NenuFAR

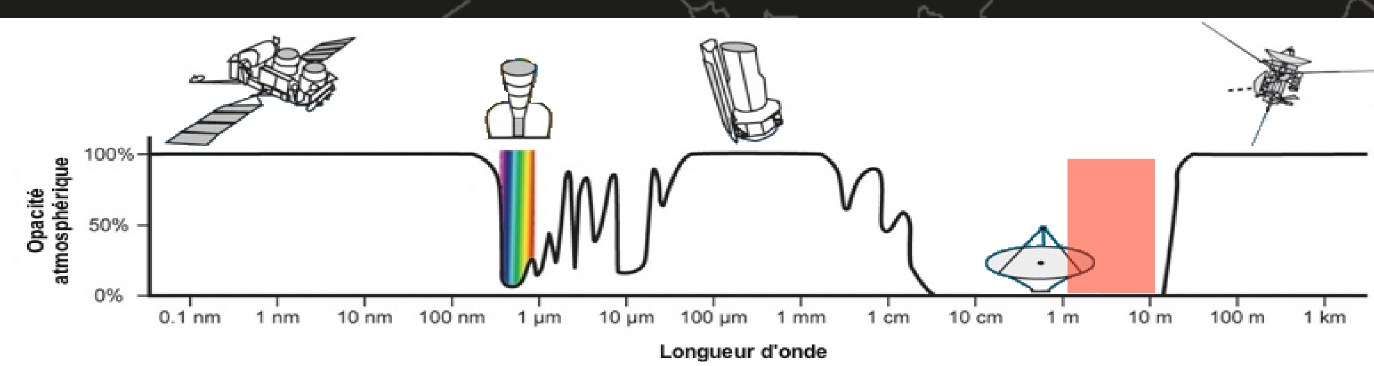
New Extension in Nançay Upgrading LOFAR

P. Zarka[1]

& the NenuFAR-France team[2]

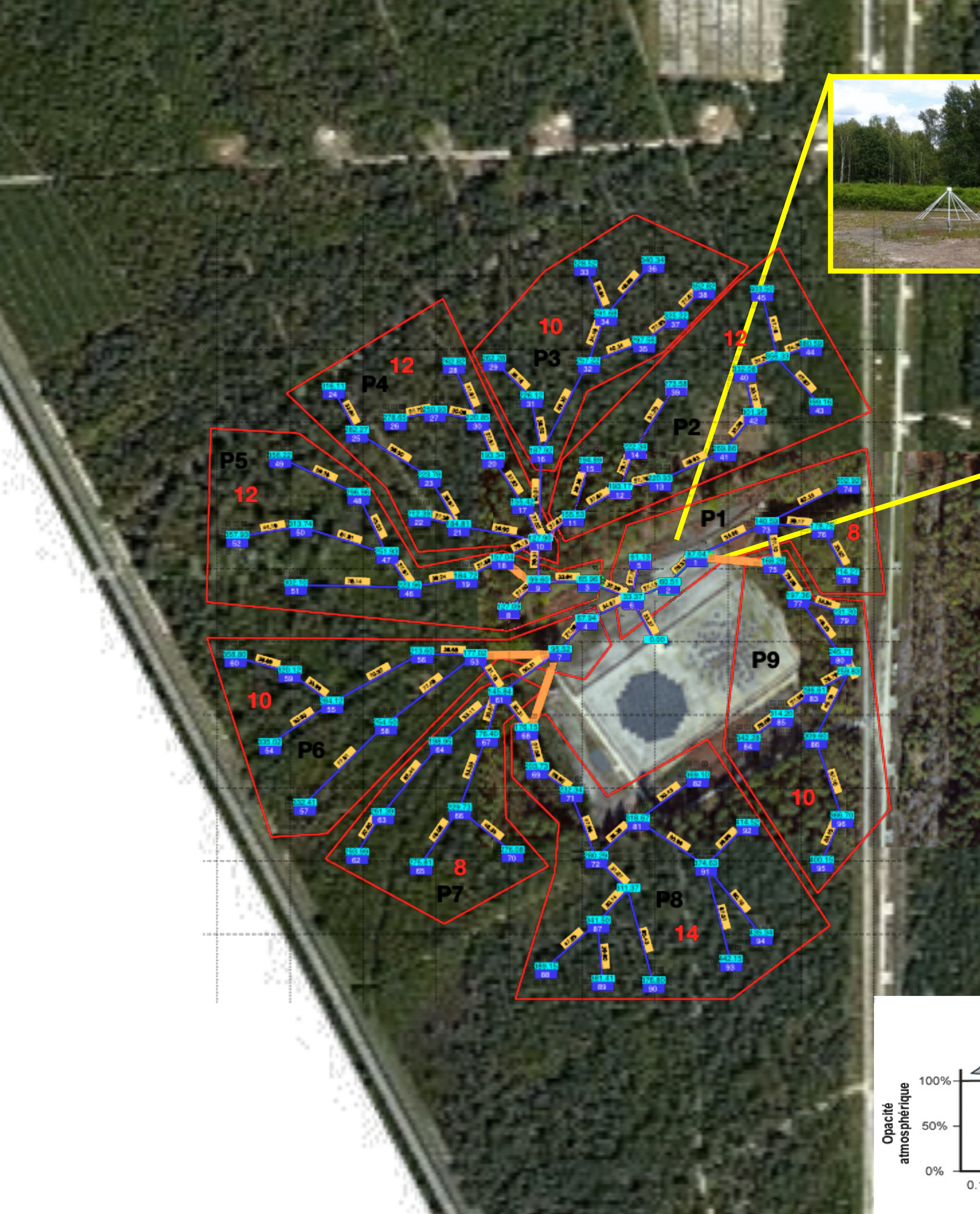
[1]LESIA—USN, OP/CNRS/PSL
[2]GEPI, LPC2E, Subatech, CEA/AIM, OCA, ONERA, LERMA, PRISME, APC …

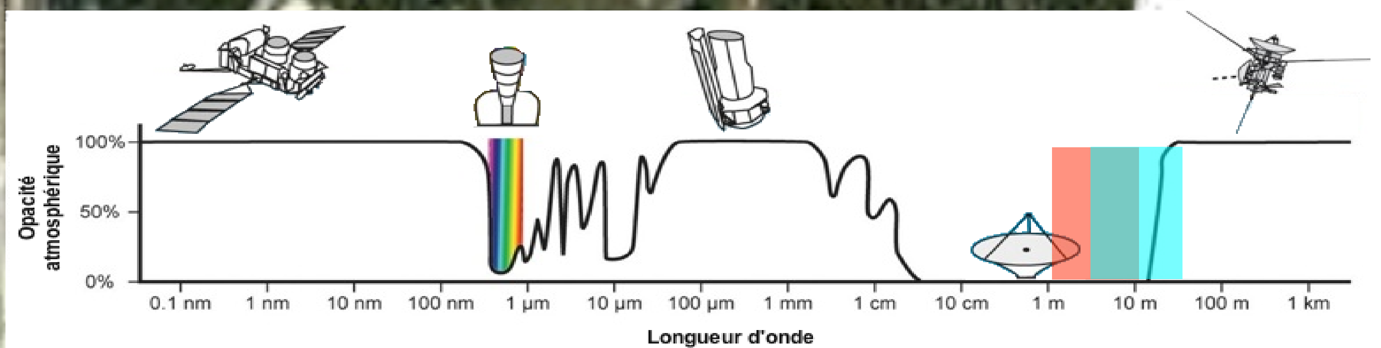
LOFAR



- 1824 Dutch + 1248 International LBA antennas / HBA tiles

From LOFAR … to NenuFAR





Motivations

- Interesting scientific «niches» for a large compact LF array :
    - more sensitivity at low / very low frequencies
    - more sensitivity to extended structures (short baselines)
    - compactness, large FoV, high sensitivity in beam formed mode

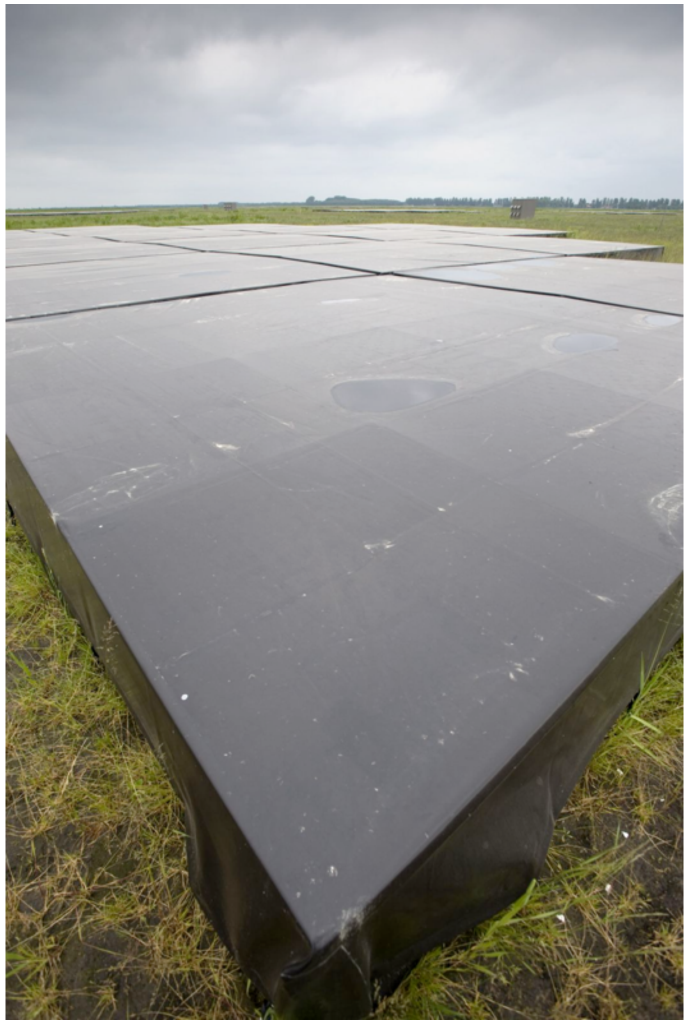
    ⇒ large programs : *pulsars & transients at LF, dark ages, exoplanets, active/flaring stars*

- Complementarity with LOFAR
    - enabling very high resolution in LBA with sensitive international baselines

- Developing the French LF radio community

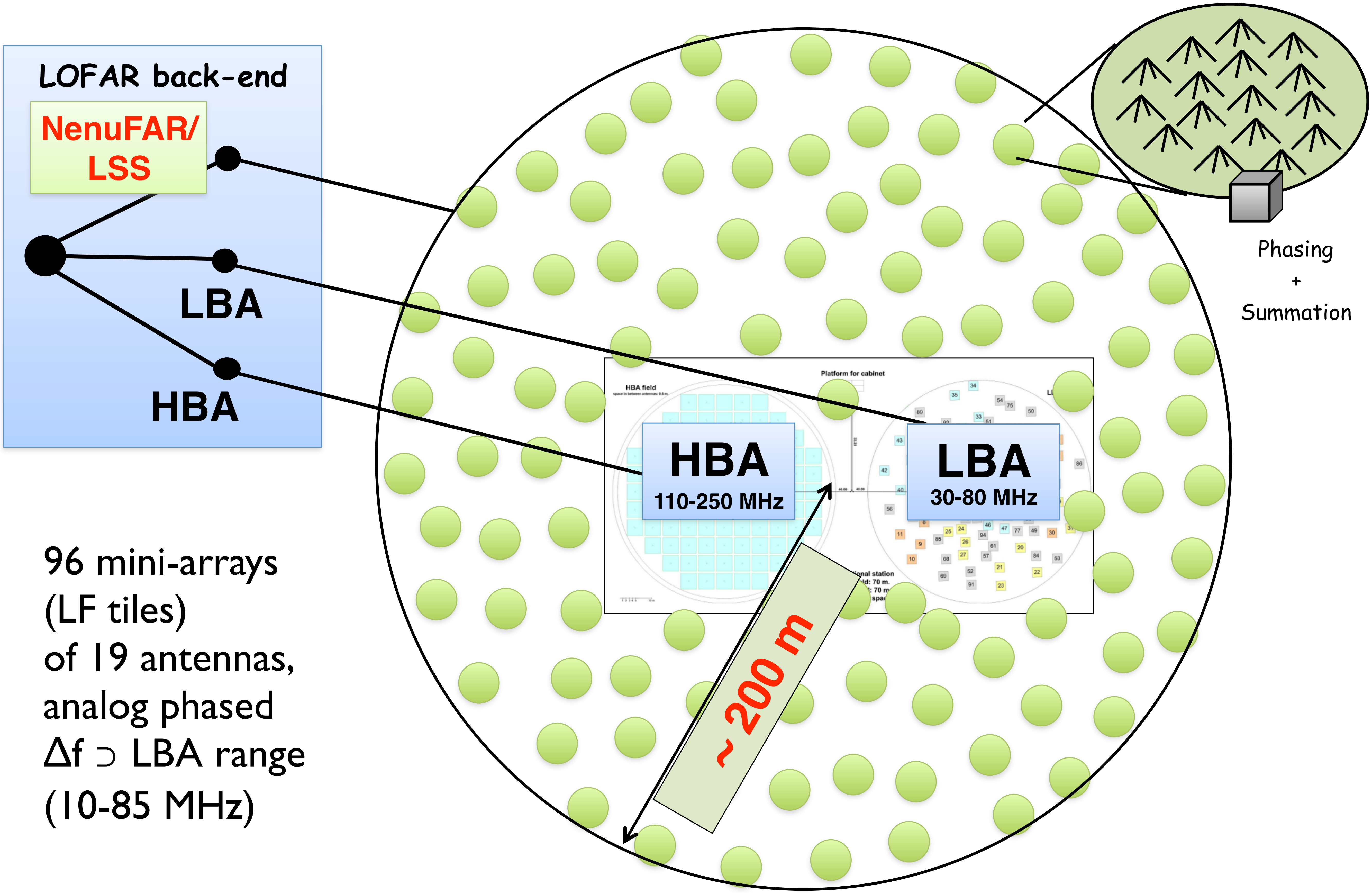
Concept

x



=

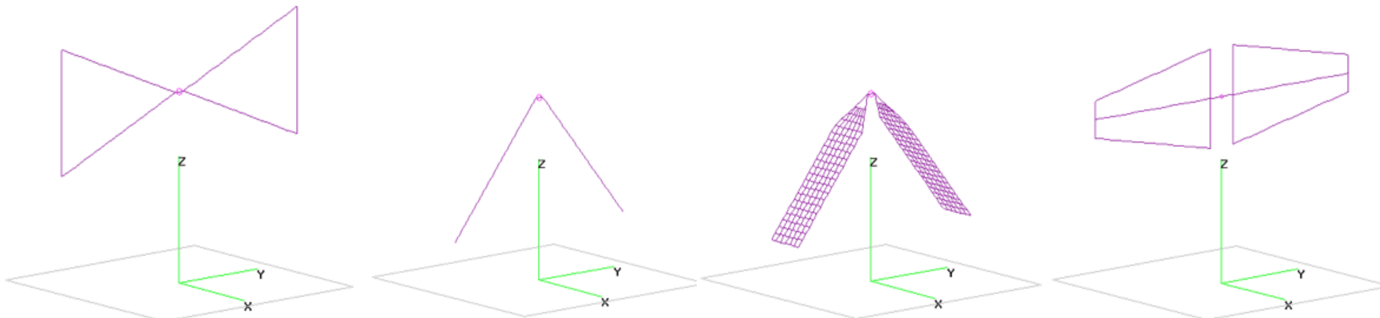
Initial idea : a LOFAR Super Station

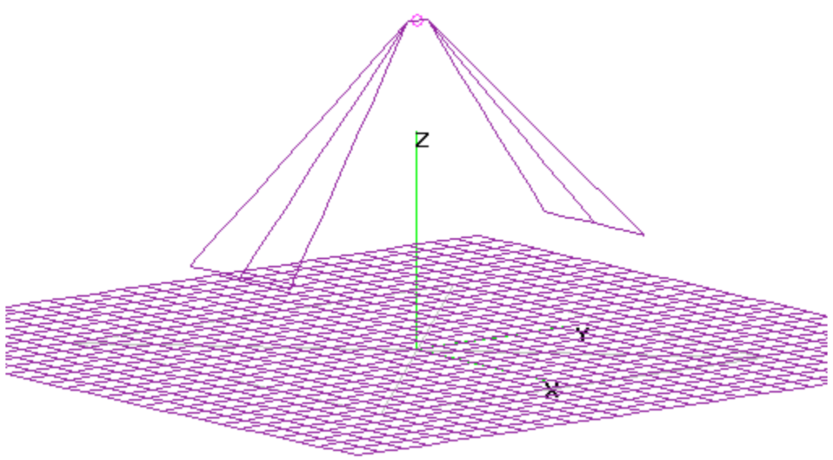


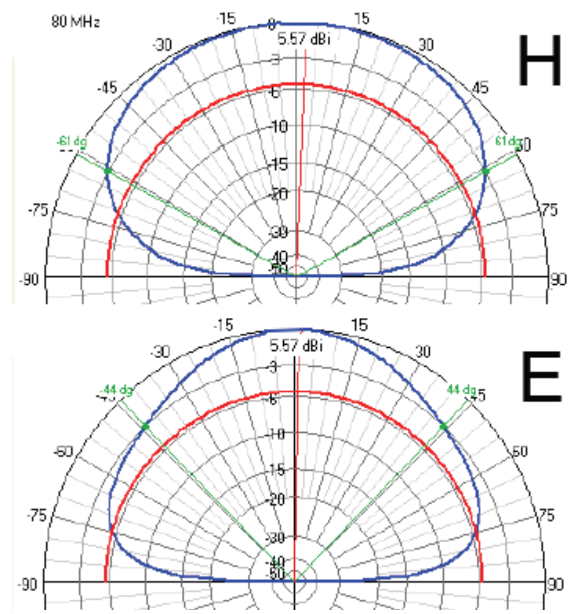
96 mini-arrays
(LF tiles)
of 19 antennas,
analog phased
$\Delta f \supset$ LBA range
(10-85 MHz)

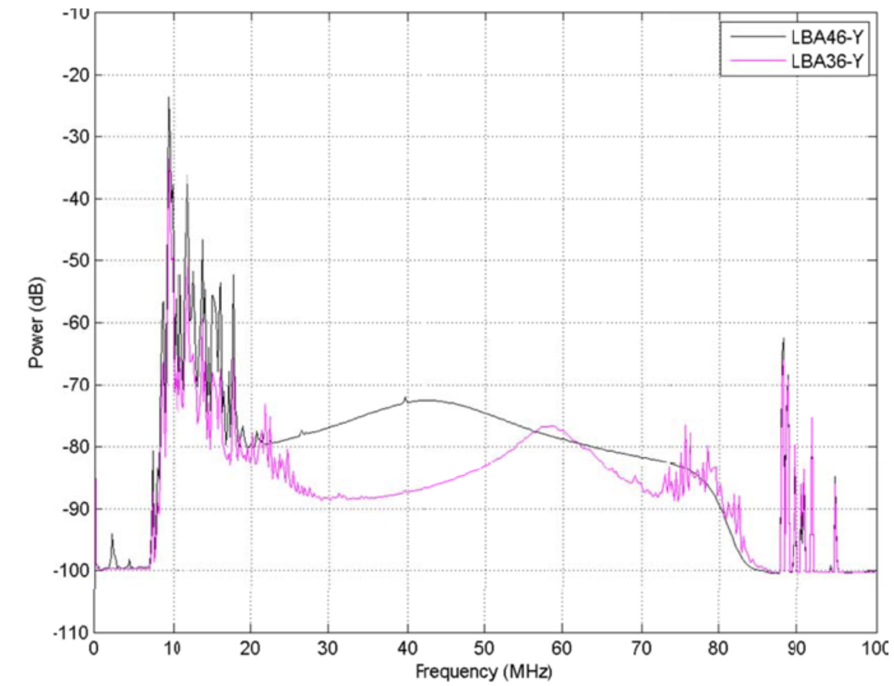
Designing / Prototyping

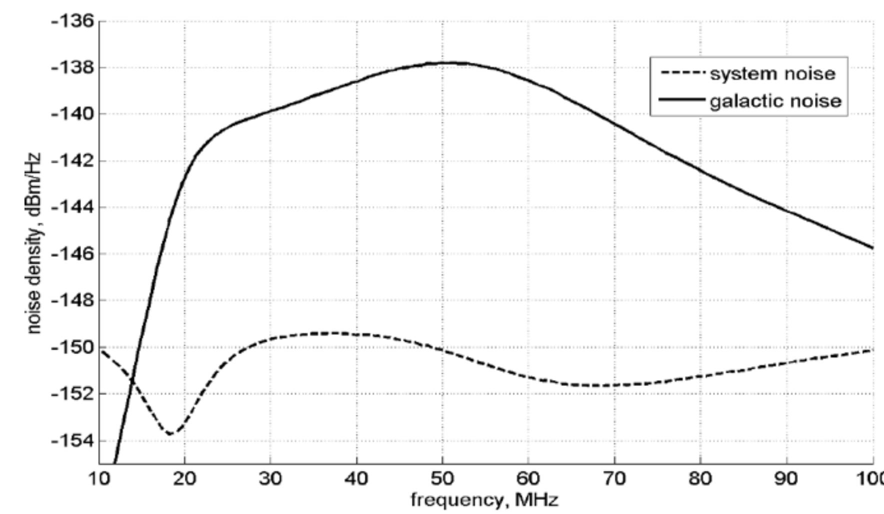
ANR 10/2009-2/2013, Nançay, Subatech, LESIA, LPC2E, Kharkov(PICS), ALSE & other subcontractors …

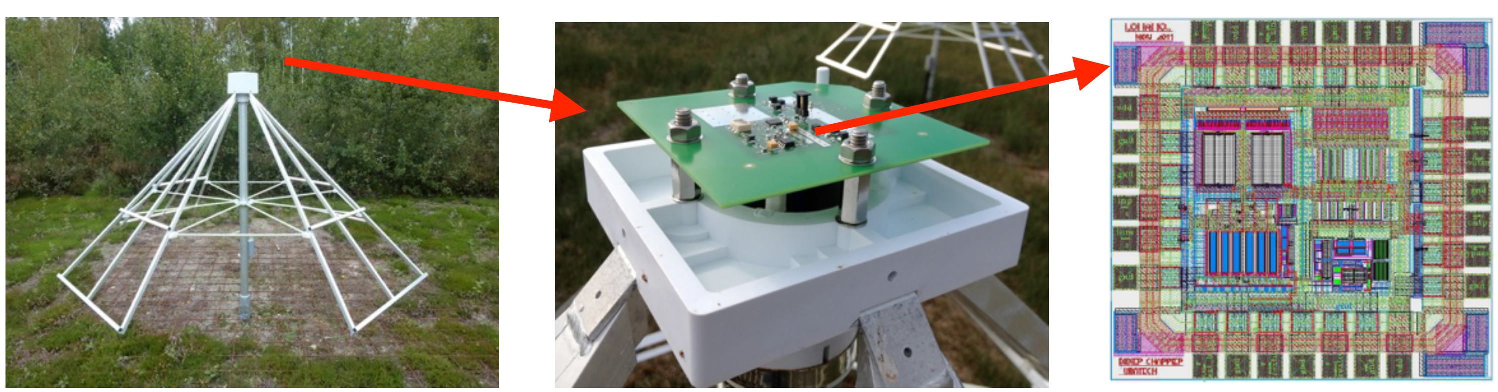








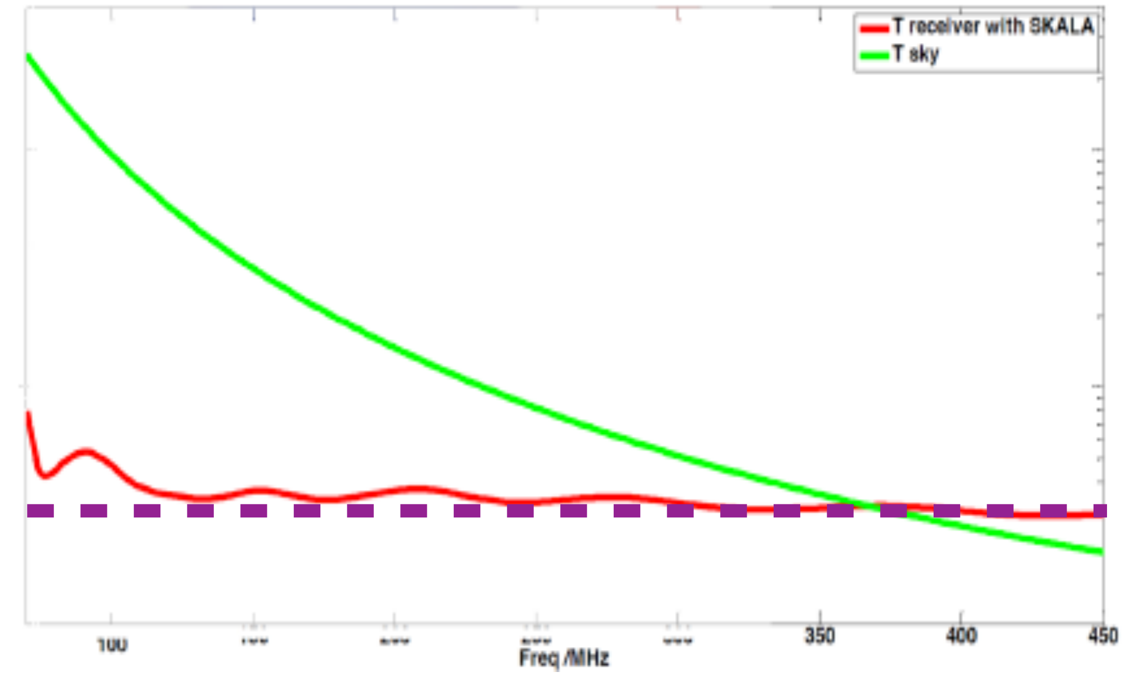




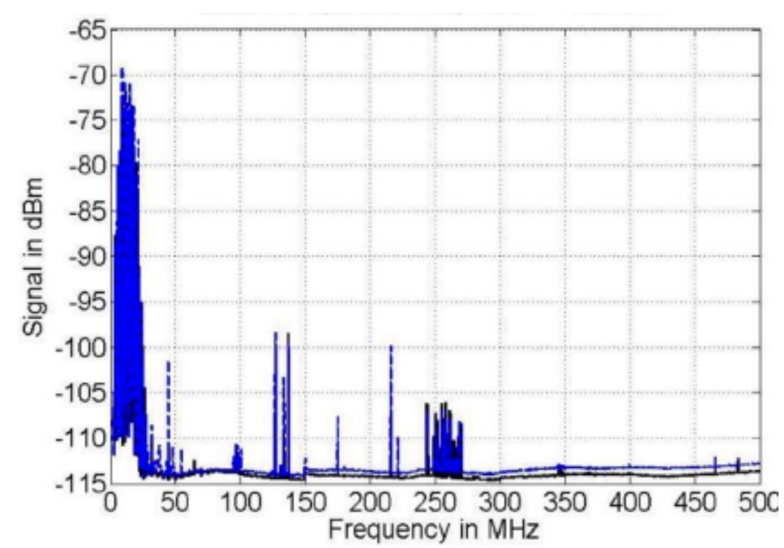
- Good LF antenna radiator, H & V polar [Hicks et al., 2012]
- Ground plane <u>needed</u> <100 MHz, esp. to avoid time variation of ground properties
- Good LNA response, consumption 70 mA x 9 V = 630 mW per channel

Possible implications for SKA-Low

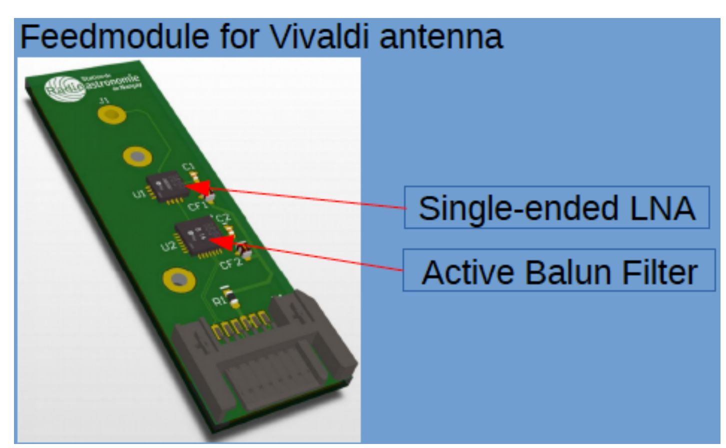
- Possible evolution toward a 50-500 MHz LNA in ASIC (SiGe, Si-on-Insulator), with low gain dispersion, low consumption (<160 mA x 5V = 800 mW), good linearity, cost-effective, smart (integrated phase corrector - Memphis project) ?

