Technical studies for a SKA-LF precursor: Antennas & Mini-arrays

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+ the LSS/NenuFAR team

[1]CEA/SAp-Saclay, [2]LESIA-Obs. Paris, [3]LPC2E-Orléans, [4]USN-Nançay

Large instruments

LWA 256 dipoles

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LWA 256 dipoles

Large number of elements

- sensitivity ++
- imaging ++

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LWA 256 dipoles

Large number of elements vs. Hardware/software effort

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- imaging ++

- signal acquisition
- computational load and tractability
- cost...

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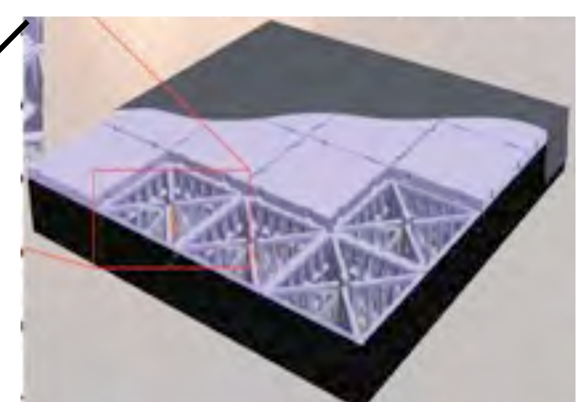
➡ Hierachical instrumentation

ex:HBA field 96 x (4x4 dipoles)



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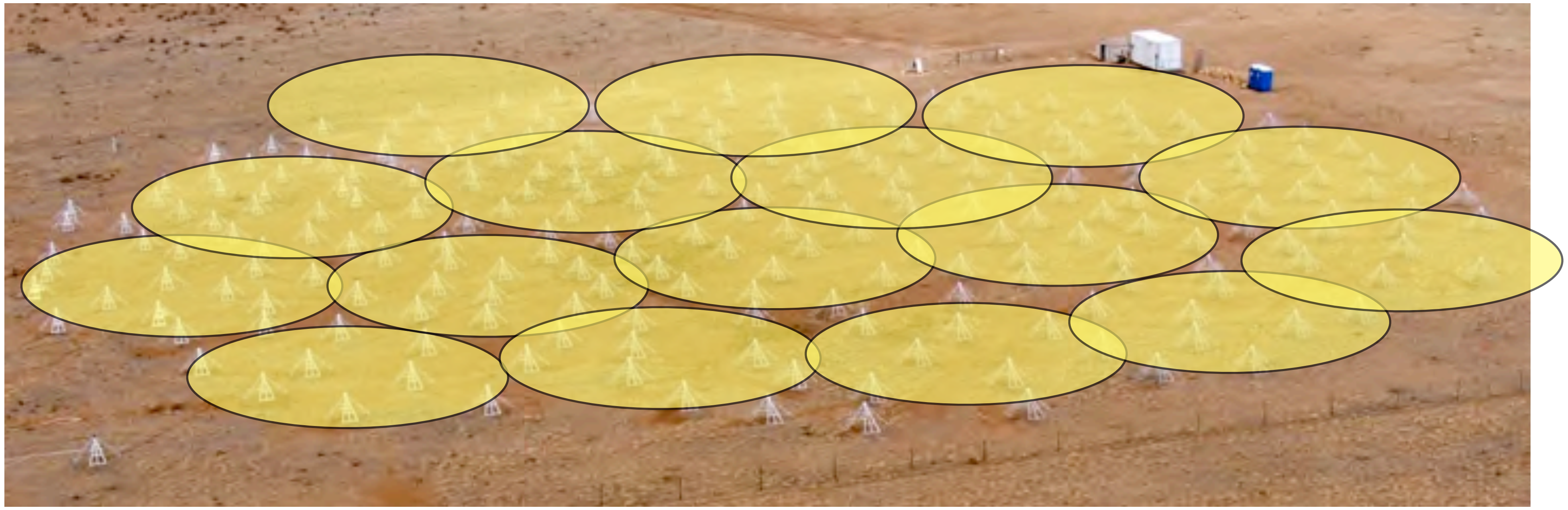

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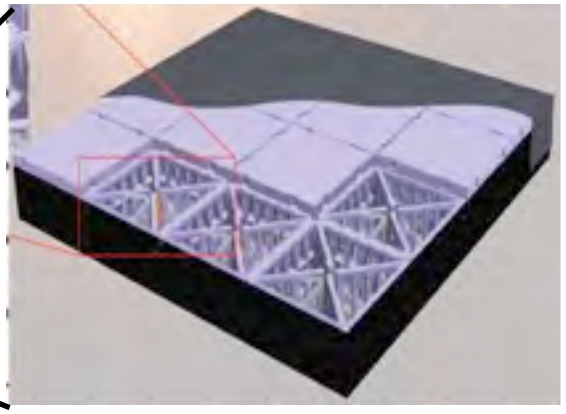

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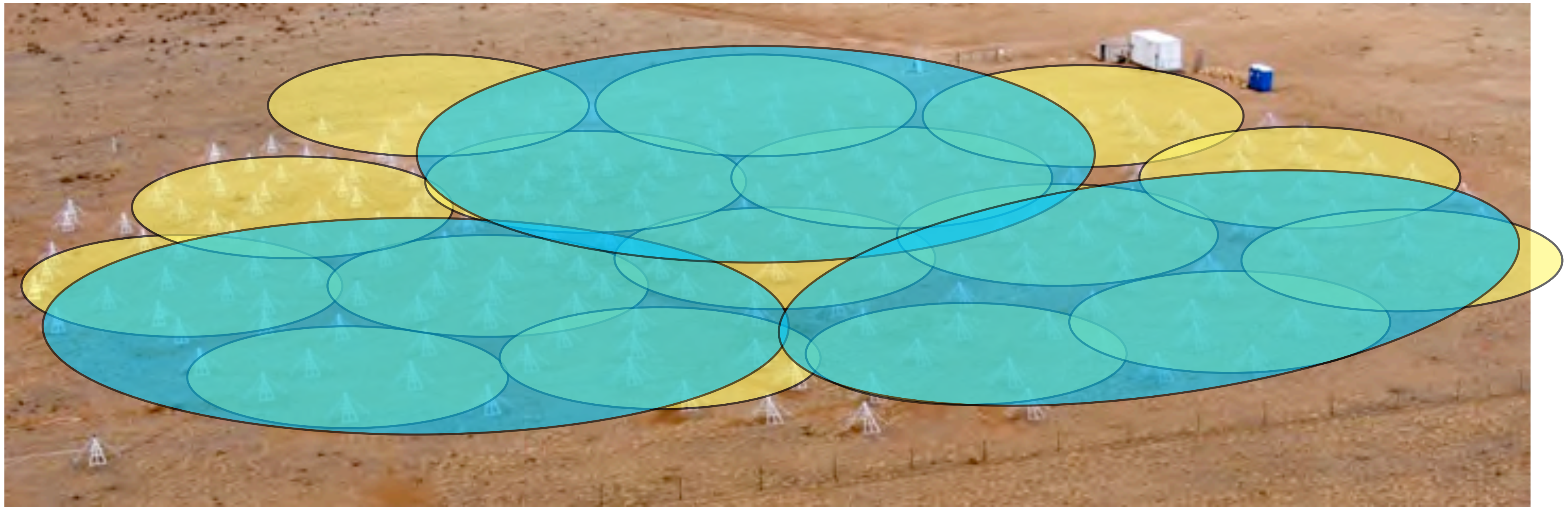

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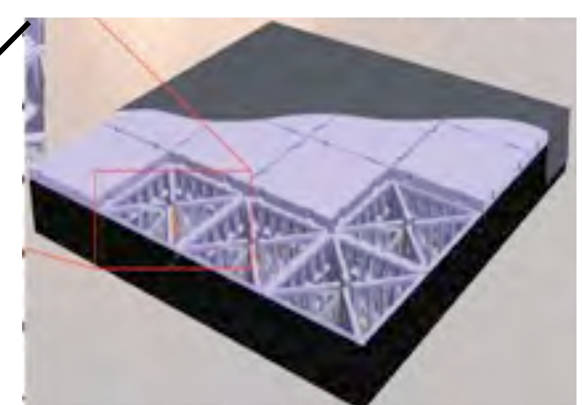
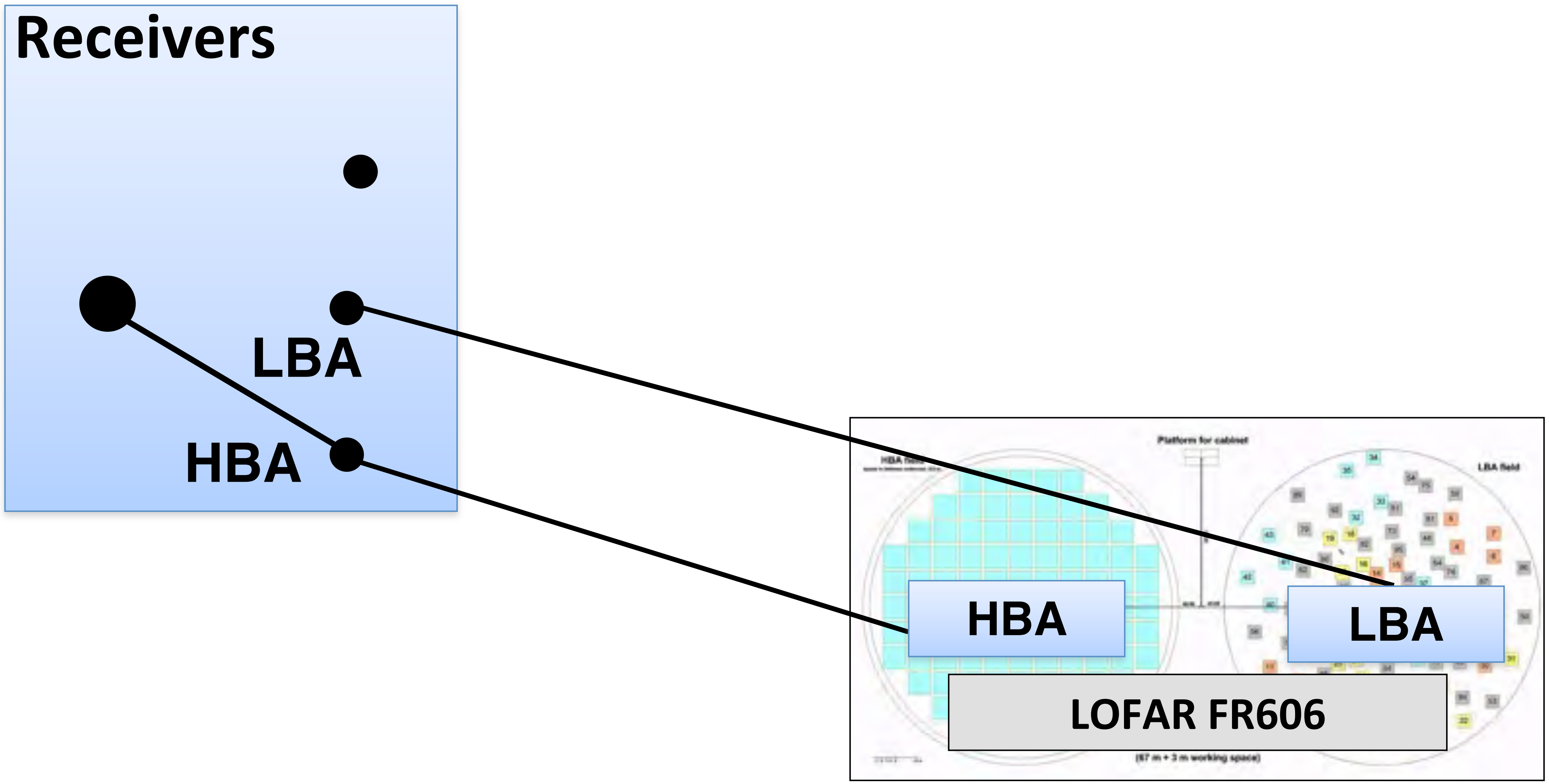


NenuFAR (LSS)


Receivers
LBA
HBA
Platform for cabinet
LBA field
HBA
LBA
LOFAR FR606

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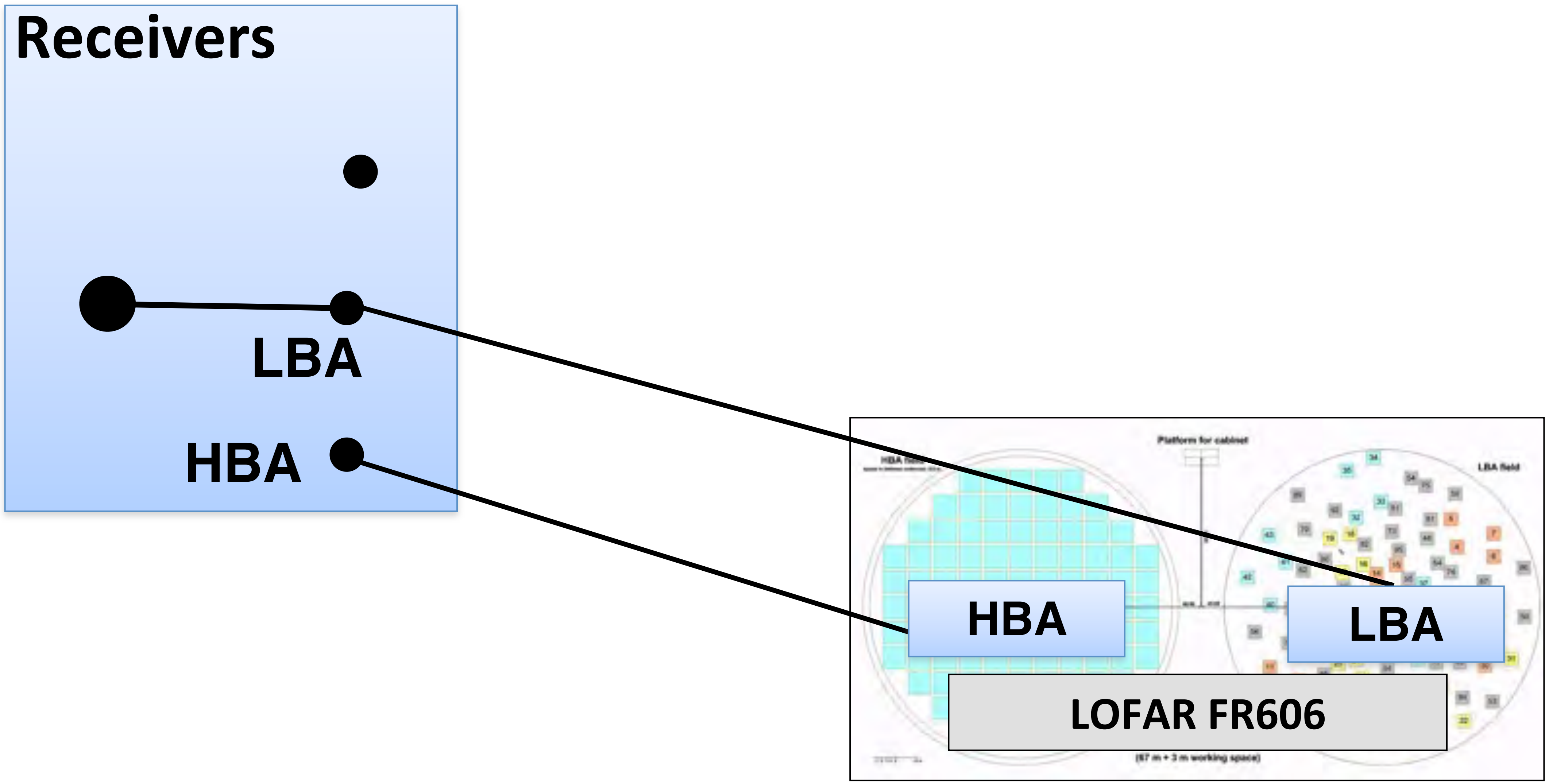
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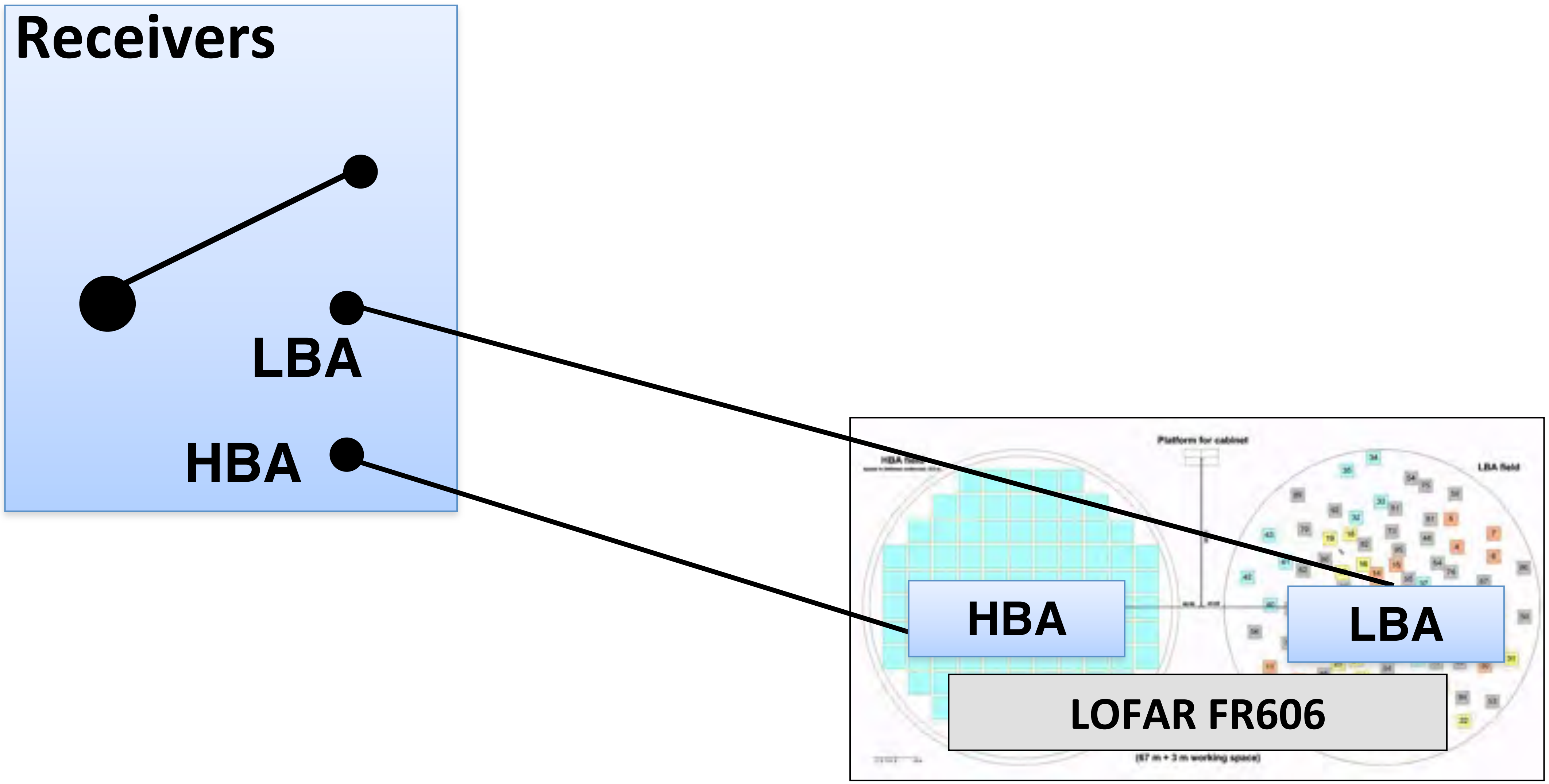

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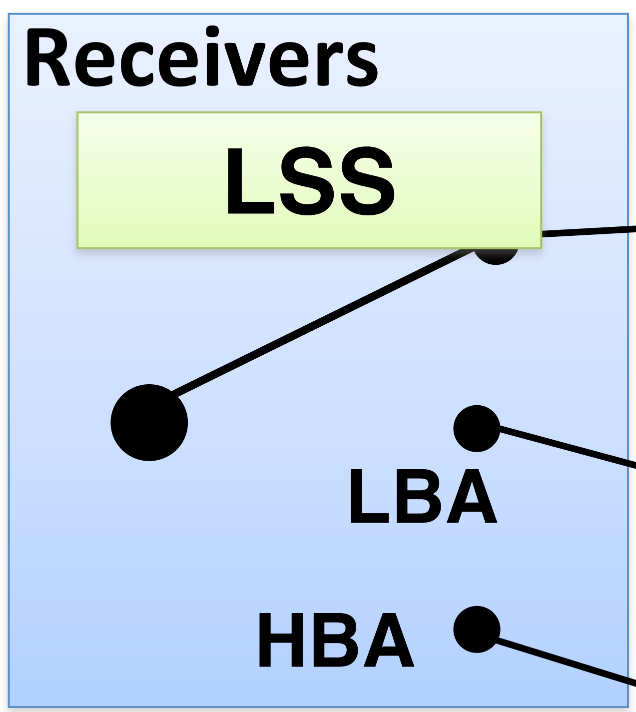
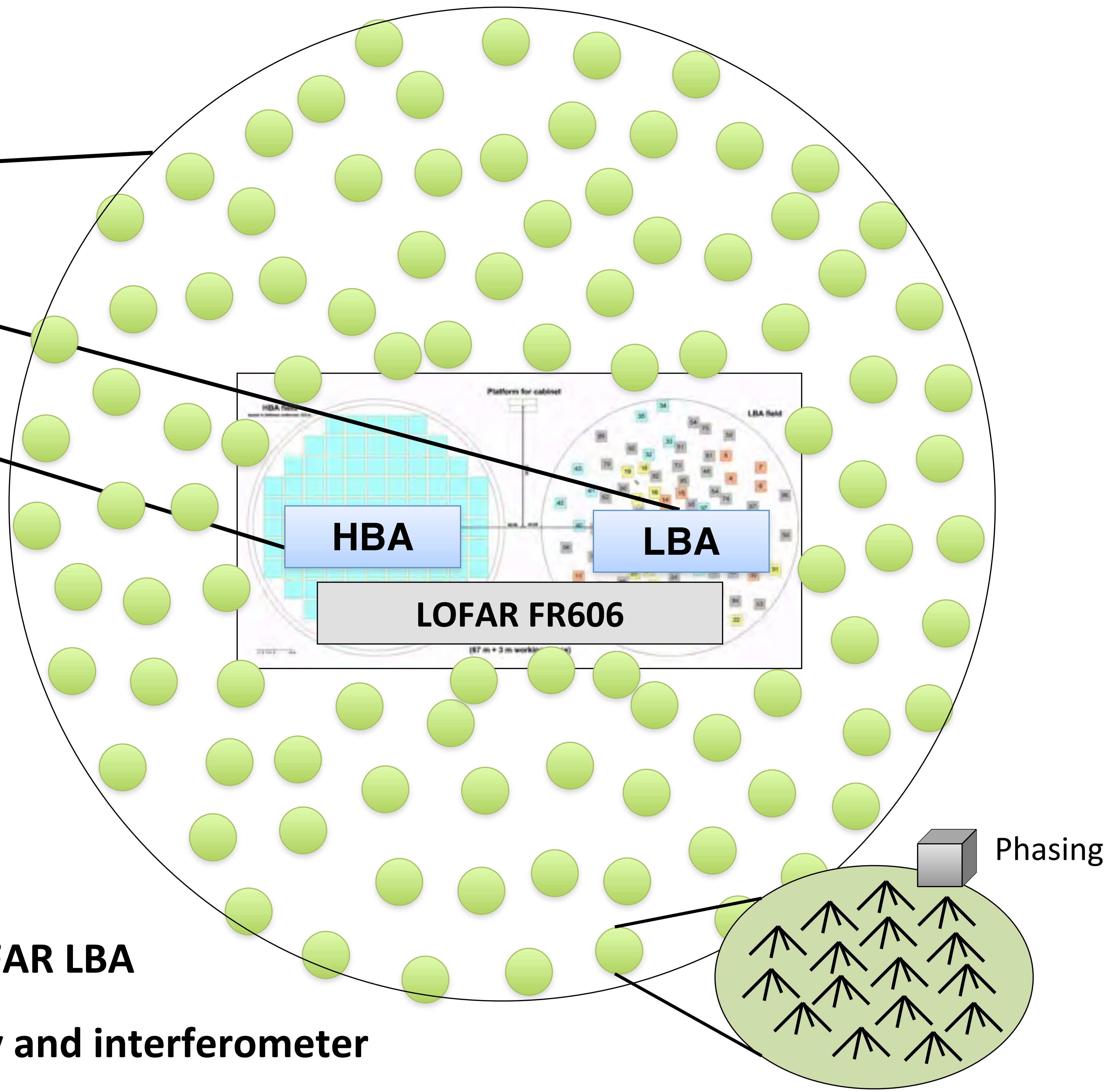




- 96 LF tiles
phased in analog
(≥16 antennas / tiles)

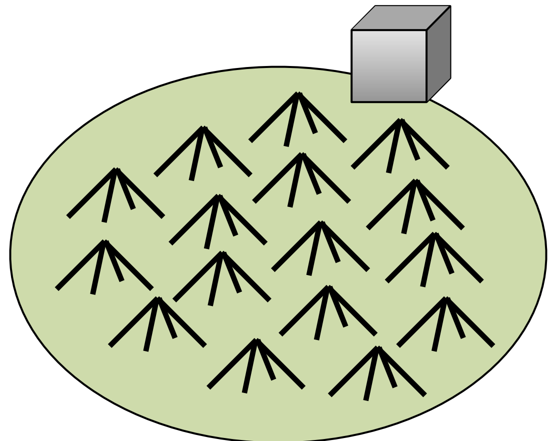
- diameter ~ 400 m

- frequency band ⊃ LOFAR LBA

- LSS = Big phased array and interferometer

LSS project (ANR 2009-2012)

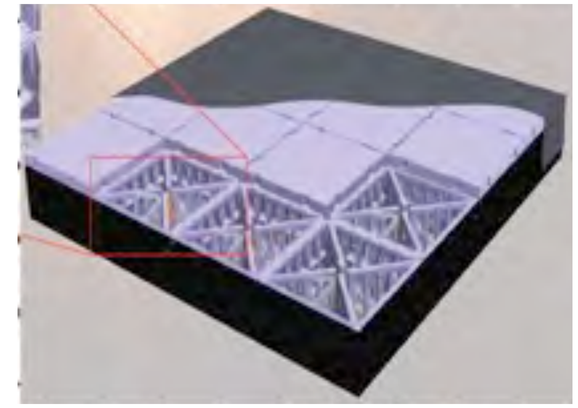
Problematic:



x 96

~

LOFAR HBA tile



4x4 antenna tile x 96

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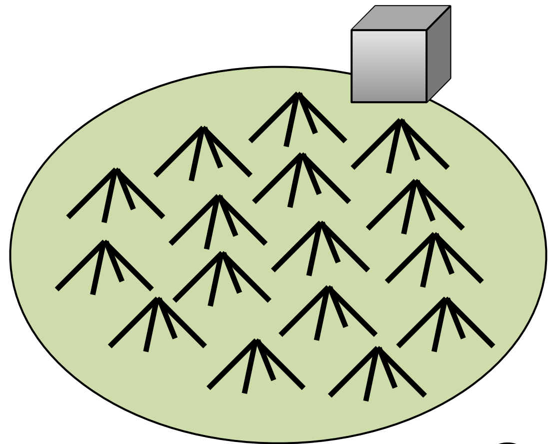

