Overview of NenuFAR project & data products

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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 (multi-)beam formed mode

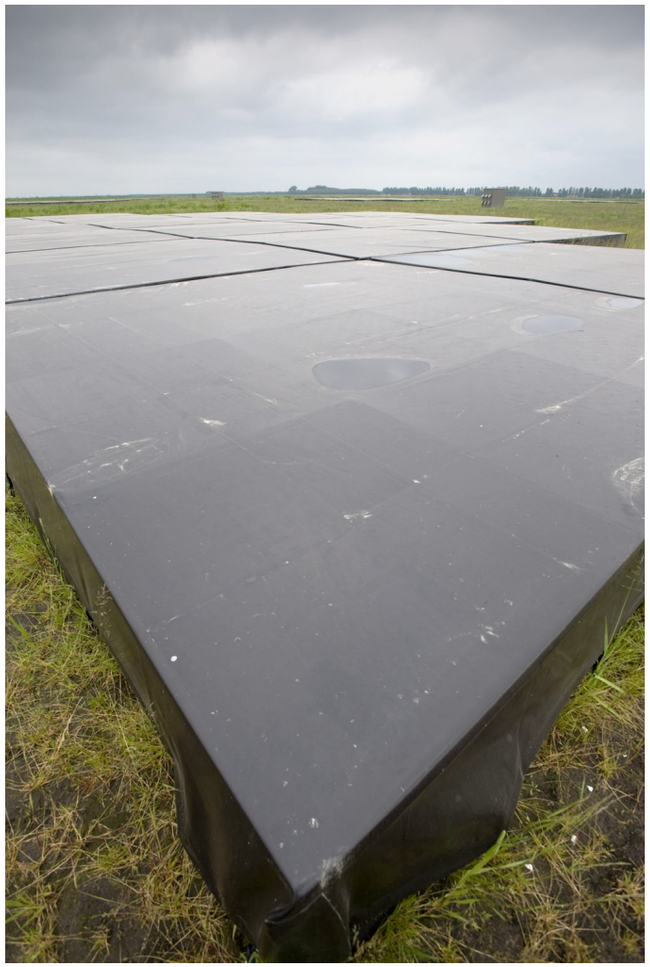
  ⇒ large programs : *cf. KP list & discussions*

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

- Developing the French LF radio community

Basic Principle

x



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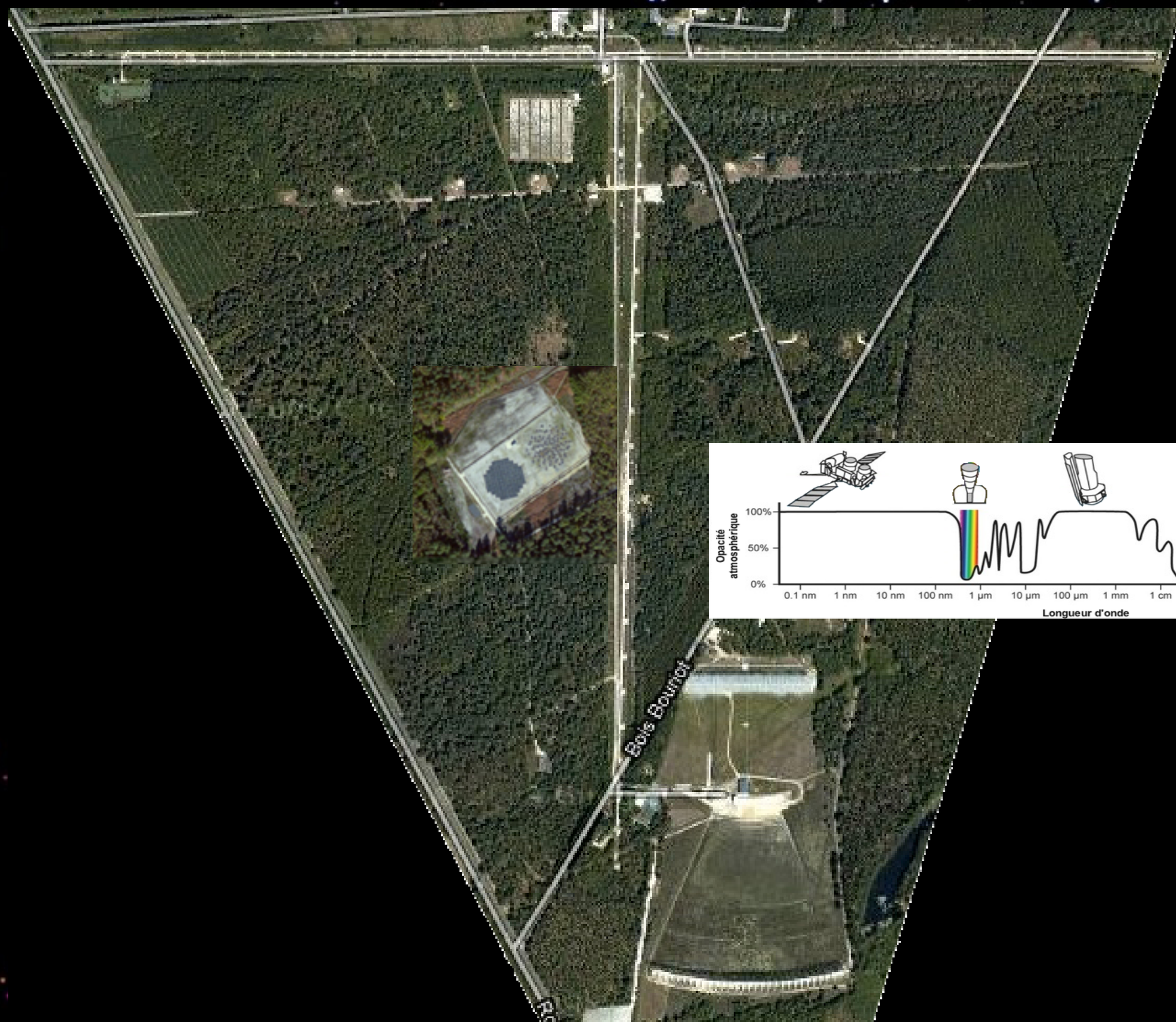
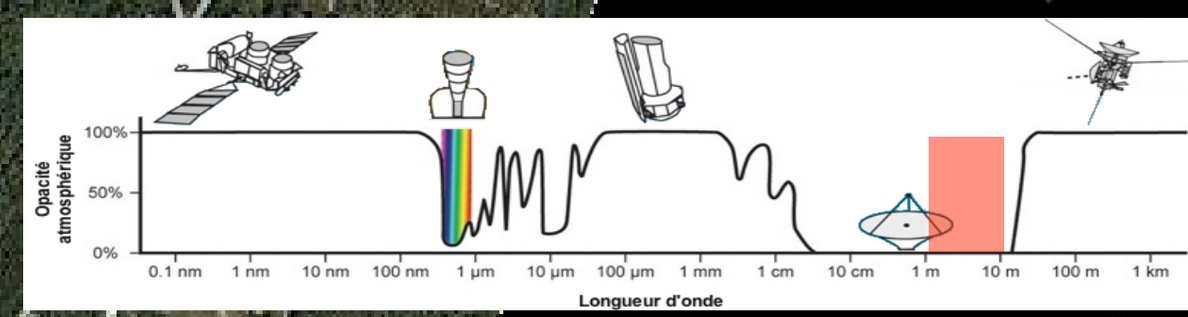
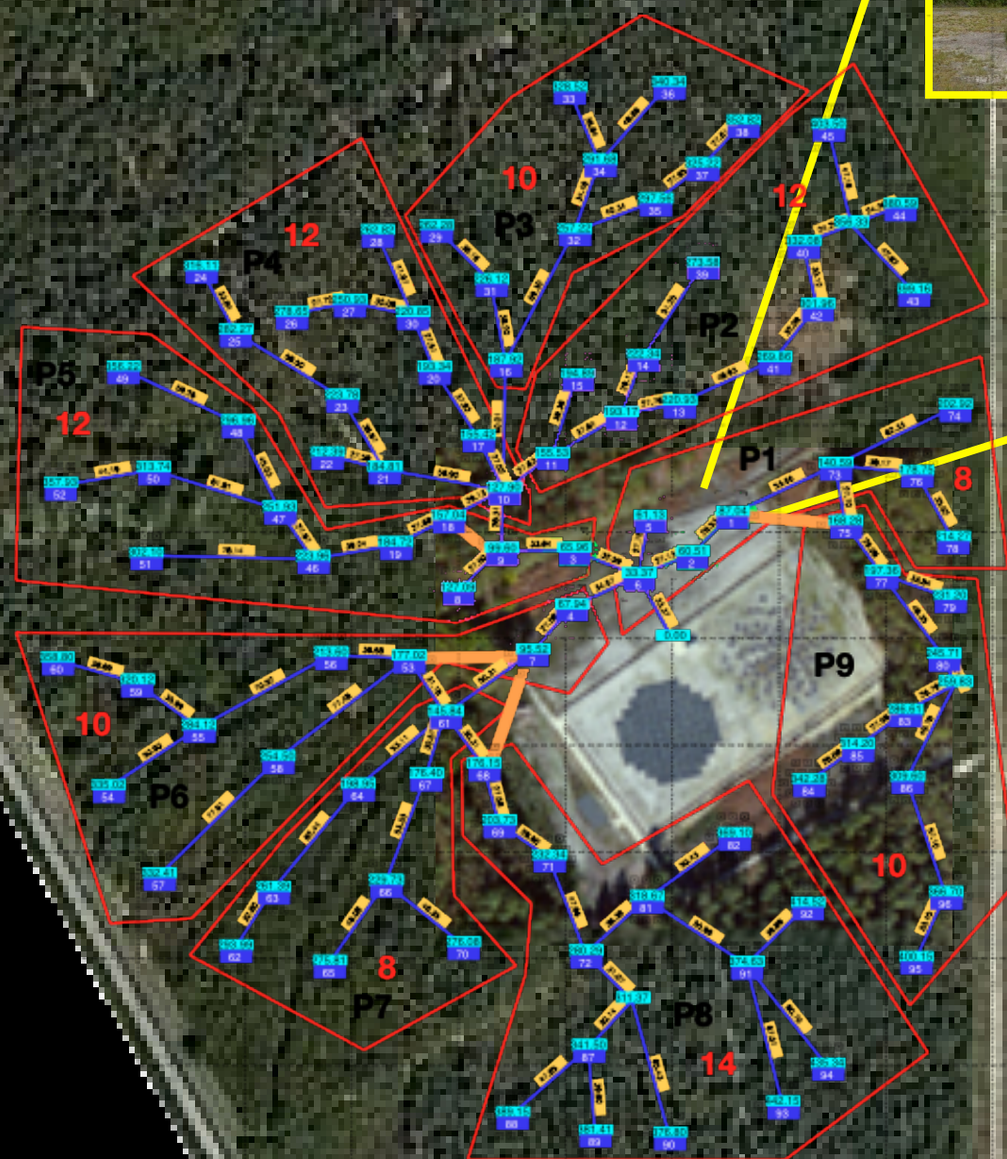
From LOFAR (FR606) to …

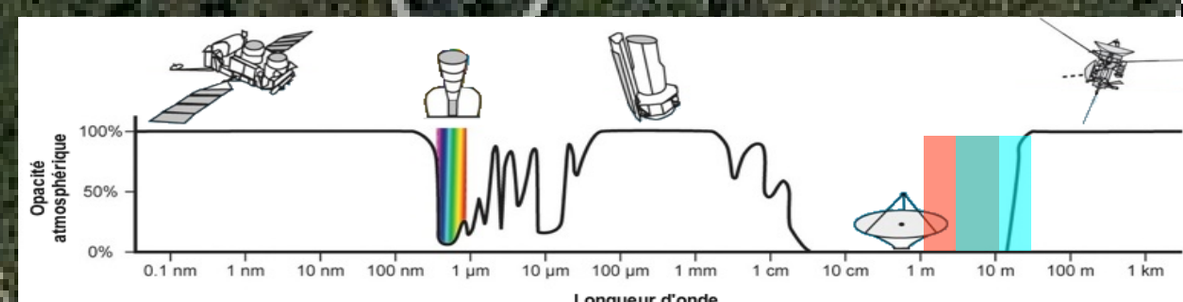




… NenuFAR

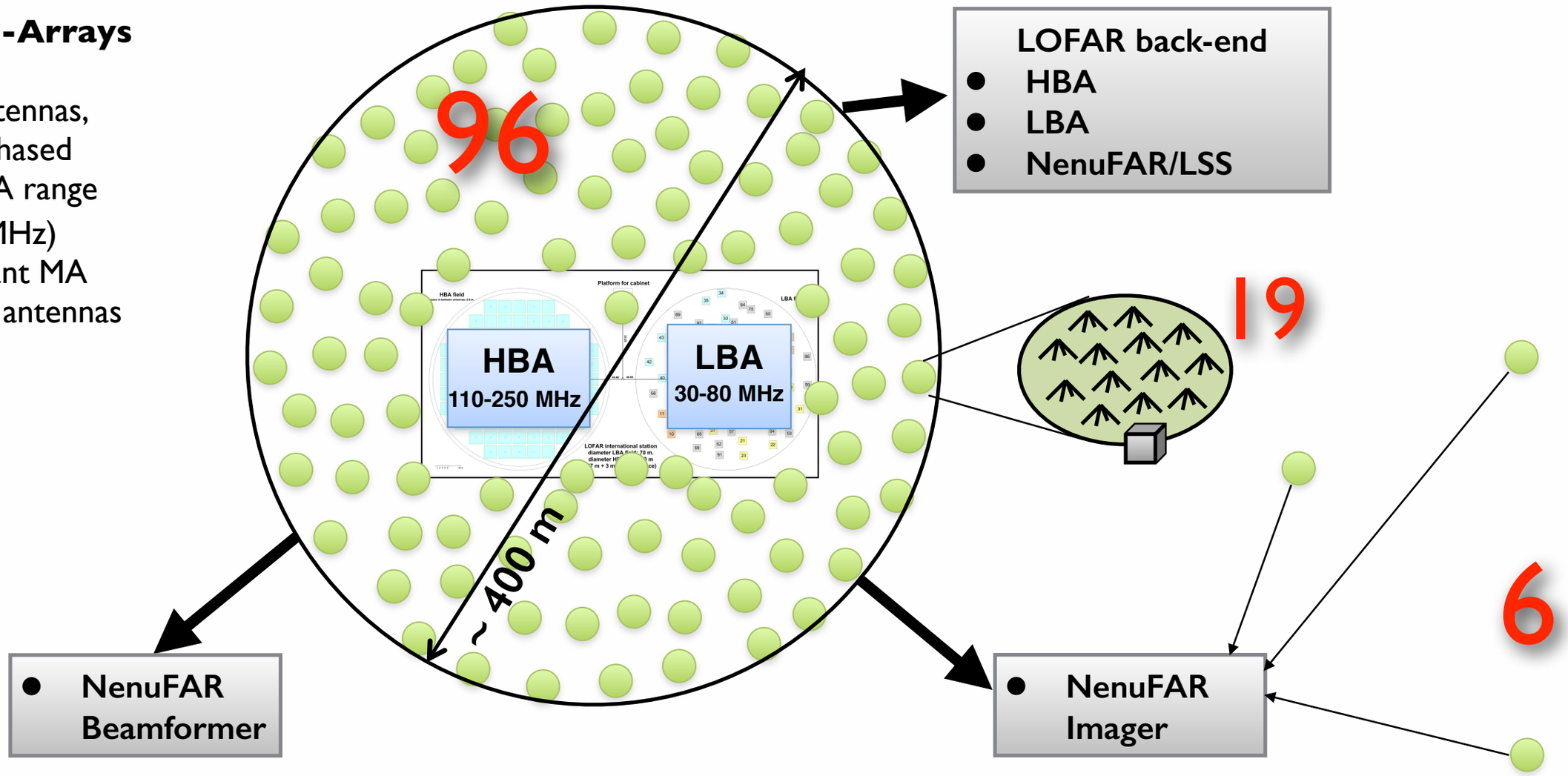
New extension in Nançay upgrading LOFAR





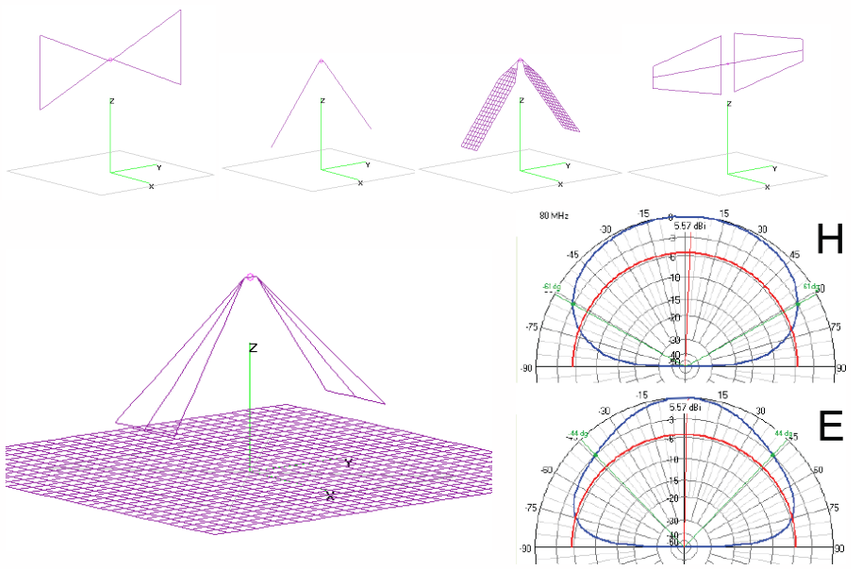
Concept

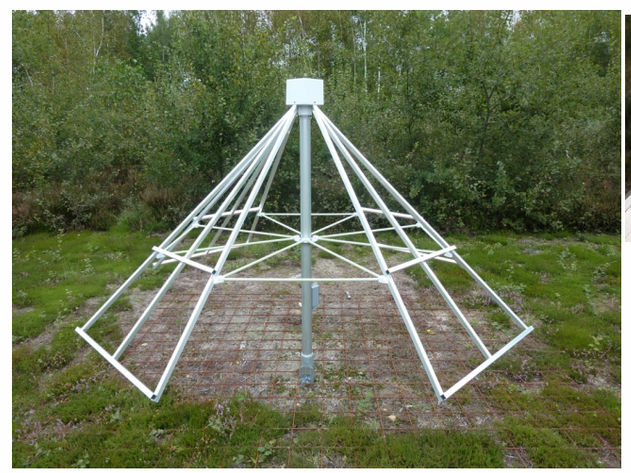
96 **Mini-Arrays**
(LF tiles)
of 19 antennas,
analog phased
Δf ⊃ LBA range
(10-87 MHz)
+ 6 distant MA
→ 1938 antennas

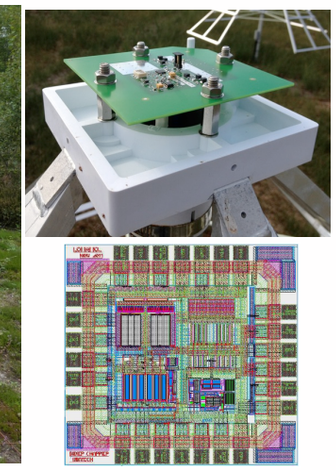


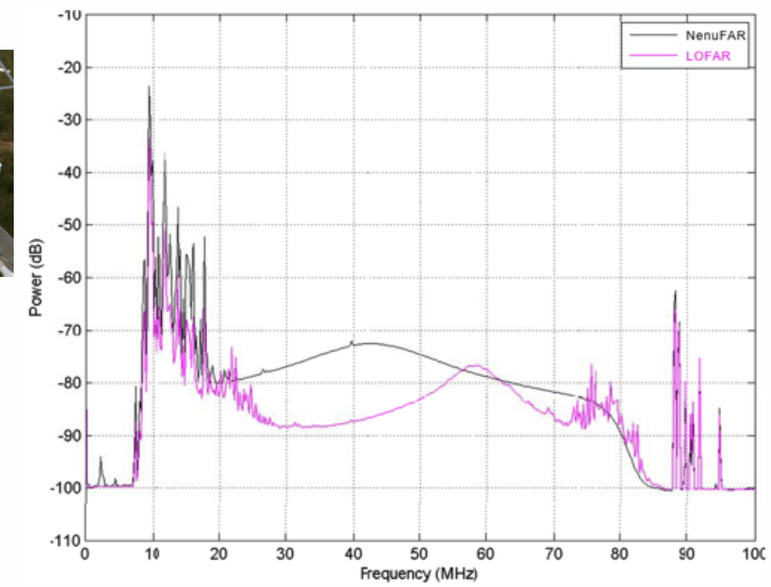
- Standalone Beamformer
- Standalone Transient Buffer
- Standalone Imager
- LOFAR Super Station

