NenuFAR*,
the LOFAR Super Station

* New Extension in Nançay Upgrading LOFAR

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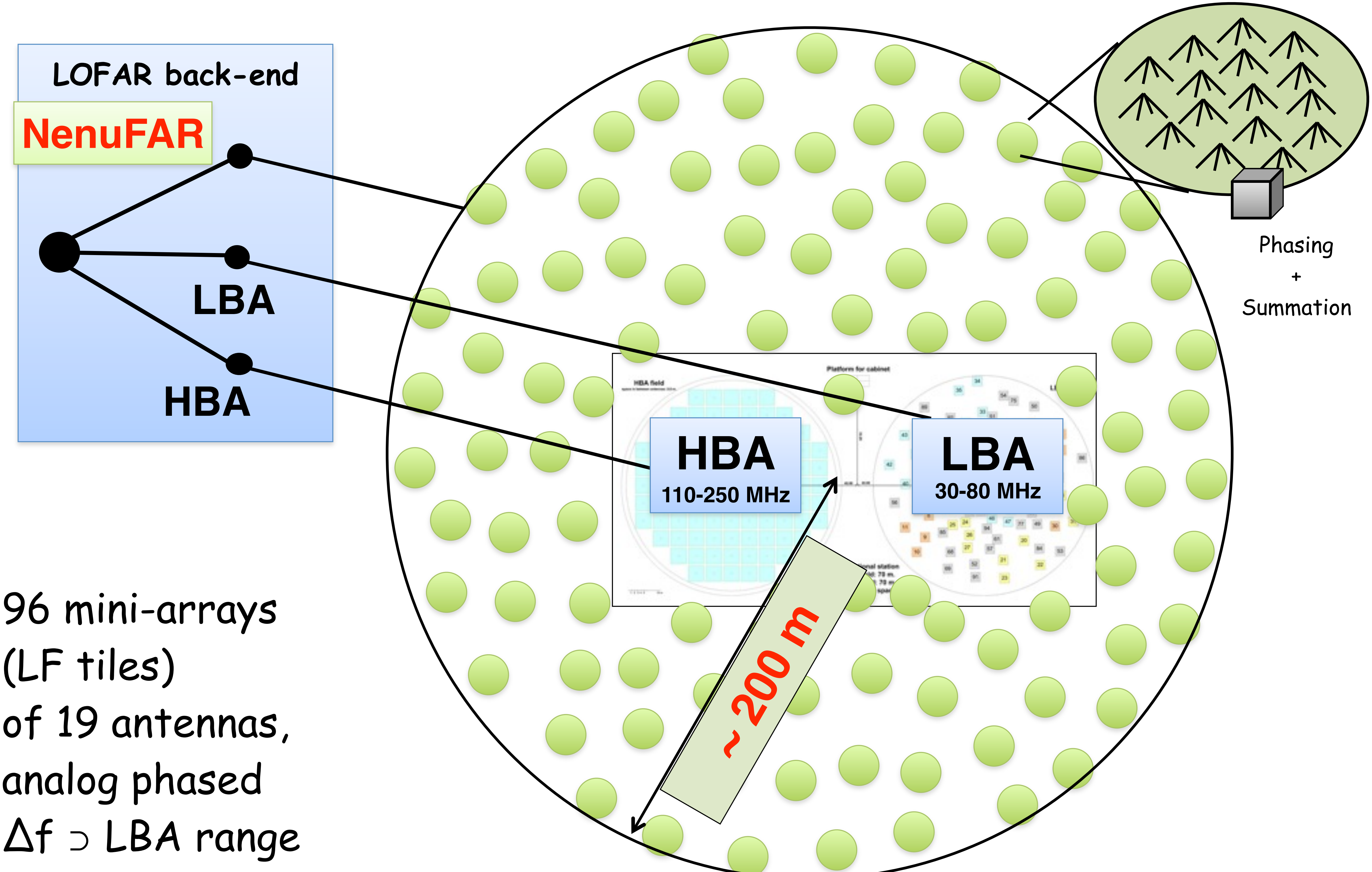
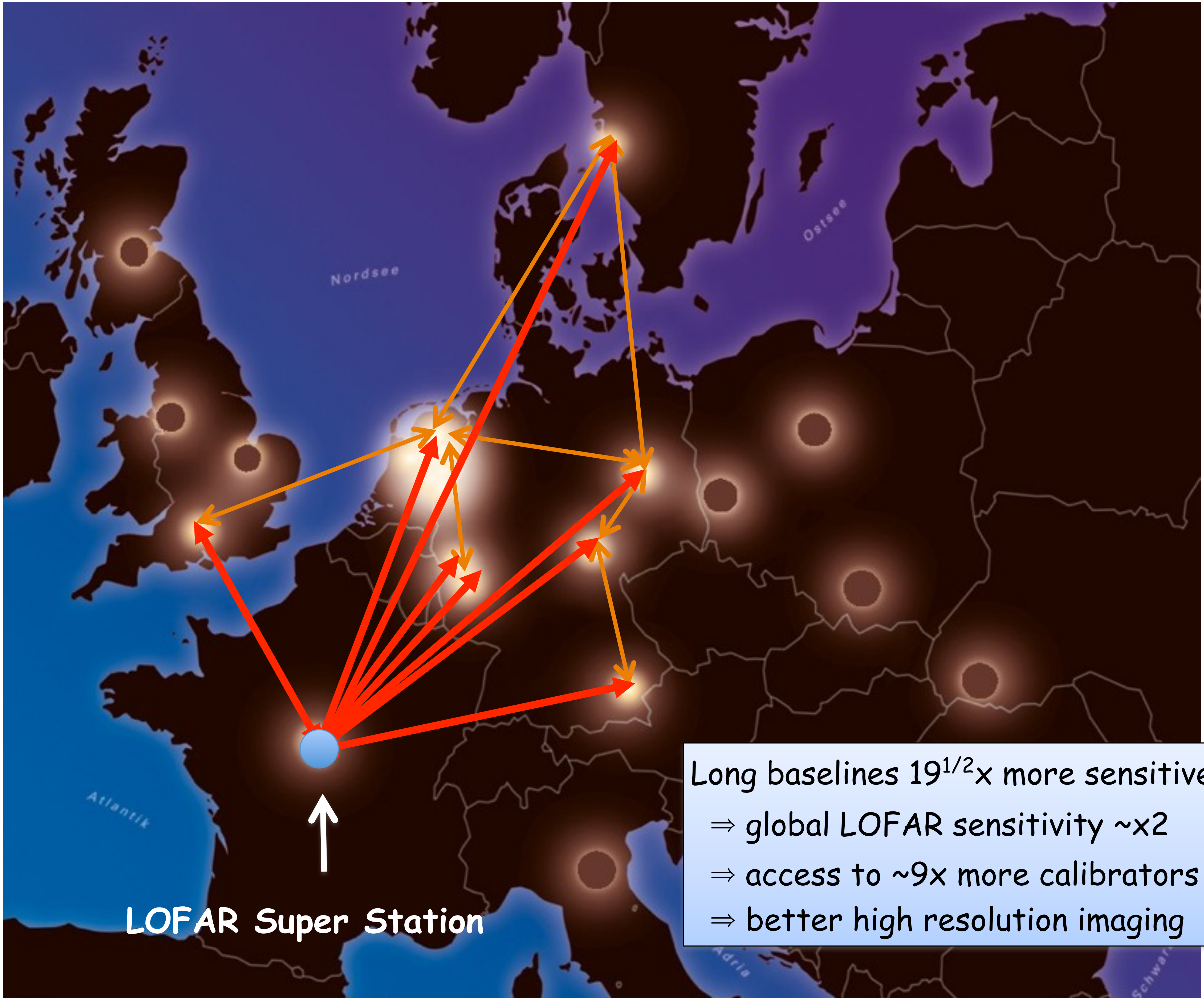
LOFAR station in Nançay : FR606

The LSS/NenuFAR concept : giant local phased array + interferometer



96 mini-arrays
(LF tiles)
of 19 antennas,
analog phased
Δf ⊃ LBA range

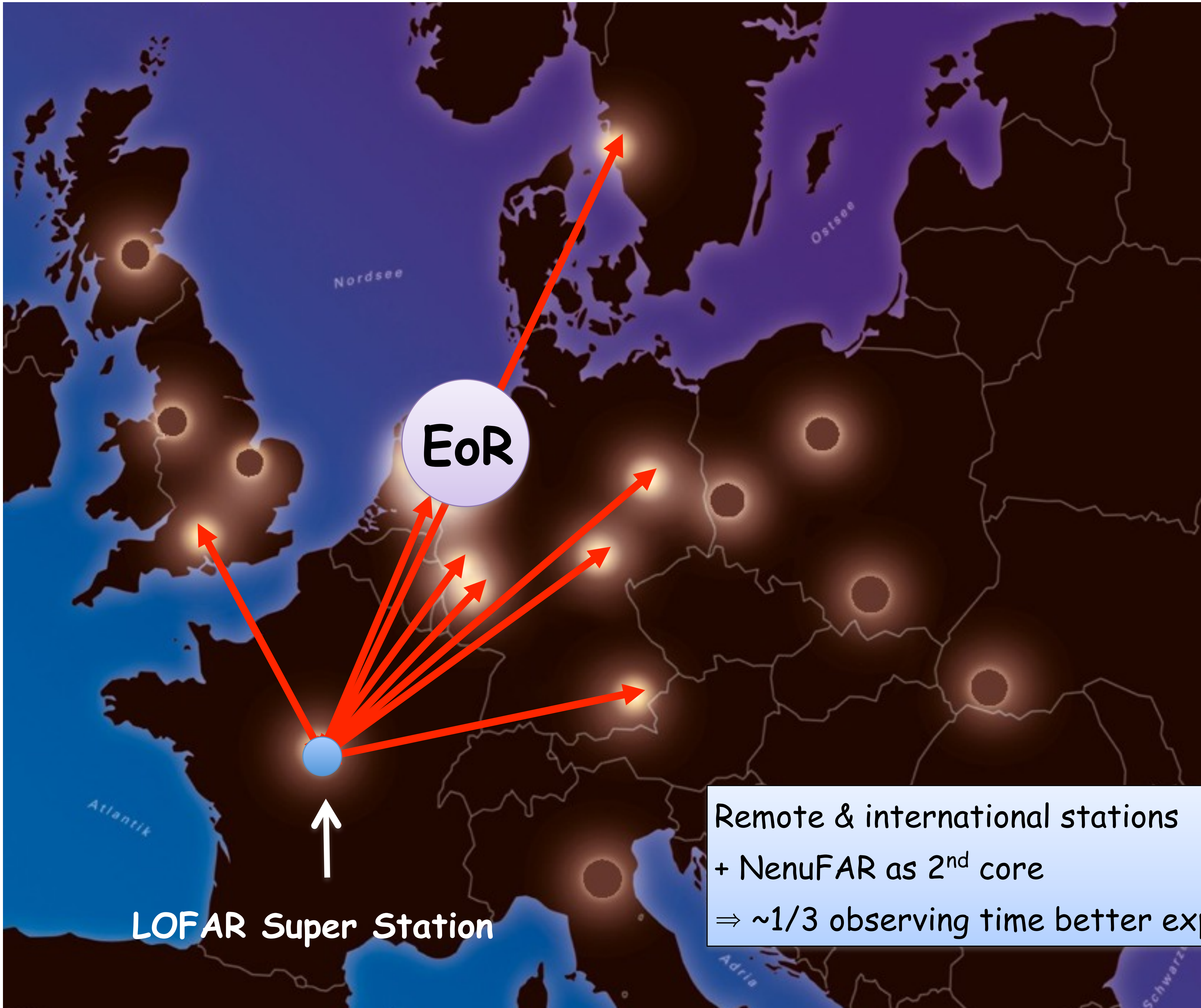
What will bring LSS/NenuFAR ?



Long baselines $19^{1/2}$x more sensitive

- ⇒ global LOFAR sensitivity ~x2
- ⇒ access to ~9x more calibrators
- ⇒ better high resolution imaging

What will bring LSS/NenuFAR ?

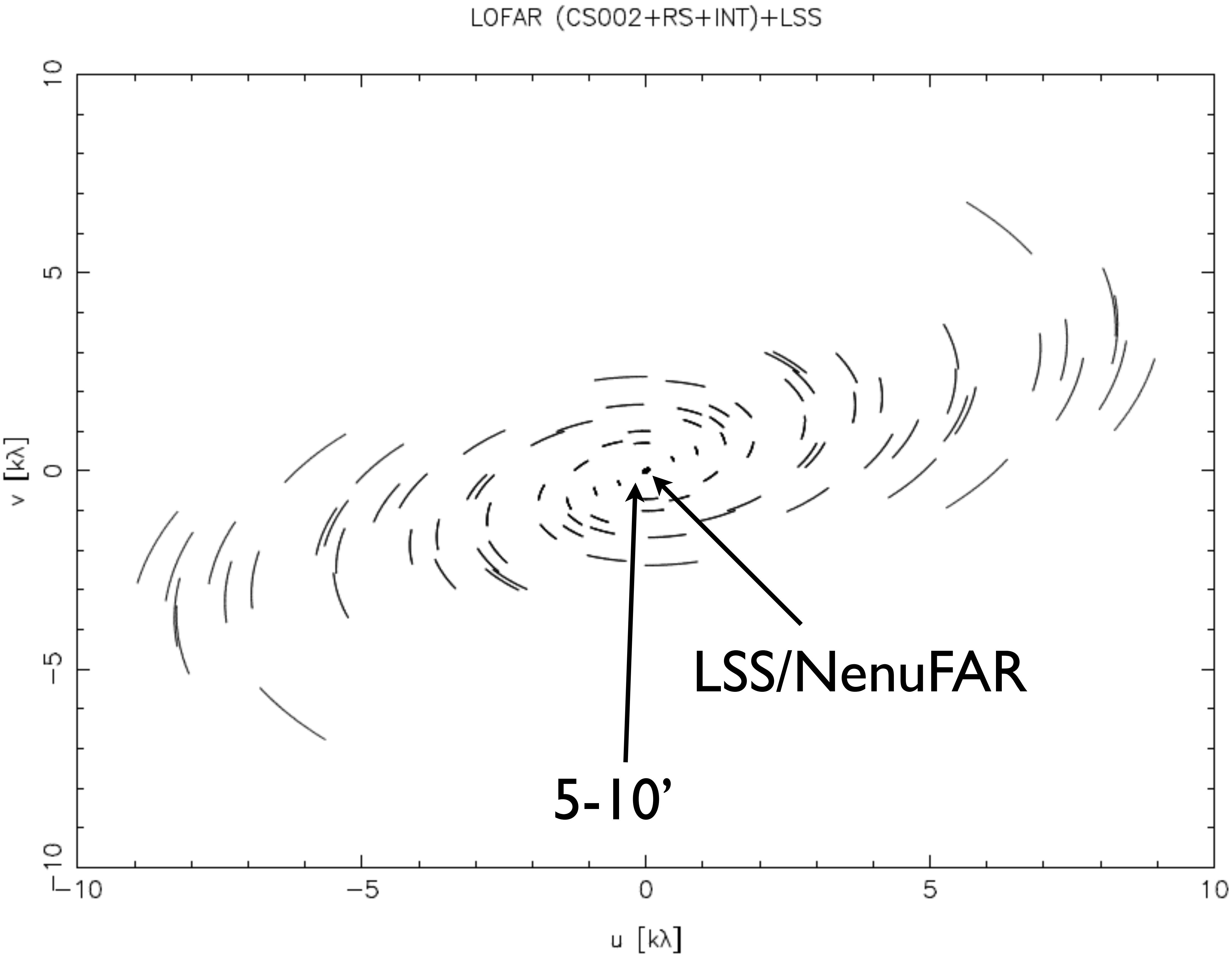


Remote & international stations

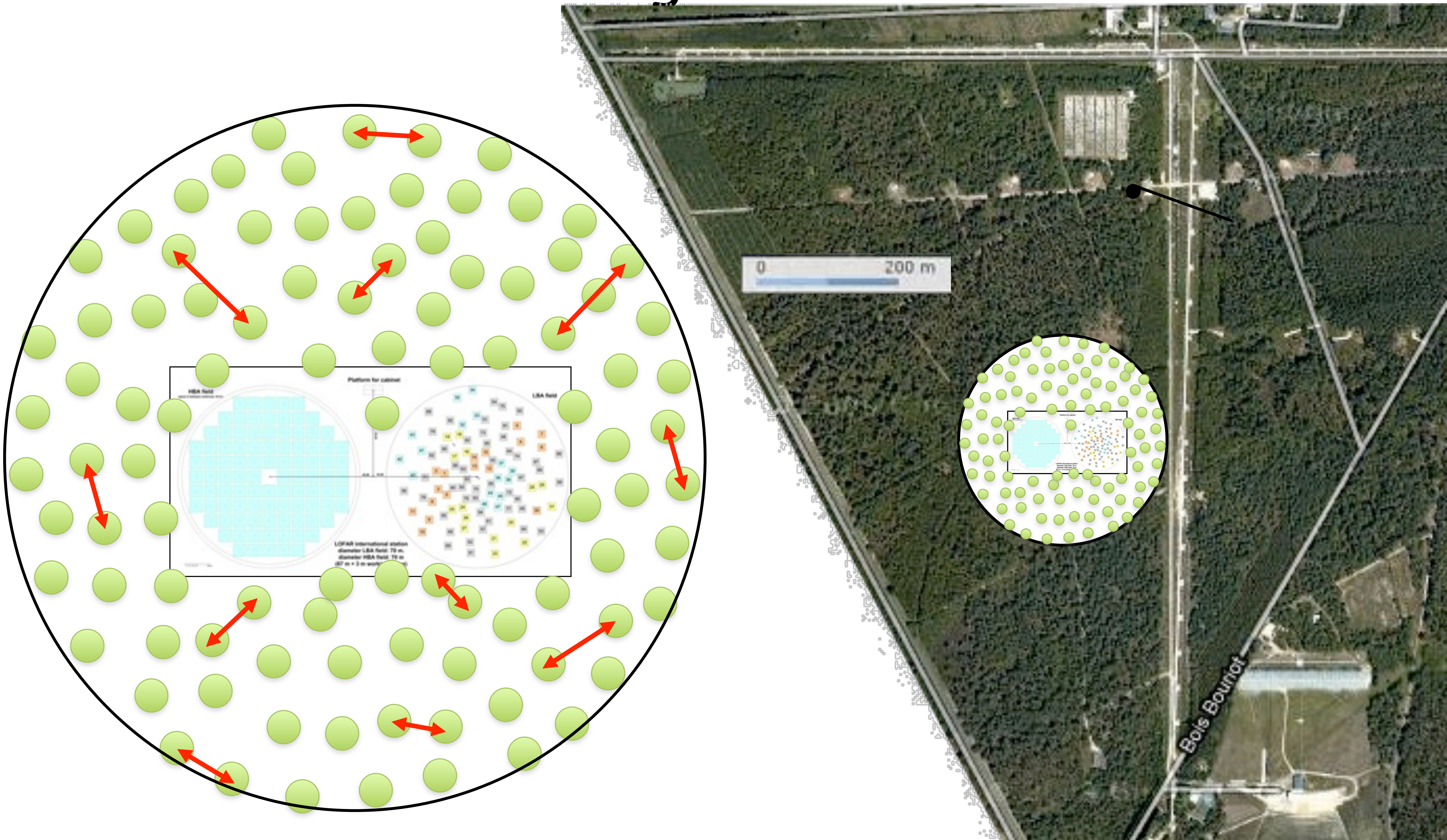
+ NenuFAR as 2nd core

⇒ ~1/3 observing time better exploited

LSS/NenuFAR as a second LOFAR core



What will bring LSS/NenuFAR ?