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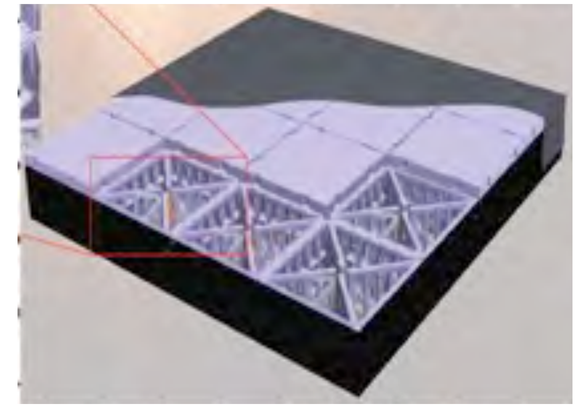

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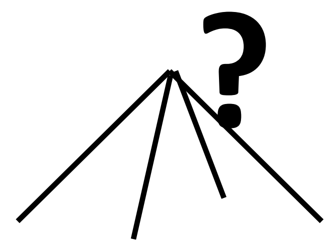

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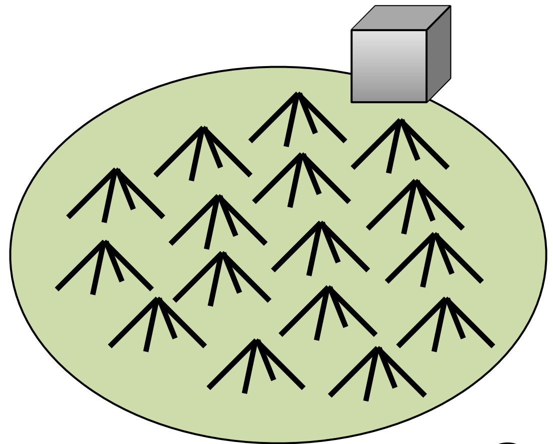

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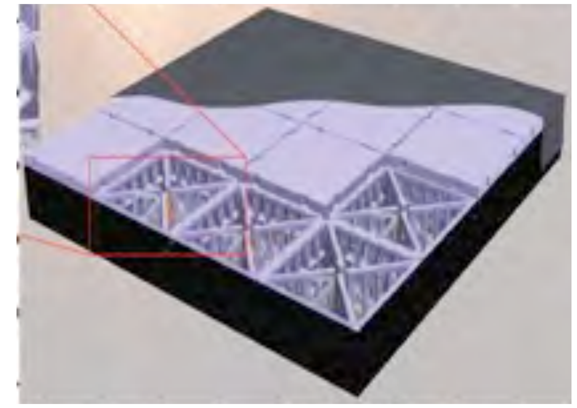

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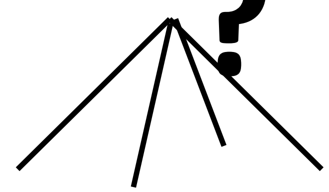

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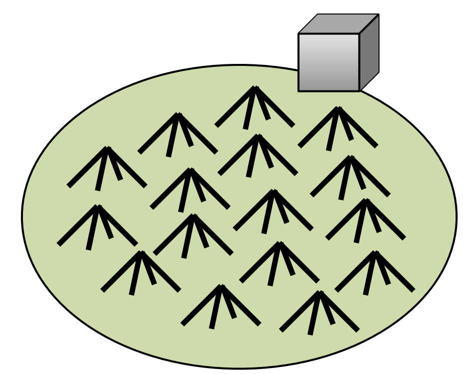
→ What topology for Mini-Arrays ?

phasing strategy?



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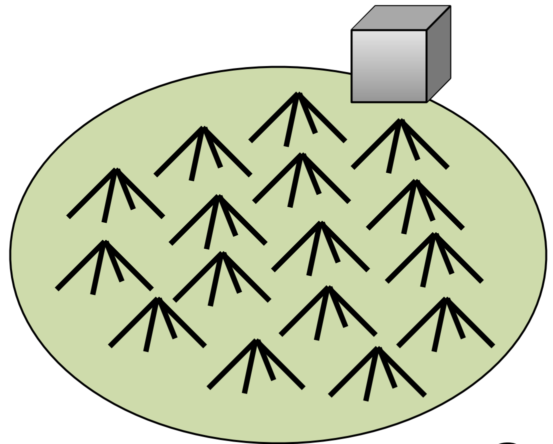

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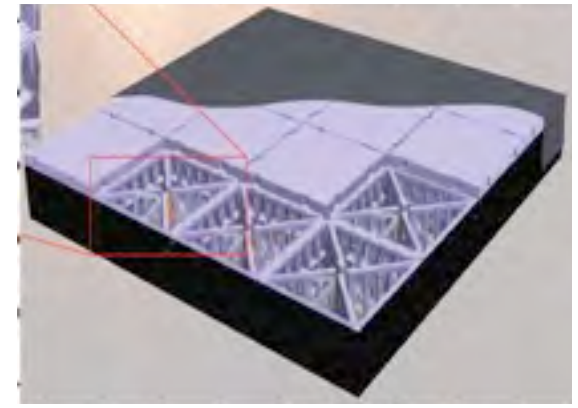

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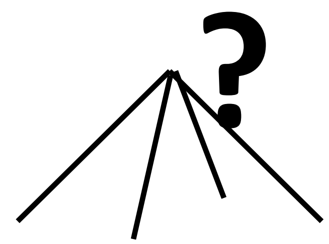

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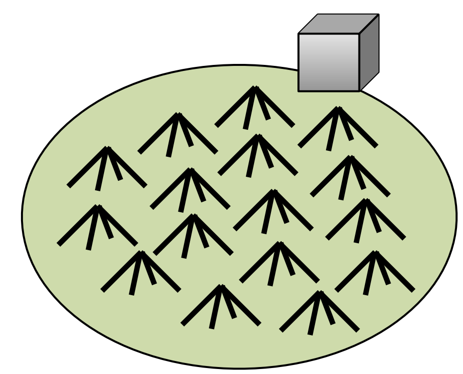
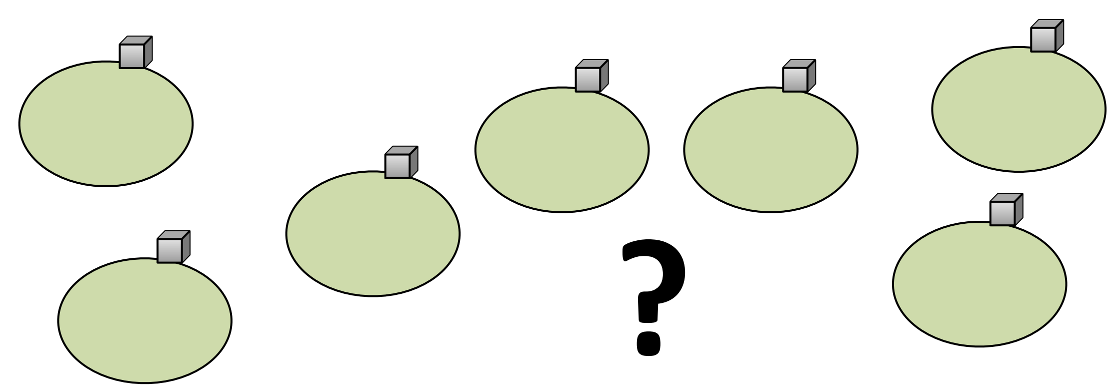
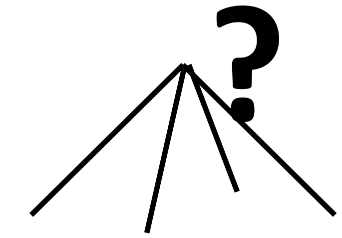


?

→ Which global MA distribution ?



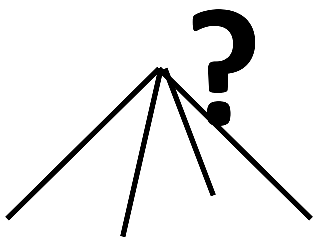
LSS Elementary antenna



Specifications

- **Large FOV & Smooth antenna pattern** - quasi-isotropic ≥20° elevation
  - rapidly decreasing ≤20° elevation
- **Broadband** electrical properties in 15-80 MHz
- **Simple** & **cost-effective** design

LSS Elementary antenna



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Studies

- **EM simulations** using NEC (*Numerical Electromagnetics Code*, NRL)

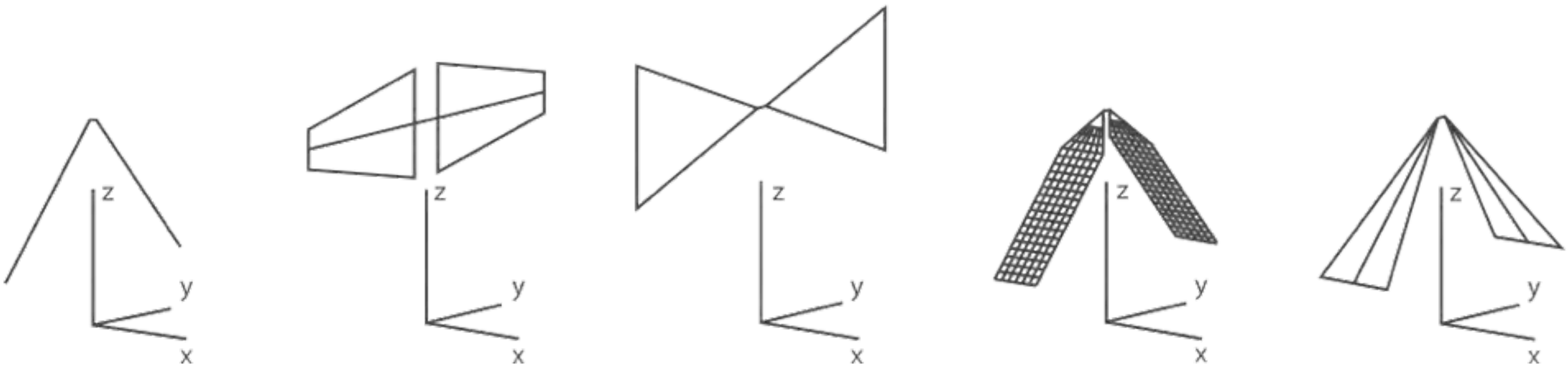
  → Effect of the antenna geometry of the antenna (parametric study)

  → Effect of the environment (ground, losses ...)

LSS Elementary antenna

- Study relevant existing antenna designs

LOFAR LBA | GURT Butterfly | SUBATECH Butterfly | LWA Big Blade | LWA Fork



Numerical models (NEC)

LSS Elementary antenna

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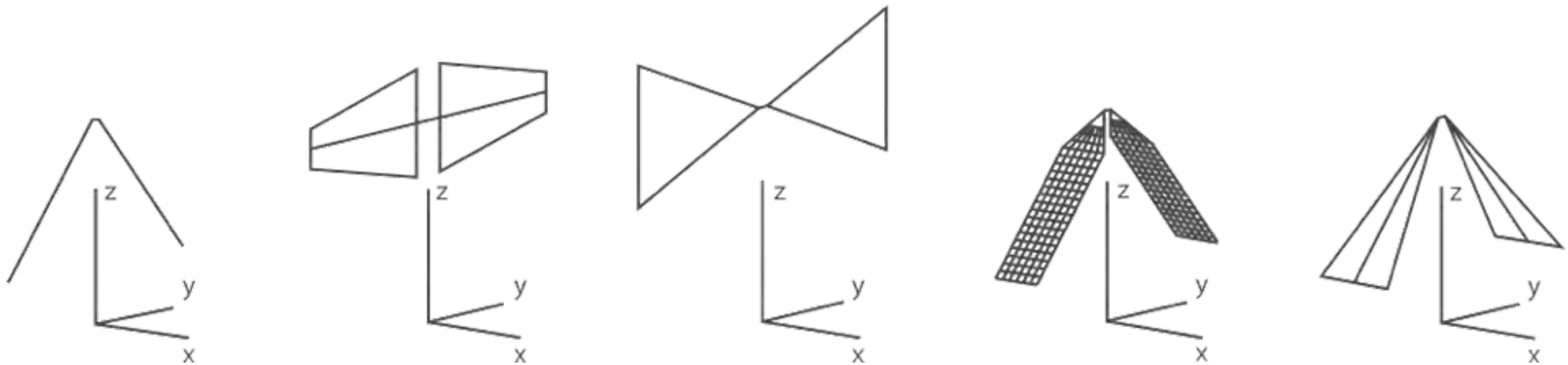

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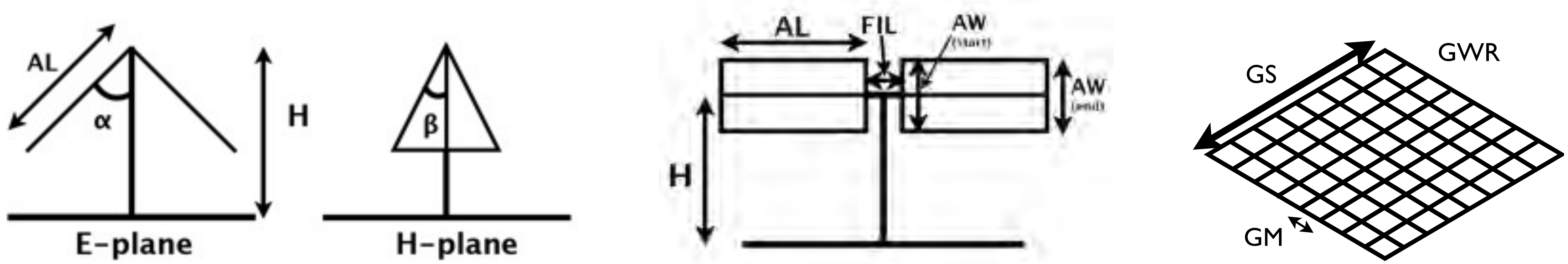
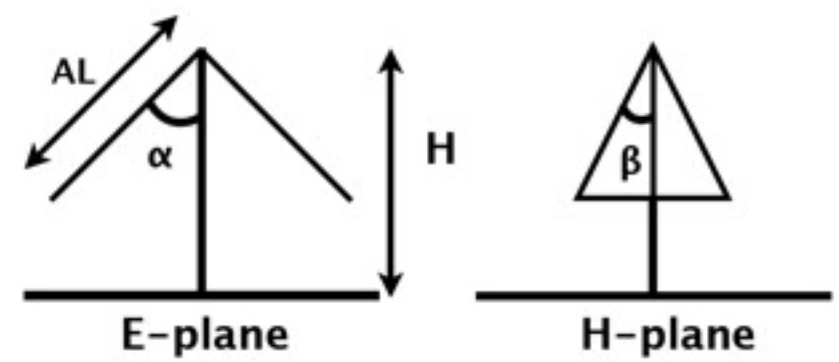


Parametrization of geometry and environment

LSS Elementary antenna

[Girard, et al., CRAS, 2012]

L	1.42
H	1.5 m
α	45°
β	14.8°

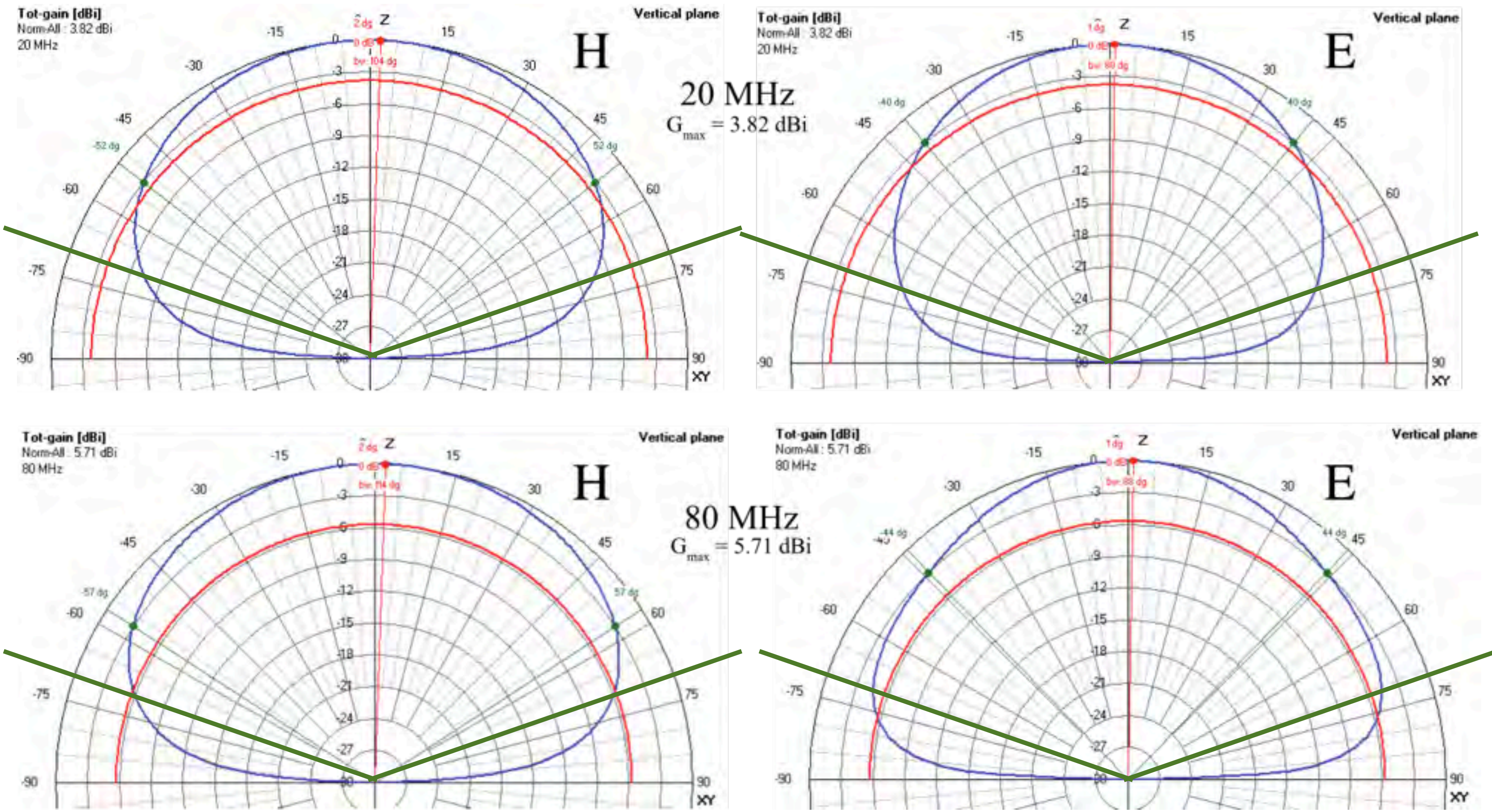


- Definition of the optimal antenna (radiator ~ LWA + grid)
    - Antenna impedance
    - Beam smoothness

LSS Elementary antenna

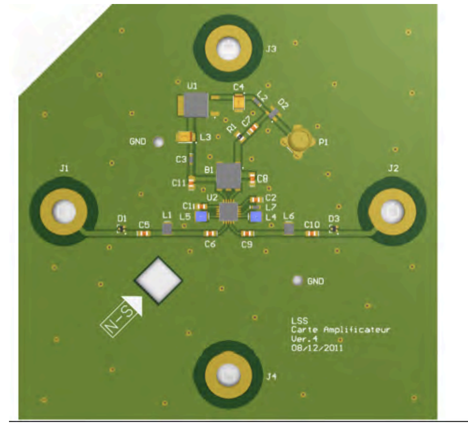
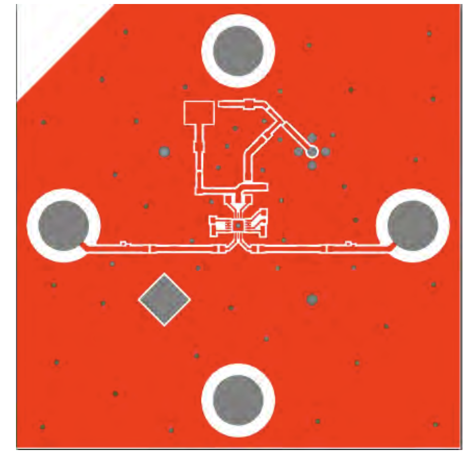
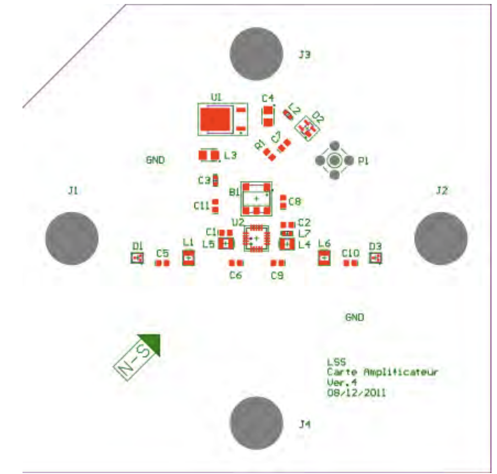
Resulting antenna pattern in its principal planes

HPBW E/H = 90°/92° @ 20 MHz & 180°/118° @ 80 MHz

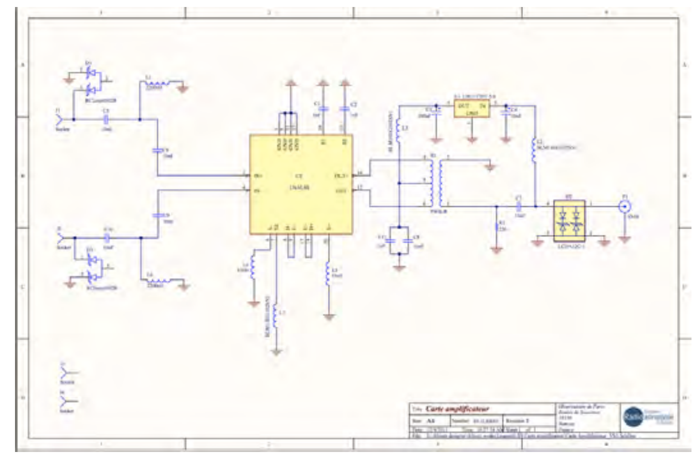
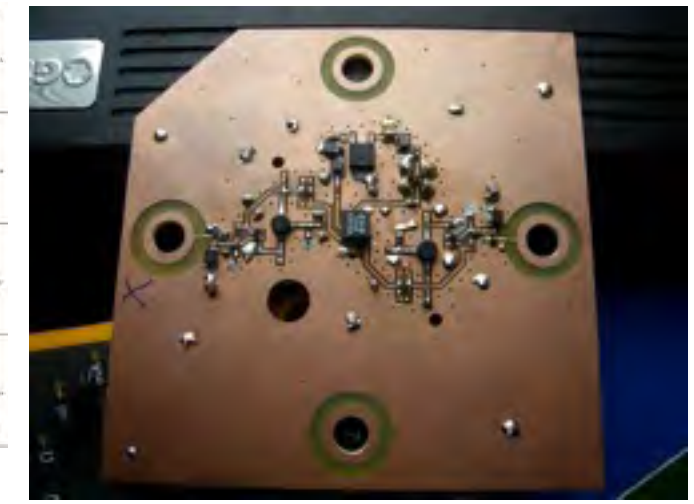
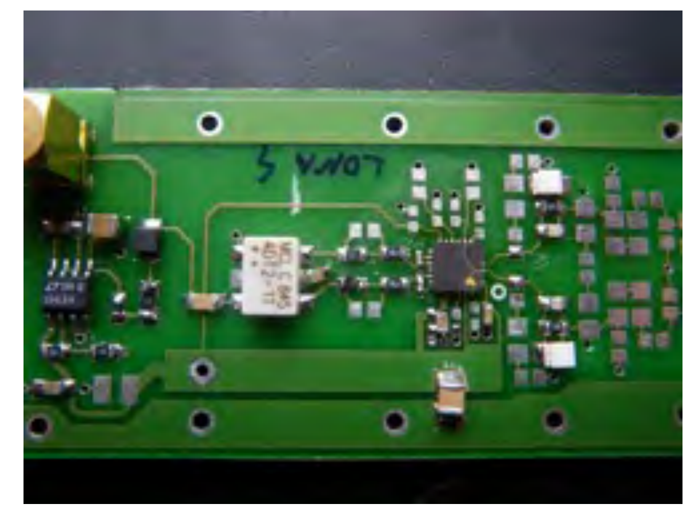


Antenna preamplifier (ASIC)

wideband
stable
Gain of >10 dB over the sky

GURT design
Nançay design
Subatech design

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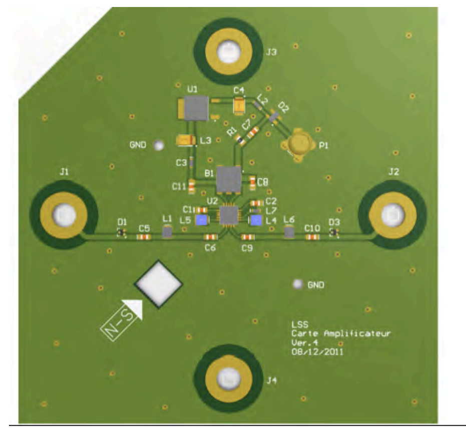

