The NenuFAR* low-frequency radiotelescope

(*New Extension in Nançay Upgrading LOFAR)

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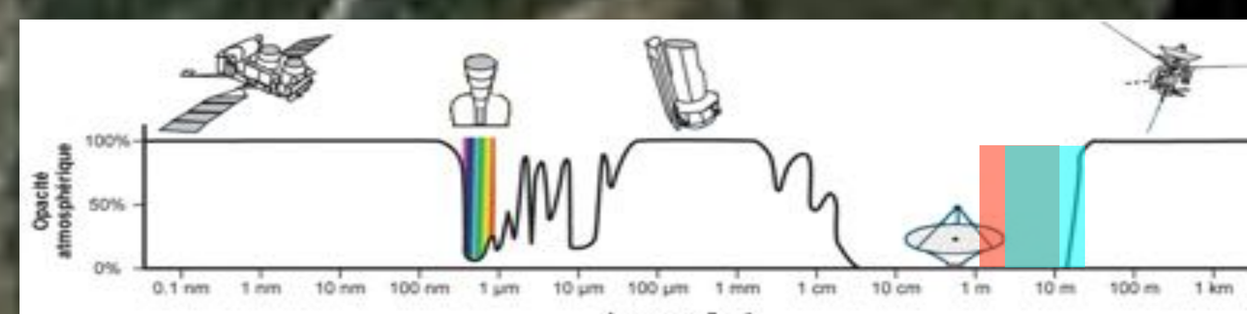
[5]GEPI, Subatech, OCA, ONERA, LERMA, PRISME, APC …

LOFAR = 1er instrument du nouvel âge d'or de la radioastronomie BF

A Nançay : de LOFAR à . . .

… NenuFAR

New extension in Nançay upgrading LOFAR



Pourquoi un nouveau Radiotélescope BF ?

- LOFAR :
  - HBA (110-250 MHz) ++,
  - Performances limitées < 80 MHz

- LWA(s) :
  - Bonnes antennes 10-88 MHz, couverture dense
  - Sensibilité modeste (256 dipoles)

- MWA :
  - Imagerie ++ 80-300 MHz
  - Pas de beamforming haute-résolution

→ Niche scientifique pour un instrument *BF, très sensible, compact (grand FoV), multi-faisceaux + imageur*

→ Grands programmes : *aube cosmique, exoplanètes/étoiles actives, pulsars, transitoires BF ...*

→ Complémentarité avec LOFAR : *très haute résolution angulaire*

+ Développement de la communauté BF Française vers SKA

NenuFAR en bref

NenuFAR, un instrument BF (10-85 MHz)

- triple: LOFAR Super Station, Beamformer autonome, Imageur autonome

- complexe: dialogue avec LOFAR/récepteurs FR606, récepteurs LaNewBa+UnDySPuTeD, Corrélateur, SETI-machine?

- d'envergure: multiples thématiques scientifiques (communauté de 60-80 utilisateurs identifiée), SKA pathfinder, IR MESR, devant préparer la communauté Française à SKA

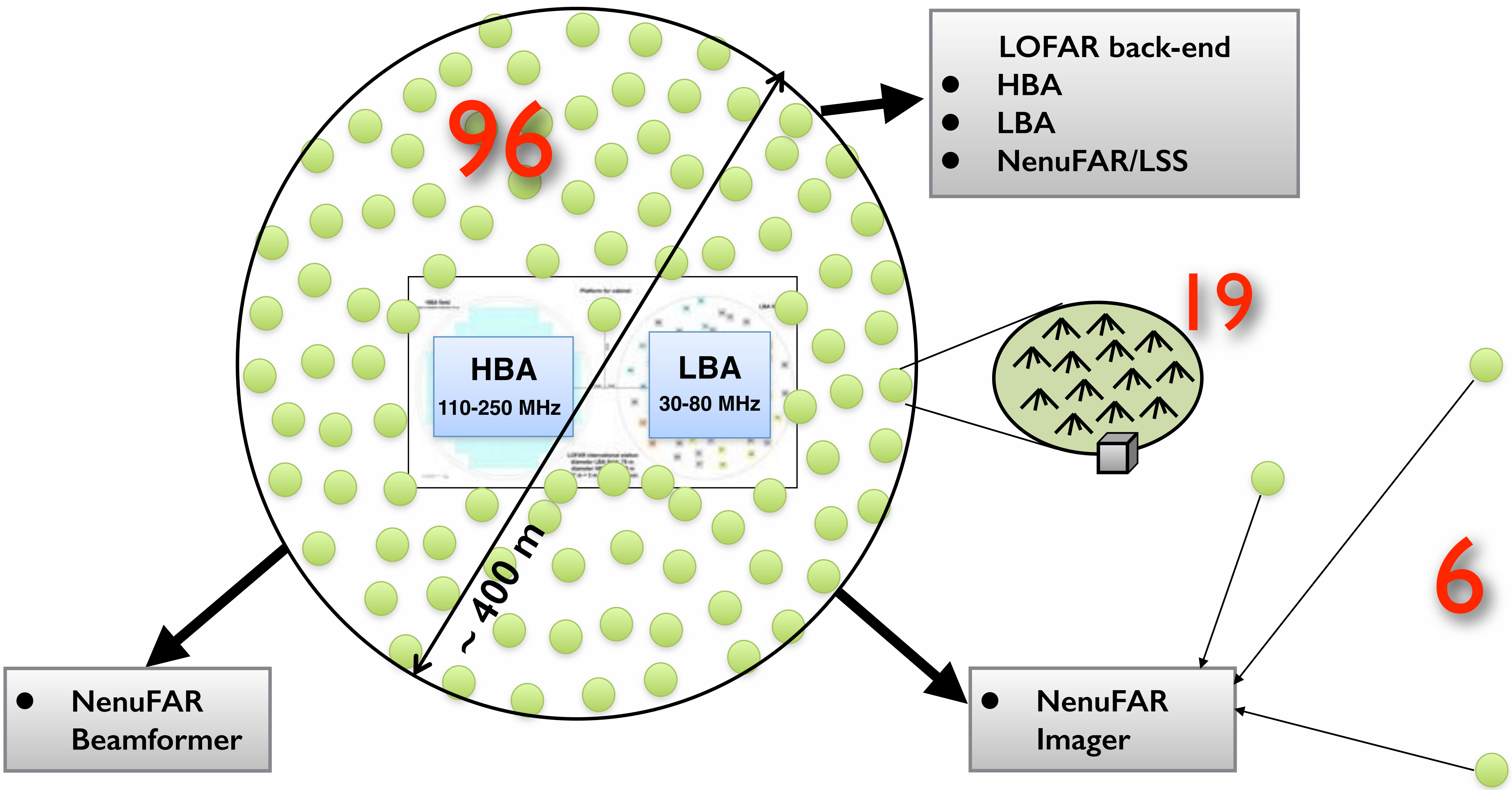
→ réalisé avec des moyens limités (total ~5.9 M€ + RH) et une petite équipe (USN + commissioning)

Le concept de NenuFAR

x

=

Le concept de NenuFAR

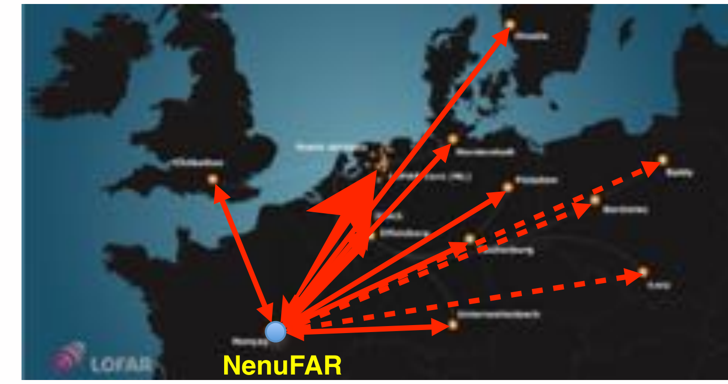


Beamformer, Imageur, Station géante LOFAR (Pulsar machine, SETI machine)