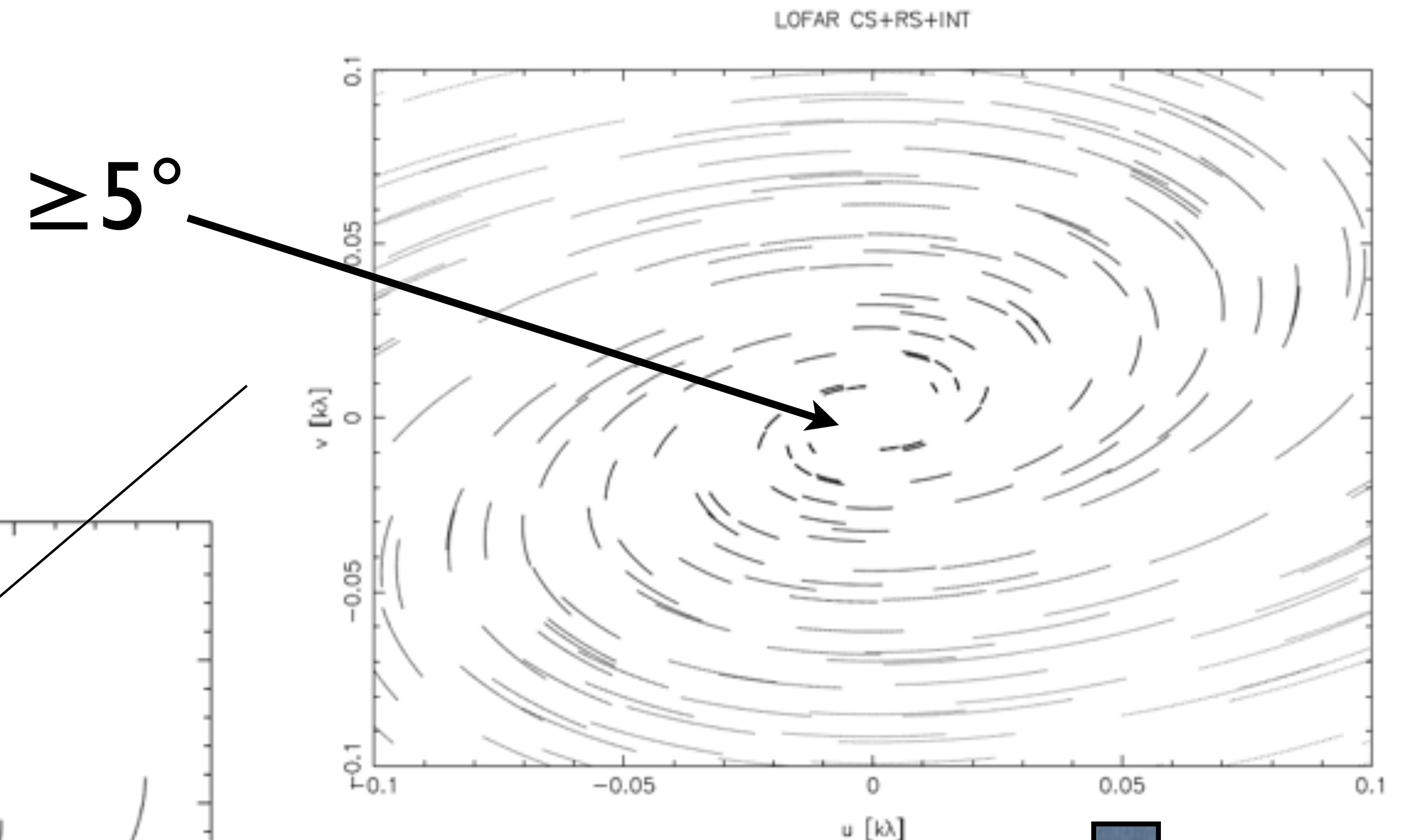


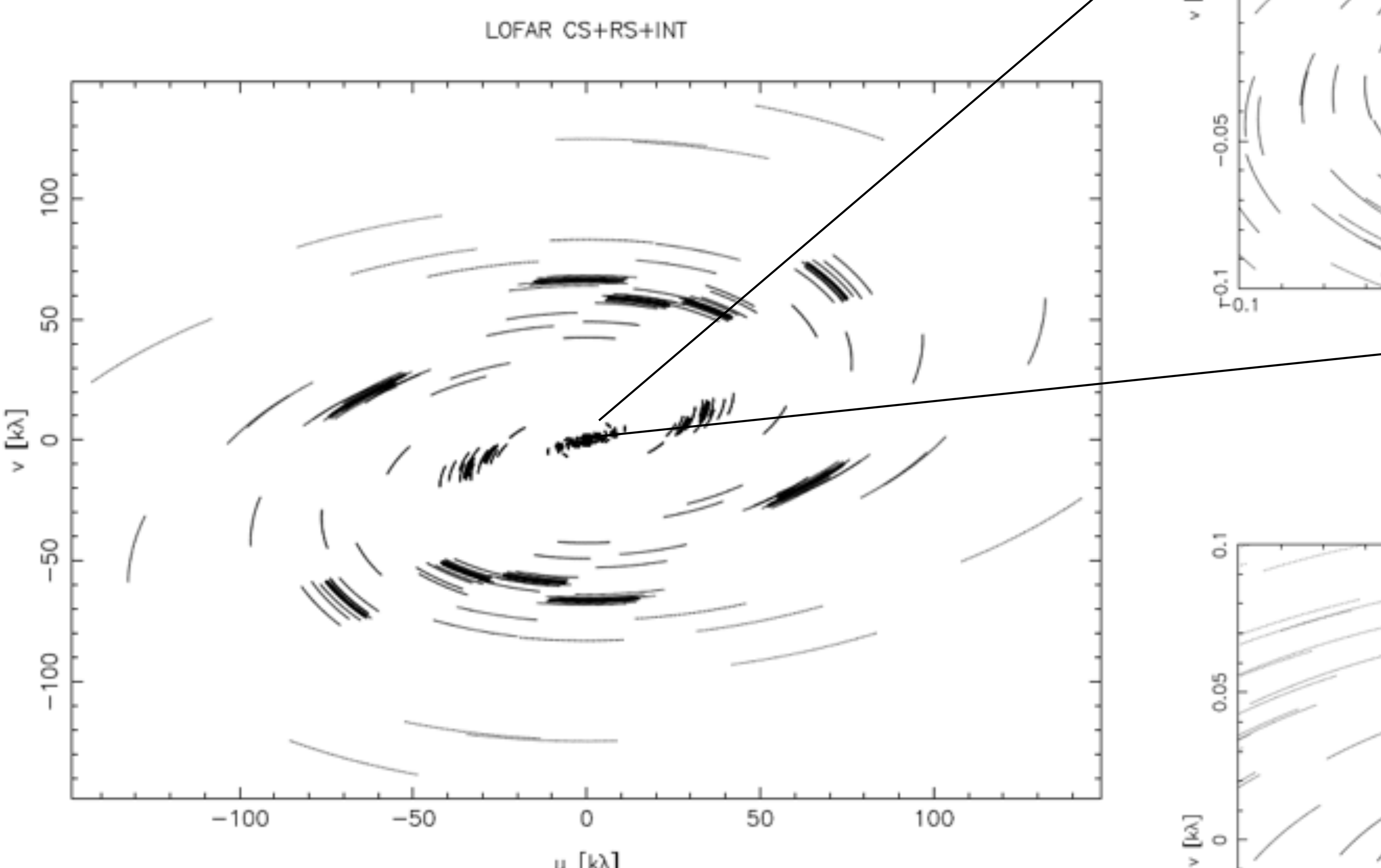
Sensitive short baselines (< ∅ station LOFAR)

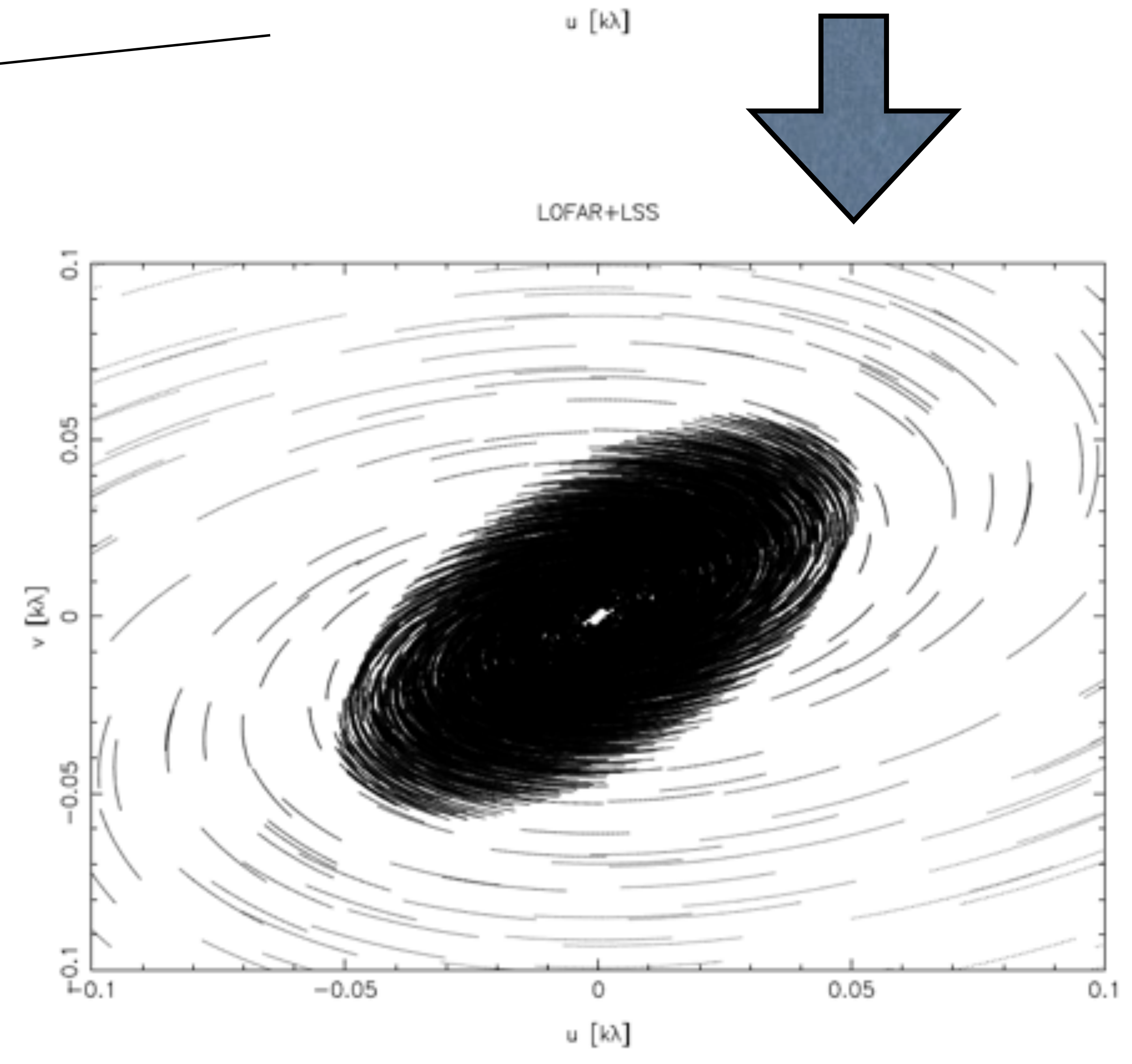
⇒ imaging large-scale structures

(> instantaneous station FoV ~10° @ 30 MHz)

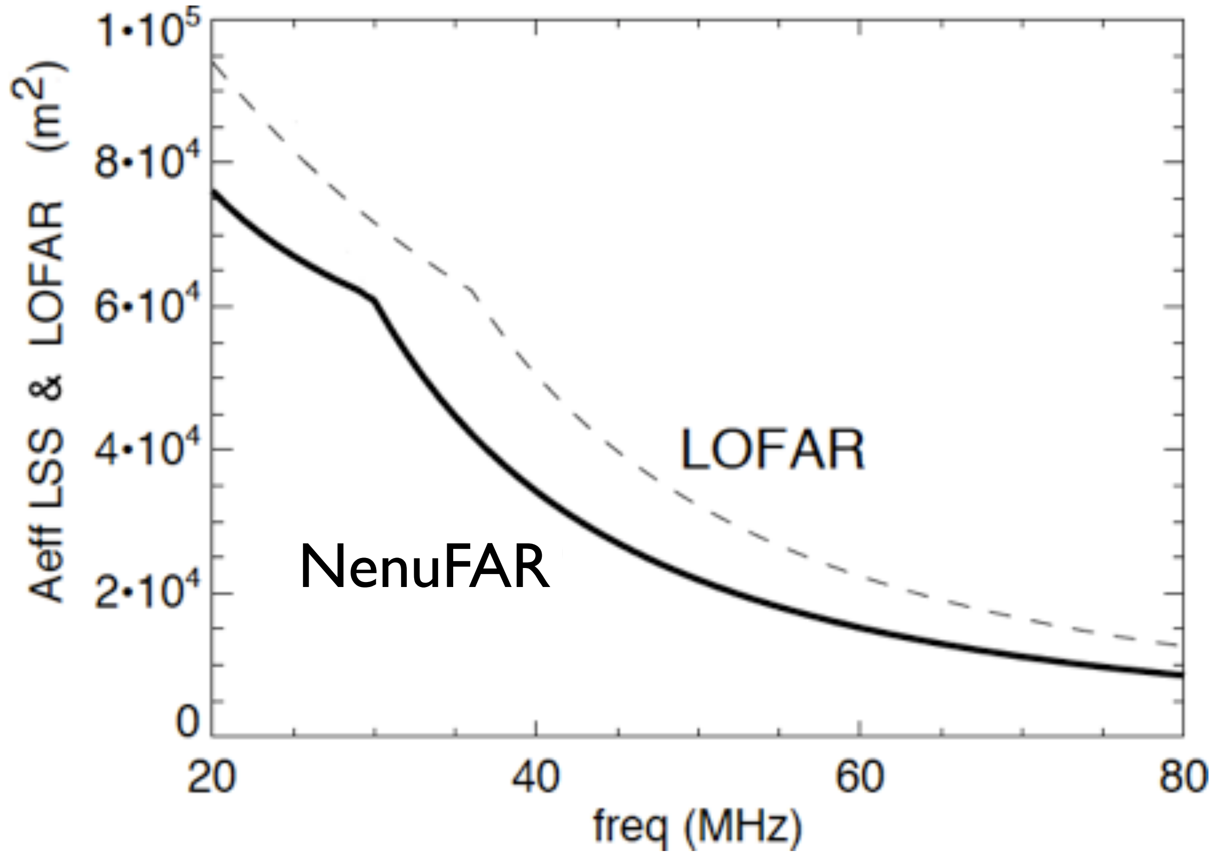
Short baselines

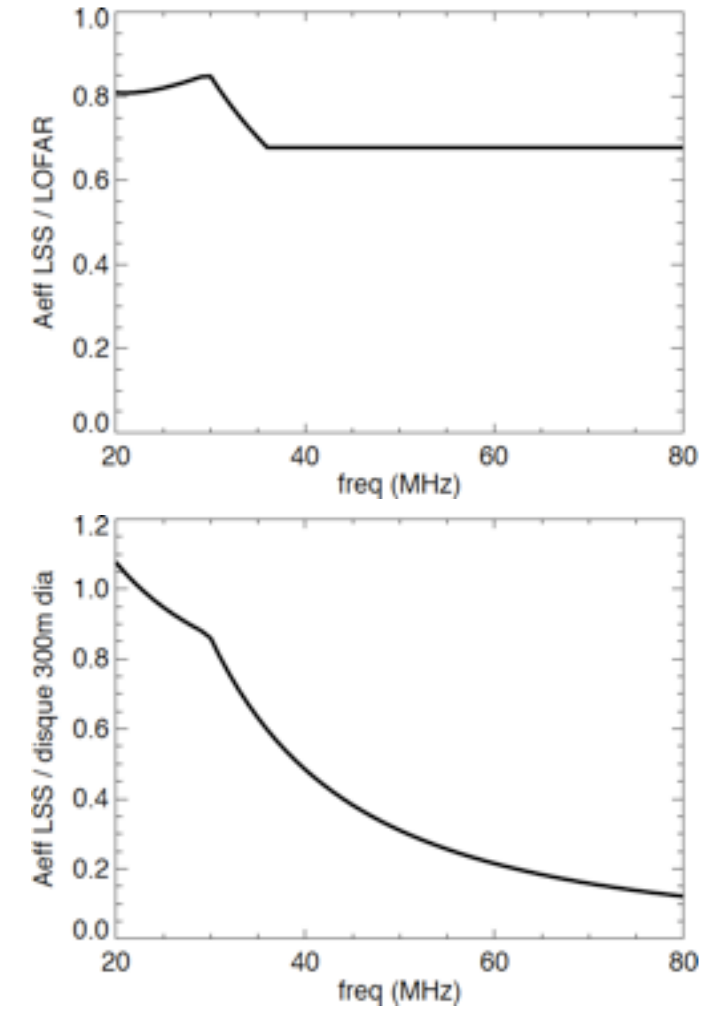






What will bring LSS/NenuFAR ?





Large standalone instrument with high instantaneous sensitivity

- ~19x the sensitivity of an international LOFAR station in LBA range
- A_{eff} = 70-80% x A_{eff} LOFAR LBA = 190% x A_{eff} LOFAR core LBA
- Access to VLF (15-80 MHz)
- 2 full-band (70 MHz) full-polarization simultaneous coherent tied-array beams

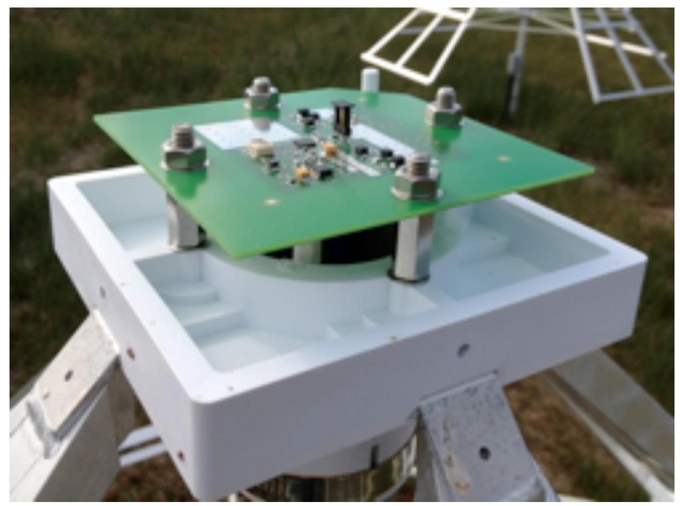
⇒ coherent TAB mode > 2x more efficient than LOFAR

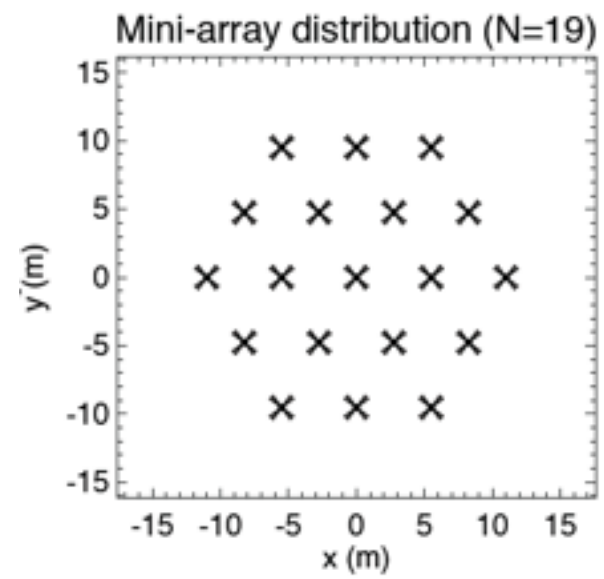
⇒ Instantaneous polarized imaging with 256 pixels in 8°-45° FoV within TBD bandwidth

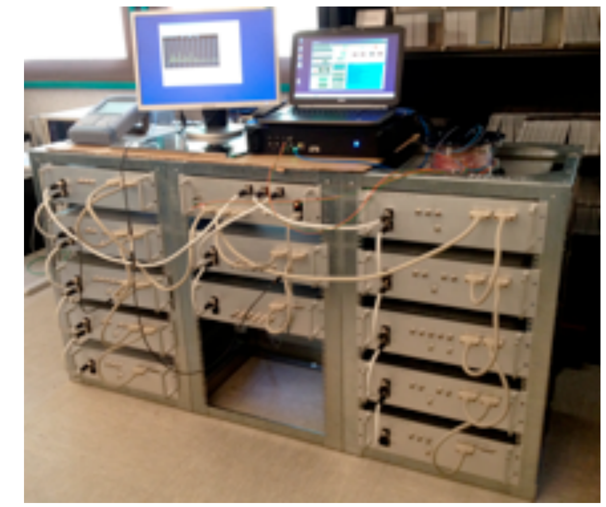
Designing + Prototyping LSS/Nenufar

ANR program 9/2009 2/2013

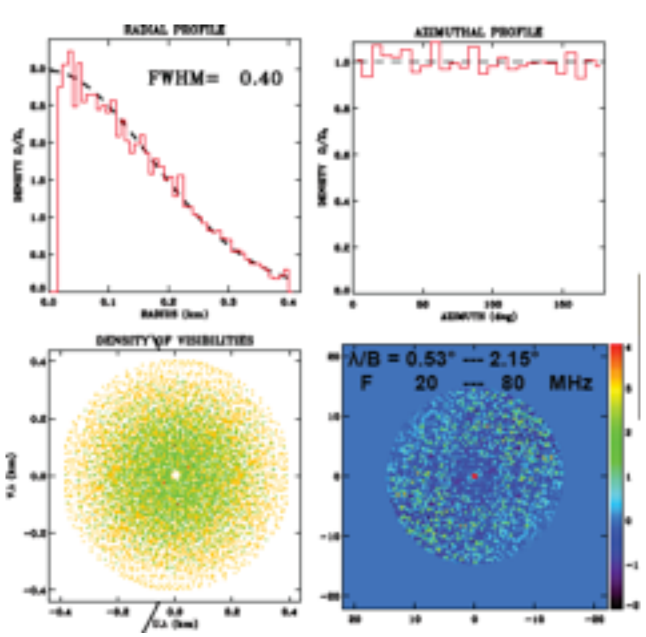
http://www.obs-nancay.fr/lss/ (ask for passwd)

