inhomogeneities ?)



[Arkhipov & Rucker, 2007]

+ multi-wavelength correlations (Radio, UV, IR, X)

→ LOFAR fast imaging should provide NEW remote information about Jupiter's magnetospheric structure and dynamics

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

  P. Zarka*

  Planetary and Space Science 52 (2004) 1455–1467

- A Science Case for an extended LOFAR

  edited by Corina Vogt - ASTRON, Dwingeloo, The Netherlands

  September 11, 2006

→ Instrumental constraints

- ❑ **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

- Jupiter's radiophysics unveiled by 2 decades of decameter observations in Nancay

- Fast LF radio imaging of Jupiter's magnetosphere with arcsecond resolution

- Long baseline interferometry test on Jupiter with NDA and LOFAR

- There is scientific + strategic interest for 10 x higher resolution
  → Scientific objectives of LF radioastronomy with arcsec resolution
  → European extension of LOFAR to ~1000 km baselines

Current discussions:

Germany ~12 stations

UK ~2-3 stations

Italy ~2 stations

France ~1 station

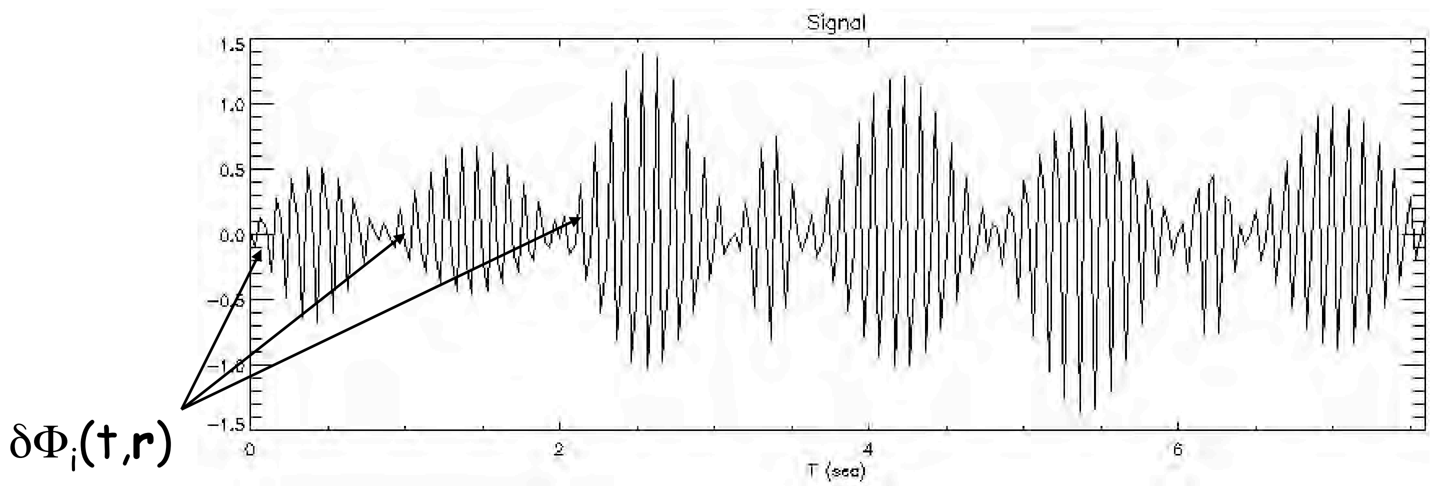
Poland ~1 station ?

• But ionosphere → propagation effects on LF radio waves (refraction, scattering scintillation), vary in $1/f^n$ with n=2-4

→ Random time variable phase shifts decorrelated at two distant locations (isoplanetic spot in ionosphere ~ km-10's of km at LF)

→ loss of phase coherency of the wave

→ no (phase) interferometry



• Question : which % of the time phase coherency is preserved, as a function of time and frequency ?

• Previous studies since 1965 : down to f=18 MHz, baselines up to 7000 km

- Jupiter @ 34 MHz, baseline 4300 km, δf=3 kHz [Dulk, 1970]

→ instantaneous source, iff incoherent, «400 km at Jupiter = 0.1"

- Jupiter @ 18 MHz, baselines 218-6980 km, δf=2.1 kHz

[Brown et al., 1968; Lynch et al., 1972]

- Radiosources @ 81.5 MHz, baselines ≤ 1500 km [Hartas et al., 1983]

- Radiosources @ 20 & 25 MHz, baseline 900 km [Megn et al., 1997]

• But few studies, narrowband, heterodyne, analog observations with 1-bit a posteriori digitization & correlation.

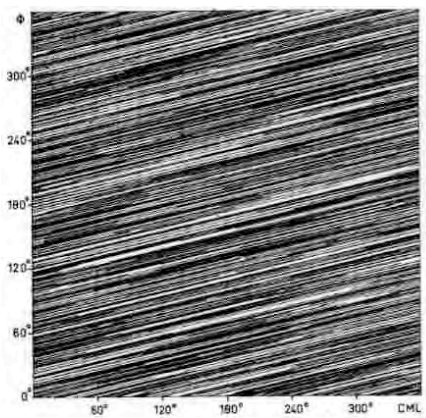
• Here : broadband, baseband, 12-14 bit digitization, today, at LOFAR site

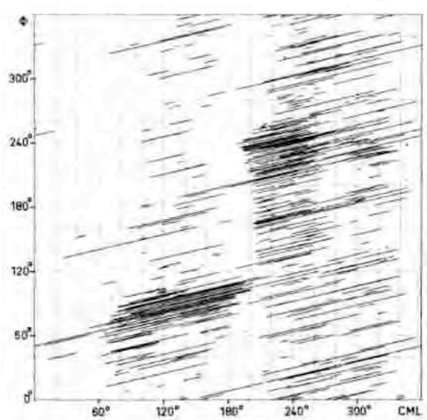
→ VLBI observations between Nançay and LOFAR proposed to ASTRON in 2004