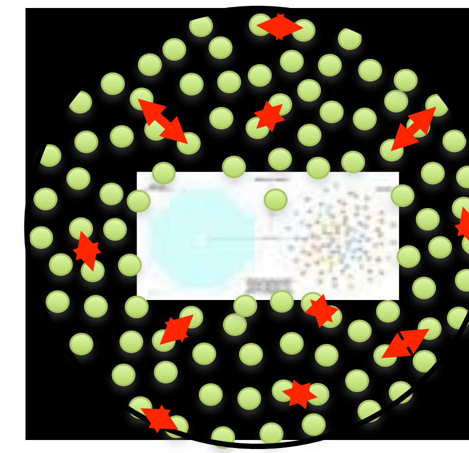
(96+6) Mini-Réseaux x19 antennes = 1938 antennes++

(> LOFAR), Sensibilité 2-8 x LOFAR, 10-85 MHz,

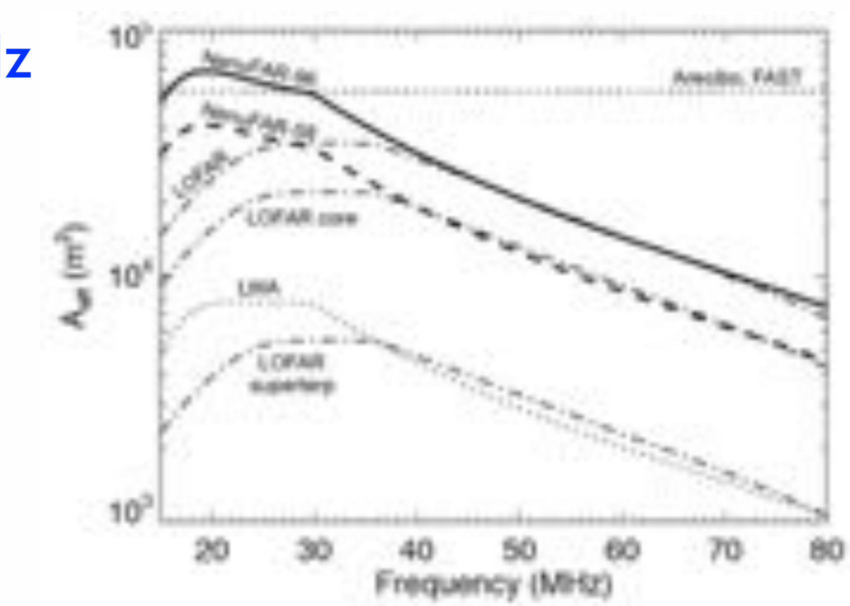
Apports de NenuFAR



- LOFAR Super Station (LSS)
  - ➡ Longues bases ~4x plus sensibles → meilleure imagerie haute res. (0.1")
  - ➡ Sensibilité globale LOFAR LBA x 2
  - ➡ NenuFAR comme 2ème coeur ?
  - ➡ Bases courtes internes à NenuFAR ⇒ structures à grande échelle (>10°)



- Beamformer (réseau-phasé) autonome
  - ➡ Haute sensibilité (>LOFAR) basse fréquence, jusqu'à ~10 MHz
  - ➡ Large bande instantanée (150 MHz, polar. complète)
  - ➡ Faisceaux cohérents multiples (768 beamlets x 200 kHz)
  - ➡ Grand champ de vue (10's°)
  - ➡ Grands programmes avec fort « duty-cycle »



- Imageur (interféromètre) autonome
  - ➡ Imageur rapide (1 sec., coeur seul) → (40/f)° ~1°
  - ➡ Imageur lent (6-8 h, coeur + MR distants) → (340/f)' ~8'

➡ Tout en parallèle

➡ Recette en cours ...

Développements techniques

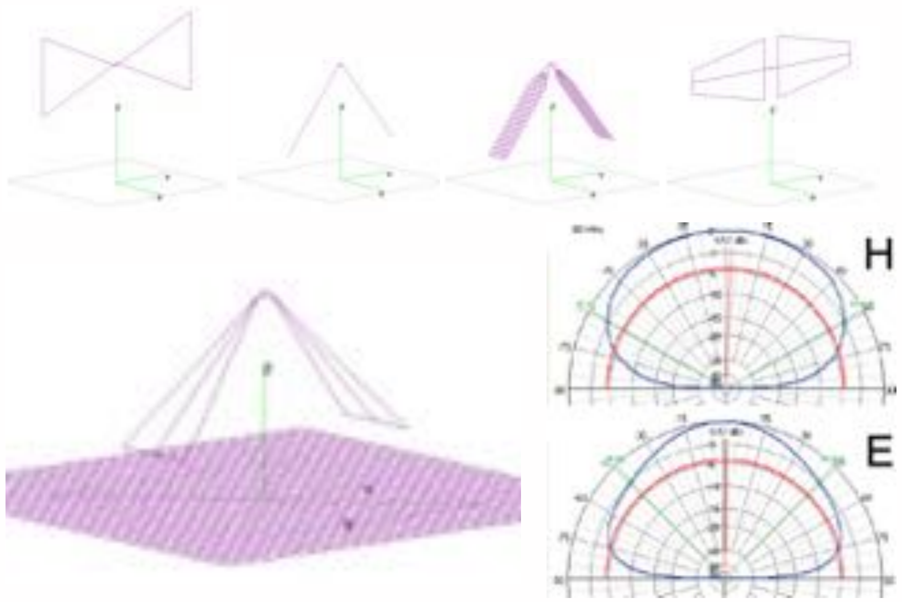
ANR «Design» 2009-2013

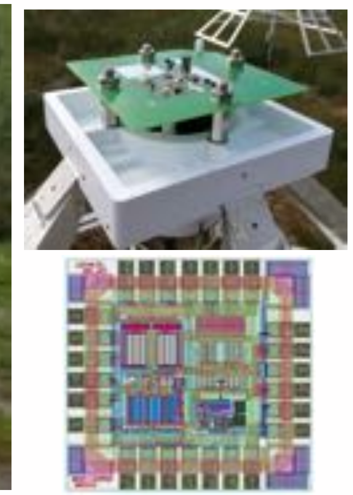
- Antenne (LWA) + préamplificateur (Subatech / Nançay)
- Mini-Réseau hexagonal de 19 antennes
- Optimisation de la distribution globale des MR
- Contrôle/commande silencieux
- Récepteur LANewBa (FPGA, 768 beamlets x 200 kHz)
- Dialogue NenuFAR-LOFAR (finalisé côté Nançay, en cours côté ASTRON)
- Pointage : rapide, avec Beam Squint, Web-service IMCCE pour observations planétaires
- GUI contrôle/commande, gestion/surveillance instrument & données, parsets

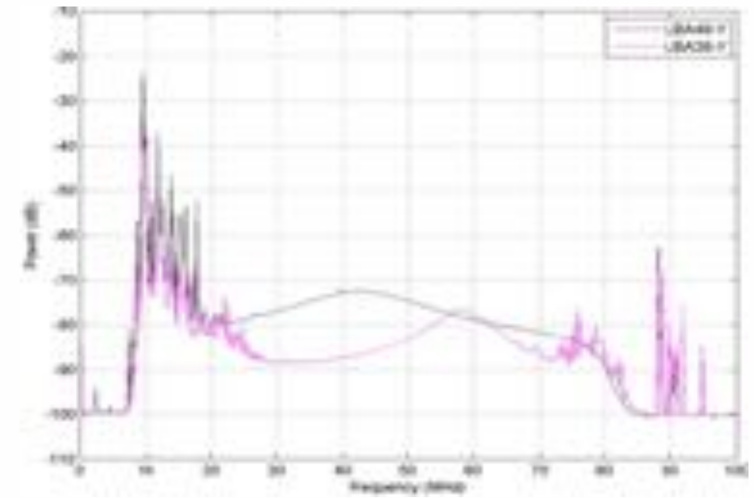
+ *Design du NenuFAR-Radio-imageur (2015-2017)*