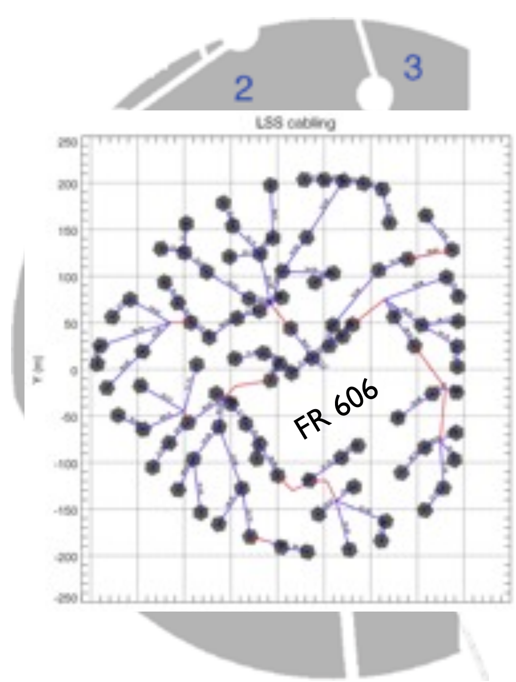


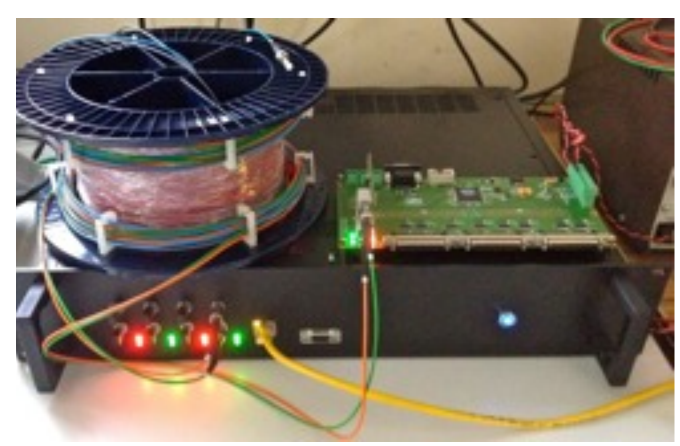


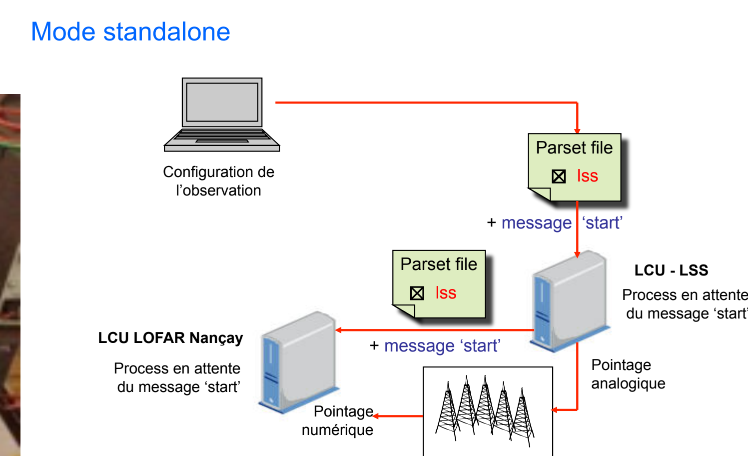


- Study of all aspects of the project : antenna, preamp., distribution mini-arrays & global, phasing, cabling/trenches, silent control/command, dialog with LOFAR

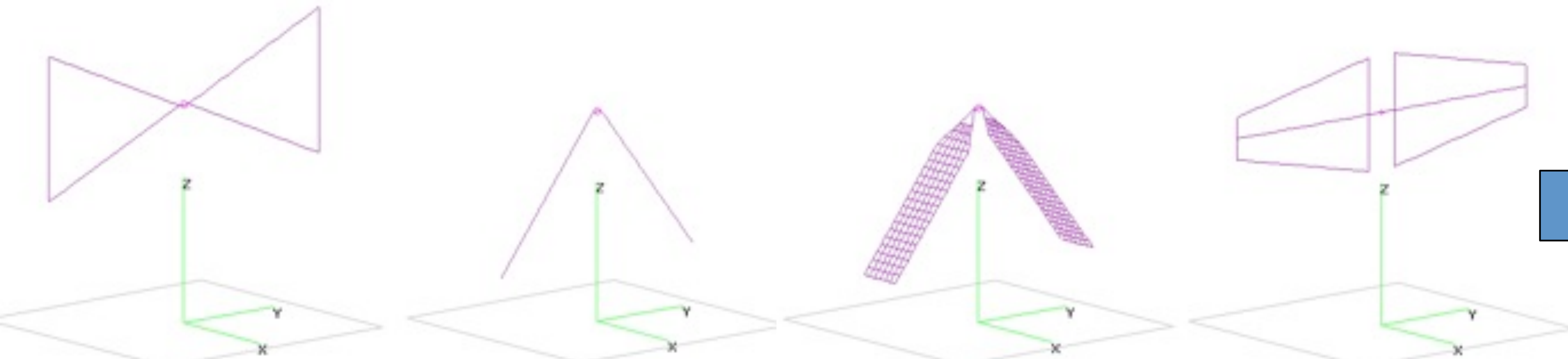




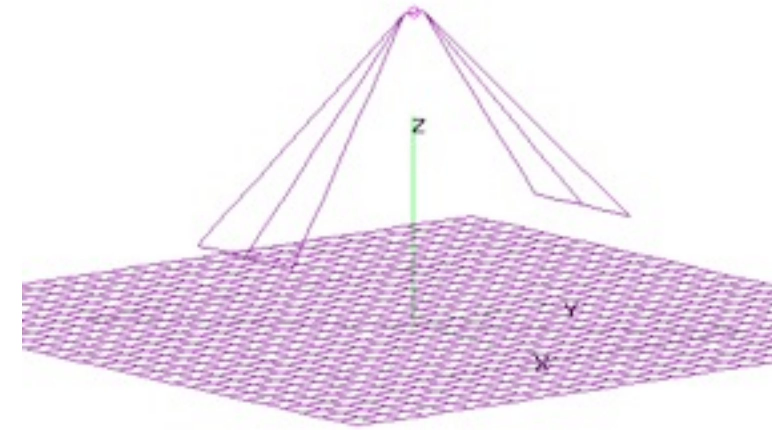




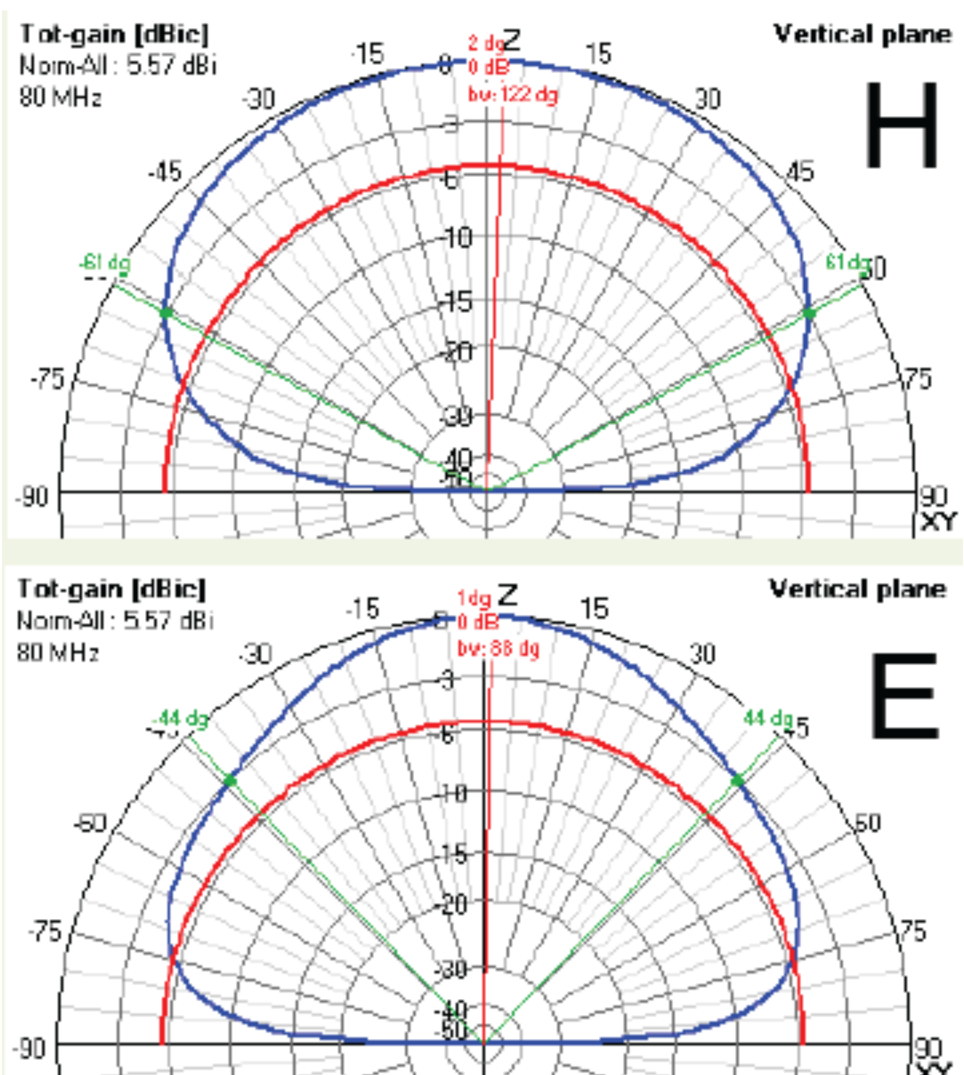
Antenna development



CODALEMA LOFAR LBA LWA « Big Blade » GURT

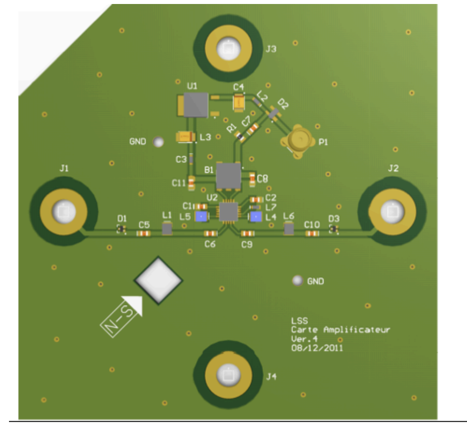


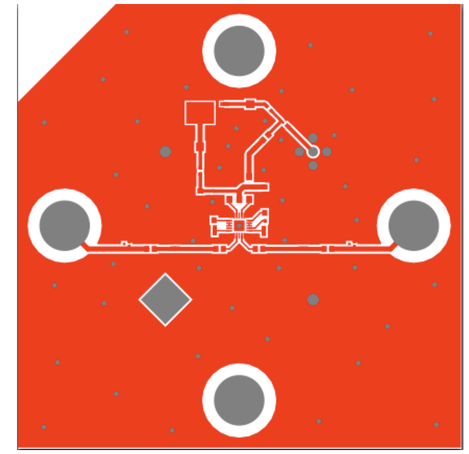
NEC EM simulation

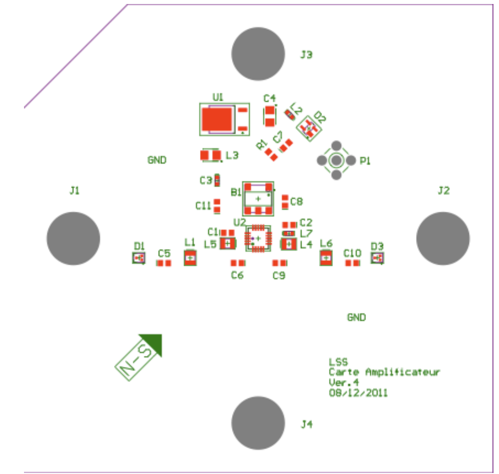


Simulated Beam pattern

Antenna preamplifier (ASIC)



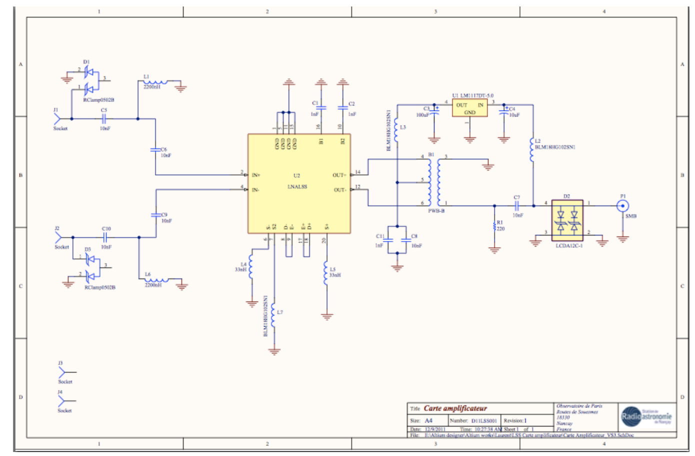


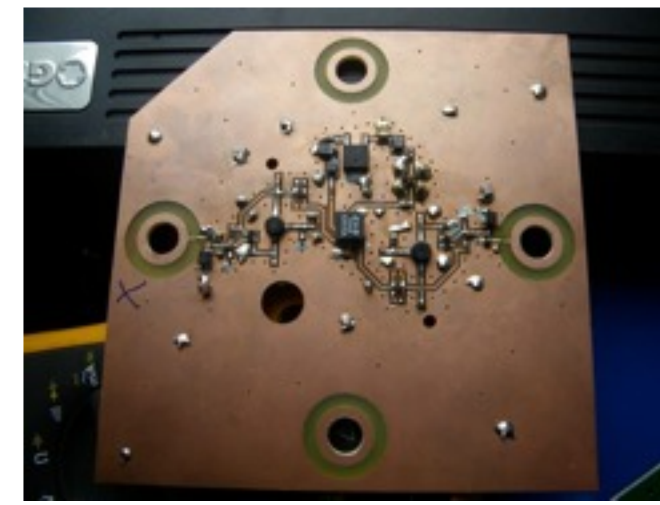


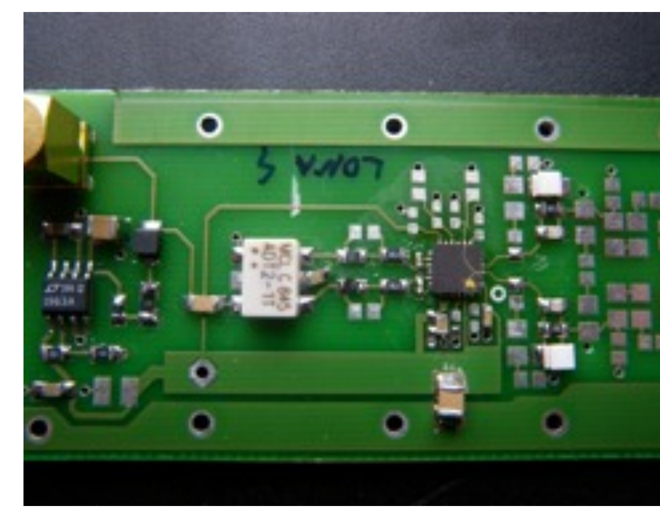
GURT design

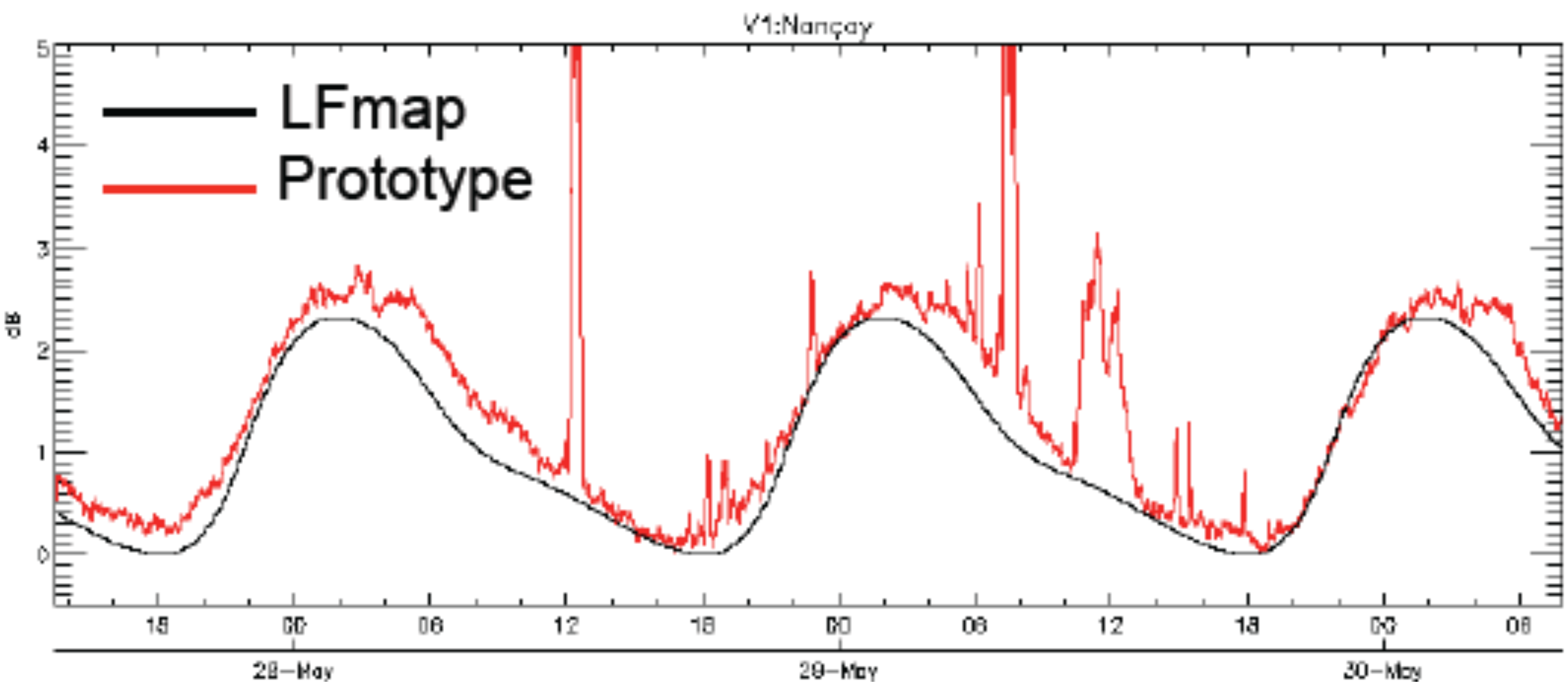
Nançay design

Subatech design





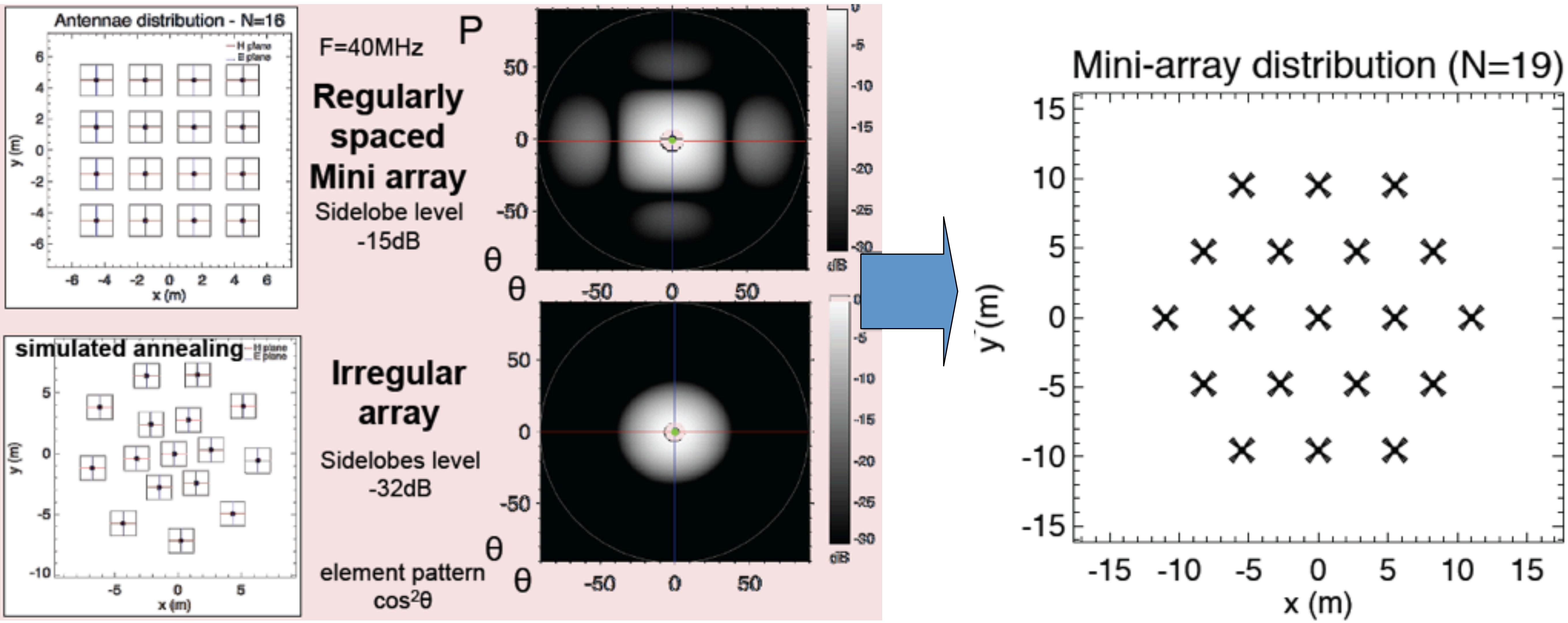




Drift scan of the sky compared to LFmap

Mini array layout & phasing

Scale	Layout	Phasing
Mini-array (10-20 elements)	A_{eff} & beam optimized	Analog (using cable delays)
LSS (96 MA)	(u,v) optimized	Digital (using station back-end)