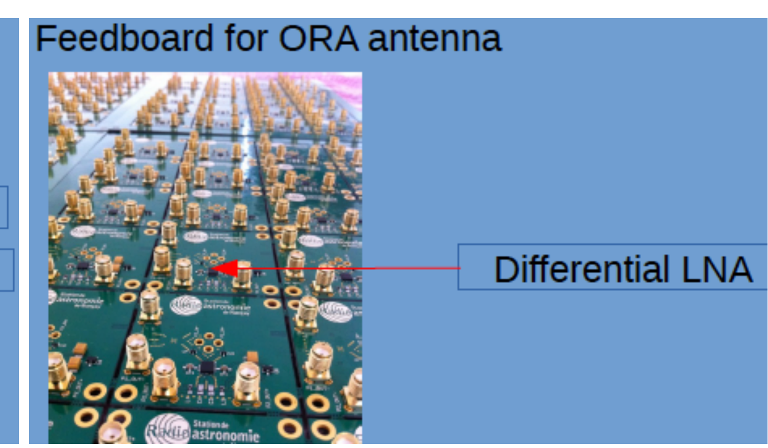


- Hi-pass filter behind antenna ?



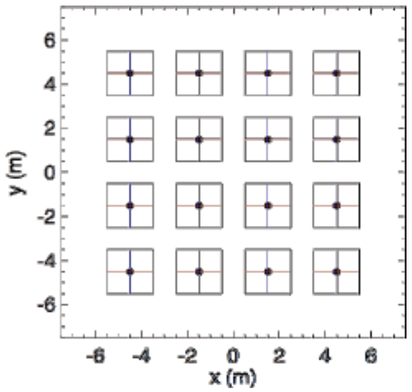
- Experience NenuFAR + Vivaldi antennas : possibility to design an integrated single-ended LNA (full feed board system, ASIC, analogue optical output link)

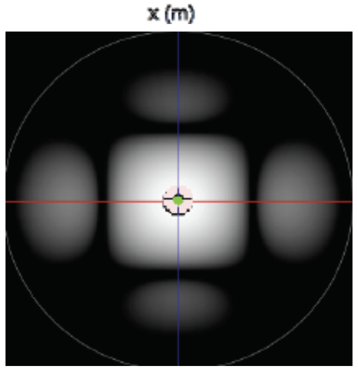




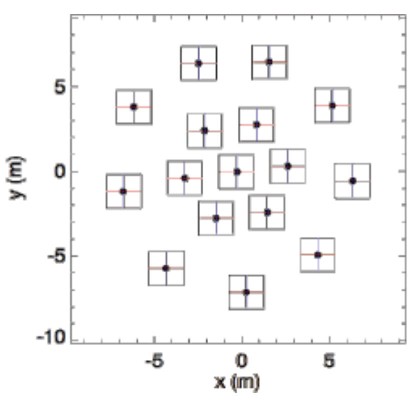
Designing / Prototyping

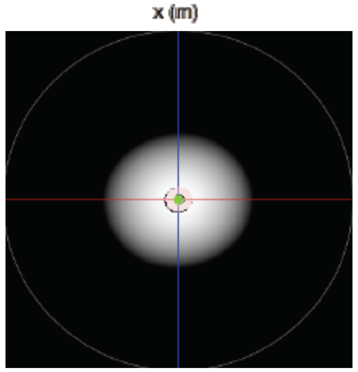
40 MHz



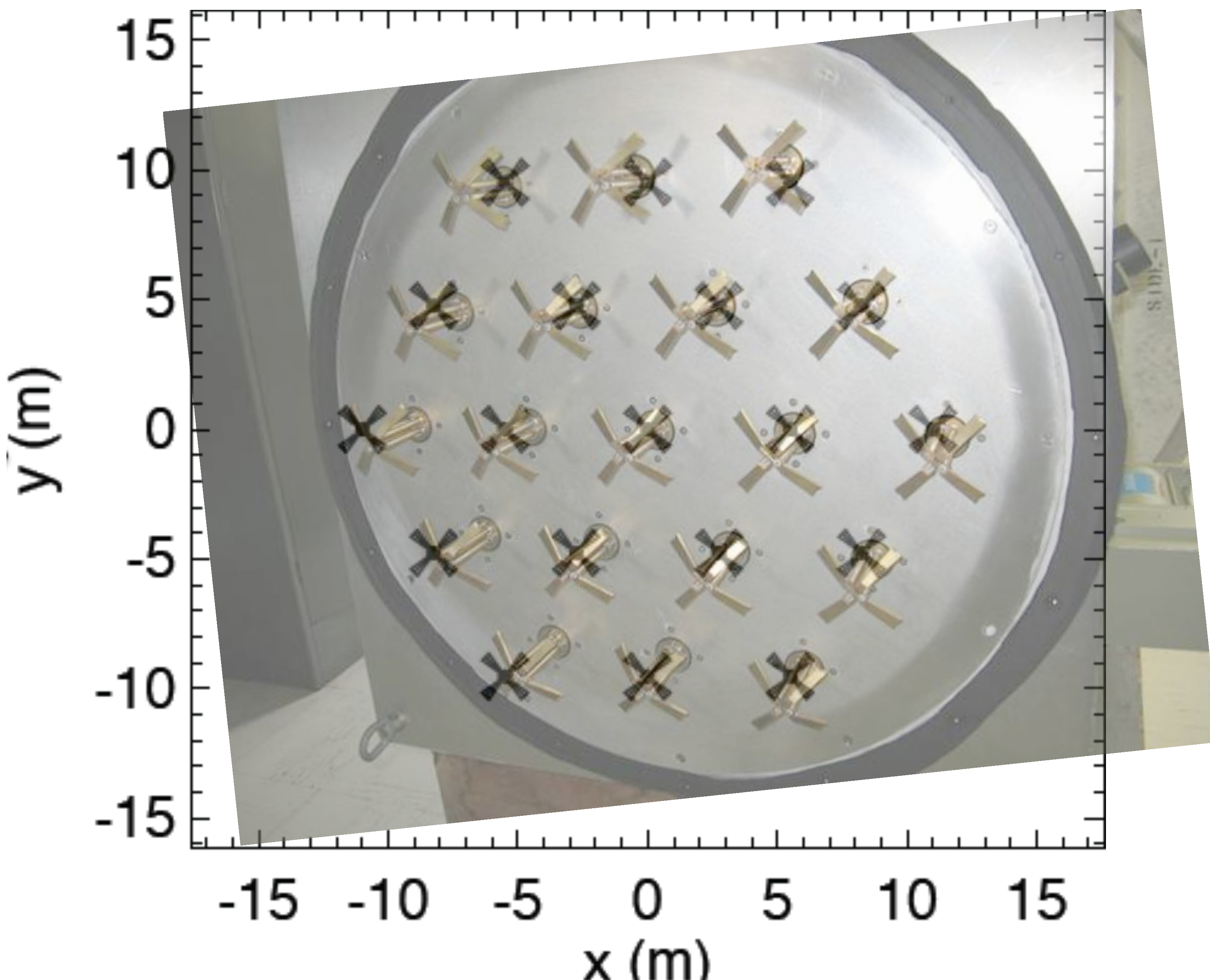


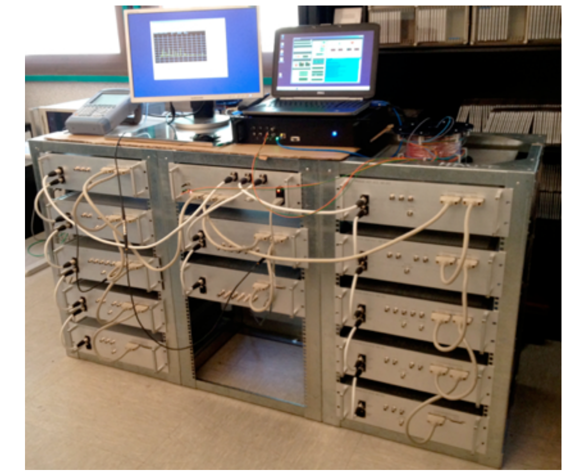
-15 dB sidelobes





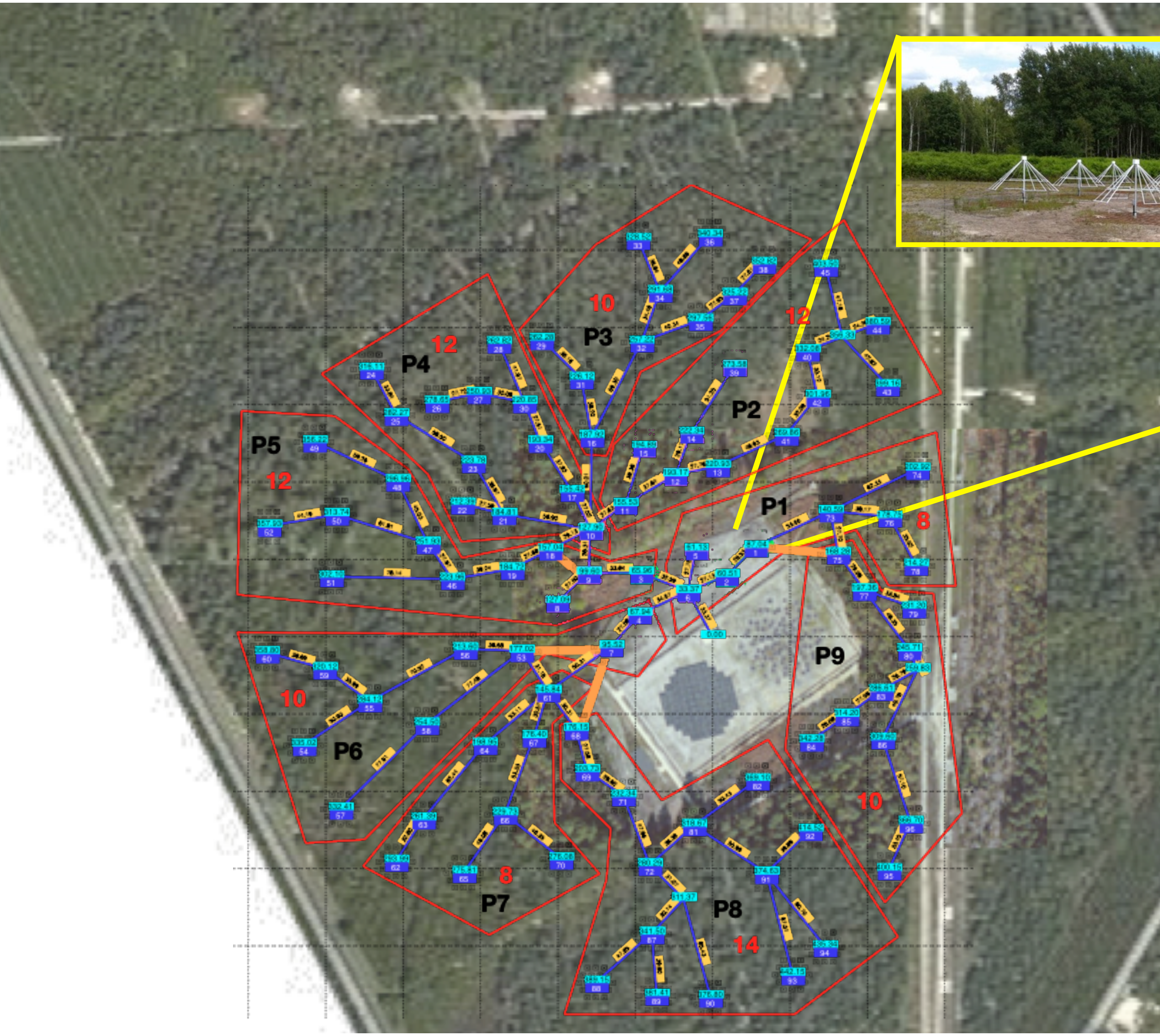
-32 dB sidelobes

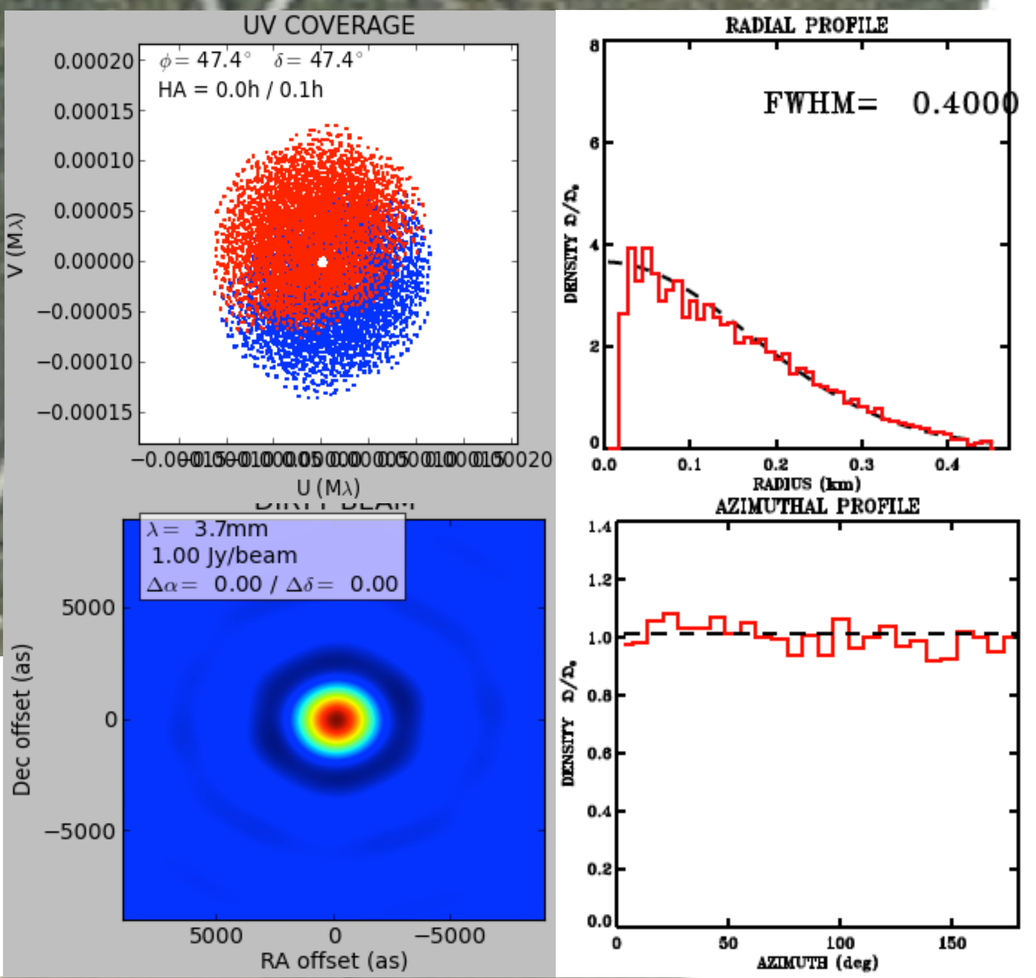




- Optimized antenna distribution within Mini-Arrays

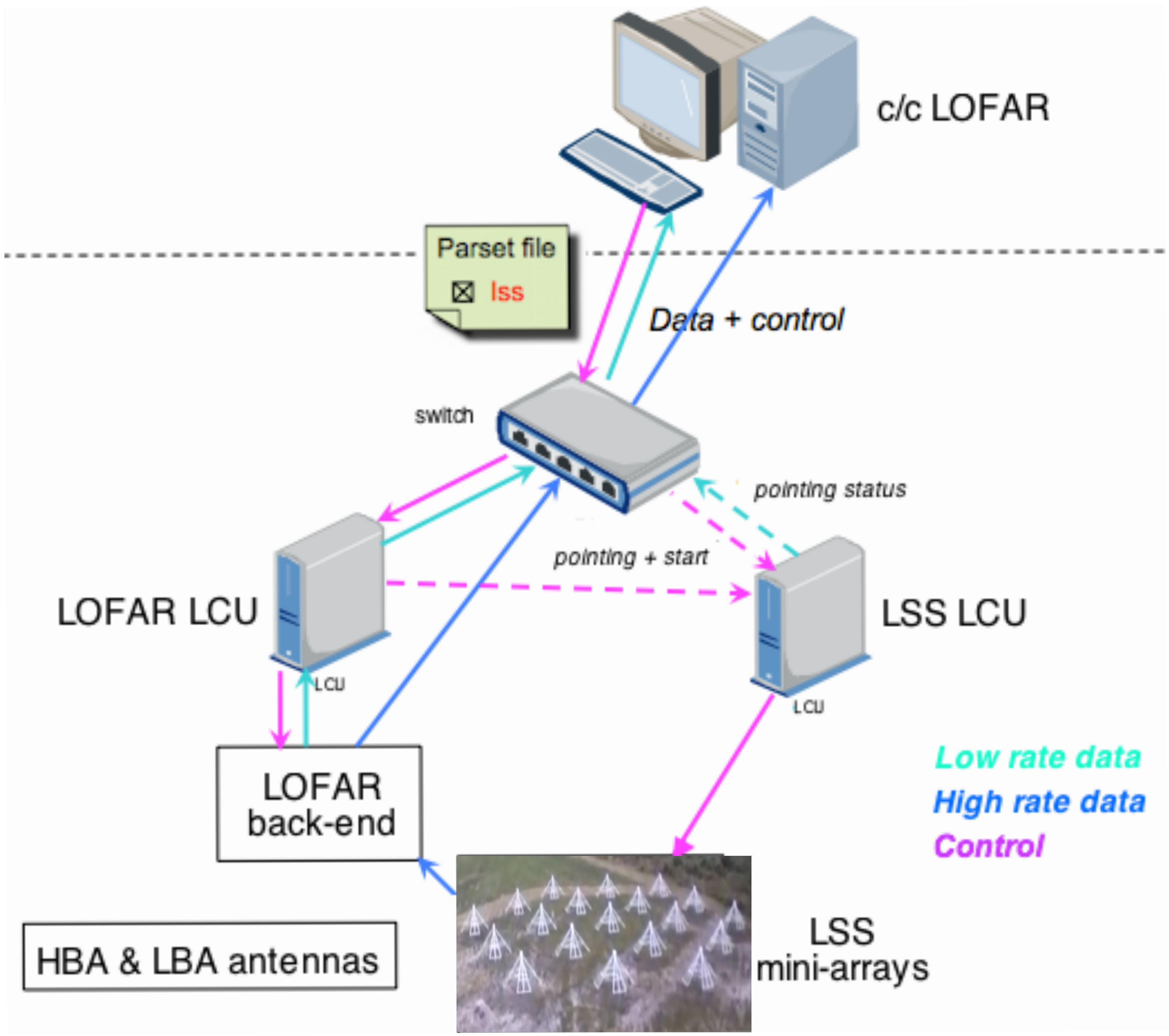
Designing / Prototyping



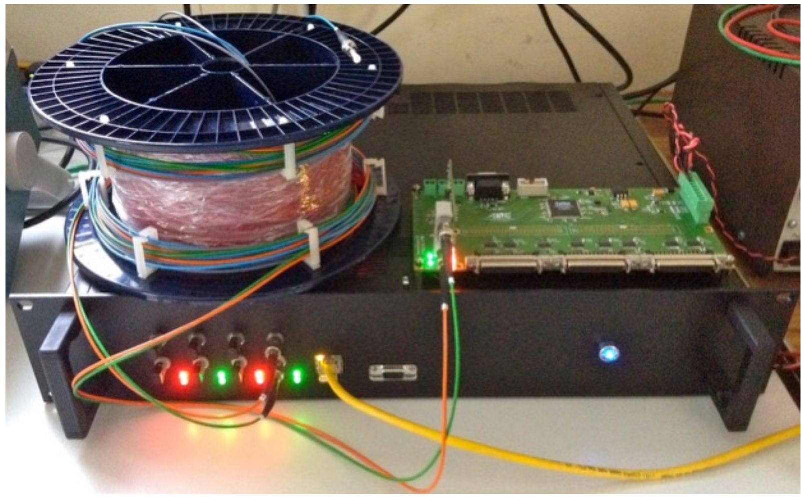


- Global design optimized for 96 MA, incl. MA rotations
- Trenches/cables optimization [Vasko et al., 2016]
- Construction in 9 petals
- Total electrical consumption ~50 kW