- Emplacement des Mini-Réseaux distants
- Infrastructure, Synchronisation (White Rabbit)
- Corrélateur

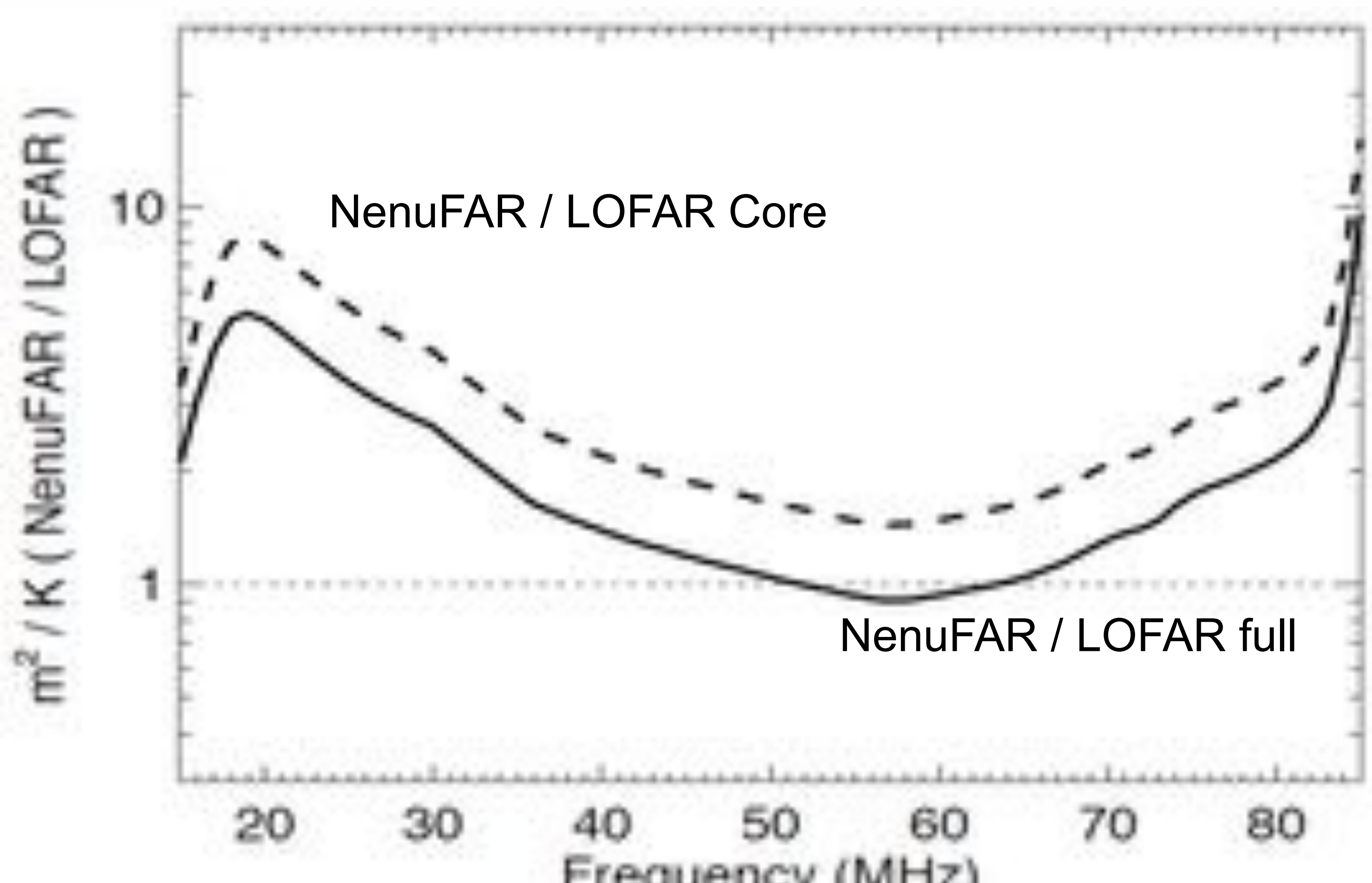
Antenne, Sensibilité





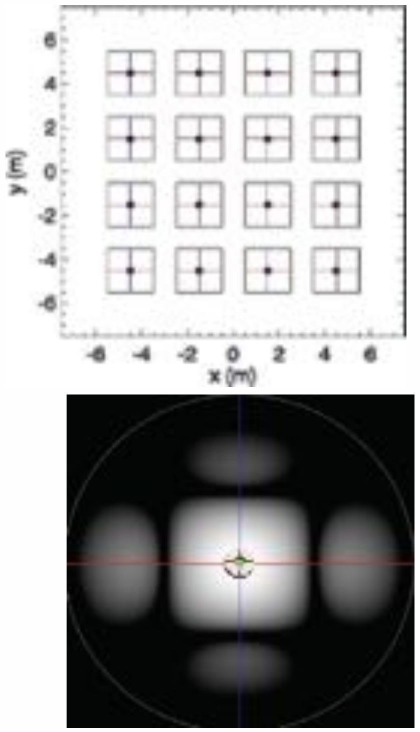


- Bon radiateur d'antenne [Hicks et al., 2012 ; Girard et al., 2012] + LNA Fr. [Charrier et al., 2014]
- Plan conducteur au sol <100 MHz → meilleure réponse, constante / t