Pointing by mutualization of 7 bits analog delay lines in two directions (x & y)
Relative gain variation between two pointing directions ≤10%
LOFAR back-end will then beamform within this « pre-pointed » antenna beam

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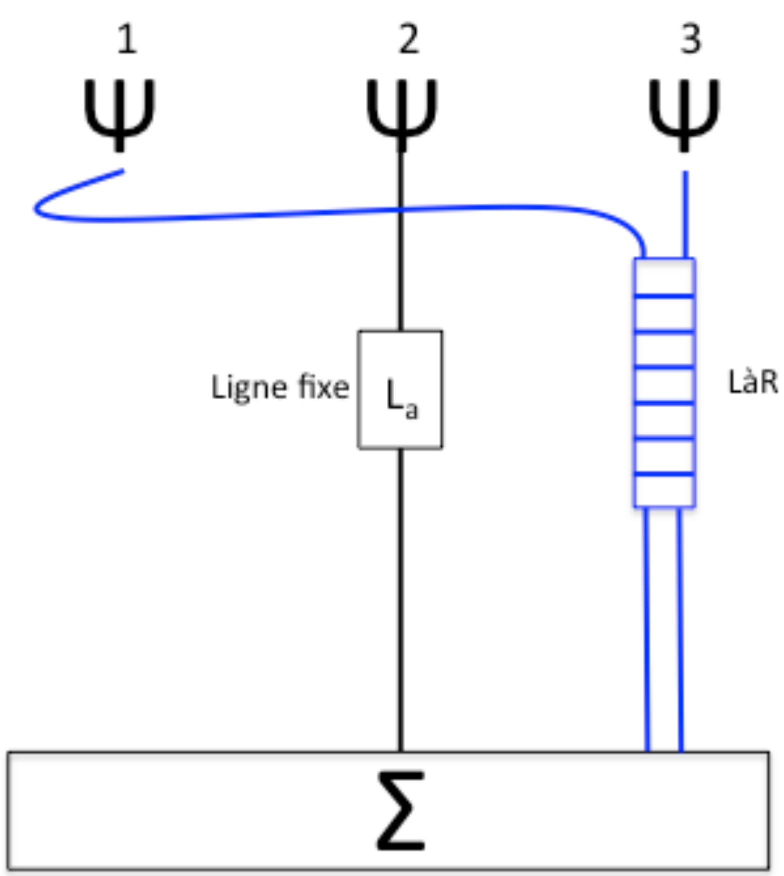
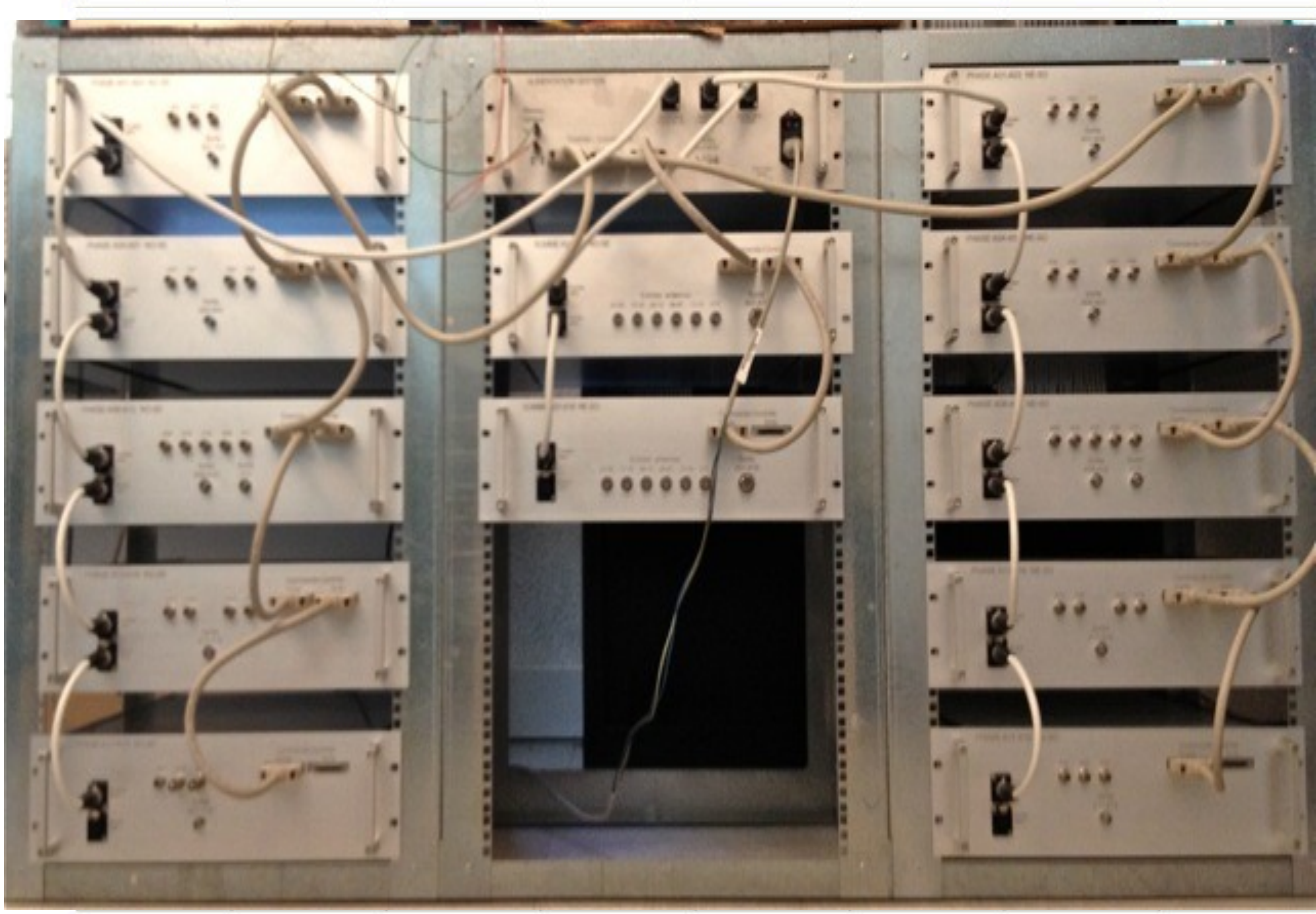


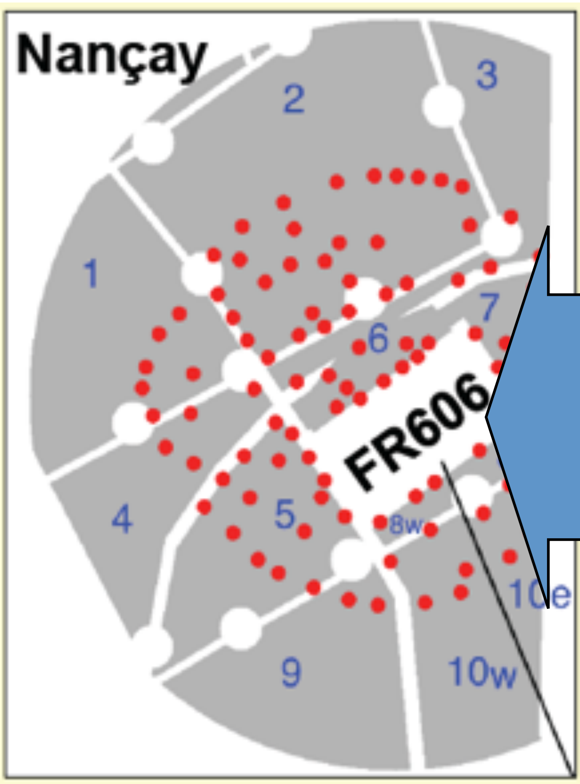
Ligne à 3 antennes

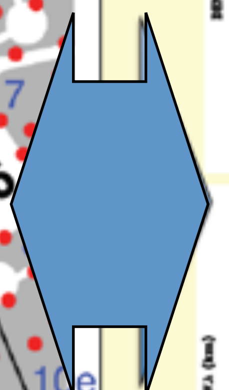


Pointing by mutualization of 7 bits analog delay lines in two directions (x & y)
Relative gain variation between two pointing directions ≤10%
LOFAR back-end will then beamform within this « pre-pointed » antenna beam

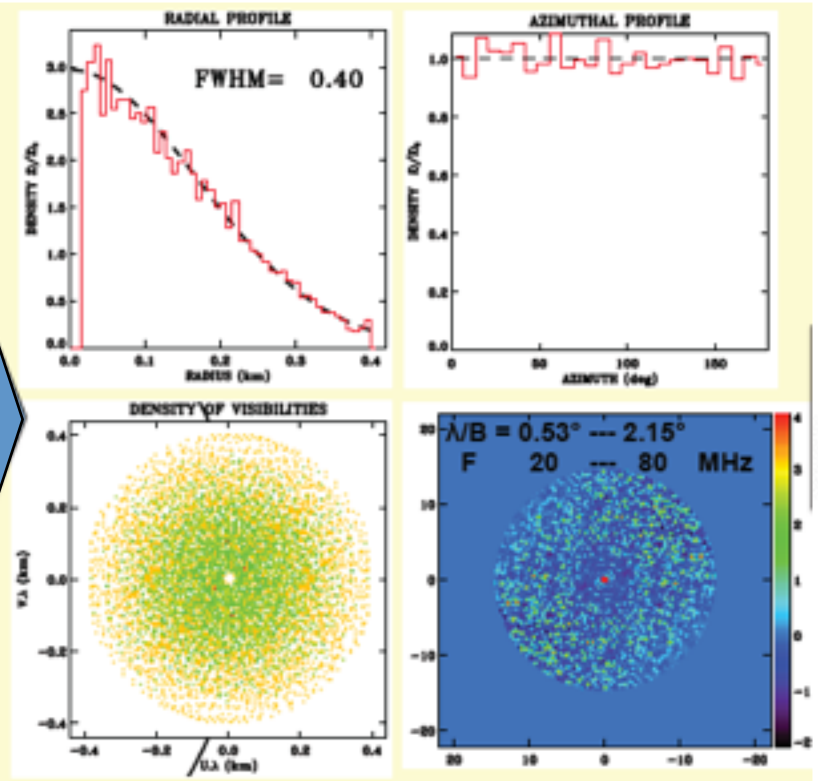
Station layout & cabling (near-final)

Scale	Layout	Phasing
Mini-array (10-20 elements)	A_{eff} & beam optimized	Analog (using cable delays)
LSS (96 MA)	(u,v) optimized	Digital (using station back-end)

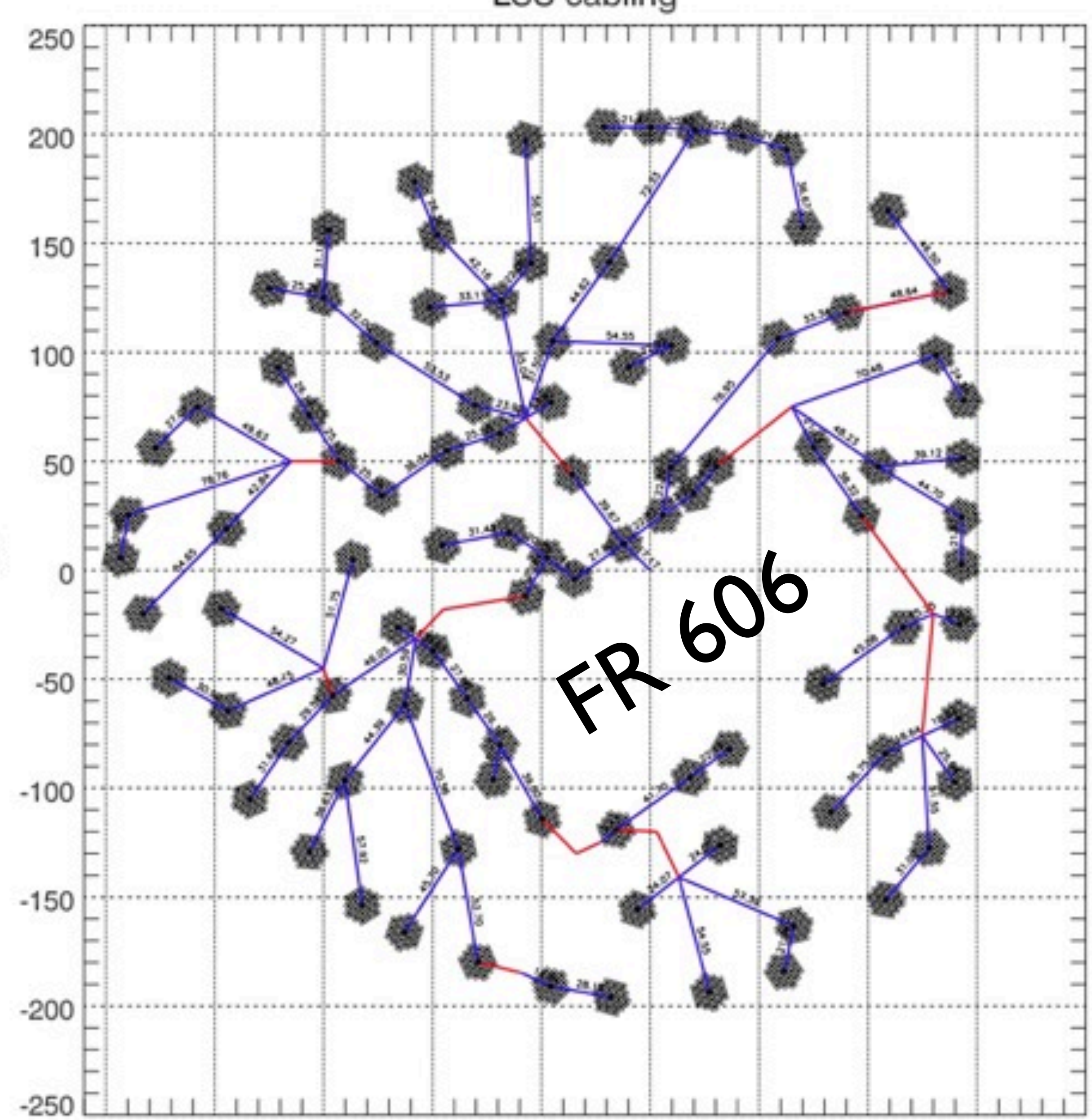




(u,v) optimization given a site mask

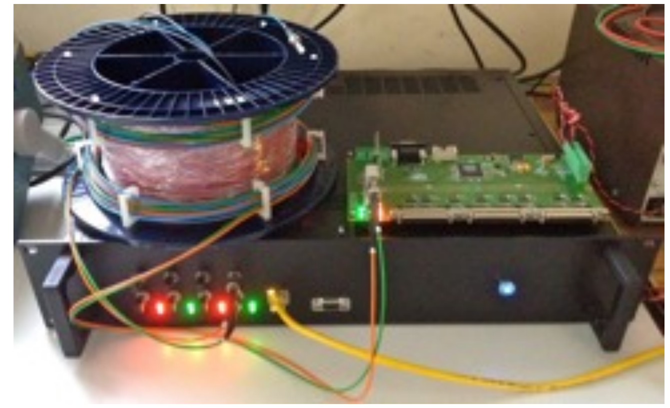


(u,v) density and PSF



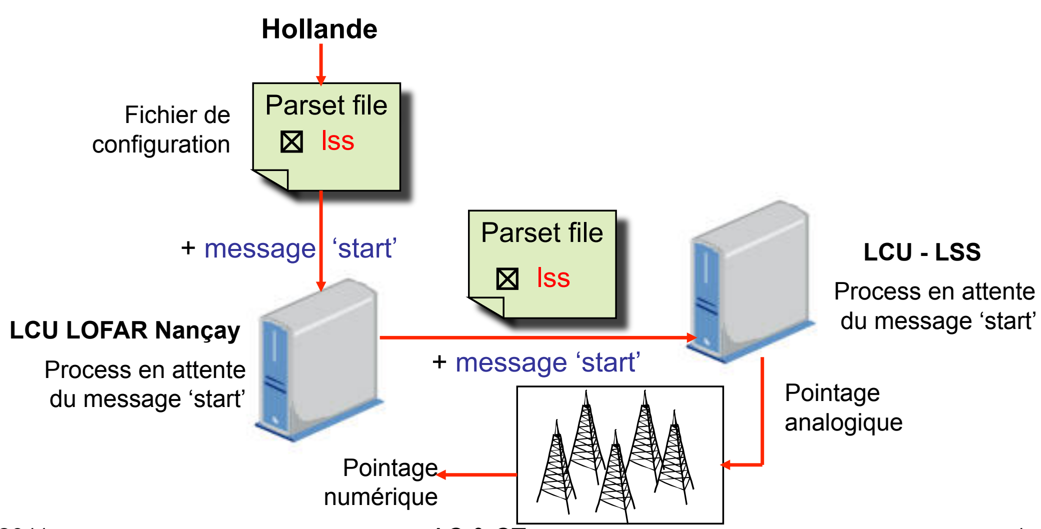
Optimized (u,v) coverage (gaussian) using pressure-driven Boone algorithm
Relative rotations of Mini Arrays to temper grating/side lobes (but keeping all antennas //)
Optimized infrastructure costs : Cable-Trench problem (total cable length ~20 km)