Designing / Prototyping



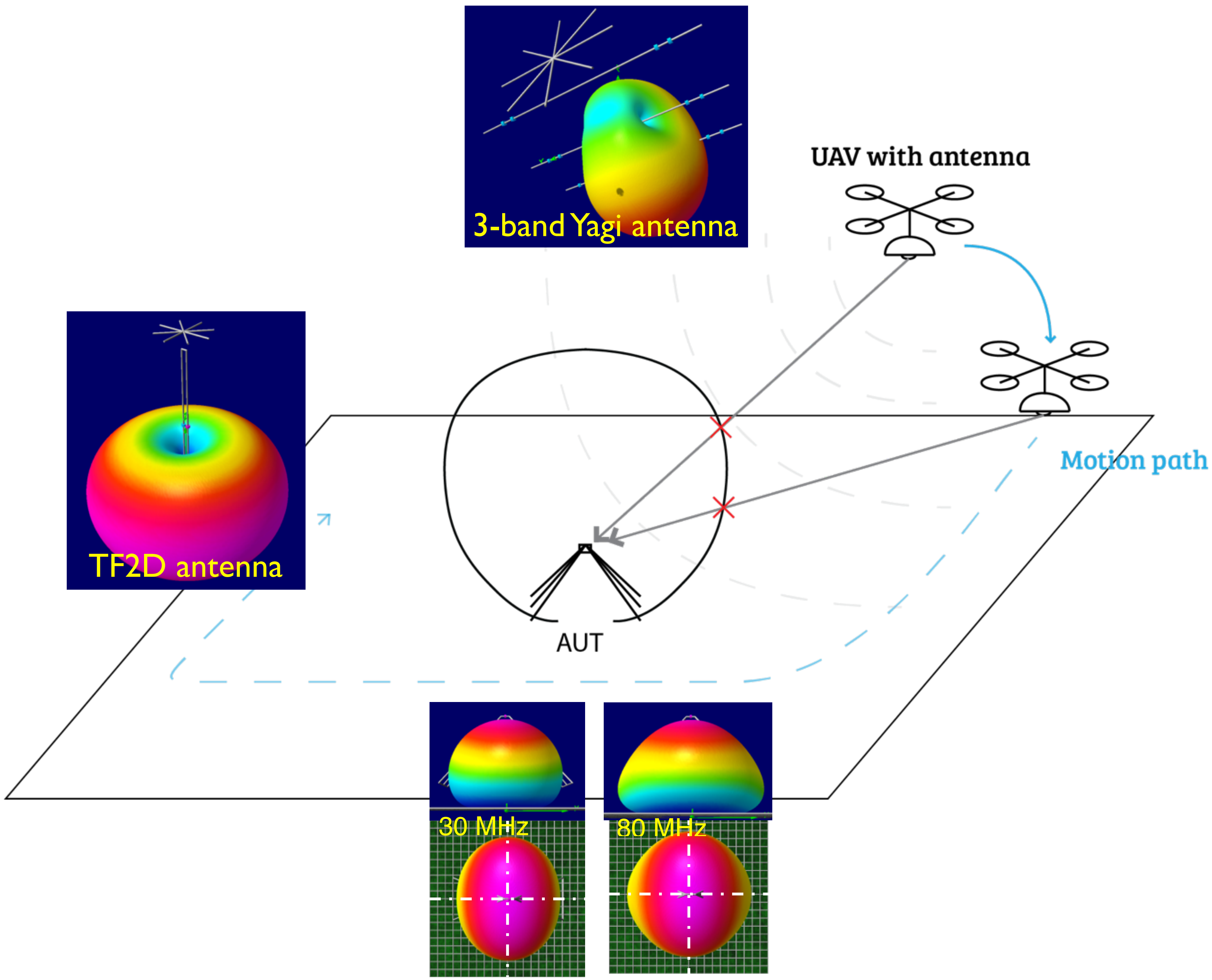
dialog with LOFAR/ASTRON



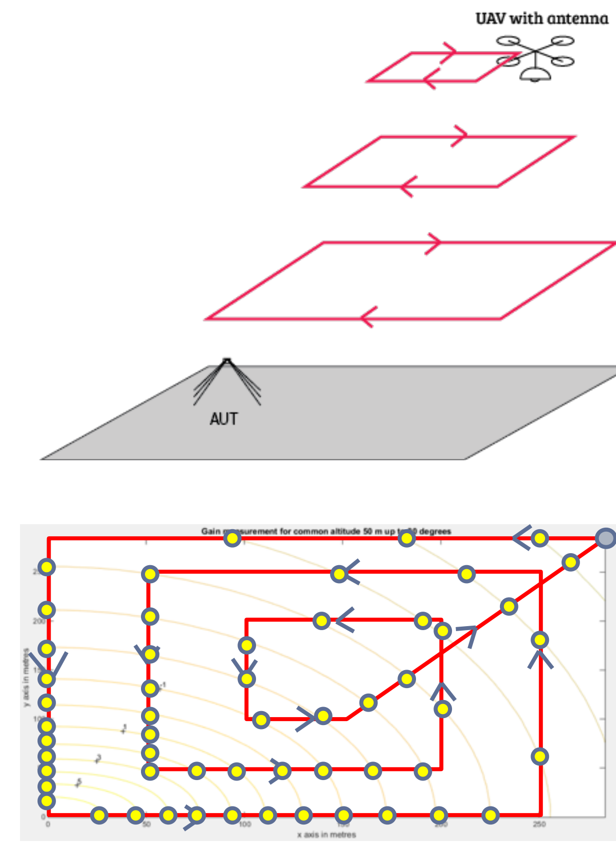
silent c/c system

- Silent control/command system
- Pointing protocol : analog phasing switches distributed over a few msec at round multiples of 10 sec.

Testing

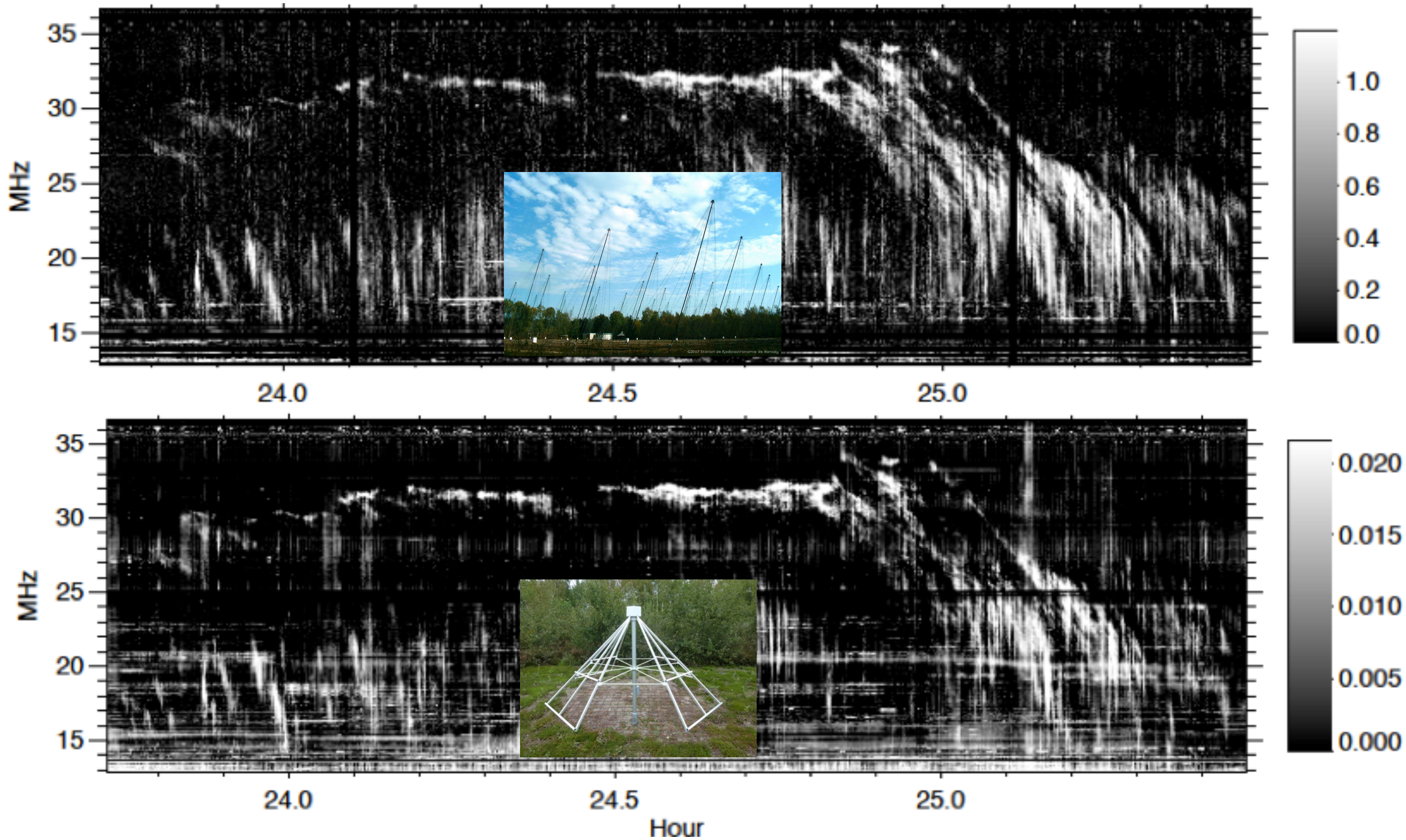


Height: 50 m, 50/70/90 m
Flight distance: ~2000m
Flight time: ~12min 30sec

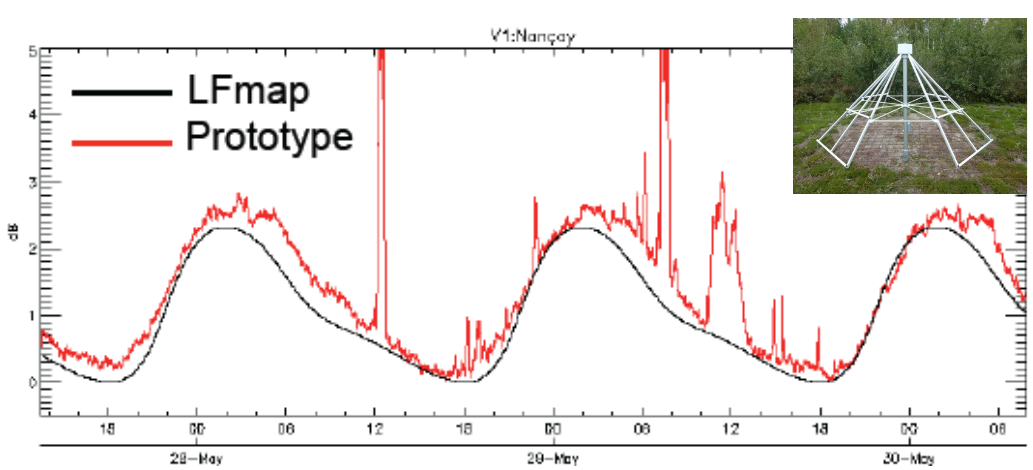


- Drone measurements of antenna (far-field ≥10’s m) and mini-array (far-field >500 m) patterns (ONERA - *ongoing*)

Testing



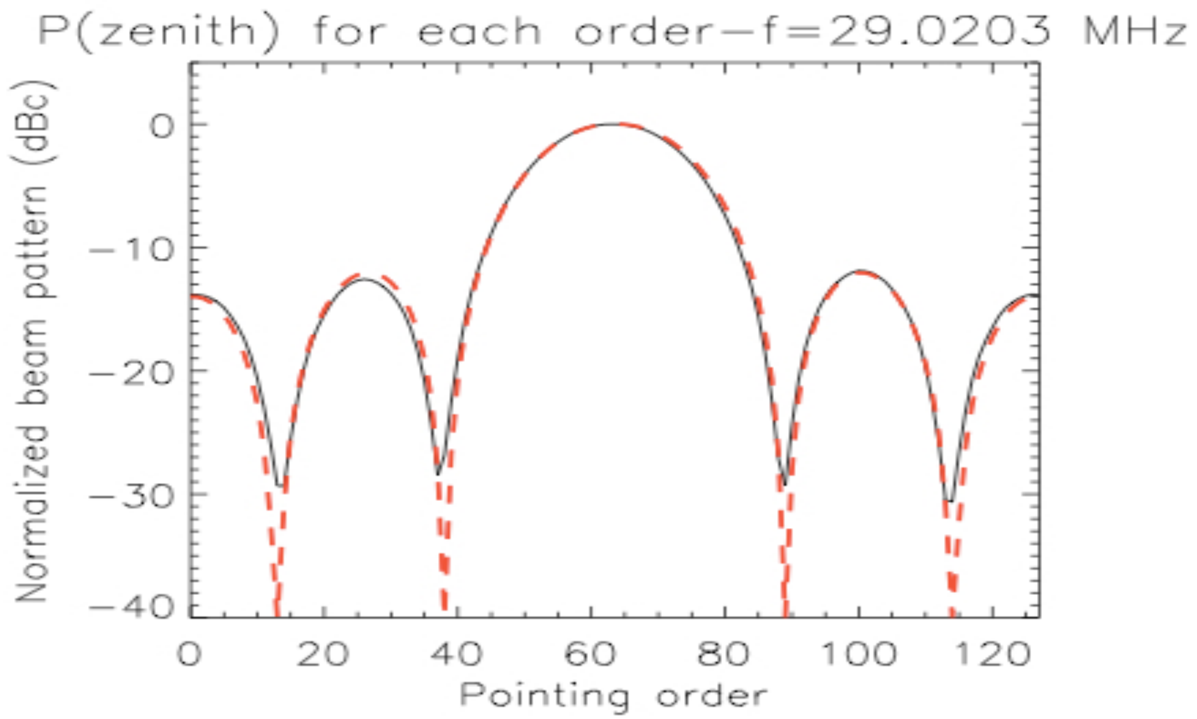
Jupiter

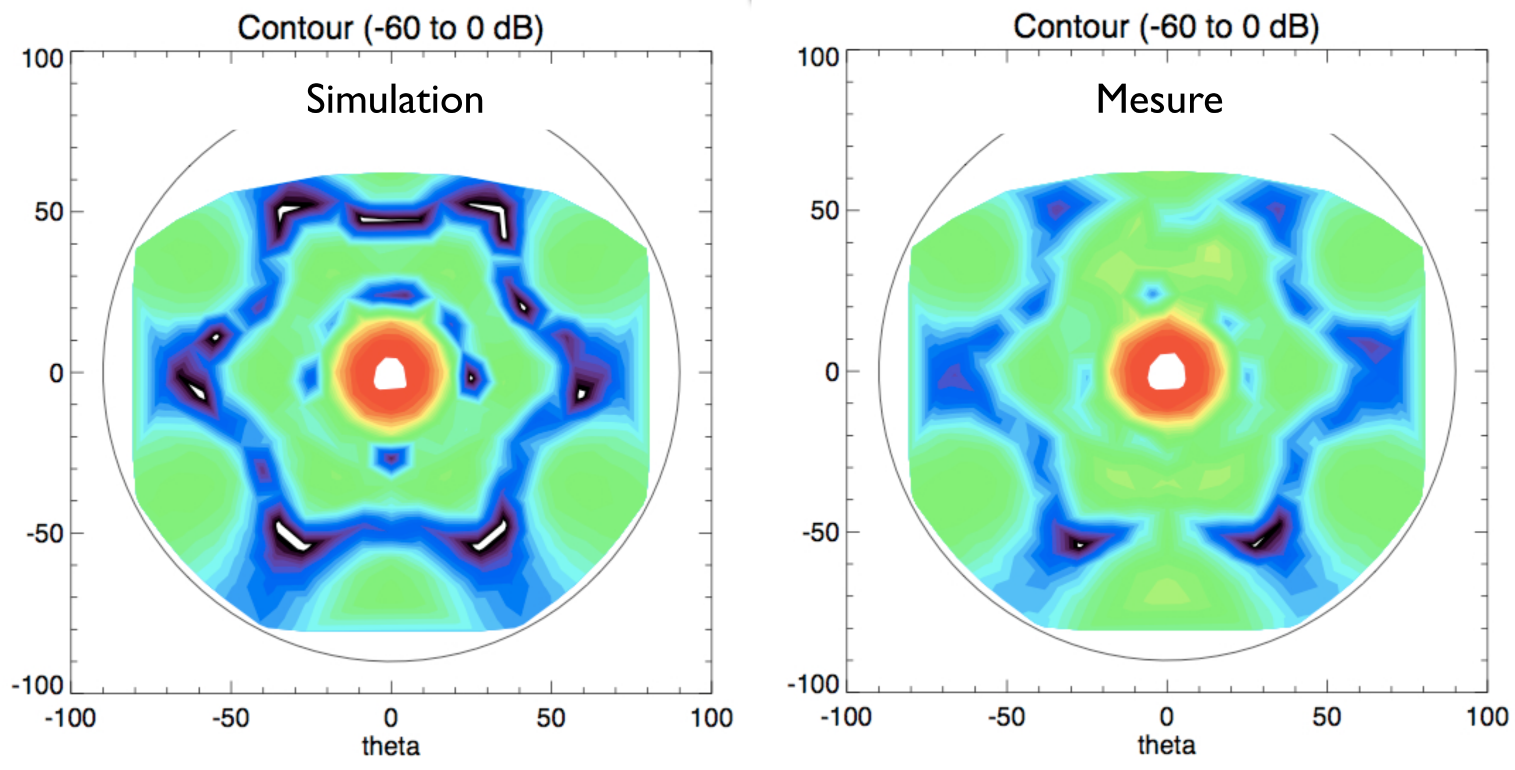


Galaxy

- Antenna + preamplifier on the sky

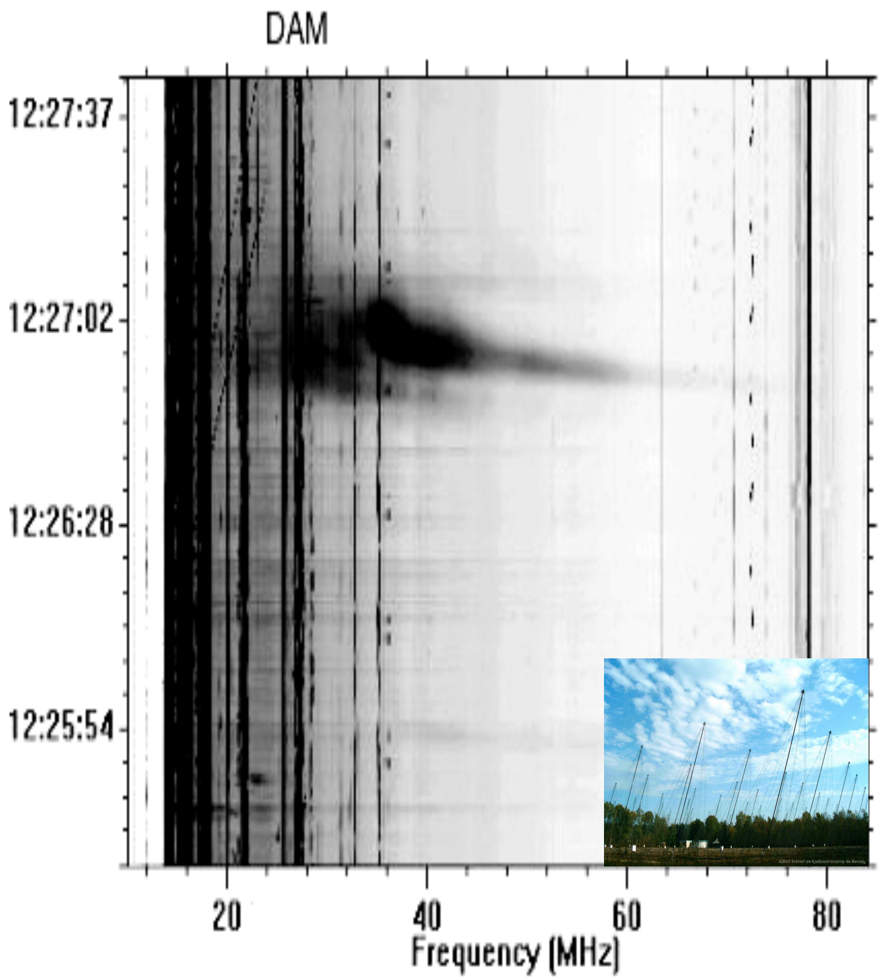
Testing

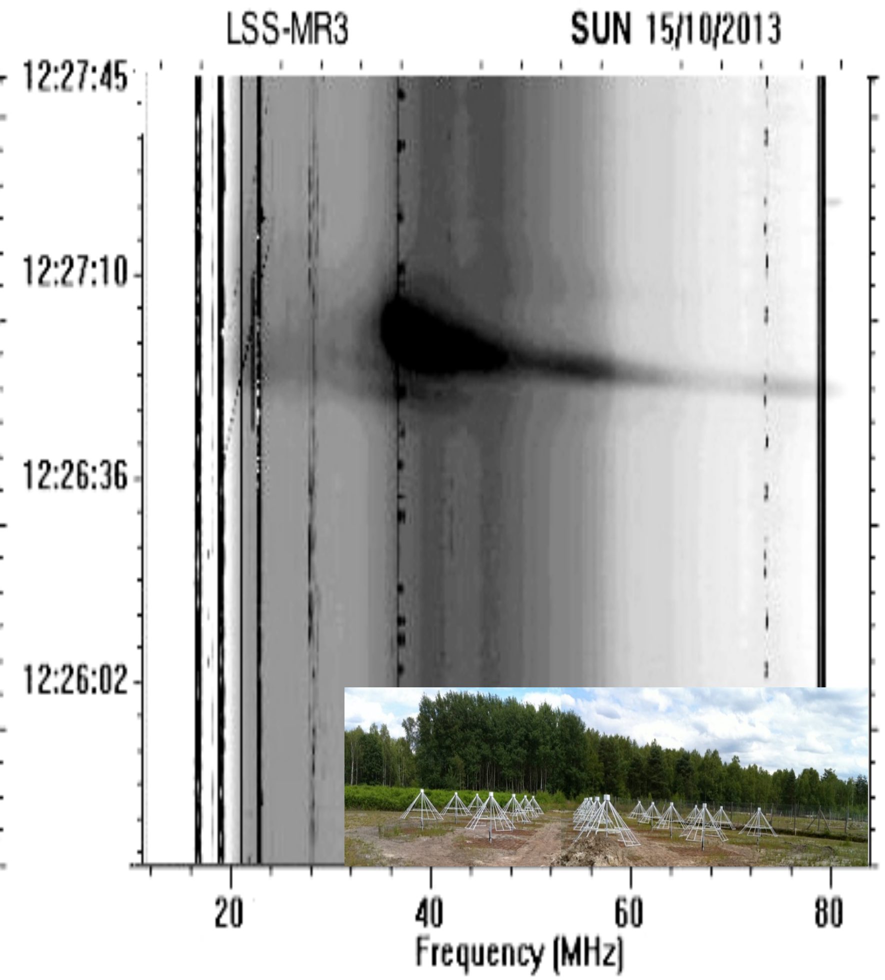




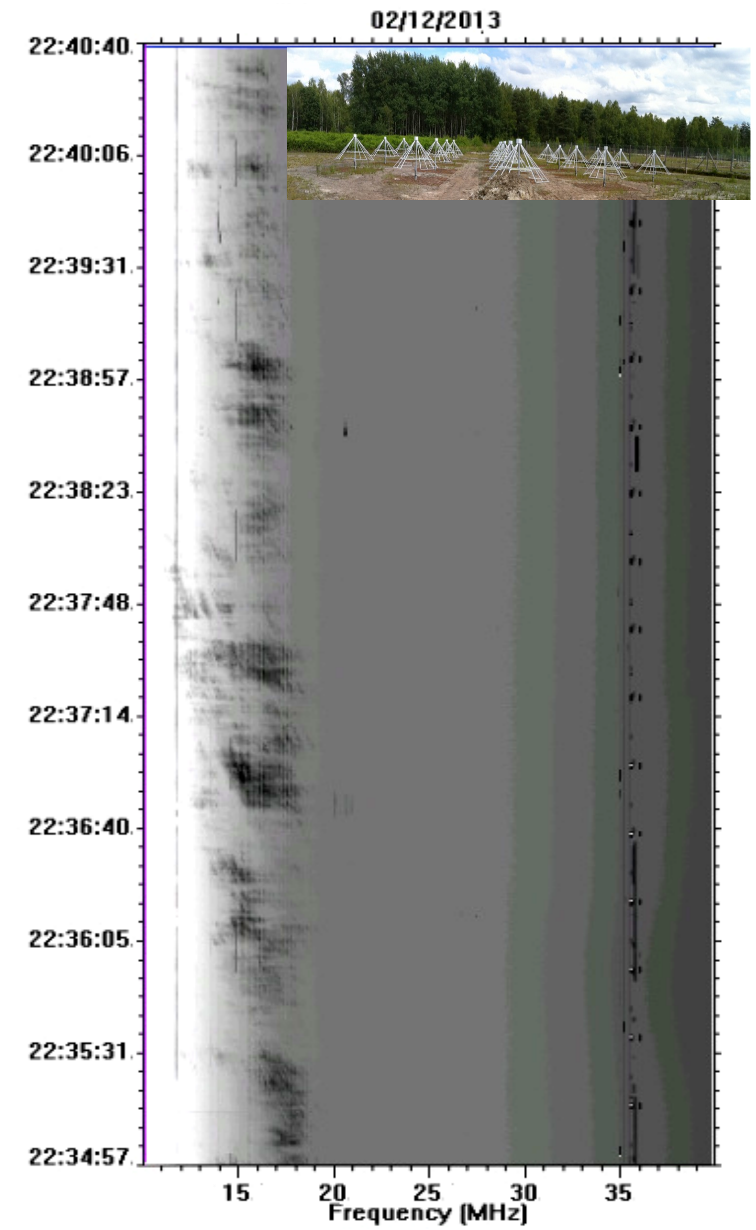
- Phasing system : simulation + laboratory