Antenna (+ preamplifier) & Sensitivity

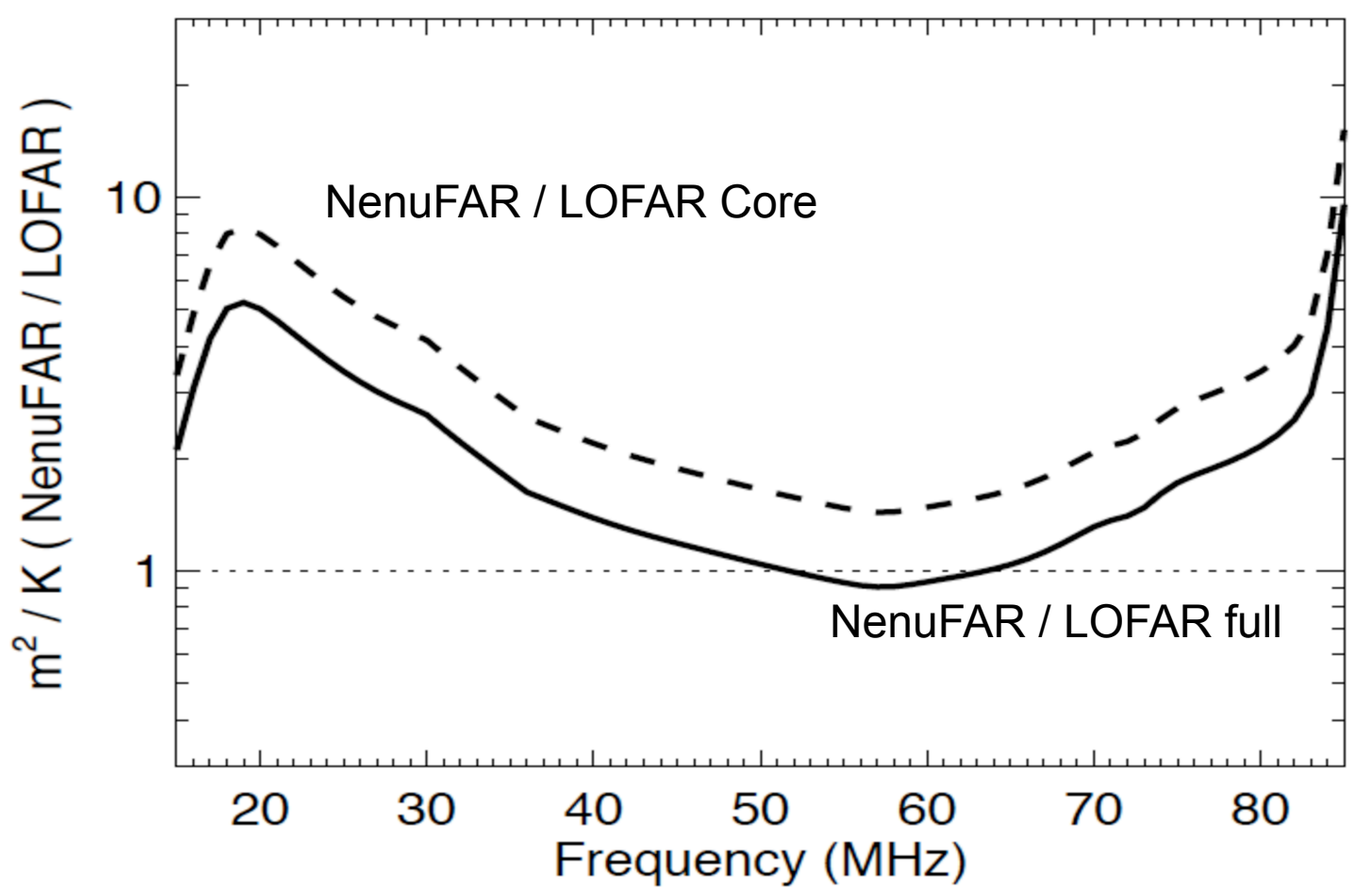






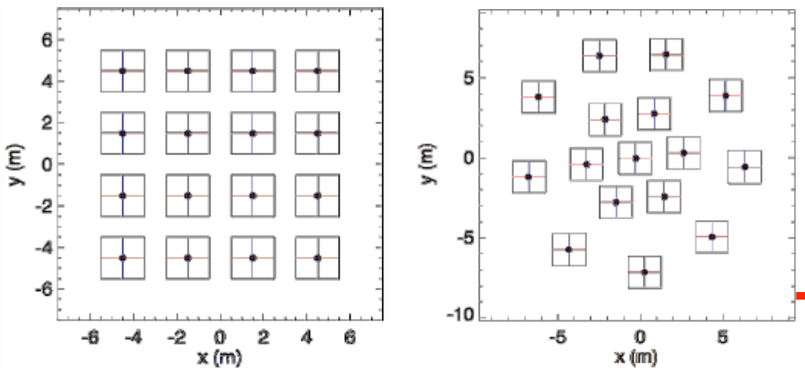


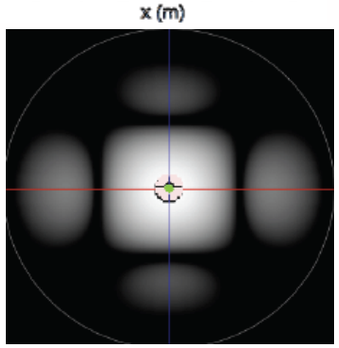
- Good LF antenna radiator + LNA [Hicks et al., 2012 ; Girard et al., 2012 ; Charrier et al., 2014]
- Ground plane improves antenna response and avoids variation / t of ground properties



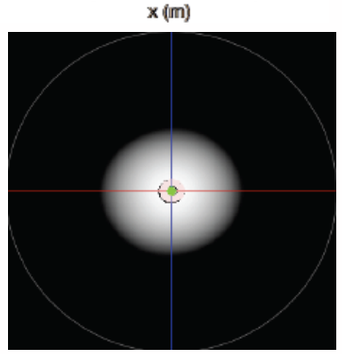
Mini-Array

40 MHz

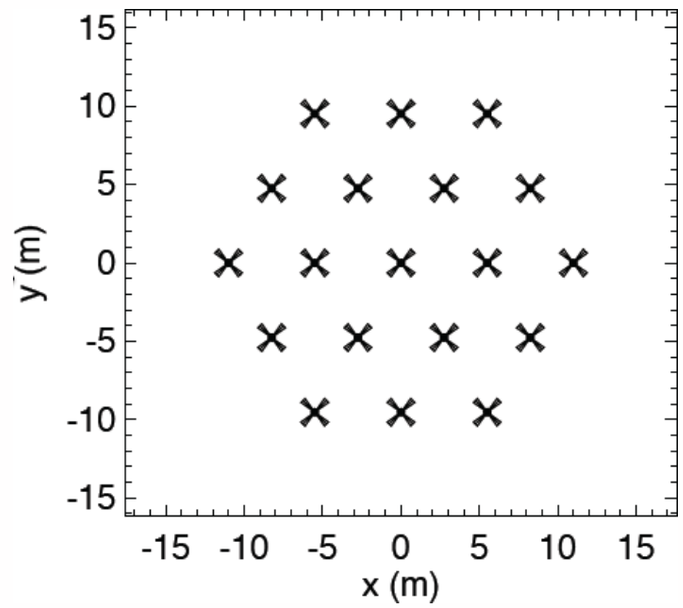


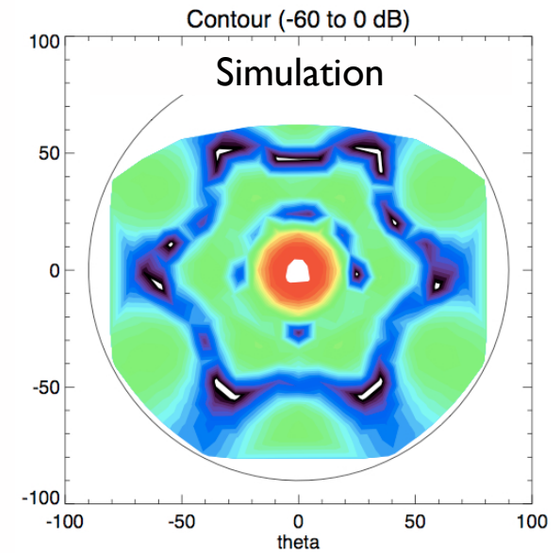


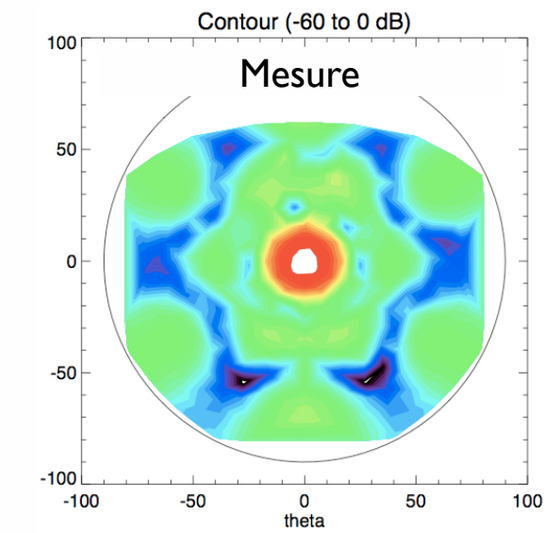
-15 dB sidelobes

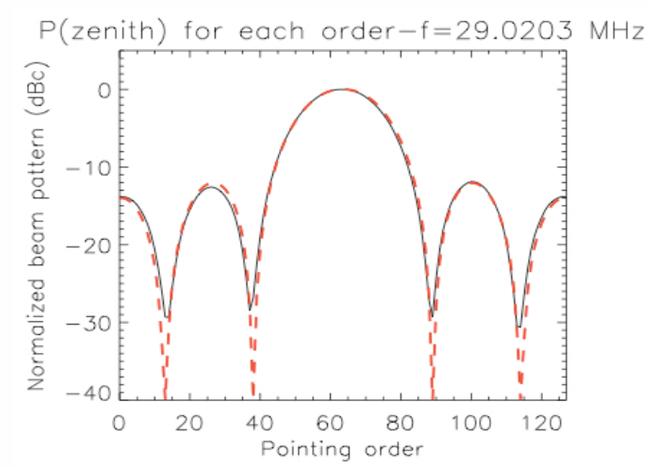


-32 dB sidelobes





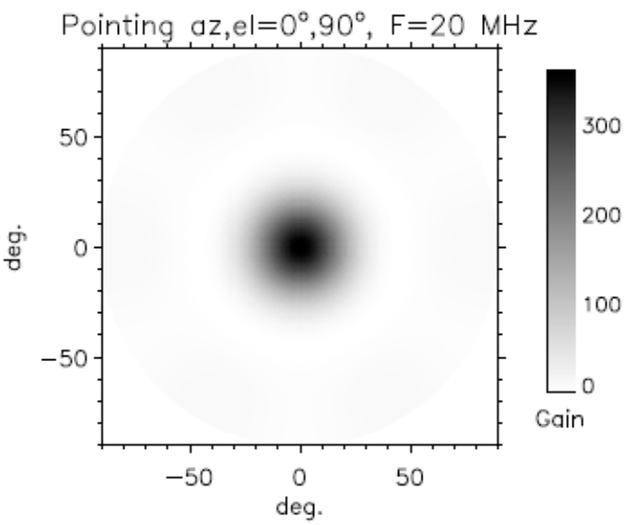


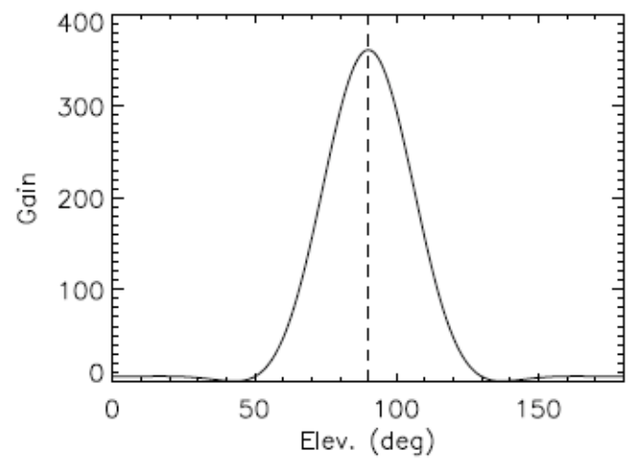


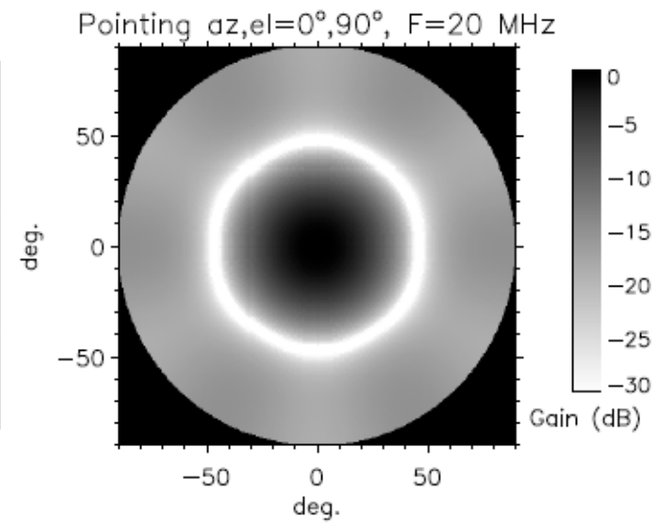
- Optimized 19-antenna distribution within Mini-Arrays