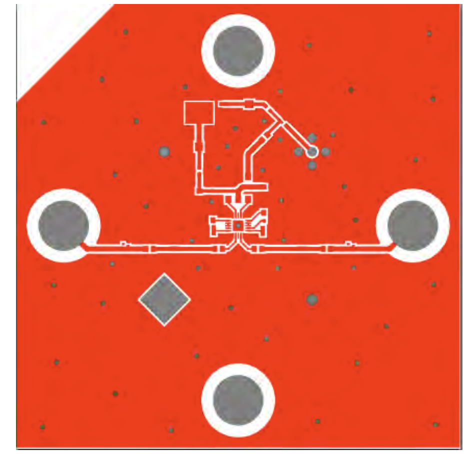

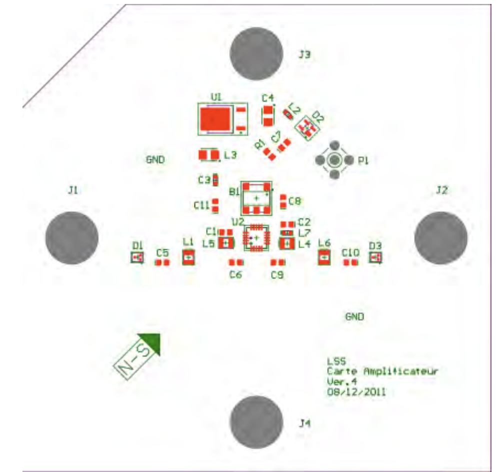

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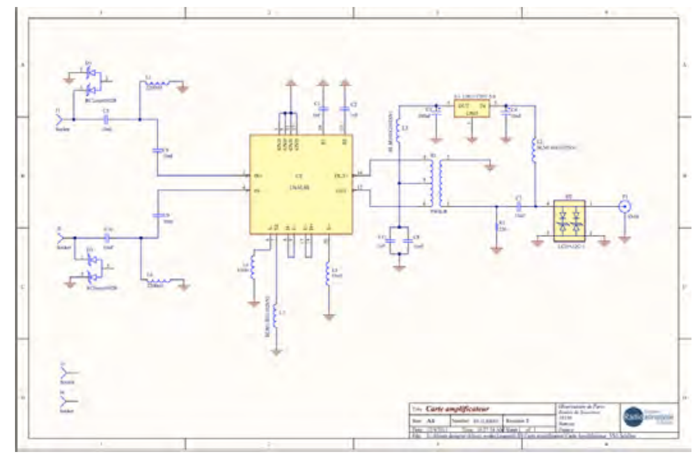

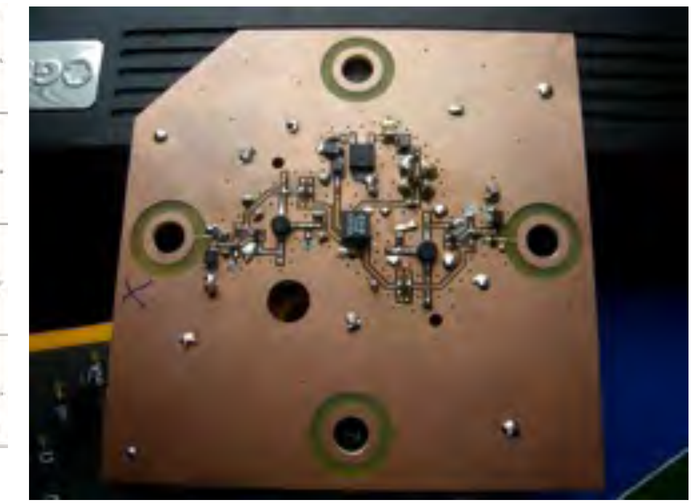

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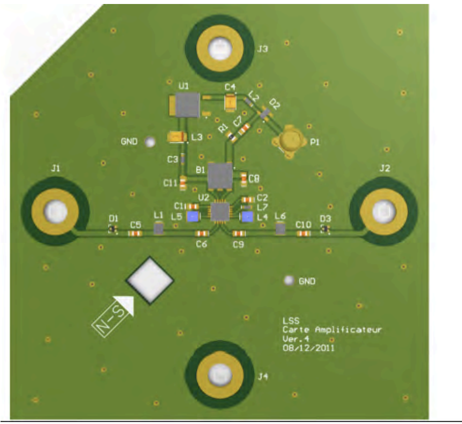
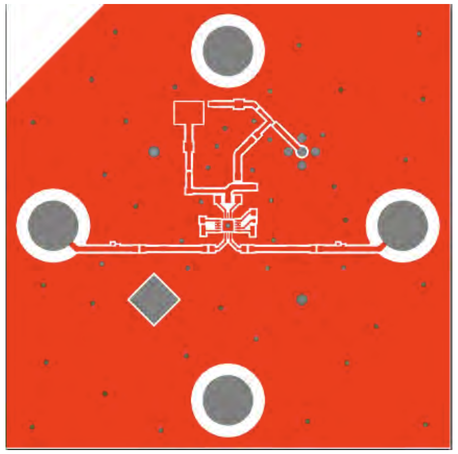
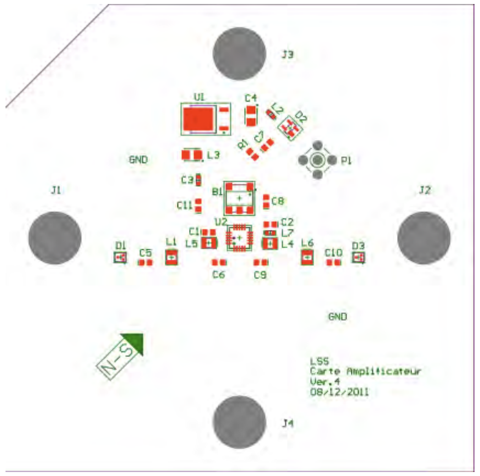

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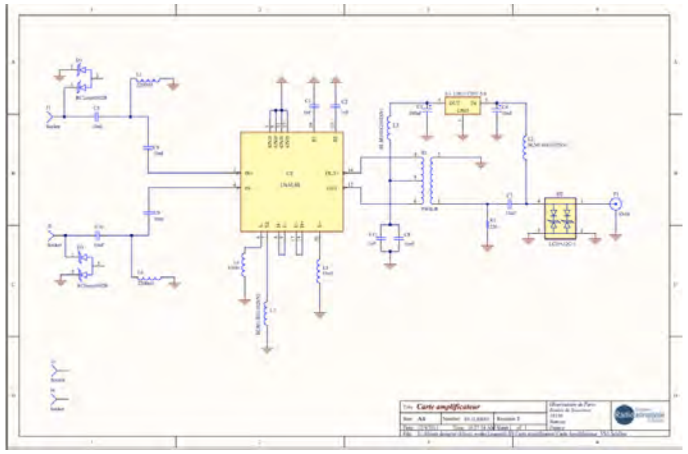
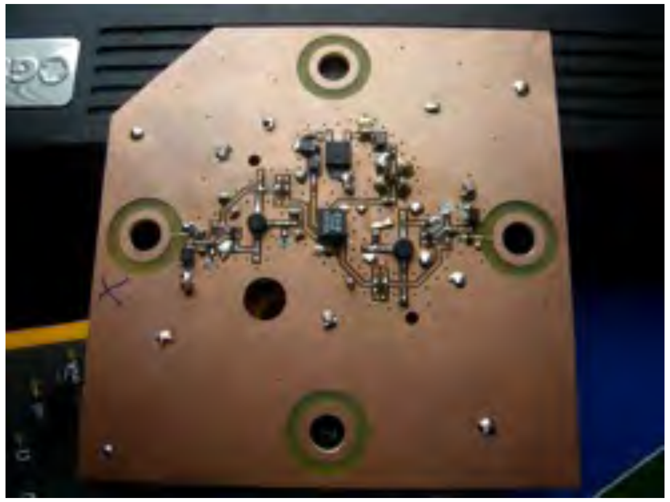
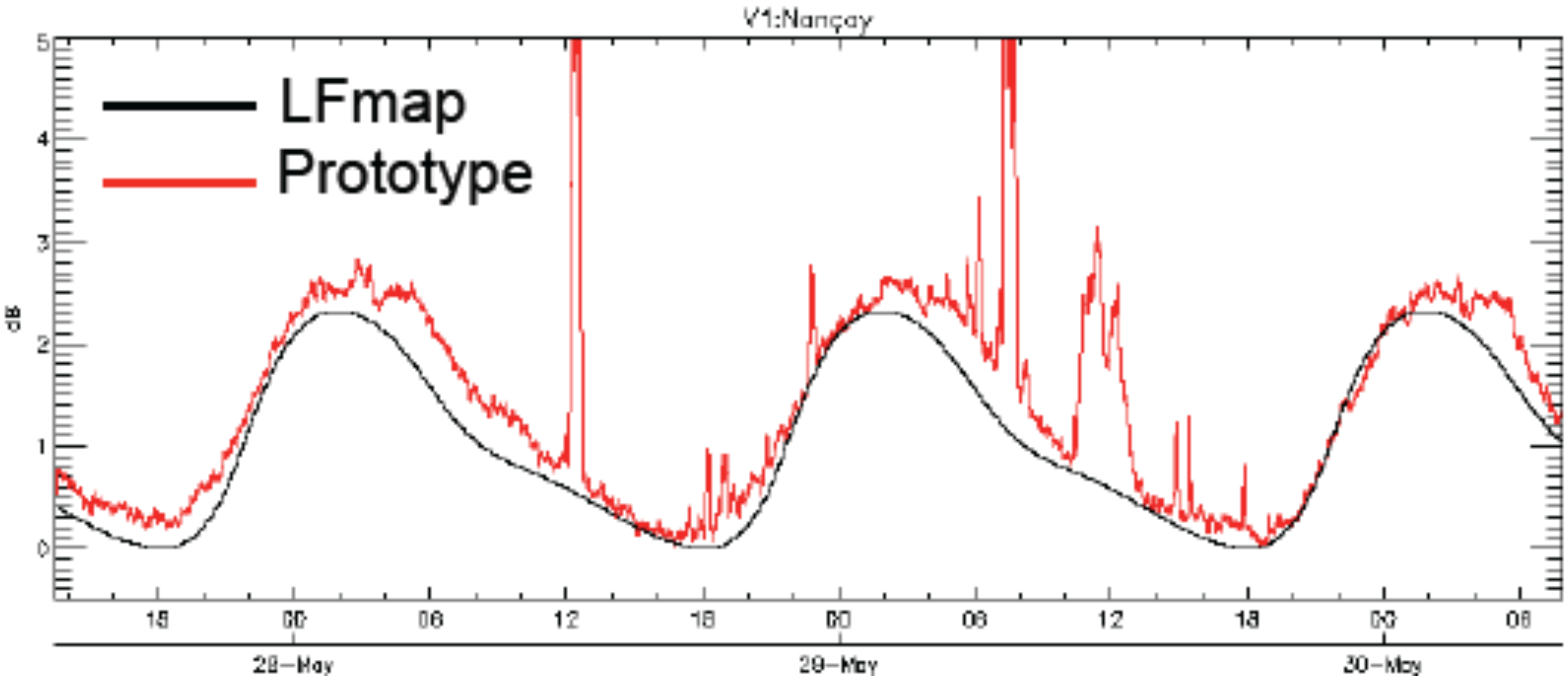
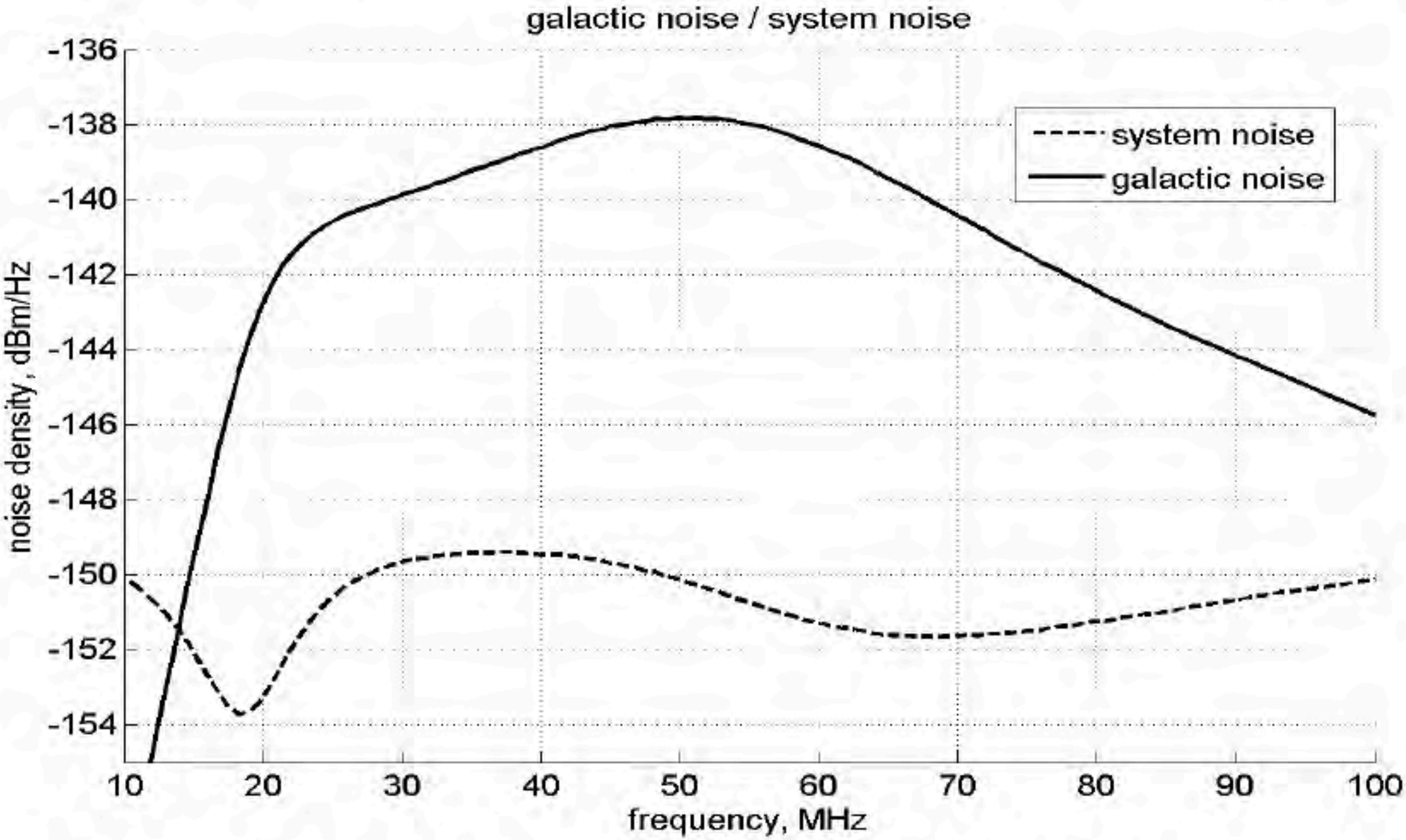





Drift scan of the sky compared to LFmap

Sensitivity to the galactic background with the LSS antenna (LSS-LONAMOS output)

Slide from Didier Charrier, SUBATECH



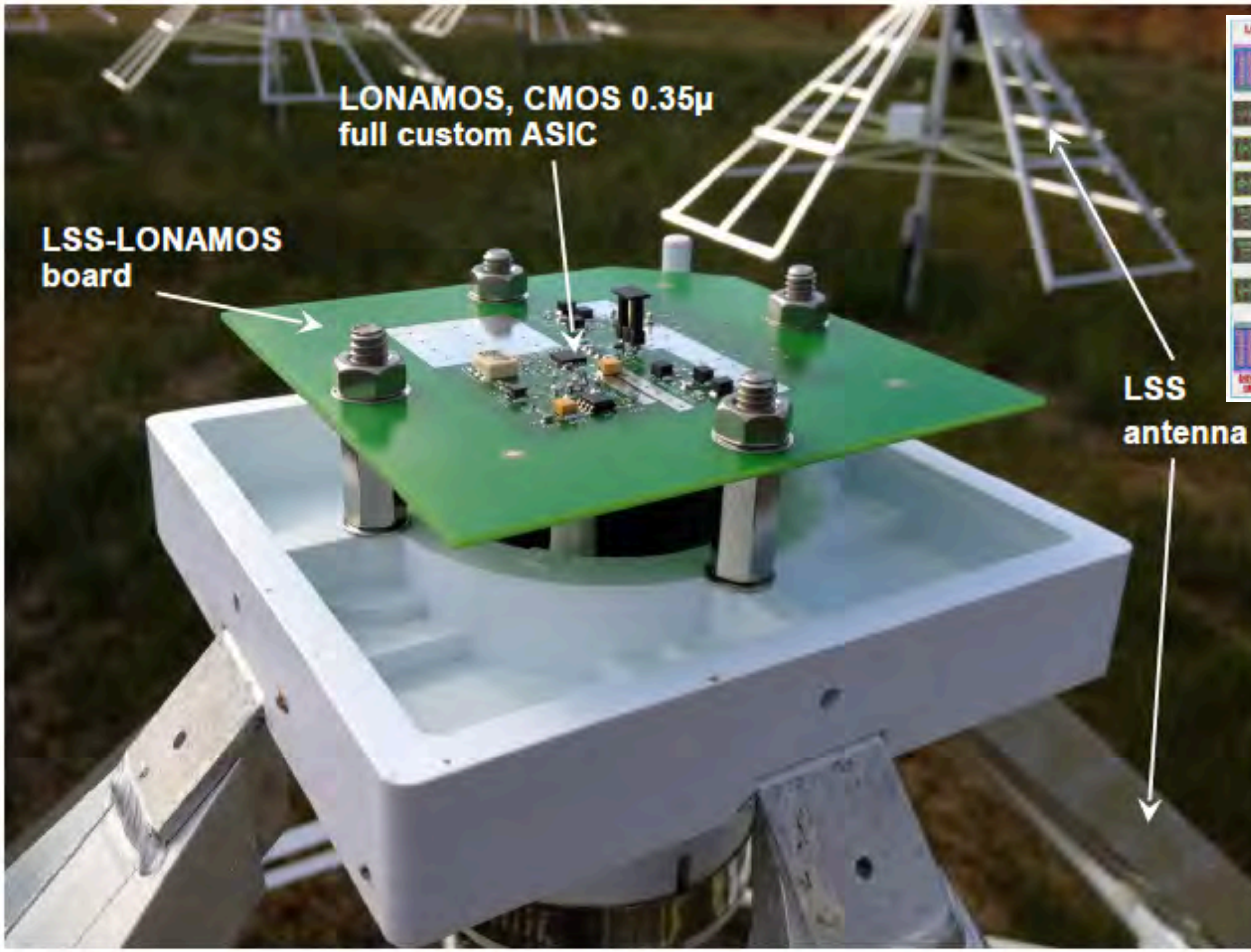
- The system noise is calculated from measured LONAMOS characteristics and simulated parameters of the LSS antenna.
- The galactic noise is calculated from typical minimum galactic temperature, simulated parameters of the LSS antenna and measured parameters of LONAMOS
- The low cut-off frequency can be decreased or increased

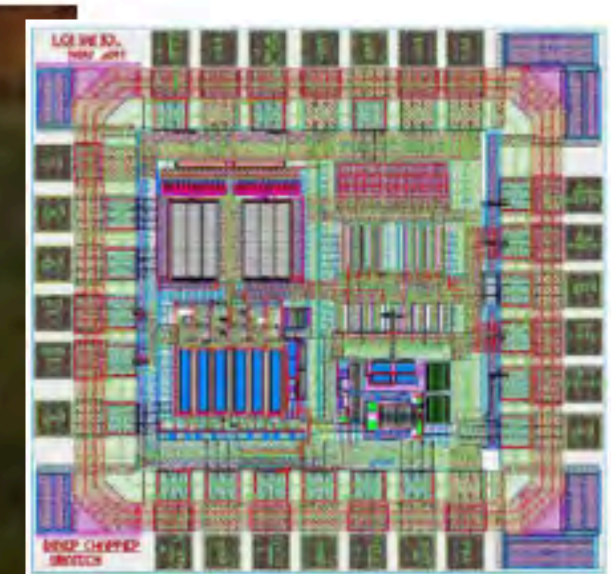
LSS-LONAMOS specifications, Didier Charrier, Subatech/CNRS, February 2013

The LSS-LONAMOS board

Slide from Didier Charrier SUBATECH

The LSS-Lonamos board is a dual polarization LNA designed by the Nançay observatory for the LSS active antenna. It uses a dedicated micro chip circuit called 'LONAMOS ' and designed at the Subatech laboratory

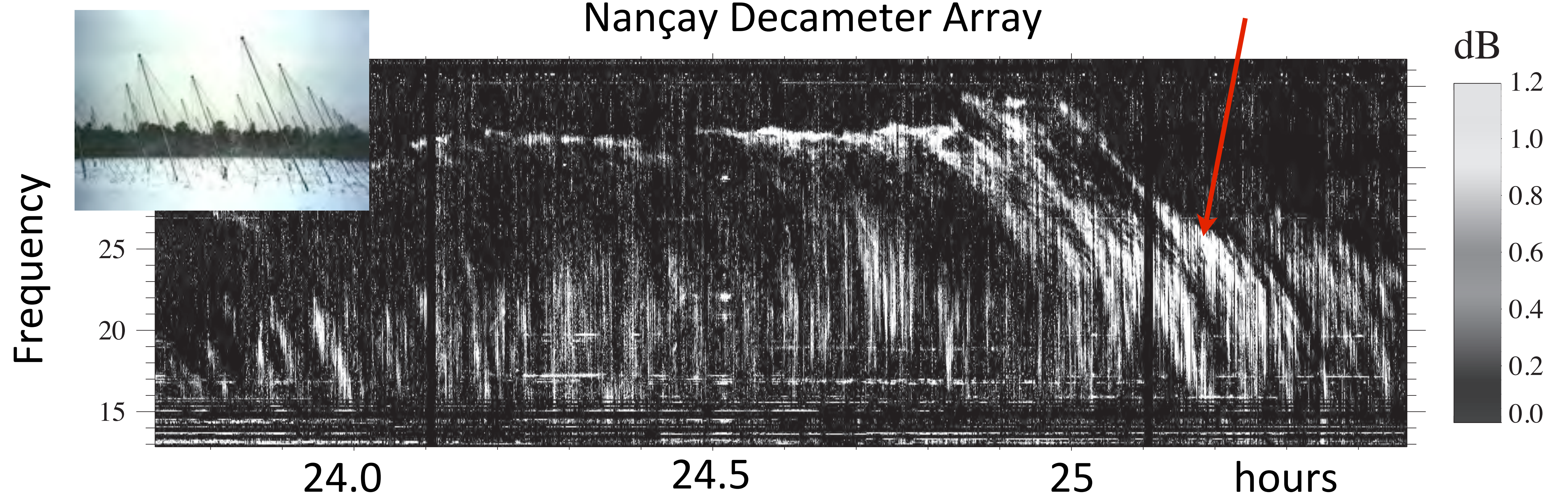




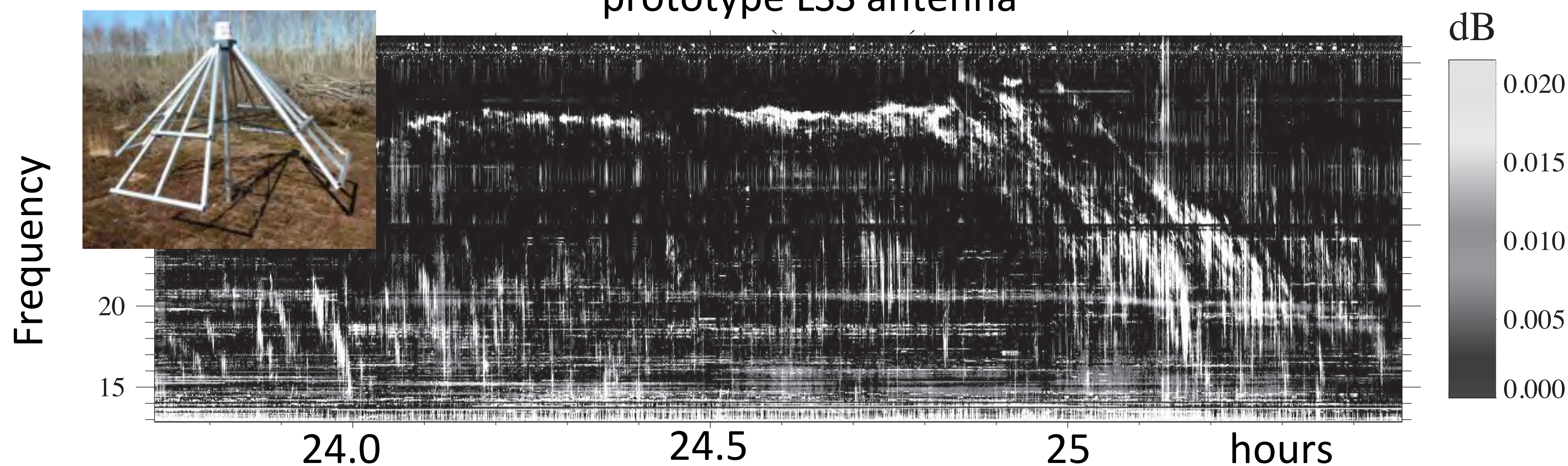
LSS Elementary antenna

Decameter emission from Jupiter
(intense, <40 MHz)

Nançay Decameter Array



prototype LSS antenna



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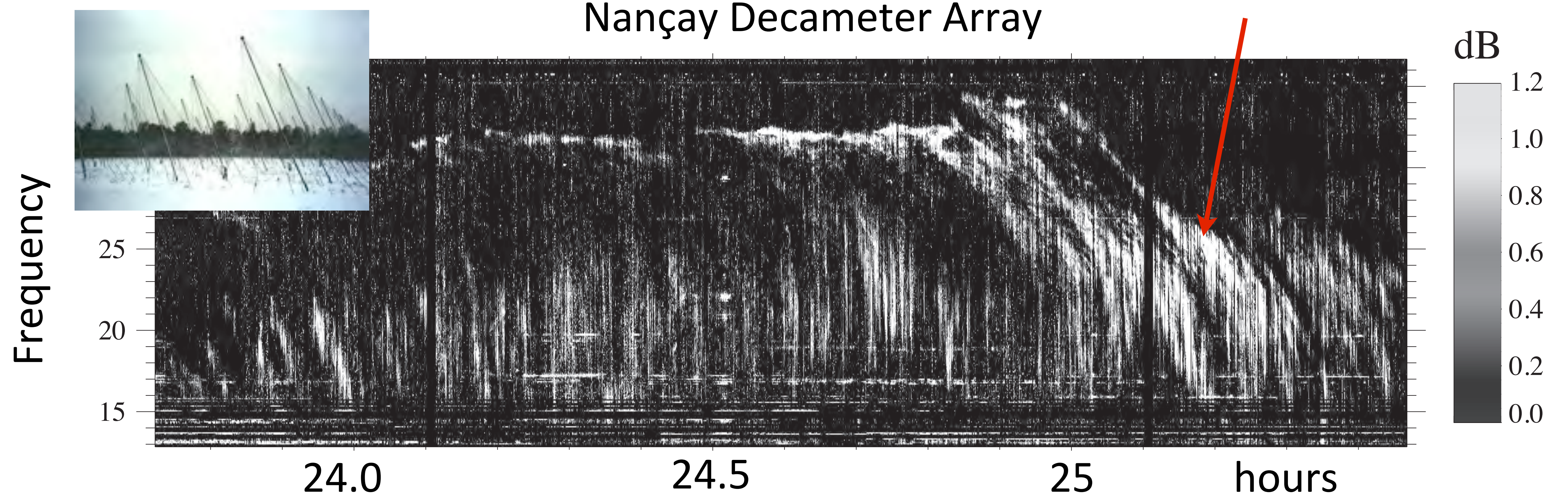