Testing





Sun

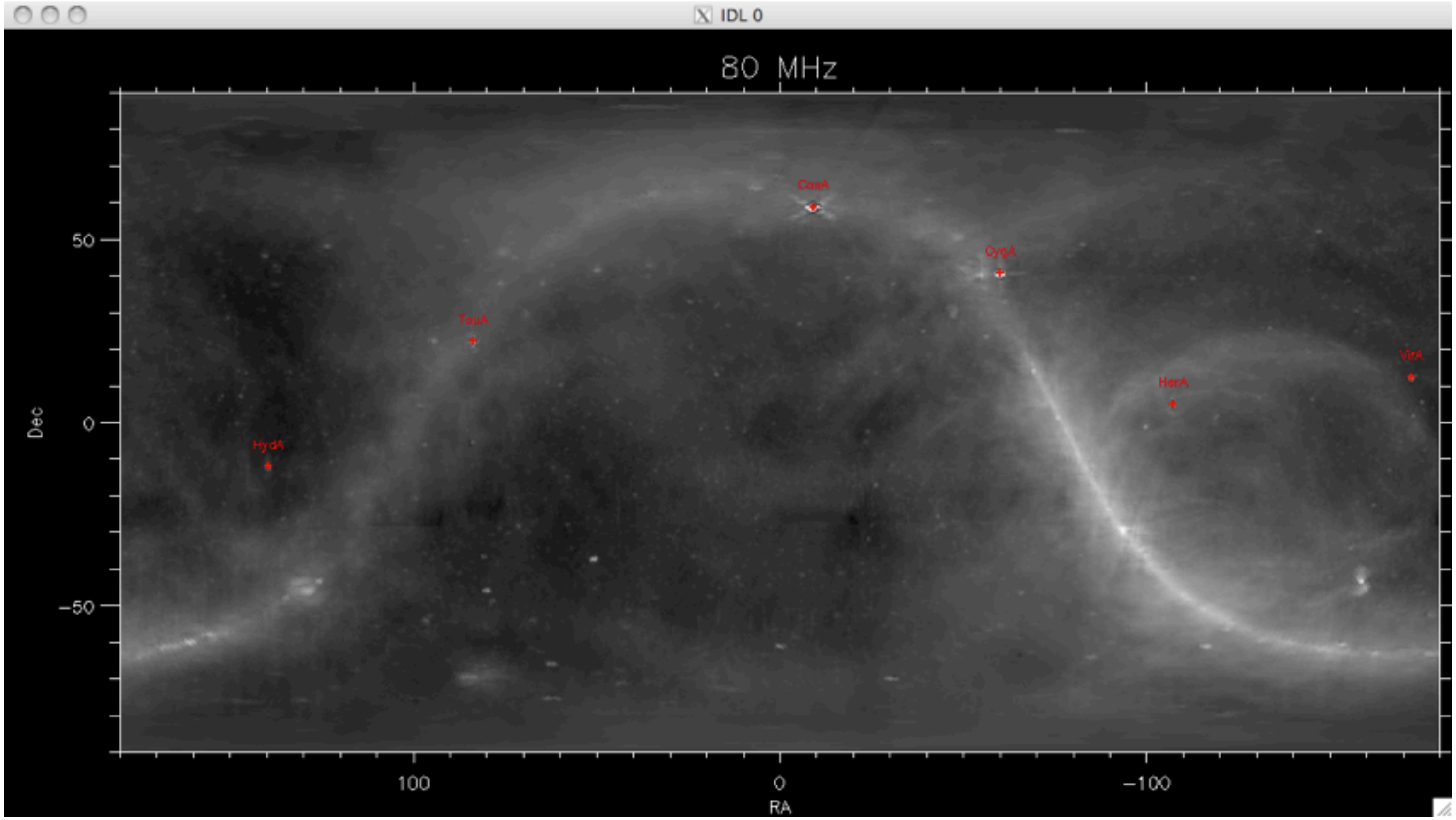


Jupiter

- Phased mini-array on the sky

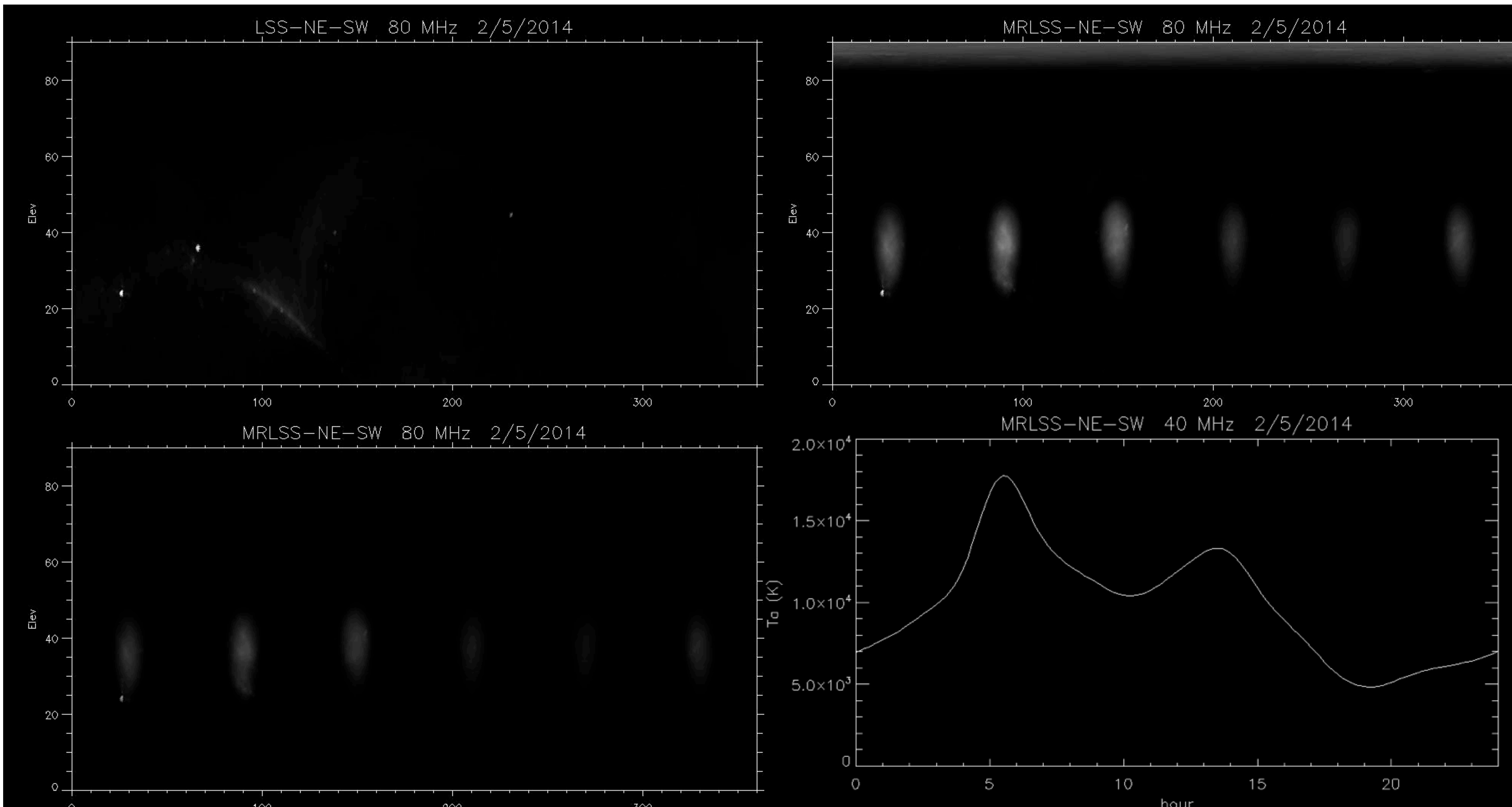
Testing

Galaxy (LF map)



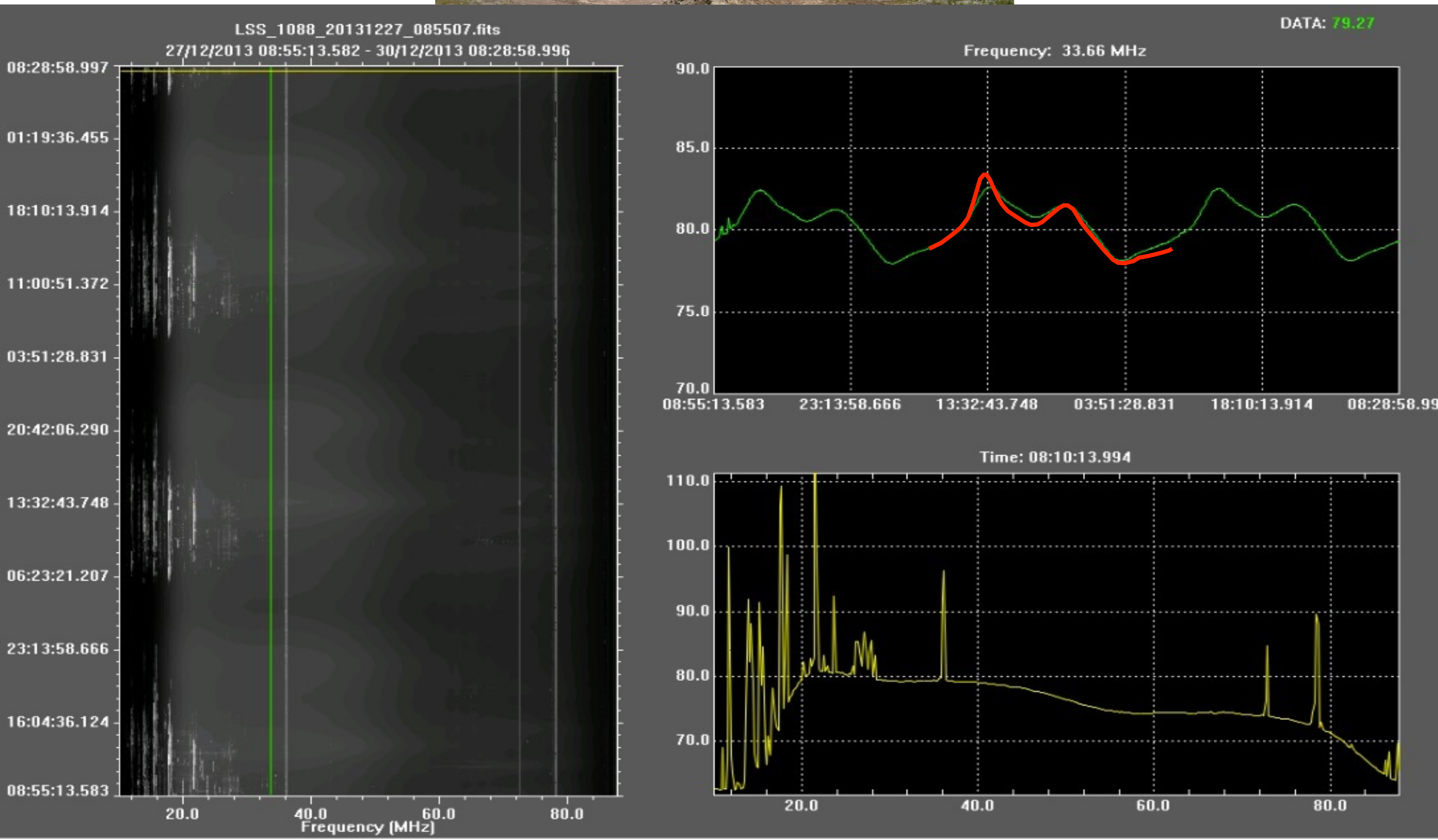
- Phased mini-array on the sky

Testing



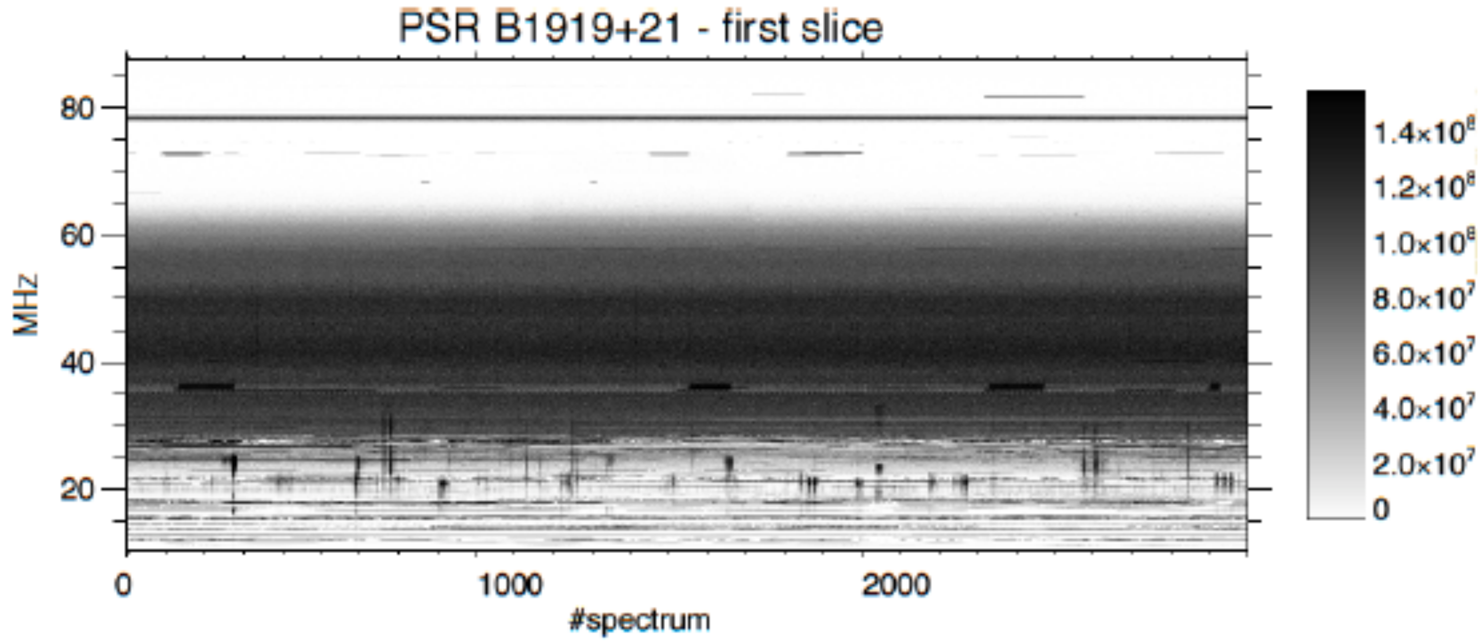
LSS–NE–SW 80 MHz 2/5/2014
MRLSS–NE–SW 80 MHz 2/5/2014
MRLSS–NE–SW 80 MHz 2/5/2014
MRLSS–NE–SW 40 MHz 2/5/2014
Elev
Ta (K)
hour

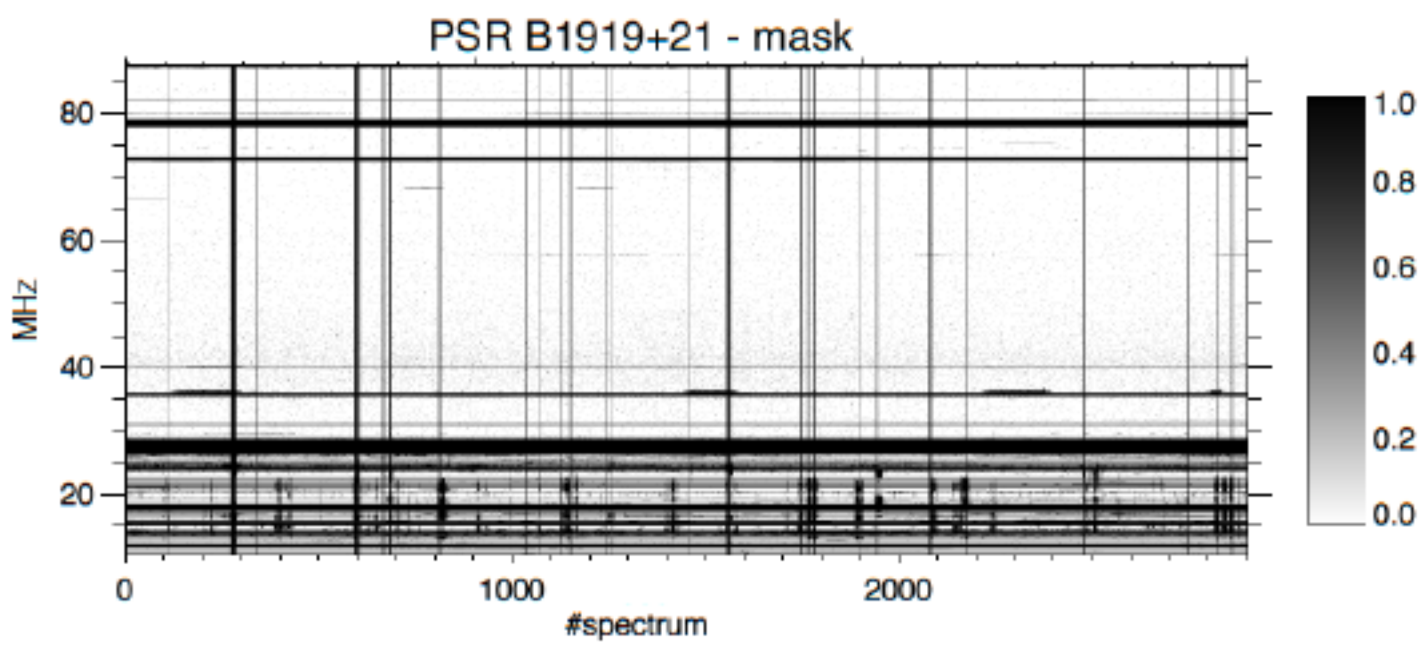
Testing

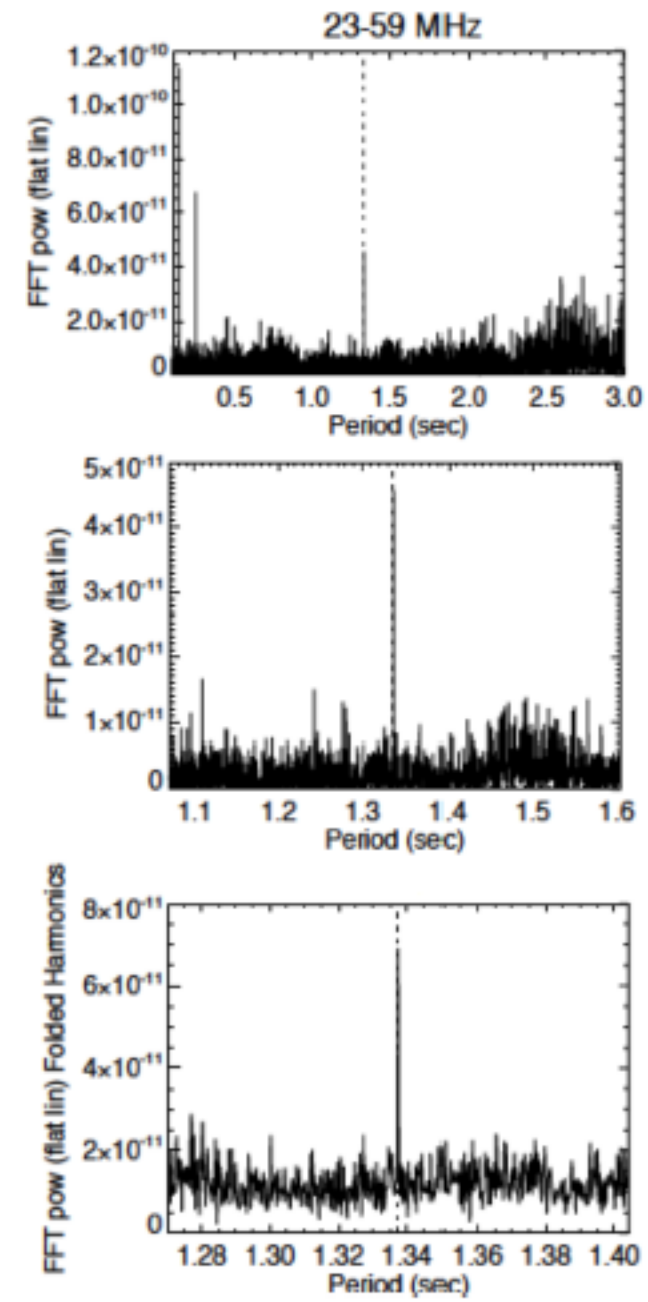


LSS_1088_20131227_085507.fits
27/12/2013 08:55:13.582 - 30/12/2013 08:28:58.996
08:28:58.997
01:19:36.455
18:10:13.914
11:00:51.372
03:51:28.831
20:42:06.290
13:32:43.748
06:23:21.207
23:13:58.666
16:04:36.124
08:55:13.583
20.0
40.0
60.0
80.0
Frequency (MHz)
DATA: 79.27
Frequency: 33.66 MHz
90.0
85.0
80.0
75.0
70.0
08:55:13.583
23:13:58.666
13:32:43.748
03:51:28.831
18:10:13.914
08:28:58.99
Time: 08:10:13.994
110.0
100.0
90.0
80.0
70.0
20.0
40.0
60.0
80.0