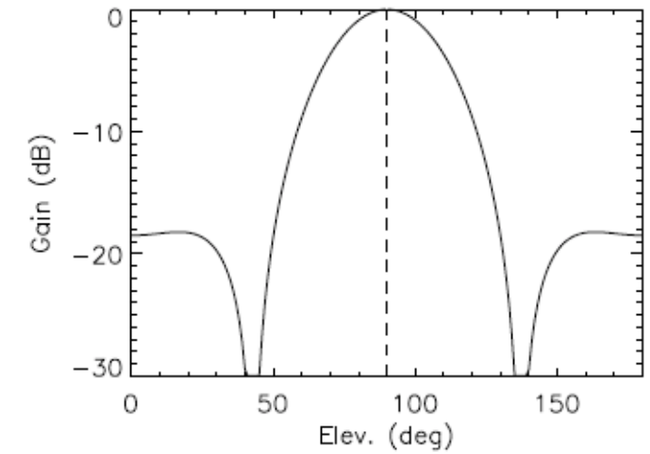
Mini-Array

- f = 20 MHz

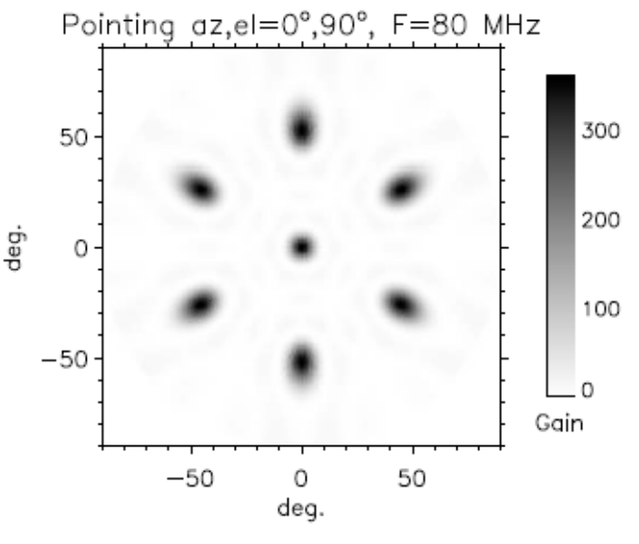


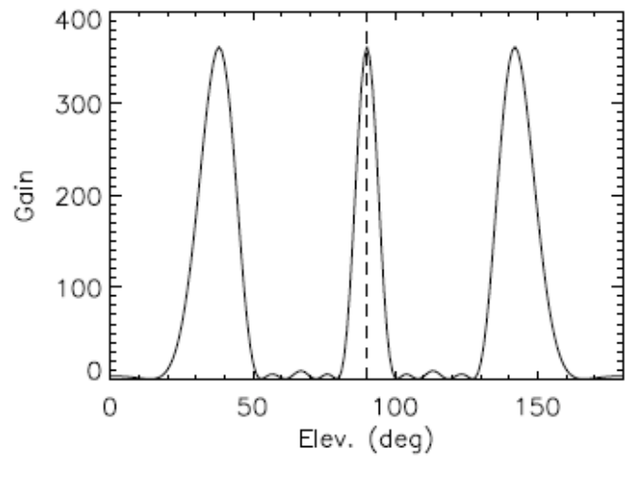


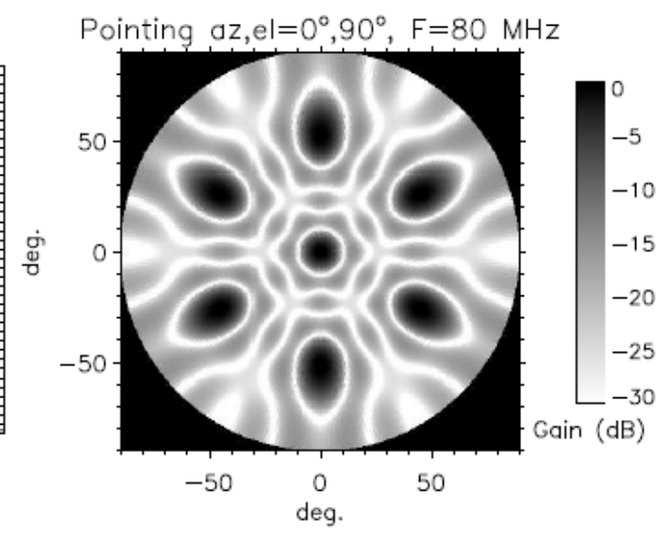


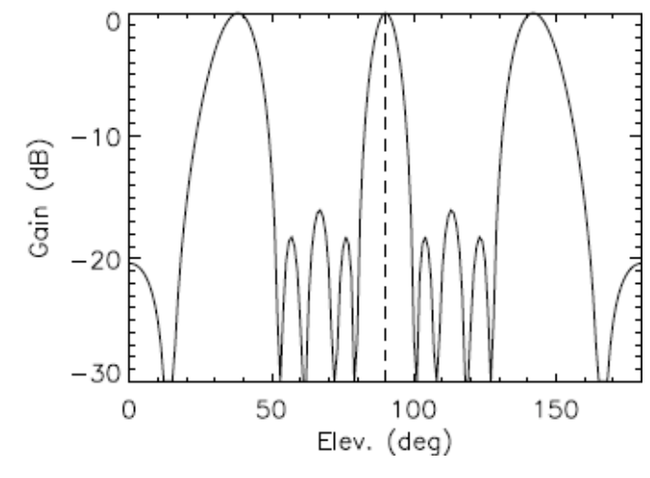


- f = 80 MHz

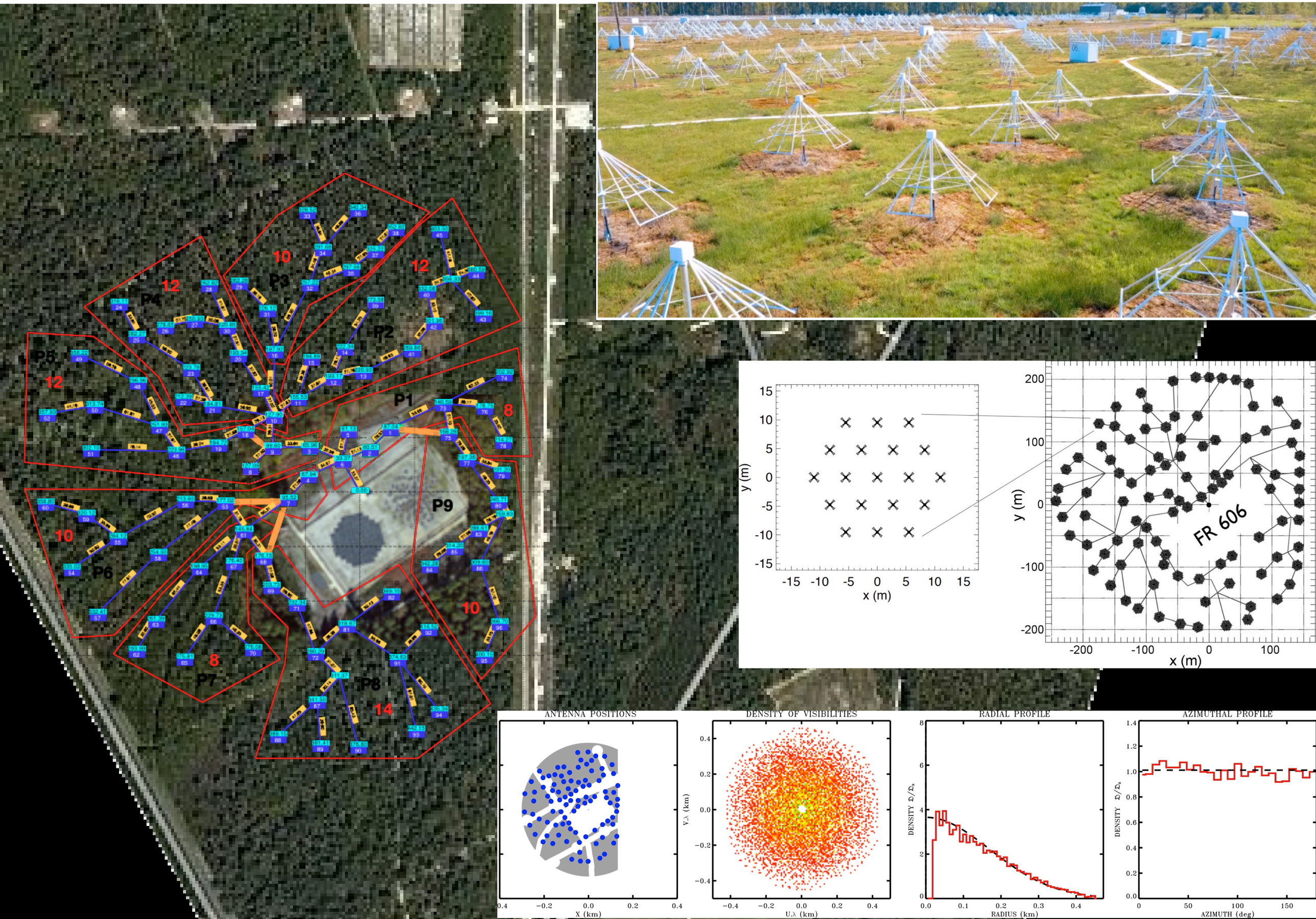




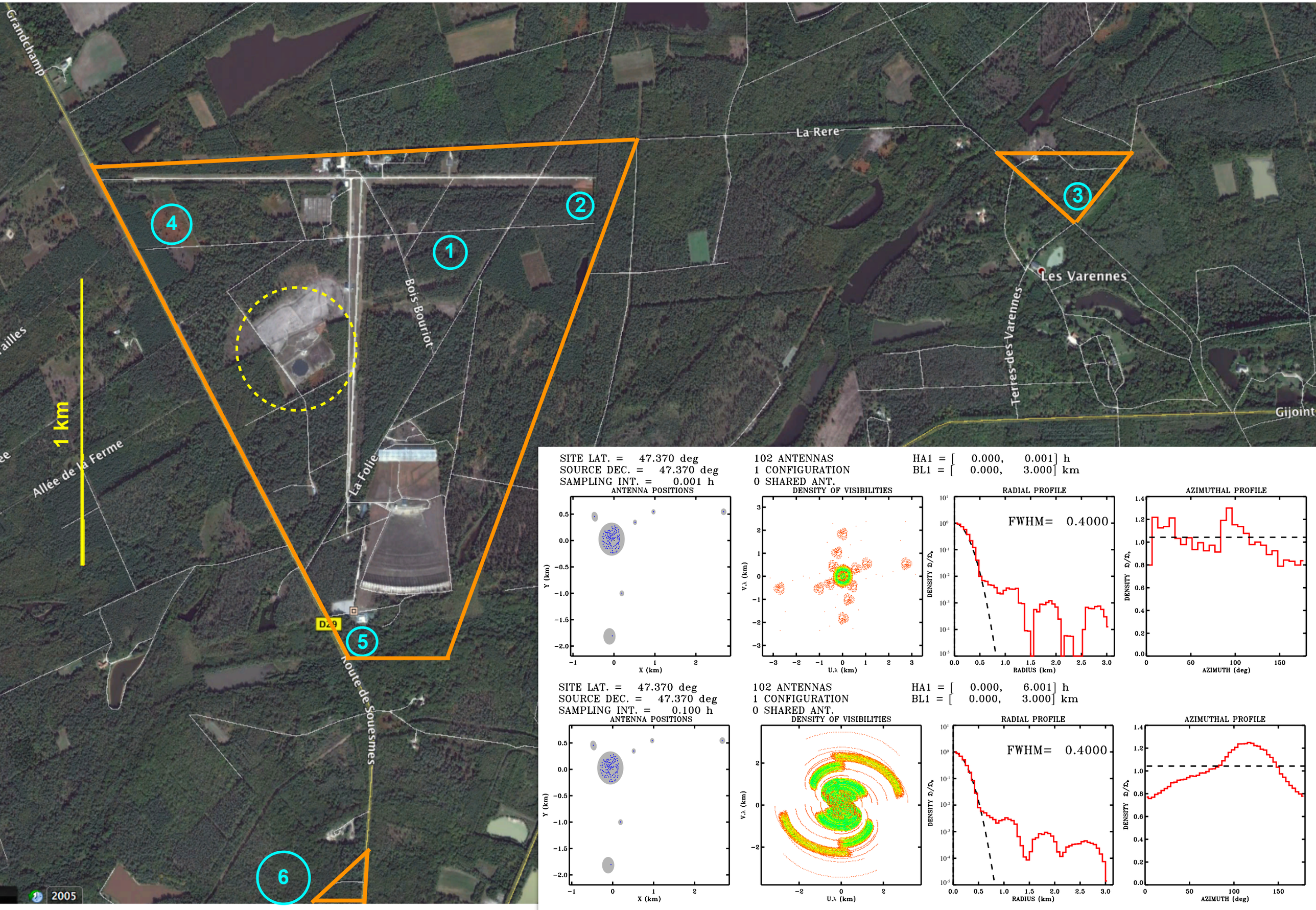




NenuFAR array

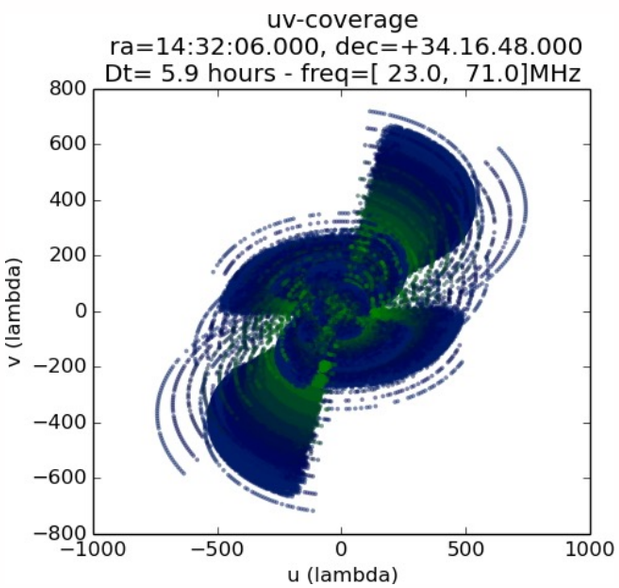


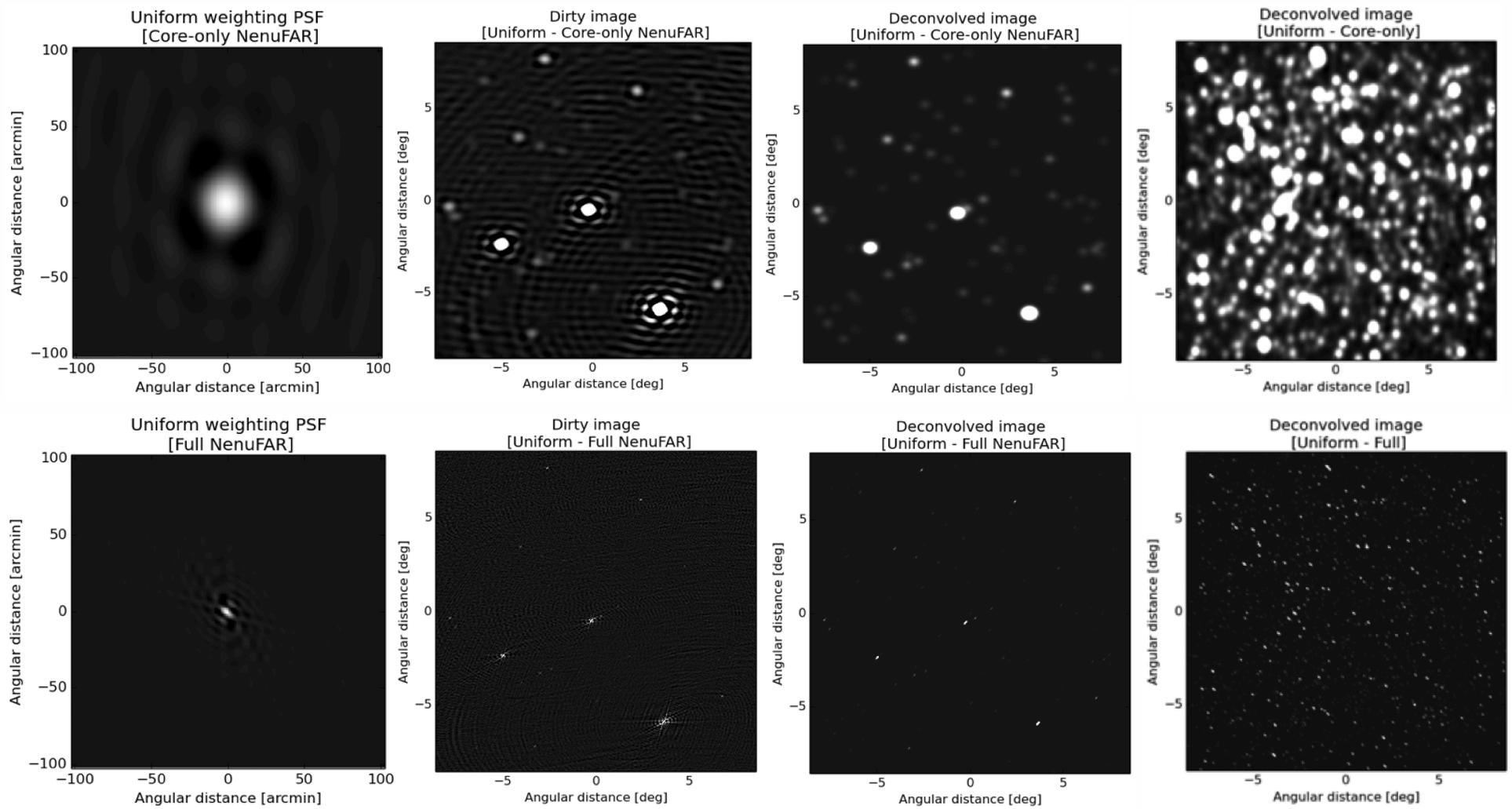
NenuFAR array



NenuFAR imager

- $\sigma_{confusion}$ [mJy/beam] ~ $(\nu$ / 100 MHz$)^{-0.7}$ $(\theta$ / ' $)^2$ [Condon, 2002, 2005] → 1-50 Jy @ 20-80 MHz (unpolarized signal)
- 6 distant MA + multi-λ synthesis → angular res. x 7 for stationnary broadband sources → $\sigma_{confusion}$ / 50
- Relative sensitivity beyond compact core = $(N_{distant}/N_{core})^{1/2}$ ~ 25%
- Synchronization via White Rabbit
- Correlator under study (COBALT-2 vs FPGA)



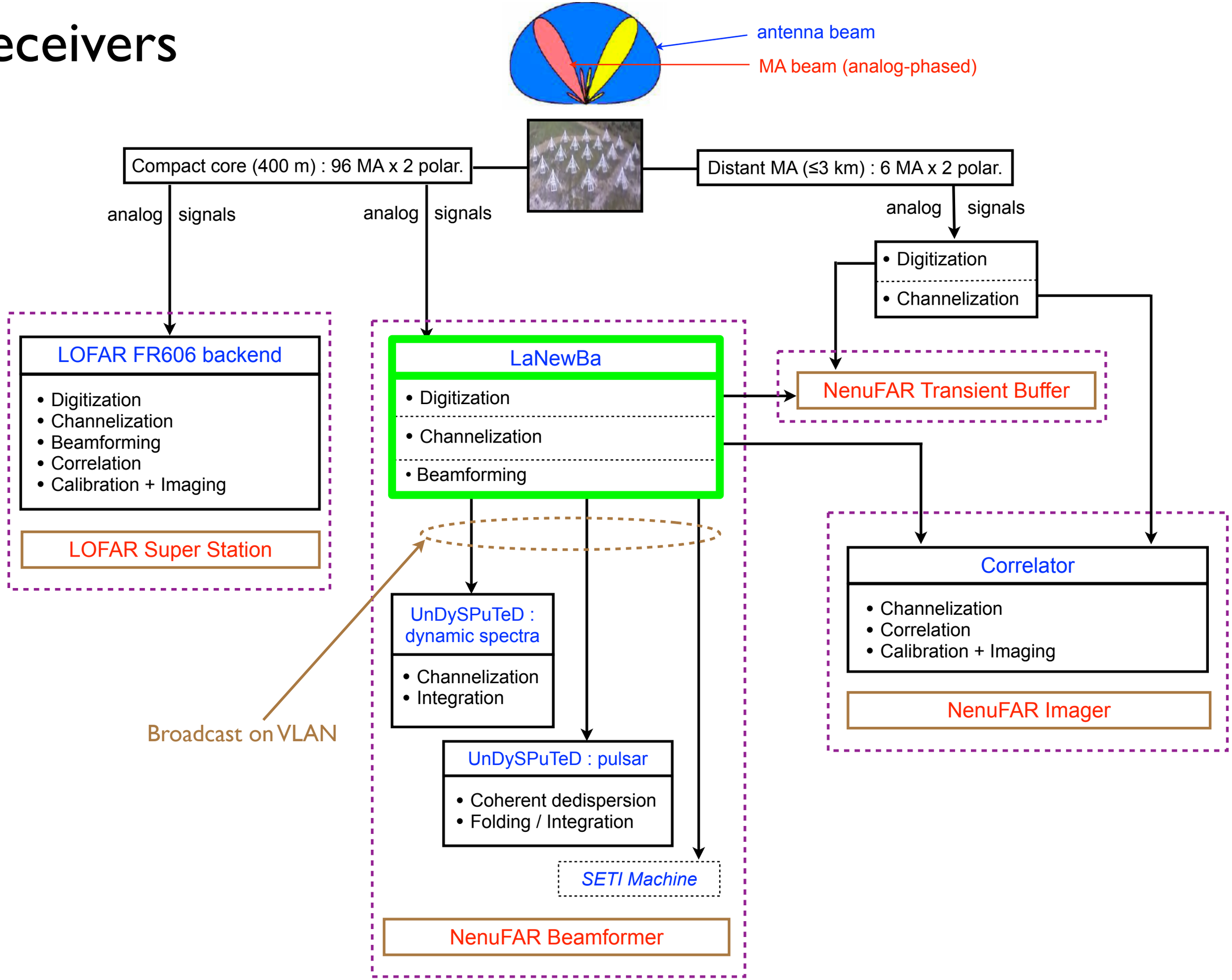


NenuFAR array

Frequency (MHz)	Wavelength (m)	$A_{e\text{-}dipole}$ (m^2)	$A_{e\text{-}MA}$ (m^2)	$A_{e\text{-}core}$ (m^2)	$A_{e\text{-}all}$ (m^2)
15	20.	133	864	83001	88189
27	11.1	41	568	54612	58025
48	6.2	13	247	23750	25234
85	3.5	4	78	7574	8047

Frequency (MHz)	Wavelength (m)	θ_{MA} (°)	FoV_{MA} ($°^2$)	θ_{core} (°)	θ_{all} (')
15	20.	46	1650	2.9	23
27	11.1	26	509	1.6	13
48	6.2	15	161	0.9	8
85	3.5	8	51	0.5	4

Receivers


antenna beam
MA beam (analog-phased)
Compact core (400 m) : 96 MA x 2 polar.
Distant MA (≤3 km) : 6 MA x 2 polar.
analog signals
analog signals
analog signals
• Digitization
• Channelization
LOFAR FR606 backend
• Digitization
• Channelization
• Beamforming
• Correlation
• Calibration + Imaging
LOFAR Super Station
LaNewBa
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• Channelization
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NenuFAR Transient Buffer
Correlator
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• Calibration + Imaging
NenuFAR Imager
UnDySPuTeD : dynamic spectra
• Channelization
• Integration
UnDySPuTeD : pulsar
• Coherent dedispersion
• Folding / Integration
SETI Machine
NenuFAR Beamformer
Broadcast on VLAN

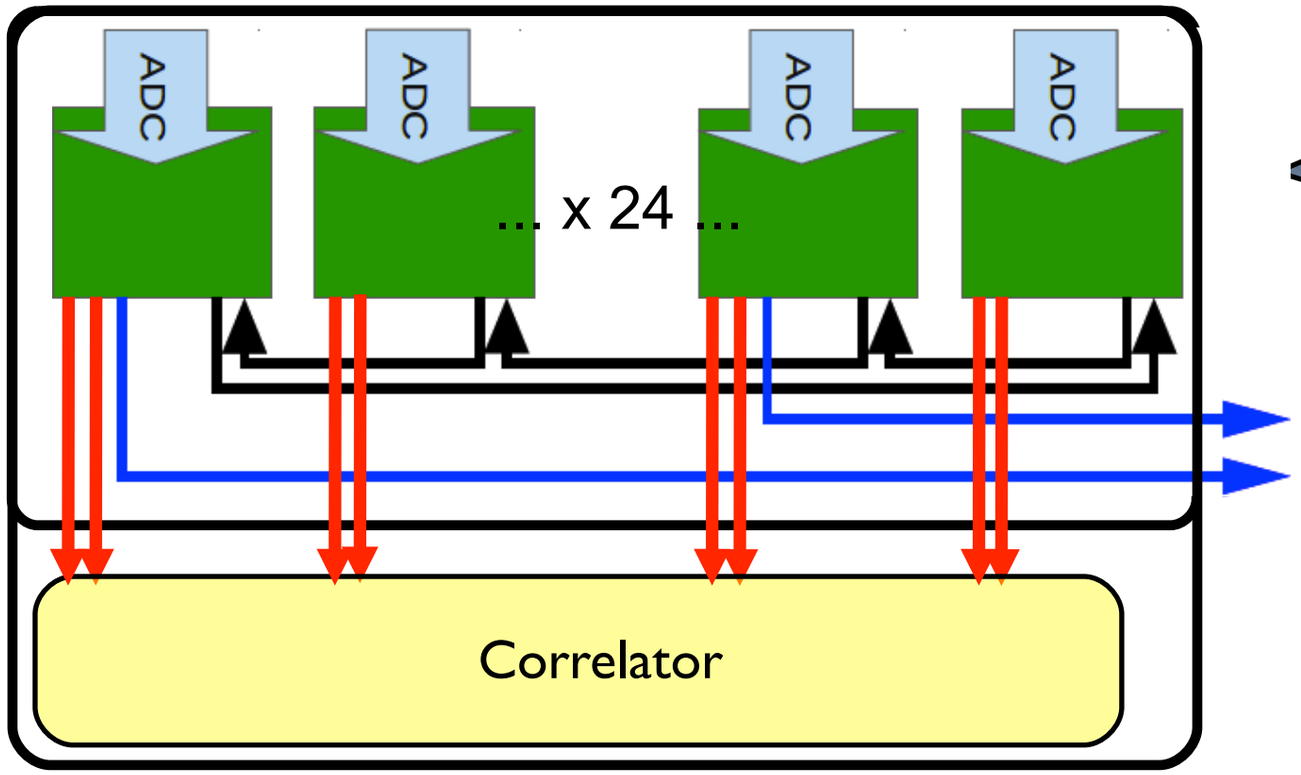
LANewBa (LOFAR-like Advanced New Backend) **(CV)**

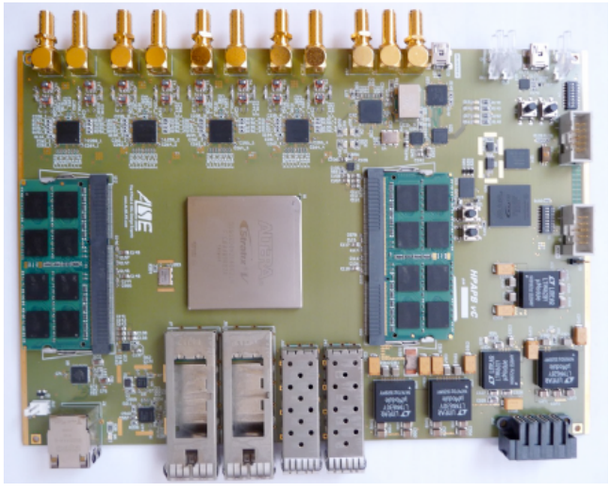
- **Digitization** (96 x 2 x 200 MHz, 14-bits ADCs)

  (~400 MB/s/input, 77 GB/s for full NenuFAR Core, 24/7)

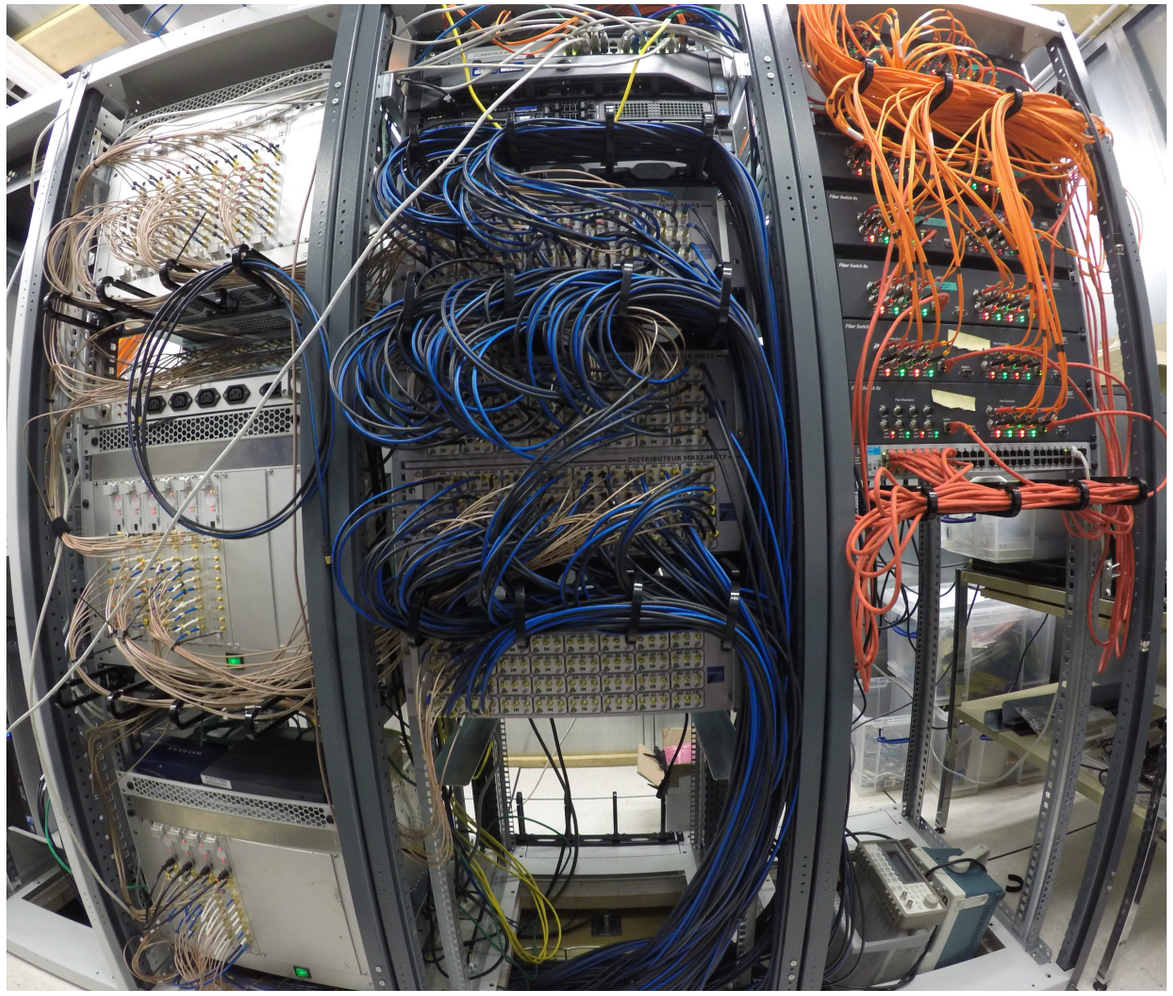
- **Signal processing** implemented on 24 FPGA compute nodes (ALSE+USN+LOFAR RSP)
  - **Channelization** (PFB+FFT) in 512 x 195.3125 kHz subbands (hereafter 200 kHz SB)
  - **Beamforming** (phased array mode)
    - Beamlet = 200 kHz SB in selected (θ,φ) direction (200 k-complex/s per beamlet)
    - Selection of up to 768 beamlets from 512 ~ 2 full-band 75 MHz beams
    - Phasing using complex weighting (Narrow band approximation)
    - Distributed sum over a ring, synthesized beam exported at 2x 300-600 MB/s
    - Broadcast to multiple listeners on VLAN
- **Output** selected subbands to a 102 x 102 correlator
- **Parallel computation of Crosslet STatistics** (XST, 16 SB/s)
- **TBB** :
  - 5 s of raw ADC data from all Mini-Arrays
  - Software trigger and built-in hardware trigger