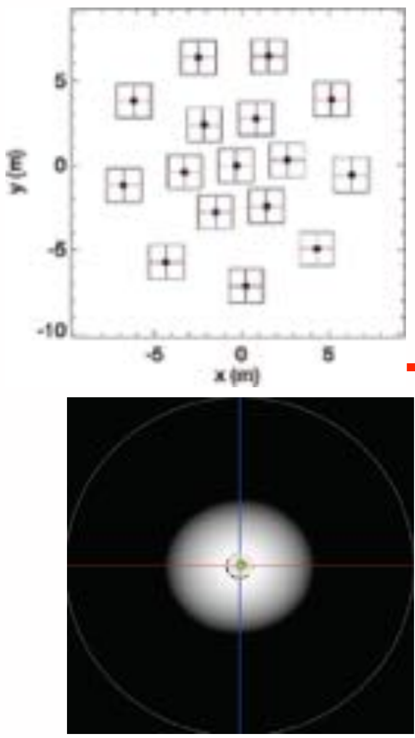


Mini-Réseau

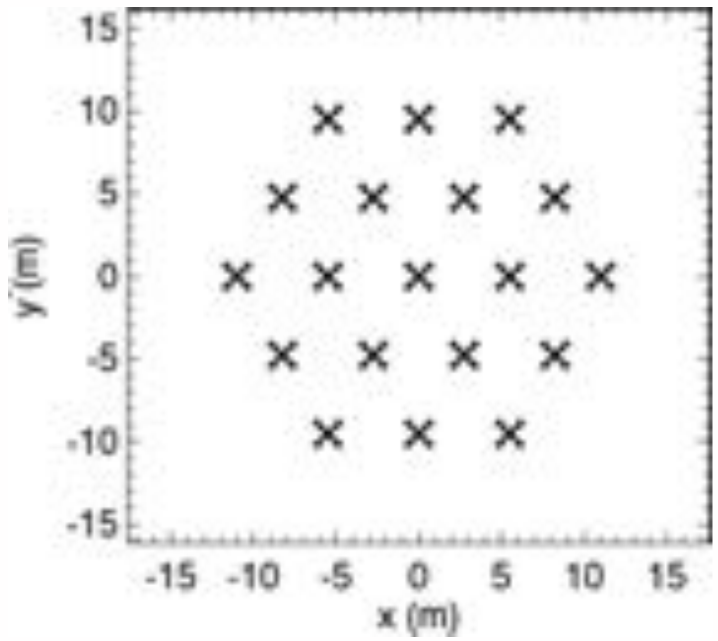
40 MHz

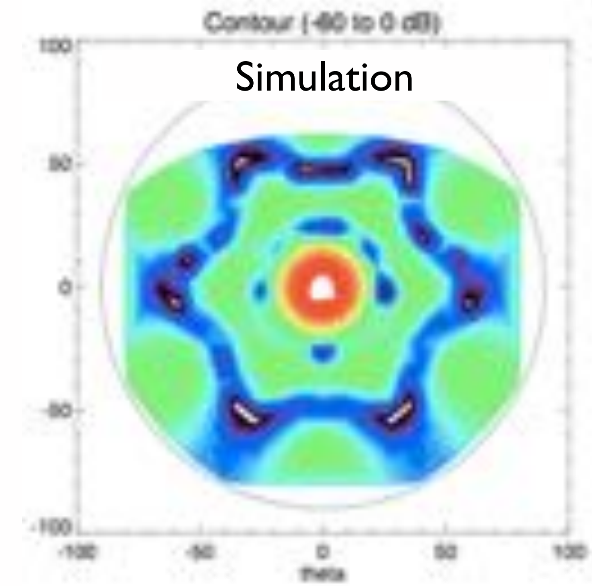


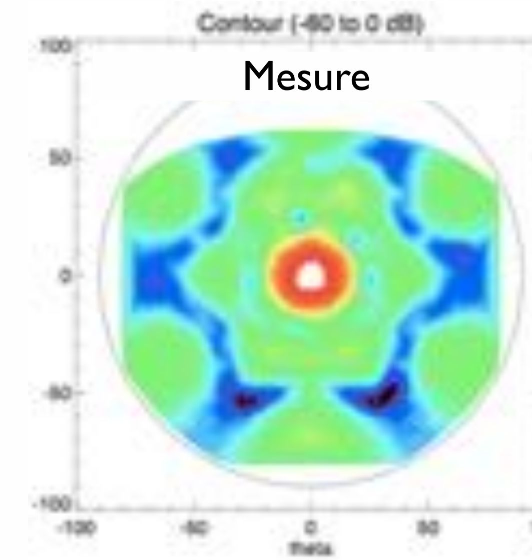
-15 dB sidelobes

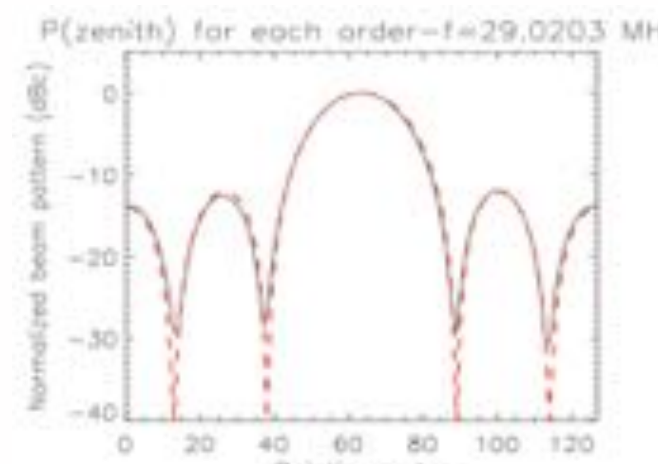


-32 dB sidelobes



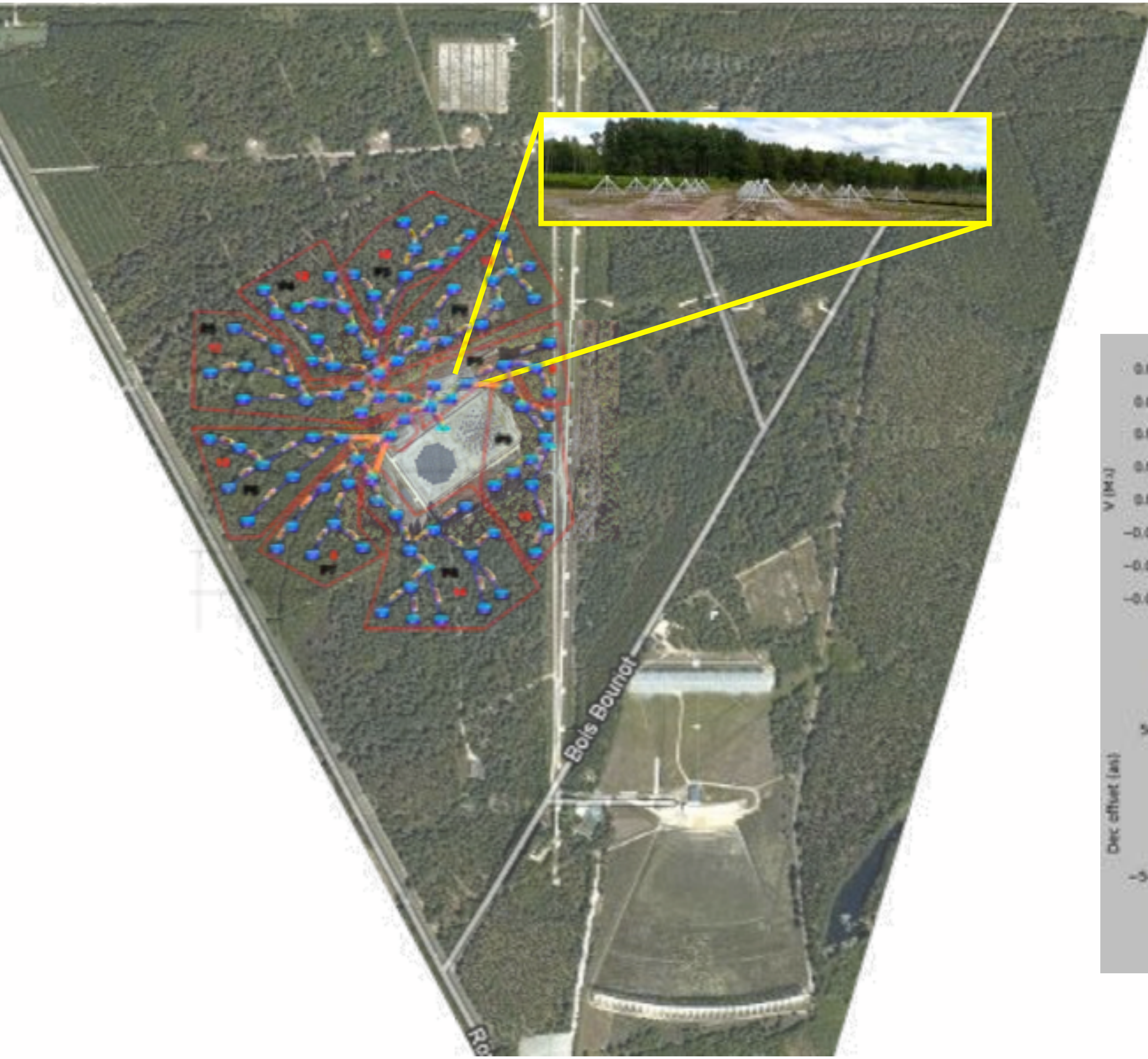


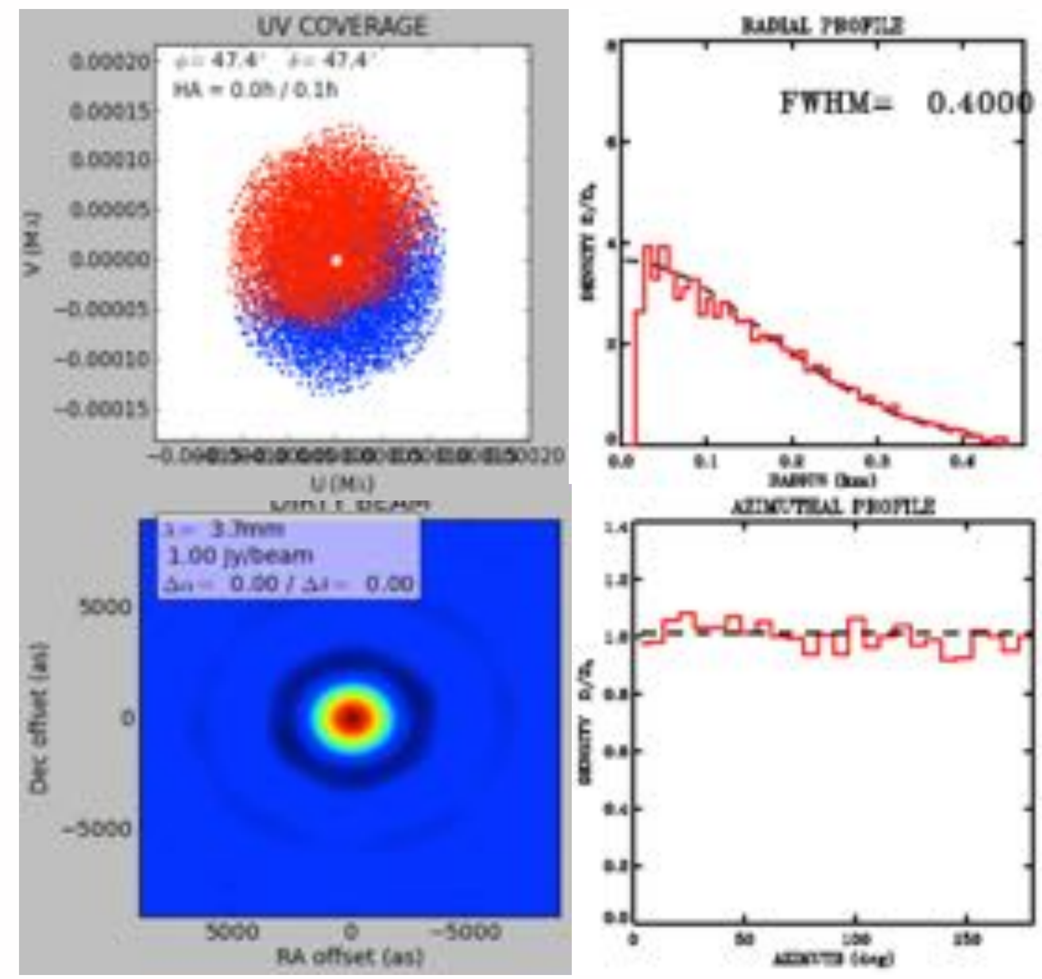