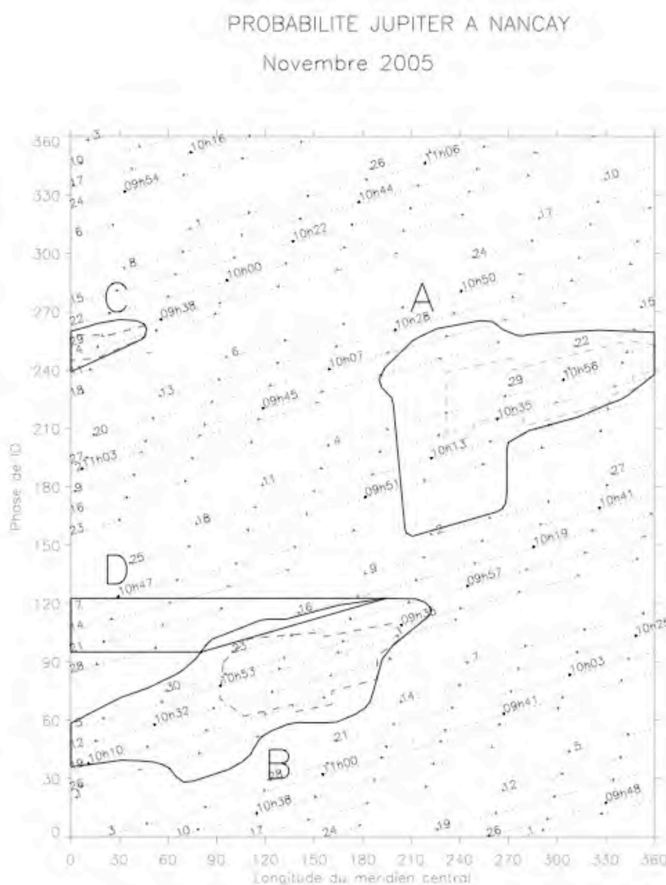
• Baseline = 700 km

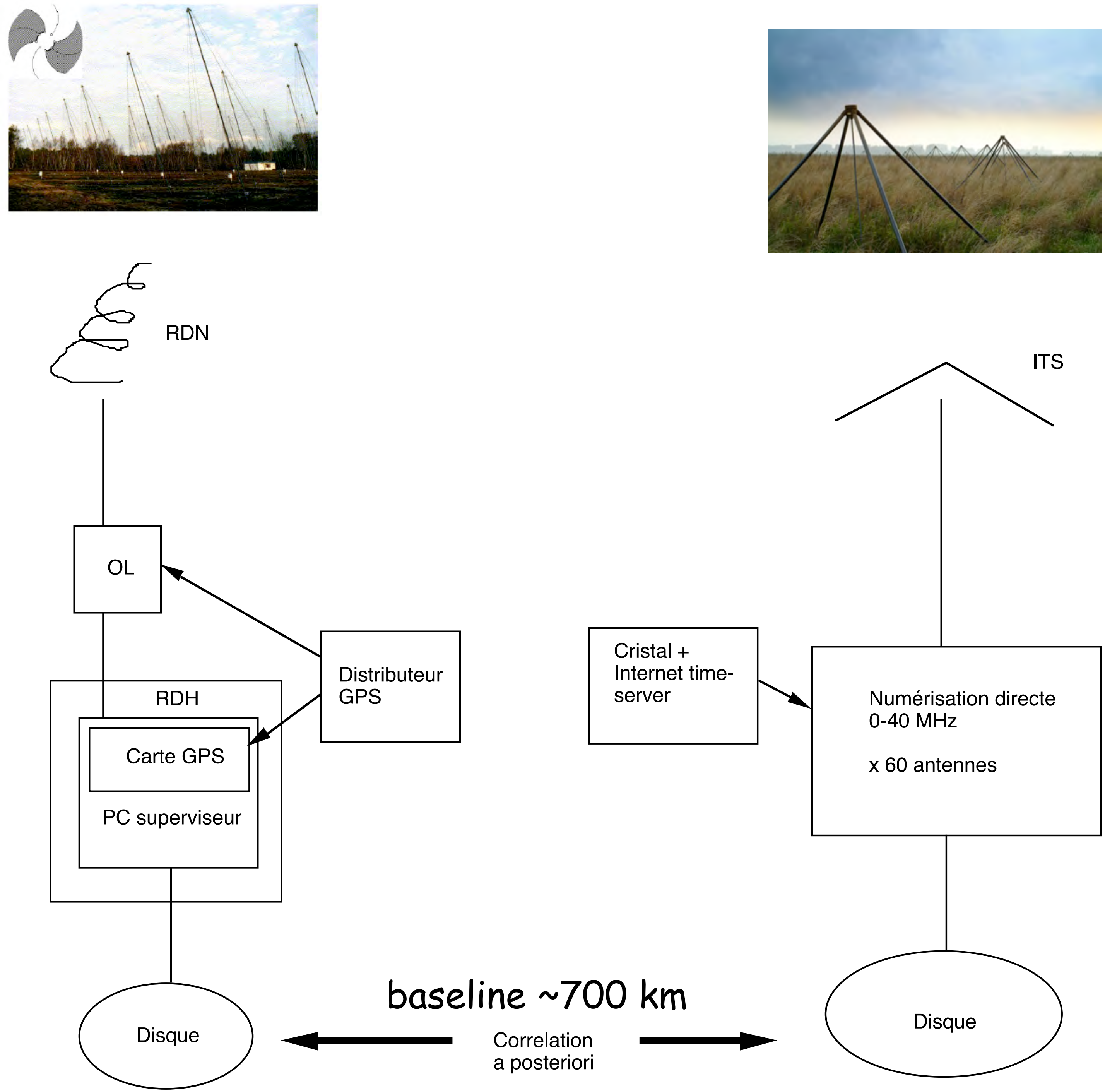
• Target : must be intense (small antennas) and point-like (to get fringes)

→ best source = Jupiter, but sporadic and <u>partly</u> predictable







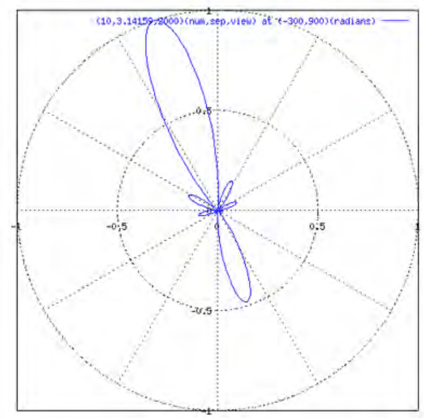

RDN
ITS
OL
Distributeur GPS
Cristal + Internet time-server
RDH
Carte GPS
PC superviseur
Numérisation directe 0-40 MHz
x 60 antennes
Disque
baseline ~700 km
Correlation a posteriori
Disque

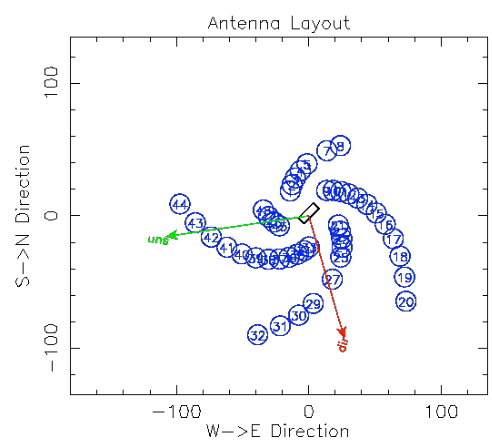
- Instruments

LOFAR-ITS : in Exloo, 30x2 V-dipoles, 5-35 MHz, 12-bit digitization, 80 Msamples/sec (12.5 nsec/sample), storage 1 Gb = 6.7 sec

offline digital beamforming (per time blocks of 0.2 msec with Hamming windowing, FT, phase gradient & reconstruction)

Time reference : crystal + Internet time server



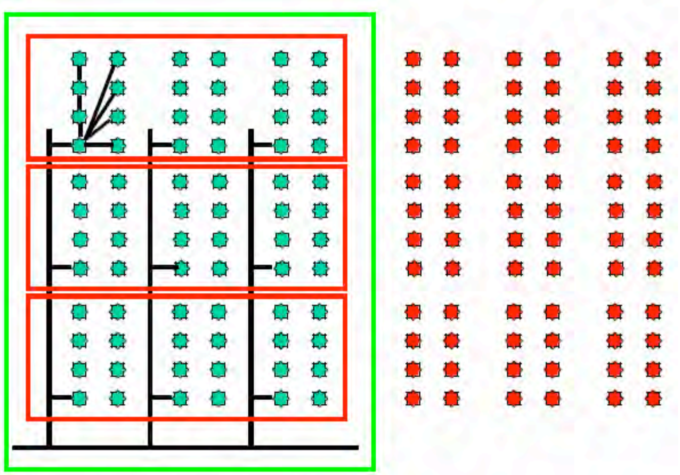


- Instruments

Nançay Decameter Array : 2x72 spiral antennas (RH & LH), 10-100 MHz, 14 bit digitization, 80 Msamples/sec, continuous storage.

analog real-time beamforming

Time reference : GPS + broadband noise generator On 5 msec / sec (+ UTC Radio France)