LANewBa (LOFAR-like Advanced New Backend)

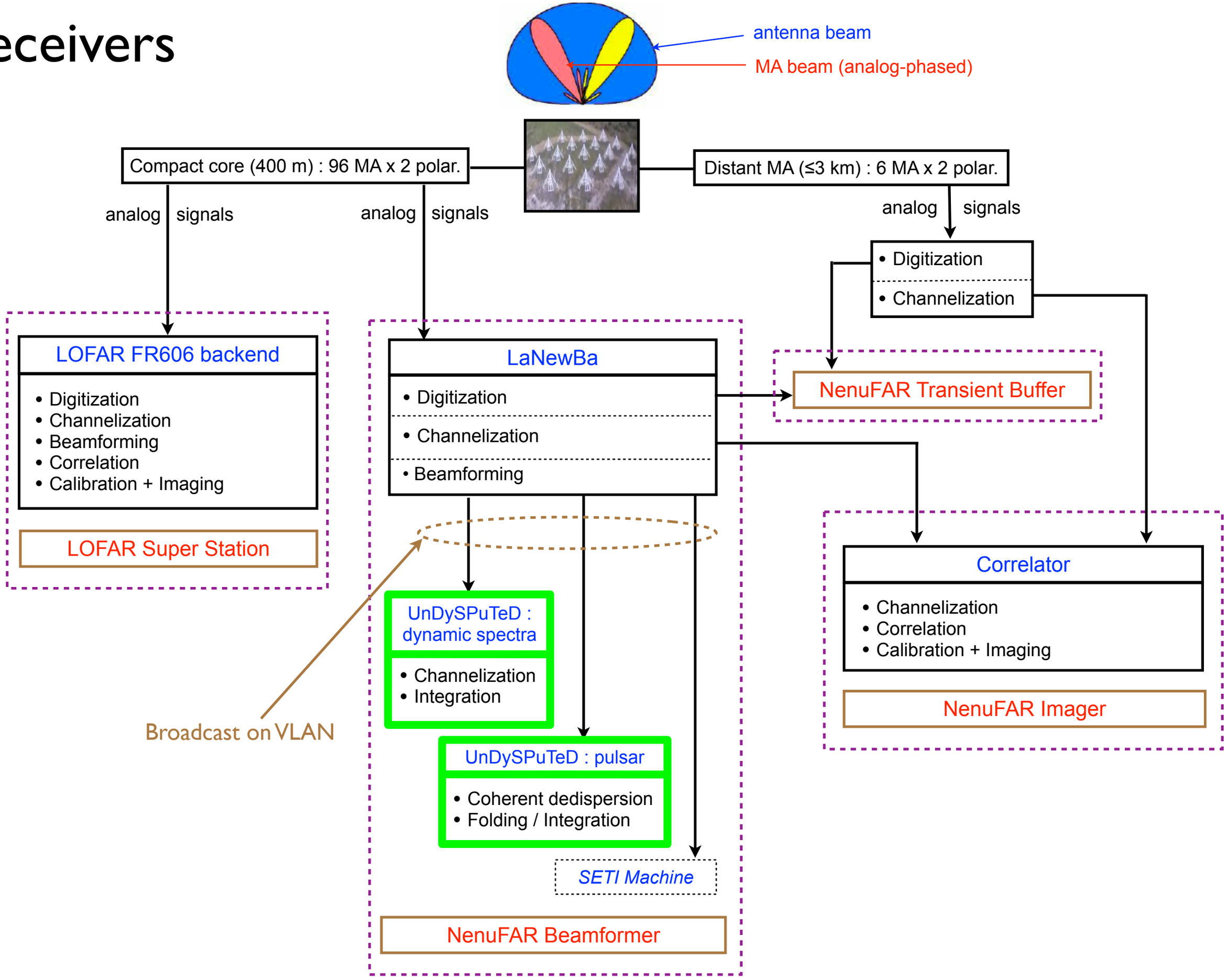




2 beams full-band (~10-85 MHz), full-polar.



Receivers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NenuFAR Imager

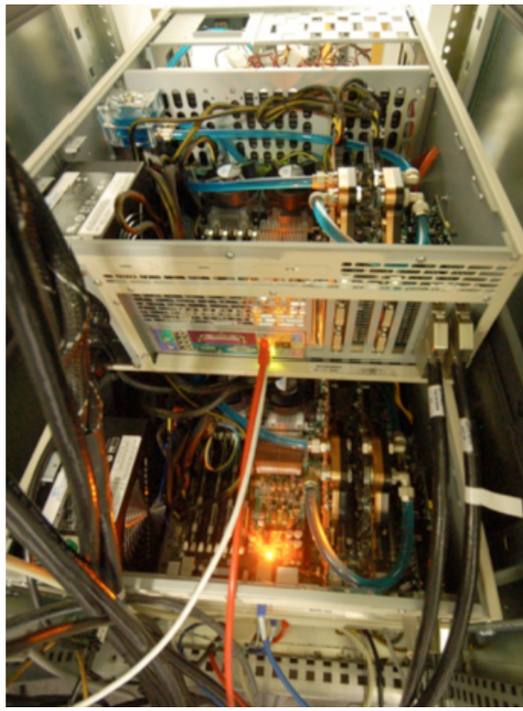
UnDySPuTeD calculators

(IC)

- **2 identical servers** CPU + GPUs (~2 GFlops)
- **2 operating modes** : Pulsar & Time-Frequency (Dynamic Spectrum)
  - Processing per lane of 192 beamlets (2 lanes / server)
  - **Pulsar** : coherent dedispersion in 200 kHz SB, folding, integration, 4 Stokes

    → **LB**

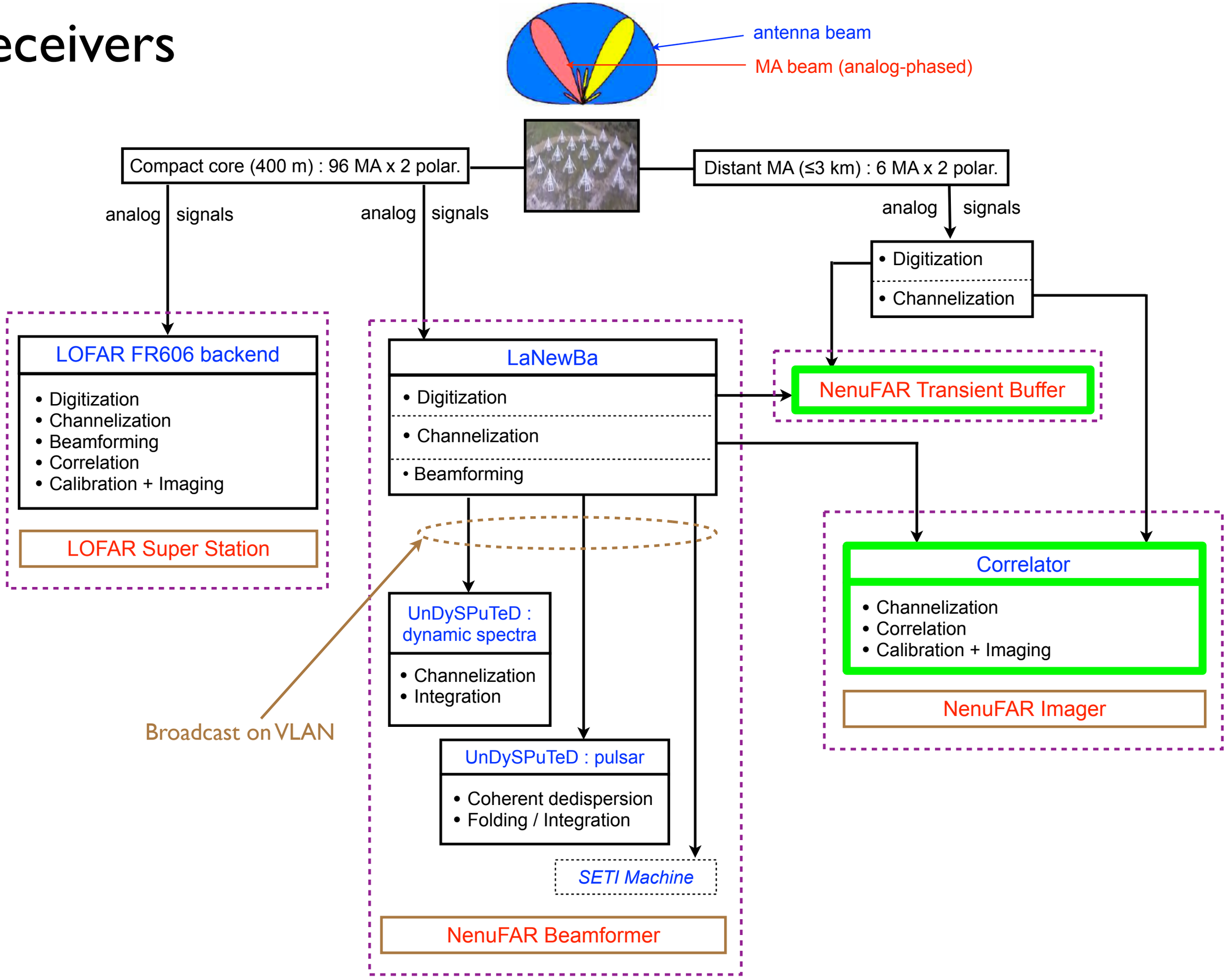
    (incoherent sum mode possible only with 200 kHz spectral resolution)
  - **Dynamic spectrum** : channelization down to 0.2 kHz (FFT, 1024 channels), integration / t down to 1 msec, 4 Stokes
- **Waveform dump** (beamformed, in 200 kHz beamlets)



SETI receiver in project

- In discussion with Berkeley/Breakthtough Listen lab. + ICRAR/Curtin Univ.
- Plugged to VLAN
- Piggyback mode only

Receivers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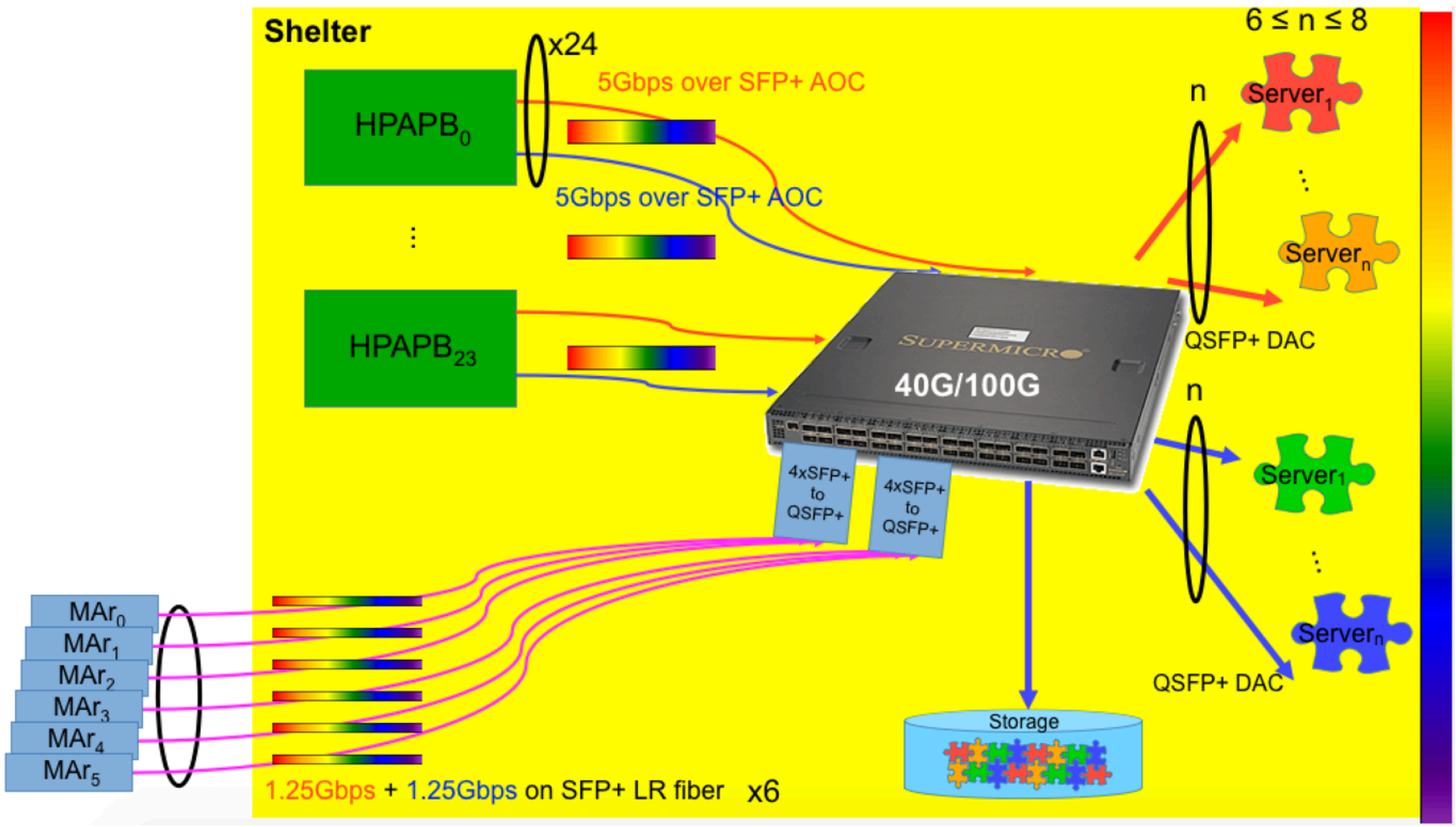
NenuFAR Imager

Correlator and TBB

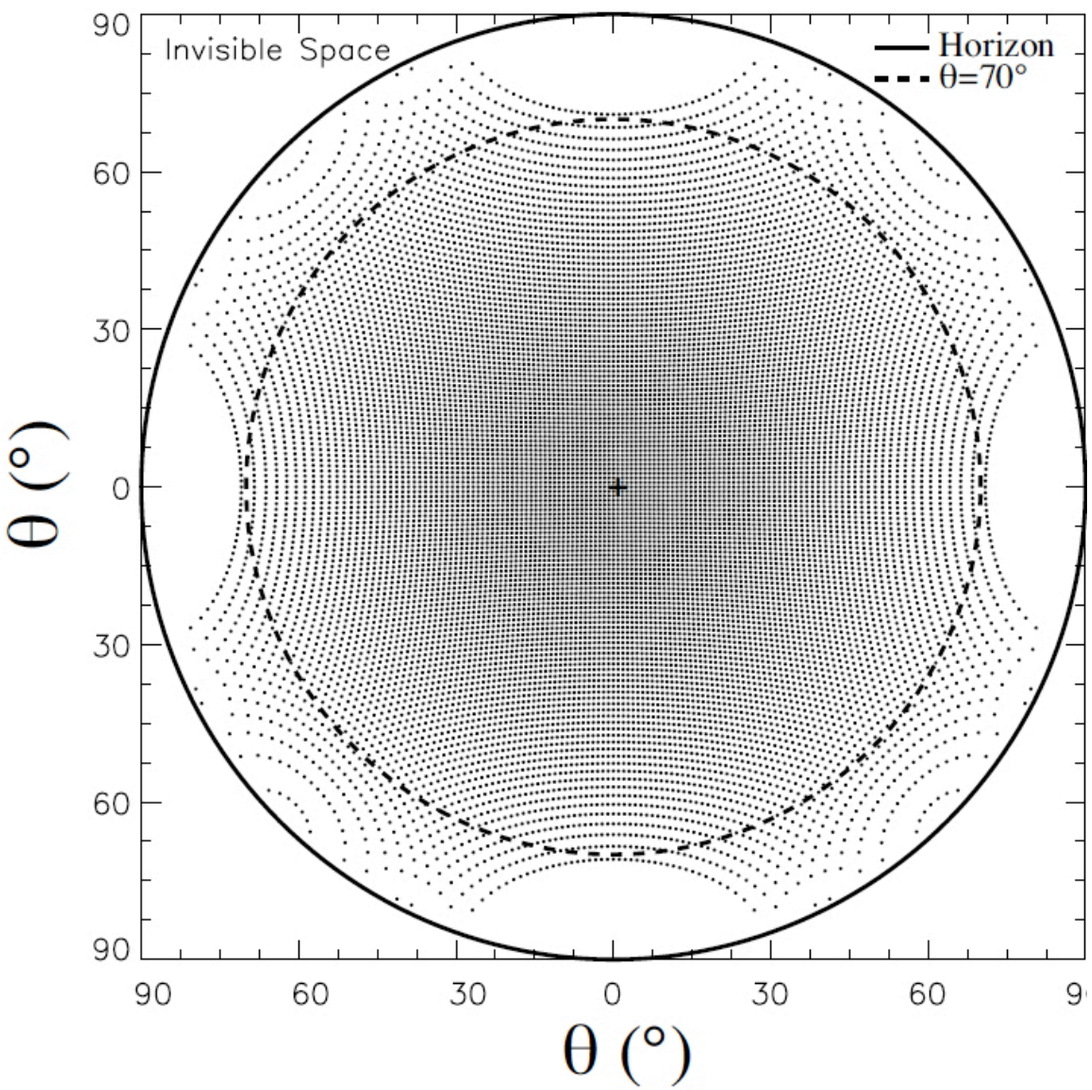
(CV)

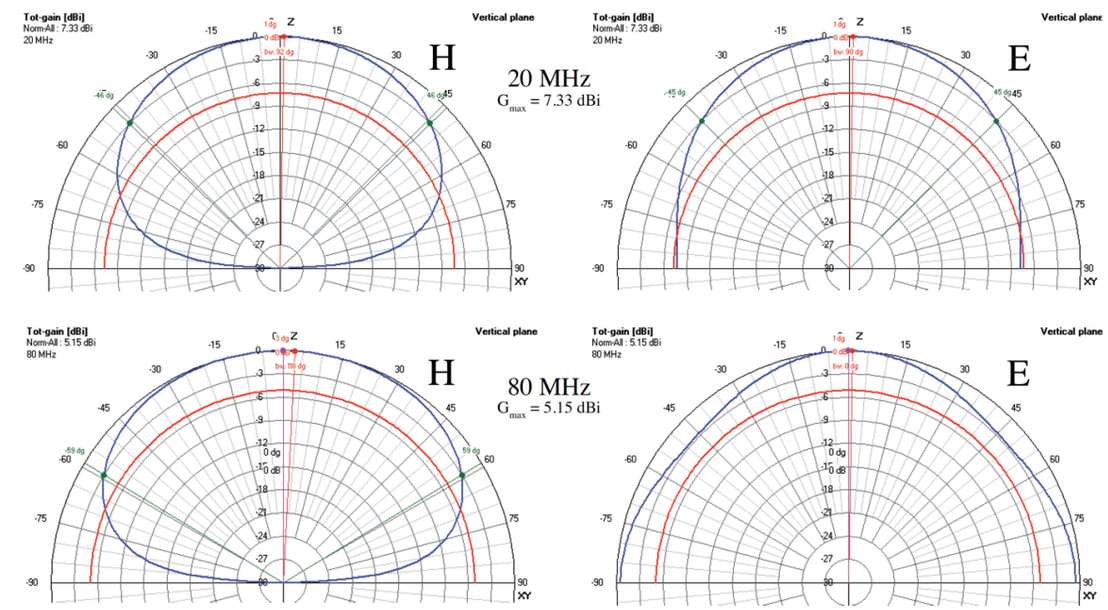
- Correlator, tbd COBALT-2 or FPGA-based
  - fed by LaNewBa
  - 75 MHz instantaneous bandwidth, 384 beamlets, df = 3 kHz, dt = 0.5-2 s
- TBB : 5 s of raw ADC data from all Mini-Arrays, Software trigger and built-in hardware trigger

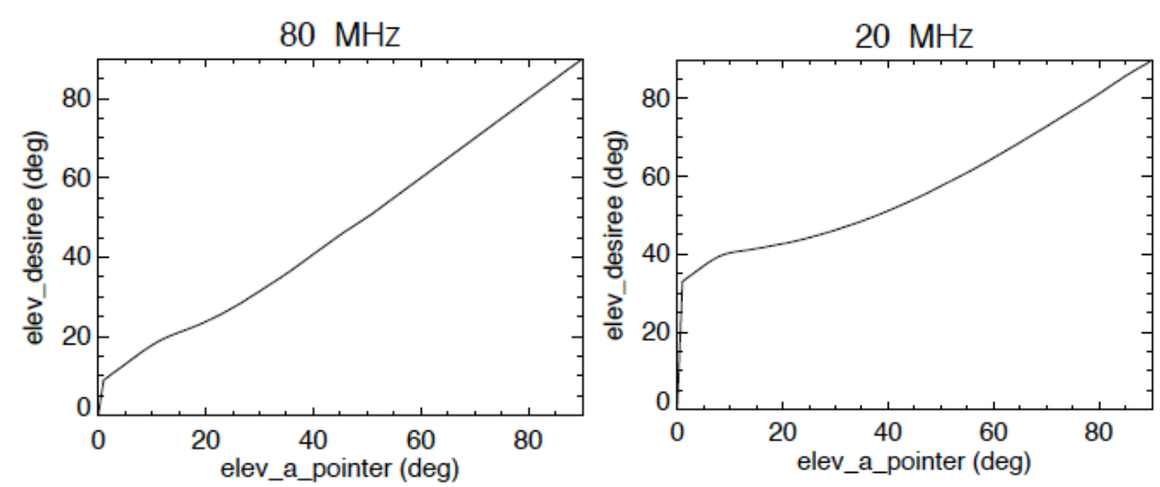


Pointing

- **Analog** pointing of Mini-Arrays :
  - 128 x 128 pointable positions > 20° elevation
  - from declination δ = -23° to δ = +90°
  - beam squint (elevation >20° !)
  - silent pointing system, 10 sec scheme