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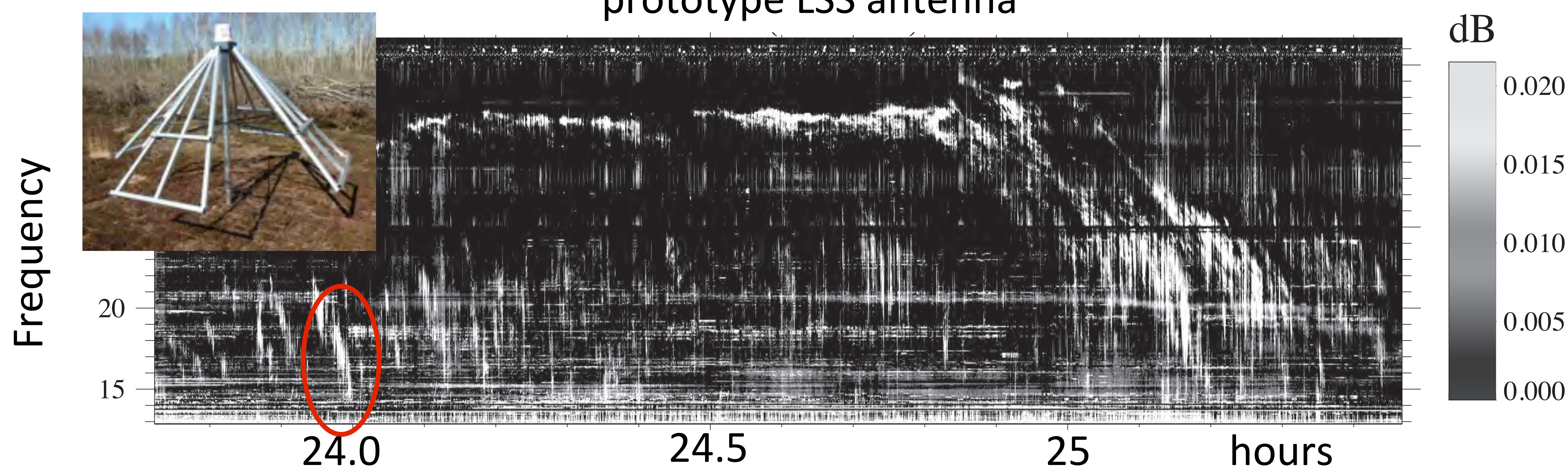
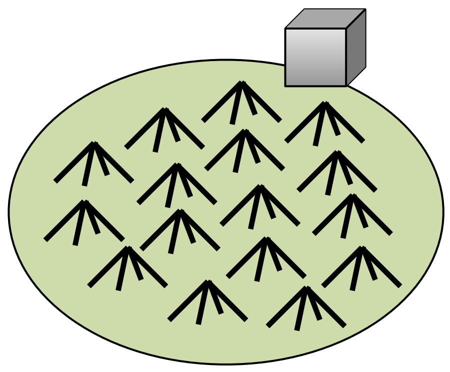


- 1 LSS antenna detect jovian decameter emission down to ~10 MHz
- Measured gain consistent with EM simulations (NEC = 5,5 dB)

LSS Mini-array



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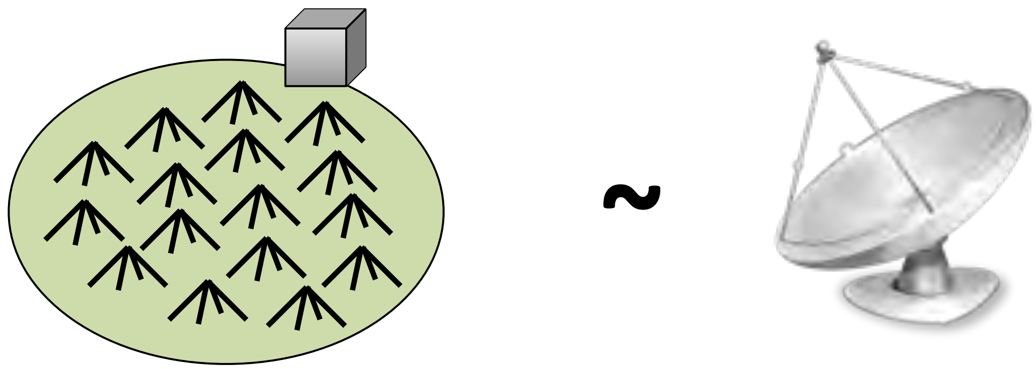
Specifications

- **Sensitivity** of the MA (should detect main radiosources: CygA, CasA)
- **FOV**: Large primary lobe, low side lobe levels
- **Broadband** characteristics (f_{max}/f_{min} >5)
- **«Fine» pointing**
- **Analog** phasing system

LSS Mini-array



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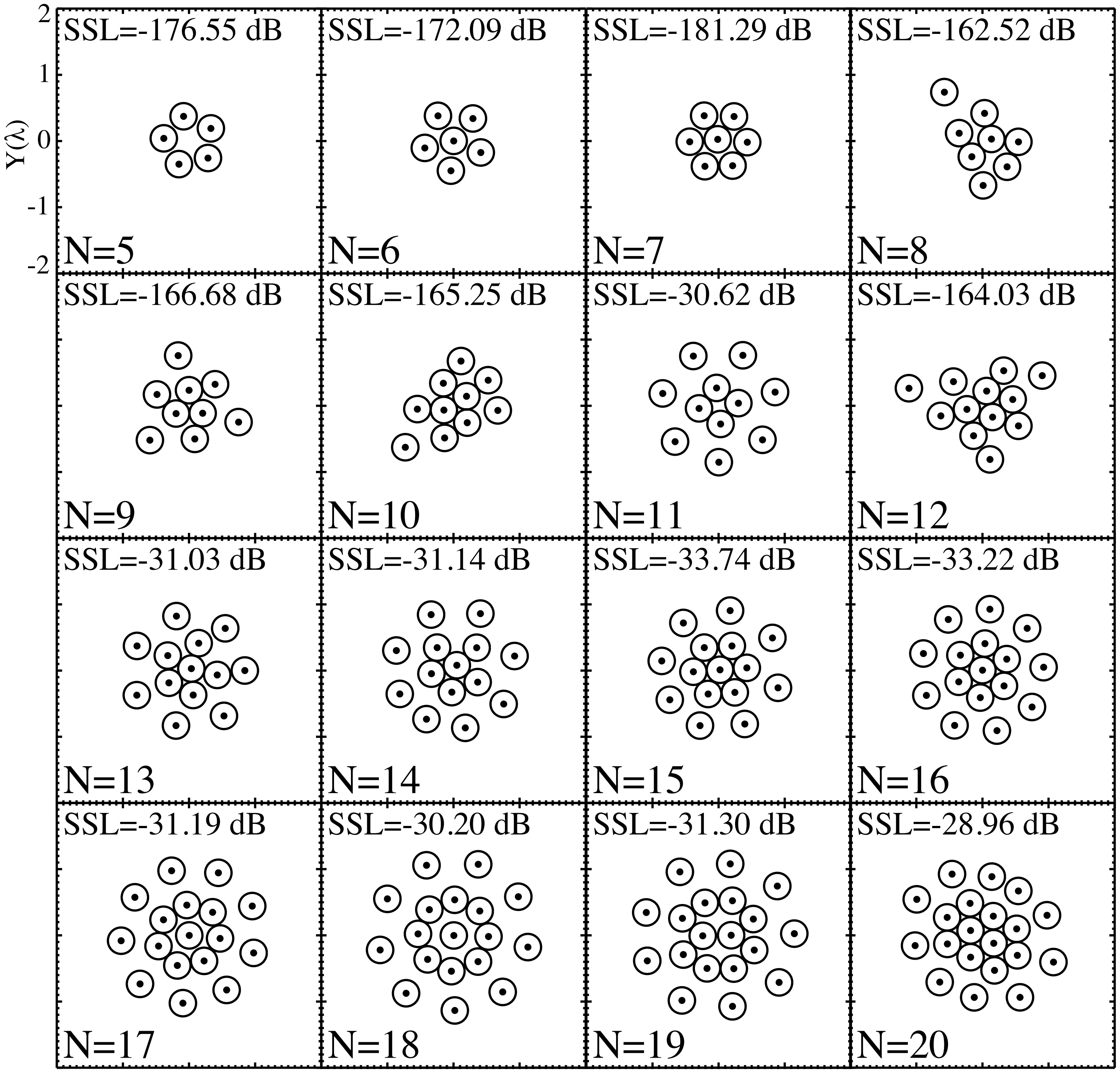
Studies

- Optimal number of antennas in MA
- Distribution of antennas in MA
- Phasing system design

LSS Mini-array: topology

Generalized study of the optimal free positioning of MA

- **Deterministic algorithm**: Kogan algorithm [Kogan, 2000]
- **Non deterministic algorithm**: Simulated annealing [Kirkpatrick et al., 1989]



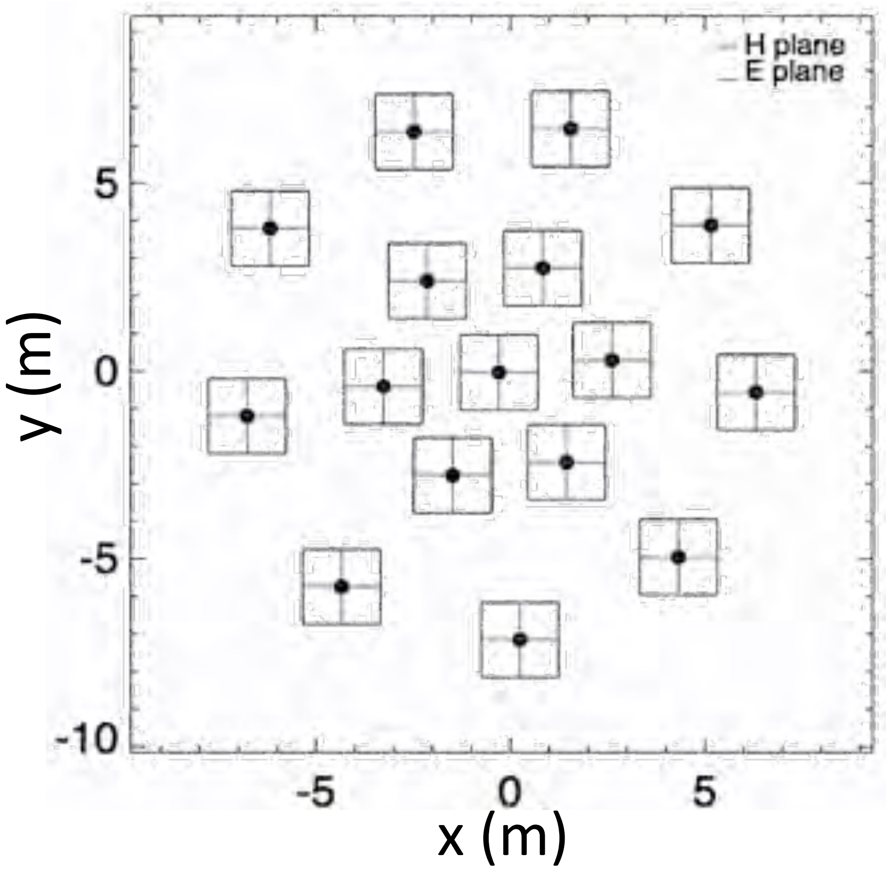
Optimal distributions Prop.

- Compacts
- Irregular
- with ~ axial symmetry

[Girard, Zarka, in revision]

LSS Mini-array: topology

Optimal solutions exist (N ≥ 16 antennas)



Irregular phased array → **Analog phasing very complex**

very expensive

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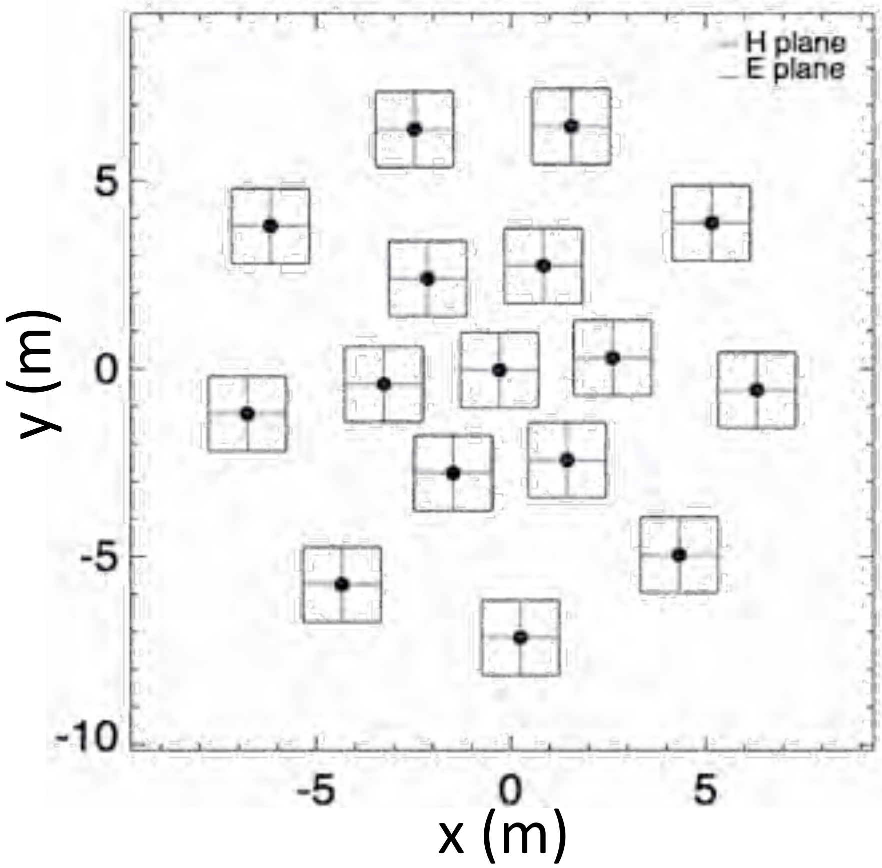

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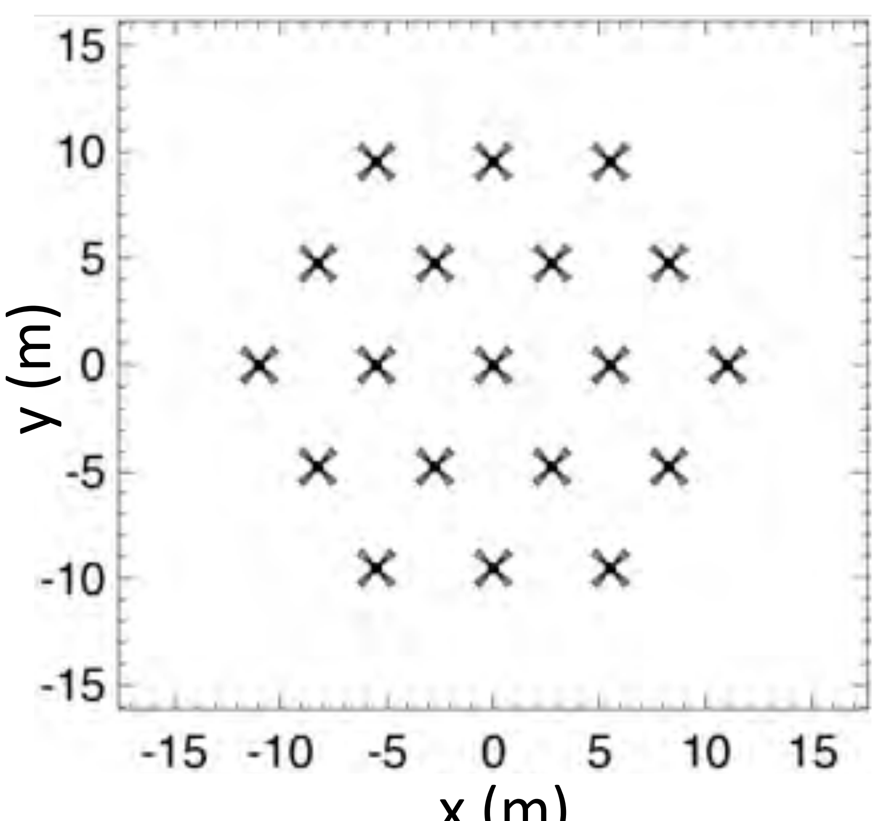
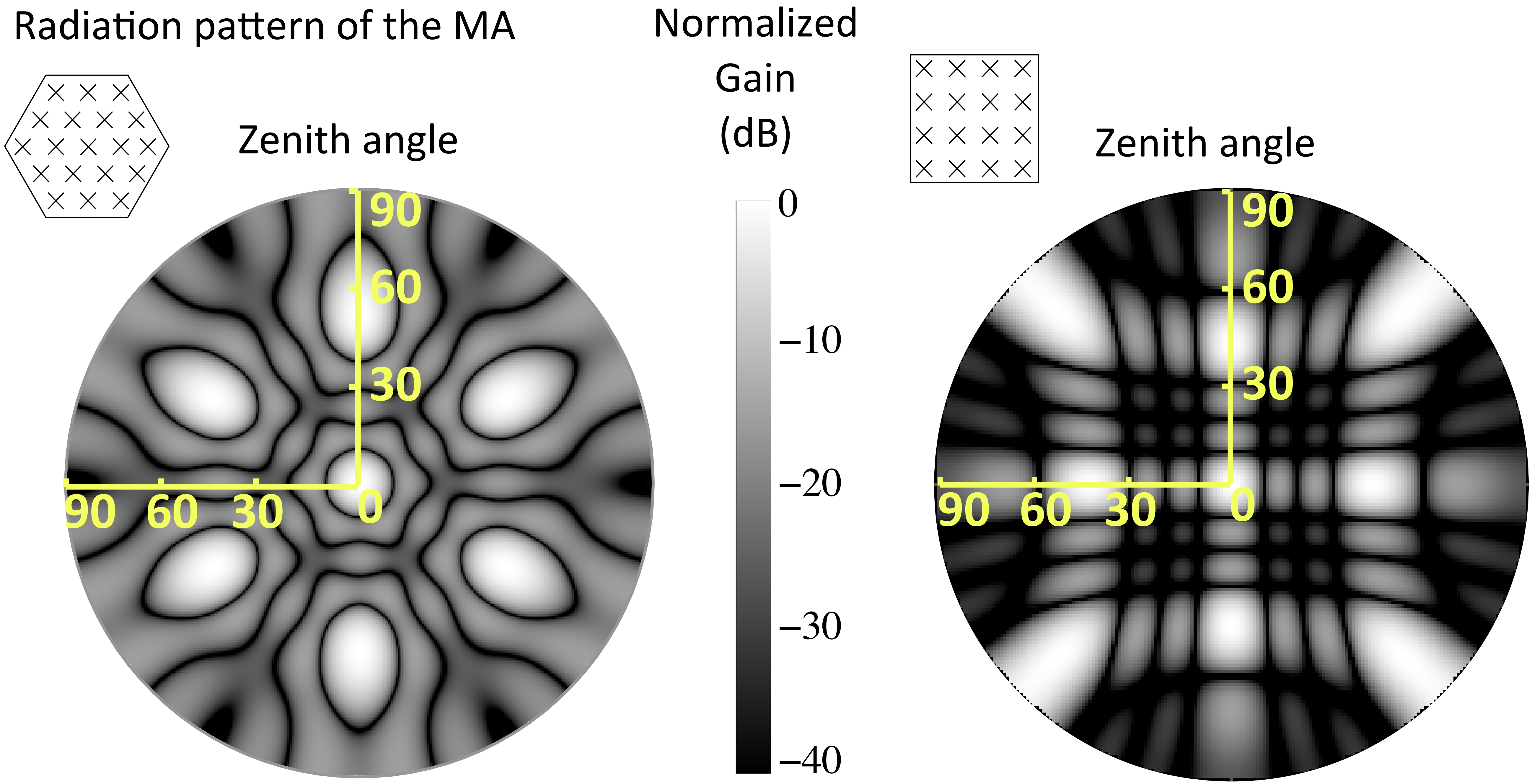


Compromise between
Radiation pattern → hexagonal MA
and regular topology of 19 antennas

$D_{inter\text{-}antennes}$= 5,5 m → Compromise between $\mathbf{A_{eff}}$
and **radiation pattern quality**

LSS Mini-array: topology

Radiation pattern of the MA

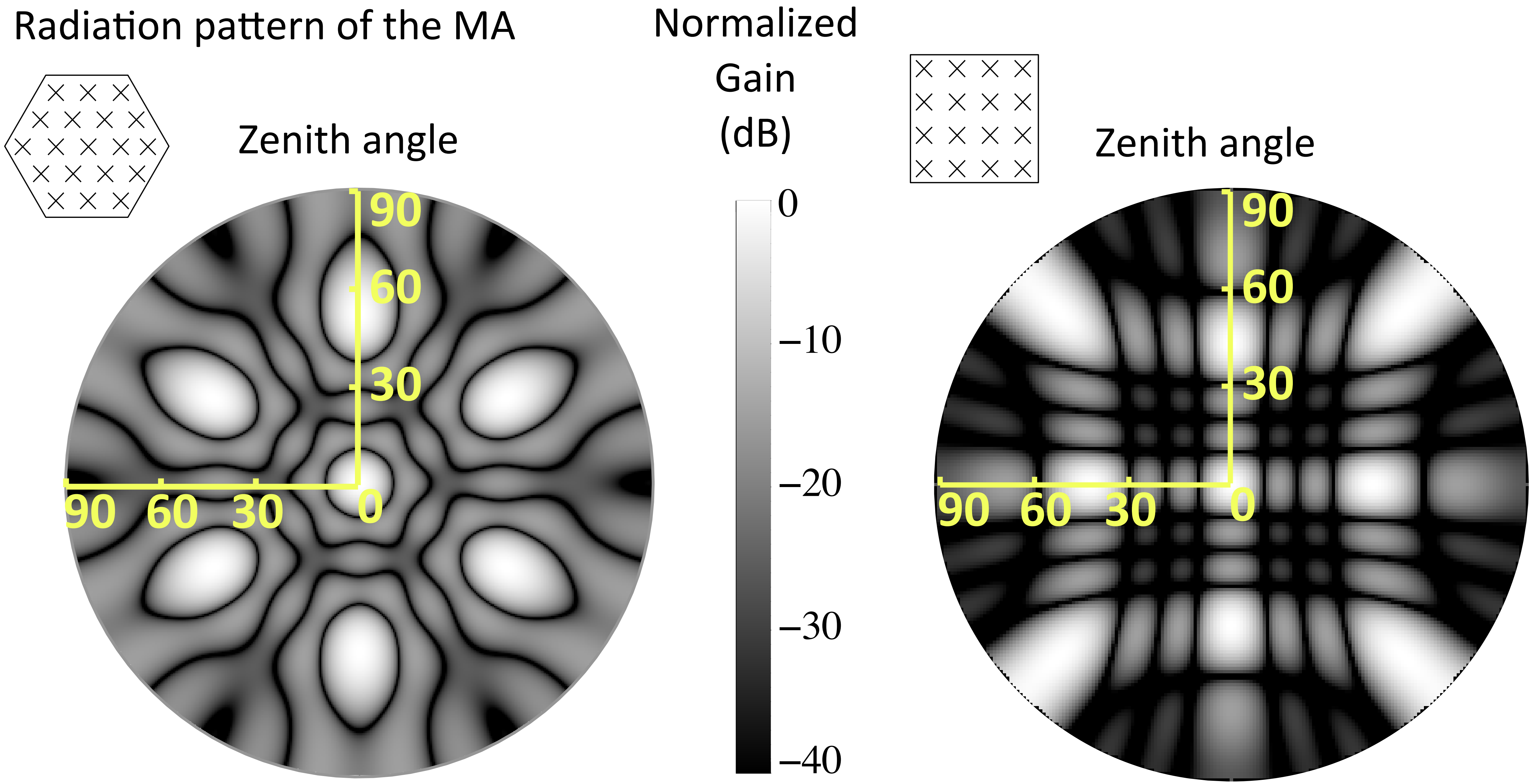


Primary lobe: 9° at 80 MHz
33° at 20 MHz

[Girard, et al., CRAS, 2012]

LSS Mini-array: topology

Radiation pattern of the MA



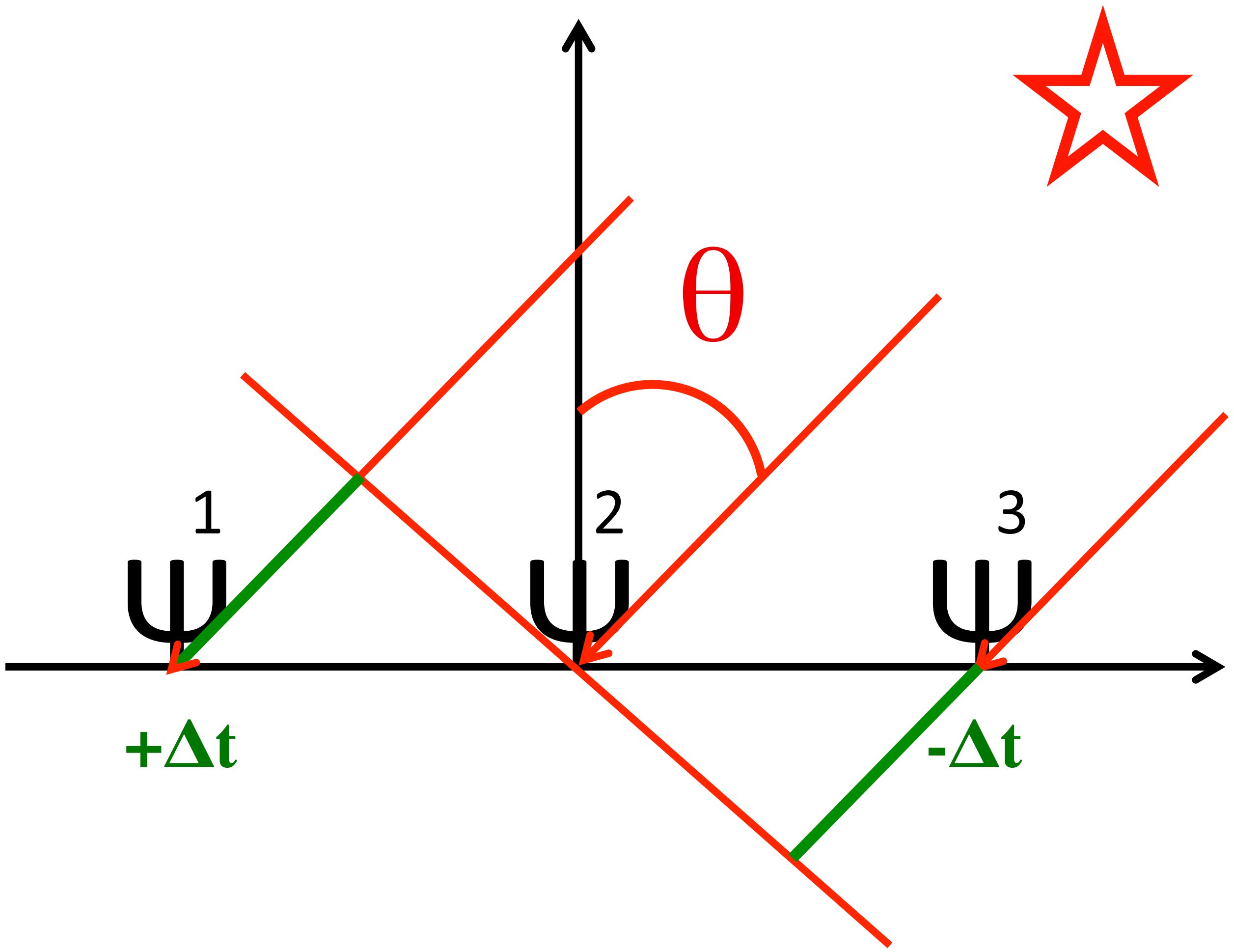
Primary lobe: 9° at 80 MHz
33° at 20 MHz