Control/command system & protocol



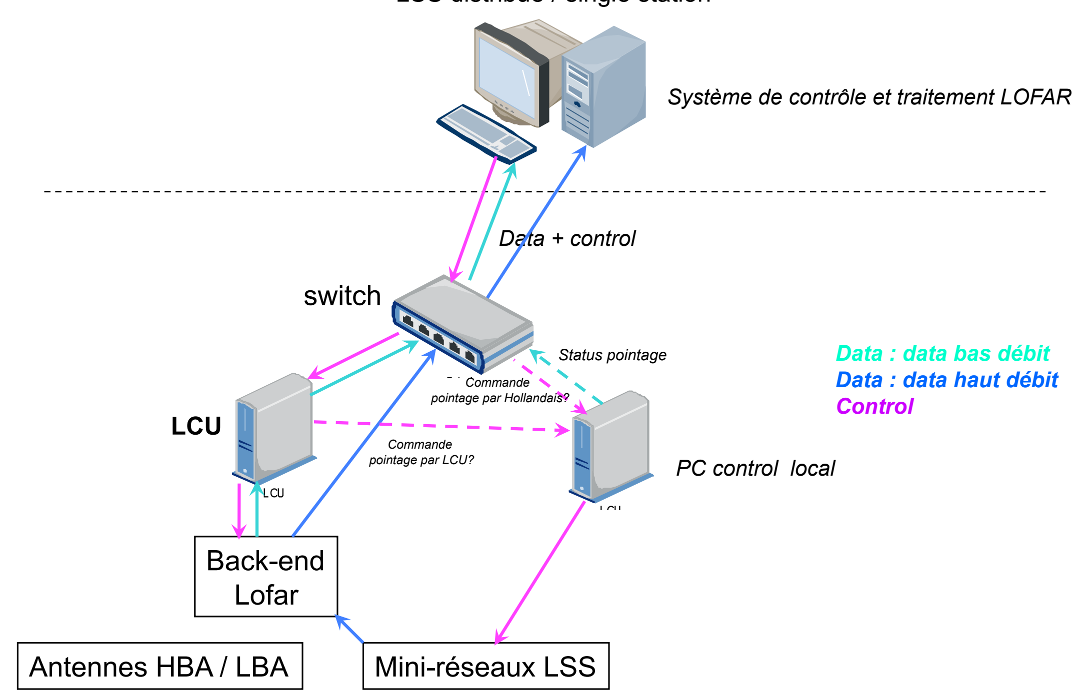
silent c/c system

Mode international

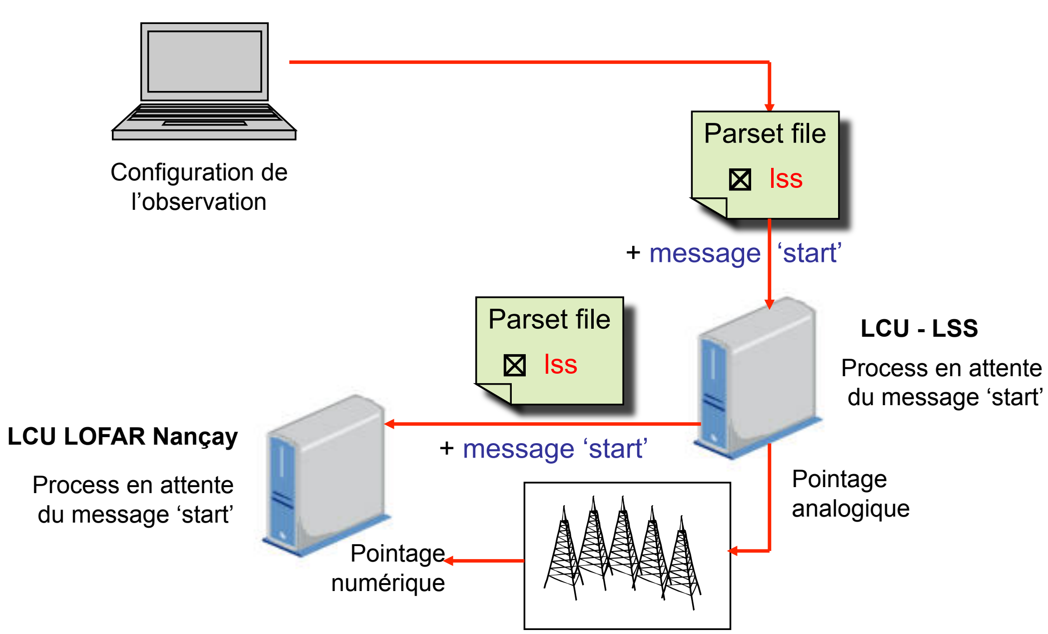


19/07/2011 AC & CT 1

LSS distribué / single station

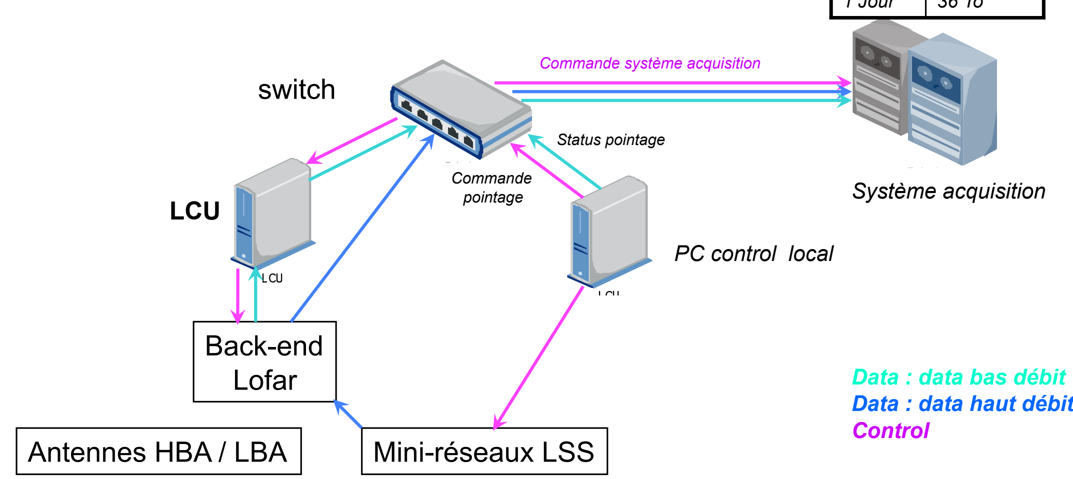


Mode standalone



LSS standalone – solution back-end « lofar »

Temps	*Capacité*
1 s	*400 Mo*
1 heure	*1,5 To*
1 Jour	*36 To*



Designing + Prototyping LSS/Nenufar

ANR program 9/2009 2/2013

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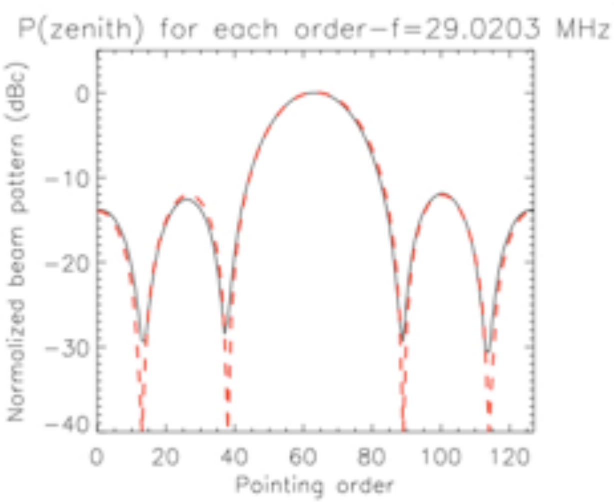
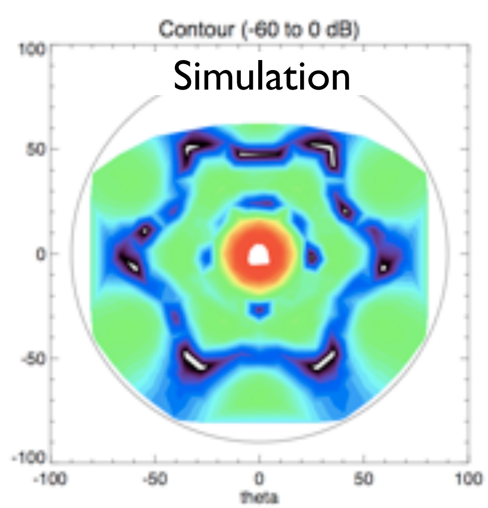
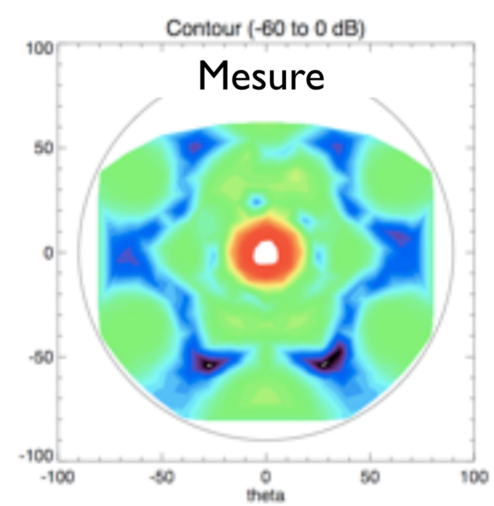
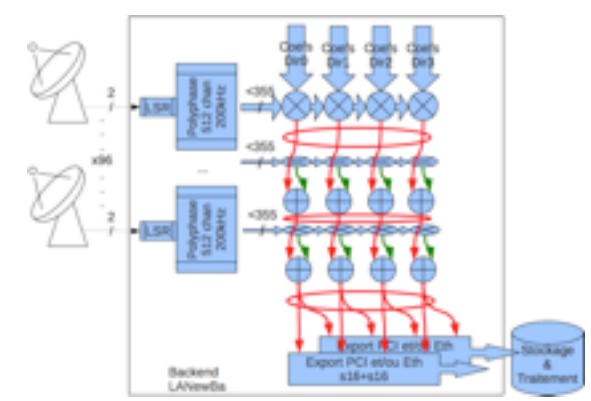


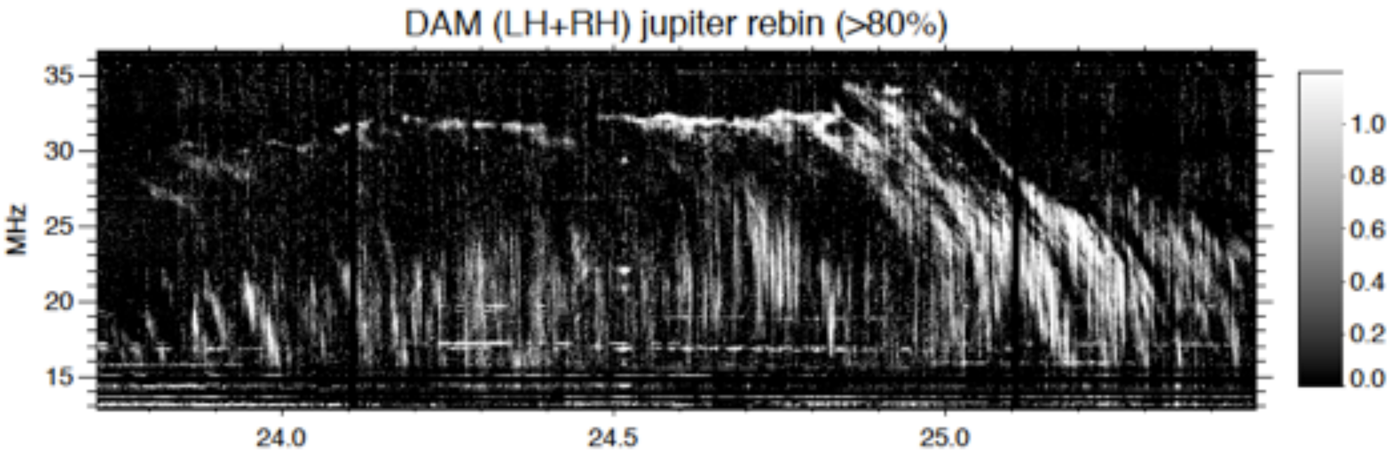


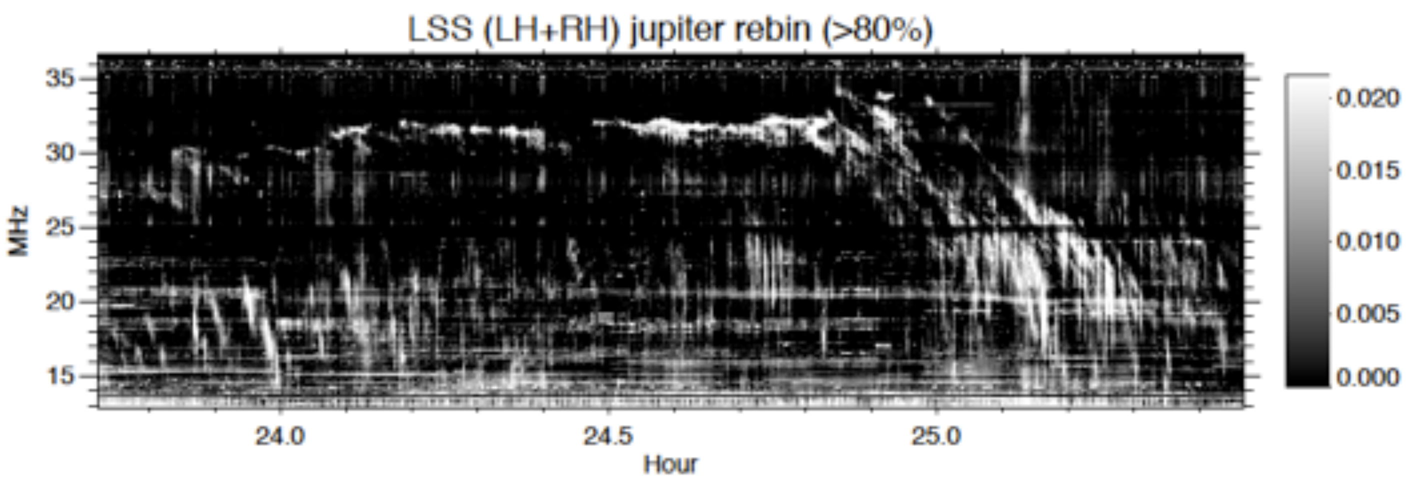




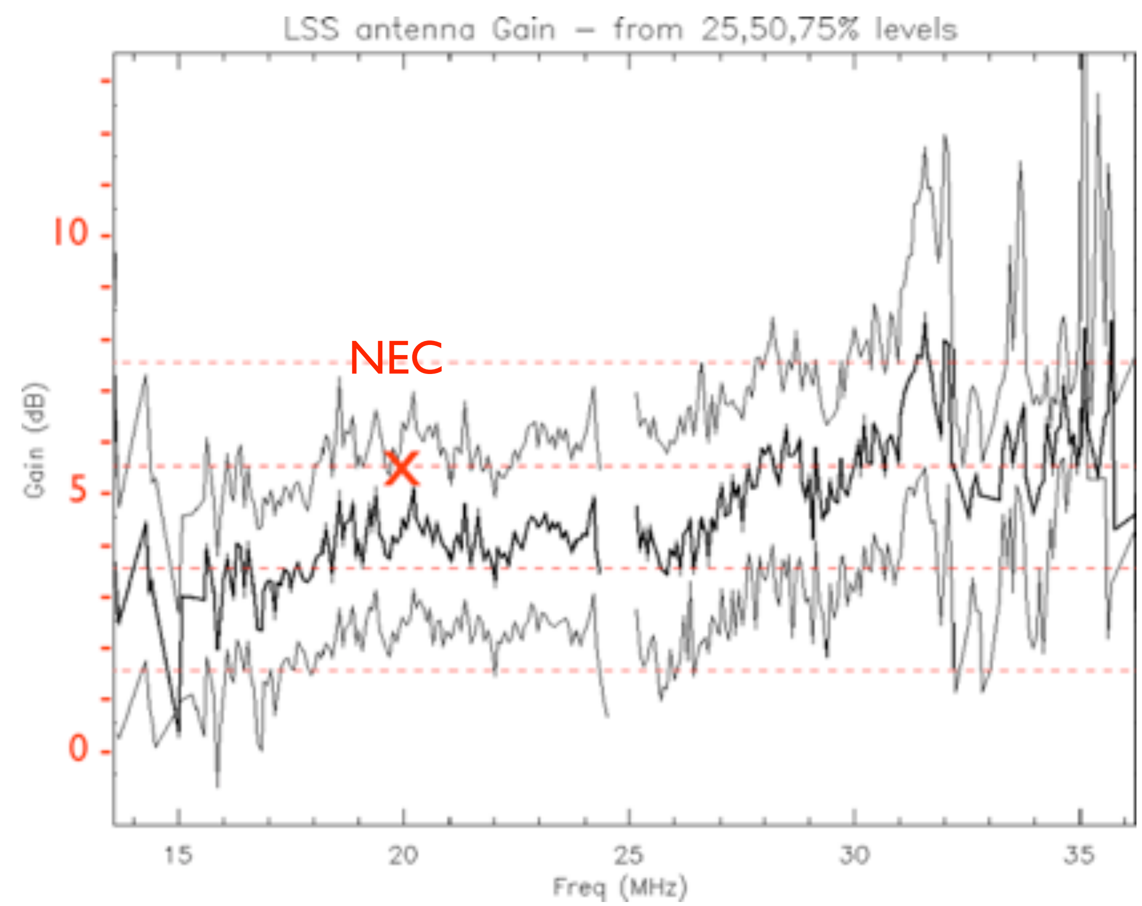
- Construction of 3 mini-arrays (x 2 polarizations) + dedicated test receiver
- Definition of a **standalone dedicated NenuFAR receiver** (Nançay/ALSE)
  ⇒ "duty-cycle" ~100% in the analog mini-array beam (~30° @ 30 MHz)
- Industrialization studies, site study (ONF), costing, sub-contracting, schedule

LSS / DAM calibration
(1 antenna)

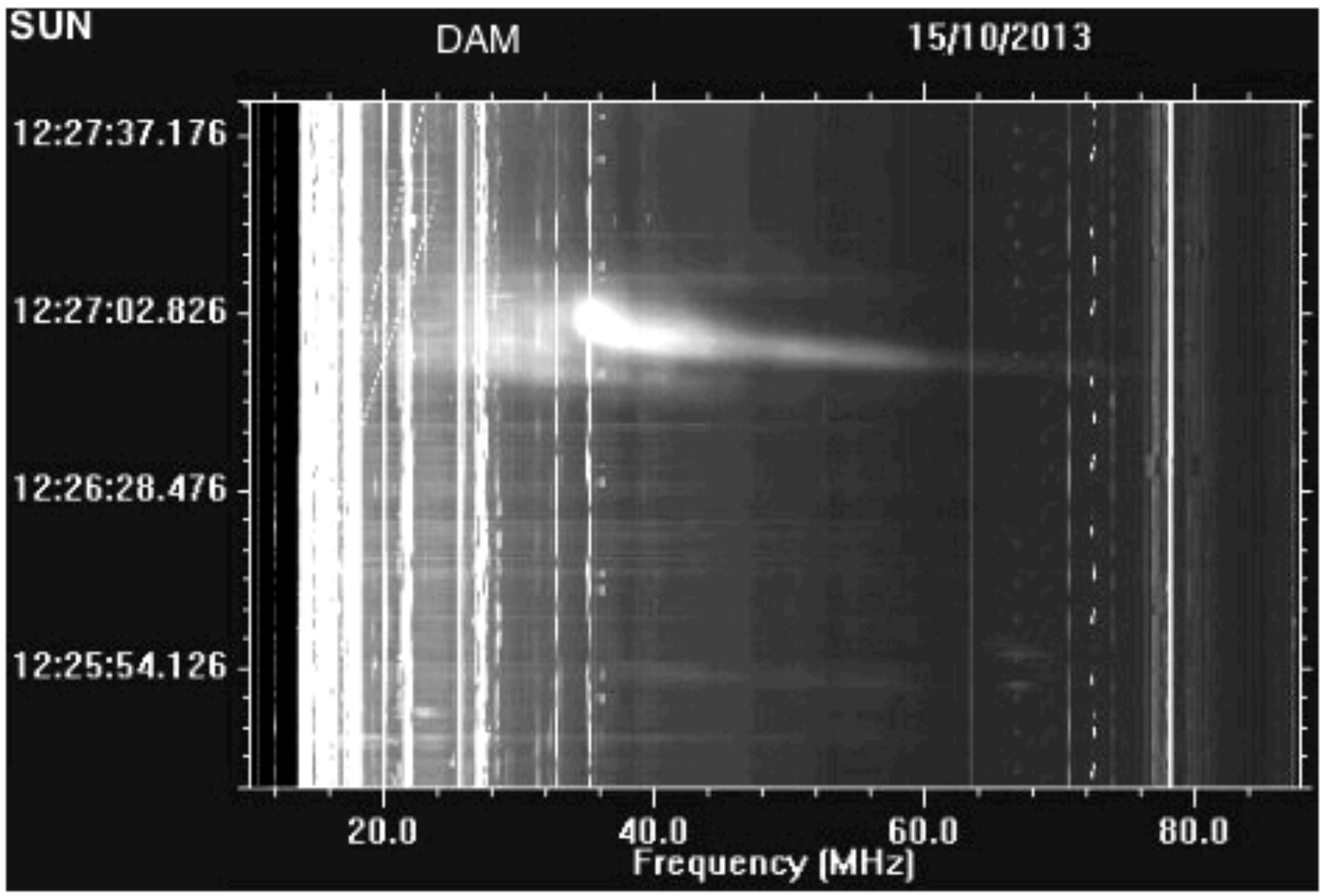


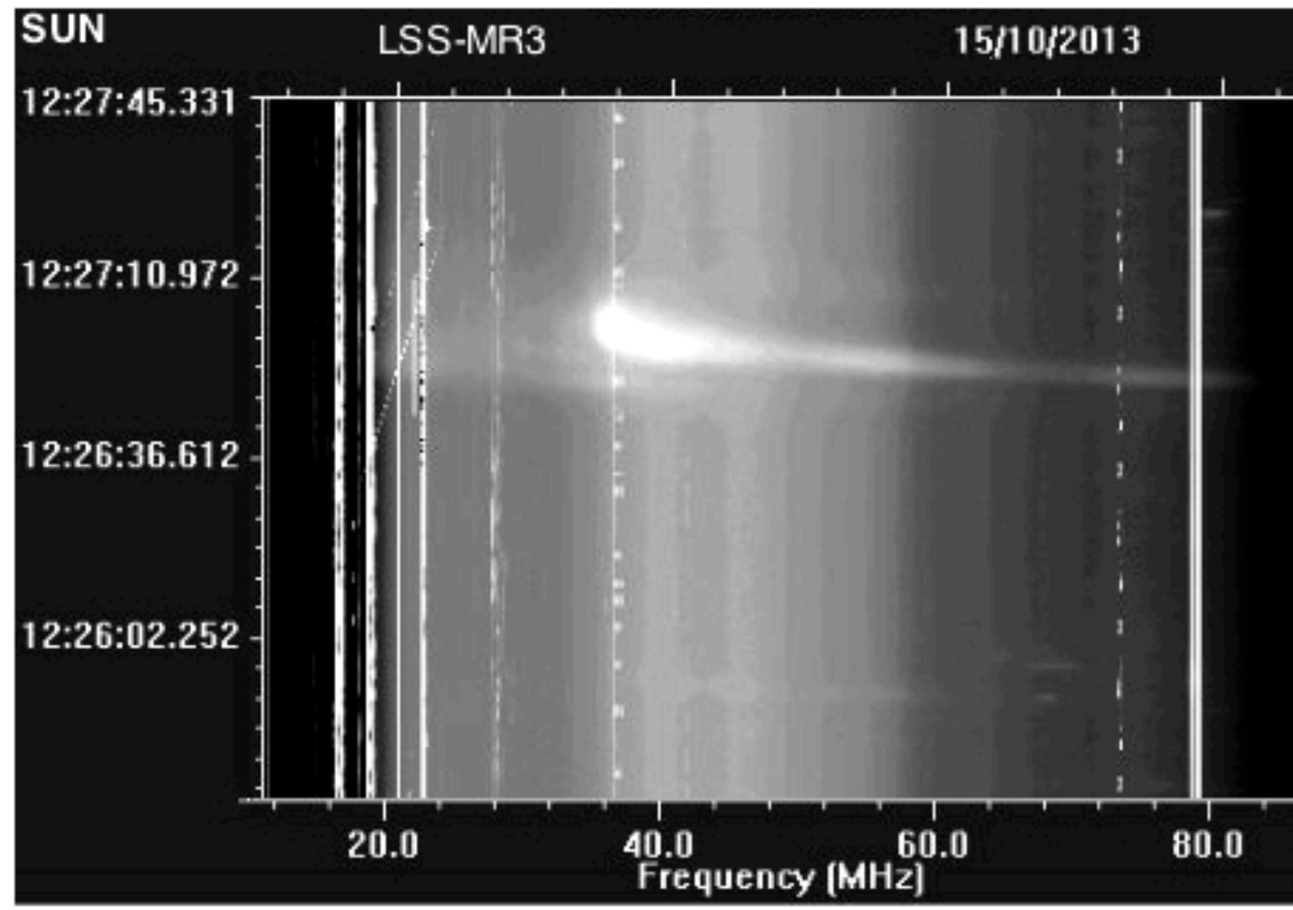


$$\frac{(S_{jup} / S_{gal})_{DAM}}{(S_{jup} / S_{gal})_{LSS}} = \Omega_{LSS}/\Omega_{DAM} = G_{DAM}/G_{LSS}$$