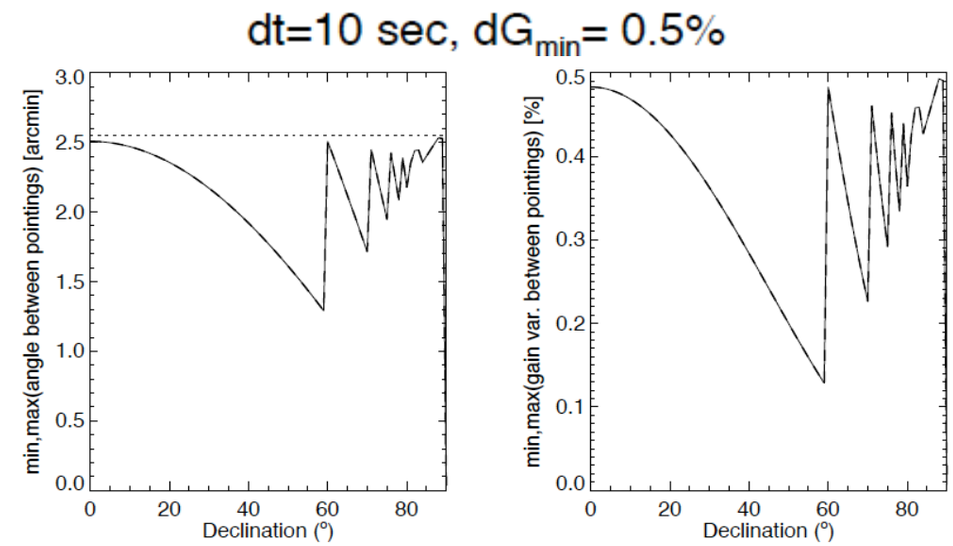




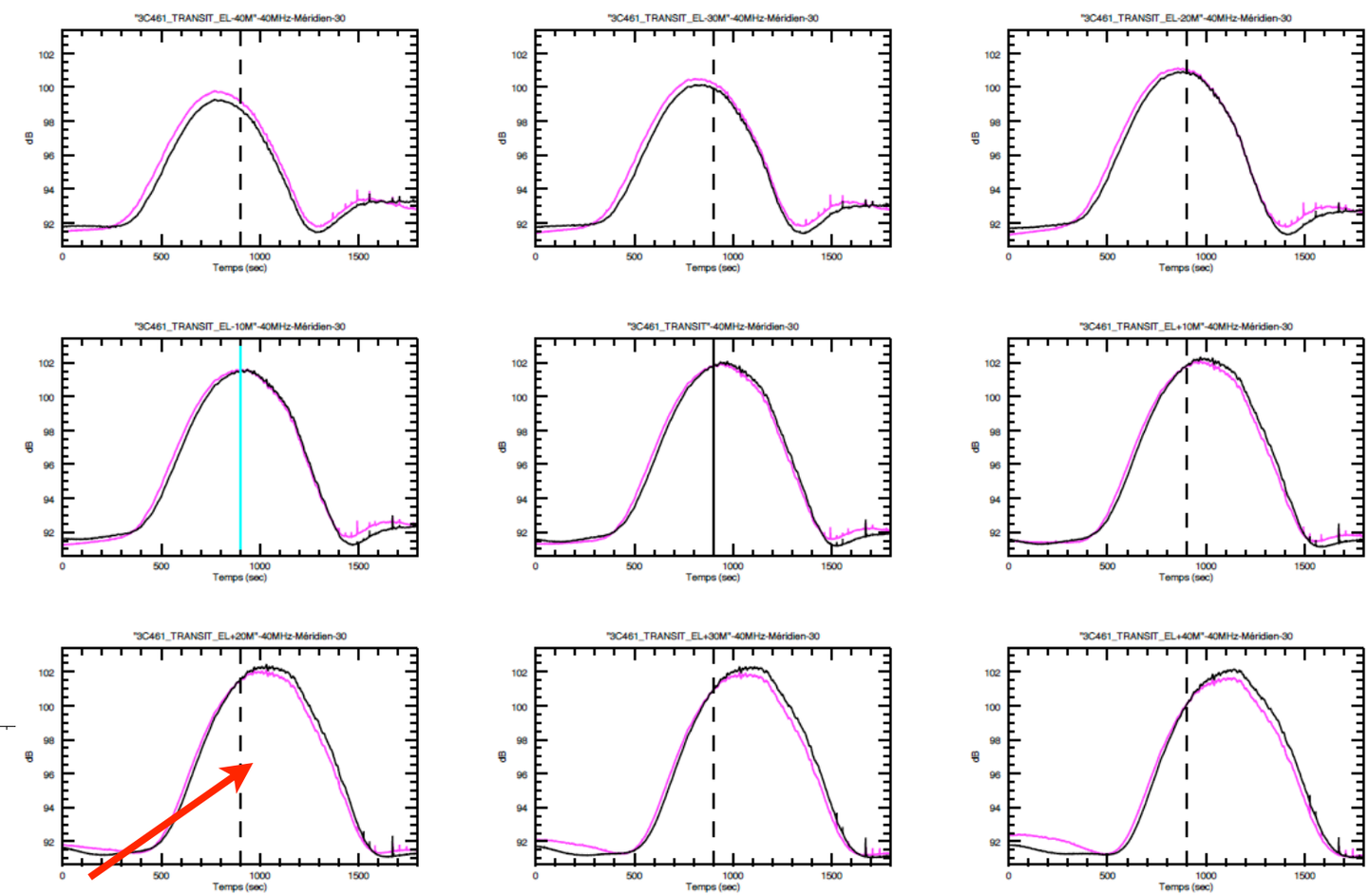
Pointing

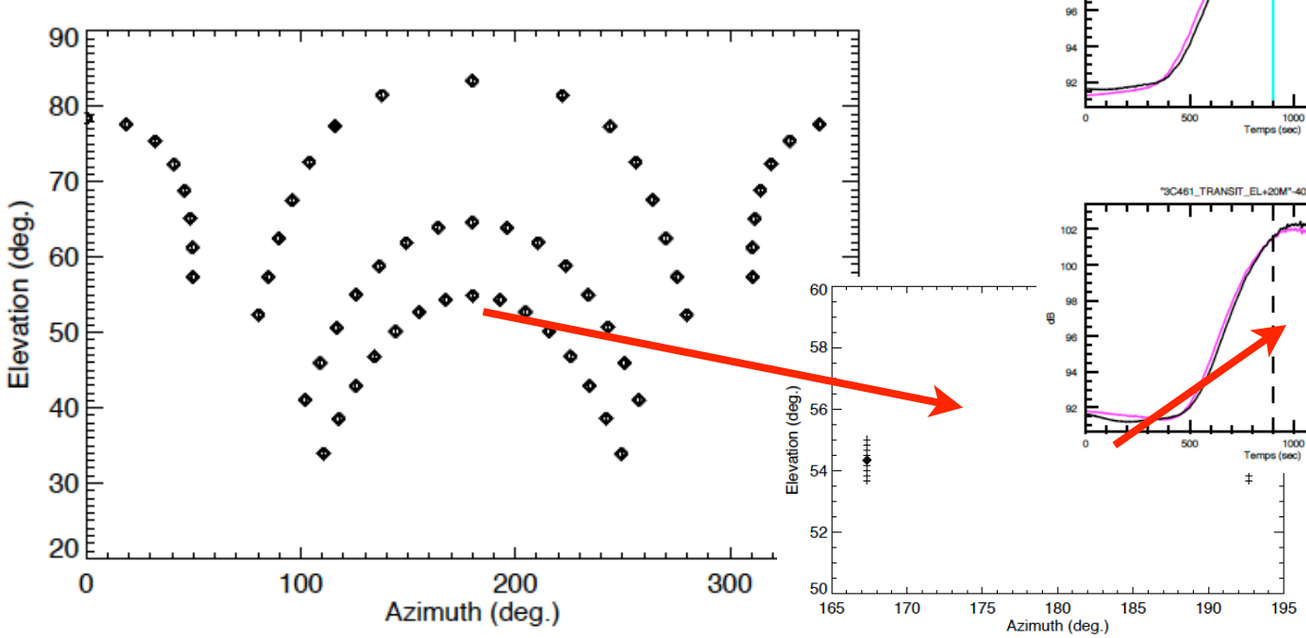
- **Digital** pointing of NenuFAR :
  - real, computed : tracking (RA,δ), fixed pointing or table (az,el)

    IMCCE Web-service for Solar system bodies
  - 10 sec scheme (±5 sec) → <0.5% gain variations

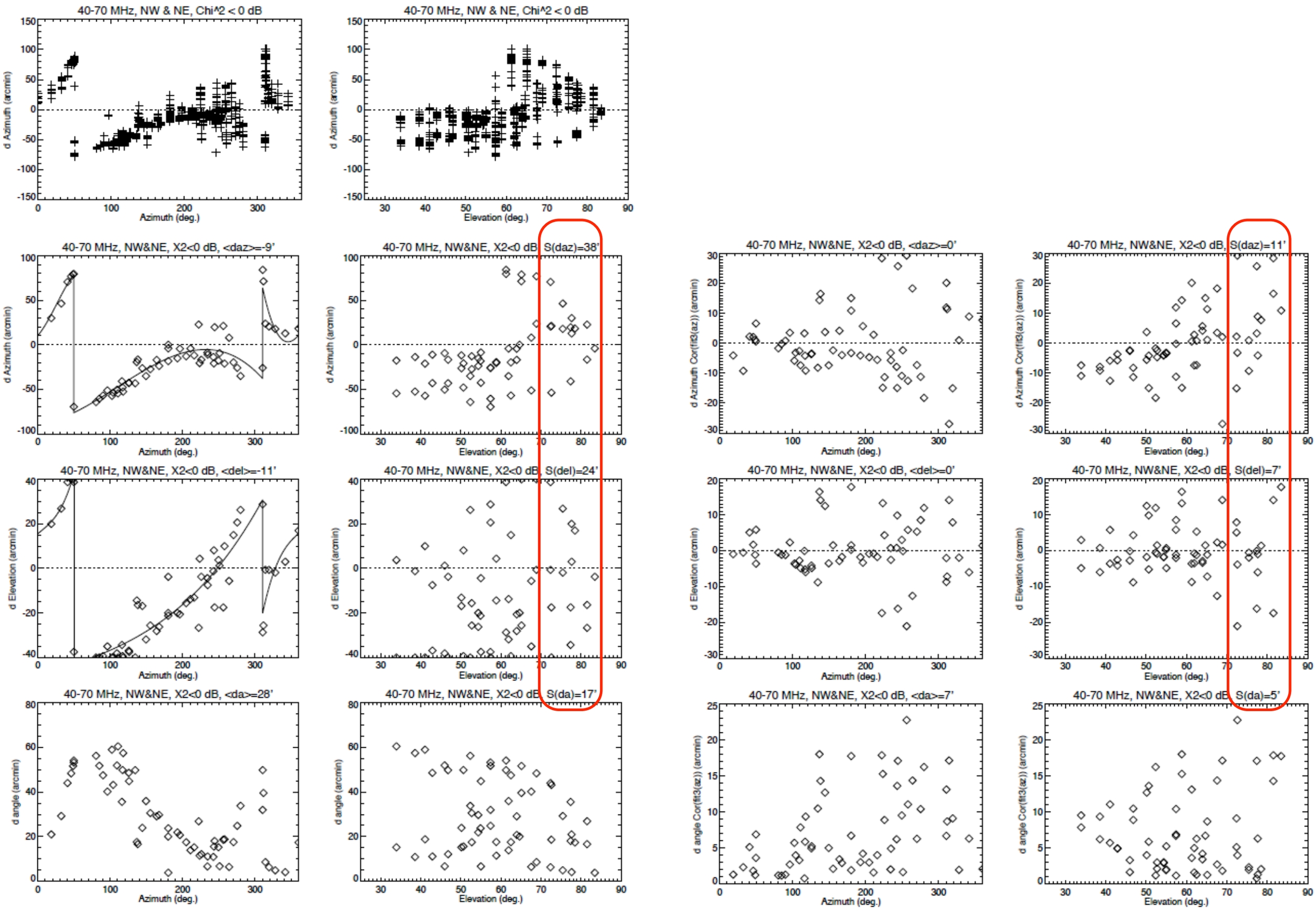


- Pointing **error** (~LWA) :
  - 10' - 100' depending on az (el)
  - correction from multi (9) beam multi-transits
  - ≠ global sky rotation (≠ LWA)
  - order 3 polynomial vs azimuth
  - accuracy reached ~5' (1 σ)





Pointing


40-70 MHz, NW & NE, Chi^2 < 0 dB
d Azimuth (arcmin)
Azimuth (deg.)
40-70 MHz, NW & NE, Chi^2 < 0 dB
d Azimuth (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <daz>=-9'
d Azimuth (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(daz)=38'
d Azimuth (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <daz>=0'
d Azimuth Cor(fit3(az)) (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(daz)=11'
d Azimuth Cor(fit3(az)) (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <del>=-11'
d Elevation (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(del)=24'
d Elevation (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <del>=0'
d Elevation (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(del)=7'
d Elevation (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <da>=28'
d angle (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(da)=17'
d angle (arcmin)
Elevation (deg.)
40-70 MHz, NW&NE, X2<0 dB, <da>=7'
d angle Cor(fit3(az)) (arcmin)
Azimuth (deg.)
40-70 MHz, NW&NE, X2<0 dB, S(da)=5'
d angle Cor(fit3(az)) (arcmin)
Elevation (deg.)

Summary of NenuFAR characteristics

- **Number of antennas :** 1938 = 96 core + 6 remote MA of 19 antennas each
- **Dimensions :** MA diameter = 25 m, core diameter ~400 m, remote MA up to ~3 km
- **Number of baselines :** 5151

  = 4560 baselines from 25 m to 400 m + 591 baselines from 400 m to 3 km
- **Frequency range :** 10-85 MHz (λ = 3.5 – 30 m)
- **Time-Frequency resolutions :** δf = 195.3125 kHz x δt = 5.12 µs

  Channelization down to 3.05 kHz x time integration down to 1 ms

  Waveform at 5 ns time resolution
- **Full polarization** (4 Stokes)
- **Collecting area :** from ~220 λ^2 to ~ 650 λ^2 (function of effective area overlap within MA)

  from ~83000 m^2 at 15 MHz to ~7500 m^2 at 85 MHz for the core

  from ~88000 m^2 at 15 MHz to ~8000 m^2 at 85 MHz for core+remote MA
- **Pointing :** from declination δ = -23° to δ = +90°
- **Field of View :** ~46° (1650°^{2}) at 15 MHz to ~8° (51°^{2}) at 85 MHz
- **$Angular Resolution :** from 2.9° at 15 MHz to 0.5° at 85 MHz for the core

  from 23' at 15 MHz to 4' at 85 MHz for the core+remote MA (down to 0.4″ in LSS mode)
- **Sensitivity** (thermal noise) :

  from ~130 mJy at 15 MHz to ~9 mJy at 85 MHz with Δf=10 MHz x Δt=1 h

  (similar values for the core & core+remote MA)
- **Confusion at zenith :**

  from ~120 Jy at 15 MHz to ~2 Jy at 85 MHz for the core

  from ~5 Jy at 15 MHz to ~100 mJy at 85 MHz for the core+remote MA

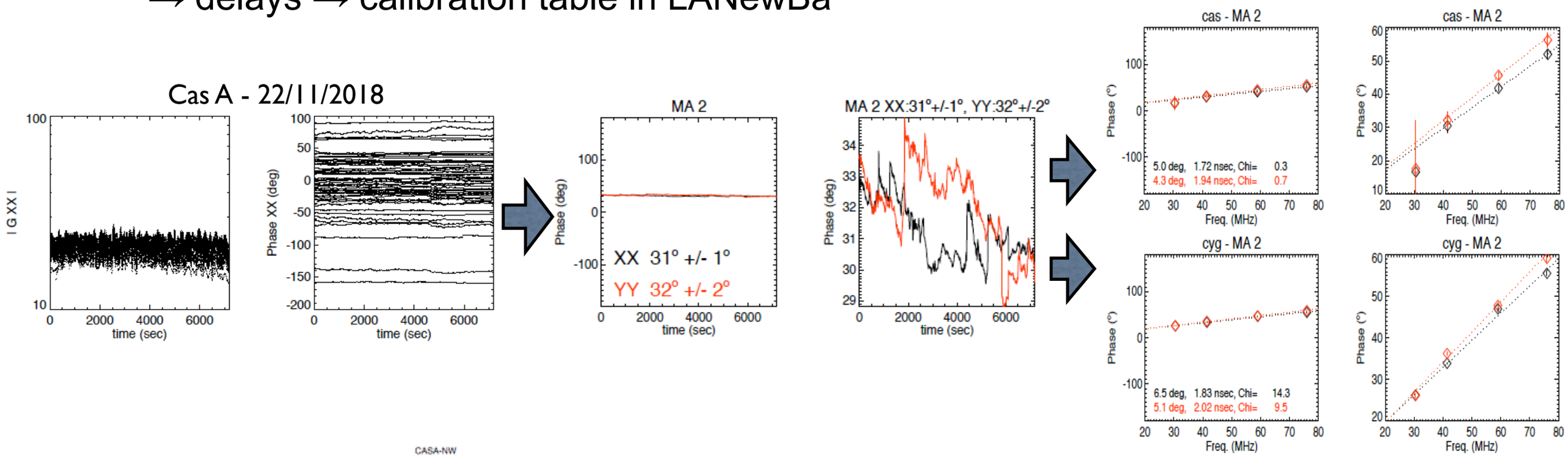
Data products (see details on Astronomers page)

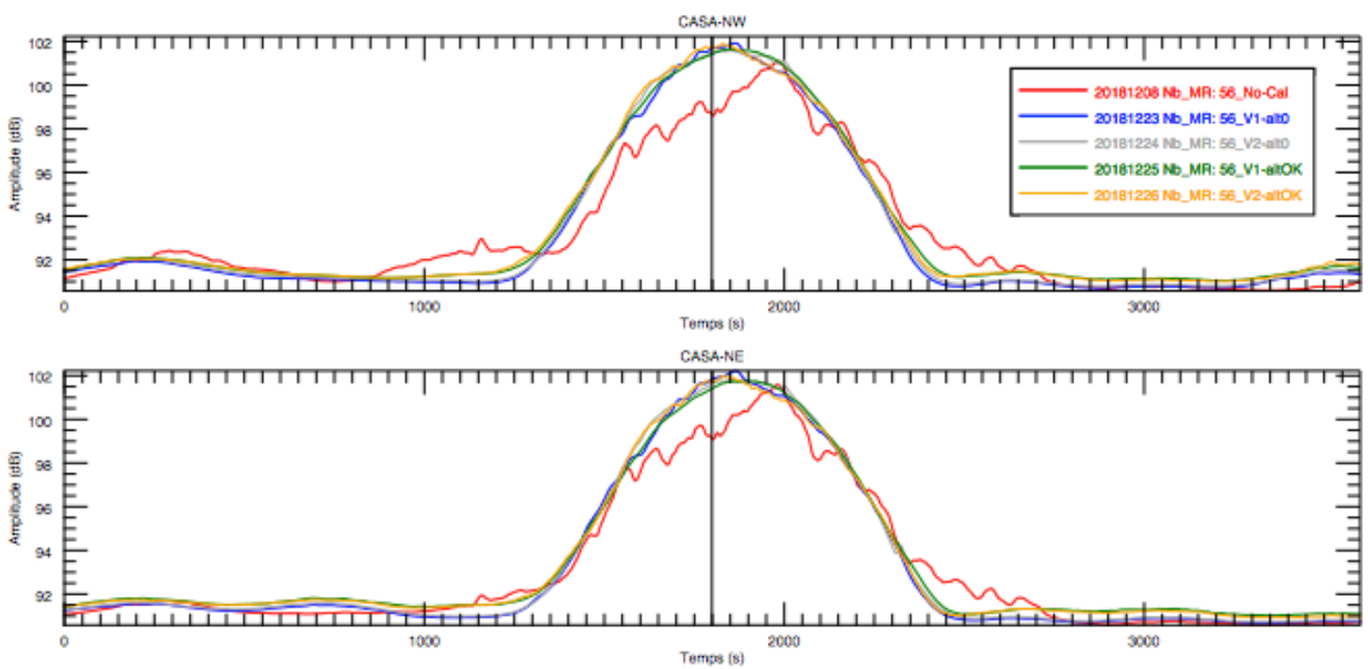
- **Beamformer mode :**
  - Pulsar (PSRFITS format → Presto, DSPSR...) : coherently dedispersed at known DM + folded, or filterbank/search mode, full polar
    → **LB**
  - DynSpec (proprietary format): down to 0.2 kHz & 1 msec, full polar
  - Waveform (proprietary format): 200 k-complex/s X & Y signals written to disk
  - SETI data
  - BST (Beamlet STatisics) data (FITS format): systematically recorded in //, 200 kHz x 1 s resolution, X & Y, include full setup info
- **Transient Buffer mode :**
  - TBB (Transient Buffer Board) data (proprietary format) :last 5 seconds of 200 MHz waveform per MA (or selected antenna), X & Y, written to disk
- **Imager mode :** (2-hour files max)
  - Visibilities data (LOFAR MS format) : 75 MHz, 384 SB, down to 3 kHz, 0.5-2 s, 1 MS / SB, phased to RA,δ (incl. fringe stopping + delay tracking)
  - XST (Cross-Correlation STatistics) data (Fits → MS format *v.0*) : 16 SB / s ~ 3 MHz bandwidth, 1 MS / SB, phased to zenith ; tracking computed at conversion to MS → calibration
  - LOFAR Super Station mode : Visibilities data (LOFAR MS format) : 48+ MHz, 244+ SB, produced by LOFAR
    → **CT**
- **Other products :**
  - SST (Spectral STatisics) data (FITS format) : 1 spectrum at 200 kHz x 1 s resolution per MA, X & Y ; integrated to 10 s after 6 months → engineering
  - Incoherent summation data (format tbd) : summation of the intensities from each MA at 200 kHz resolution