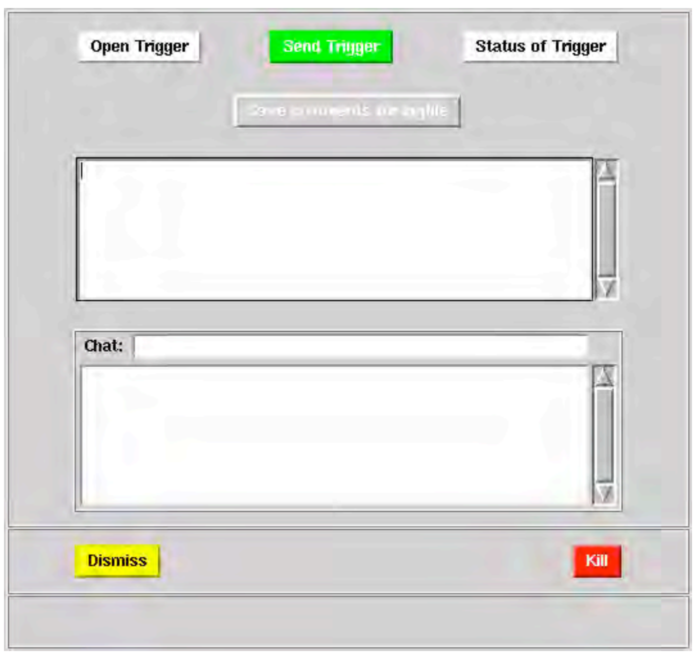
- Observations

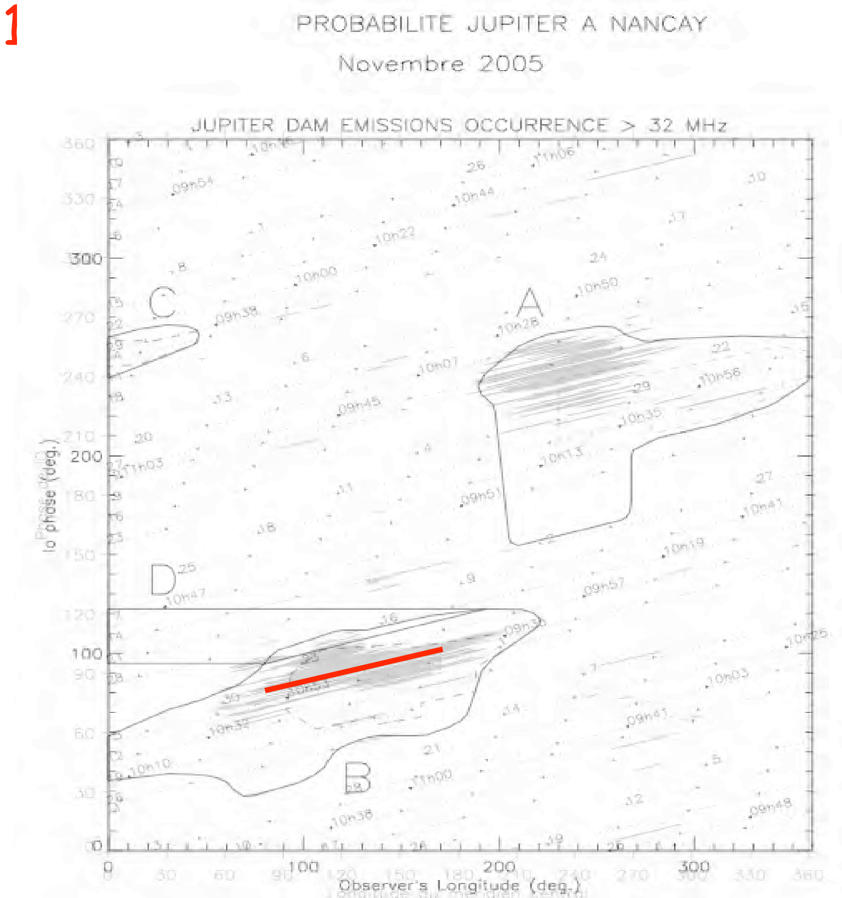
→ Triggering for simultaneous waveform capture + offline correlation

→ Remote control of ITS from Nançay (real-time display) via the internet for 6.7 sec snapshots

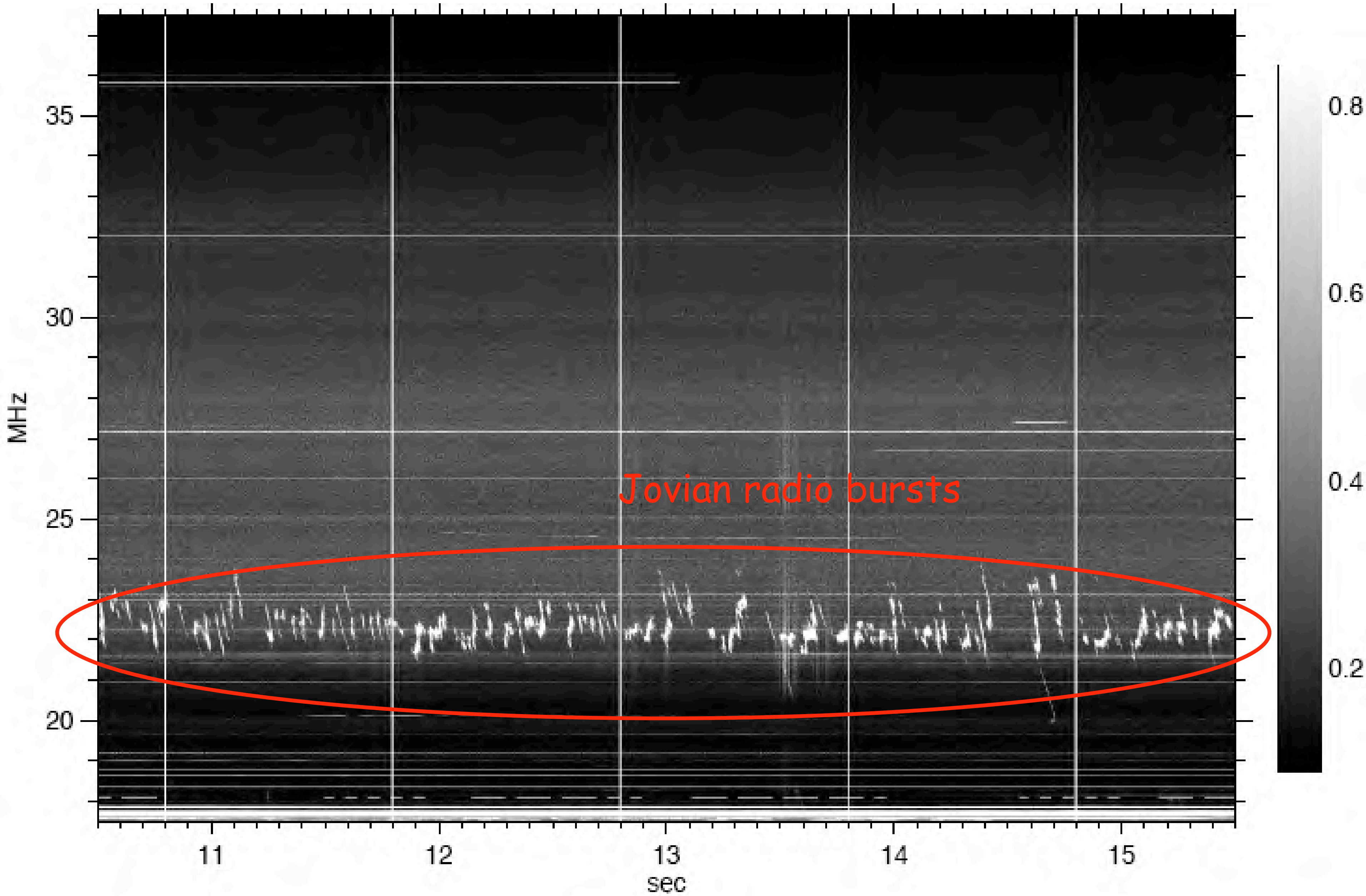
→ HF Jovian emissions (>32 MHz) occurrence probability ~100%