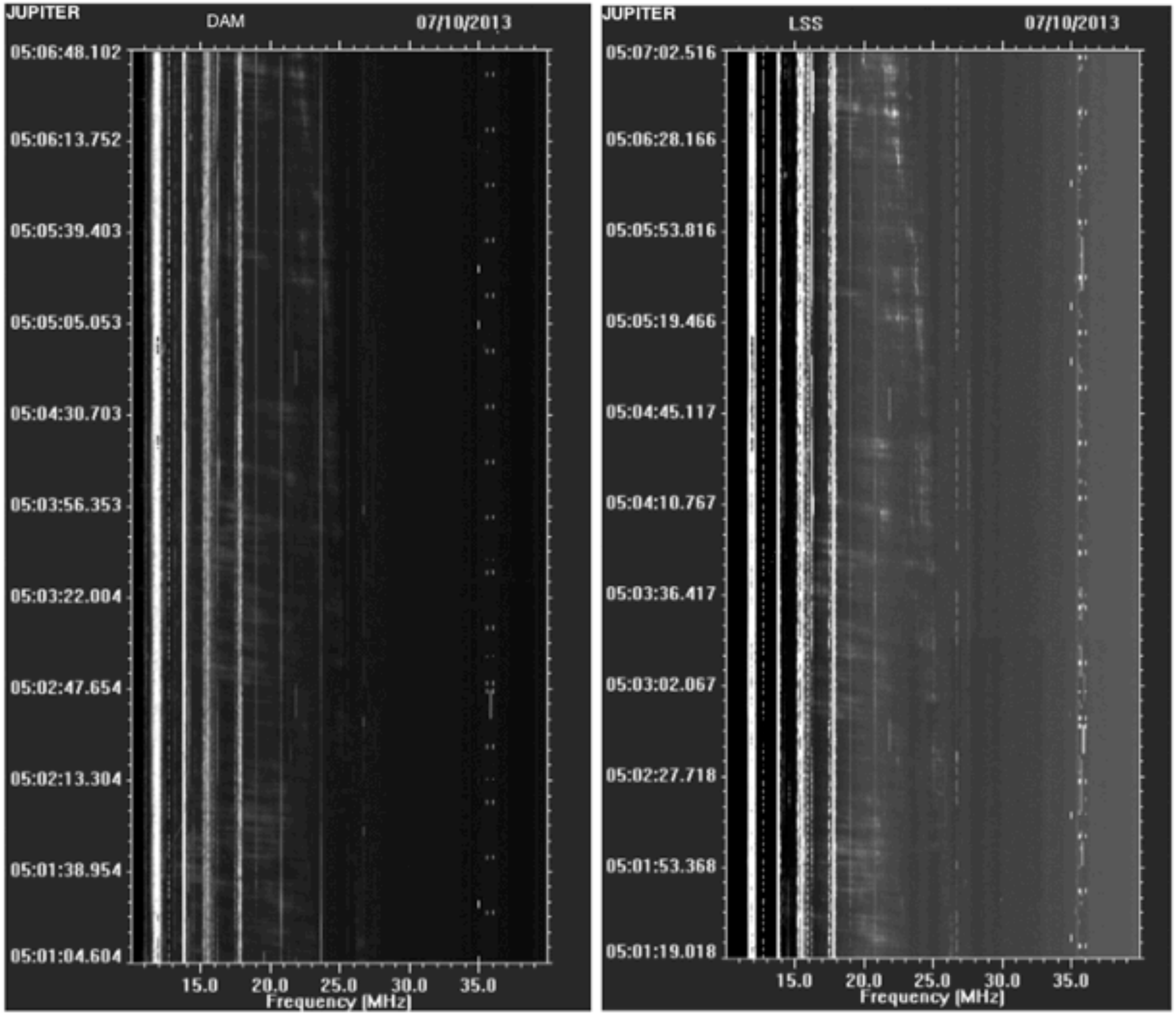
LSS / DAM calibration
(1 mini-array)

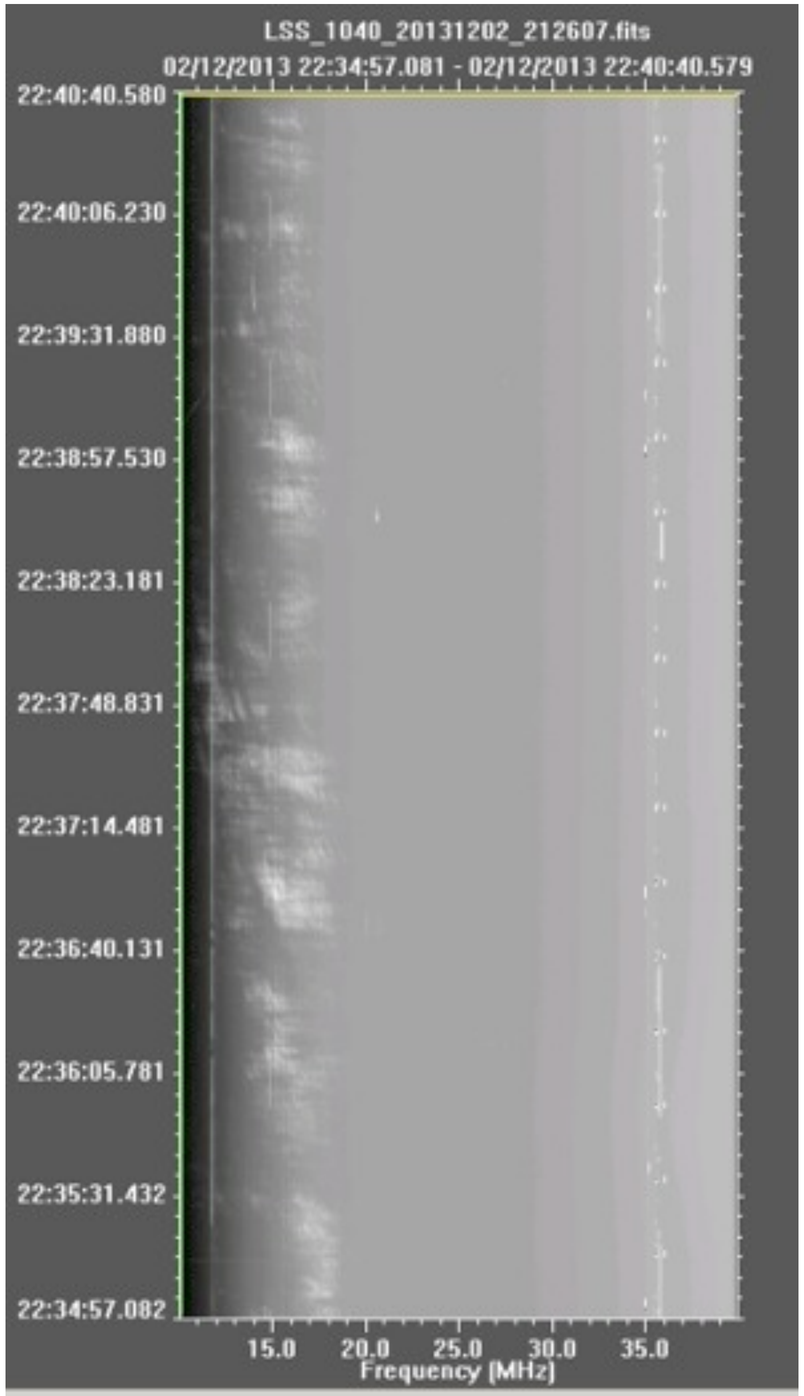




Solar type III

LSS / DAM calibration
(1 mini-array)



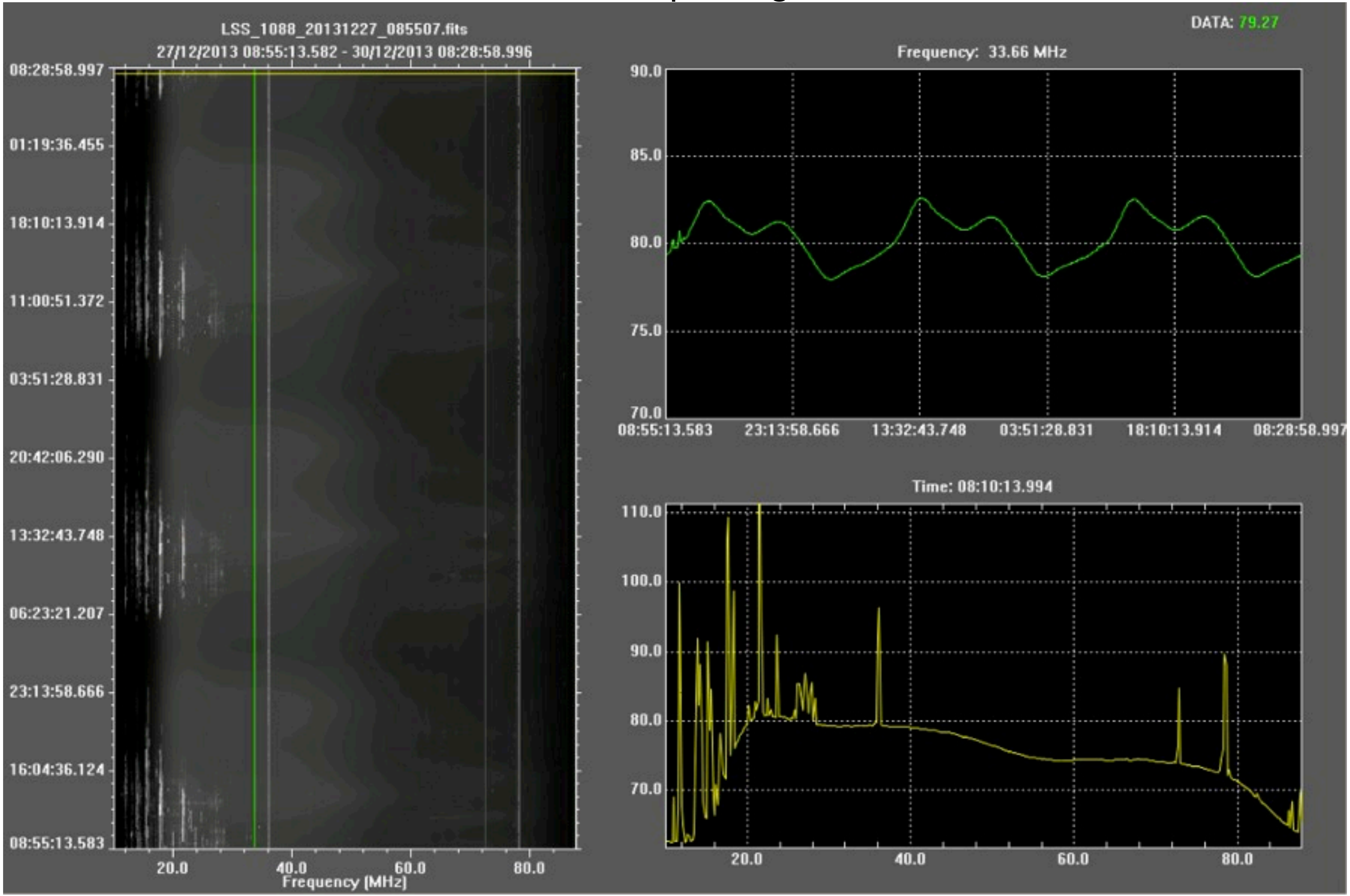


Jovian DAM

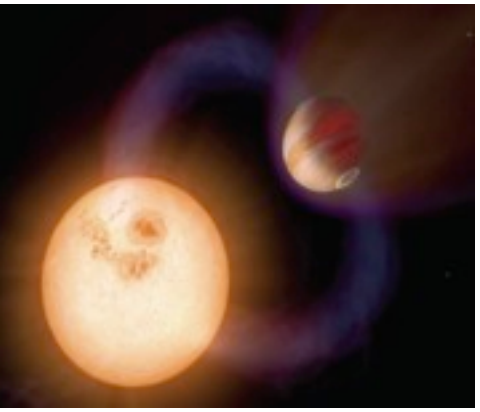
down to 10 MHz

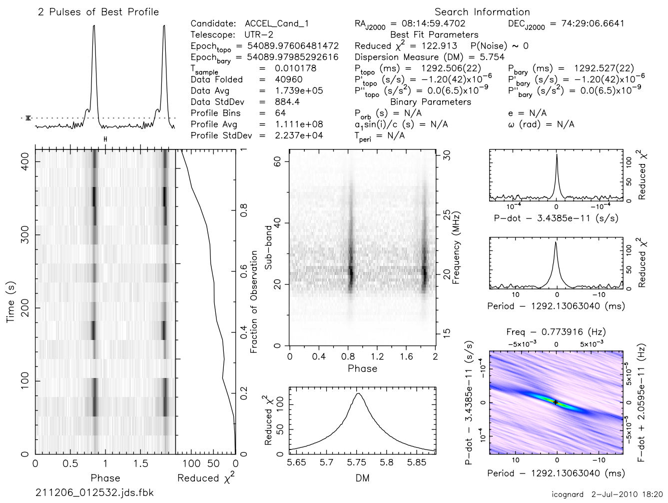
LSS calibration
(1 mini-array)

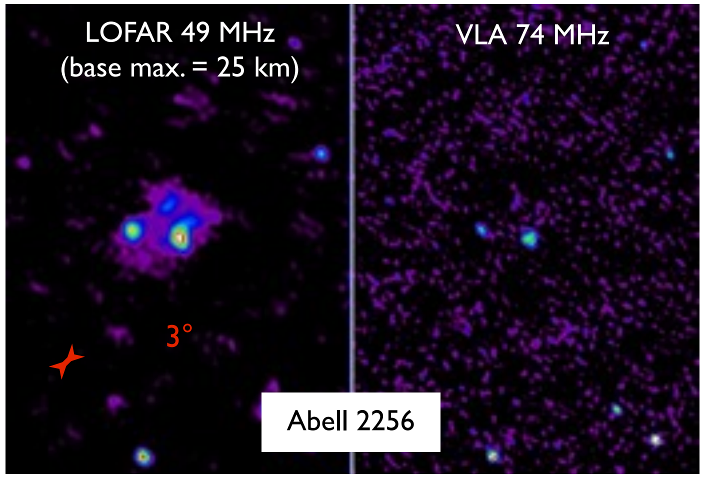
Zenith pointing

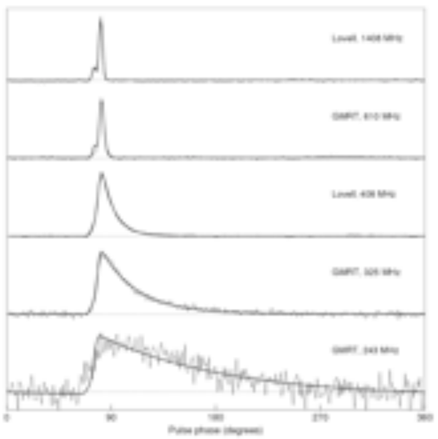


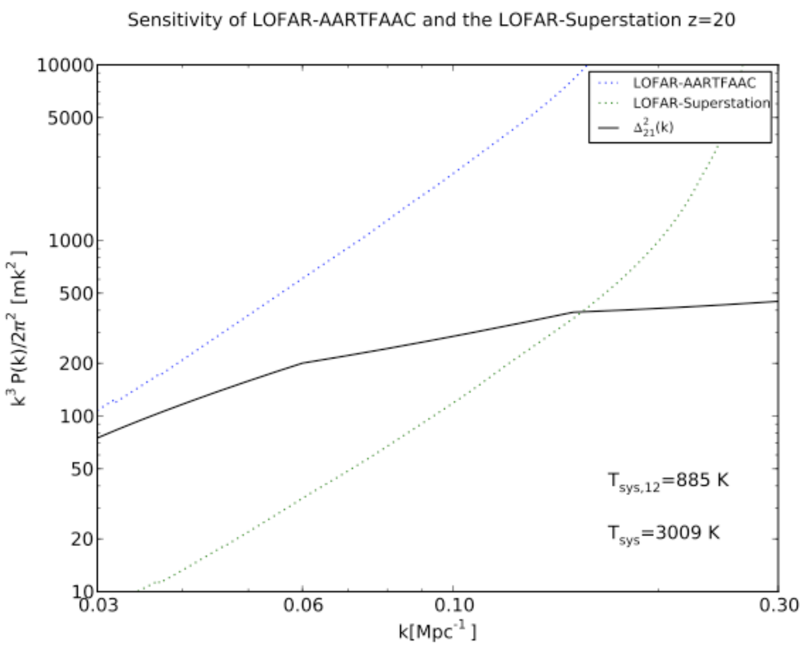
Science case of LSS/NenuFAR





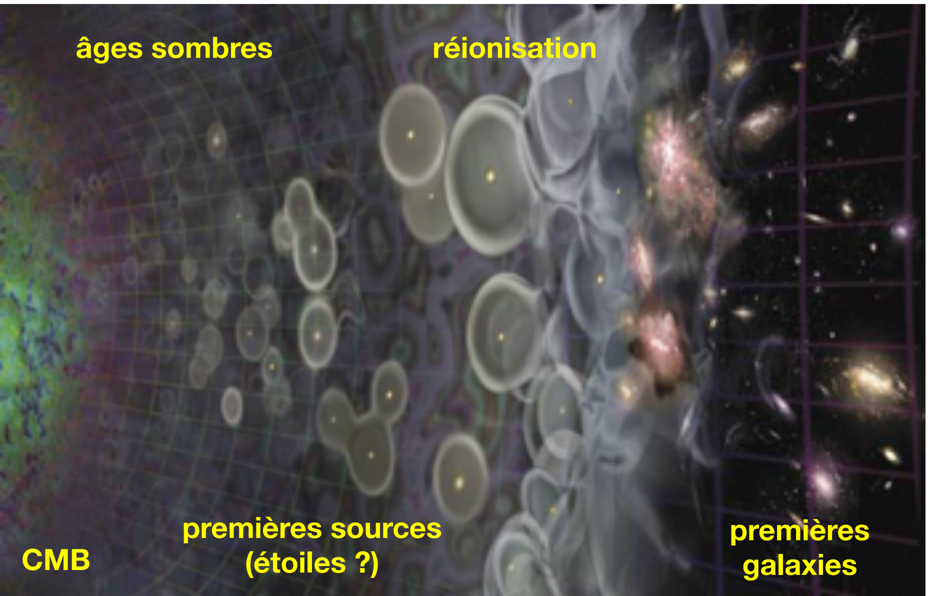






- Cosmology (dark ages) and galaxy formation
- Structure of Galactic Interstellar Medium
- Pulsars & Rotating radio transients (RRATs)
- Binary/flaring stars & Exoplanets
- The Transient Universe
- Light flashes in Terrestrial and Planetary atmospheres

⇒ LSS standalone, LSS+LOFAR, LSS//LOFAR



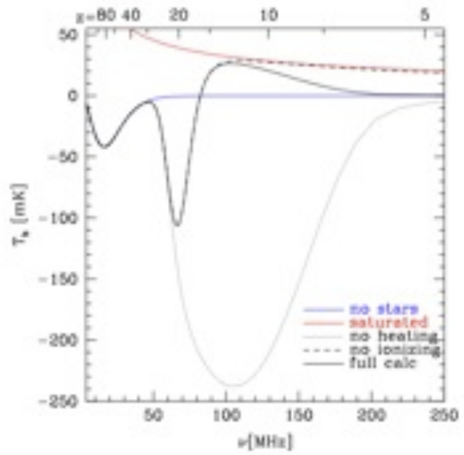
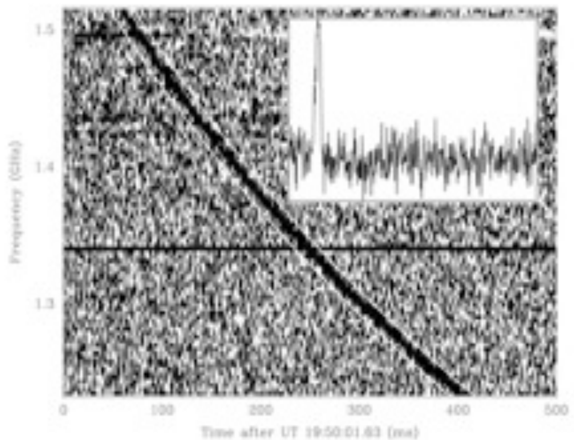
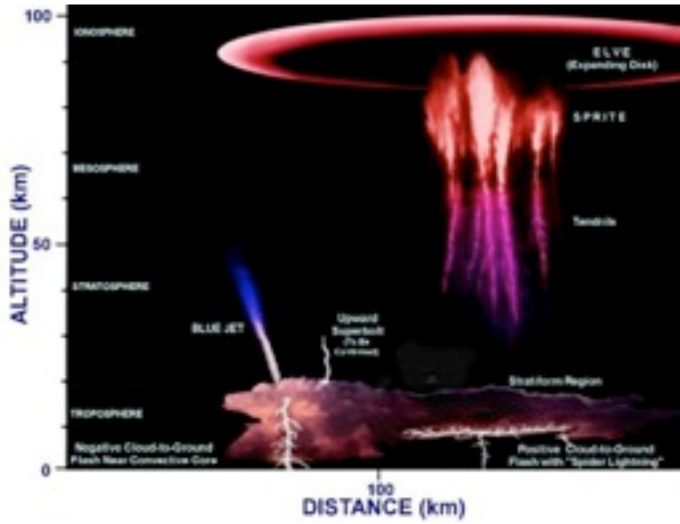


FIG. 1 (color online). Evolution of the 21 cm global signal for different scenarios. Solid blue curve: no stars; solid red curve: $T_s \gg T_\gamma$ and $x_H = 1$; black dotted curve: no heating; black dashed curve: no ionization; black solid curve: full calculation.