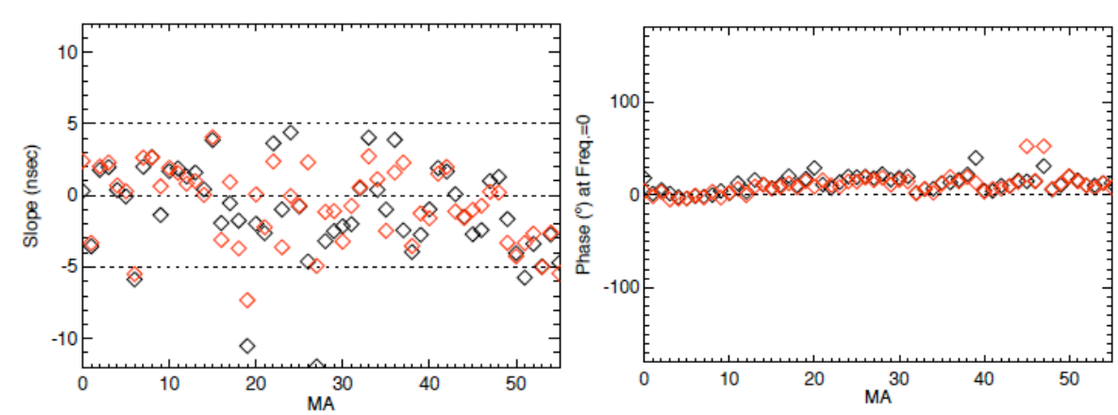
Calibration

(JG)

- **Phase calibration** of beamformer mode
  - from XST (rephased) tracking obs. of A-team sources (Cas, Cyg),
  - NDPPP (X & Y) with 1 source sky model → complex gains of each MA, X & Y → delays → calibration table in LANewBa







Calibration

- **Flux calibration** of beamformer mode
  - from Galaxy and A-team sources (LFmap, GSM)

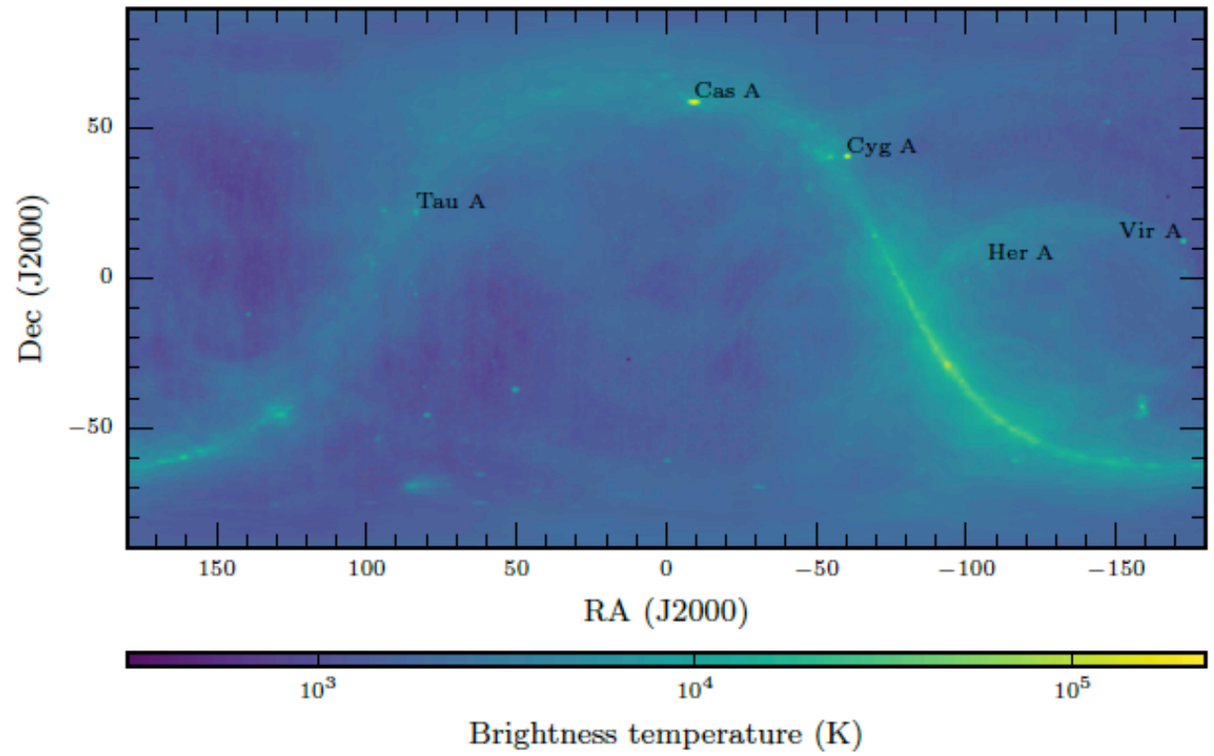
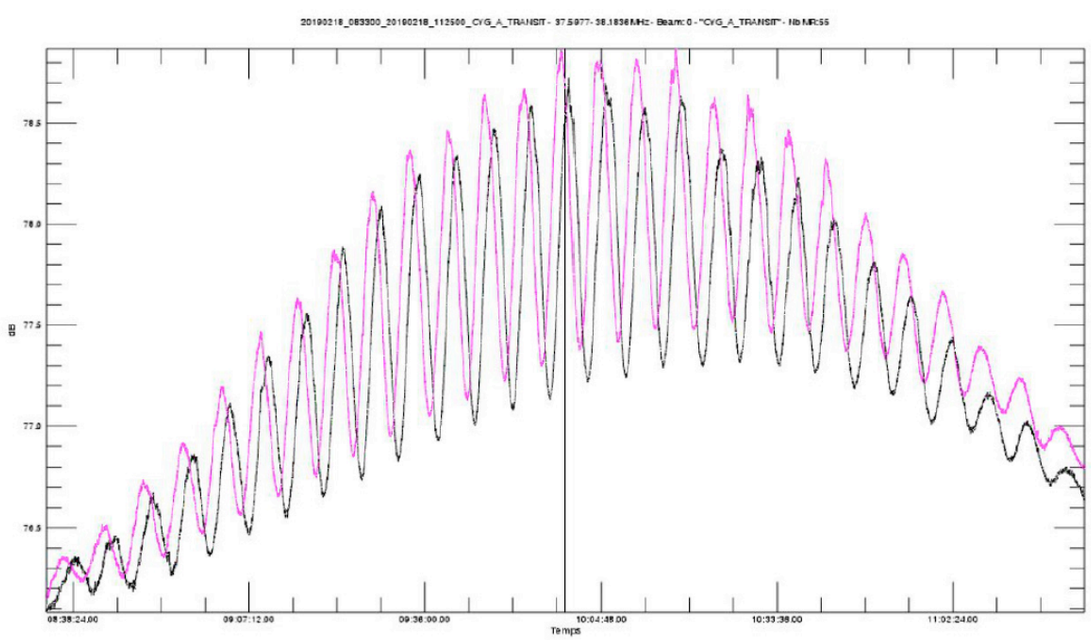
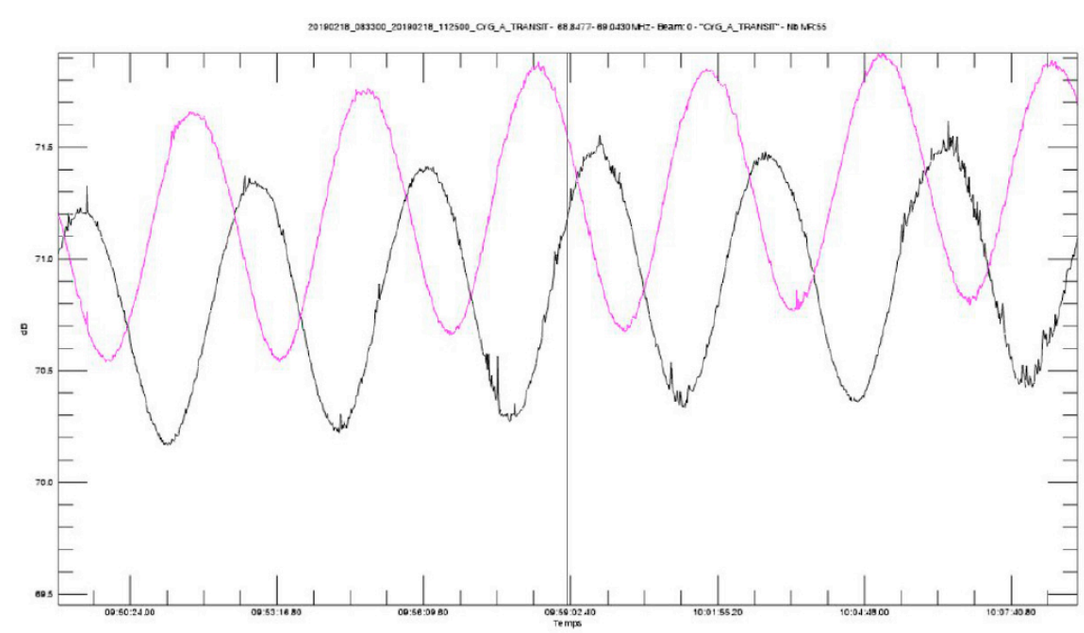


Figure 1: GSM low-frequency sky model at 72 MHz.

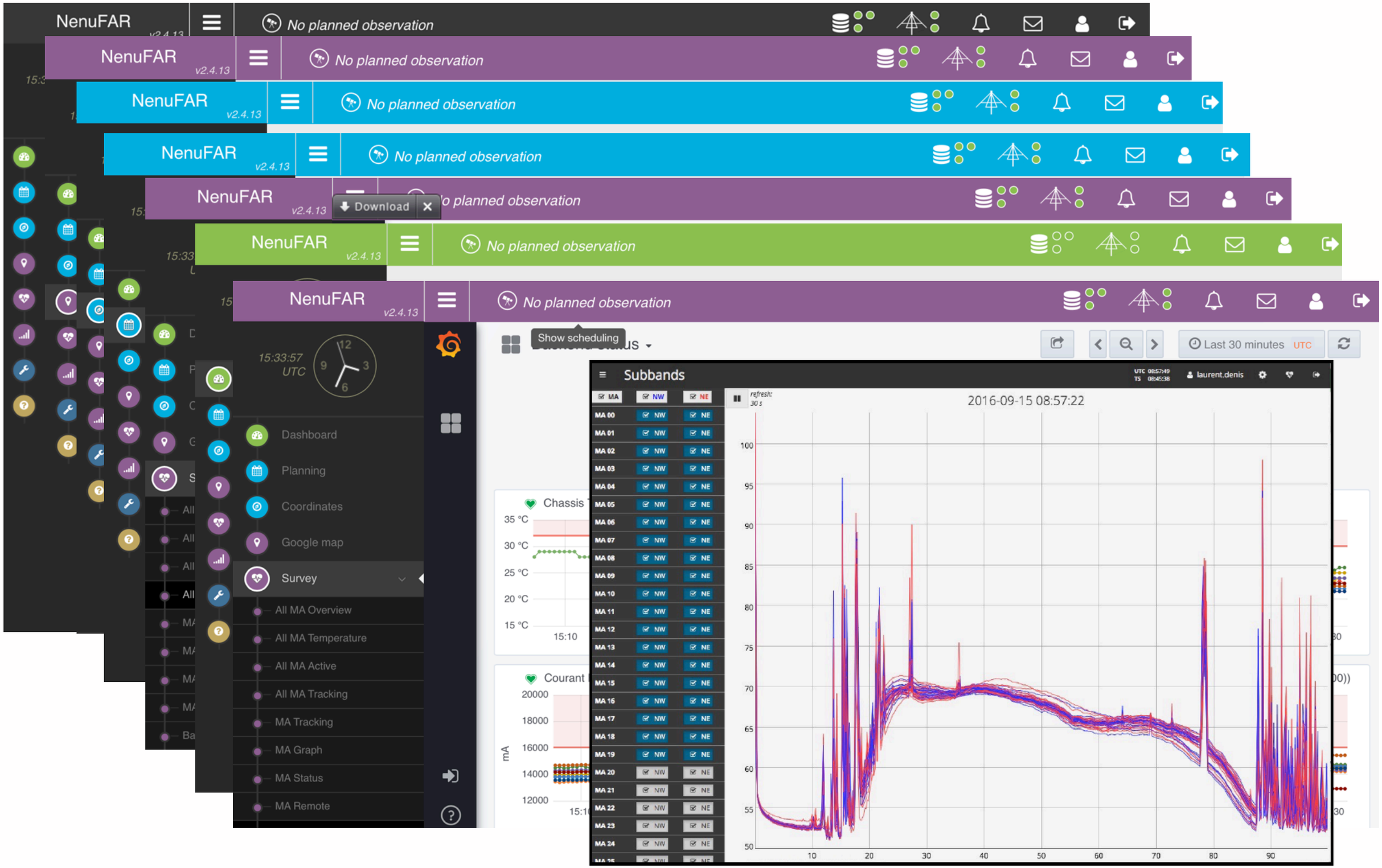
- **Polarization calibration** of beamformer mode
  - from XST using NDPPP in full polarization (full Jone matrix)





Telescope operation

- parset files, GUI → **LD (AC)**



Simulations

- Instrument (MA or NenuFAR) + GSM, necessary for proper use/interpretation of BF mode

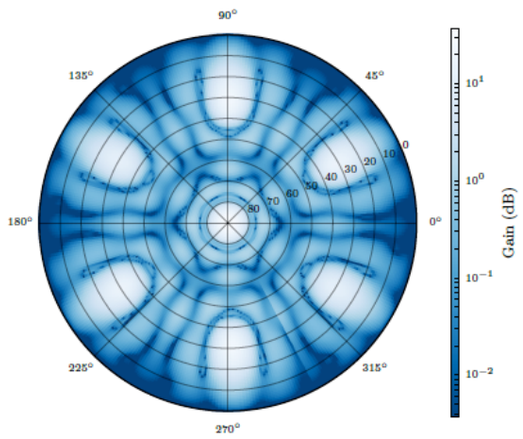


Figure 3: Gain pattern of the Mini-Array 0 (with the 88° offset angle). North is at 0°, East at 90° in azimuth.

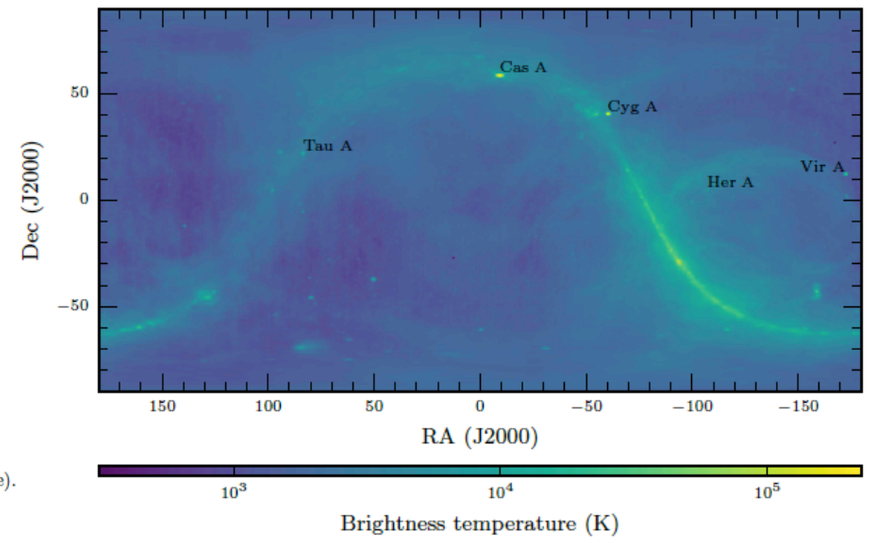
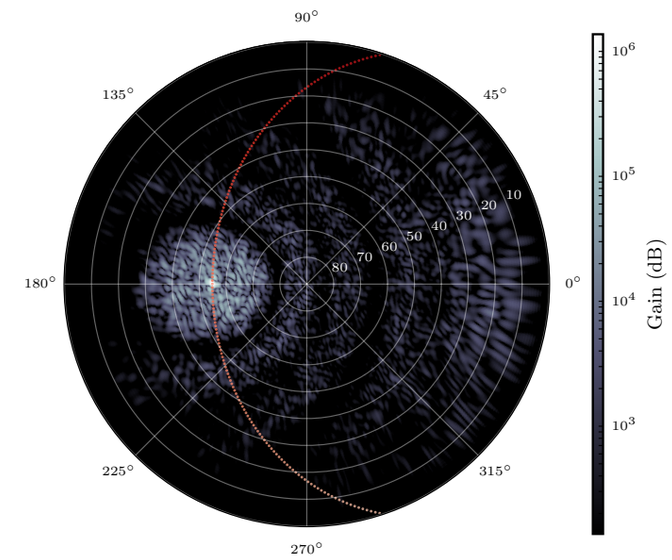


Figure 1: GSM low-frequency sky model at 72 MHz.



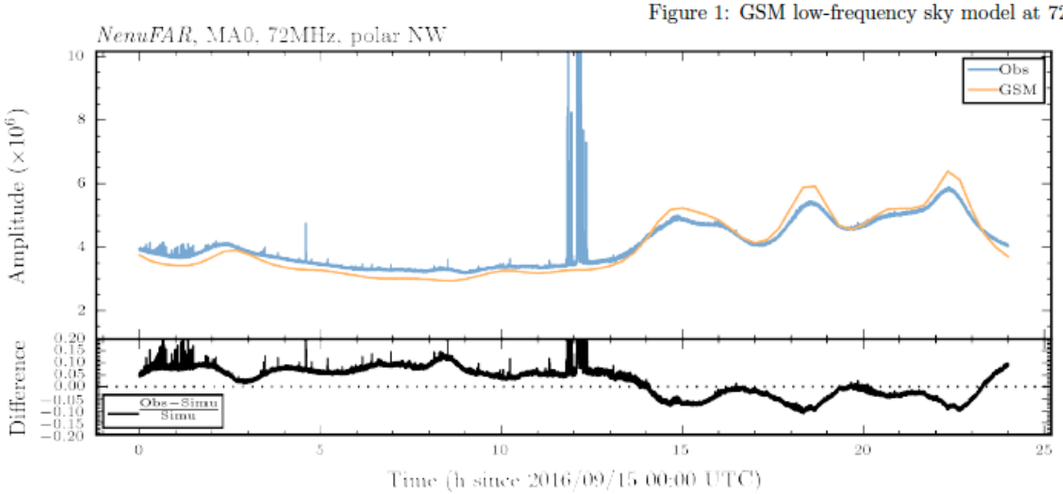
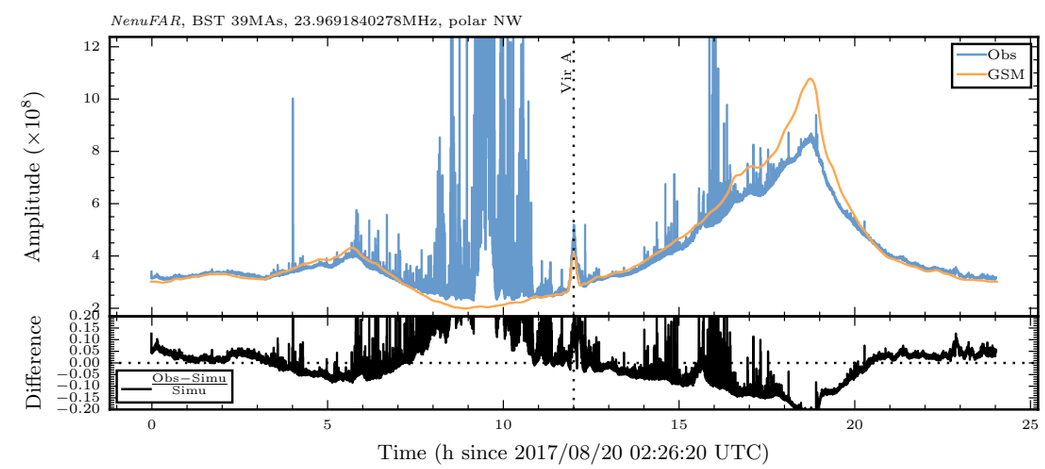
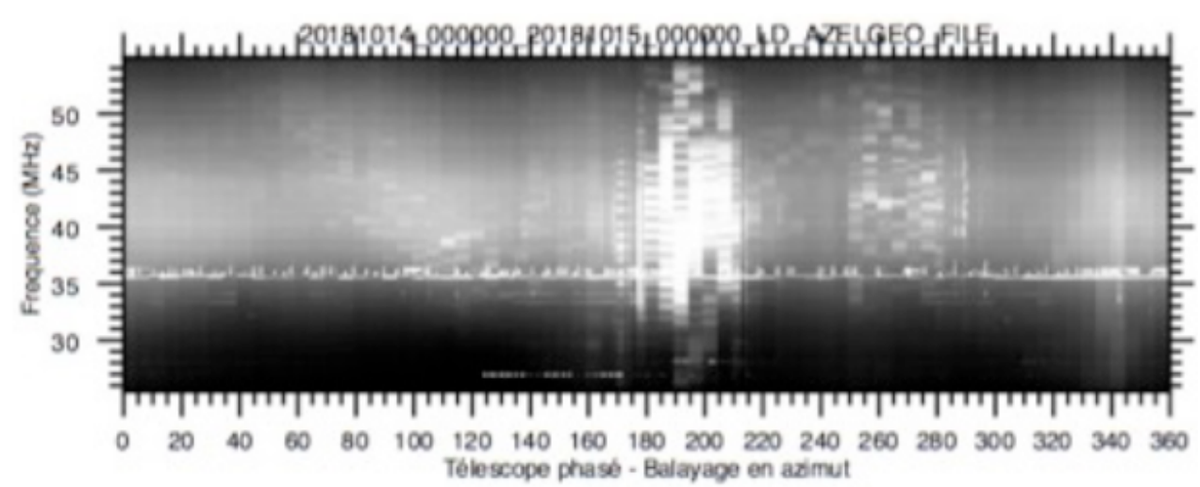


Figure 4: Time profile at 72 MHz of the Mini-Array 0 during the zenith observation on 2016 October 15 and simulation using a 88° offset angle.