→ First successful observation 30/11

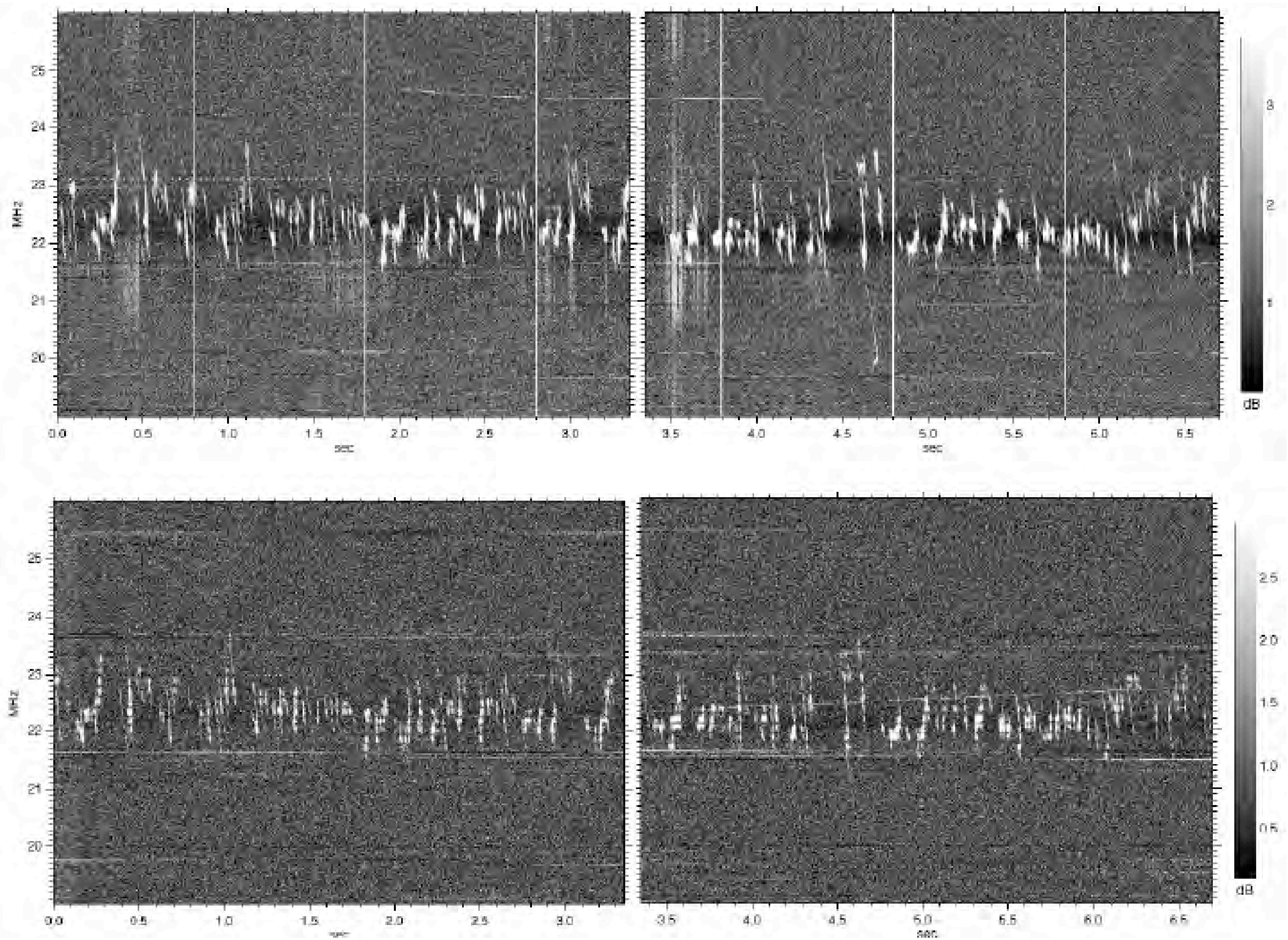




- Excerpt of an observation with Nançay Decameter Array

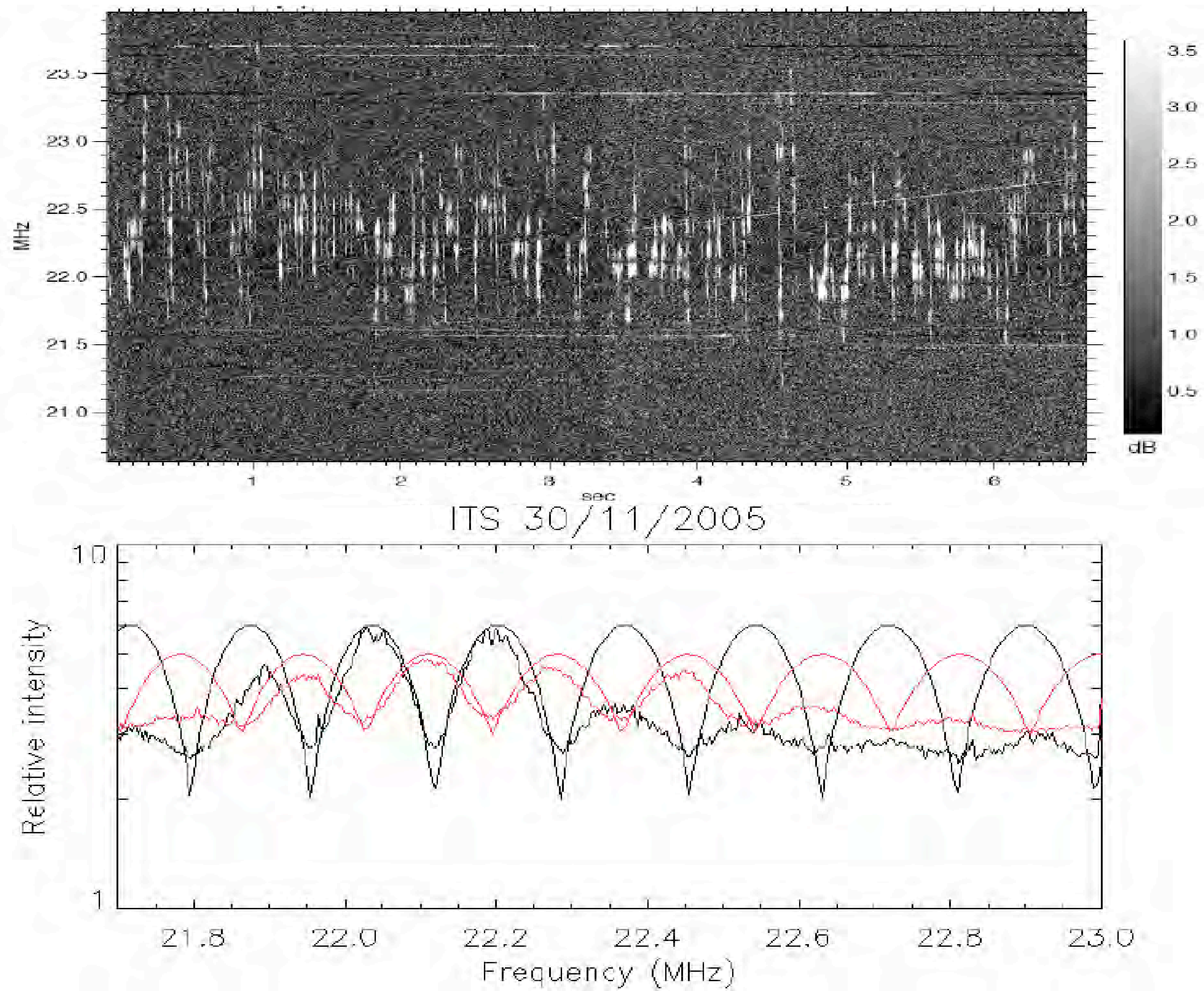


• Simultaneous Jovian S-bursts identified on dynamic spectra



• Faraday fringes on ITS (linear polarization) data

→ bands fitted (correlation better performed in/near band peak)

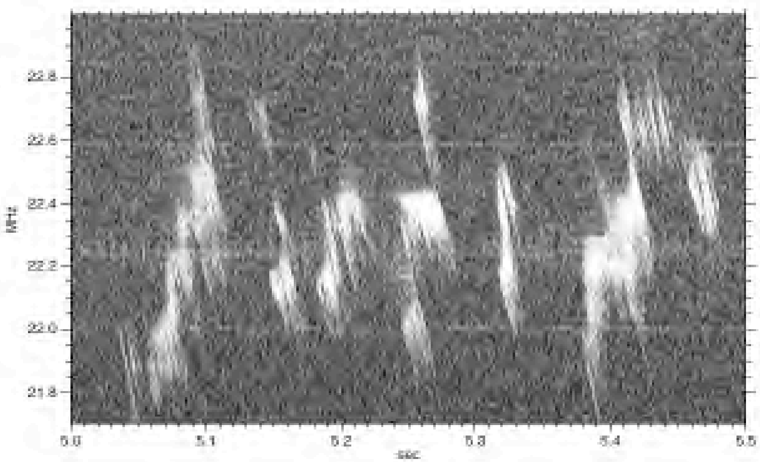


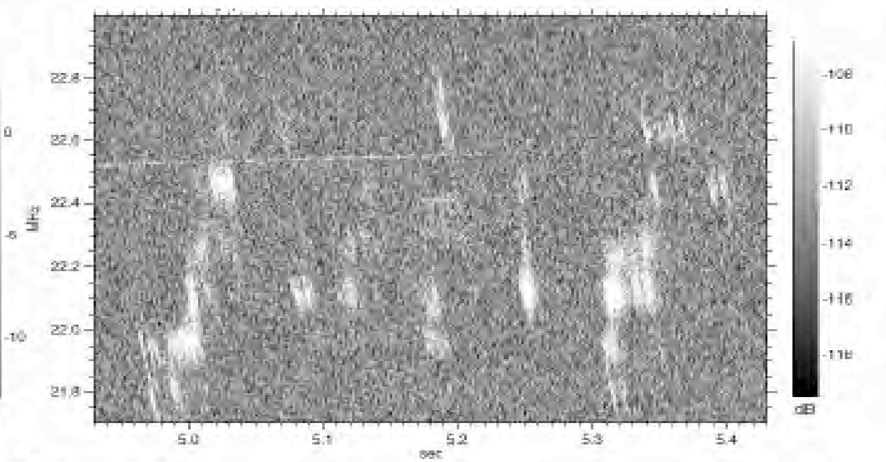
- Synchronization of data (absolute timing no much better than 1 sec) :