- Distribution optimisée à 19 antennes

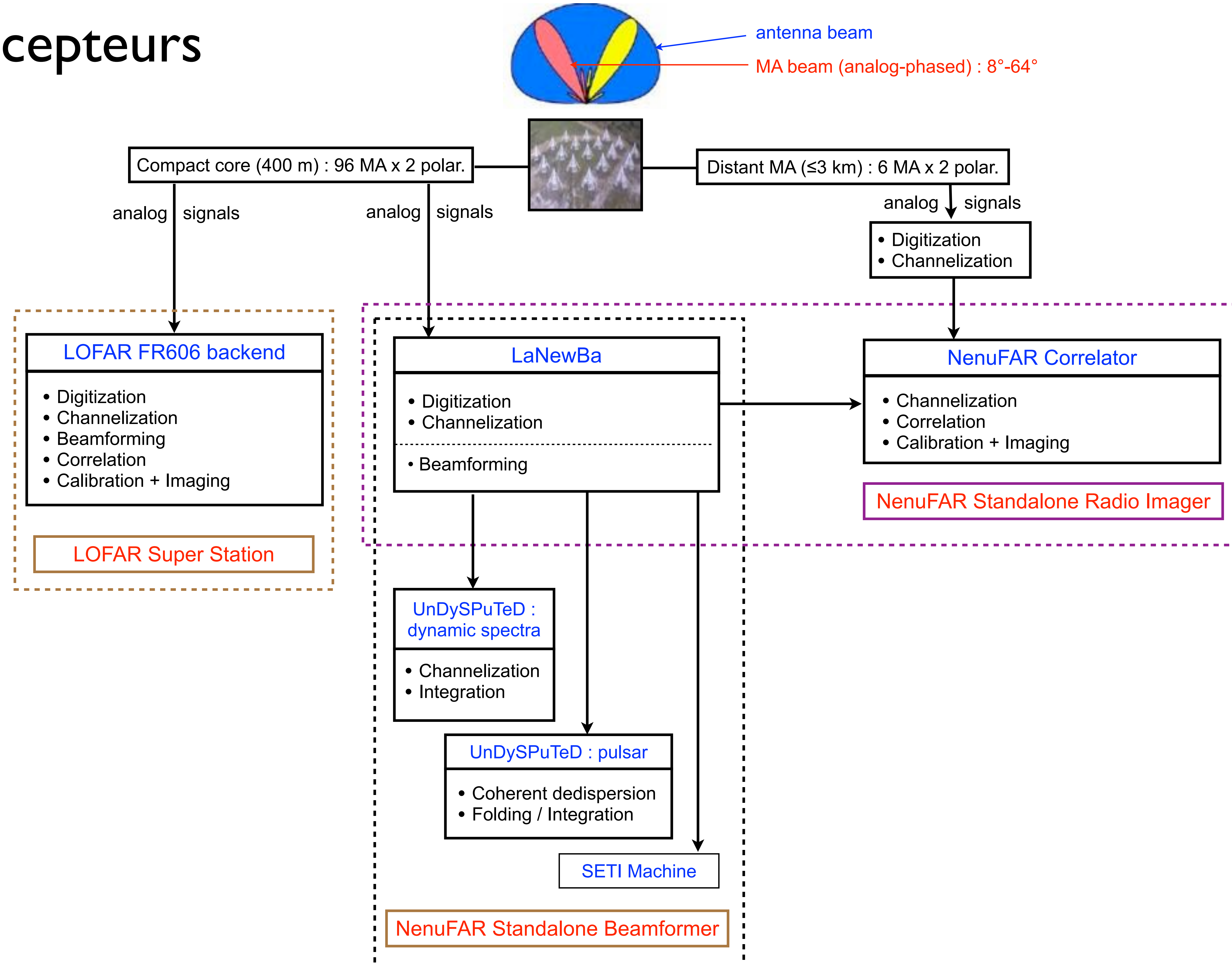
Distribution globale



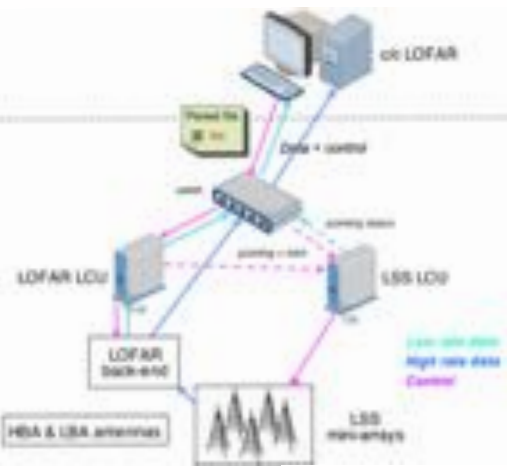


- Optimisée pour 96 MR [Boone, 2000, 2001] (incl. rotations MR) + 6 MR distants
- Optimisation tranchées/câbles [Vasko et al., 2016]
  → construction en 9 pétales (consommation ~50 kW)