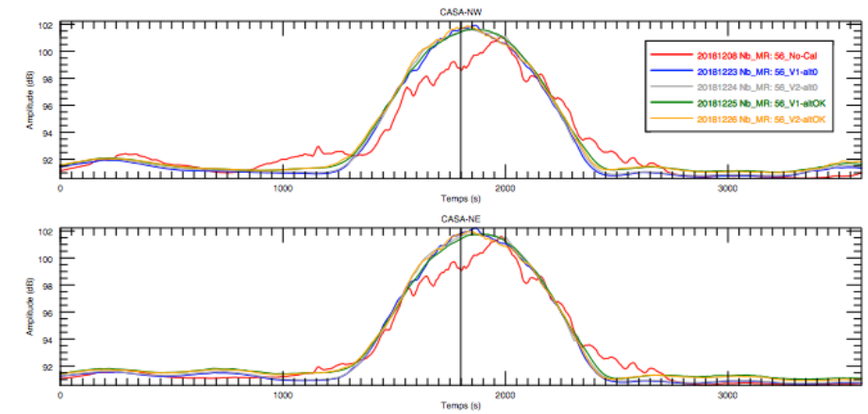


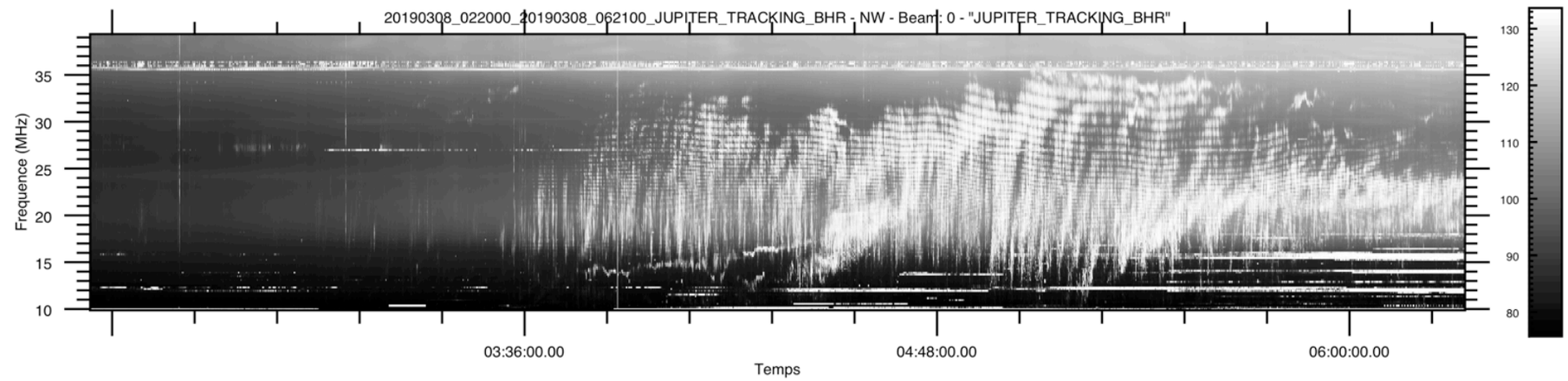
- RFI localization
  - rotating phased beam 0°-360° by 5° steps, elev. = 20°

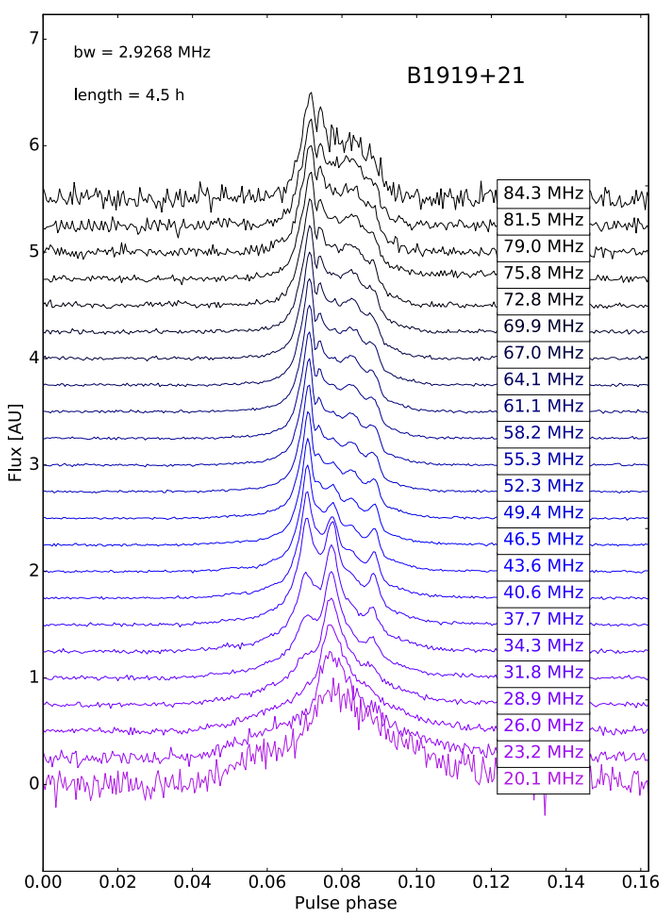


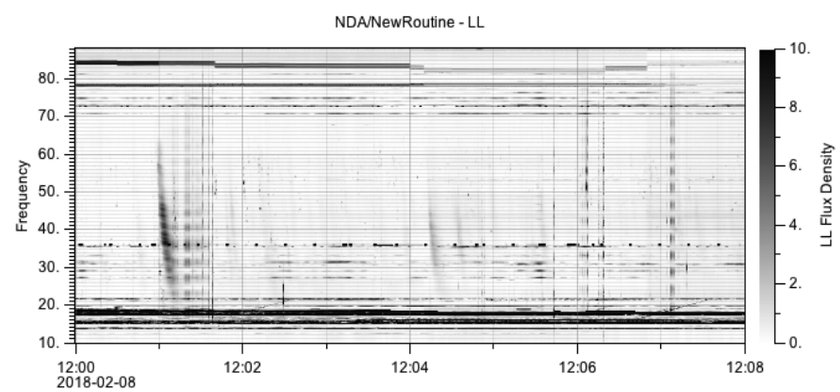
Tests / Qualification (commissioning)

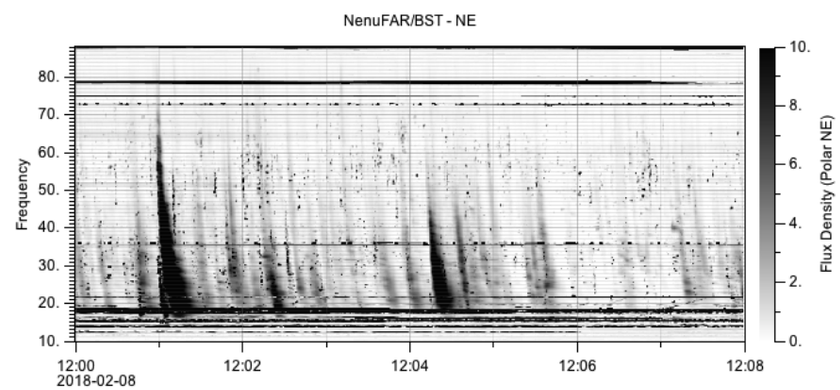
- Radiosource transits
- Jupiter, Sun, compared to Nançay Decameter Array
- Pulsars
- RFI monitoring & localization





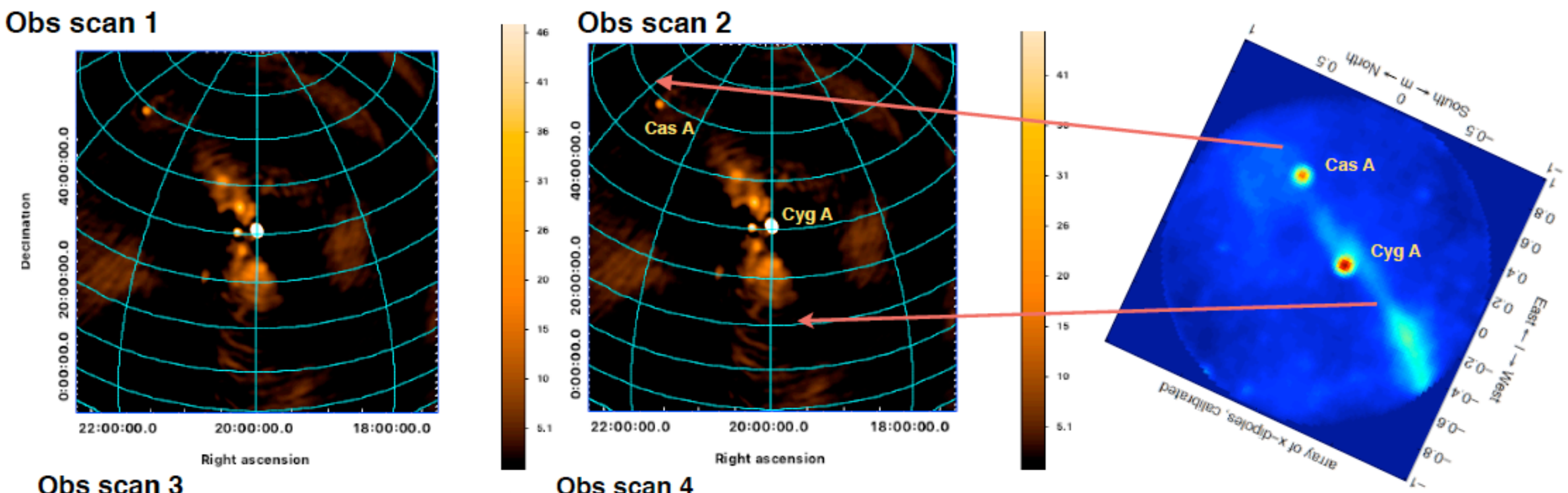




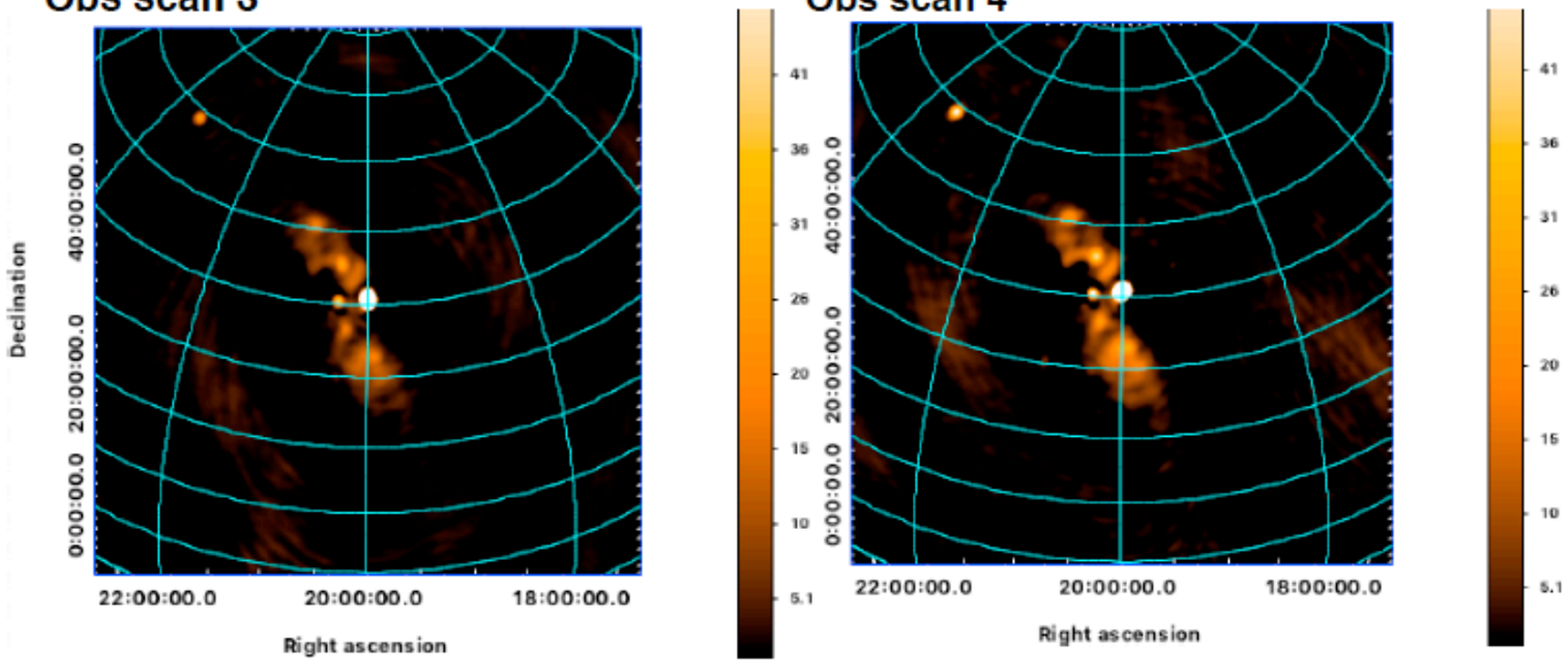


Tests / Qualification (commissioning)

- Radiosource imaging from XST (A-team, LOFAR calibrator, weaker sources ongoing → wide field imaging quality assessment)



LOFAR single station map @ 60 MHz , resolution = 5.4 deg



Multiple sources detected with diffuse emission

Data output

- To Nançay Data Center (databf storage + nancep computing nodes) → **ET, BC**
- Archive under study

User software

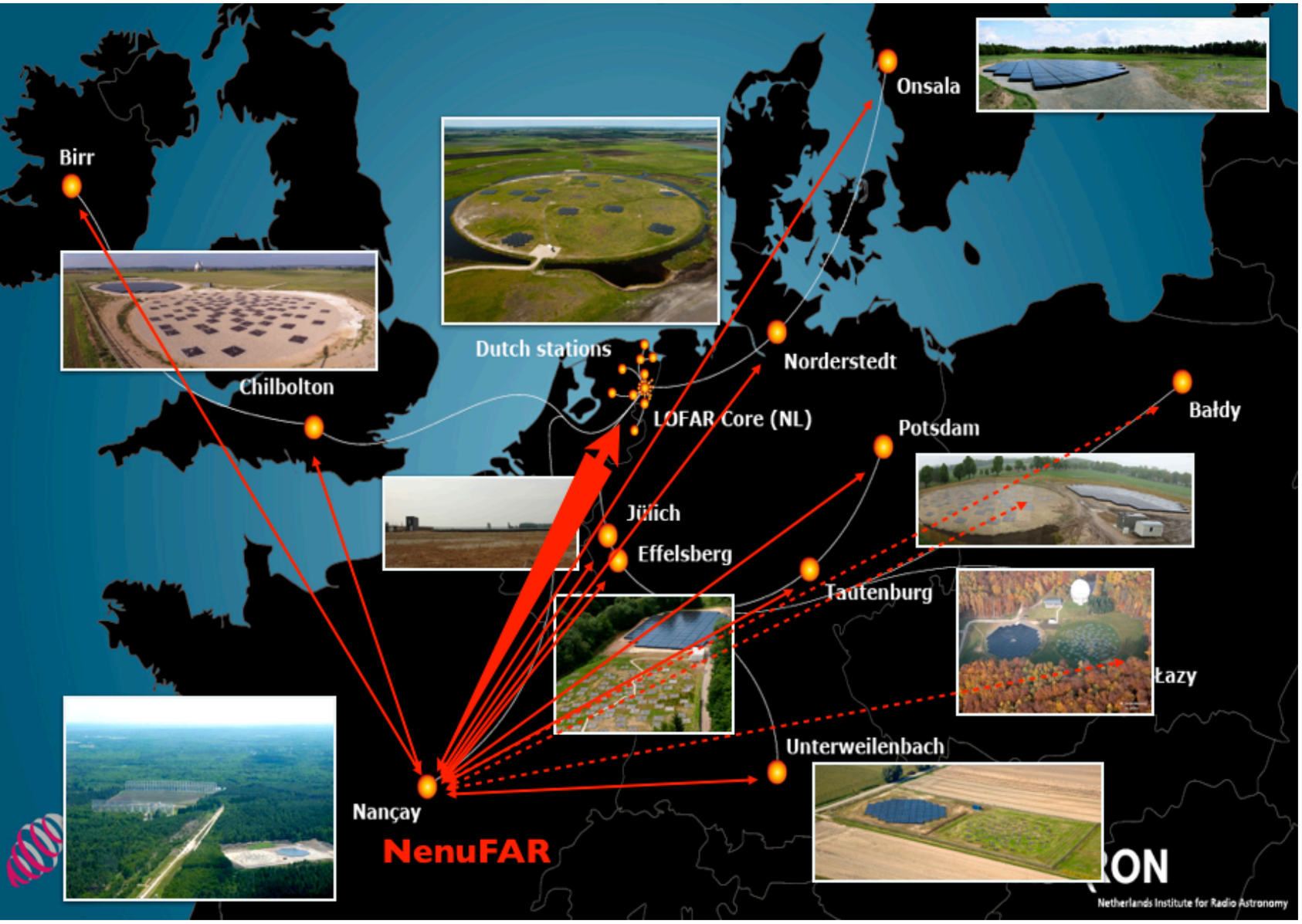
- Python routines → **AL**
- IDL routines → **PZ, CB**
- /cep/lofar/nenufar common directory on nancep
- Collaborative organization to be discussed

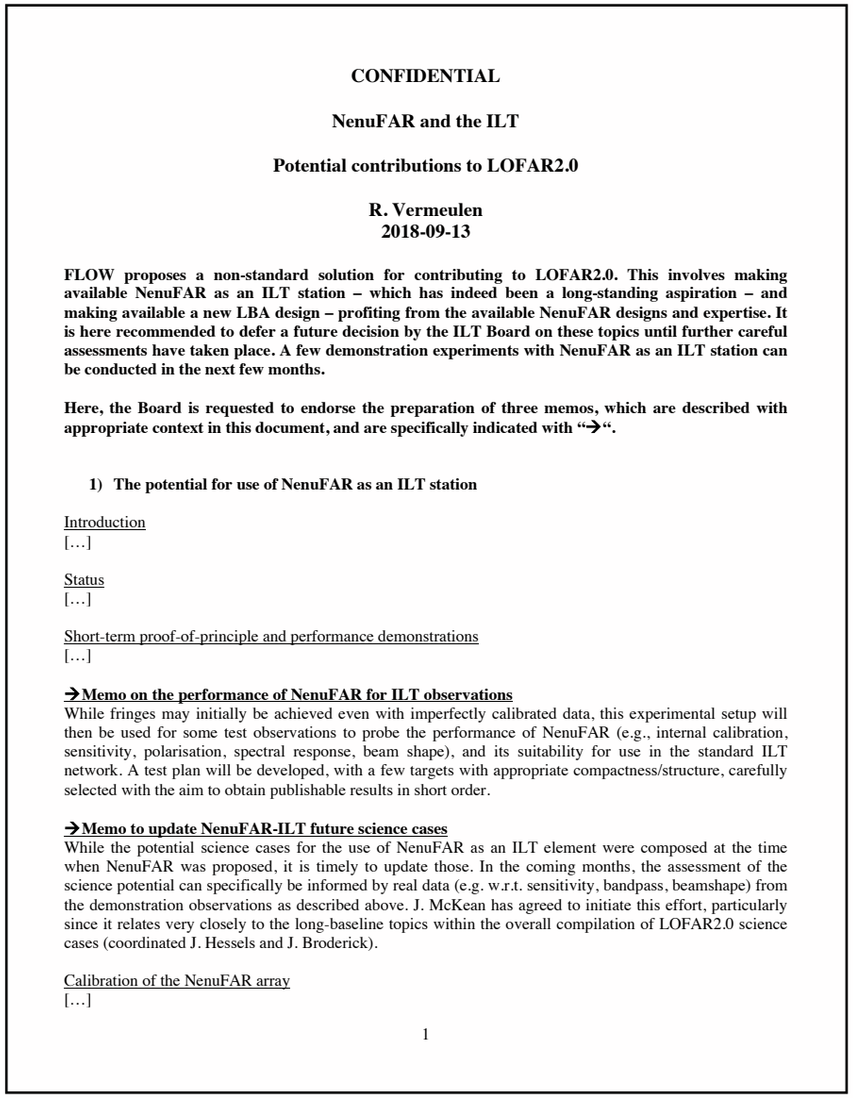
Data use policy

- Management plan, exploitation phases, ... → **FC**

LOFAR Super Station mode

- Tests in progress → **CT, JG**
- Exploitation via LOFAR (ILT plan 23/9/2018, need ASTRON manpower for full integration)





CONFIDENTIAL

NenuFAR and the ILT

Potential contributions to LOFAR2.0

R. Vermeulen
2018-09-13

FLOW proposes a non-standard solution for contributing to LOFAR2.0. This involves making available NenuFAR as an ILT station – which has indeed been a long-standing aspiration – and making available a new LBA design – profiting from the available NenuFAR designs and expertise. It is here recommended to defer a future decision by the ILT Board on these topics until further careful assessments have taken place. A few demonstration experiments with NenuFAR as an ILT station can be conducted in the next few months.

Here, the Board is requested to endorse the preparation of three memos, which are described with appropriate context in this document, and are specifically indicated with "→".