Science case of LSS/NenuFAR

- **Galaxy formation & Cosmology (dark ages)**

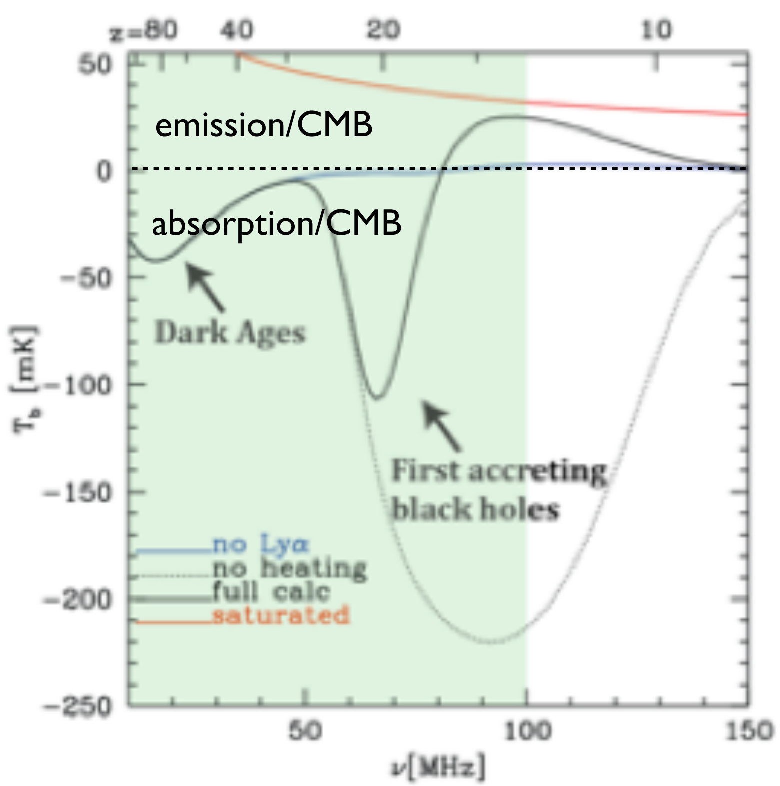
Formation of large structures (NAG at $z<1$, blobs at $z\lesssim 2$, star formation in nearby galaxies, magnetic fields)

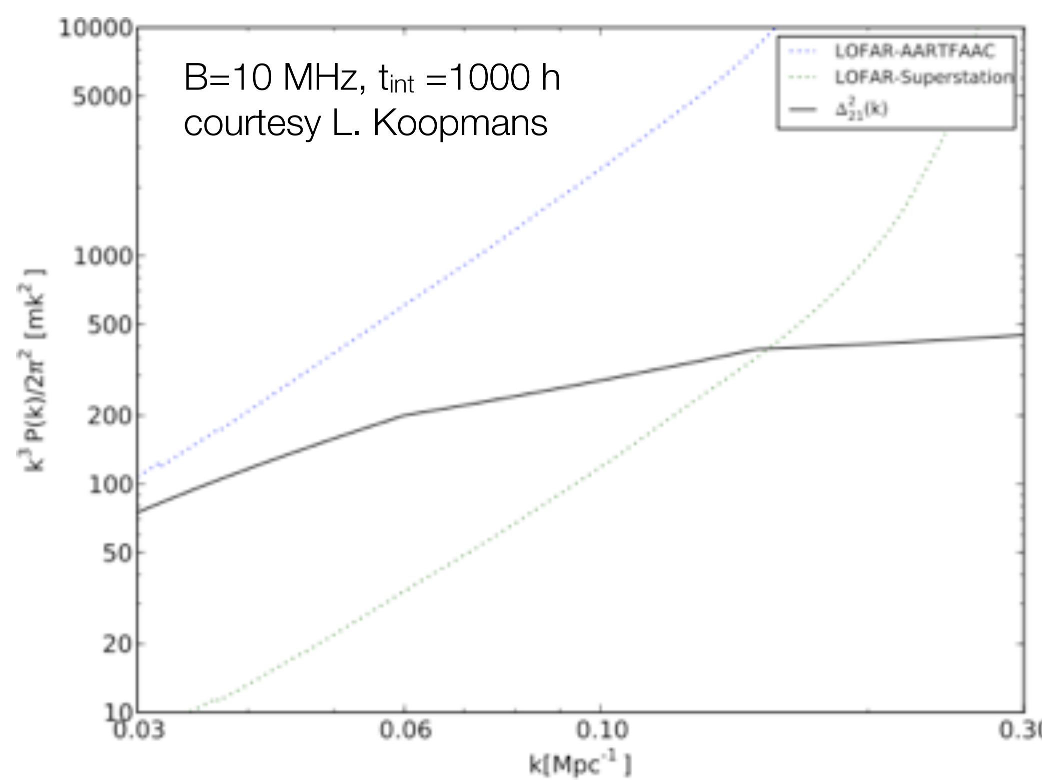
⇒ LSS+LOFAR (sensitive long baselines)

<u>Signature of pre-EoR "dark ages" :</u>

- all-sky H_I spectrum at $z \geq 12\text{-}20$: $\delta T_b \sim -100$ mJy ≤ LBA range, $\delta T_b/T_b \sim 10^{-6}$
- possibly larger spatial fluctuations of H_I at $z\sim 20$

⇒ LSS standalone + dedicated receiver (large sensitivity, accurate bandpass calibration via instantaneous cross & autocorrelation measurements)





Science case of LSS/NenuFAR

- **Structure of Galactic Interstellar Medium**

Extended objects (> instantaneous "station" FoV ~10° @ 30 MHz)

⇒ LSS+LOFAR (short baselines)

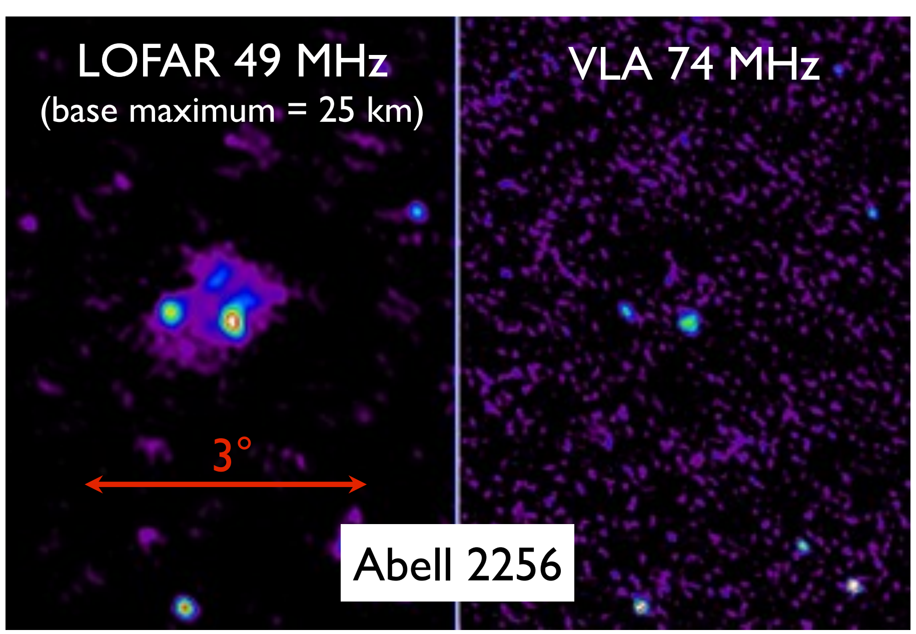
Measurement of small-scale magnetic field (RM without depolarization)

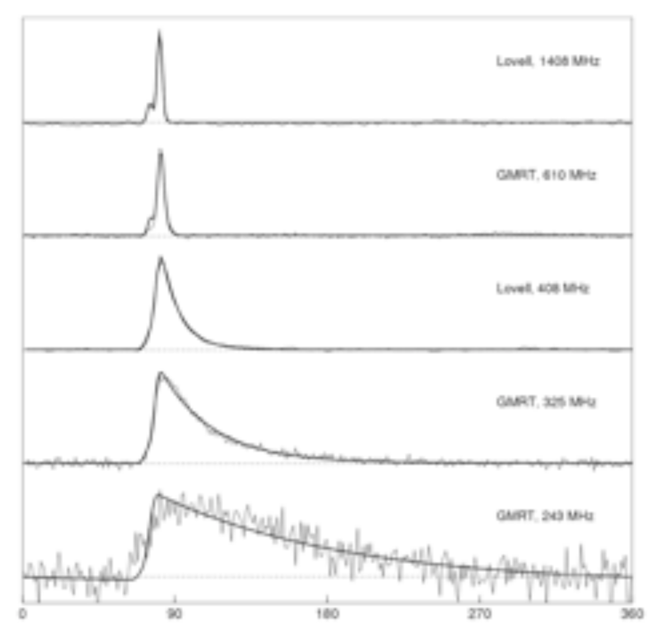
⇒ LSS+LOFAR (sensitive long baselines)

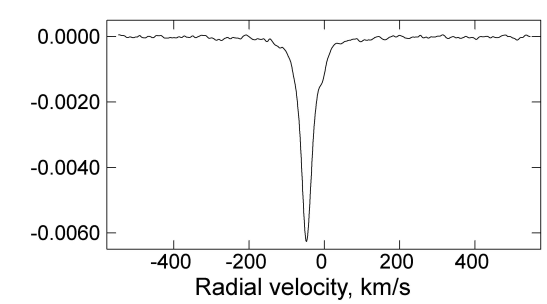
Maximum scale of ISM turbulence (temporal broadening of radio pulses), Atomic recombination lines

⇒ LSS standalone (instantaneous sensitivity, access to LF)

⇒ LSS+LOFAR (sensitive long baselines)





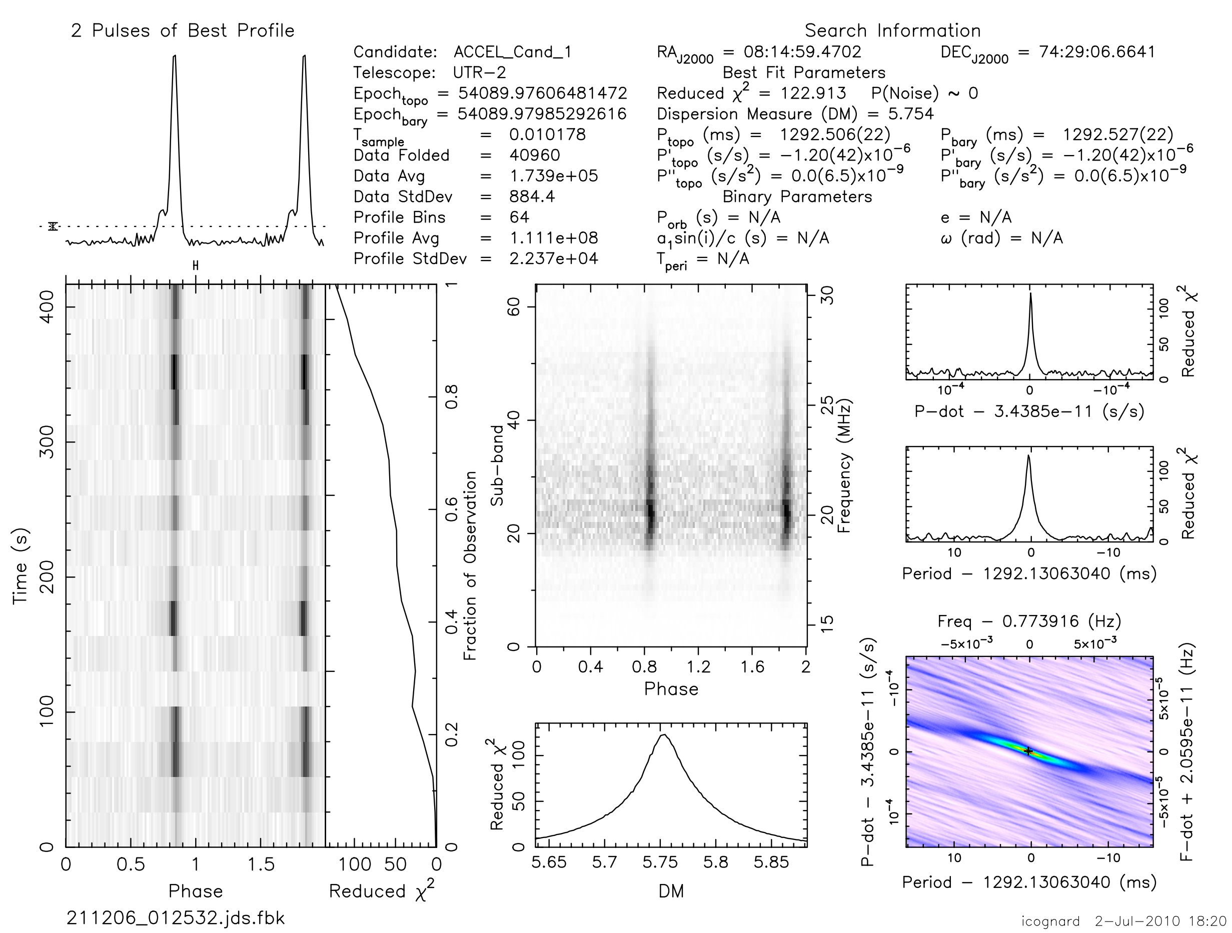


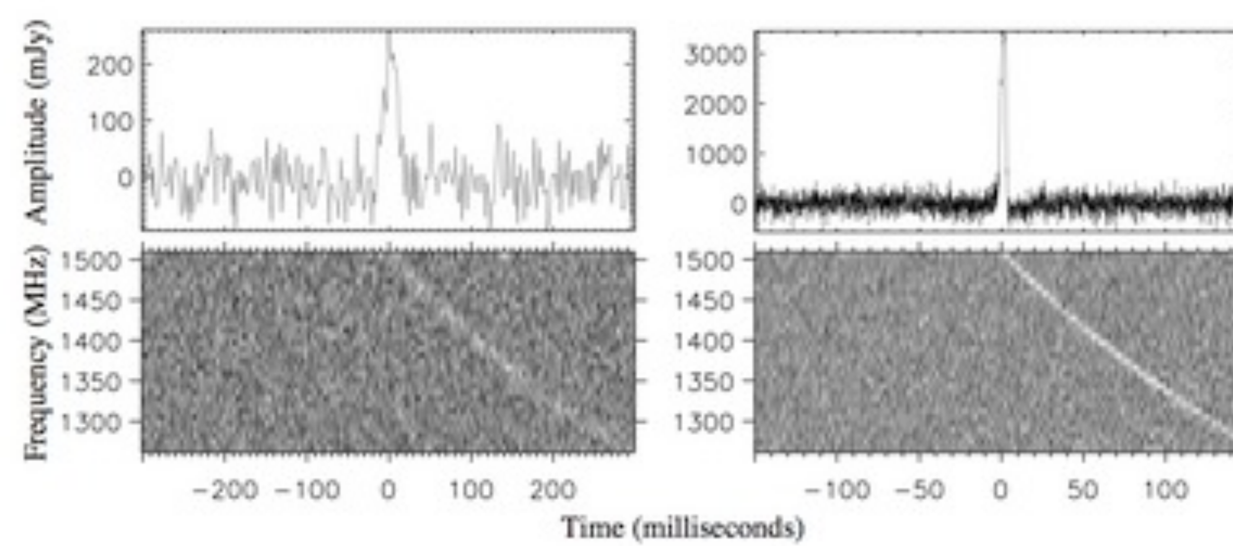
Science case of LSS/NenuFAR

- **Pulsars & Rotating radio transients (RRATs)**

Detection, especially at LF, Nature of RRATs, Giant Pulses, Physics of the environnement of compacts objects, Planets orbiting pulsars ?

⇒ LSS standalone (sensitivity + FoV = high efficiency for discovery, access to LF)





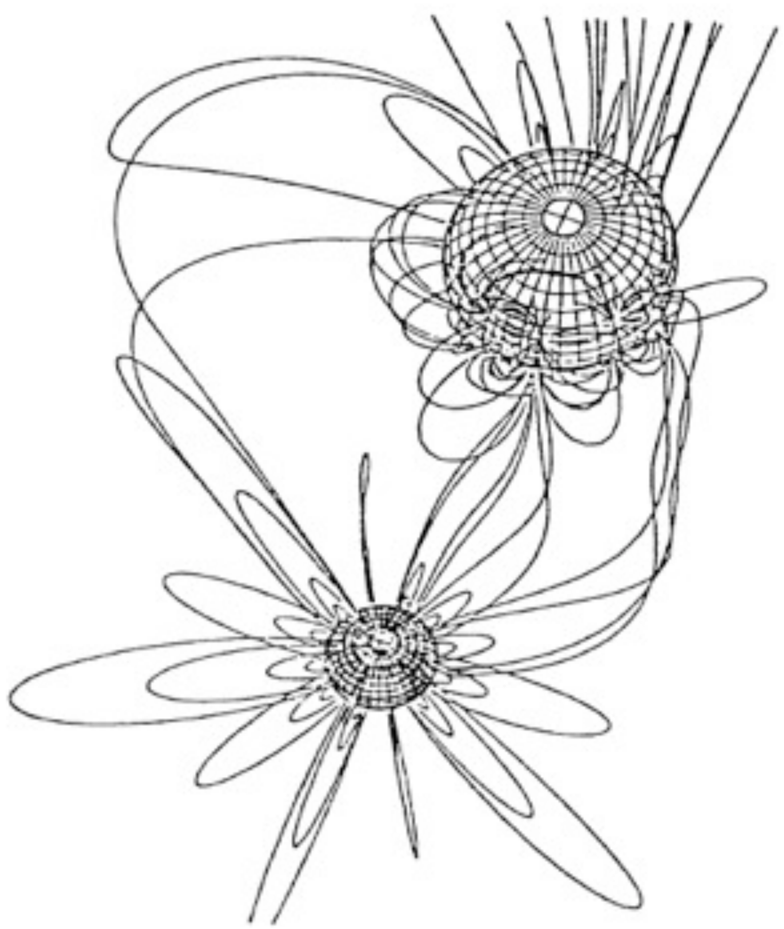
Science case of LSS/NenuFAR

- **Binary/flaring stars & Exoplanets**

Existence and characteristics of radio emission, Star-Planet plasma Interactions, Comparative magnetospheric physics, Implications on habitability.