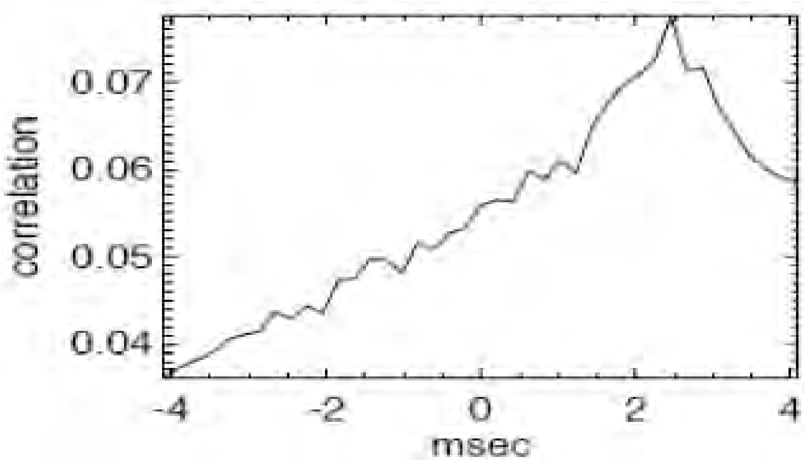
→ use S-bursts via cross correlation of dynamic spectral structures

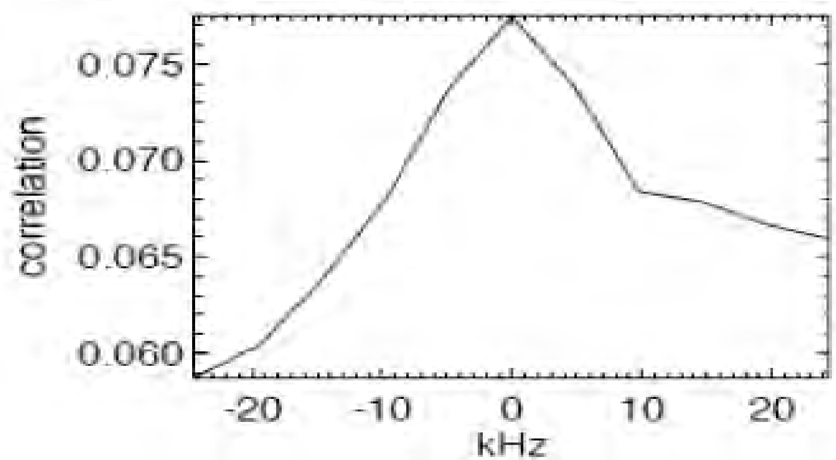
→ $\delta f \times \delta t \sim 1$ → increase of time resolution at expense of spectral resolution

→ ITS-NDA synchronization at ~microsecond level : $t_{Nançay} - t_{ITS} = 0.072379$ sec









• Waveform cross-correlation

→ in Fourier space (Wiener-Khintchine)

→ filtering (Hanning), reconstruction of waveform (with 50% overlap), FT (Hannning), cross product by conjugate

$$C = FT^{-1}[FT(W_N) \times FT(W_1)^*] / (\sigma_{W_N} \cdot \sigma_{W_1})$$

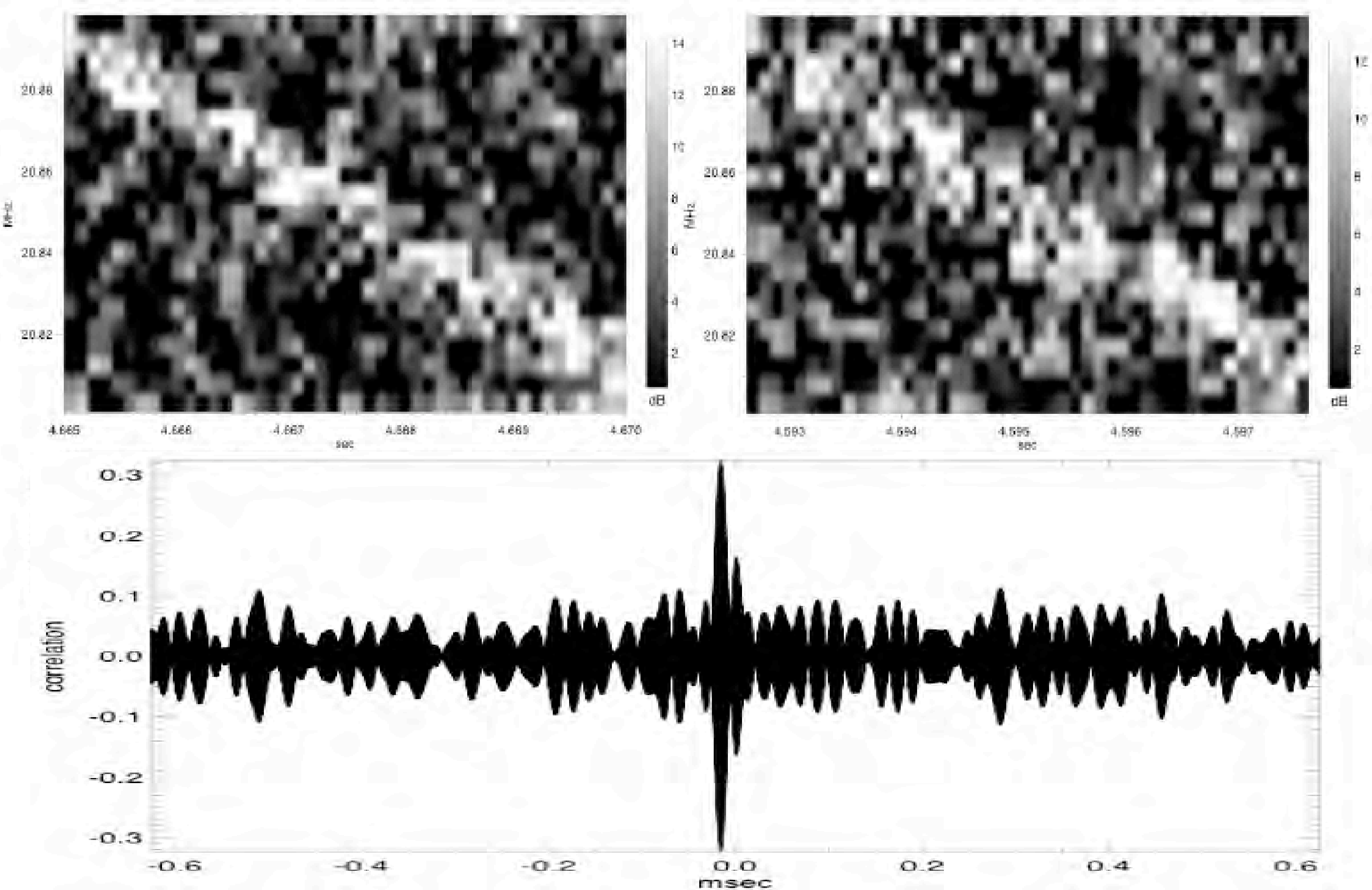
• Constraints on filtering : Jupiter bursts = wave packets of

~0.1 msec duration

→ band ≤ Faraday fringe width (100-150 kHz)