Testing

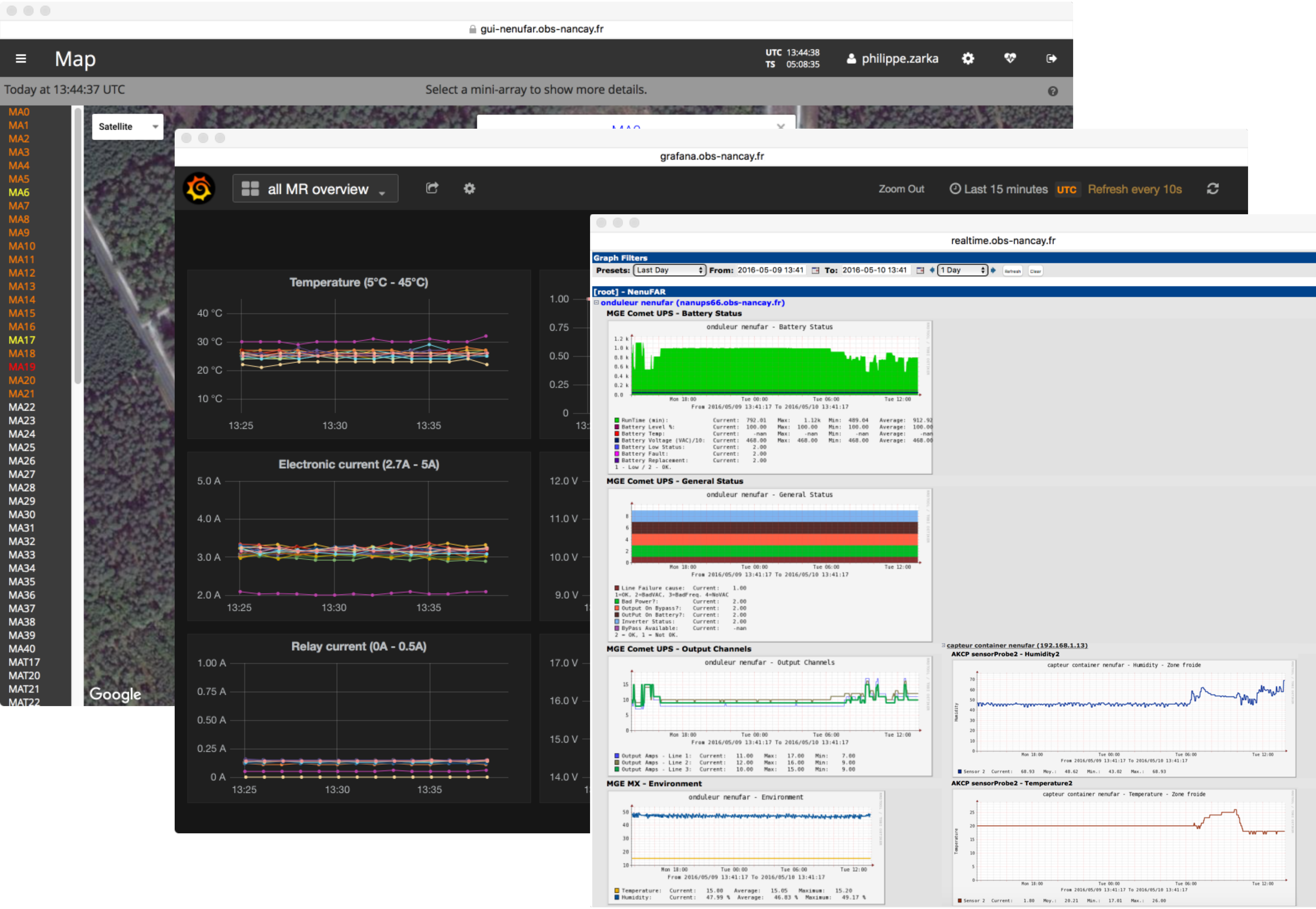




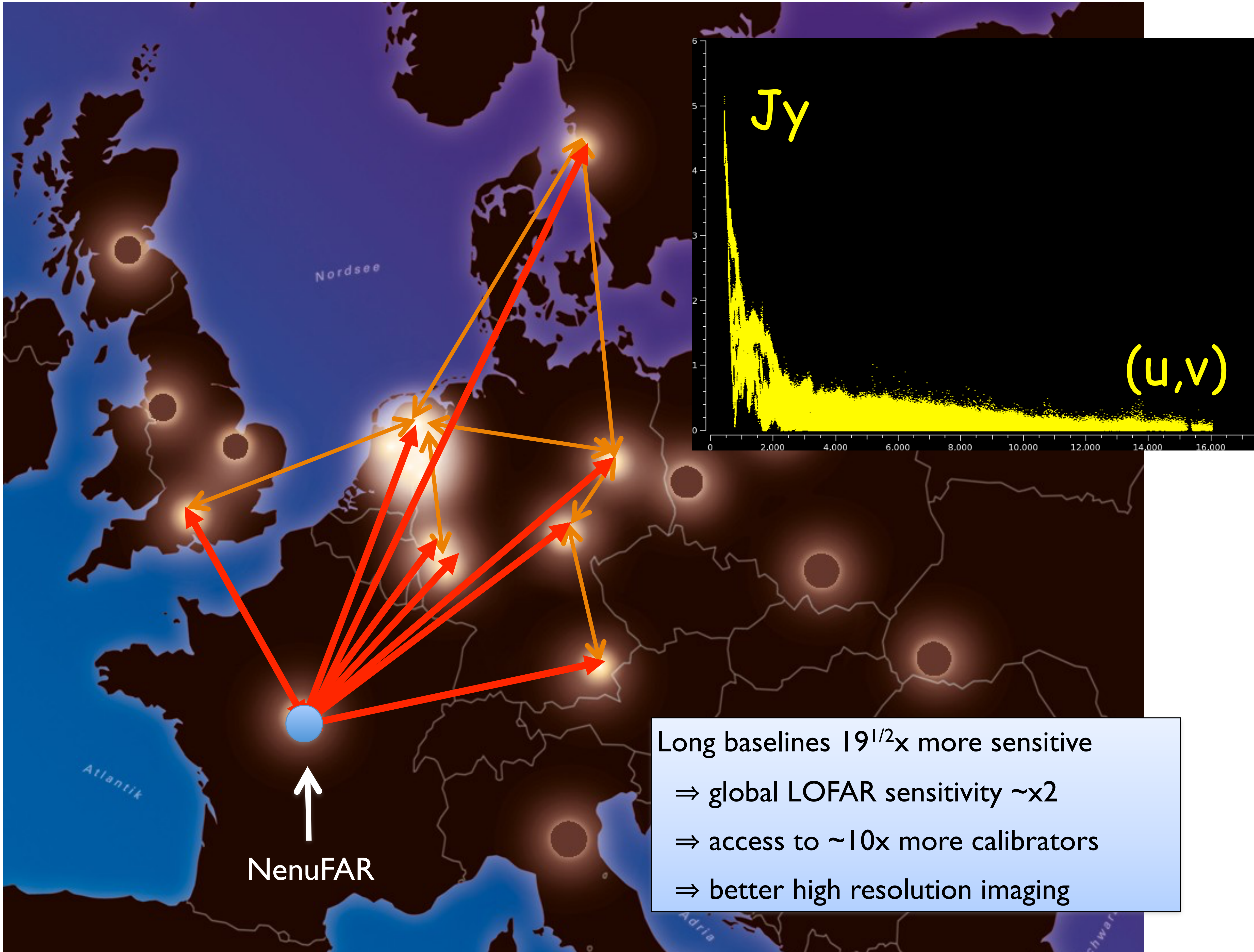


- 2-hour observation of PSR1919+21 (0.5 - 2 Jy) with the incoherent sum of 6 MA

Online Realtime Monitoring



What NenuFAR/LSS will bring



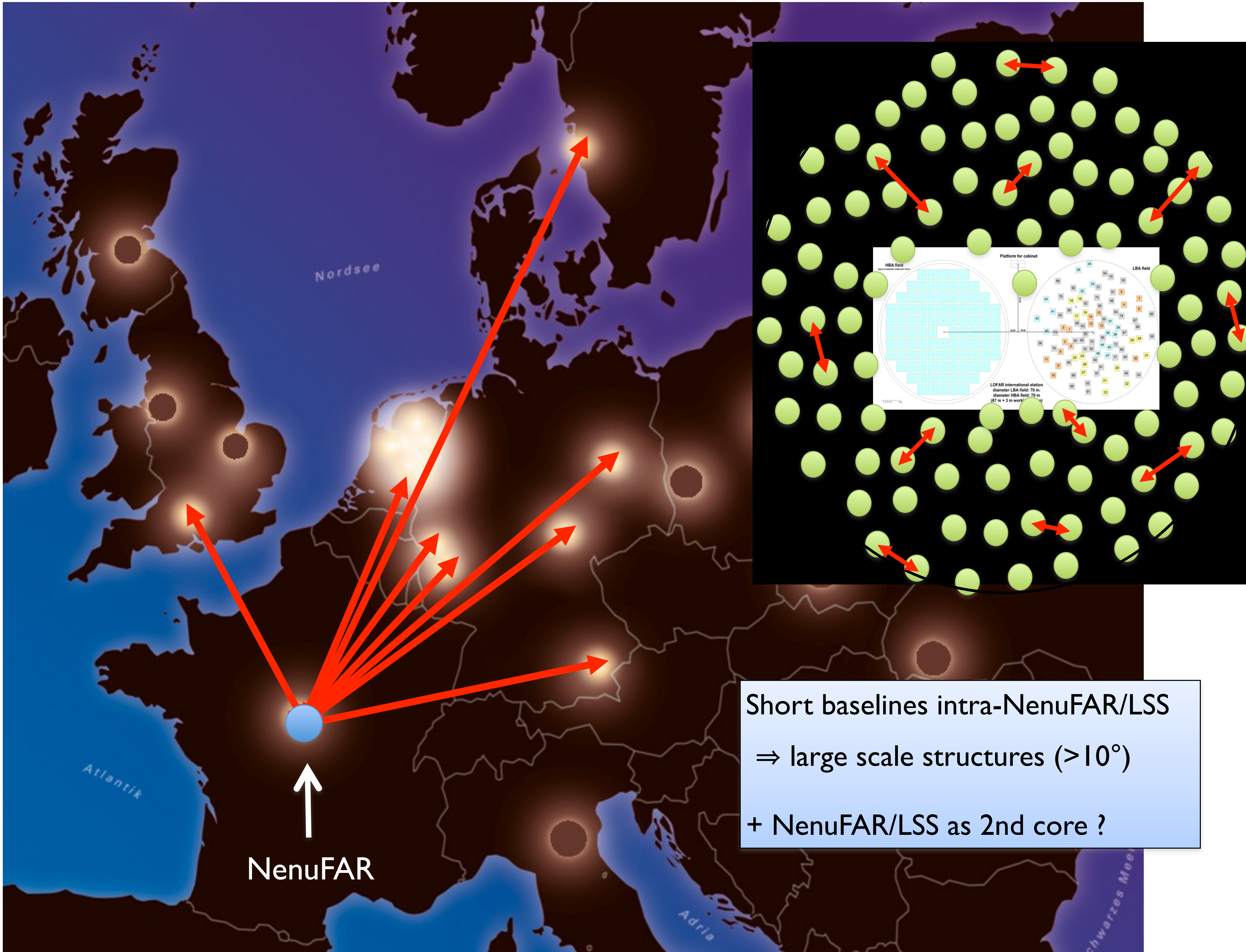
Long baselines $19^{1/2}$x more sensitive

⇒ global LOFAR sensitivity ~x2

⇒ access to ~10x more calibrators

⇒ better high resolution imaging

What NenuFAR/LSS will bring

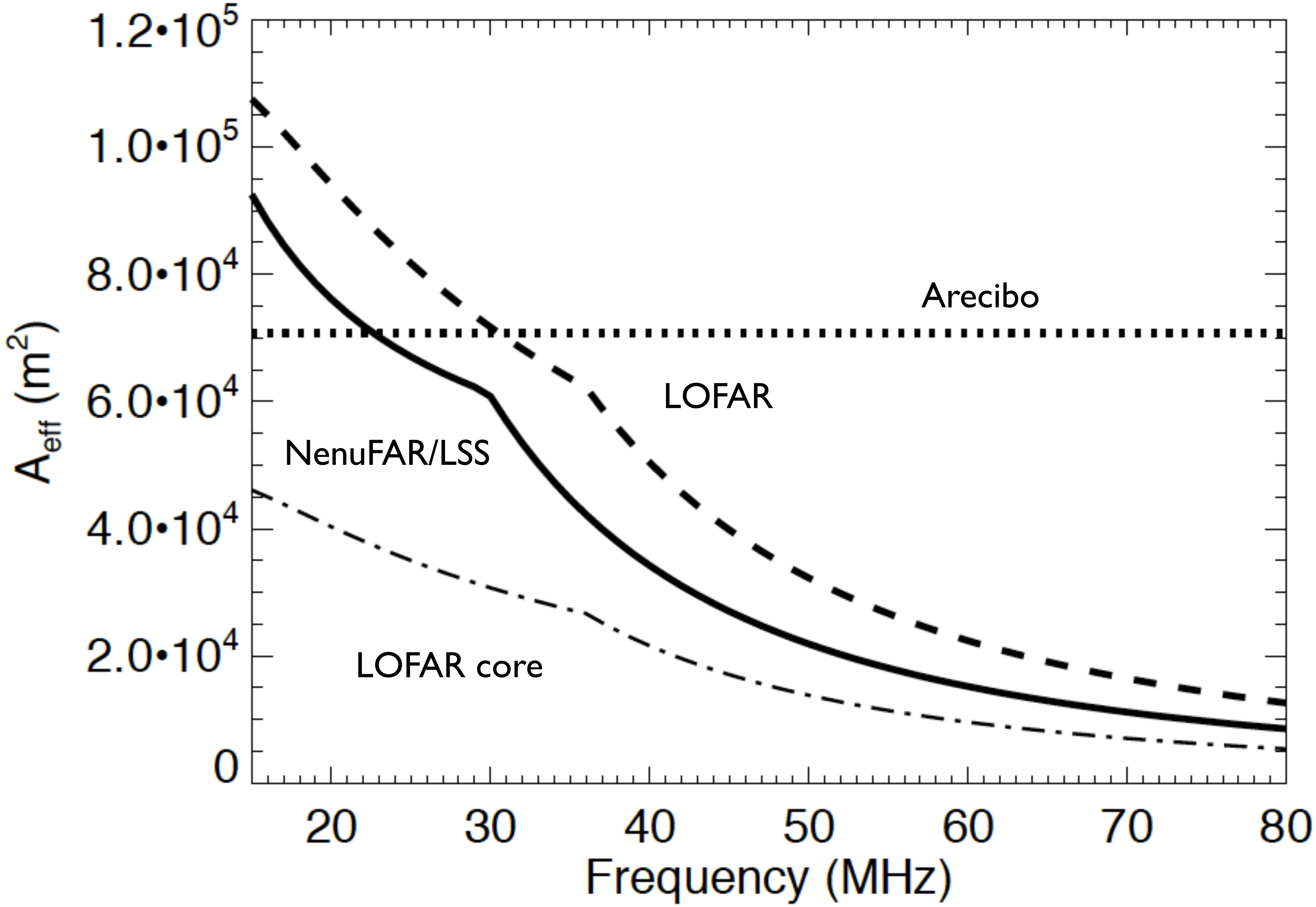


Short baselines intra-NenuFAR/LSS

⇒ large scale structures (>10°)

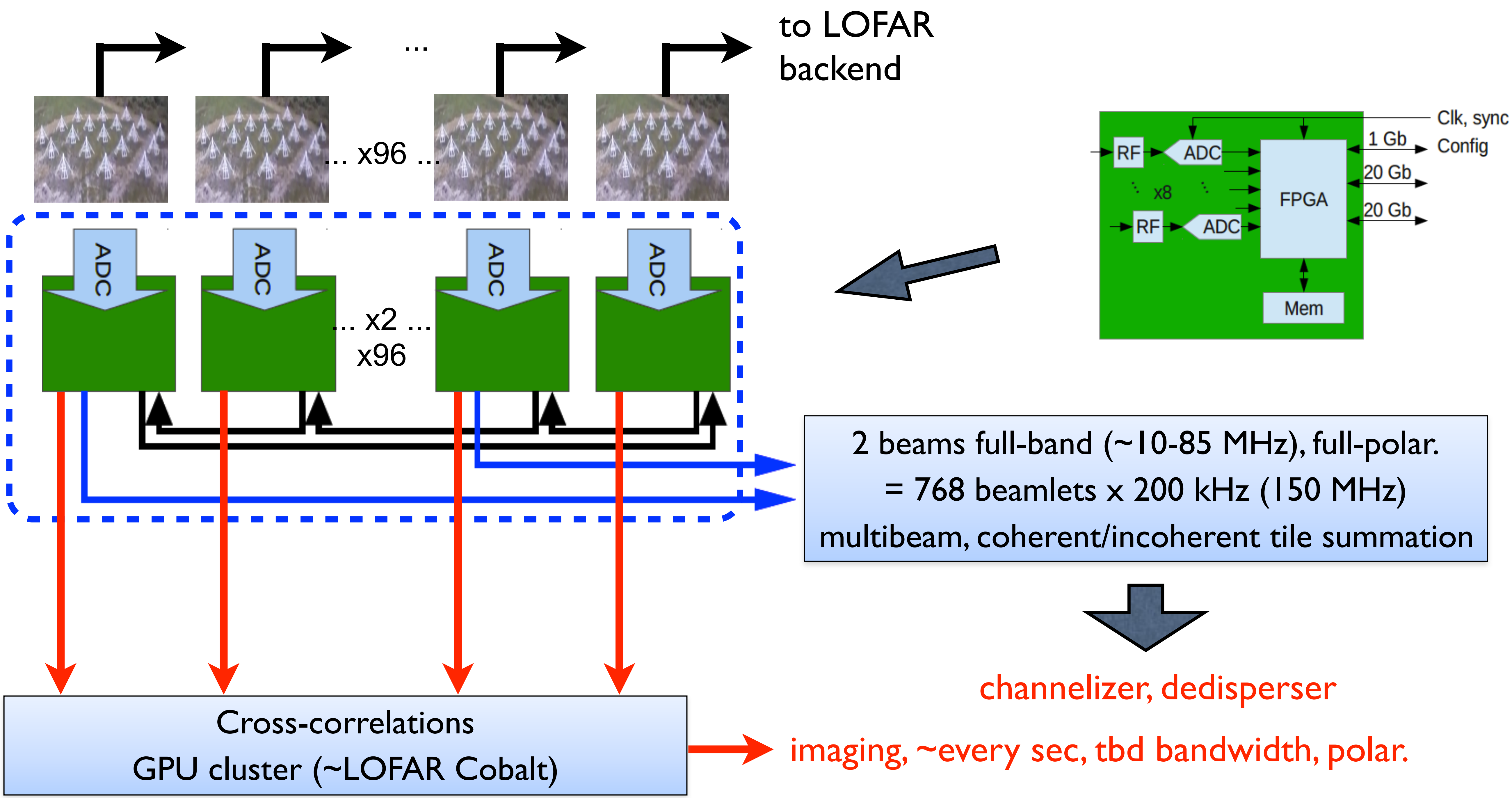
+ NenuFAR/LSS as 2nd core ?

What NenuFAR/Standalone will bring



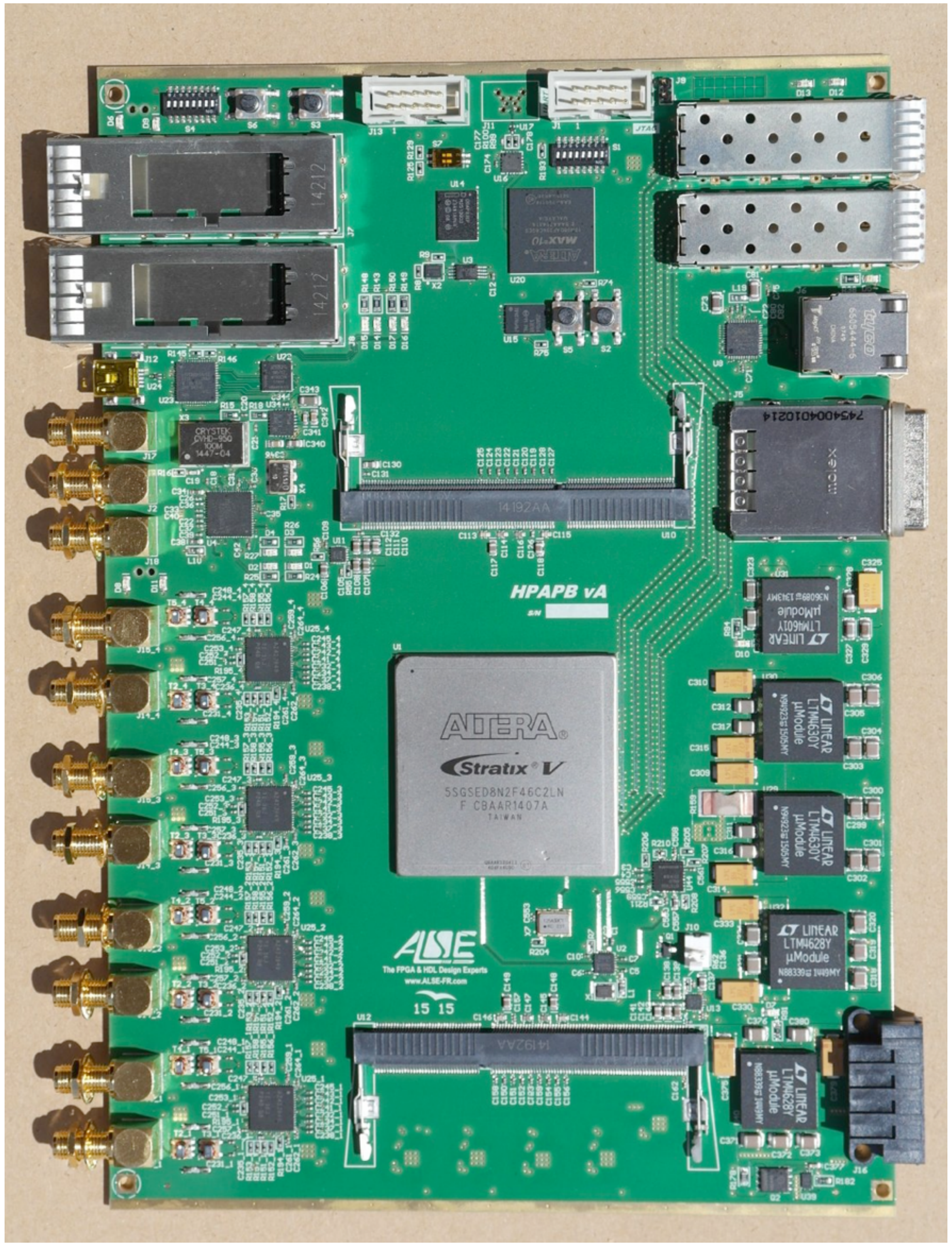
- ~19x the sensitivity of an international LOFAR station in LBA range
- N antennas = Dutch LOFAR (LBA)
- Access to VLF (10-85 MHz)
- A_{eff} ~ 2 x A_{eff} LOFAR core LBA above 35 MHz, ~ 10 x below 35 MHz
- International LBA stations used <25% of the time ⇒ Strong interest for standalone use

The NenuFAR Beamformer + Imager



- **NenuFAR** = 3 instruments in 1 { NenuFAR/LSS, NenuFAR/Standalone Beamformer, NenuFAR/Standalone Imager
- Fully parallel use of LSS & Standalone modes ⇒ "duty-cycle" ~100% in the analog mini-array beam

Beam former ADC+Computing board



- LaNewBa Beamformer

  Per FPGA :

  2.6 GB/s ADC data

  34.4 GMAC/s for beamforming

  (no correlation (XST))

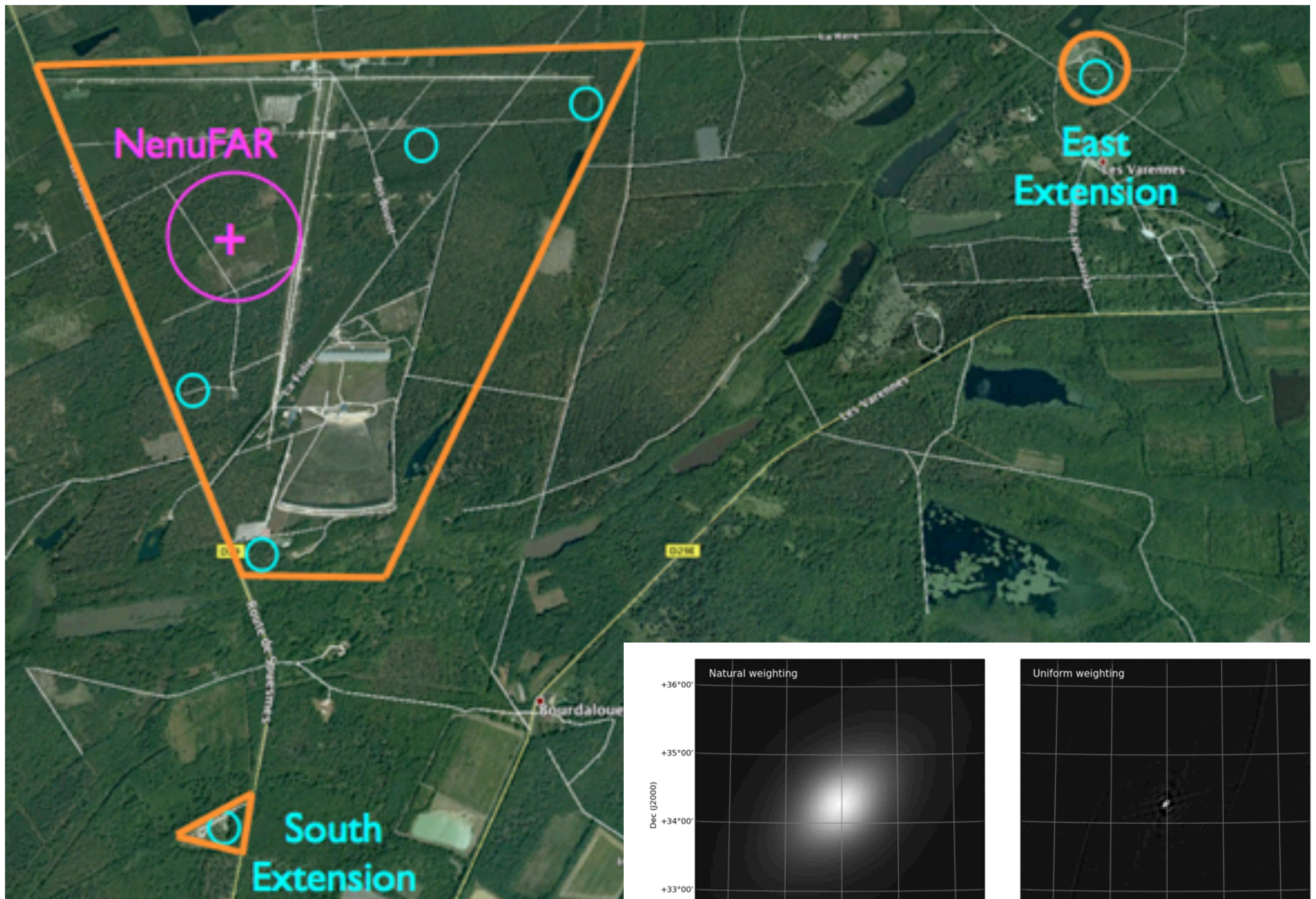
  NenuFAR-96 (x24):