Hexagonal MA

- Less grating lobes
- Lower energy lost in side lobes

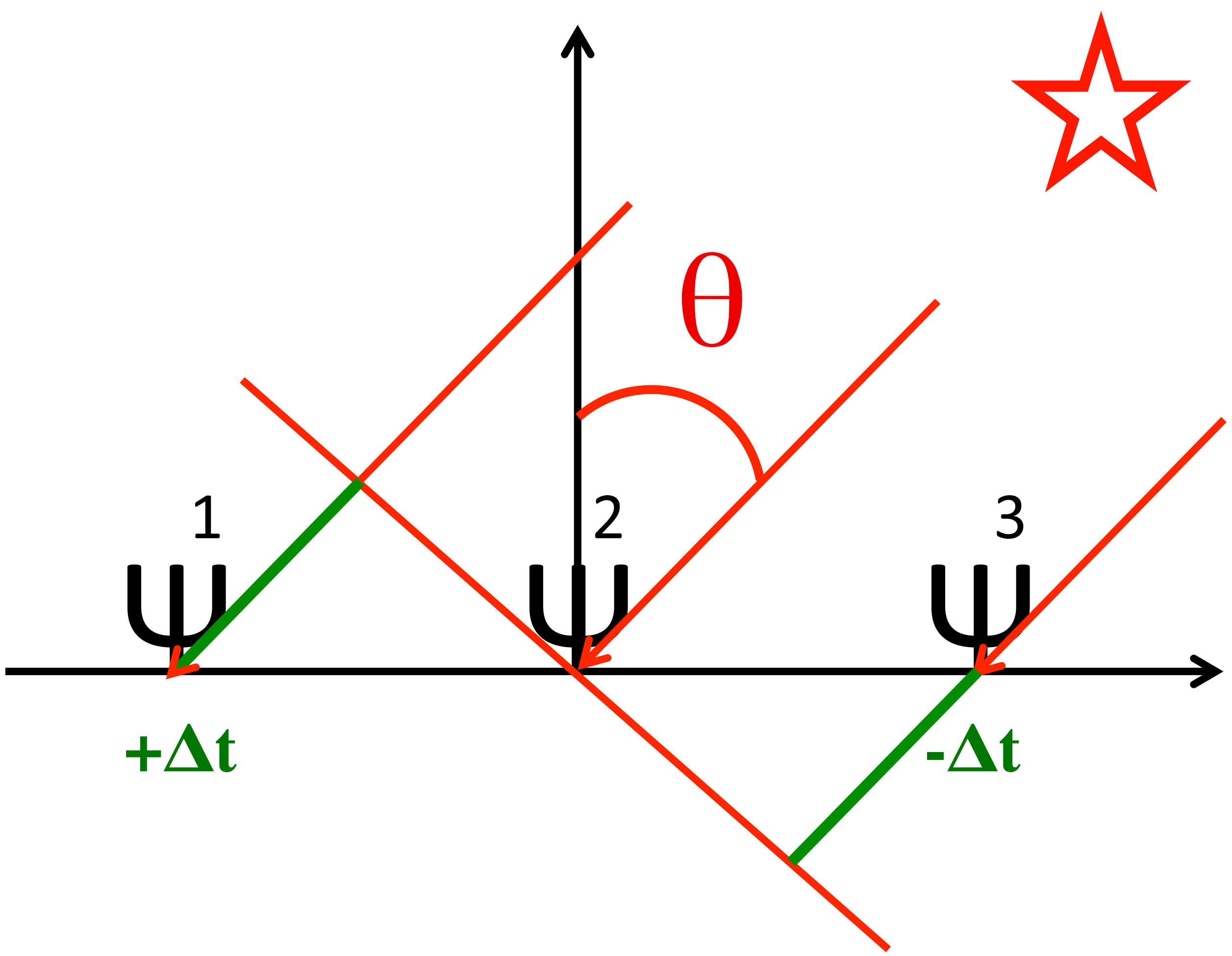
[Girard, et al., CRAS, 2012]

LSS Mini-array: Phasing



Compensating from positive/
negative time delays

LSS Mini-array: Phasing



Compensating from positive/
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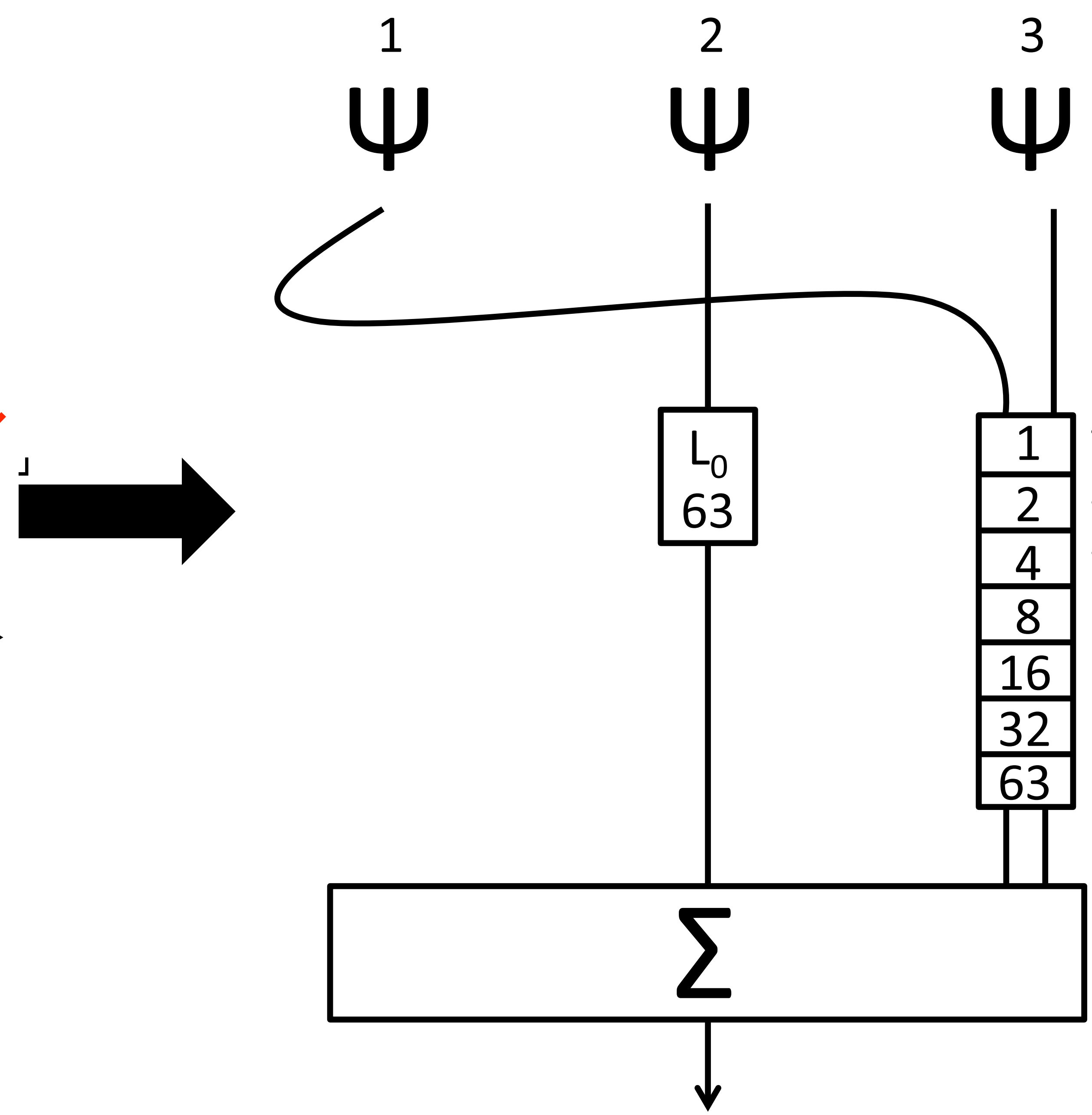
In practice



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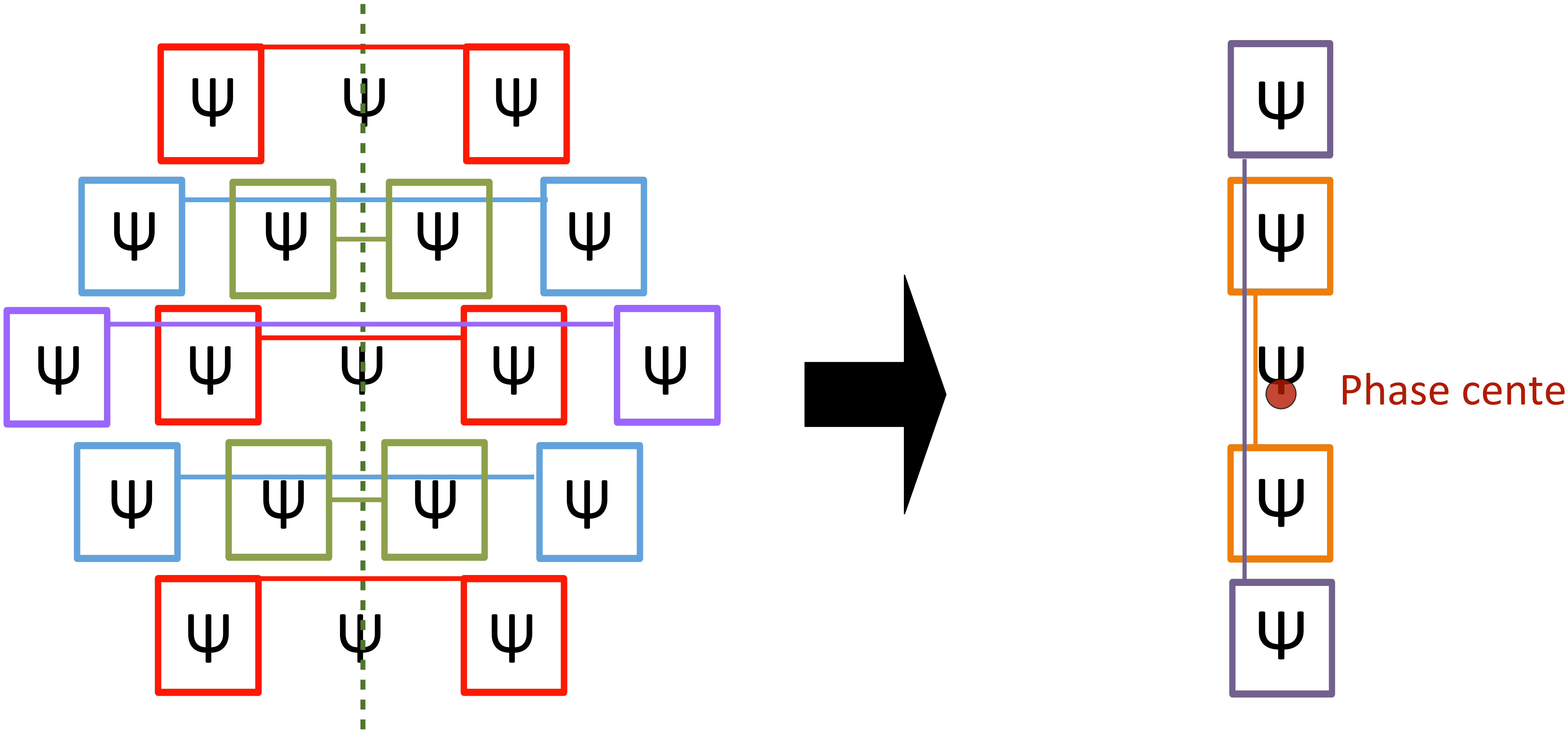


Lines phase centers

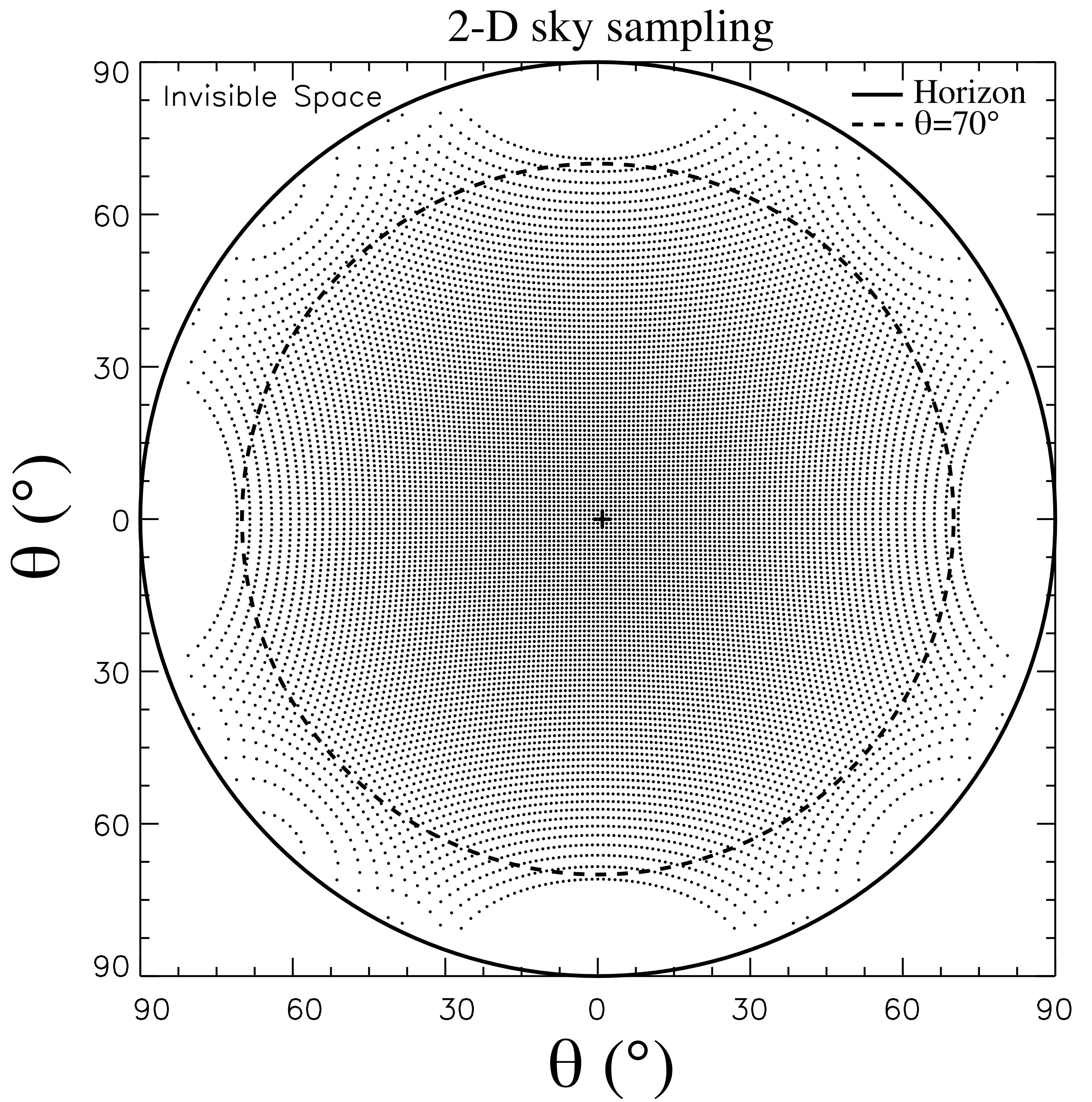
1st stage of phasing
= 8 delay lines

2nd stage of phasing
= 2 delay lines

In total, 10 delay lines /pol /MA (same number as for a 4x4 array)

LSS Mini-array: Phasing

Pointing direction map: ~1° accuracy subject to $\frac{\Delta \mathrm{Gain}}{\mathrm{Gain}} \leq 10\%$



With isotropic antennas

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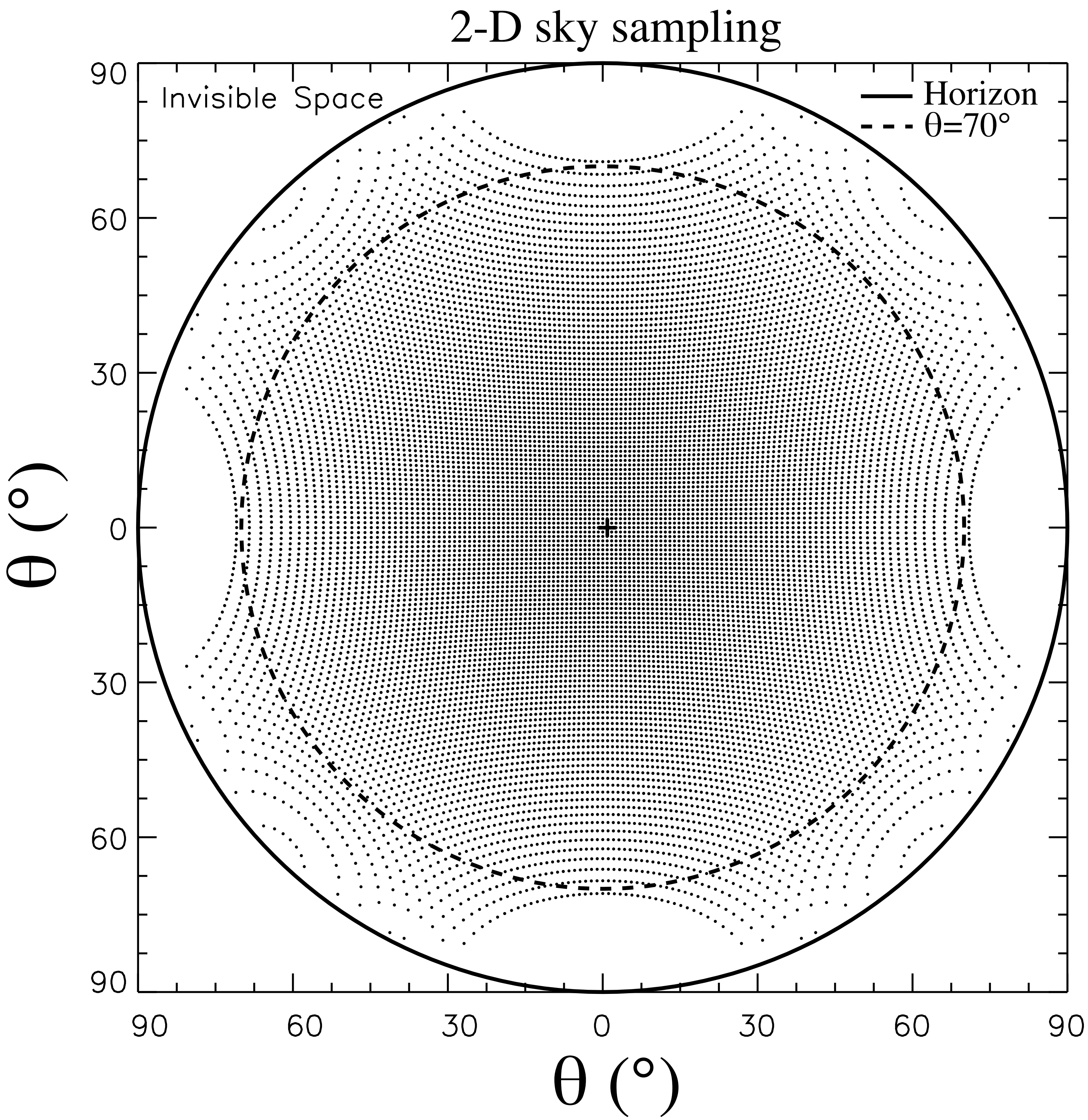

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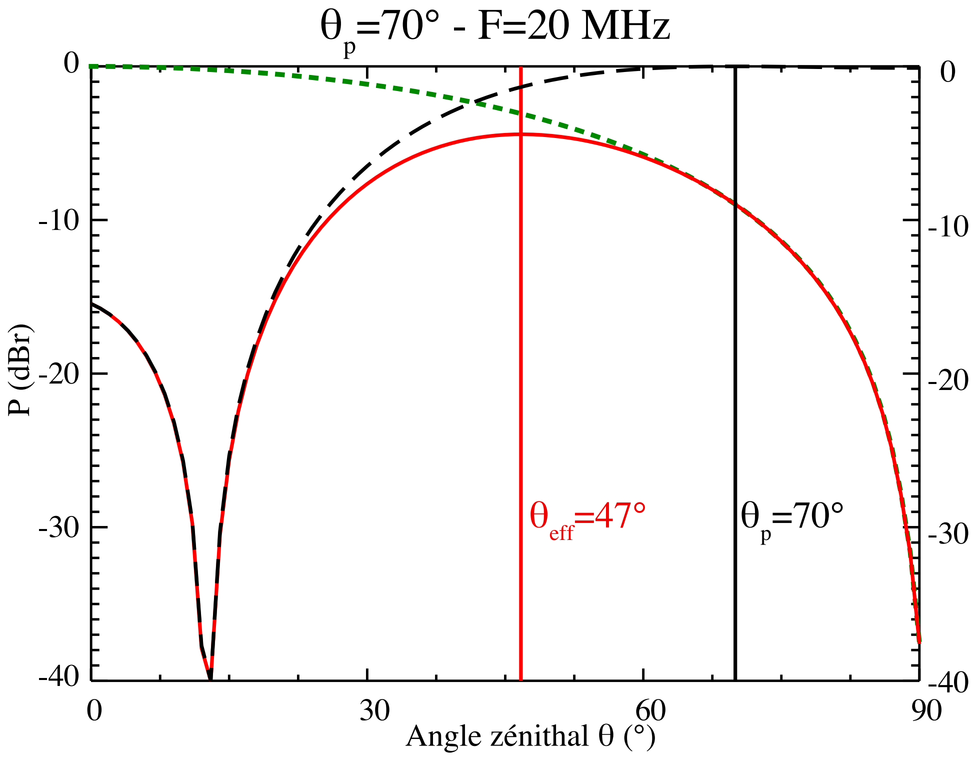
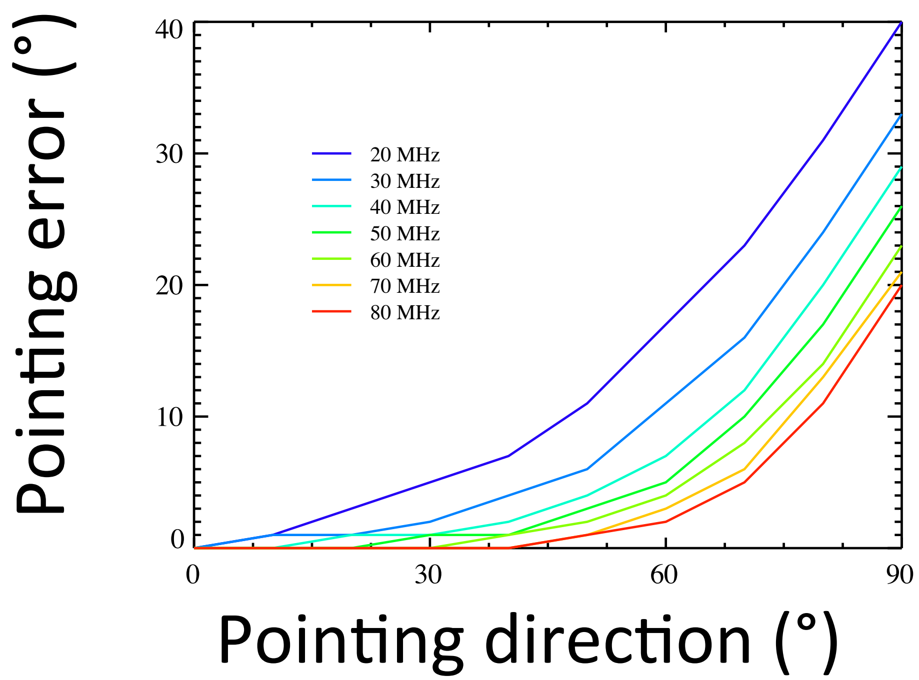
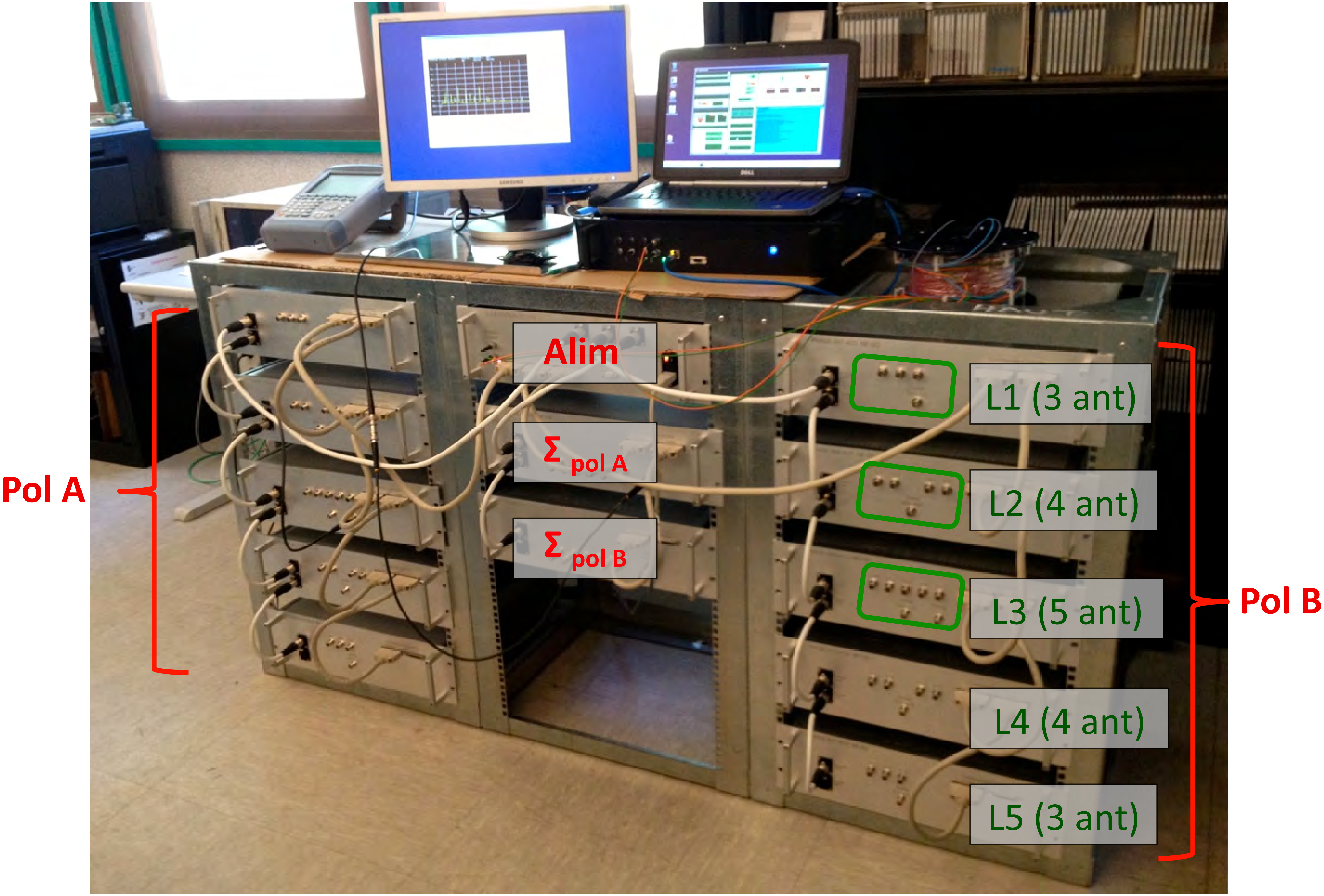




with LSS antenna pattern
→ beam squint at low elevation

LSS Mini-array: Phasing

Prototype phasing system (MR N°1)