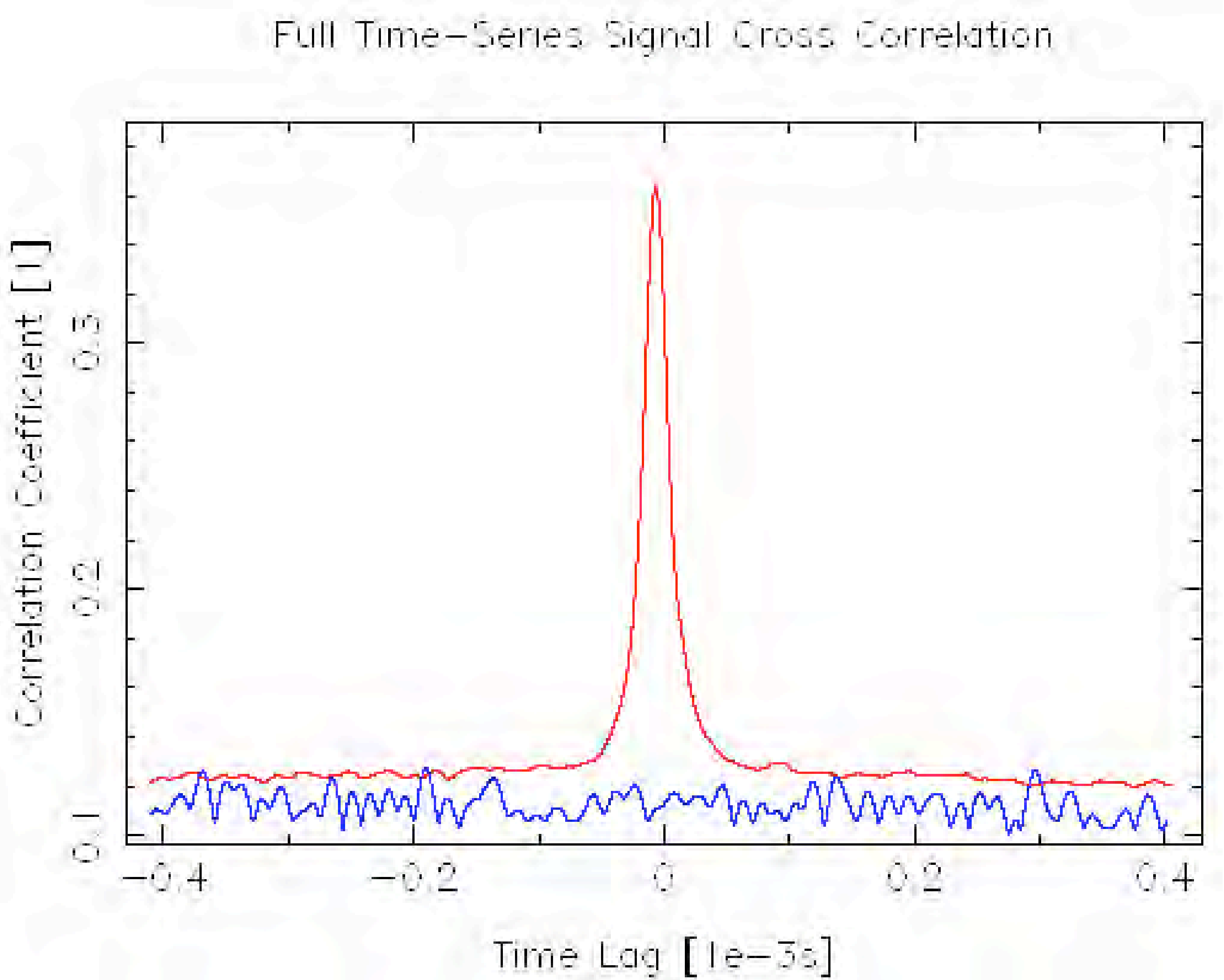
→ δt >> wave packets ~40 μsec, δf >> natural bandwidth of ~30 kHz

- Test on random data sample → correlation > 0.3

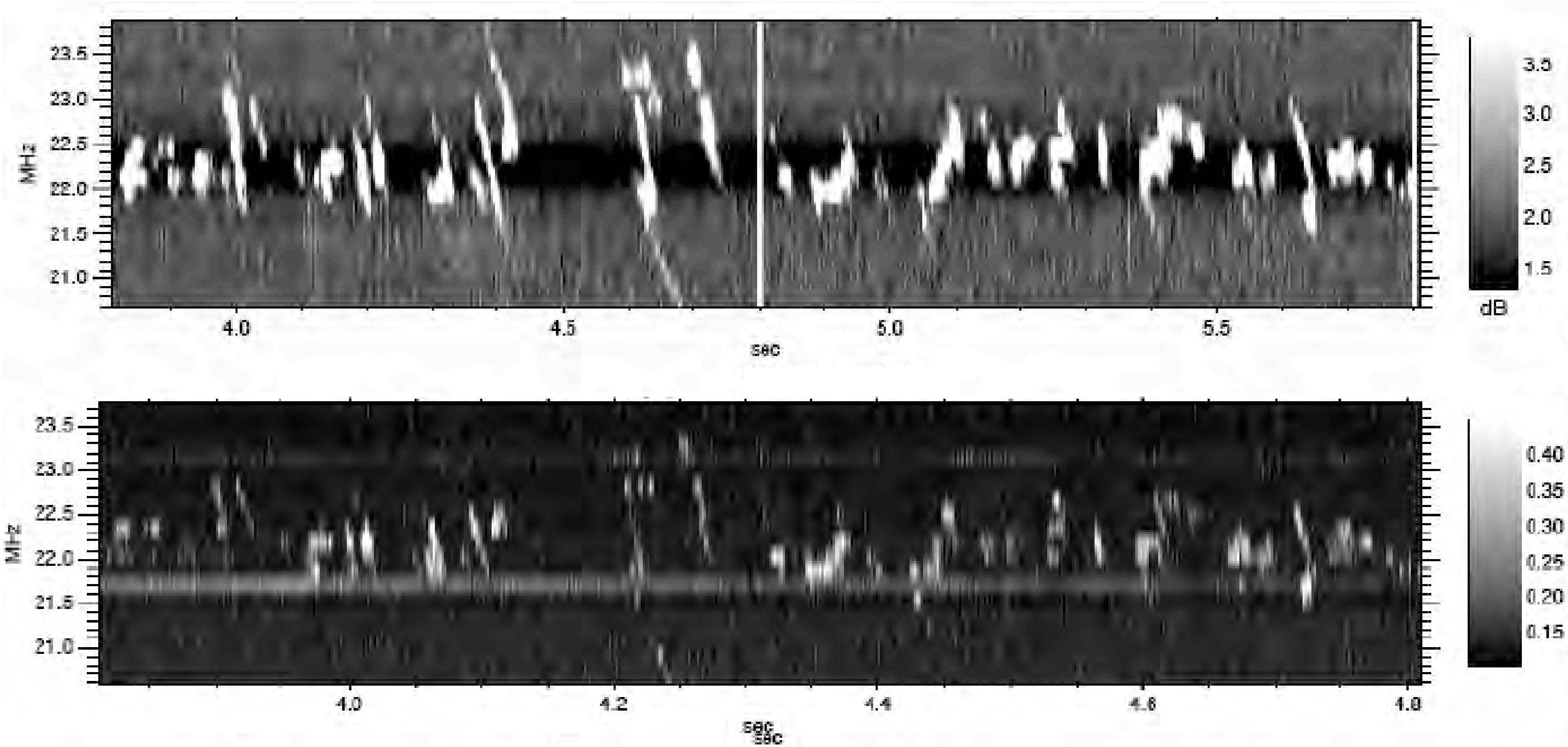


• Fringe integration method ($\Sigma\, C_o + C_{\pi/2}$) with integration over ~1000 correlation results on 1 msec time intervals