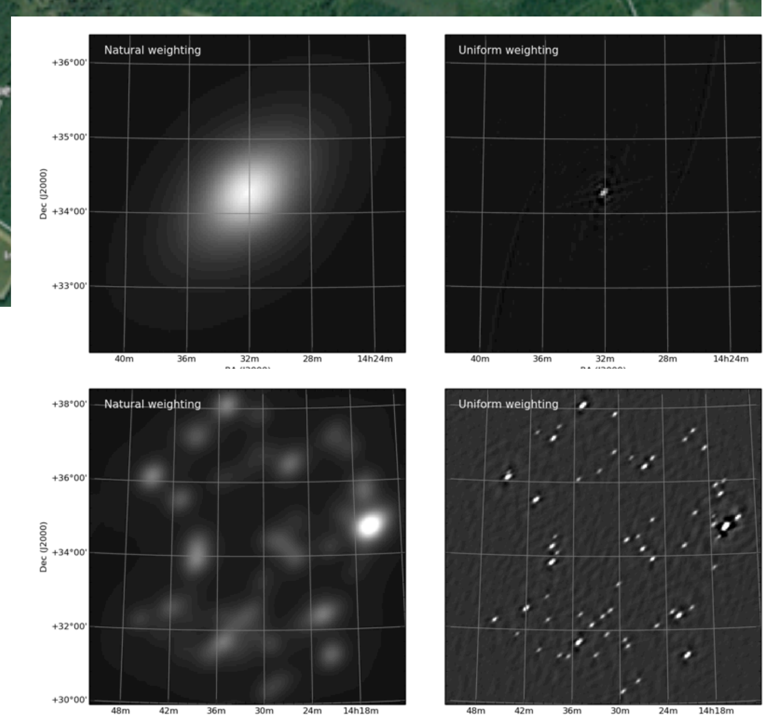
  63 GB/s ADC data

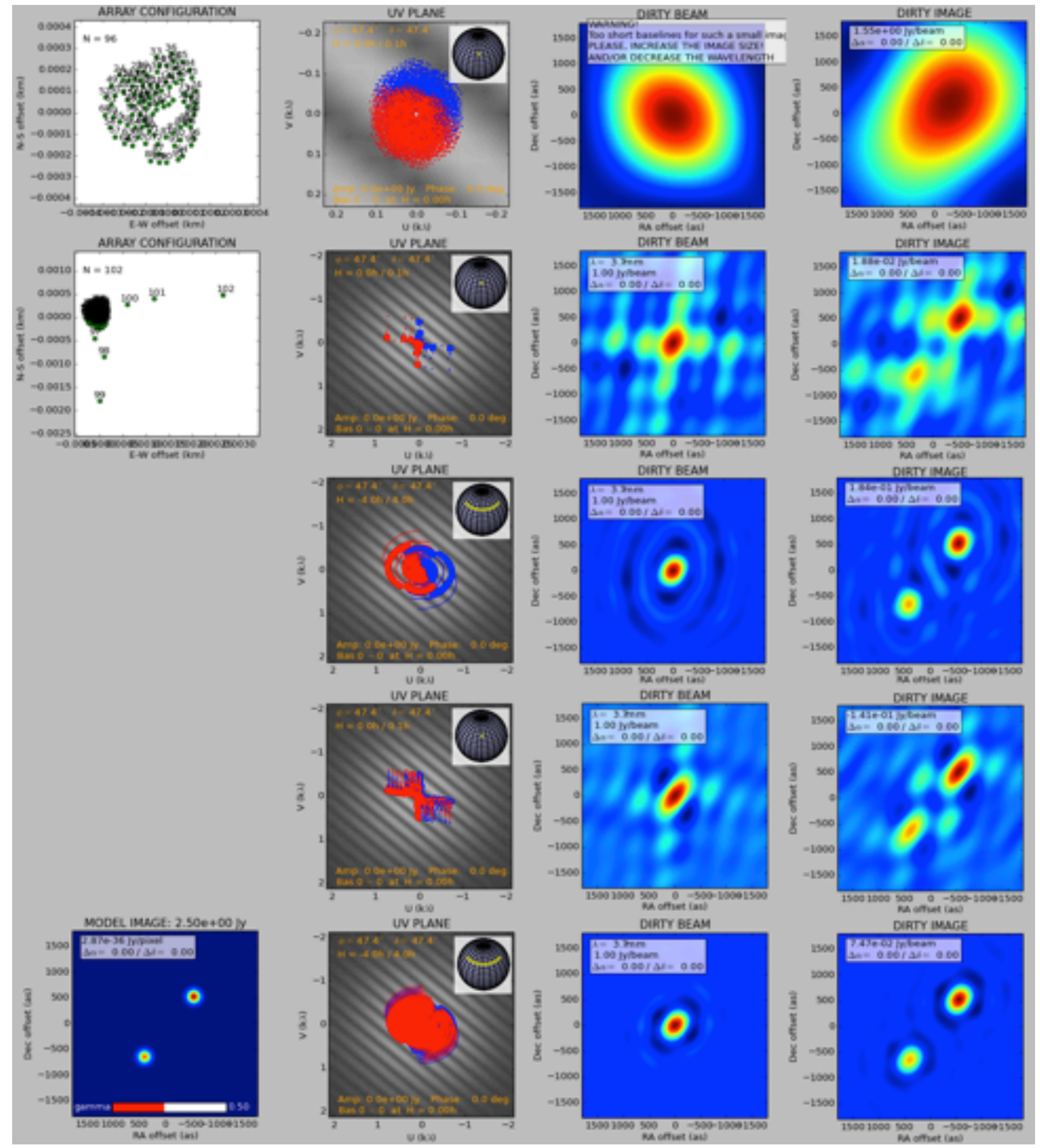
  826 GMAC/s

The NenuFAR Radio Imager

- $\sigma_{confusion}$ [mJy/beam] ~ $(\nu$ / 100 MHz$)^{-0.7}$ $(\theta$ / ' $)^2$ [Condon, 2002, 2005]
- +6 distant MA + multi-λ synthesis ⇒ angular res. x6 for stable broadband sources
- Relative sensitivity beyond compact core = $(N_{distant}/N_{core})^{1/2}$ ~ 25%







Technical characteristics of NenuFAR

- Large LOFAR-compatible phased array & interferometer
- 1824 antennas : 96 mini-arrays of 19 antennas each (25 m ∅)
- Diameter ~400 m + 6 distant mini-arrays (up to ~3 km)
- ~5000 baselines
- Frequency range = 10-85 MHz (λ=3.5-30m)
- Resolutions: δf = 100 kHz (standalone) → 1 kHz, δt = 5 µsec, TBB @ 5 nsec
- Full polarization (4 Stokes)
- Collective area ~600λ^2 ≤ 62 000 m^2
- FoV = 32° - 8° @ 20-80 MHz ; pointing -23° → +90°
- Angular Resolution 2°-0.5° (Standalone instantaneous),
  5'-40' (Standalone synthesis), 0.1 " (LSS)
- Sensitivity : 2 - 0.5 Jy @ 20-80 MHz (5σ, 1 sec x 10 MHz)
  ~ 31 – 9 mJy " (5σ, 1 h x 10 MHz)

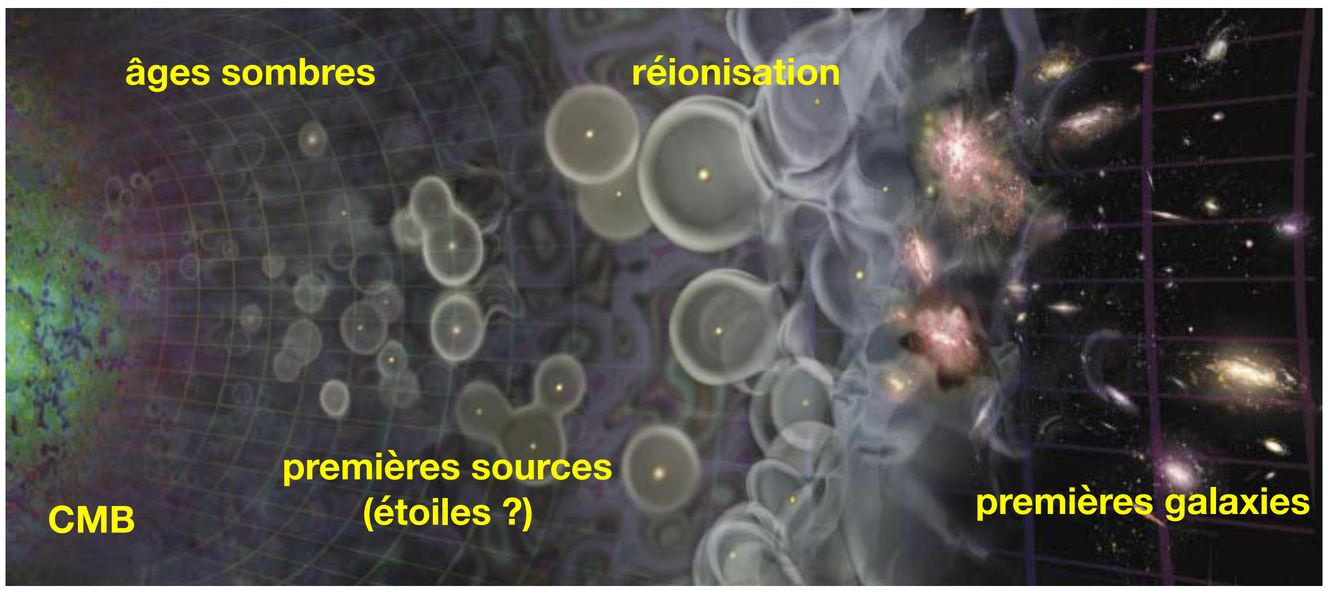
NenuFAR calibration / imaging

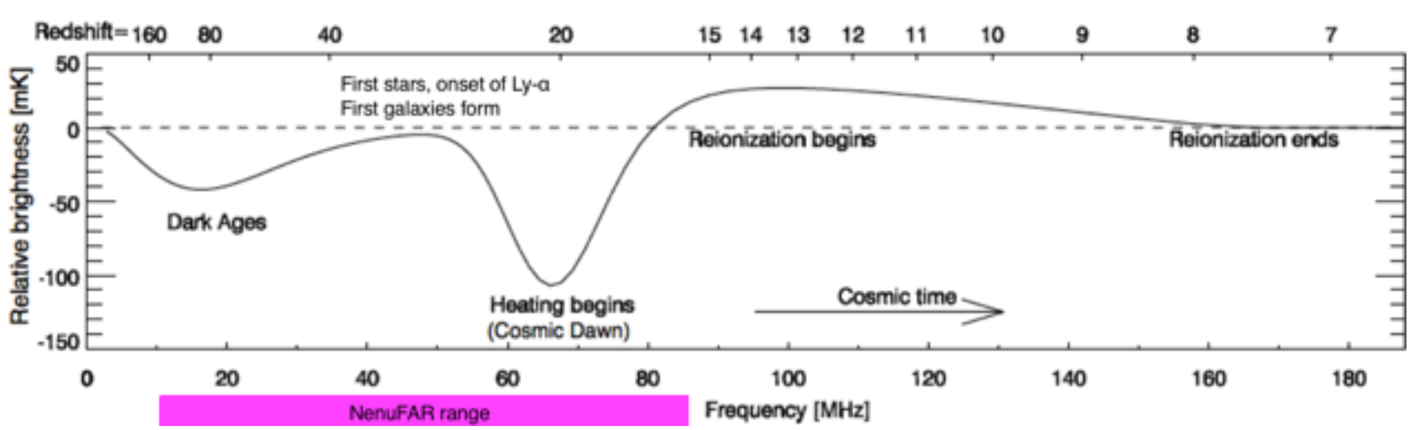
- Coupled Calibration / RFI mitigation (PRISME)
- Kill-MS / Coherent Jones / Facet-DD fast imager (Obs. Paris)
- Sparse deconvolution/imaging (OCA, CEA/AIM)

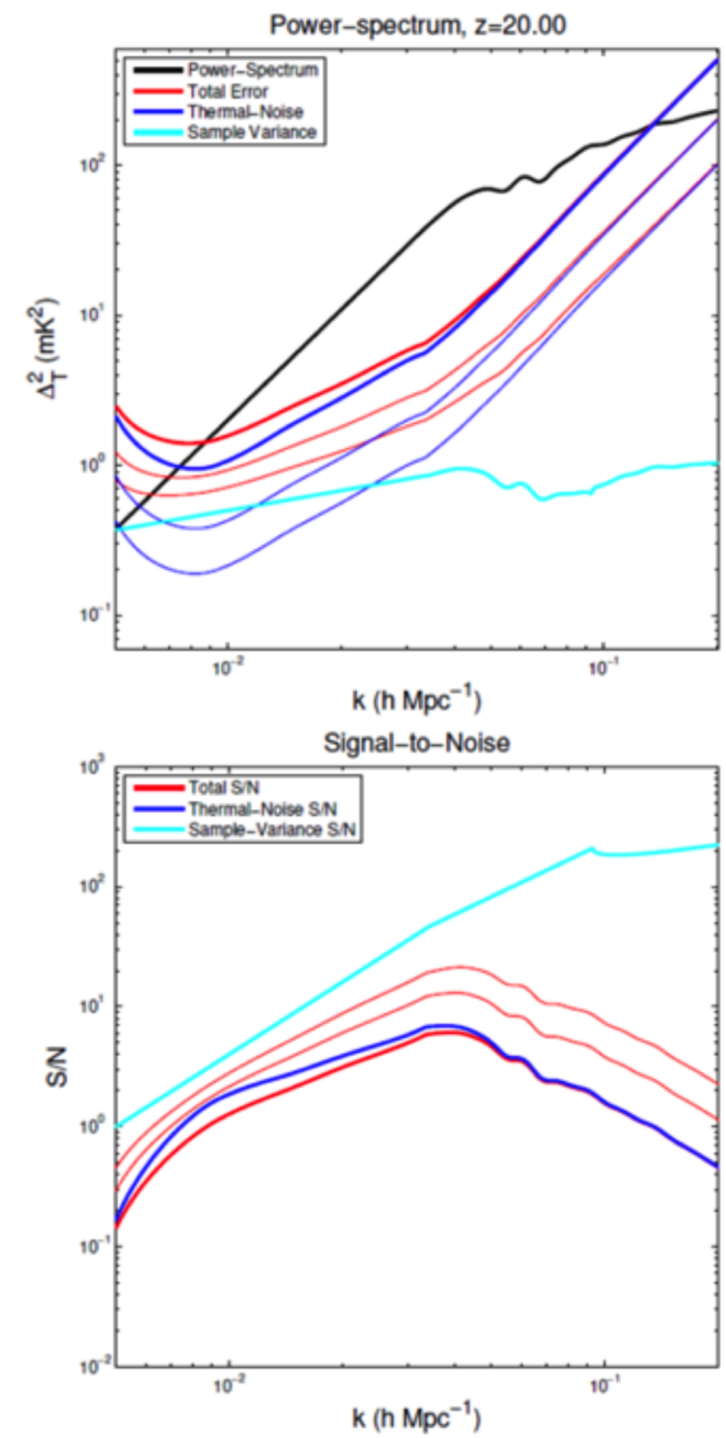
2-year post-doc position for NenuFAR commissioning
open 16/5/2016, deadline 16/6/2016, start activity ~1/9/2016

The Science

- Standalone Imaging (multi-λ rotational synthesis) : *Dark Ages/Cosmic Dawn*



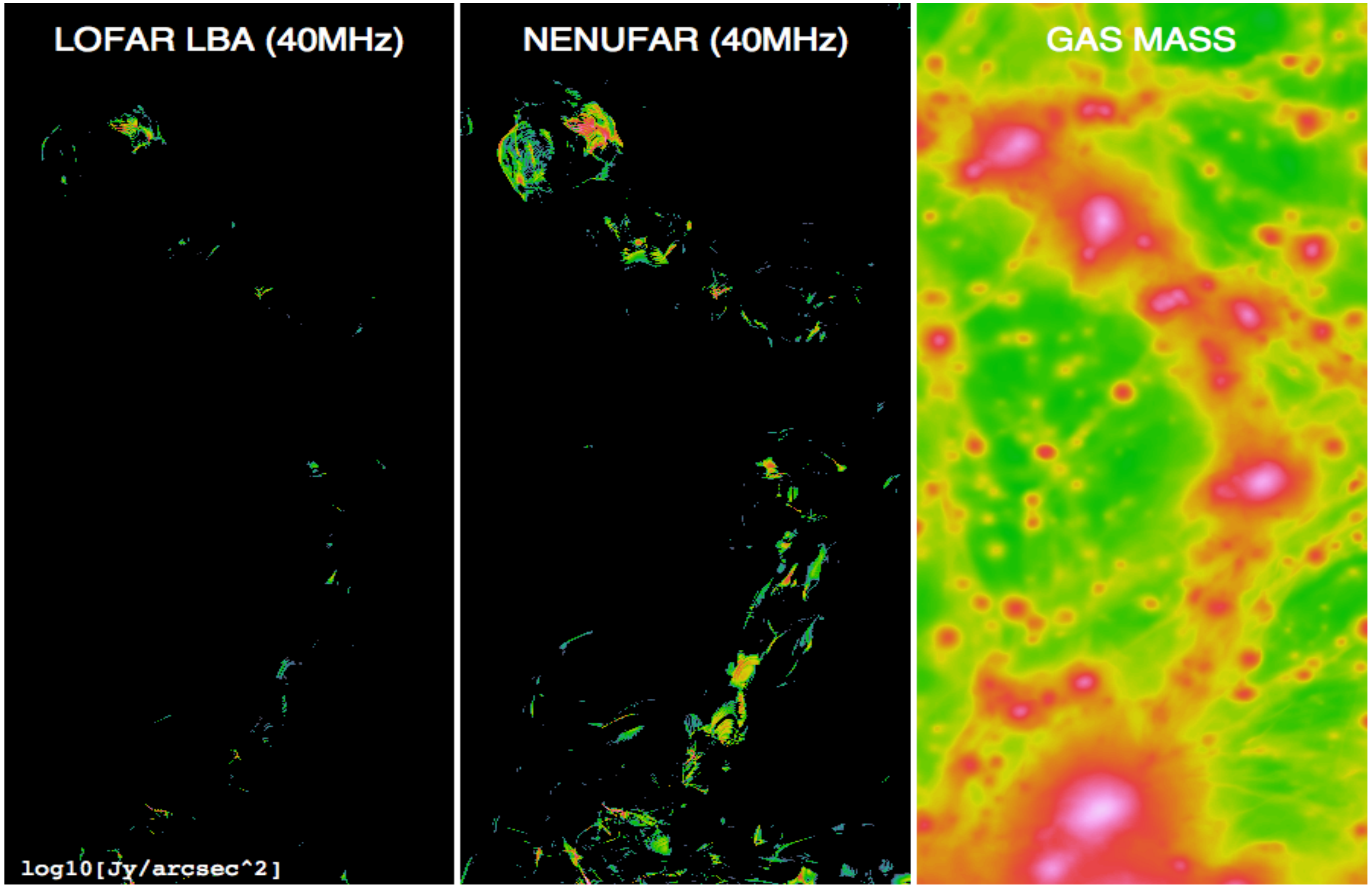




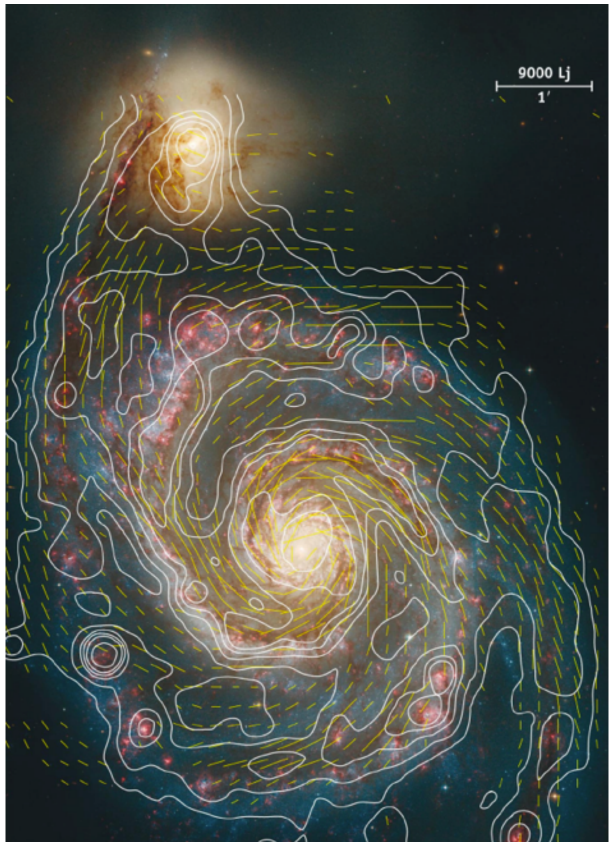
© L. Koopmans et al.

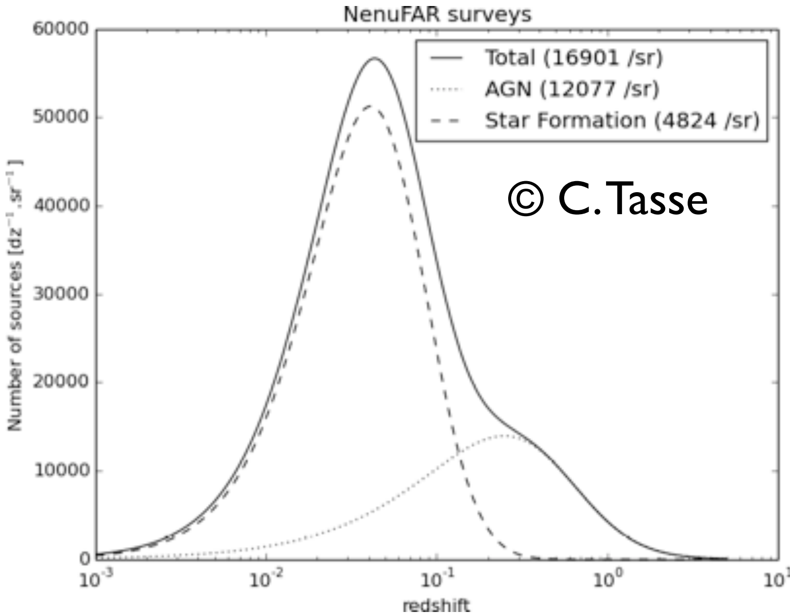
The Science

- NenuFAR / LSS : very high resolution wide-field LBA imaging,
  more sensitivity to extended structures
  (BH, AGN, star formation, IGM, clusters, haloes, relics, IGM, ISM, B fields)



© F. Vazza



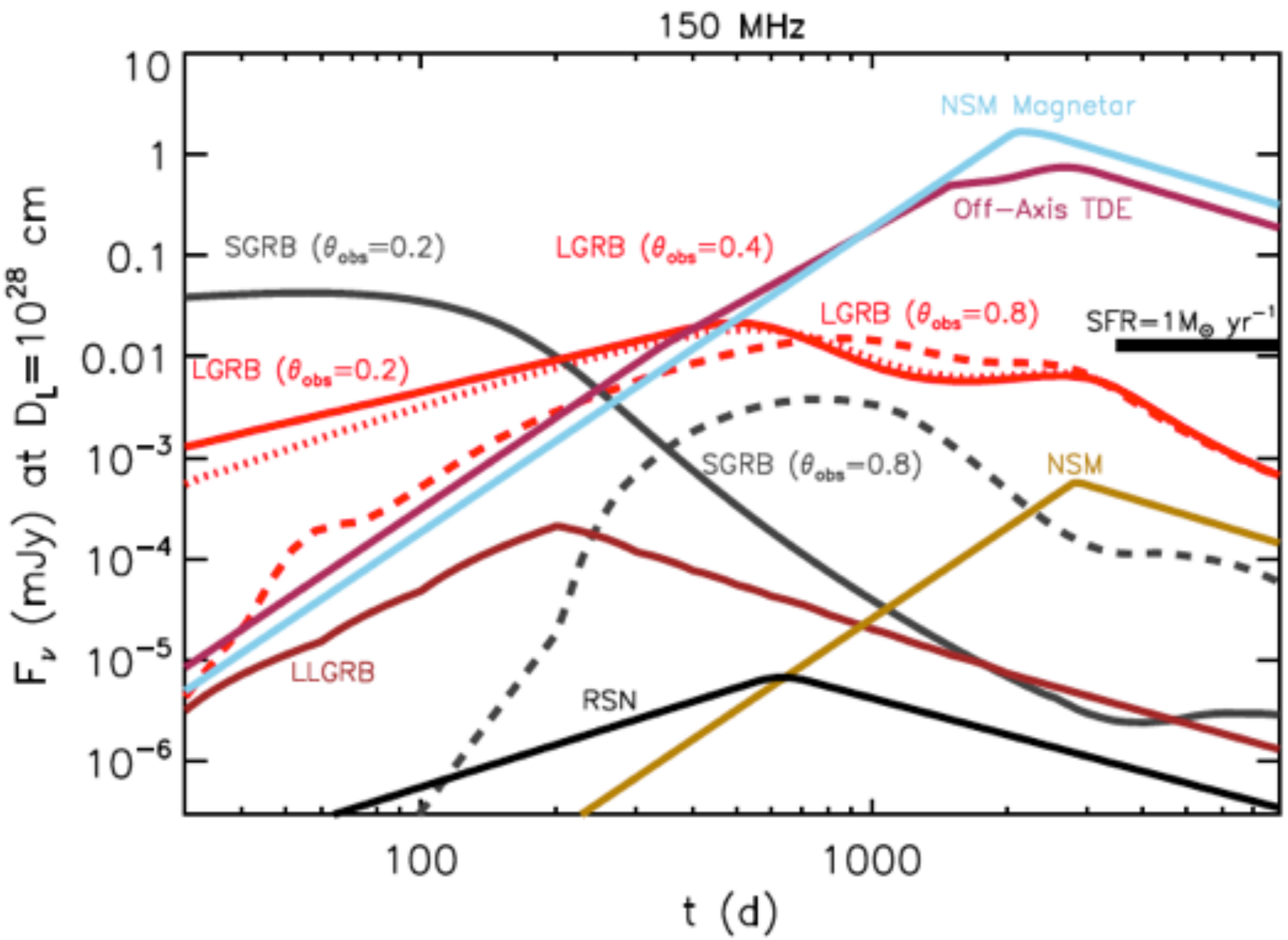


© C. Tasse

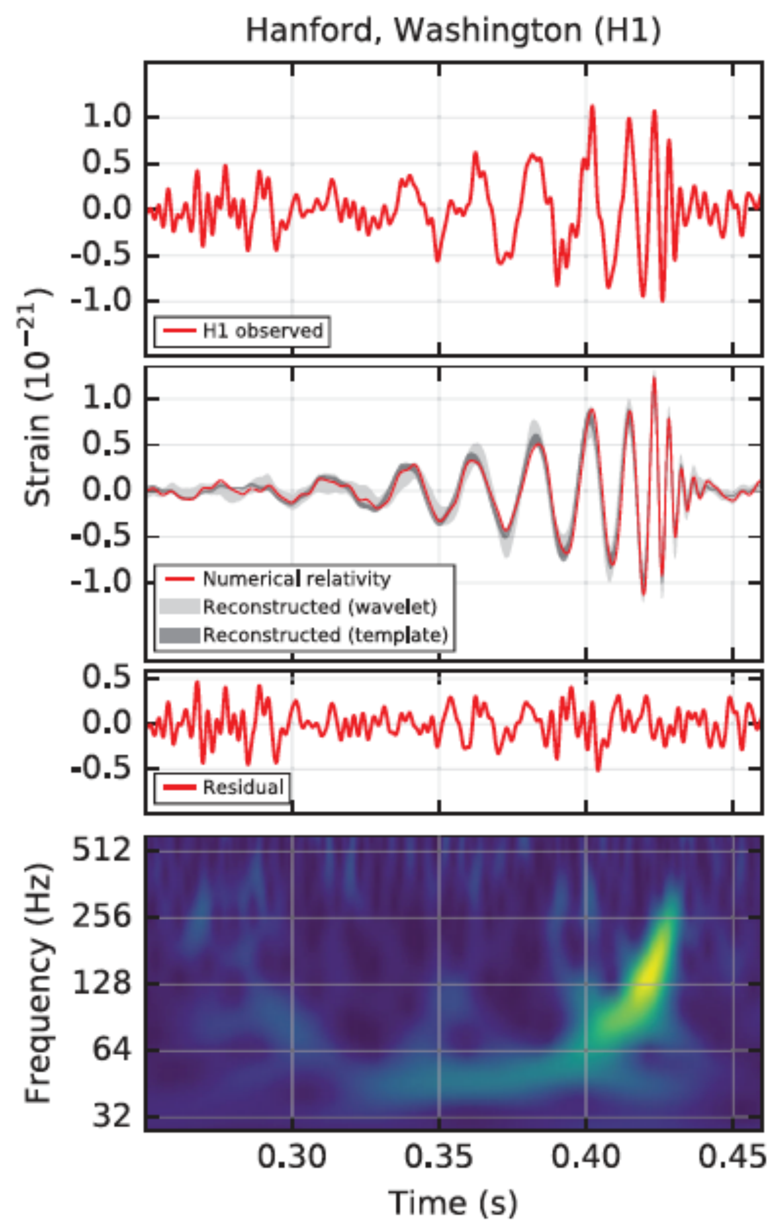
The Science

- Standalone Imaging (multi-λ rotational synthesis) : *GW/GRB afterglows ?*
- Standalone Beamformed/Fast imaging : *Prompt GW emission ?*