Récepteurs

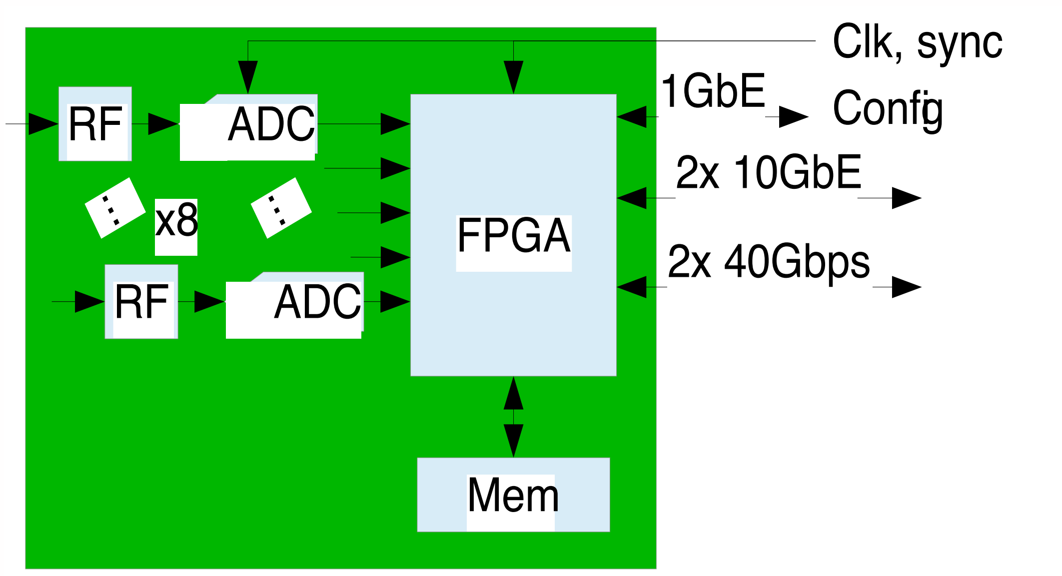

antenna beam
MA beam (analog-phased) : 8°-64°
Compact core (400 m) : 96 MA x 2 polar.
Distant MA (≤3 km) : 6 MA x 2 polar.
analog signals
analog signals
analog signals
• Digitization
• Channelization
LOFAR FR606 backend
• Digitization
• Channelization
• Beamforming
• Correlation
• Calibration + Imaging
LOFAR Super Station
LaNewBa
• Digitization
• Channelization
• Beamforming
NenuFAR Correlator
• Channelization
• Correlation
• Calibration + Imaging
NenuFAR Standalone Radio Imager
UnDySPuTeD : dynamic spectra
• Channelization
• Integration
UnDySPuTeD : pulsar
• Coherent dedispersion
• Folding / Integration
SETI Machine
NenuFAR Standalone Beamformer

Opération & Contrôle



- Dialogue avec LOFAR
- Contrôle/commande silencieux
- Pointage : synchronisé : 10 sec, correction de "squint"
- GUI de commande & monitoring temps réel

Le récepteur LANewBa



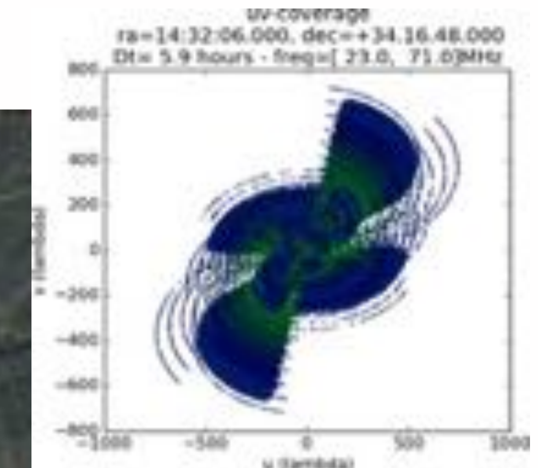
cf. présentation de Cédric VIOU

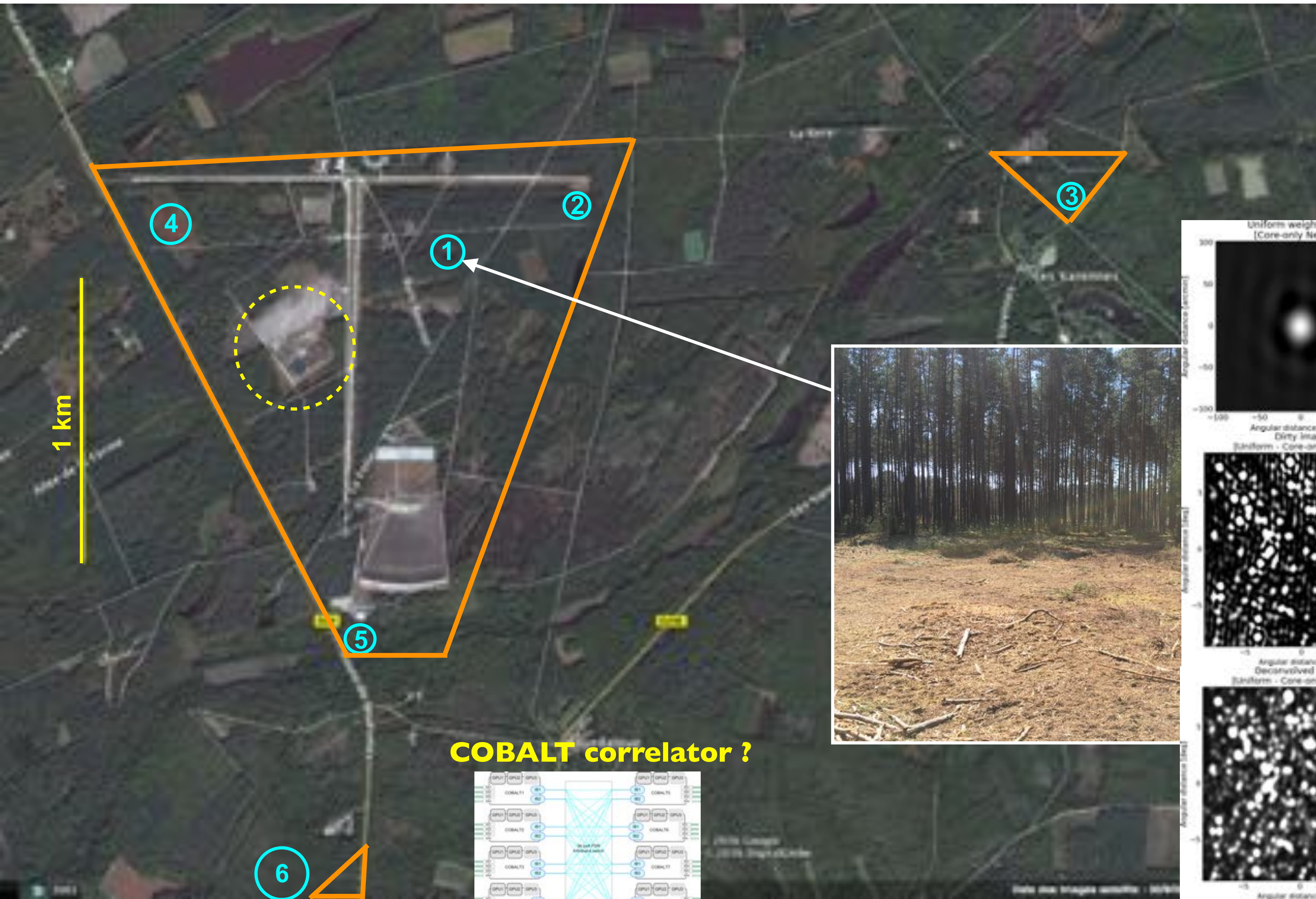
- Numérisation : 96 x 2 ADC @ 200 MHz
- Traitements FPGA : filtrage polyphase + beamforming
  - → 768 beamlets, 200-kHz, 200 k-complexes/s
  - → TBB (5 sec)
- Données statistiques :
  - → SST, BST : 1 / sec / subband, XST : 32 SB / sec
- Input vers le corrélateur NRI