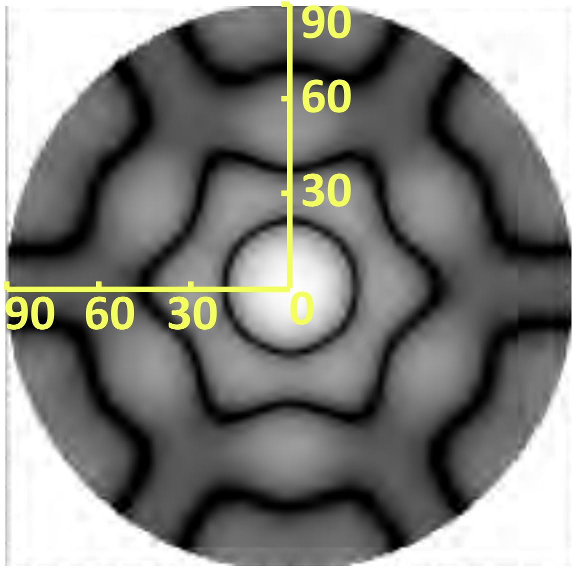


LSS Mini-array: Phasing

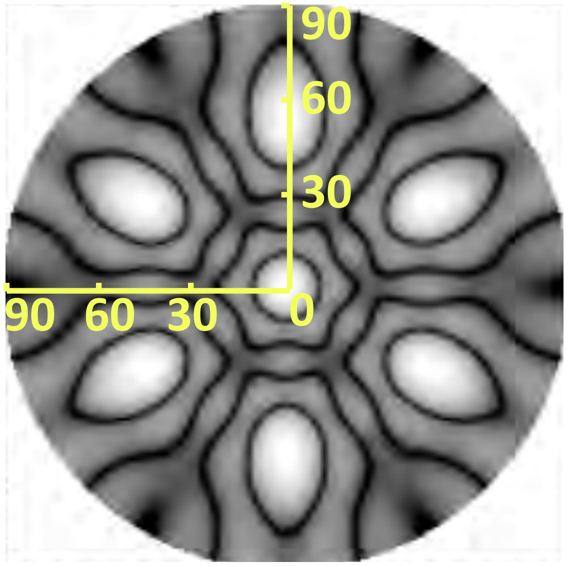
Lab tests compared to simulations

- source at the zenith, ~400 pointing directions
- agreement <<1 dB (except minima, < 5 dB)

41 MHz



Radiation pattern



79 MHz

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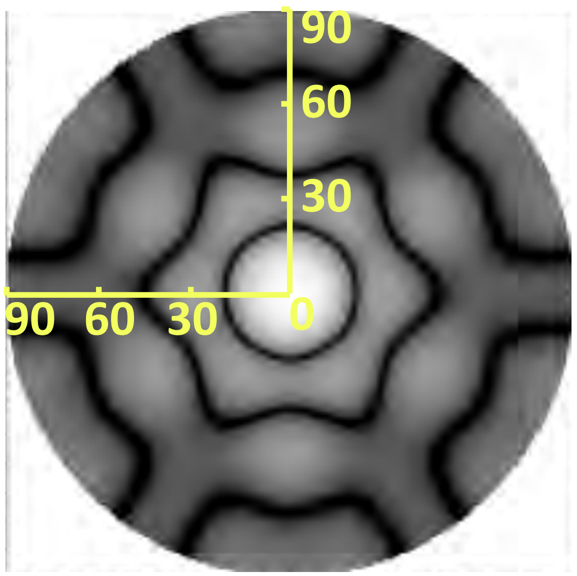
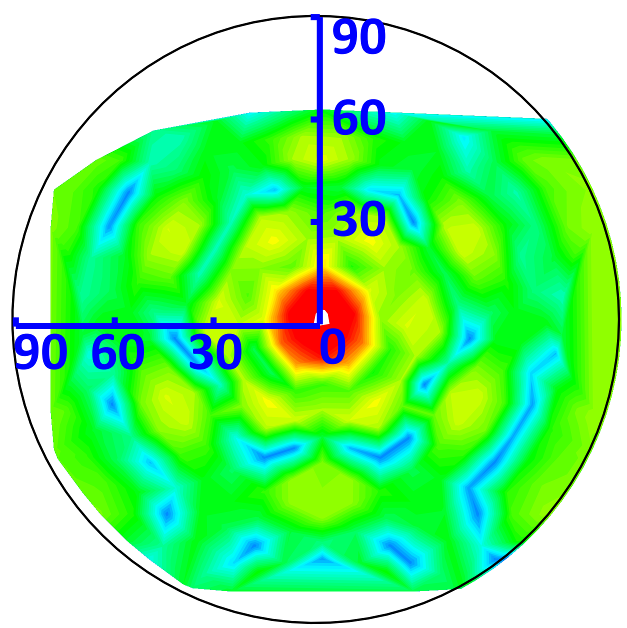
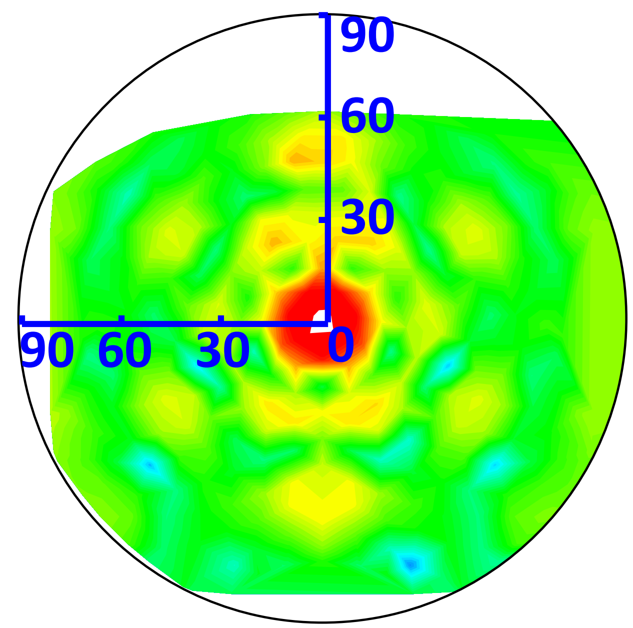
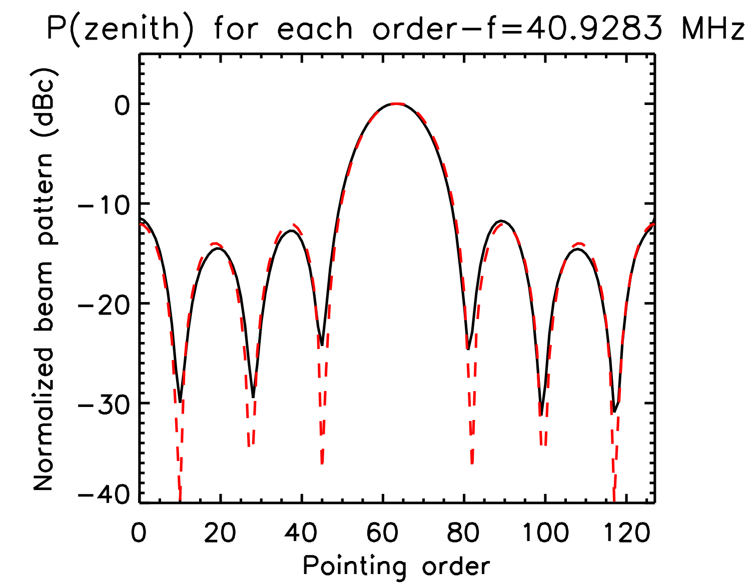
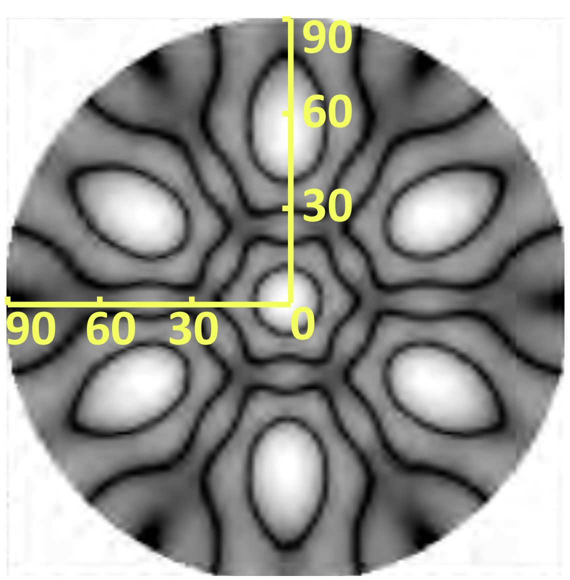


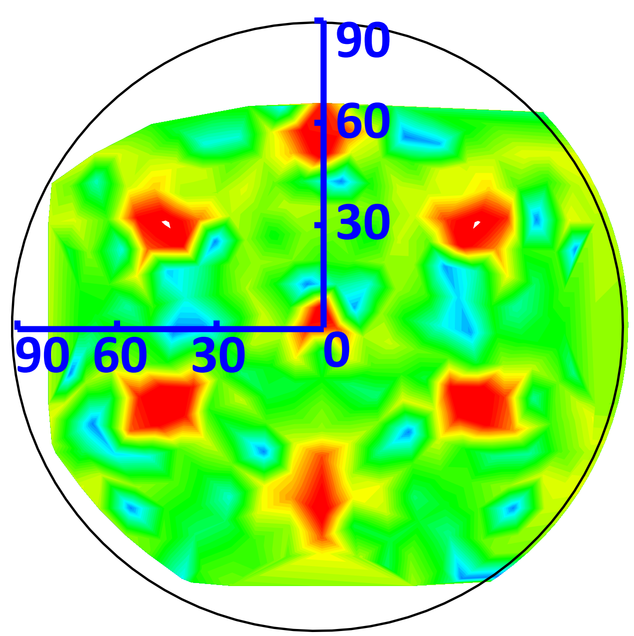


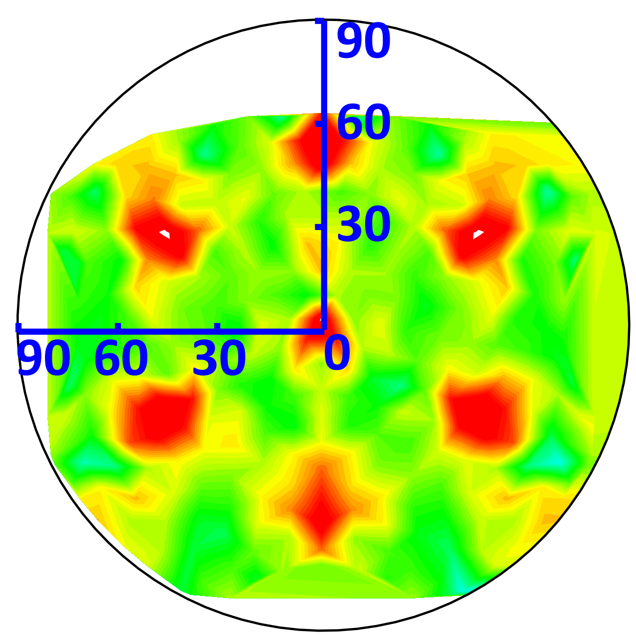


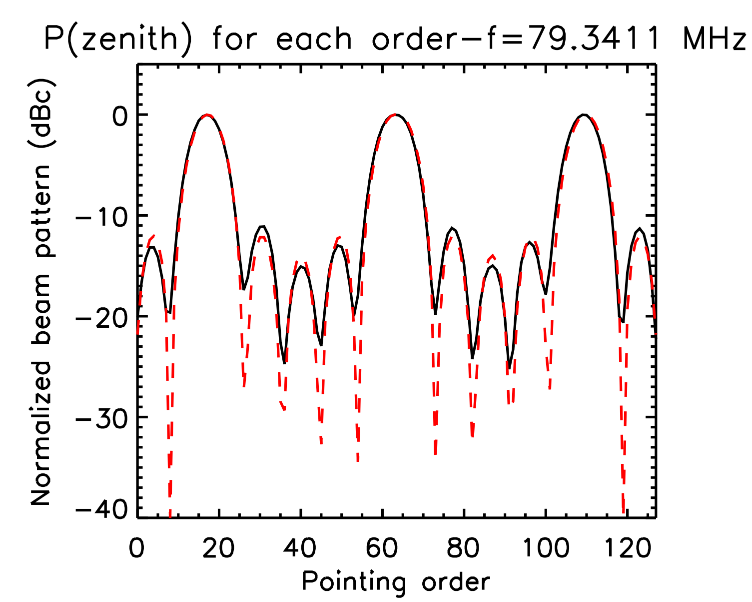


Radiation pattern | Simulations | Measures | 1D profiles







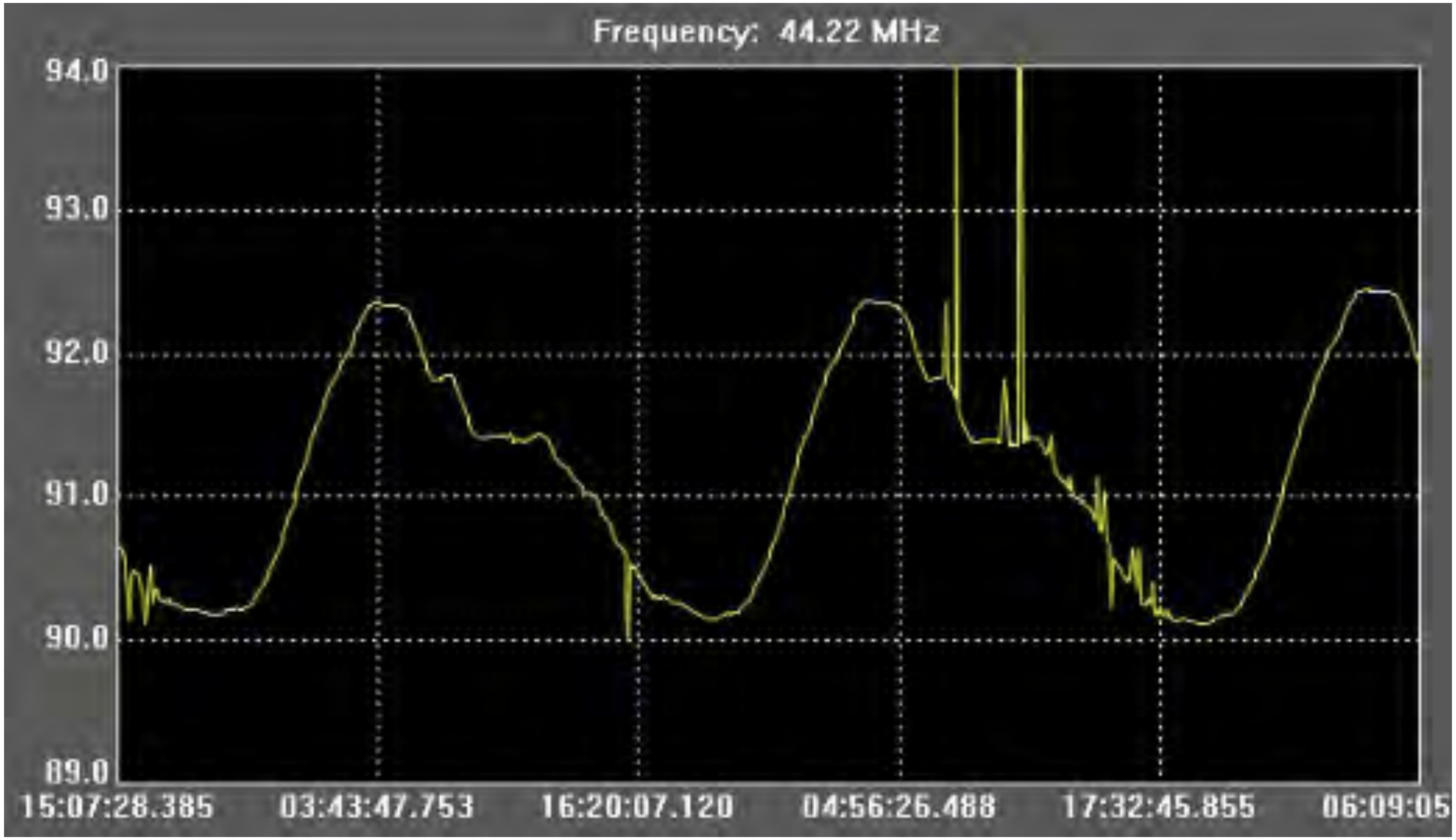


79 MHz

LSS Mini-array: Phasing

Phasing system in the MA container →

Galaxy transit with one MA ↓



LSS Mini-array: Phasing (Future?)

(pers. com. Stéphane Bosse, Nançay)

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NenuFAR toward SKA interest of physical miniaturization of delay lines

AAIR & MFAA projects knowledge of ASIC concept, phasing and integration of delay lines

AAIR = Aperture Array Integrated Receiver, MFAA = Middle Frequency Aperture Array

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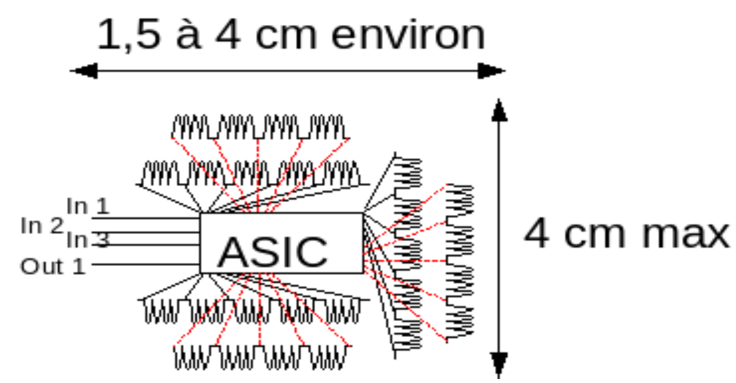
Electrical modeling of a time delay unit

- Using capacities & inductors

~ Delay Coax Cable of length 13 m

- With ASIC

ASIC = Application-Specific Integrated Circuit



~ 3 Delay Coax Cable of length 3,2 m with 10 cm steps

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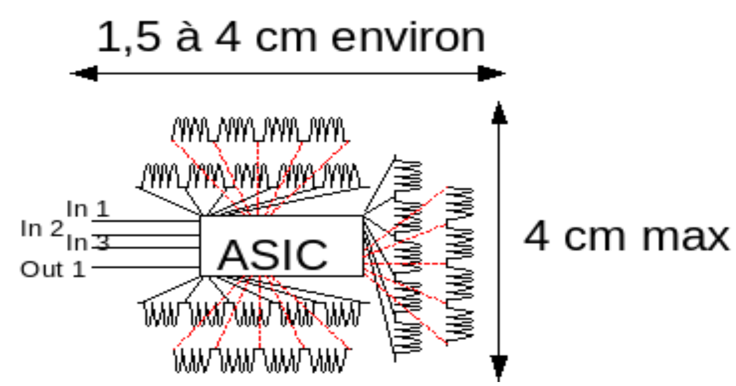

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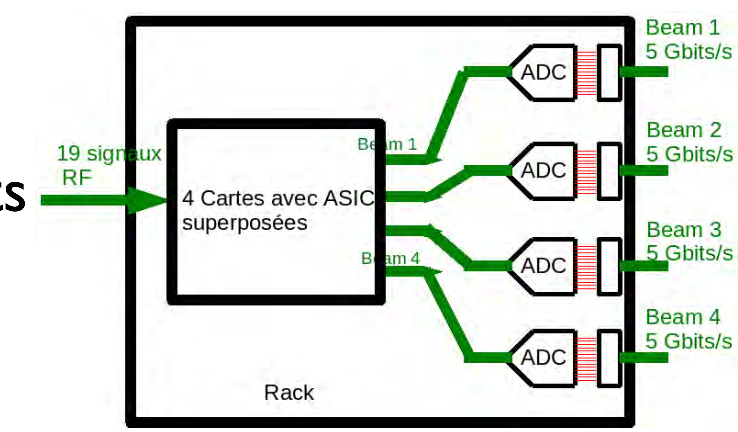
➔ Phasing 1 Mini-array, 1 pol = 20 x 20 cm rack bulk

➔ Analog (RF) Multi-Beam and direct digitization

19 ants



4 outputs = 4 Beams 5 Gbits/s

➔ Multi-beam information carried on fiber links

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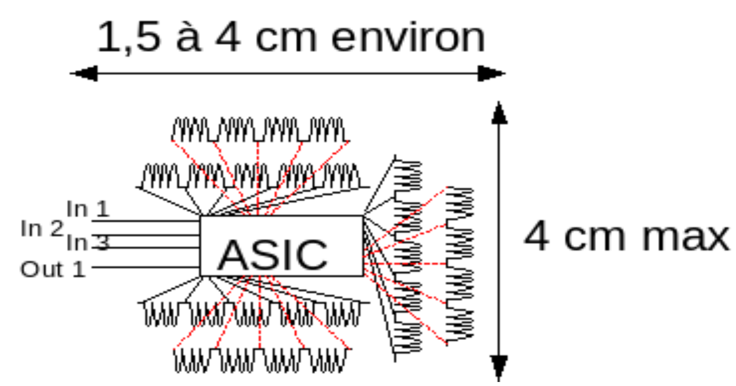

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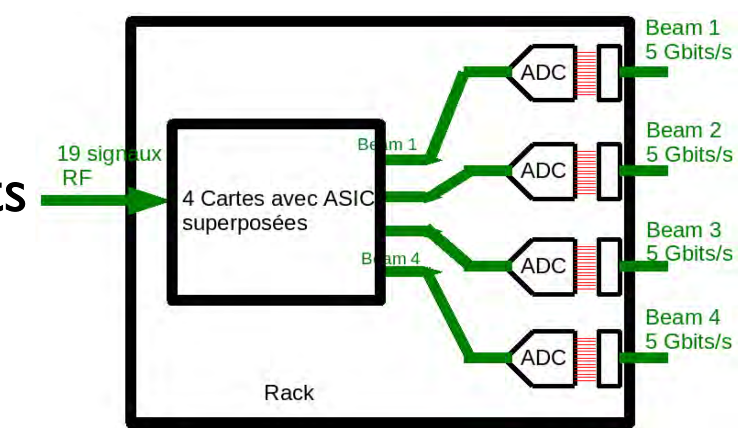

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Decrease of cost & volume

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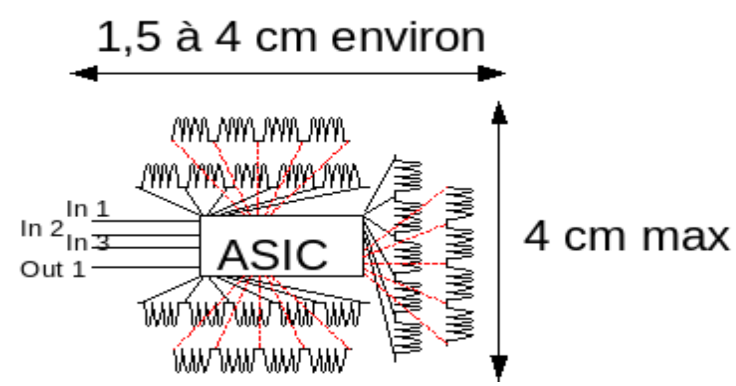

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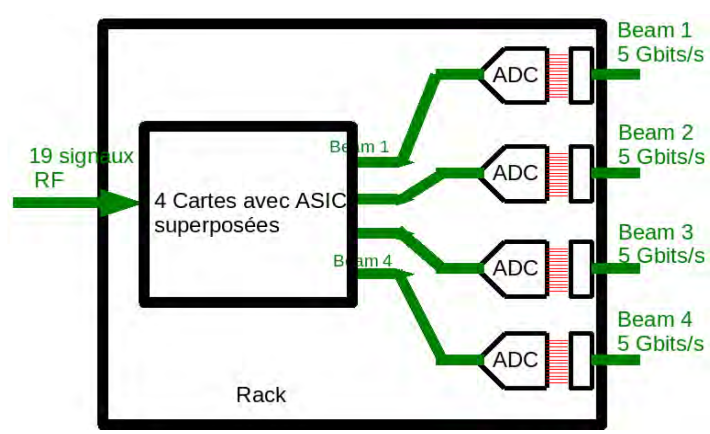

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Decrease of cost & volume

Large scale NenuFAR at low cost (➔ SKA 3 ?)