(MoU LIGO-Virgo / NenuFAR)



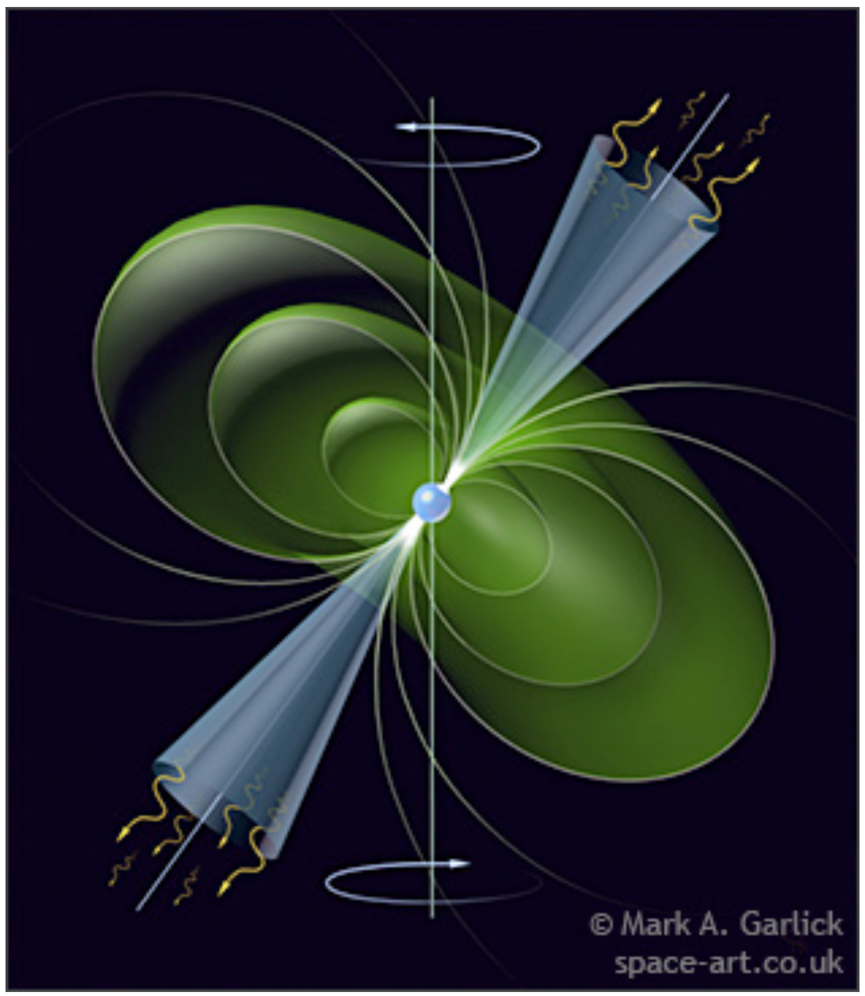
Metzger et al., 2015



LIGO coll., 2016

The Science

- Standalone Beamformed : *Pulsars searches/studies*



setup	# beams	d [m]	# stations	# dipoles/ MPA	# MPA/ station	norm. FOM₁	norm. FOM₂
single LBA station (LBA_OUTER)	1	32.25	1	1	48	1	1
Incoherent sum of superterp (LBA_INNER)	1	32.25	6	1	48	39	15
Coherent sum of superterp (LBA_INNER)	100	300	6	1	48	270	980
Incoherent sum of **LOFAR** core (LBA_INNER)	1	32.25	22	1	48	140	56
Coherent sum of **LOFAR** core (LBA_INNER)	100	2000	22	1	48	81	2000
LOFAR INT station	1	65	1	1	96	6	5
incoherent sum of INT stations	1	65	8	1	96	51	40
Coherent sum for **LSS**	10	300	1	19	96	1100	3900
Incoherent sum for **LSS**	1	300	1	19	96	6	21
NLLOFAR Fly's Eye (LBA_INNER)	1	32.25	40	1	48	260	102
NL **incoherent** sum (LBA_INNER)	1	32.25	40	1	48	260	102
NL **coherent** sum (LBA_INNER)	100	1e5	40	1	48	0.1	131

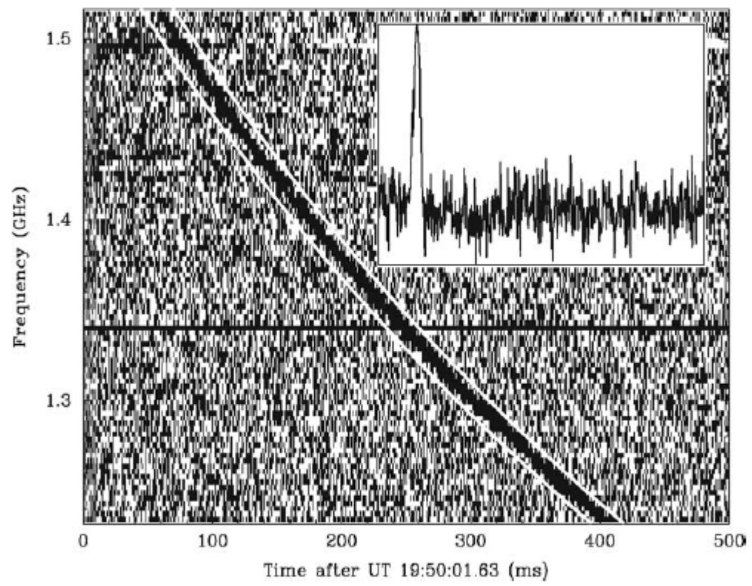
$$FoM_1 = N_{beams} * FoV * (A / T)^2 \propto N_{beams} * A^2 / D^2$$

$$FoM_2 = N_{beams} * A^2 * FoV/Beamwidth \propto N_{beams} * A^2 / D$$

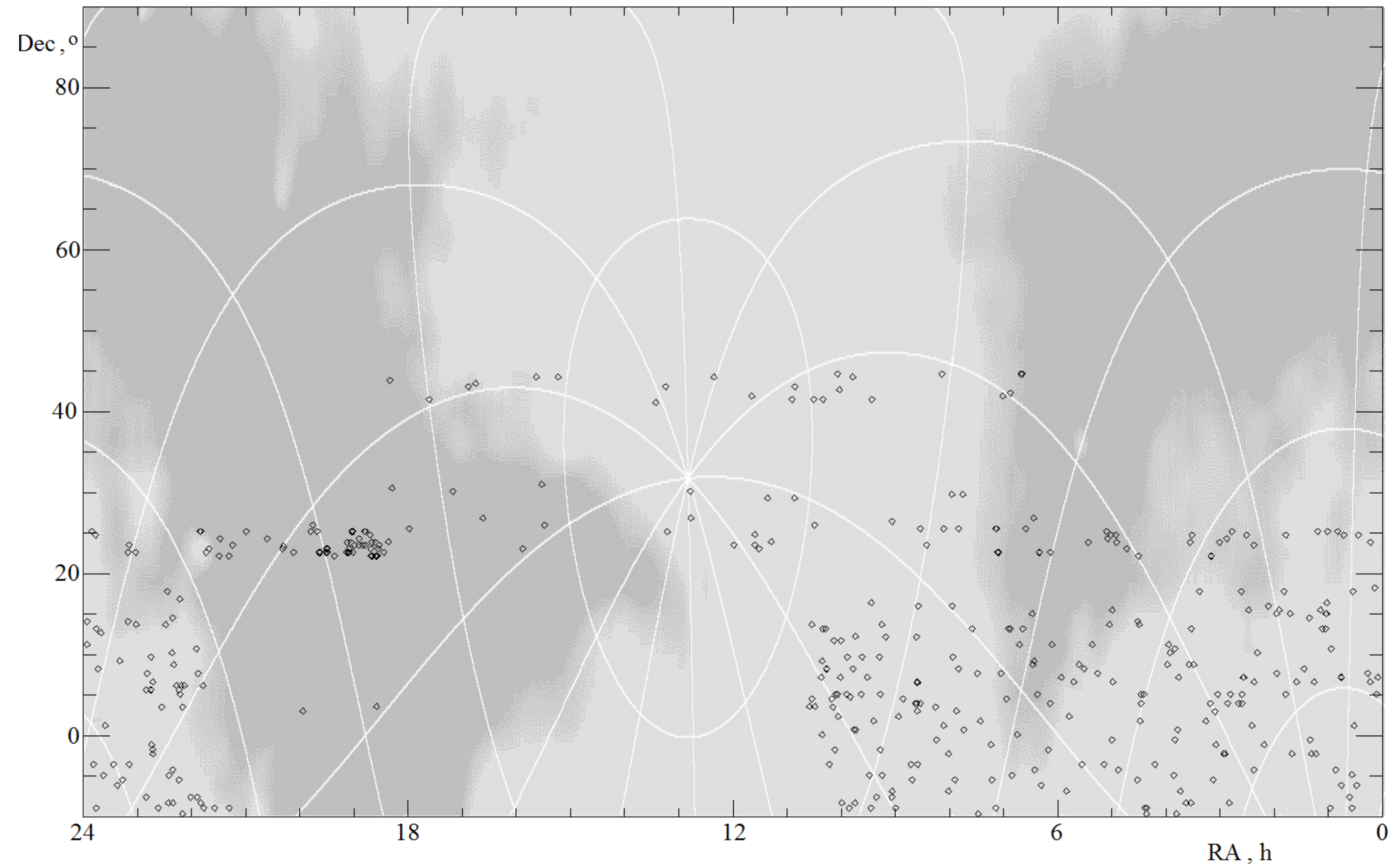
[Smits et al. 2009, Stappers et al. 2010, 2011]

The Science

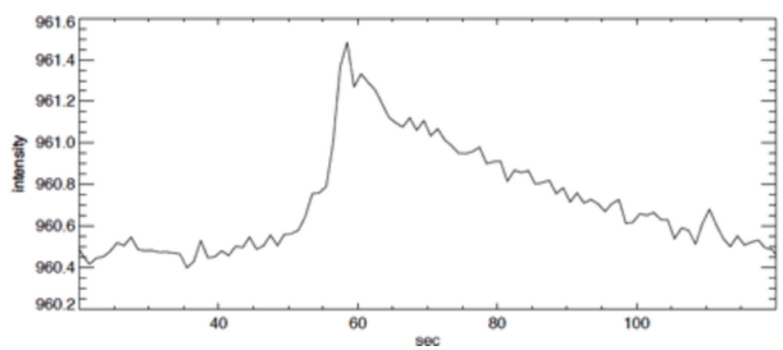
- Standalone Beamformed/Fast imaging : *fast astrophysical transients (giant pulses, RRATs, FRBs)*

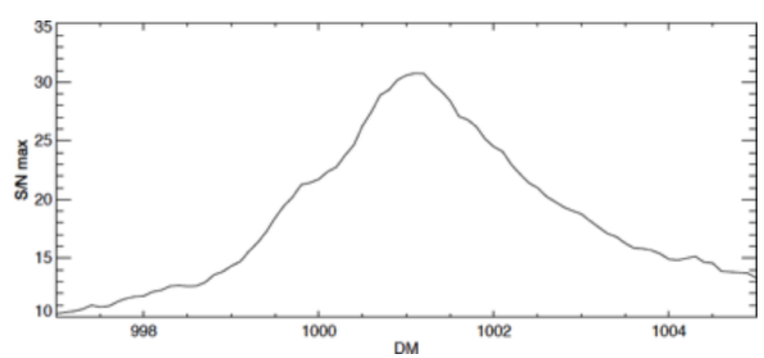


[Lorimer et al., 2007]



Part of UTR-2 transients survey ≤30 MHz
[Zakharenko, Vasylieva et al., 2015]

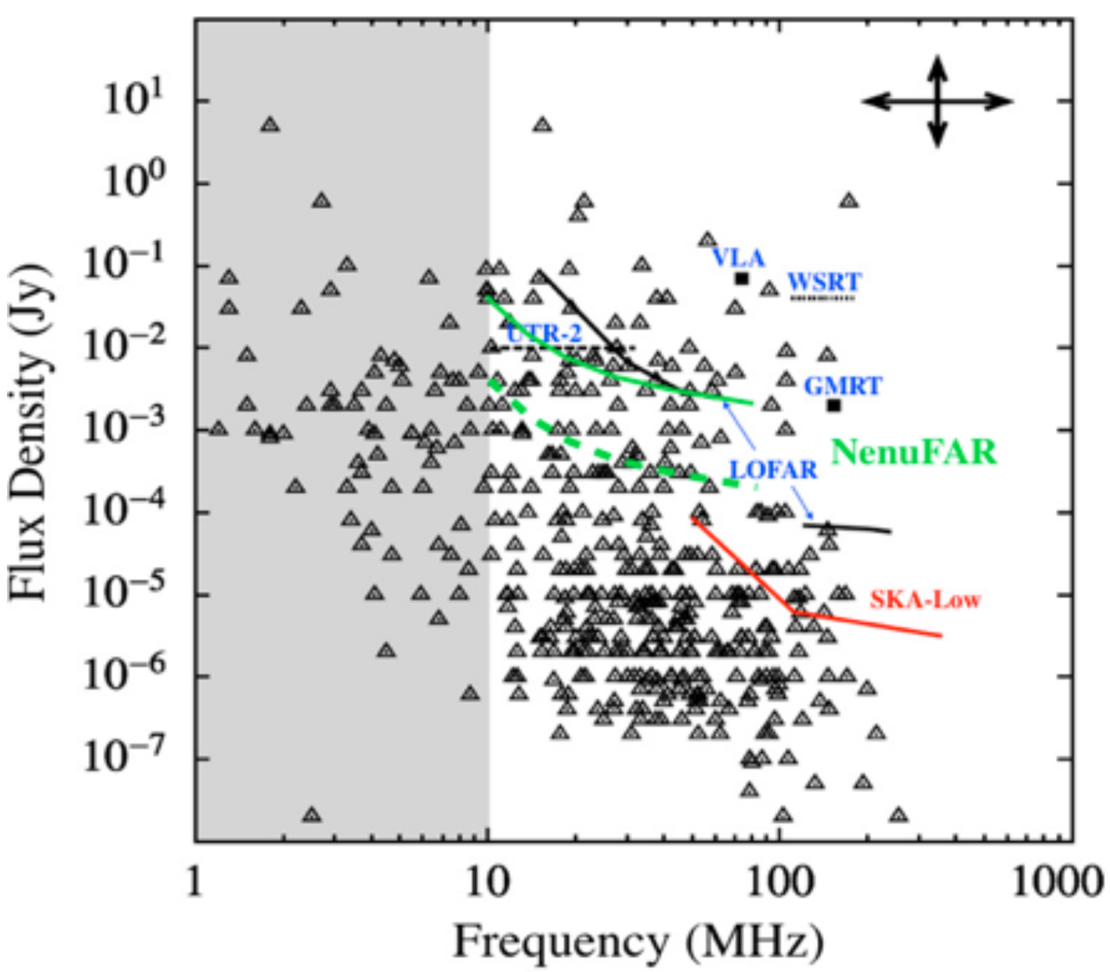




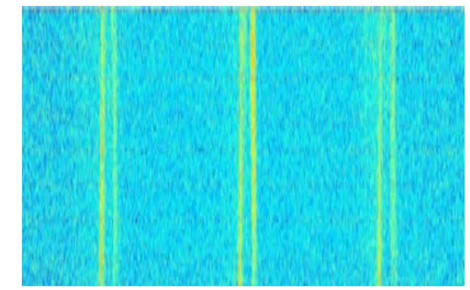
[Zarka, 2016]

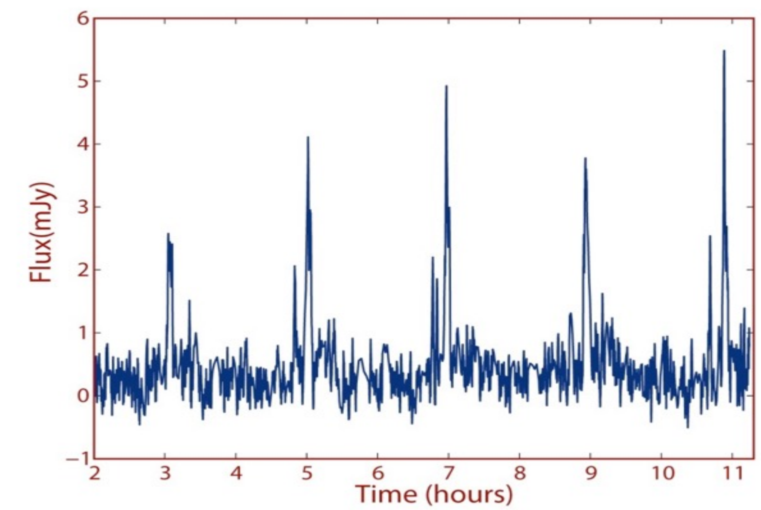
The Science

- Standalone Beamformed/Fast imaging : *Exoplanets, Star-Planet plasma interactions, Flaring/Dwarf/Cool stars*

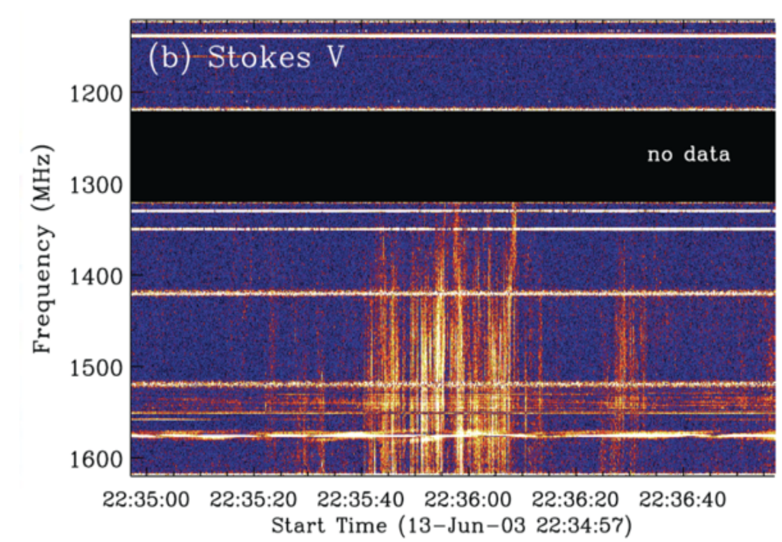


Zarka et al., 2015





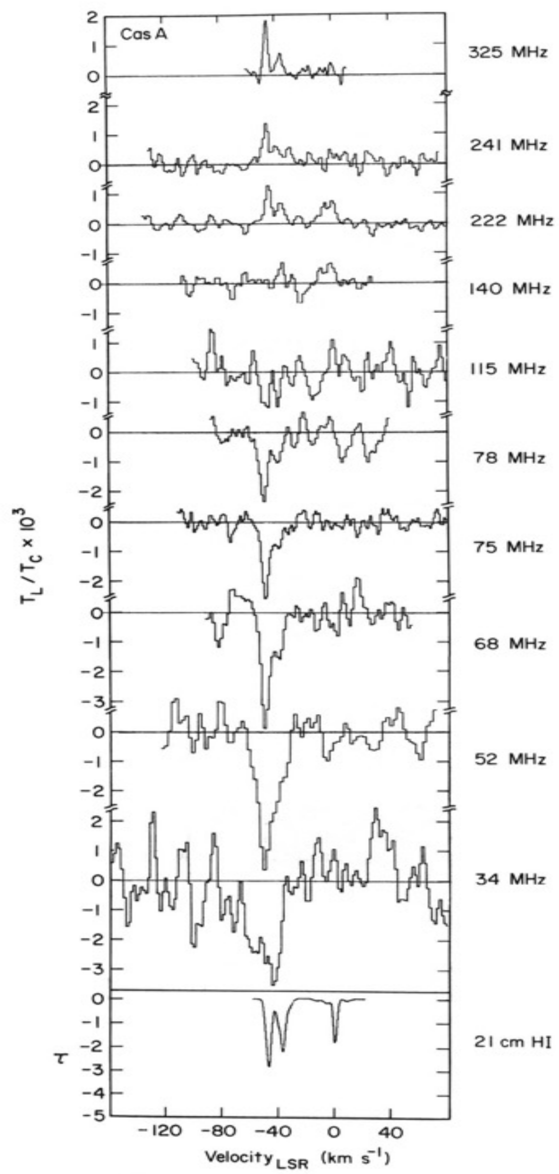
© G. Hallinan



© R. Osten

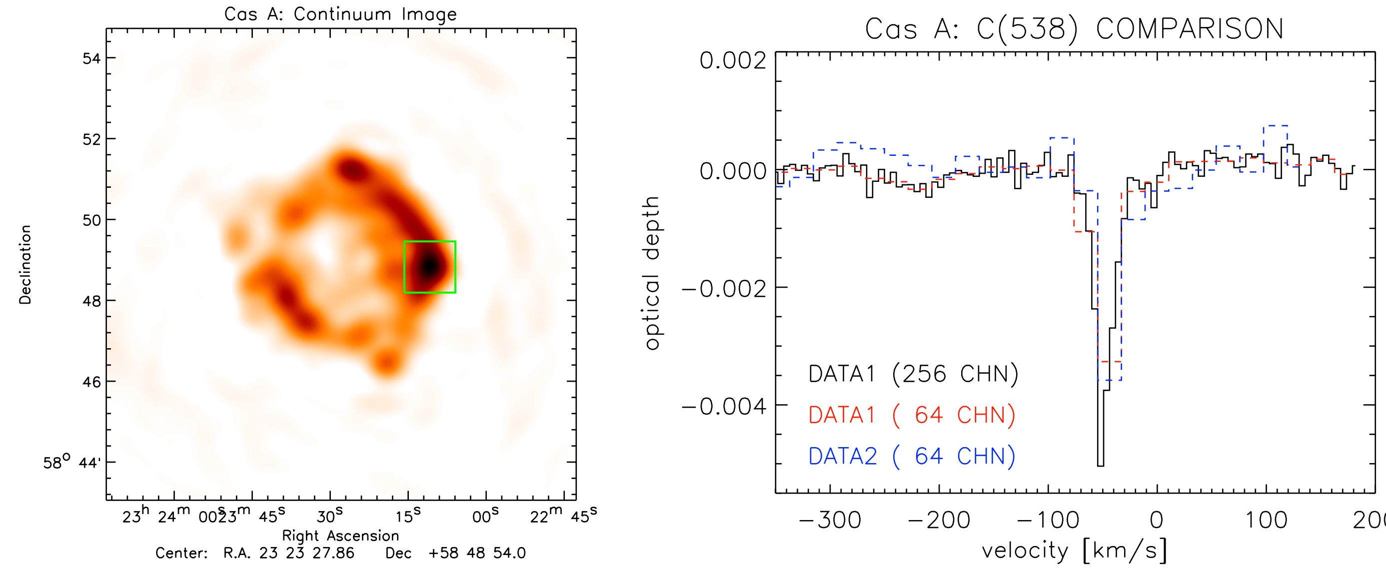
The Science

- Standalone Beamformed/Fast imaging : *Radio Recombination Lines*

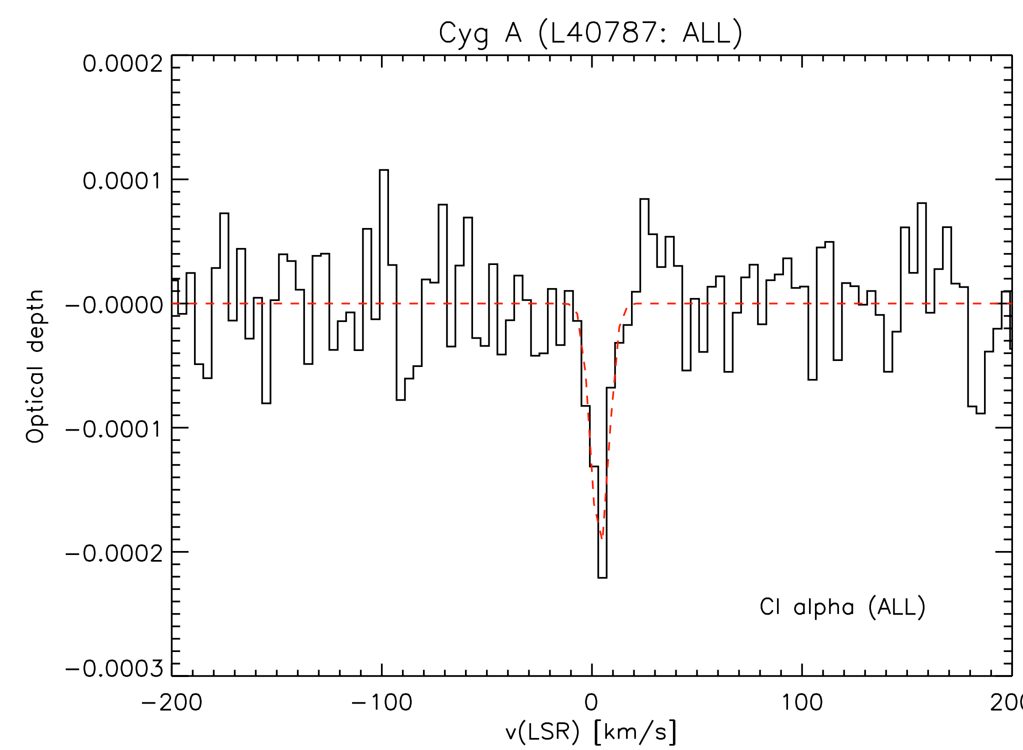


Carbon RRL's towards Cas A

[Gordon & Sorochenko, 2002]