1) The potential for use of NenuFAR as an ILT station

Introduction
[…]

Status
[…]

Short-term proof-of-principle and performance demonstrations
[…]

→Memo on the performance of NenuFAR for ILT observations
While fringes may initially be achieved even with imperfectly calibrated data, this experimental setup will then be used for some test observations to probe the performance of NenuFAR (e.g., internal calibration, sensitivity, polarisation, spectral response, beam shape), and its suitability for use in the standard ILT network. A test plan will be developed, with a few targets with appropriate compactness/structure, carefully selected with the aim to obtain publishable results in short order.

→Memo to update NenuFAR-ILT future science cases
While the potential science cases for the use of NenuFAR as an ILT element were composed at the time when NenuFAR was proposed, it is timely to update those. In the coming months, the assessment of the science potential can specifically be informed by real data (e.g. w.r.t. sensitivity, bandpass, beamshape) from the demonstration observations as described above. J. McKean has agreed to initiate this effort, particularly since it relates very closely to the long-baseline topics within the overall compilation of LOFAR2.0 science cases (coordinated J. Hessels and J. Broderick).

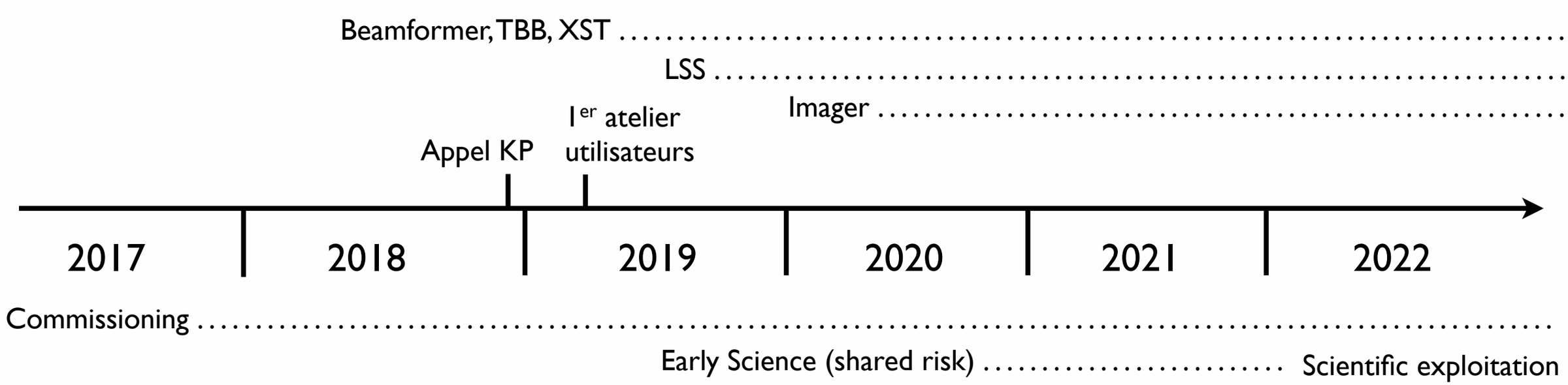
Calibration of the NenuFAR array
[…]

1

- Integration in LOFAR 2.0 in discussion

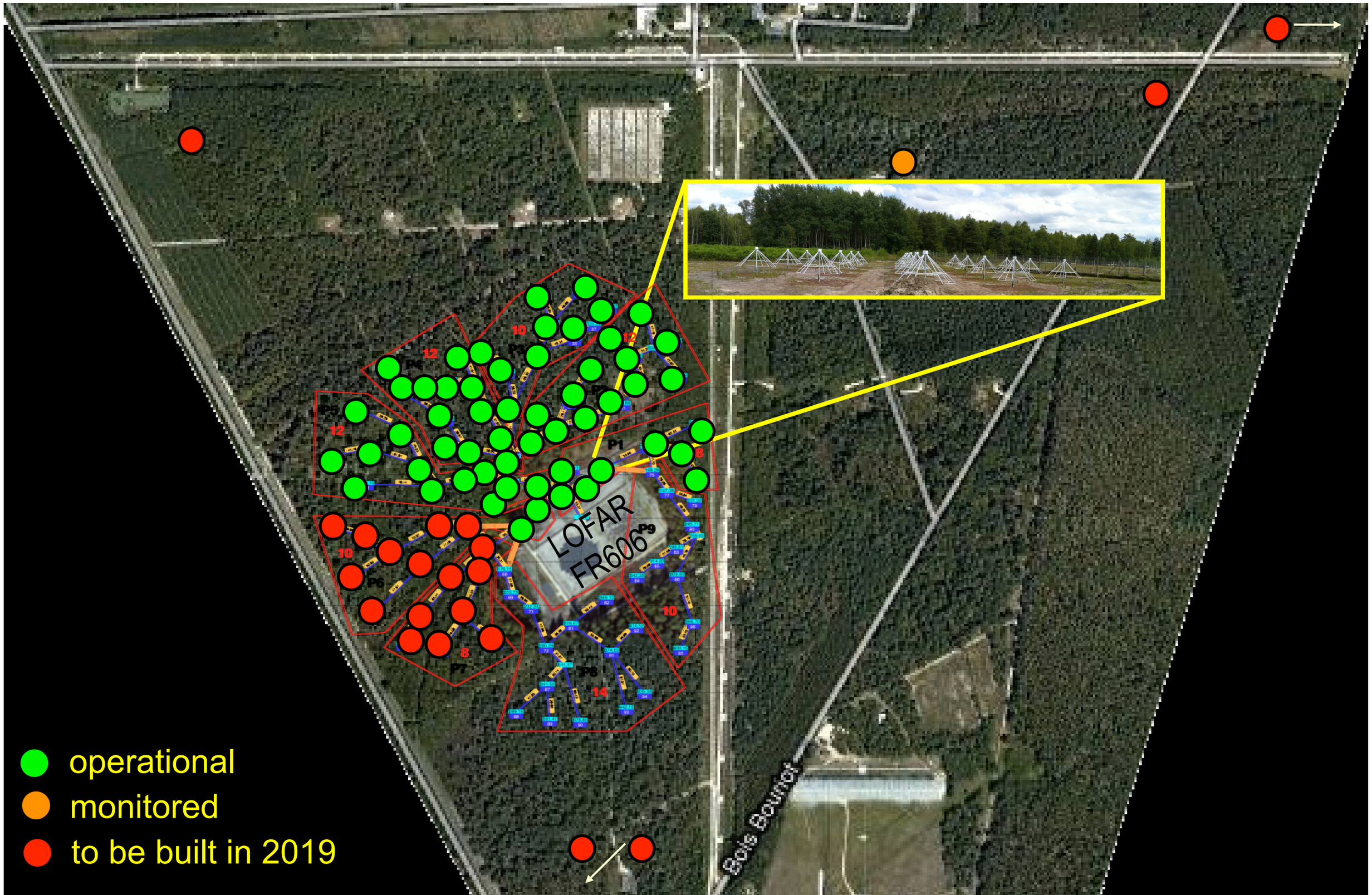
Timeline

- 2008 : Initial idea & workshop :
- 2009-2013 : Design study
- 2014-2019 : Construction (75%)
- 2016-2019 : Tests, Qualification, Commissioning
- 2019/03 : 1st Users Workshop
- 2019/9/17 - 2019/10/03 ⊃ Inauguration of NenuFAR
- 2019-2021 : Early science, end of construction (ERC, ...) ?



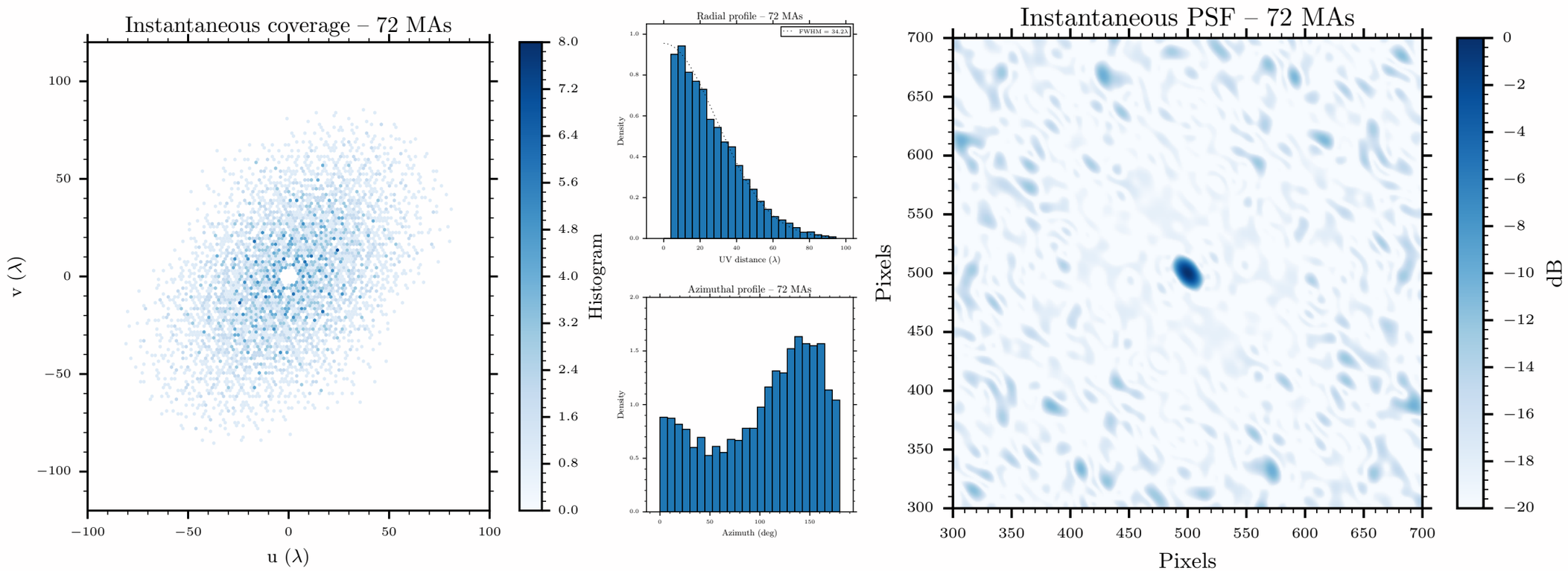
Construction

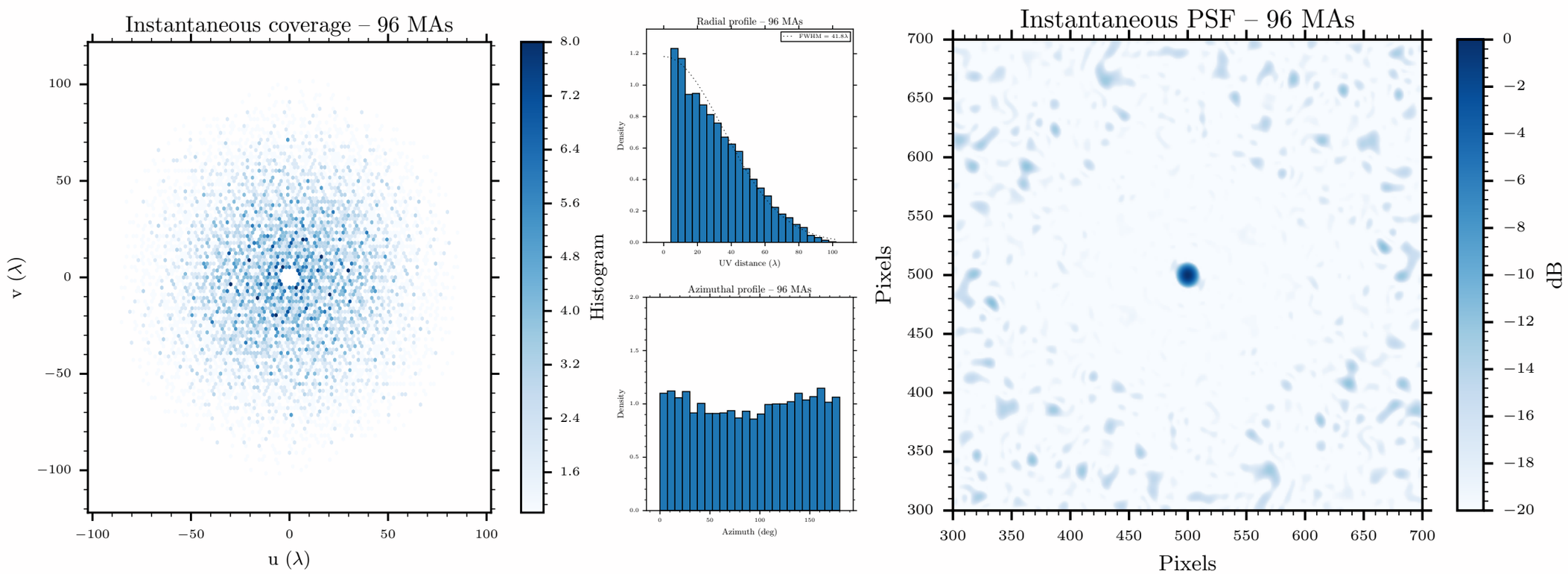
72 core MA + 4 remote funded, 56 MA core built & operational (1064 antennas)
+ 1 remote MA built & monitored



Construction

Going from 72 to 96 MA : beam, pointing accuracy ?



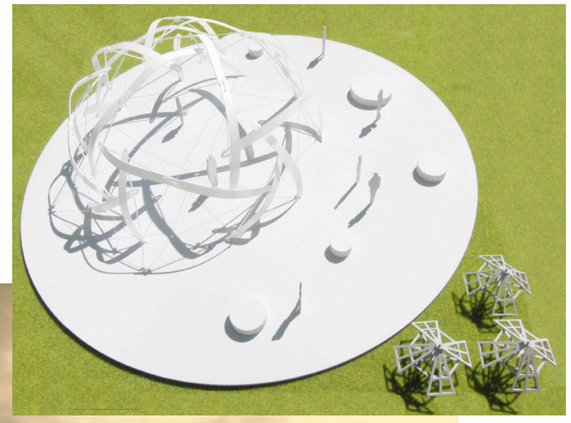


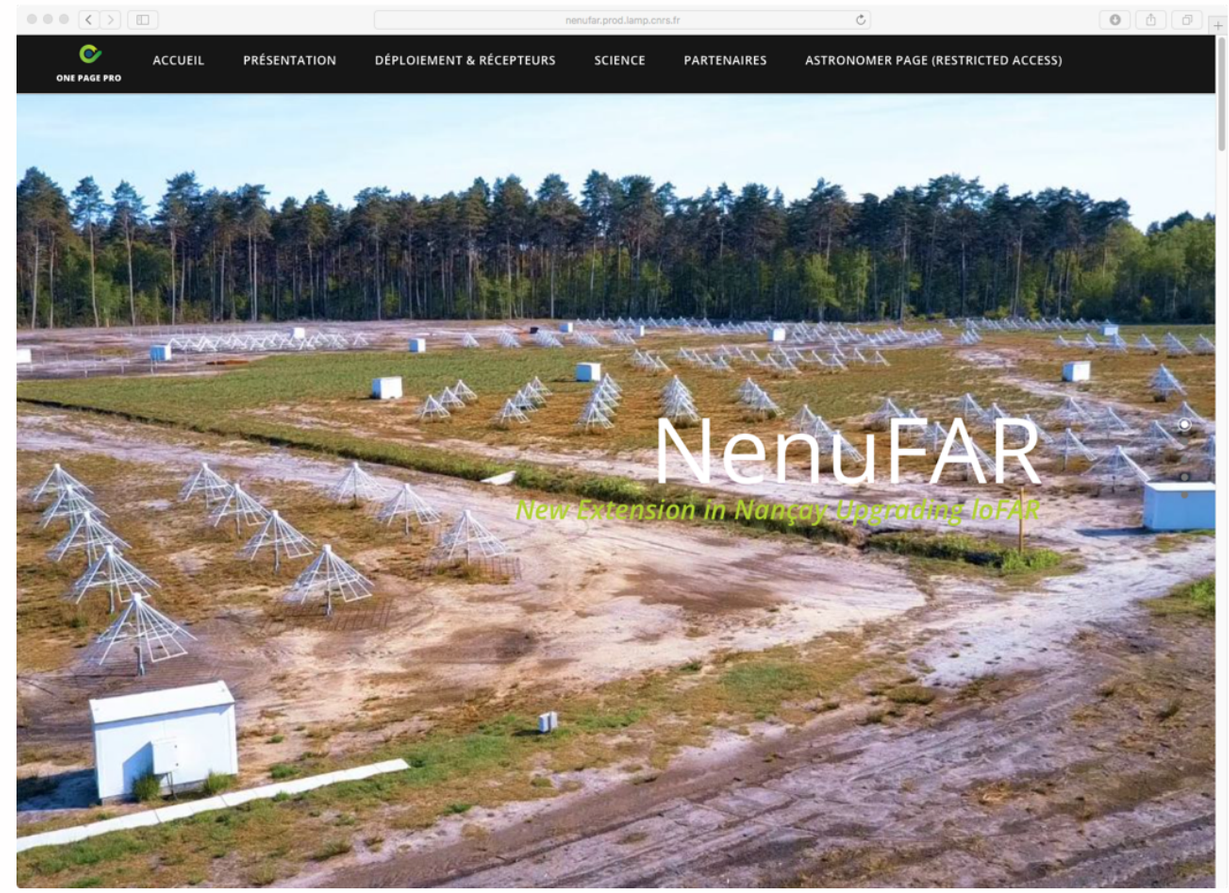
Further steps (see details on Astronomers page)

- **Preparation of observations**
  - Smart SB selection / RFI occupancy statistics
  - VOevents for GW follow-up observations
- **Data analysis**
  - Integrate LOFAR/NenuFAR subtables in MS (v.1) (MA tile definition, beam modelling, …)
  - Development of the NenuFAR pre-processing pipeline: Flagging, rebinning, demixing/ DD subtraction, …
  - Development of the NenuFAR Calibration & Imaging pipeline : DDFacet/KillMS for DI and DD calibration (A-team subtraction, beam model, wide-field imaging, polarization…)
  - Data management: XST/MS code acceleration, Hi-res Vis "direct-to-disk" ...
    → NenuFAR TV (Near Real-time "all-sky" imager in I and |V|)
- **Hardware**
  - Choice and implementation of correlator
  - End of core construction (~1 M€), of imager (2 remote MA + correlator ~200 k€)
- ...

Web site

- https://nenufar.obs-nancay.fr/en/homepage-en/
  - Art project : "Le Dôme de NenuFAR"





- Astronomers page : https://nenufar.obs-nancay.fr/en/astronomer/
  - Identified features
  - "Contact NenuFAR team" form for feedback / questions

- https://confluence2.obs-nancay.fr/display/NEN/Wiki+NenuFAR (restricted access)

The team

- **PI** : P. Zarka, M. Tagger **Project Manager** : L. Denis
- **Comité Scientifique NenuFAR** : the above 3 + F. Casoli, S. Corbel, G. Theureau
- **Commissioning team** : J. Girard, L. Denis, P. Zarka, A. Loh, L. Bondonneau, M. Pommier, J.-M. Grießmeier, C. Tasse, C. Briand, E. Bonnassieux, C. Viou, B. Censier

  → support for Early Science observations
- **Development team** :
  - Nançay : L. Denis, A. Coffre, C. Viou, C. Taffoureau, E. Thetas, A. Le Gall, F. Guilbeau, S. Garnier, B. Gond, L. Alsac, P. Cottet, J.-B. Vimon, F. Floquet, S. Joly,

    + support : G. Georges, F. Jacquet, D. Coulmance, C. Roziere, V. Etieve, Y. Bertho, S. Dubreuil, P. Rapin, P. Sandre, M. Huet, D. Capayrou, J. Pezzani, I. Thomas
  - Other : D. Charrier, J. Girard, A. Loh, L. Bondonneau, I. Cognard, B. Cecconi, P. Zarka
- **NenuFAR-France consortium** : incl. B. Semelin, E. Chassande-Mottin, G. Hellbourg, R. Dallier, L. Martin, L. Lamy, et al.
- **Artist** : C. Courte

Publications

Published / in press : NenuFAR

- Girard, J. N., Zarka, P., M. Tagger, L. Denis, D. Charrier, and A. Konovalenko, *Antennas design and distribution for a LOFAR Super Station in Nançay*, in "Planetary Radio Emissions VII", H. O. Rucker et al. eds., Austrian Acad. Sci. Press, Vienna, pp. 495-504, **2011**.

Girard et al., *Antenna design and distribution of the LOFAR Super Station*, C.R. Phys. 13, « Les radiotélescopes du futur », p. 33-37, **2012**.

- Zarka et al., *LSS/NenuFAR: The LOFAR Super Station project in Nançay*, SF2A-2012: Proc. Annual meeting of the French Society of Astronomy and Astrophysics, Eds.: Boissier et al., pp.687-694, **2012**.
- NenuFAR-France collaboration (80 co-authors), *NenuFAR : instrument description and science case*, 6/**2014**.
- Zarka et al., *NenuFAR: Instrument Description and Science Case*, International Conference on Antenna Theory and Techniques (ICATT), Kharkiv, Ukraine, pp. 13-18, 4/**2015**.
- Zyma et al., *Formulating and solving a radio astronomy antenna connection problem as a generalized cable-trench problem: an empirical study*, Int. Trans Op. Res., 1-15, **2016**.
- Zarka & Mottez, *Observations of Fast Radio Bursts and perspectives at low frequencies*, Proc. SF2A-2016, Eds.: Cambrésy et al., 343-347, **2016**.
- French SKA White Book, section 4.1.1, *LOFAR and NenuFAR*, **2017**.
- Bondonneau, L., J-M. Griemeier, G. Theureau, and I. Cognard, *Pulsar observations with NenuFAR*, Proc. SF2A 2018, P. Di Matteo, F. Billebaud, F. Herpin, N. Lagarde, J.-B. Marquette, A. Robin, O. Venot (eds), 301-304, **2018**.
- Bondonneau, L., J-M. Griemeier, G. Theureau, and the NenuFAR-France collaboration, *Low frequency pulsar observations with NenuFAR*, Proc. JS 19 URSI-France, "Approcher les deux infinis par les ondes électromagnétiques", OVSQ, 26-27/3/**2019**.

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