Global NenuFAR distribution

Specifications

- « Good »$_{|\mathrm{Boone}}$ instantaneous (u,v) distribution
- **Maximum effective area** in 15-80 MHz
- **Ground constraints** (natural, buildings)

Global NenuFAR distribution

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Studies

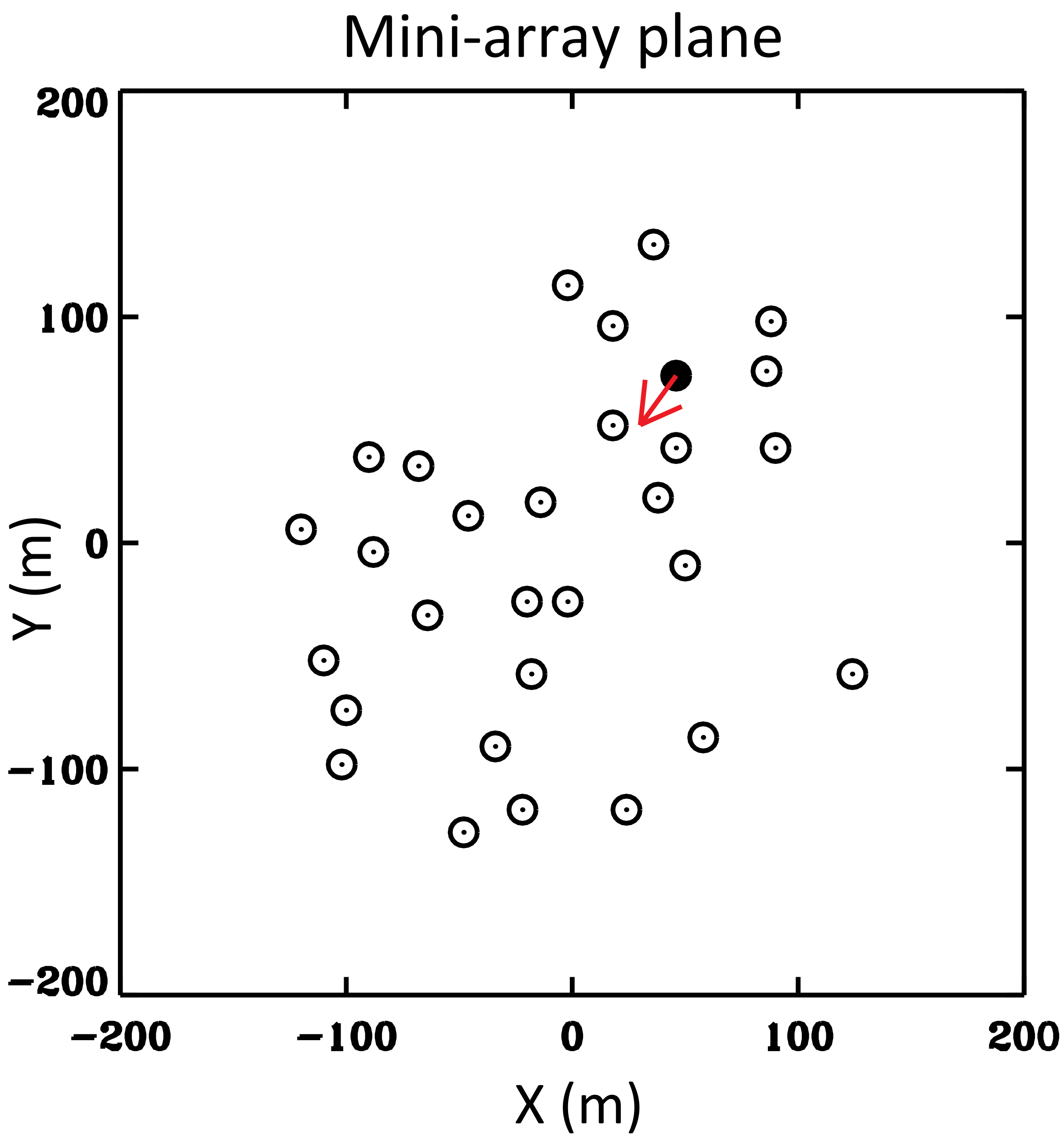
- Constrainted optimization of the MA positions
- Effect of relative rotation of MA
- Optimization of cabling MA

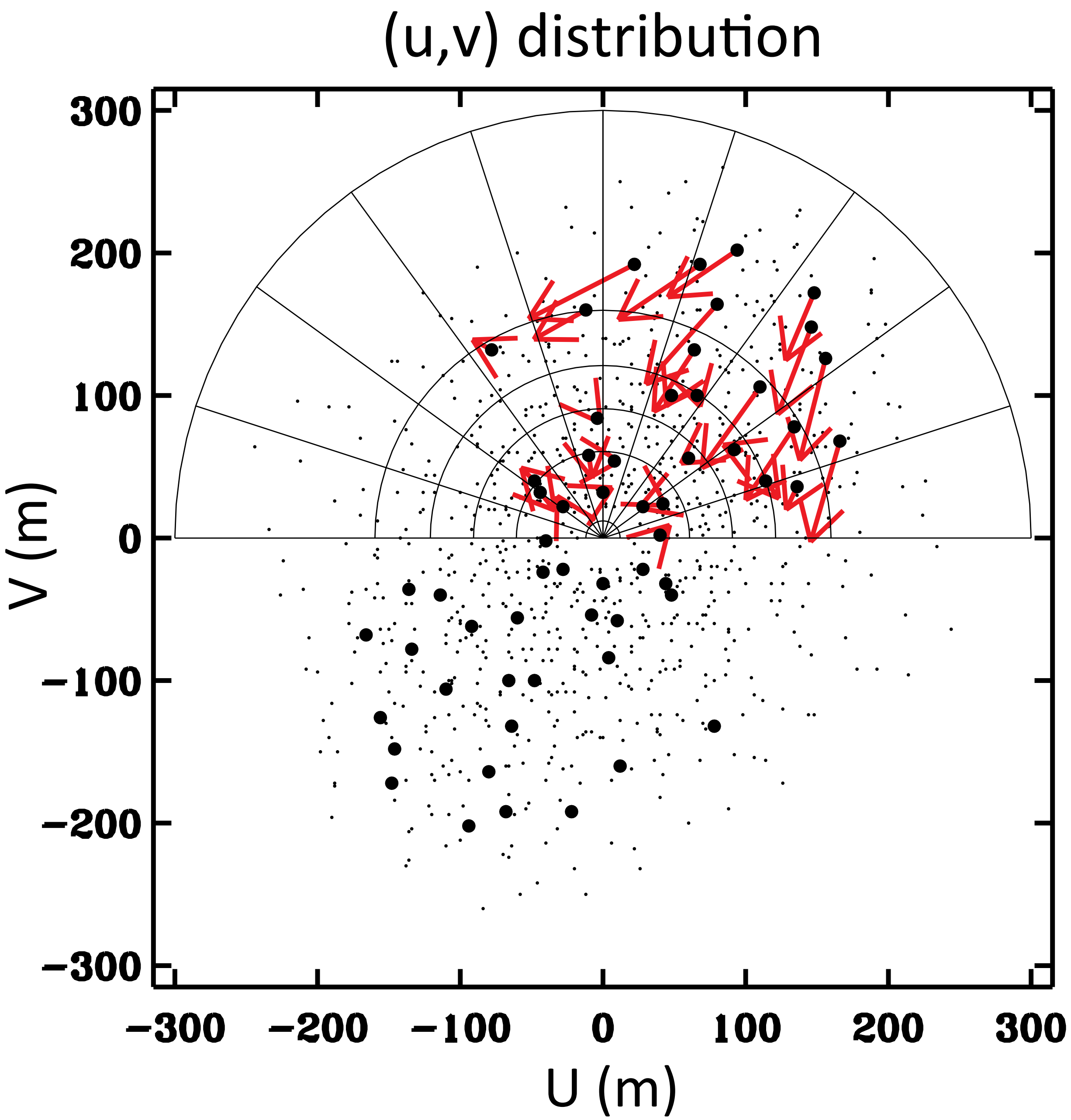
Global NenuFAR distribution

Boone algorithm: analogy between MA & gaz particles

→ enable iterative optimization of MA position toward a gaussian model

1 MA displacement is a consequence of the mean displacement imposed on the N-1 associated Fourier Measurements



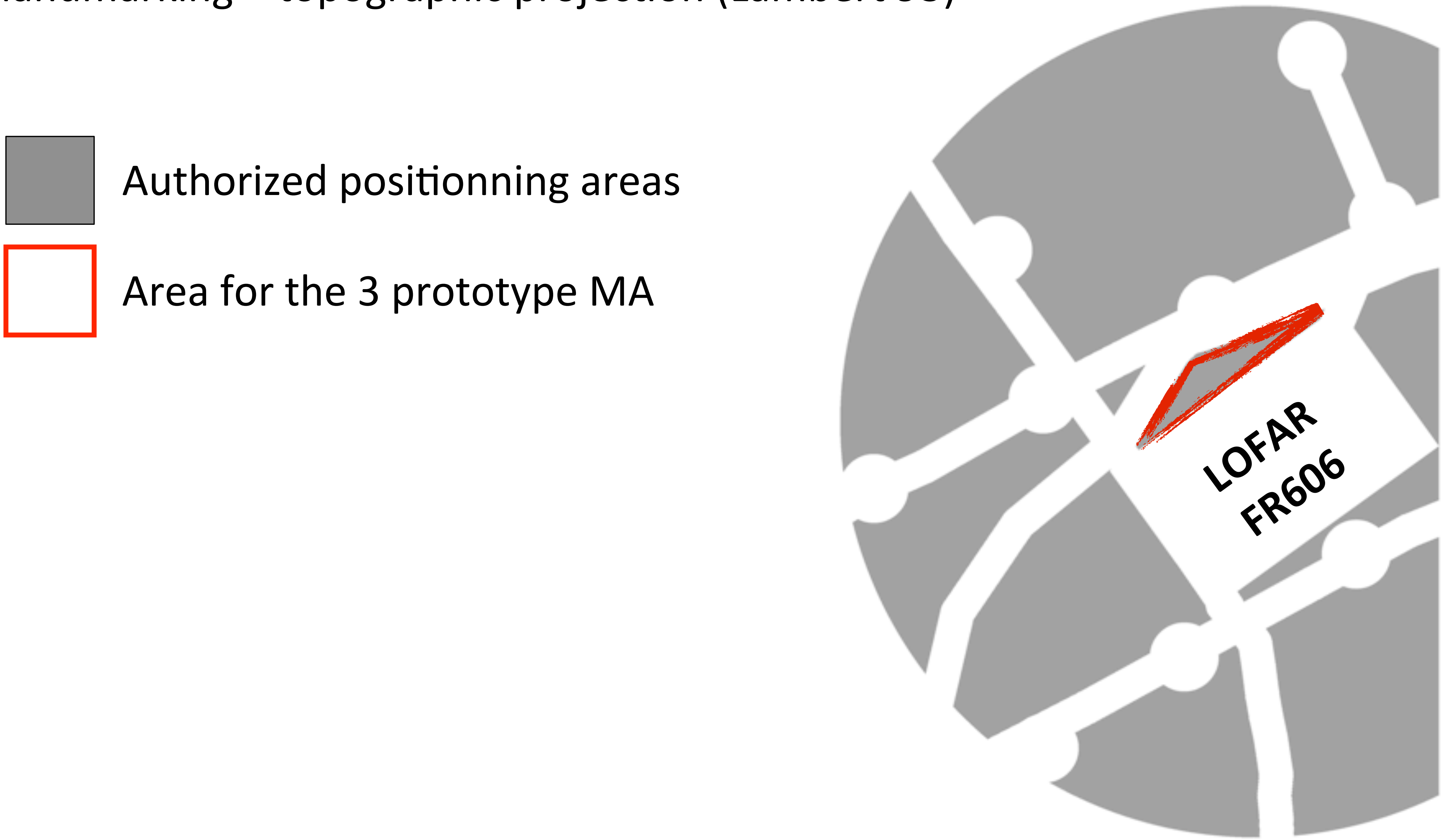


[Boone, 2001, 2002]

Global NenuFAR distribution

- Taking obstacles into account → Mask derived from Nançay ground constraints (burried cables, natural obstacles, other instruments)

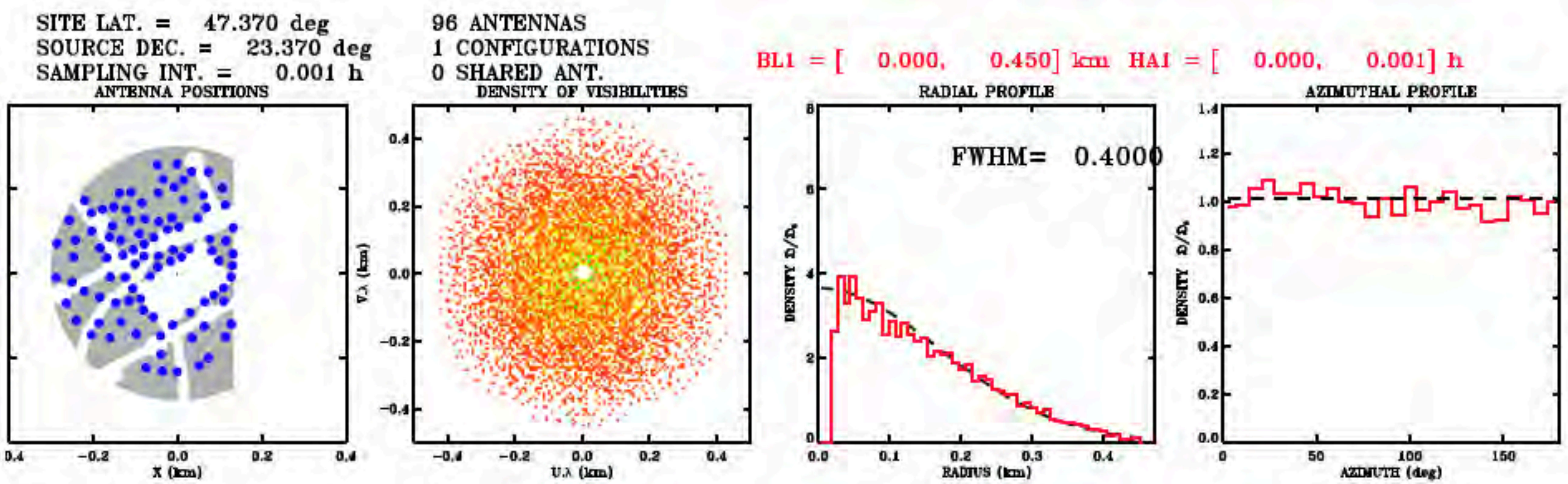
- GPS landmarking + topographic projection (Lambert 93)



Global NenuFAR distribution

Optimal distribution model: Gaussian with FWHM = 400 m B_{max} = 450 m

MA distribution (u,v) distribution Radial (u,v) histogram Azimuthal (u,v) histogram



[Girard, et al., CRAS, 2012]

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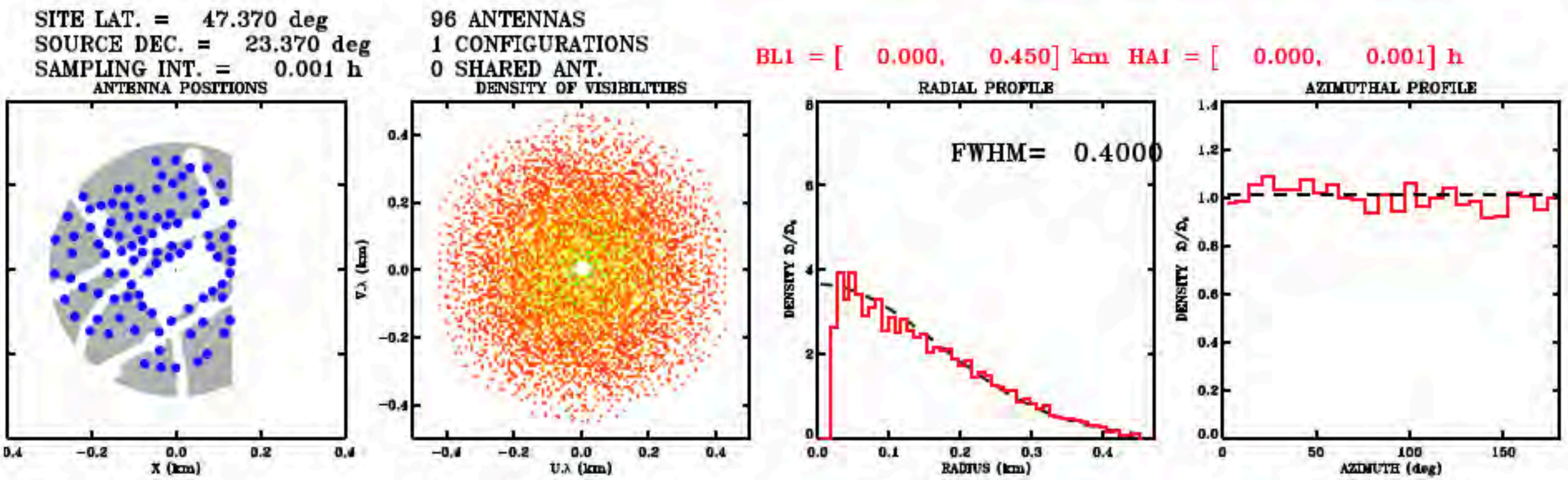
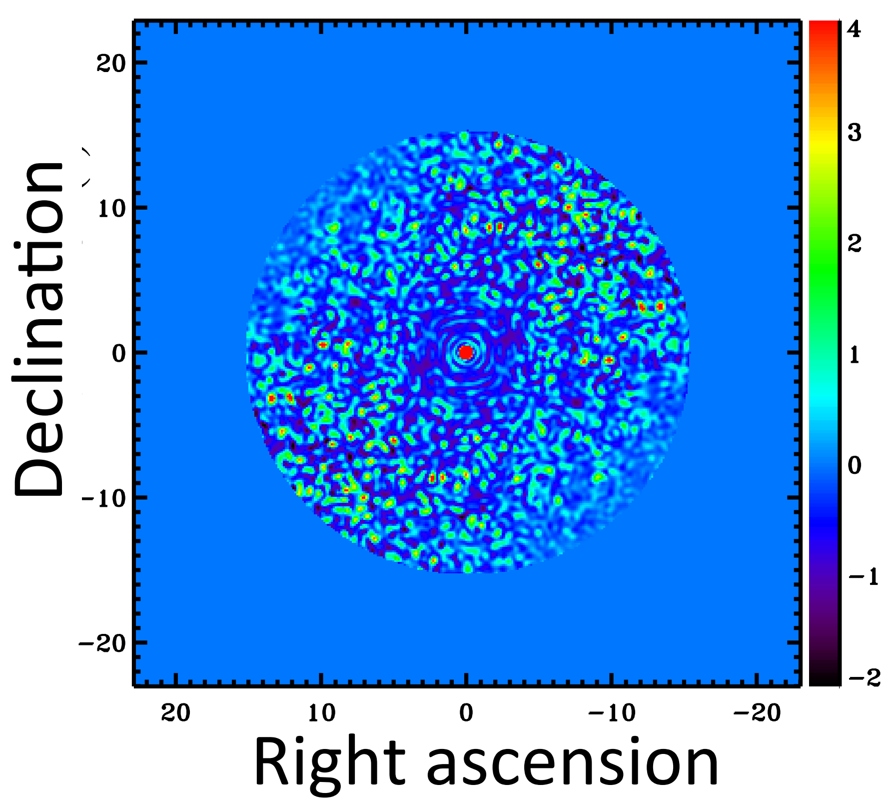




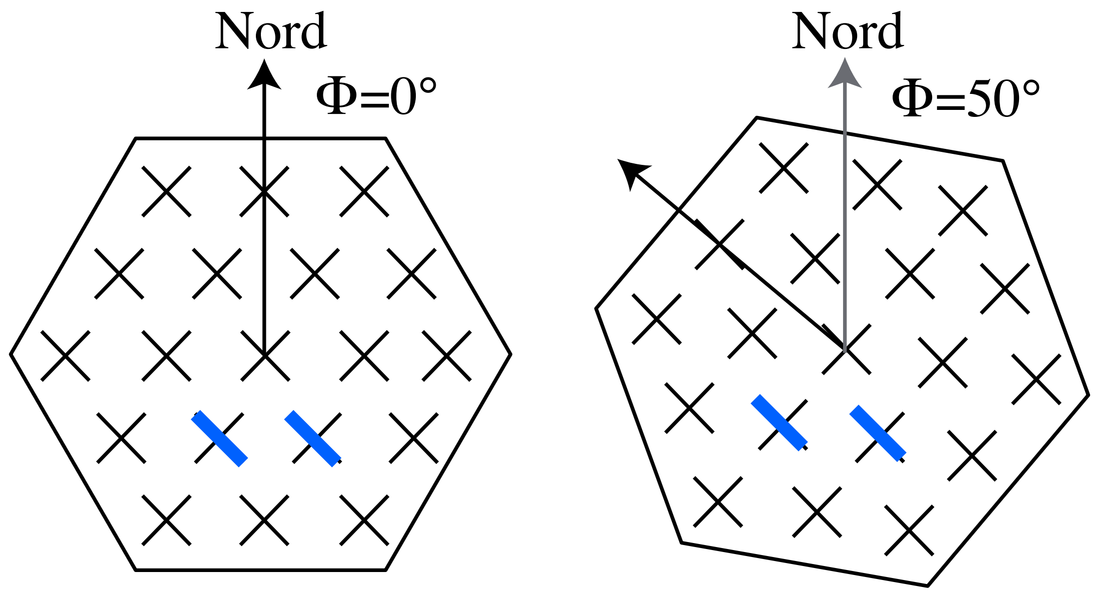
← PSF

F=80 MHz — θ ~ 0,5°

F=20 MHz — θ ~ 1,9°

[Girard, et al., CRAS, 2012]

Global NenuFAR distribution



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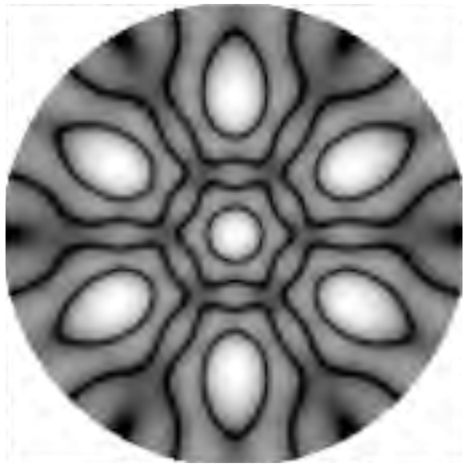
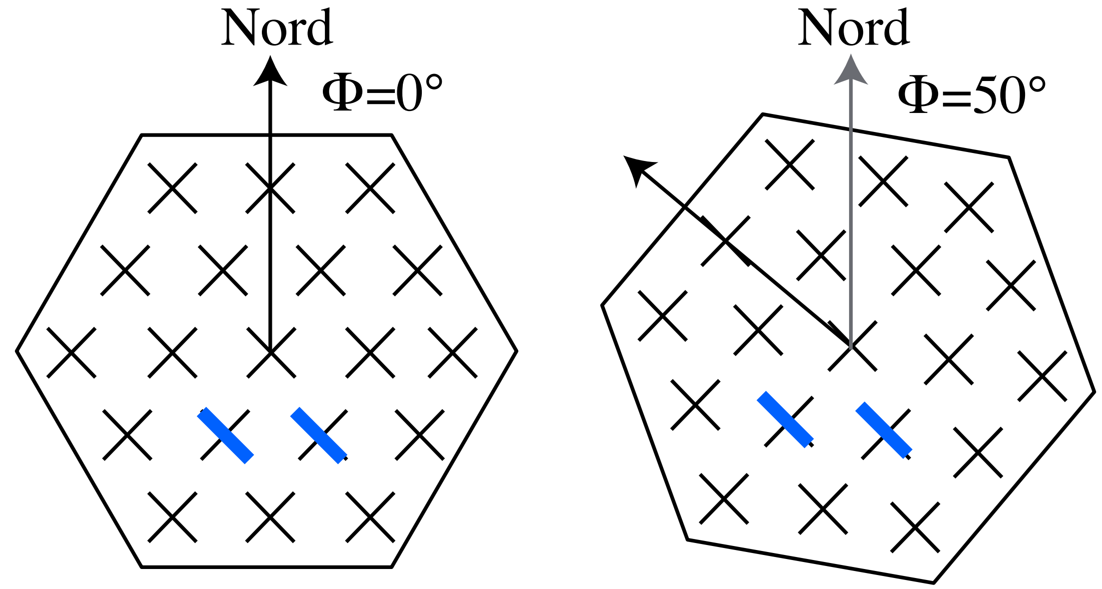
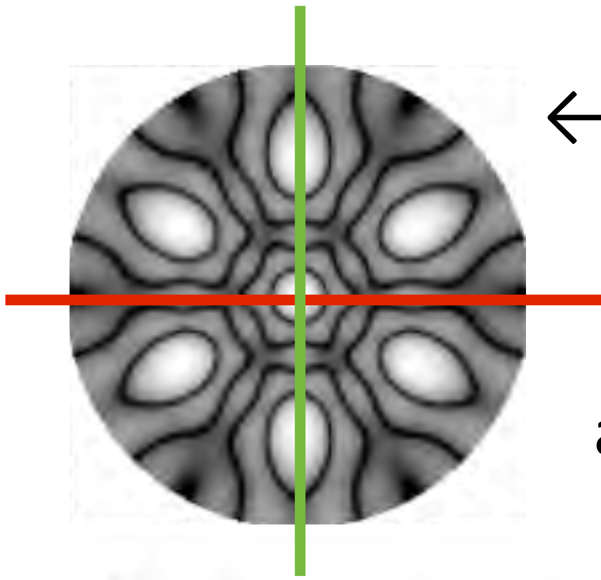