[Asgekar et al., 2013]



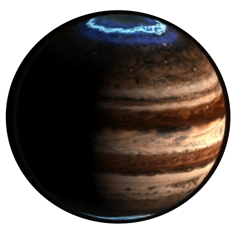
Carbon RRL's towards Cyg A (discovery with LOFAR)

[Oonk et al., 2014]

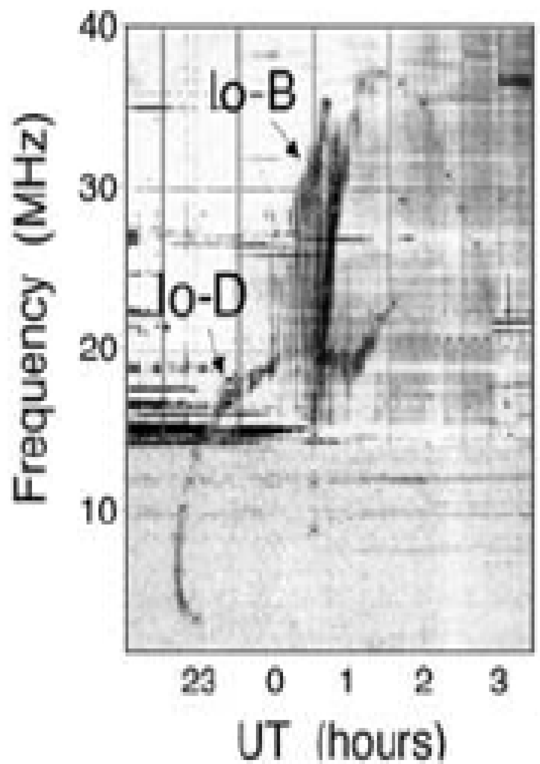
- LSS mode : *Grains ?*

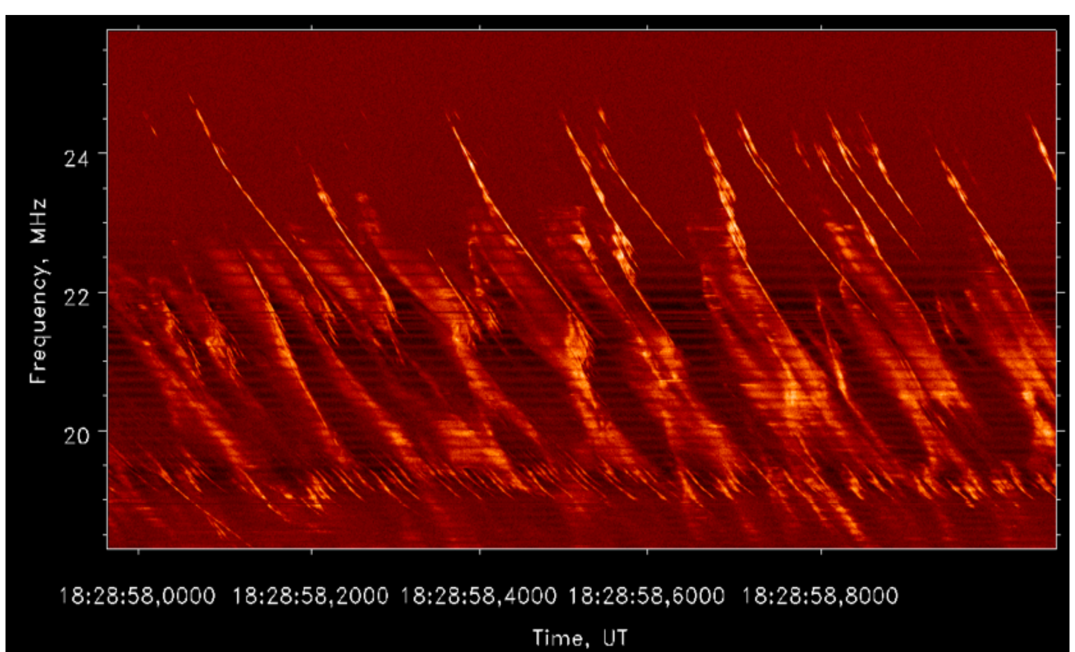
The Science

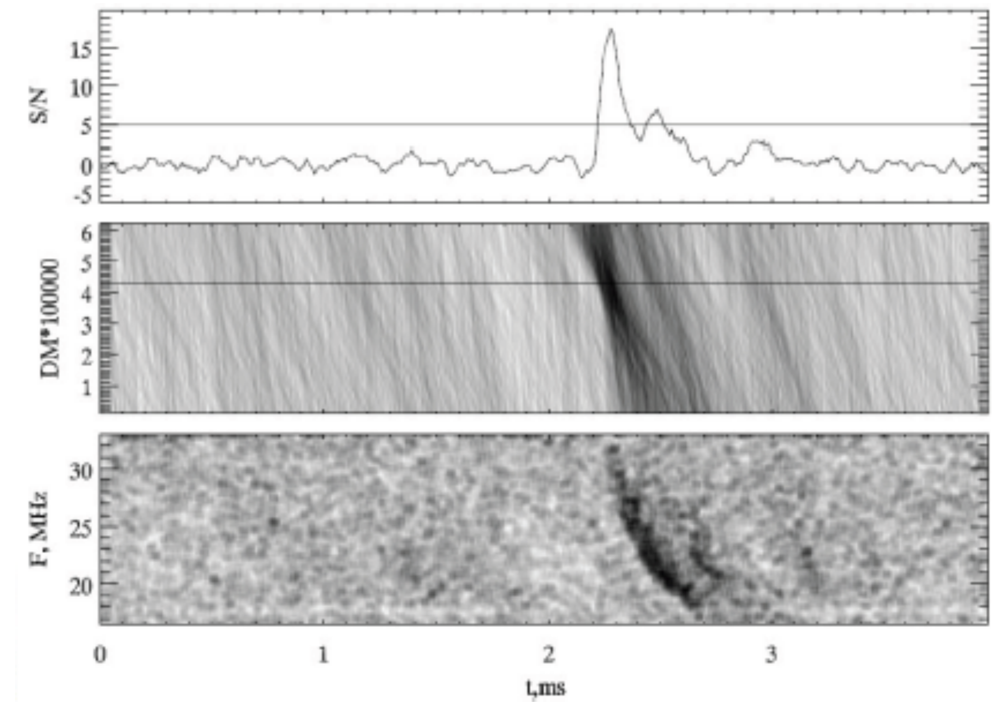
- Standalone Beamformed/Fast imaging : fast heliospheric transients
  (Solar bursts, Solar System magnetospheres, Terrestrial & Planetary Lightning and Transient Luminous Events)



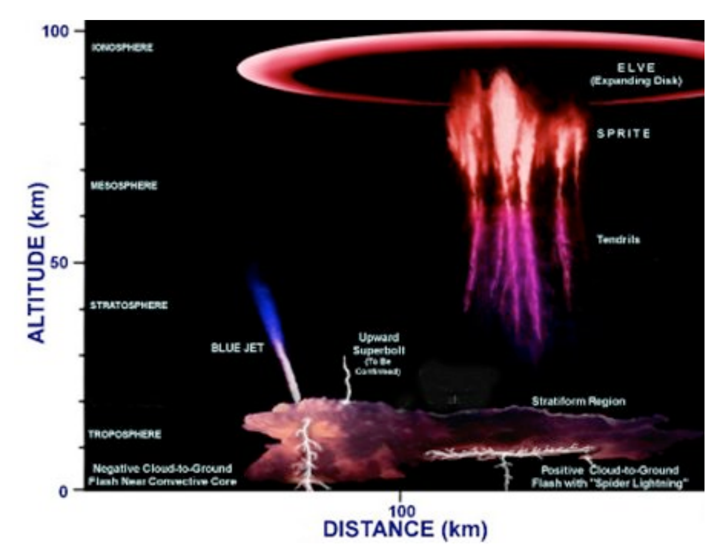
Jupiter
[Queinnec & Zarka, 1998, Ryabov et al., 2014]







Saturn lightning: finest dispersion delay measured: DM ~ 3×10^{-5} pc.cm^{-3}
→ Solar Wind probing up to 10 AU [Zakharenko,et al., 2012]



Science Case

- NenuFAR workshop & science case ⇒ Science groups (Cosmology, GW & GRB …)

Nenu
instrument
and scie

V5, 10/.

NenuFAR : instrument d

1. The NenuFAR project (introduction, cont
2. NenuFAR as a pathfinder for SKA - S. To
3. Technical specifications of NenuFAR - J.
4. NenuFAR with LOFAR : high resolution
5. NenuFAR in standalone mode: calibratior issues - C. Tasse, et al.
6. Algorithms and optimizations - T. Lanz, e
7. Dedicated standalone receiver for transien
8. Prospects for EoR and cosmic dawn obse
9. Gravitational wave signatures – M. Barsu
10. Galaxy clusters and the large-scale structu
11. Extragalactic projects - F. Combes, et al.
12. Extragalactic objects as Cosmological too
13. Nearby galaxies – A. Bosma, et al.
14. Pulsar Science - J.-M. Griessmeier, et al.
15. ISM turbulence - F. Levrier, et al.
16. Transients - S. Corbel, A. Loh
17. Cosmic Ray Extensive Air Showers - R. I
18. Solar and stellar activity - C. Briand, et al
19. Jupiter's decametric radio emissions - M.
20. Exoplanetary radio emissions - L. Lamy,
21. Observations of planetary lightning with
22. Radio emissions associated with Terrestri Fullekrug
23. Meteor radio detection - S. Azarian, J. Va
24. ExPRI : Experiment for Propagation of R et al.
25. Synergies with other instruments – P. Zar
26. NenuFAR – Art Project – C. Courte, et al.
27. Synthesis - M. Tagger, et al.

Authors list
(**French** / Foreign co-authors)
&
Supporting scientists & Others

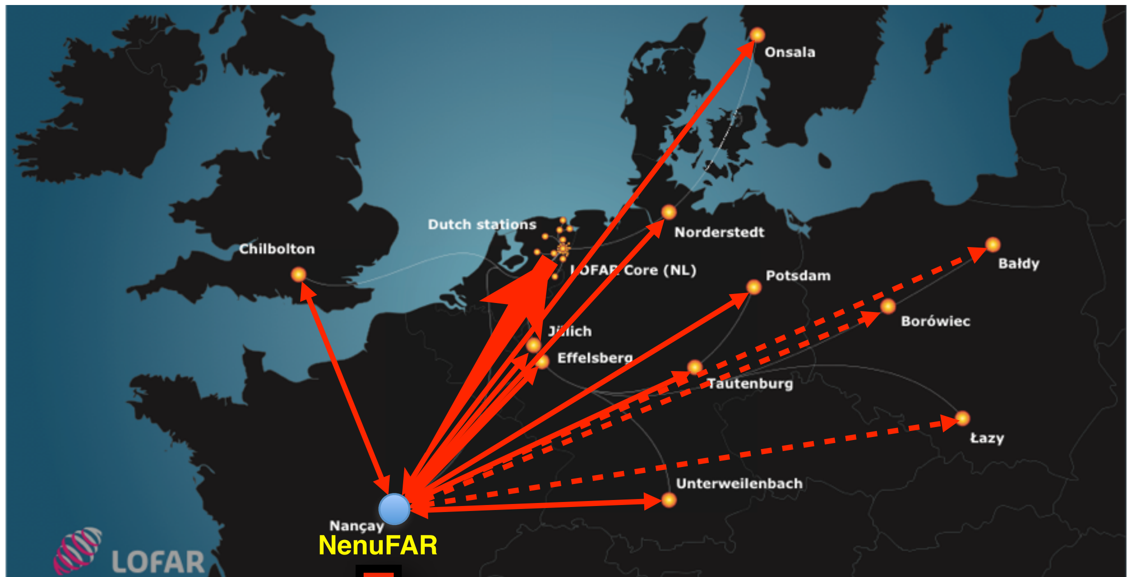
M. Atemkeng (Univ. Cape, SA)
M. Arnaud (CEA)
S. Azarian (ONERA)
M. Barsuglia (APC)
A. Bonafede (Hamburg Obs.)
F. Boone (IRAP)
A. Bosma (LAM)
R. Boyer (L2S)
M. Branchesi (INAF)
C. Briand (LESIA)
B. Cecconi (LESIA)
S. Célestin (LPC2E)
D. Charrier (Subatech)
E. Chassande-Mottin (APC)
A. Coffre (USN)
I. Cognard (LPC2E)
F. Combes (LERMA / Collège de France)
S. Corbel (Univ. Paris-Diderot, CEA)
C. Courte (ESBAT)
A. Dabbech (Lagrange, OCA)
S. Daiboo (LESIA)
R. Dallier (Subatech)
L. Denis (USN)
C. Dumez-Viou (USN)
M. N. El Korso (LEME, Univ. Paris Ouest)
E. Falgarone (ENS Paris)
I. Falkovych (IRA Kharkov) †
A. Ferrari (Lagrange, OCA)
C. Ferrari (Lagrange, OCA)
K. Ferrière (IRAP)
C. Fevotte (Lagrange, OCA)
A. Fialkov (ENS Paris)
M. Fullekrug (Univ. Bath)
E. Gérard (GEPI)
J. N. Girard (CEA/AIM)
J.-M. Grießmeier (LPC2E)
B. Guiderdoni (CRAL)
L. Guillemot (LPC2E)
J. Hessels (ASTRON)
A. Konovalenko (IRA Kharkov)
L. Koopmans (Kapteyn Univ.)
V. Kondratiev (ASTRON)
L. Lamy (LESIA)
T. Lanz (Lagrange, OCA)
P. Larzabal (ENS Cachan)
M. Lehnert (IAP)
F. Levrier (ENS Paris)
A. Loh (Univ. Paris-Diderot, CEA)
G. Macario (Lagrange, OCA)
J.-J. Maintoux (RETRAM)
J. Maintoux (RETRAM)
L. Martin (Subatech)
D. Mary (Lagrange, OCA)
S. Masson (LESIA)
M.-A. Miville-Deschenes (IAS)
D. Oberoi (MIT)
M. Panchenko (SRI Graz)
M. Pandey-Pommier (CRAL)
A. Petiteau (APC)
J.-L. Pinçon (LPC2E)
B. Revenu (Subatech)
F. Rible (RETRAM)
C. Richard (Lagrange, OCA)
H. O. Rucker (SRI Graz)
P. Salomé (LERMA)
B. Semelin (LERMA)
M. Serylak (Univ. Oxford)
M. Sidorchuk (IRA Kharkov)
O. Smirnov (Univ. Cape, SA)
B. Stappers (Univ. Manchester)
C. Taffoureau (USN)
M. Tagger (LPC2E)
C. Tasse (GEPI)
G. Theureau (LPC2E)
P. Tokarsky (IRA Kharkov)
S. Torchinsky (USN)
O. Ulyanov (IRA Kharkov)
W. van Driel (GEPI)
I. Vasylieva (LESIA & IRA Kharkov)
J. Vaubaillon (IMCCE)
F. Vazza (Hamburg Obs.)
S. Vergani (GEPI)
M. Was (LAPP)
R. Weber (PRISME / Polytech)
V. Zakharenko (IRA Kharkov)
P. Zarka (LESIA)

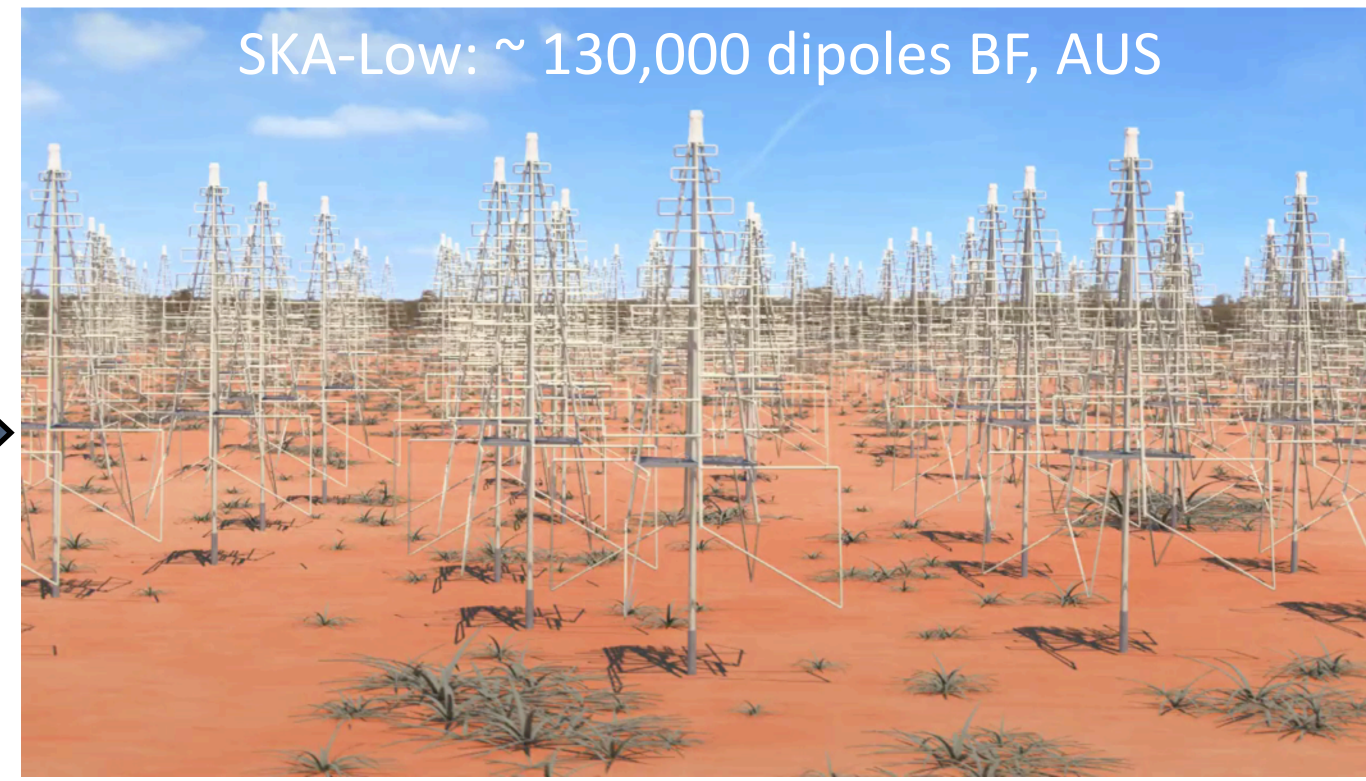
NenuFAR Operating modes & Data policy

- NenuFAR/LSS mode via ILT (MoU)
- NenuFAR/Standalone mode via FLOW PC

NenuFAR : SKA pathfinder

(8/2014)

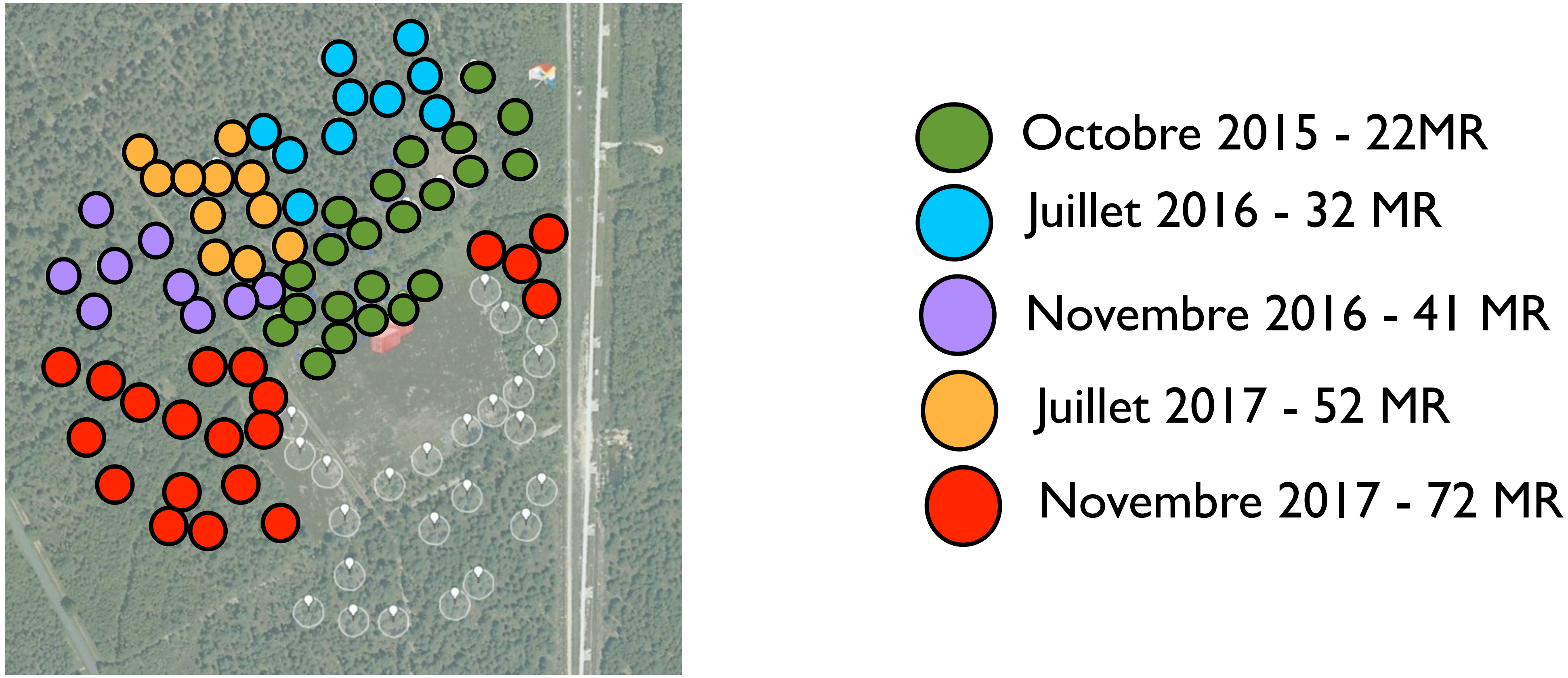




- Unique instrument / LWA, ARRTFAAC, UTR-2
- Synergy/complementarity with LOFAR, MWA, SKA …

NenuFAR today

Construction



Funding

- Total cost of NenuFAR <5 M€, ~60% funded, ongoing proposals

Links

- http://nenufar.obs-nancay.fr/
- http://nenufar.sciencesconf.org/
- https://twitter.com/SSL_Nancay
- http://journees-radio.sciencesconf.org/