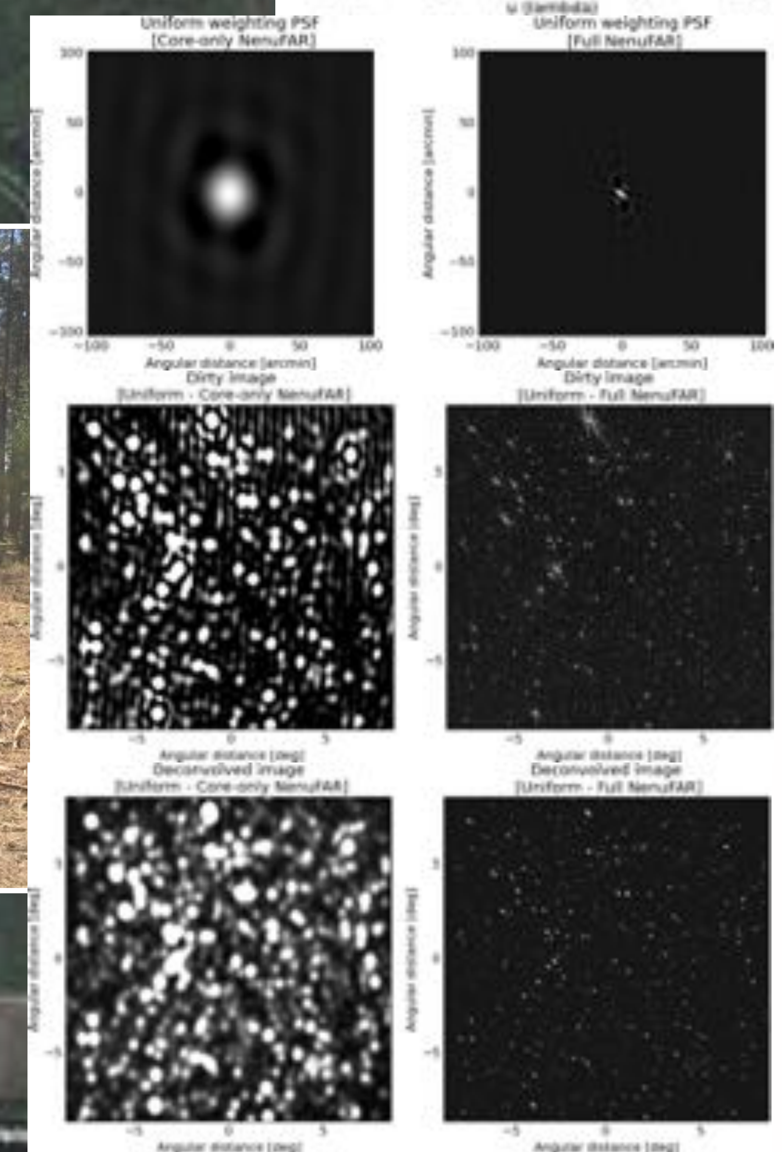
Le Radio Imageur NenuFAR

ANR «NRI» 2017-2019

- $\sigma_{confusion}$ [mJy/beam] ~ $(\nu$ / 100 MHz$)^{-0.7}$ $(\theta$ / ' $)^2$ *[Condon, 2002, 2005]* → 1-50 Jy @ 20-80 MHz (signal non polarisé)
- corrélateur + 6 MR distants + synthèse rotationnelle multi-λ
  - → résolution angulaire x7 (souces large-bande stationnaires) → $\sigma_{confusion}$ / 50



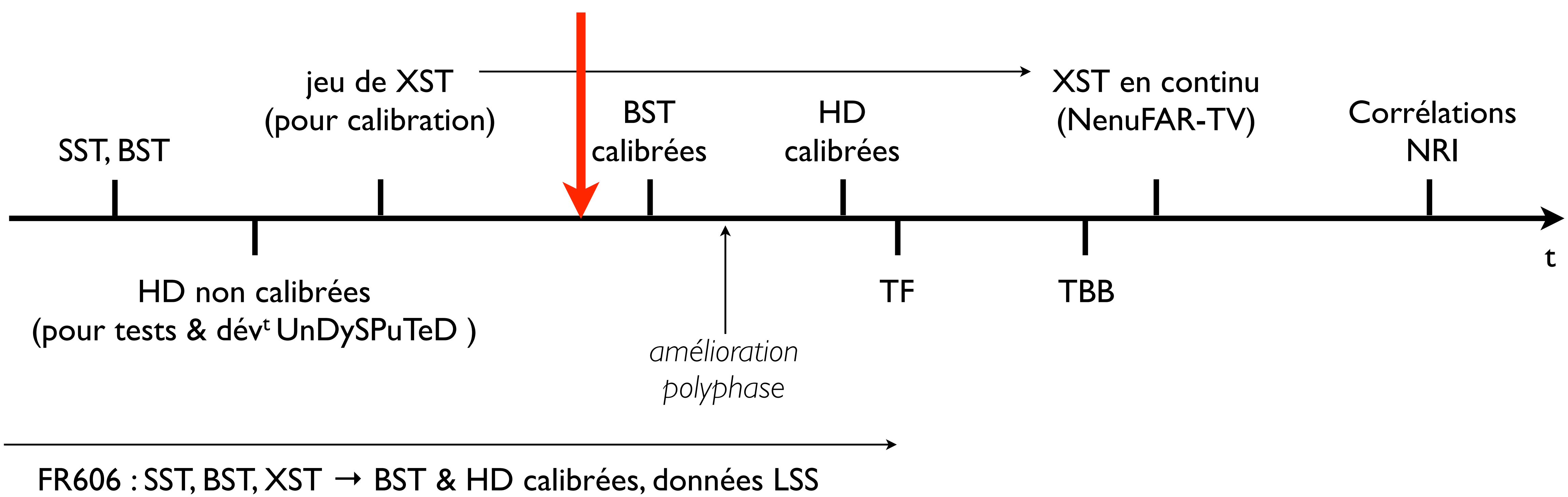




Données

- LaNewBa en cours de finalisation : SST, BST, XST (validées), conversion XST → MS en cours
  données HD produites avec setup "manuel"
  → XST utilisées pour calibration du beam cohérent & "NenuFAR-TV"

- UnDySPuTeD en cours de finalisation et commissioning (LPC2E)
  - mode "pulsar"
  - mode "temps-fréquence"
    (polarisation complète : 4 Stokes)