← MA radiation pattern

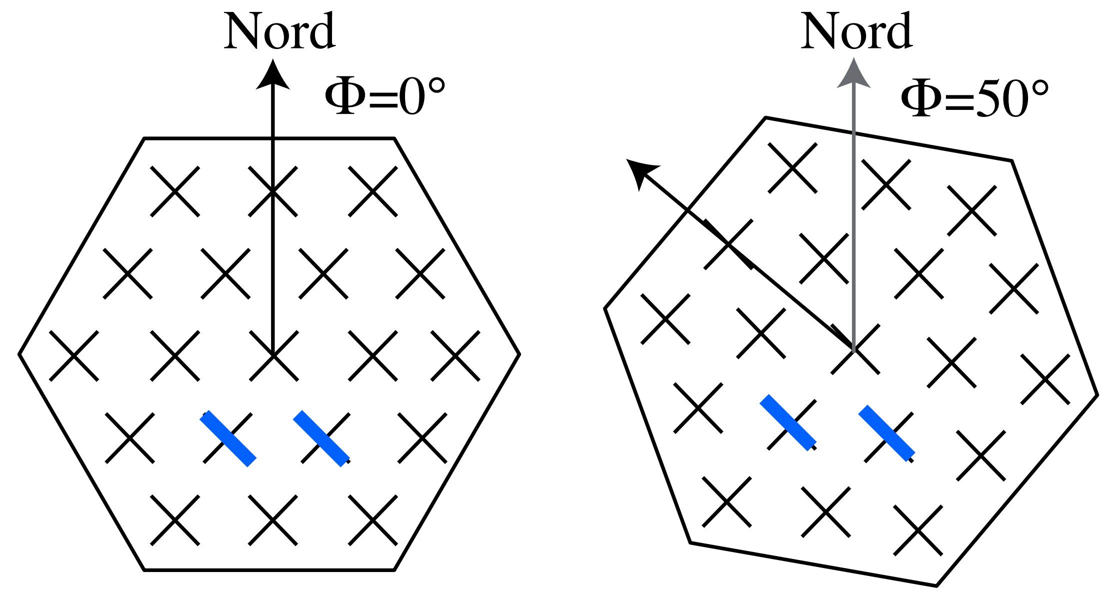


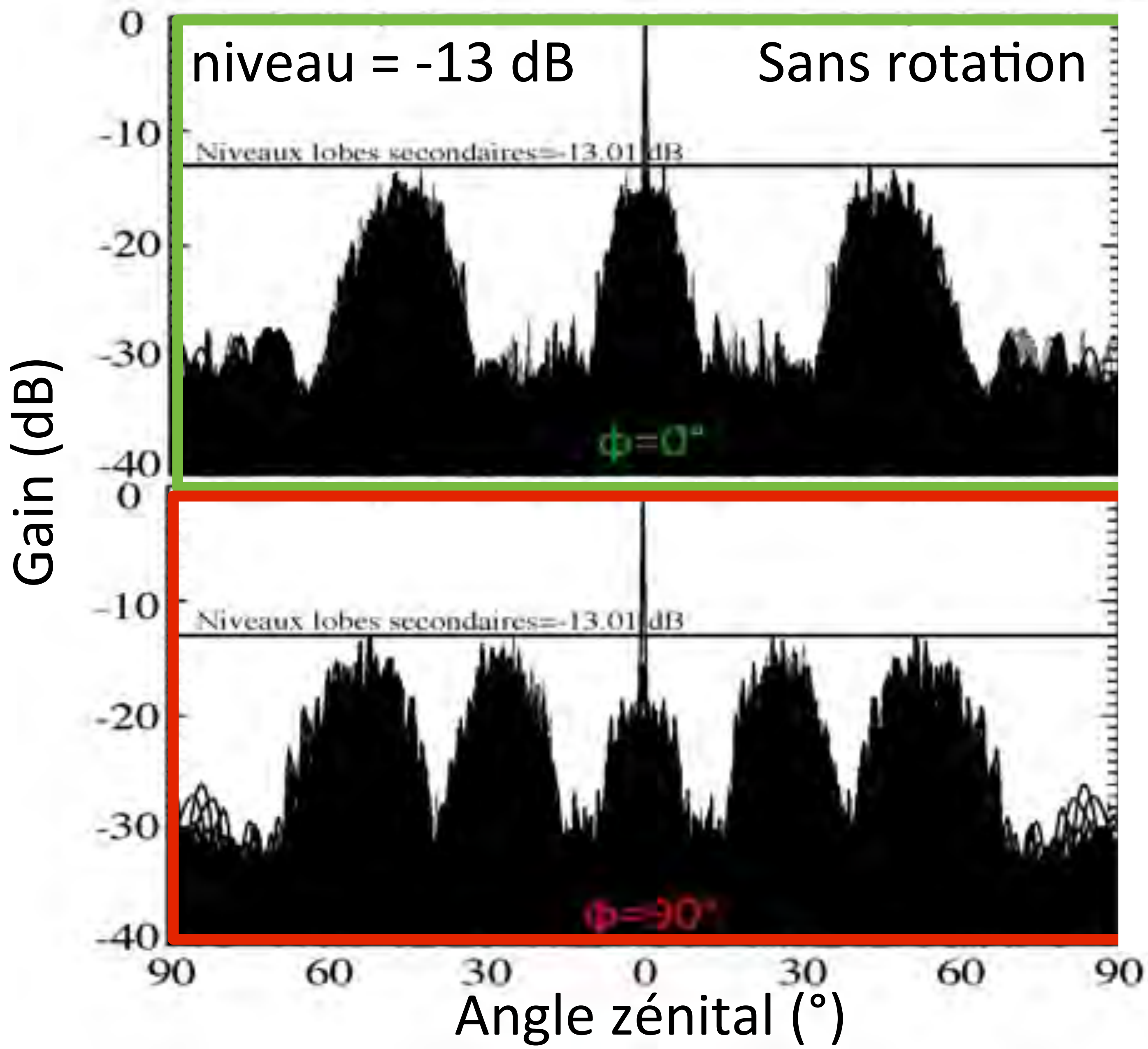
Global NenuFAR distribution



← MA radiation pattern

array of 96 MA ↓





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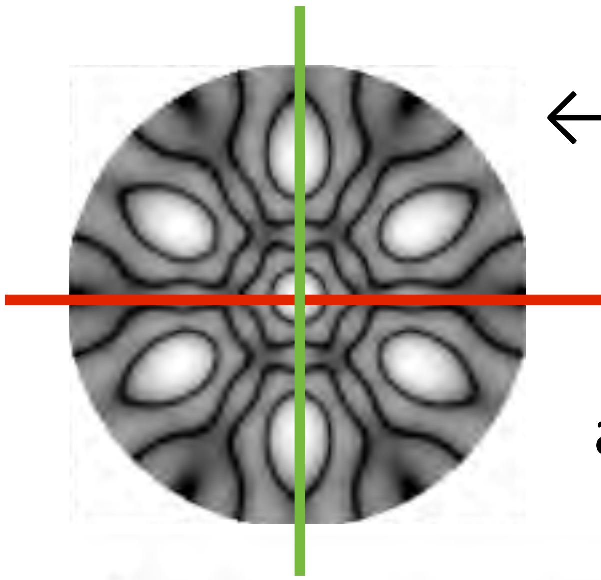

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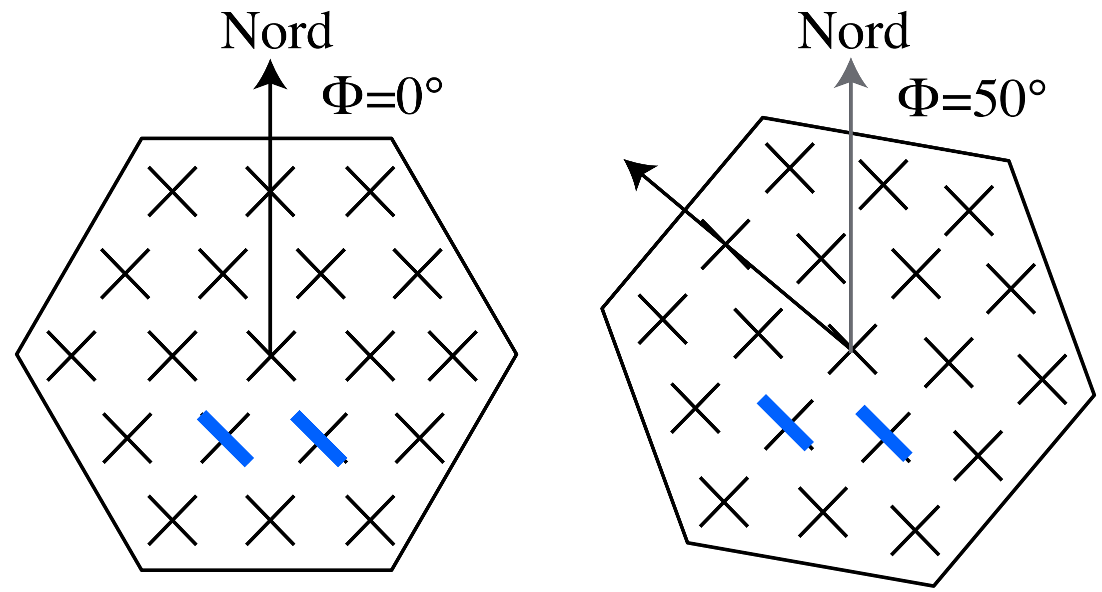
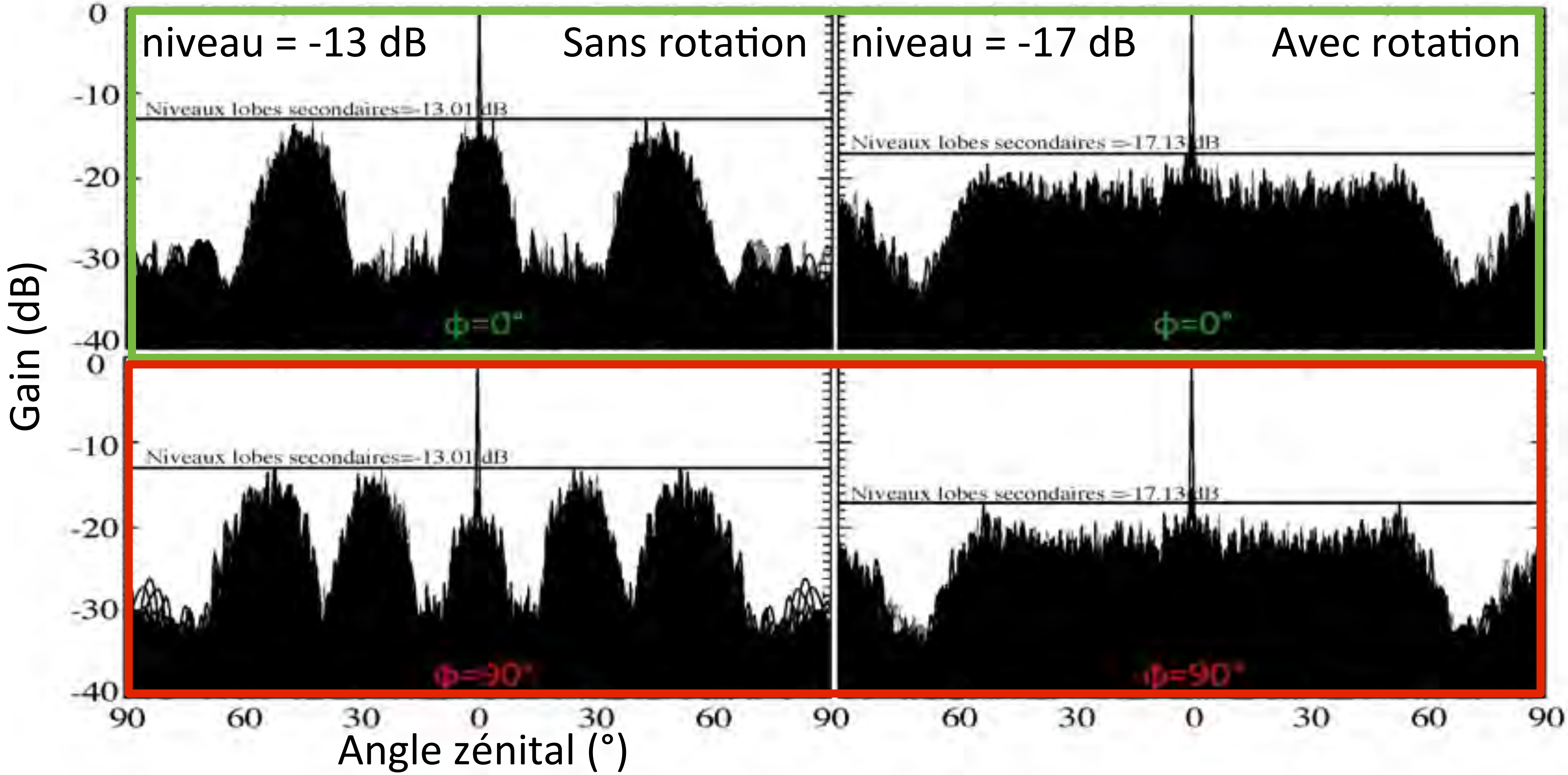
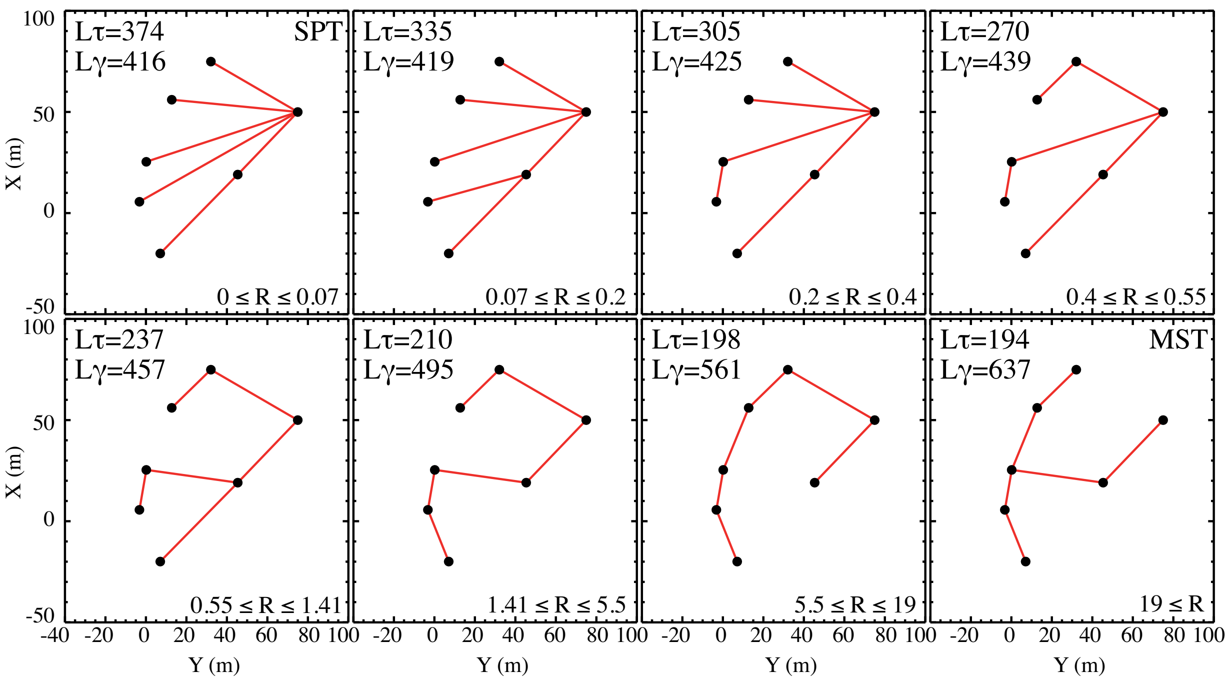




Global NenuFAR distribution

- Minimizing cable and trench length → Need to find a compromise

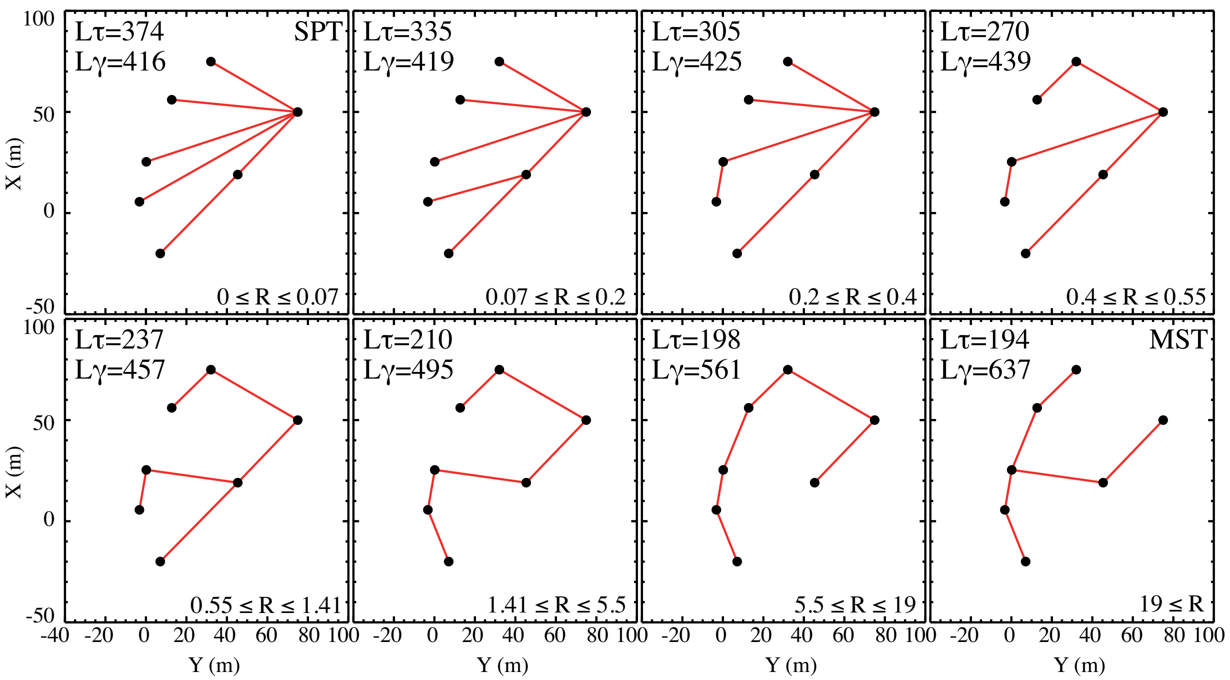


Global NenuFAR distribution

- Minimizing cable and trench length → Need to find a compromise

→Mathematical approach using graph theory : « Cable-Trench problem »
→Integrating the ground constraints in Nançay

[Vasko, 2002]



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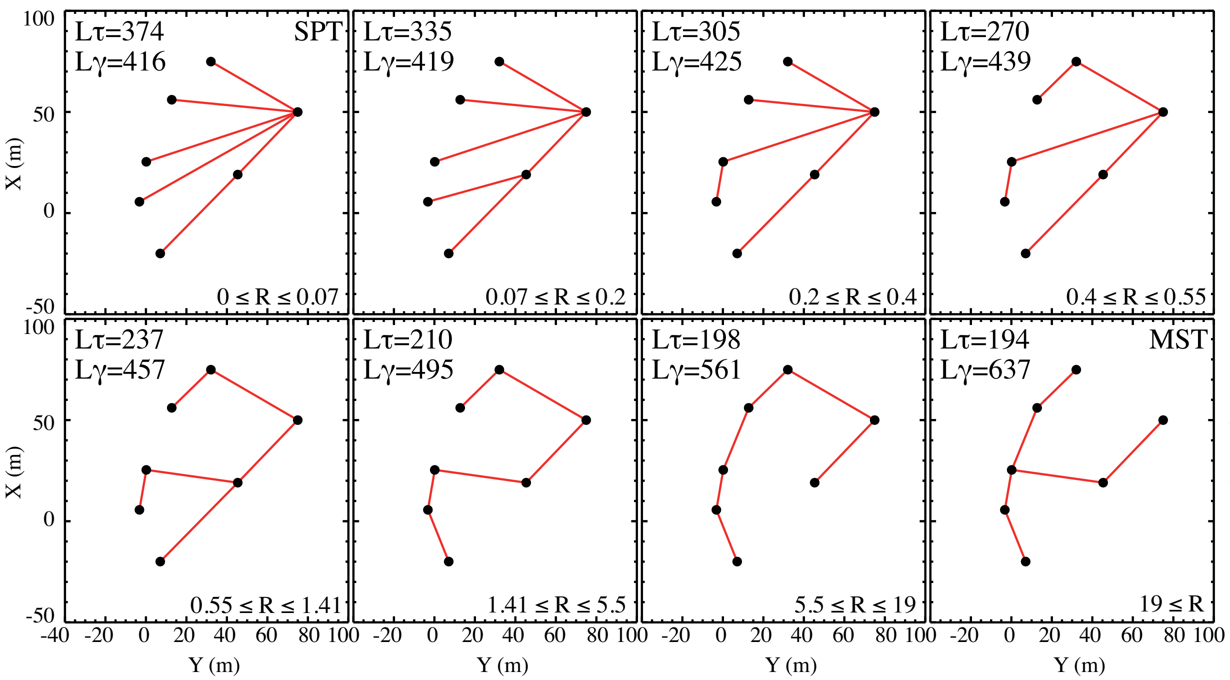
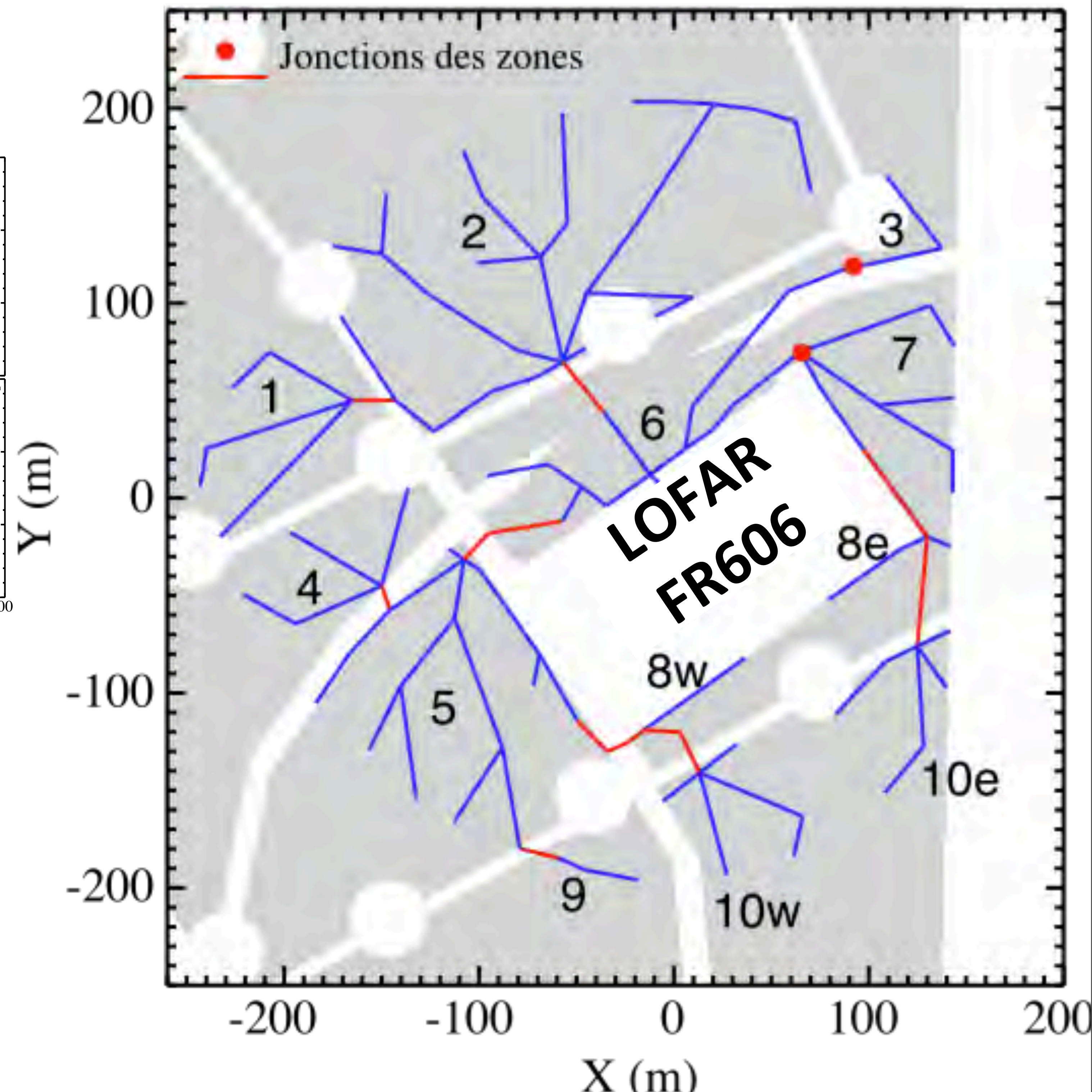
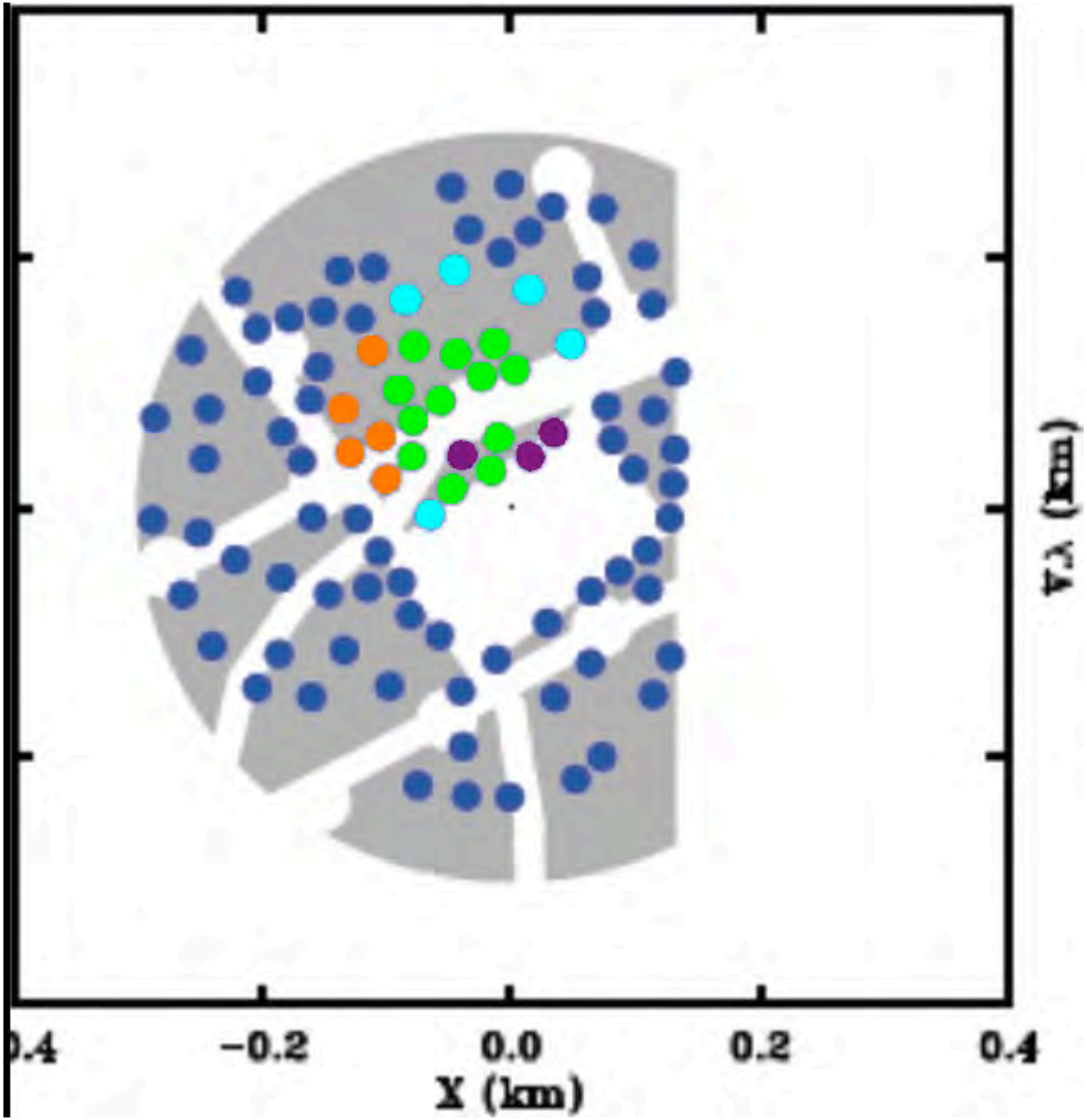




Construction in phases



Prototype	x 3	●
Phase 1	+ 12	●
…	+ 5	●
…	+ 5	●