⇒ LSS standalone (TAB sensitivity, access to LF, large duty-cycle)

⇒ LSS+LOFAR, LSS//LOFAR (global sensitivity, mitigation / RFI & ionosphere)

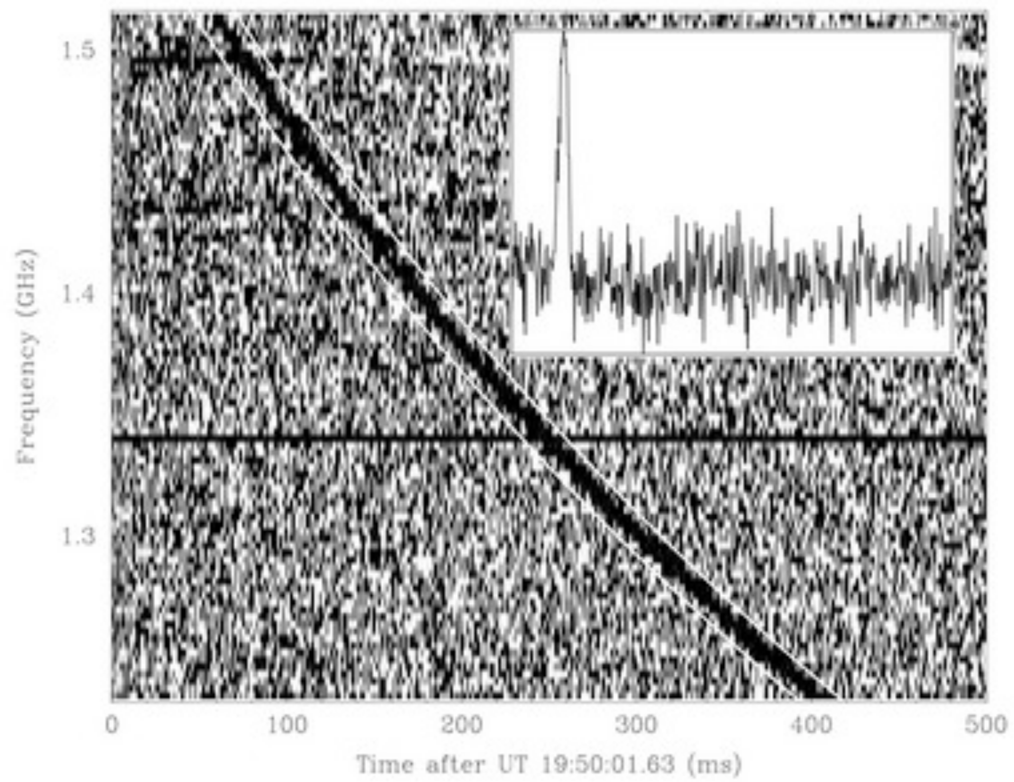


Science case of LSS/NenuFAR

- **The Transient Universe**

Exhaustive blind exploration, temporal & spectral scales of (dispersed) pulses, nature of emitters (GRB, CR, neutrinos/Moon, Gravitational Wave counterparts, serendipity...)

⇒ LSS standalone + ARTEMIS backend (coherent or incoherent TAB sensitivity, extended TBB, access to LF, large duty-cycle)

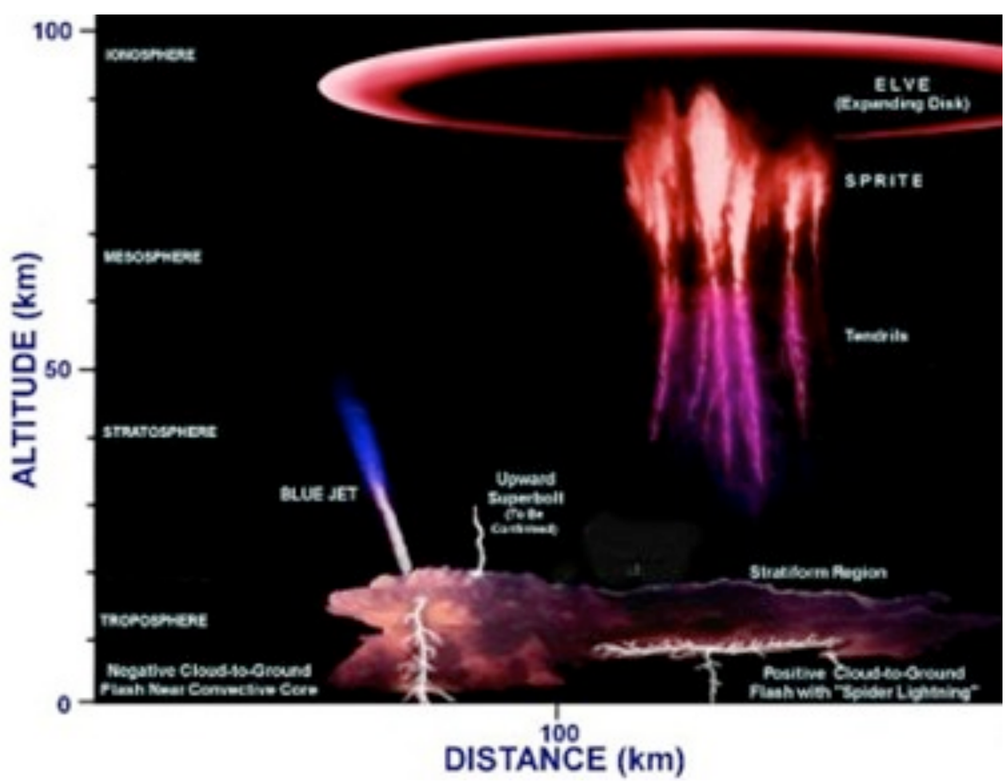


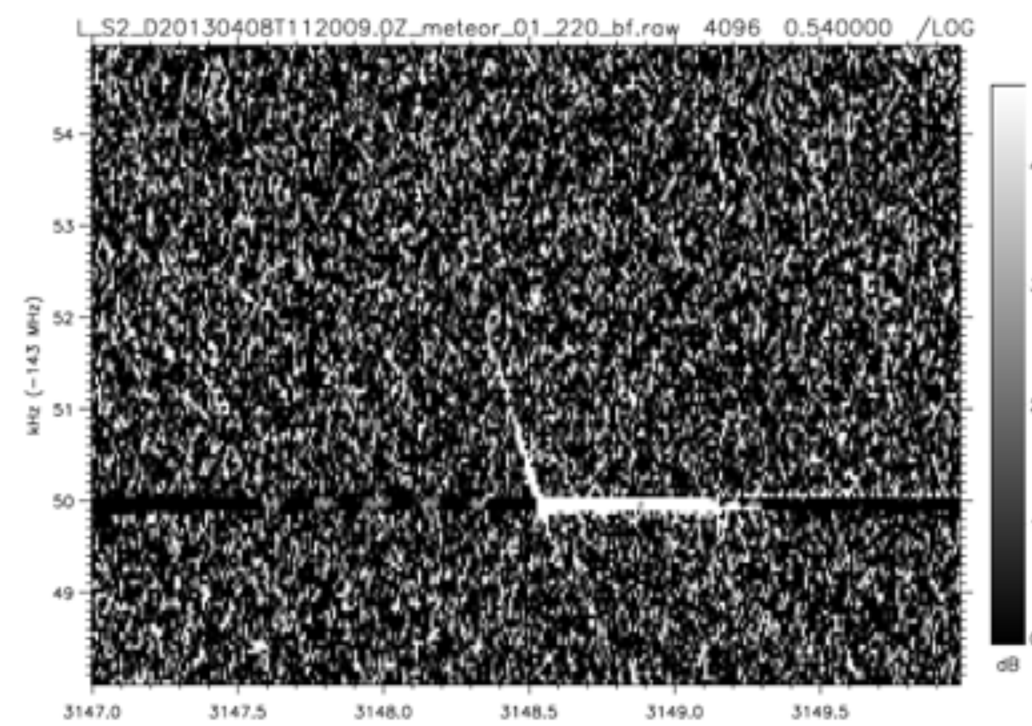
Science case of LSS/NenuFAR

- **Light flashes in Terrestrial and Planetary atmospheres**

Radio counterpart of TLEs, sprites, meteors… : origin, local distribution & dynamics, temporal & spectral scales, physical processes…

⇒ LSS standalone (coherent or incoherent TAB sensitivity, extended TBB, access to LF, large duty-cycle)





- **Solar System radiophysics**

Ionospheric scintillation & opacity, Solar & Jovian bursts, IP scintillation, active studies, meteor trails …

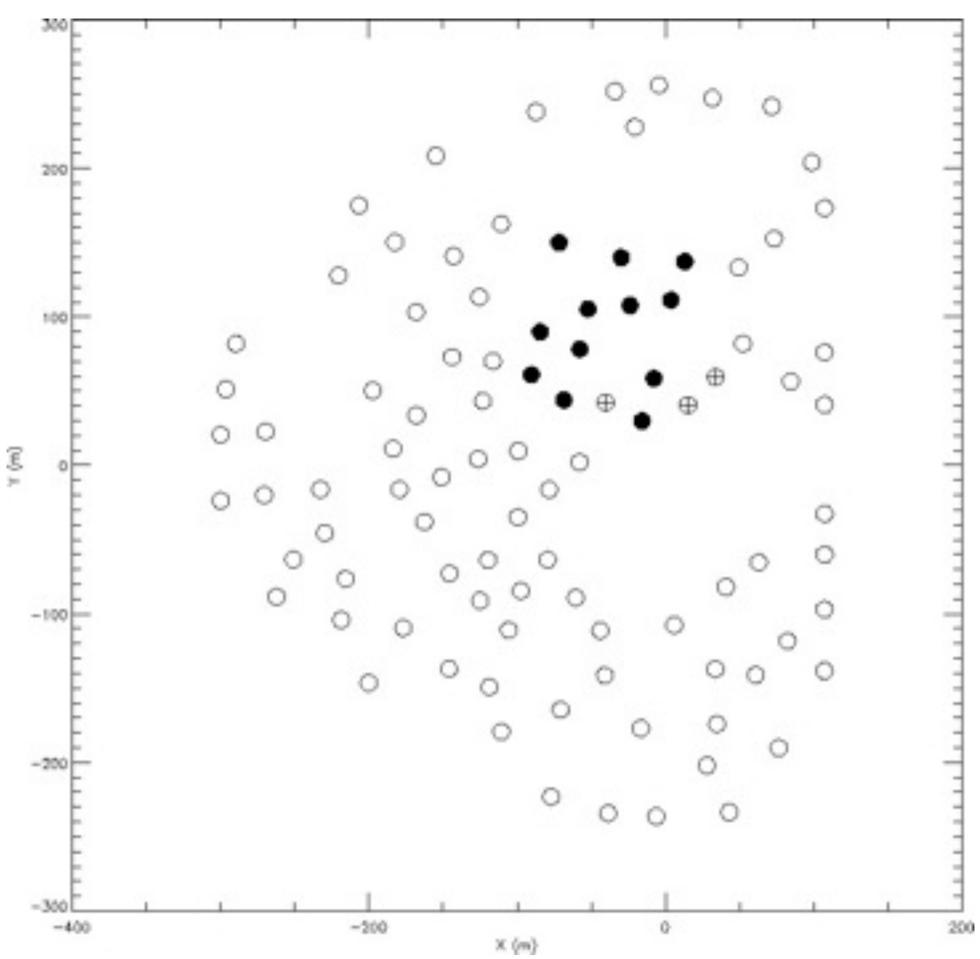
NenuFAR status

https://nenufar.obs-nancay.fr

- Construction cost : ~4.5 M€
- Low operation cost
- ≥1 M€ secured in 2013 ; ~1 M€ expected in 2014 ...

- Phase 1 (NenuFAR-1) received green light from OP/OSUC/UO (15/11/2013)

  → construction or 15 mini-arrays started, operational in ~ 1 year



NenuFAR - 1

https://nenufar.obs-nancay.fr

Technical characteristics of NenuFAR-1

- Number of antennas : 285 (15 mini-arrays of 19 antennas), within an ellipse ~110 m x ~ 140 m
- Frequency range : ~10-85 MHz (also the bandwidth per beam)
- Resolutions : down to δf = 3 kHz and δt = 5 μsec ($\delta f \times \delta t \geq 1$)
- Waveform snapshots capture mode at 5 nsec resolution (TBB)
- Polarizations : 2 linear antenna (NW-SE & SW-NE) → 4 Stokes computed
- Pointing declination : -23° to +90° (Nançay latitude = 47.38° N)
- Effective area : $\lambda^2/3$ per antenna, ~95 λ^2 for NenuFAR-1

  (≤ 10^4 m^2 due to overlapping Aeff ≤30 MHz)
- FoV : antenna ~2π sr, phased mini-array 34°–9° at 20–80 MHz
- Number of beams : 2 (full band, 70 MHz)
- Angular resolution / pencil beam size : 7°–2° per beam at 20–80 MHz
- Sensitivity S_{min} : 12-3 Jy at 20–80 MHz (5 σ , 1 secx10 MHz, polarized signal)

  55–200 mJy at 20–80 MHz (5 σ , 1 hx10 MHz, polarized signal)
- Confusion noise at zenith : 400–10 Jy at 20–80 MHz (140 m diameter)

Context of NenuFAR & NenuFAR-1

Name	Antennas	Eff. area	Freq. range	Ang. Res.	N beams	Polar.
NDA	144 circ. dipoles	2400 m^2 (*)	10-100 MHz	7.5° (*)	1 beam	4 Stokes
UTR-2	2040 dipoles	143000 m^2	8-32 MHz	0.5°	5 beams	1 lin. polar.
VLA	27 dish.× 25 m	~2000 m^2	73-74.5 MHz	0.5'	1 beam	4 Stokes
LWA (LWA1)	256 X dipoles	~8000 m^2 (*)	10-88 MHz	6° (*)	4 beams ×20 MHz	4 Stokes
OLWA	256 X dipoles (→2000)	~8000 m^2 (*) (→ 65000 m^2)	10(28)-88 MHz	≤5° (*) (→ ≤1°)	Full-sky imaging	4 Stokes
NenuFAR-1	**285 X dipoles**	**~9000 m^2 (*)**	**10-85 MHz**	**5° (*)**	**2 beams**	**4 Stokes**
AARTFAAC-LBA	288 X dipoles	~8000 m^2 (*)	30-80 MHz	2° (*)	All-Sky	4 Stokes
LOFAR-LBA	2688 X dipoles	72000 m^2 (*)	30-80 MHz	2" (*)	8+beams ×4 MHz	4 Stokes
NenuFAR standalone	***1824 X dipoles***	***62000 m^2 (*)***	***15-80 MHz***	***1.5° (*)***	***4 beams ×65 MHz***	***4 Stokes***
NenuFAR +LOFAR-LBA	***4512 X dipoles***	***134000 m^2 (*)***	***30-80 MHz***	***2" (*)***	***8+beams ×4 MHz***	***4 Stokes***
SKA	>3000 dishes +Apert. Array	~10^6 m^2	0.05 - >10 GHz	<0.1"	many (?) beams	4 Stokes

(*) at 30 MHz

LSS-France team : ~ 25 scientists + 15-20 engineers/technicians

Laboratories involved in the construction : Nançay, LESIA, GEPI, LERMA, LPC2E, Prisme, Subatech, IRA Kharkov, SRI Graz (support OP, ESEP)

⇒ Paris(Meudon)-Orléans-Nançay axis, in preparation of SKA

Users Laboratories : OP (LESIA, GEPI, LERMA, LUTh), CEA/Sap-DASE-AIM, IAS, IAP, E. Polytechnique, ENS/LRA, APC, IN2P3, LPC2E, Nançay, OCA, IRAP ...

NenuFAR status (cont'd)

- In preparation of CNRS/INSU Prospective (fall 2014), need super-strong science case

→ workshop
"The science from NenuFAR-1 to NenuFAR"
13-14/2/2014, IAP (Paris)
http://nenufar.sciencesconf.org

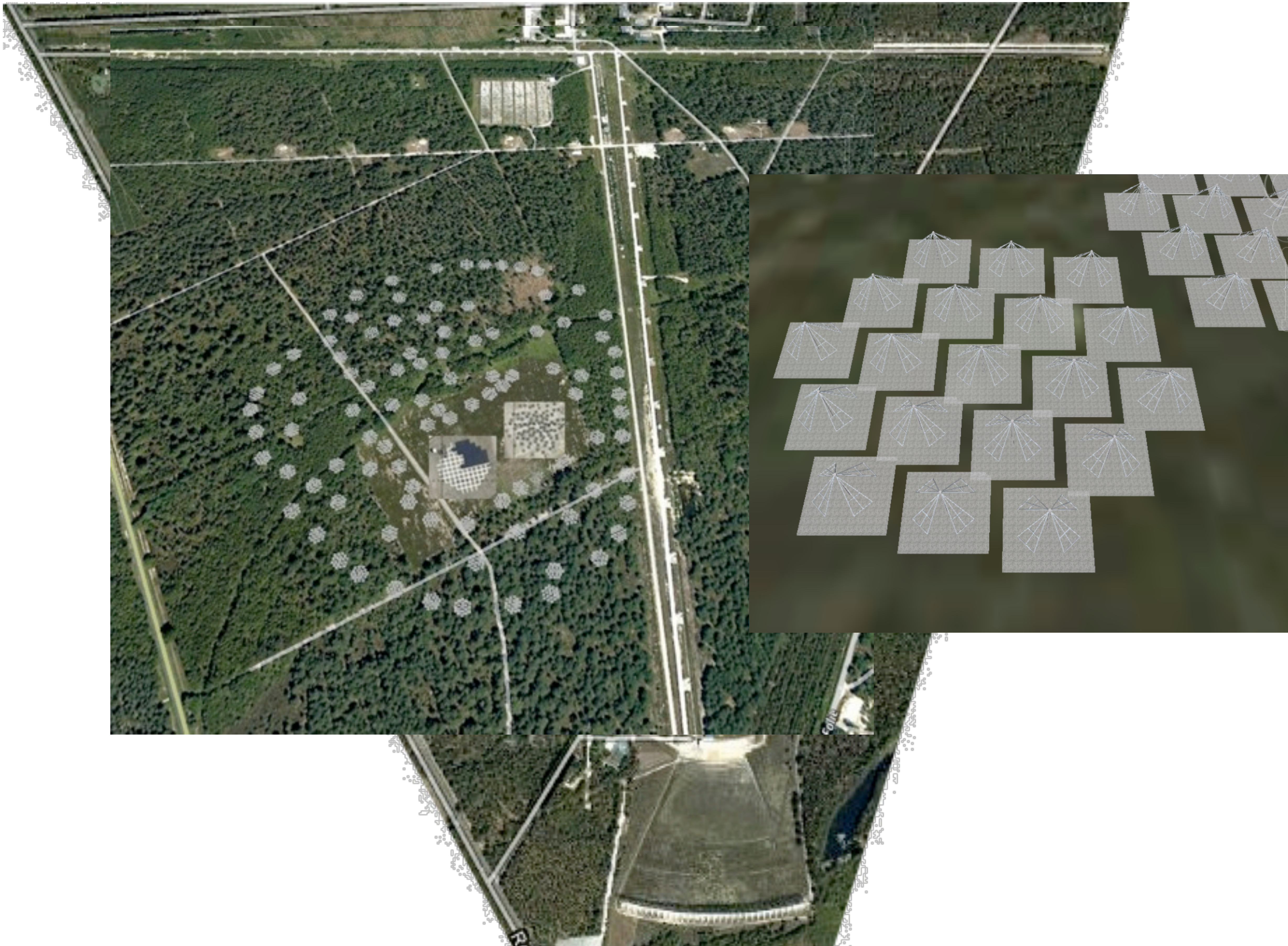
→ preceded by the "SKA-LOFAR radio days"
11-13/2/2014, IAP (Paris)
http://journees-radio.sciencesconf.org
(writing of a "white paper")

foreign participants welcome
in support of NenuFAR

Operating modes & data policy

- being discussed by ILT ...
- NenuFAR ~ super-LBA field, optional use by LOFAR
- dedicated receiver captures the signal before entering the LOFAR back-end 100% of the time
- no use of LOFAR hardware in standalone mode
- main goal: optimize the scientific return of both LOFAR & NenuFAR
- NenuFAR-within-LOFAR freely programmed by the LOFAR PC, FLOW builder's list
- NenuFAR standalone use programmed by a FLOW PC (exchange 1 PC member ?)
- sub-arrays (NenuFAR as second core) TBD
- single station mode TBD

Tomorrow NenuFAR ...



Tomorrow NenuFARs ?...