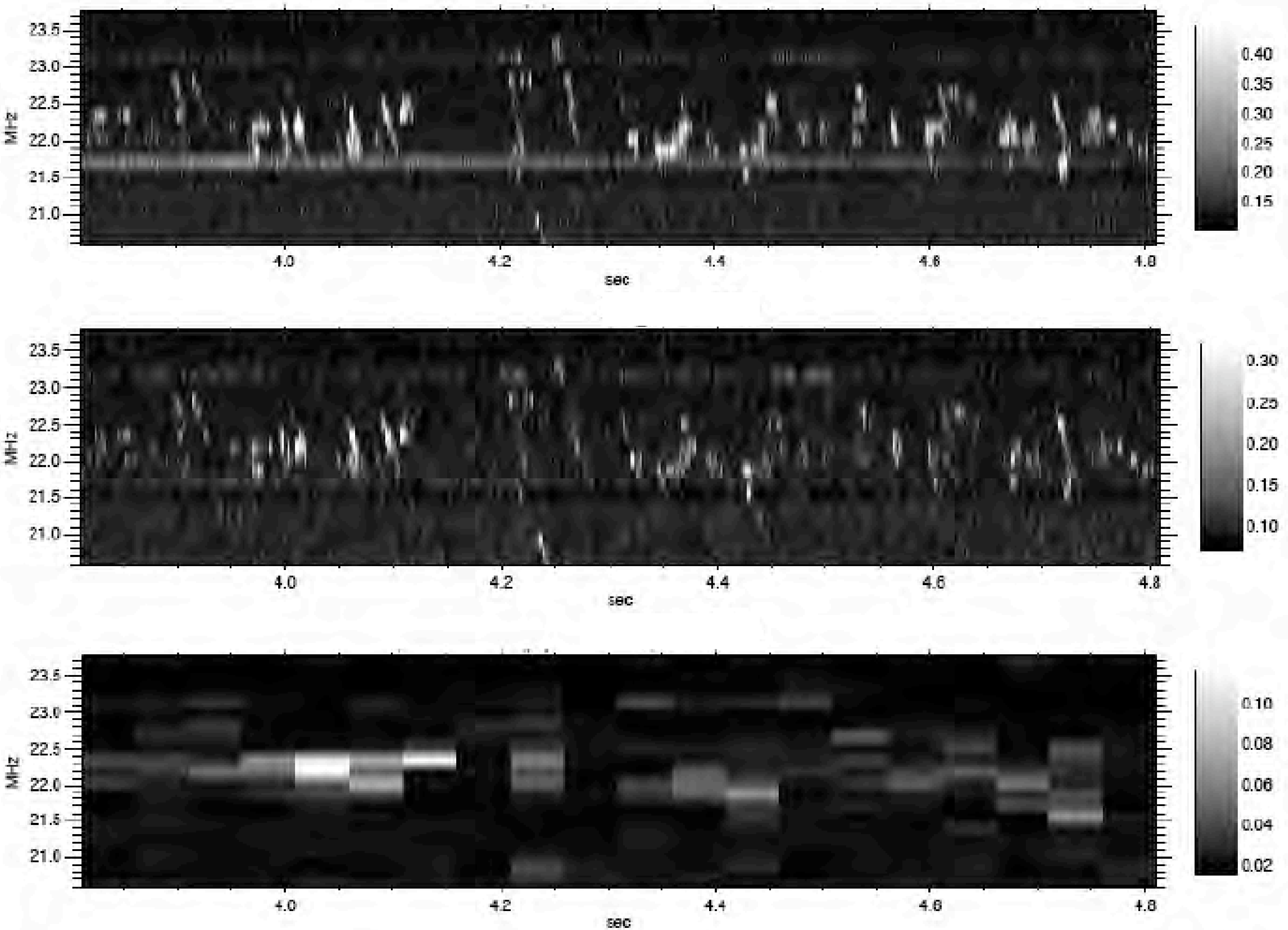
→ ~90 sigmas correlation peak



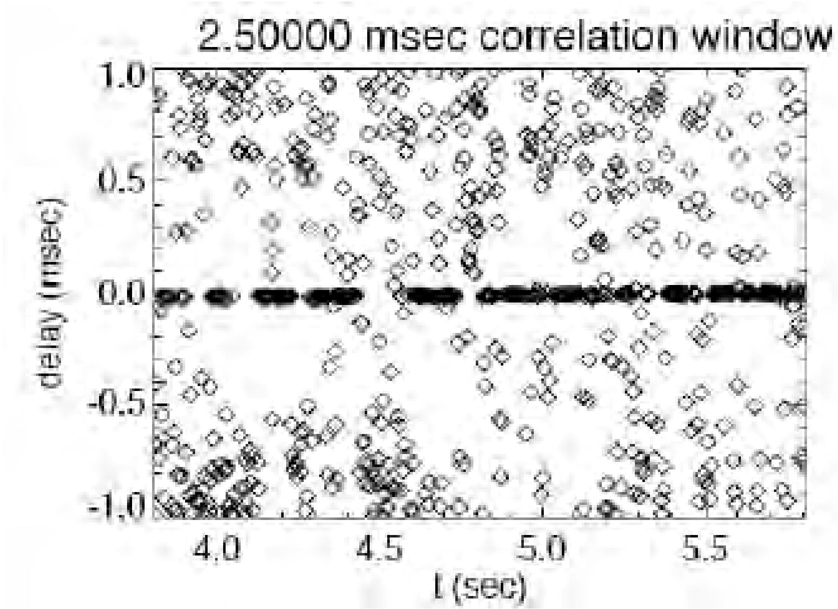
• Systematic study → C up to 0.5-0.7 where S/N high

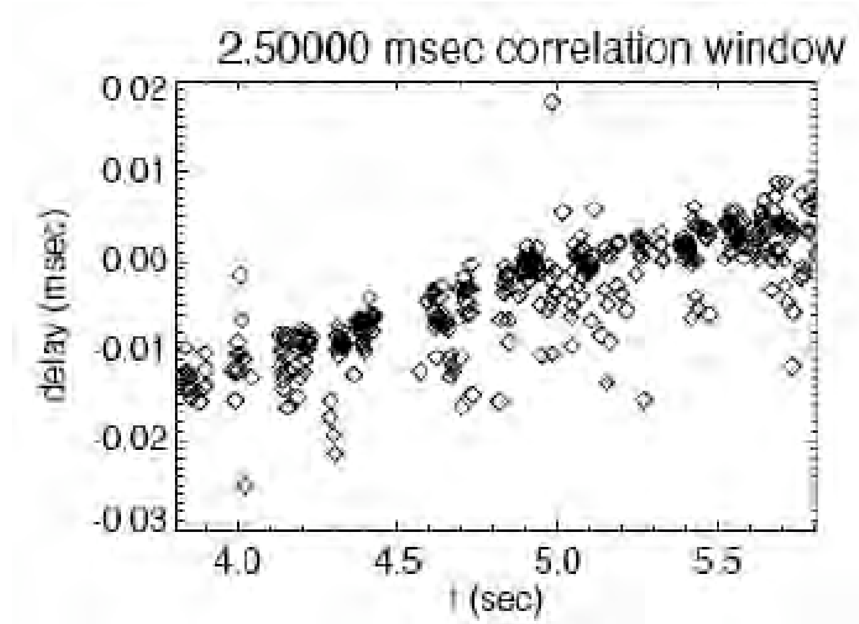


• Significant correlation up to >100 msec time window



- Drift of lag / t (8.8 μsec/sec)





→ Origin ?

- relative motion NDA / ITS (-177 ms^{-1} / -139 ms^{-1}) → 2.8 Hz spectral shift (≤100 nsec/sec)
- S burst source motion (20000 km/s //B at Jupiter → -370 nsec/sec)
- Earth rotation : +125 nsec/sec
- ionospheric & IPS effects «
- Test stability time base Nançay : 79999998 ±0.5 sps ; 1σ error = pixel/sec (10^{-8})
- Poor stability of ITS time base (crystal drift at 10^{-4} level)

→ causes dynamic spectral shift by ~191 Hz (~10 μsec/sec)

- Conclusions

→ Correlation fringes at ~22 MHz, confirm earlier results (presently in 2 cases / 2 = 100% ;-), with direct baseband digitization, broadband, 12-14 bits..., stable over 100's msec

→ Supports long baselines

→ No significant time variation of correlation found over 6.7 sec (2 files)

- Visibility $= C \times 2^{1/2} \ (k/G_\tau) \ ((S_1+N_1)(S_2+N_2)/S_1S_2)^{1/2}$

linear vs circular polarization correlation

~1 (hardware)

= 1 (correlation method with free lag)

consistently ≈ 1

→ unresolved source as expected (~4" resol at 700 km and 20 MHz)

- VLBI observations of Jupiter with the Initial Test Station of LOFAR and the Nançay Decametric Array

A. Nigl[1], P. Zarka[2], J. Kuijpers[1], H. Falcke[3], L. Bähren[3], and L. Denis[2] A&A, <u>in press</u>

• Nançay contribution to (u ,v) plane coverage

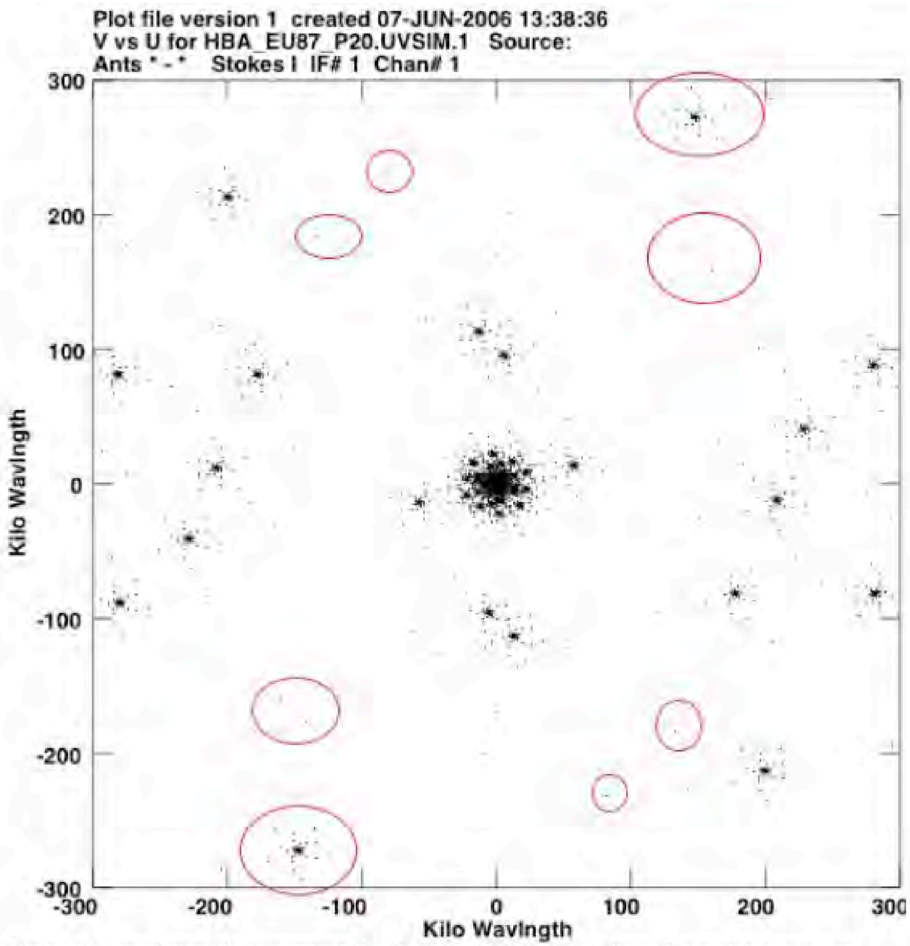


Figure 4 : simulation de couverture du plan u-v de LOFAR incluant les stations prévues en Allemagne et au Royaume-Uni. En rouge l'apport de la station de Nançay. Par intégration sur plusieurs heures, et grâce à la rotation terrestre la synthèse améliore encore la couverture du plan. Couverture instantanée pour H.A.=0 (limitée à une élévation de 45°) pour une déclinaison de 20° à 150 MHz.

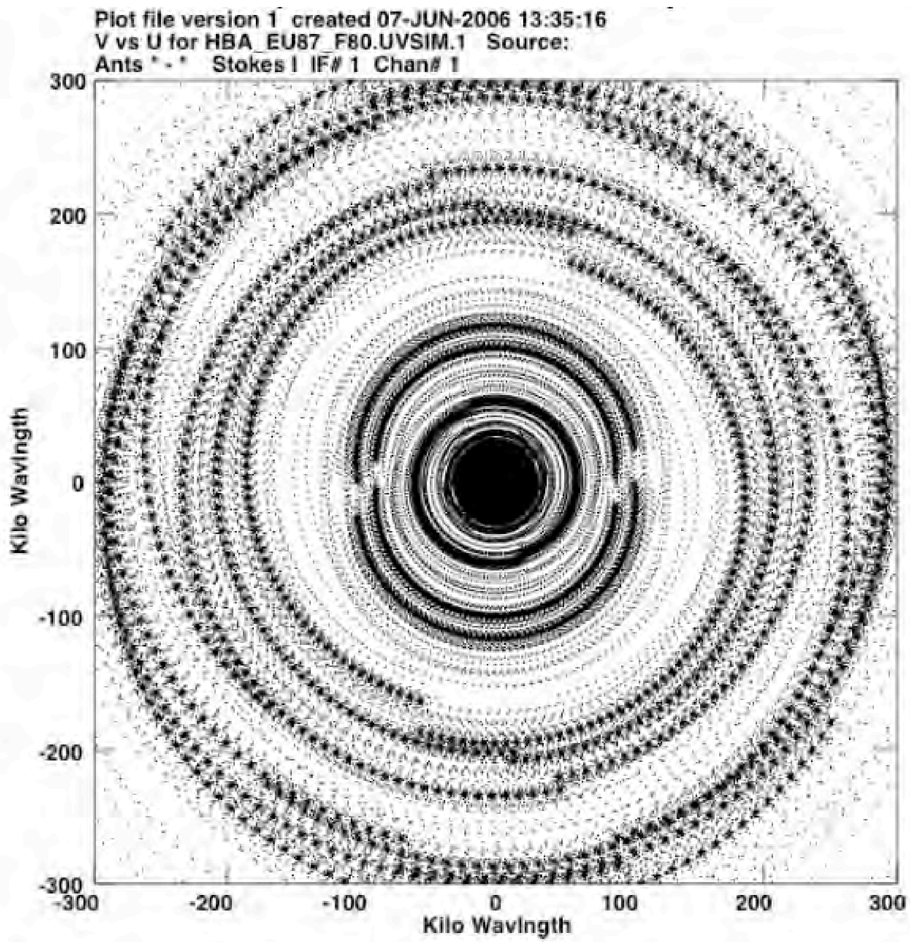
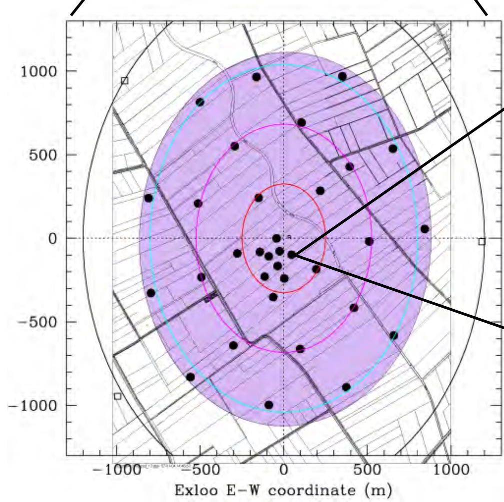


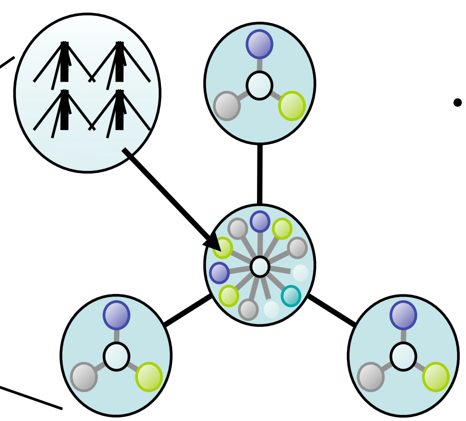
Figure 5 : Couverture du plan u-v pour une déclinaison de 80°, utilisant la rotation de la Terre pour une intégration pendant 8 heures.

• Further steps

→ More observations with CS-1 (since april) to have duty-cycle statistics

→ Observe weaker, permanent radiosources (Cas A or Tau A with core source size of resp. 3" and 1.5")





- S-1 operational since 2007 with “final” prototype hardware
- 96 dual-dipole antennas:
  - grouped in 4 clusters
  - with 6 sub-stations
  - of 4 dipoles each
  - distributed over up to 1 km
- Emulate LOFAR with 24 micro-stations at reduced bandwidth or single station at full BW