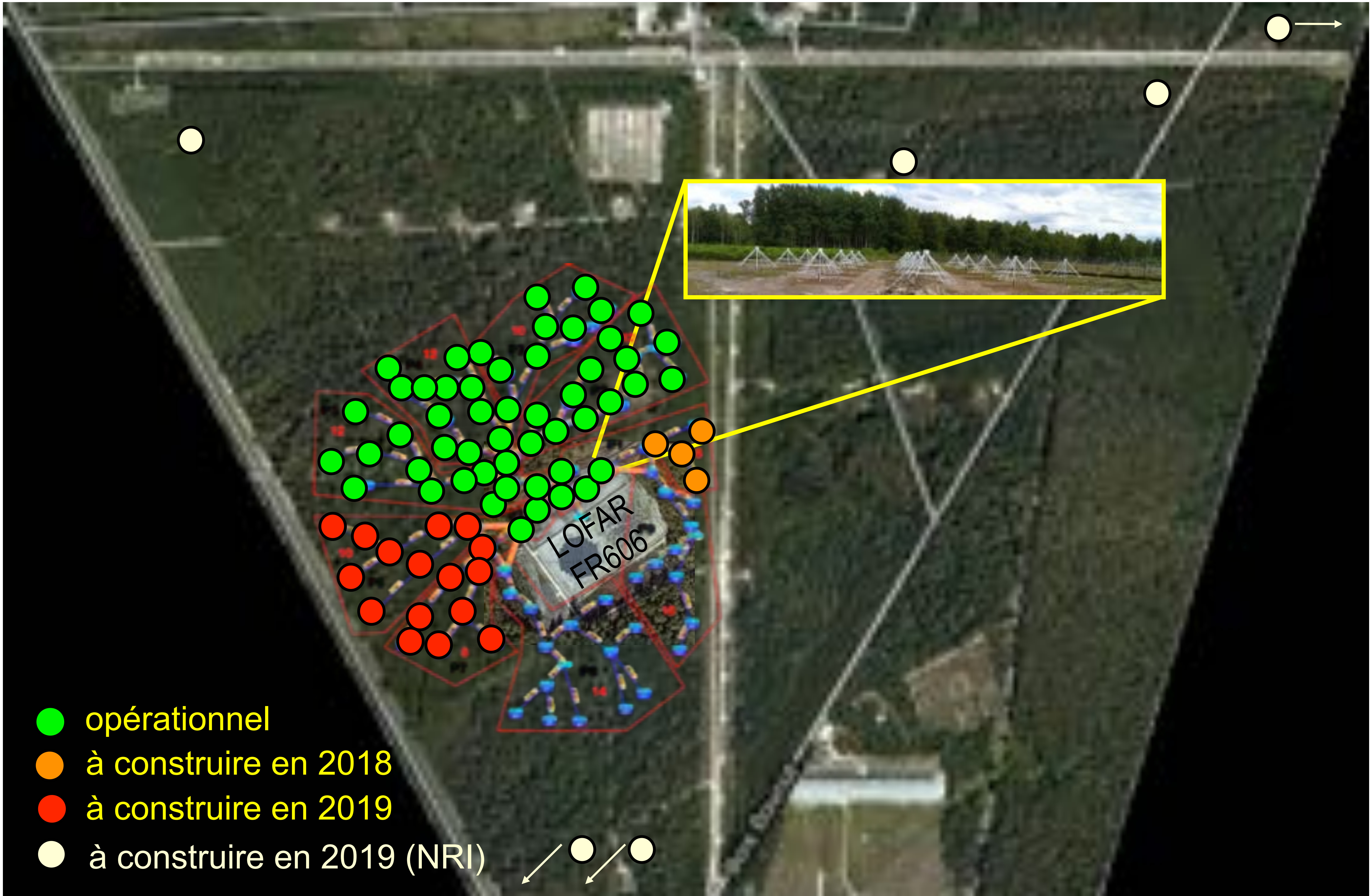
Caractéristiques techniques de NenuFAR

- Giant LOFAR-compatible phased array & interferometer
- 1938 antennes : 96+6 mini-arrays of 19 antennas each (25 m ∅)
- Diameter ~400 m + extensions → 3 km
- 5151 baselines
- Frequency range = 10-85 MHz (λ=3.5-30m)
- Resolutions: δf = 200 kHz → 1 kHz, δt = 5 µsec, Waveform @ 5 nsec
- Full polarization (4 Stokes)
- Collective area ~$650\lambda^2 \leq 65\,000$ m^2
- FoV = 32° - 8° @ 20-80 MHz ; pointing (δ) -23° → +90°
- Angular Resolution: 2°-0.5° (Standalone instantaneous Beamformer/Imager)
  17'-4' (Slow Imager), 0.1 " (LSS)
- Sensitivity : 2 – 0.5 Jy @ 20-80 MHz (5σ, 1 sec x 10 MHz, polarized signal)
  10 – 2 mJy ʼʻ (5σ, 6 h x 40 MHz)
- Confusion at zenith: 50 – 1 Jy @ 20 – 80 MHz (unpolarized, compact core)
  1000 – 20 mJy " (unpolarized, with distant MA)

NenuFAR aujourd'hui

Déploiement

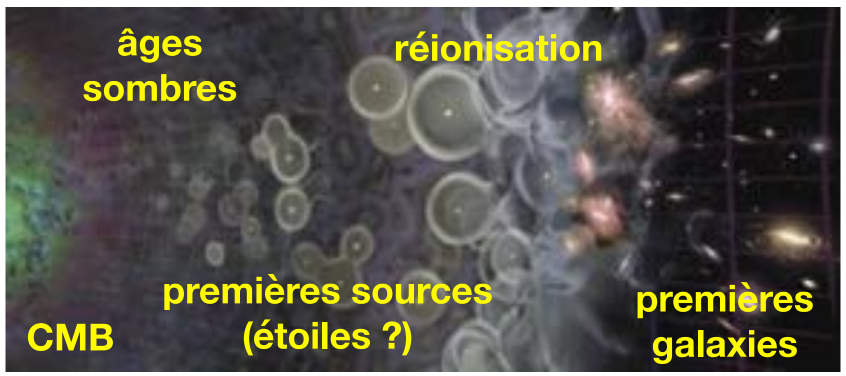
72 MR coeur financés, 52 construits & opérationnels

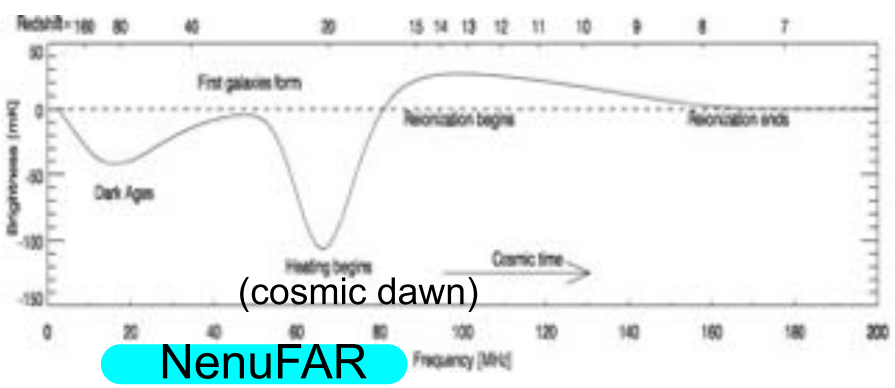


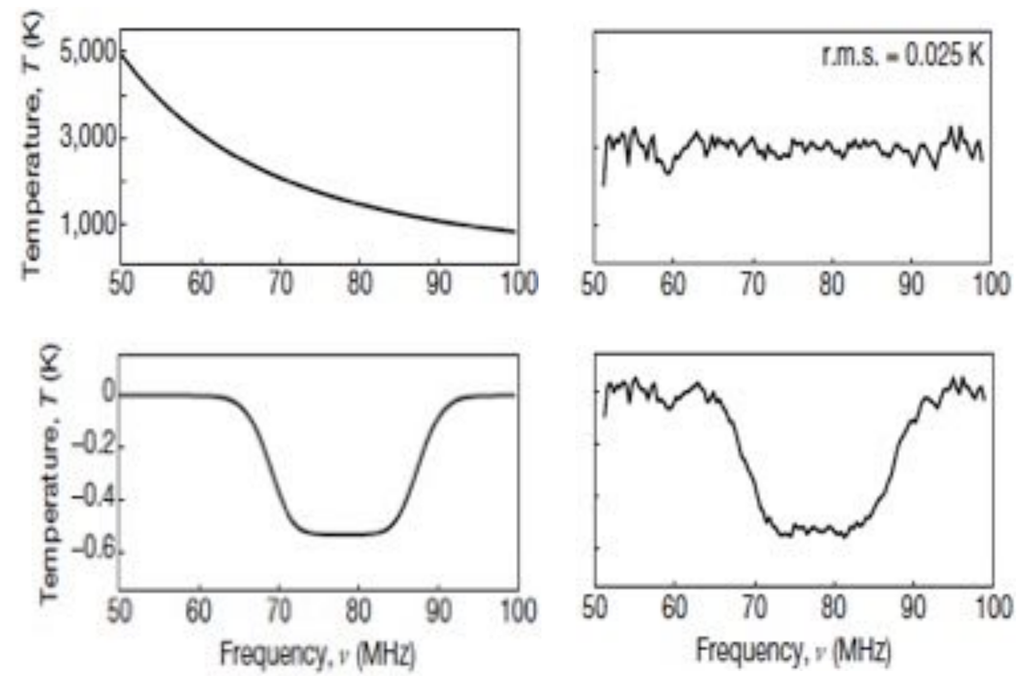
La Science de NenuFAR

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

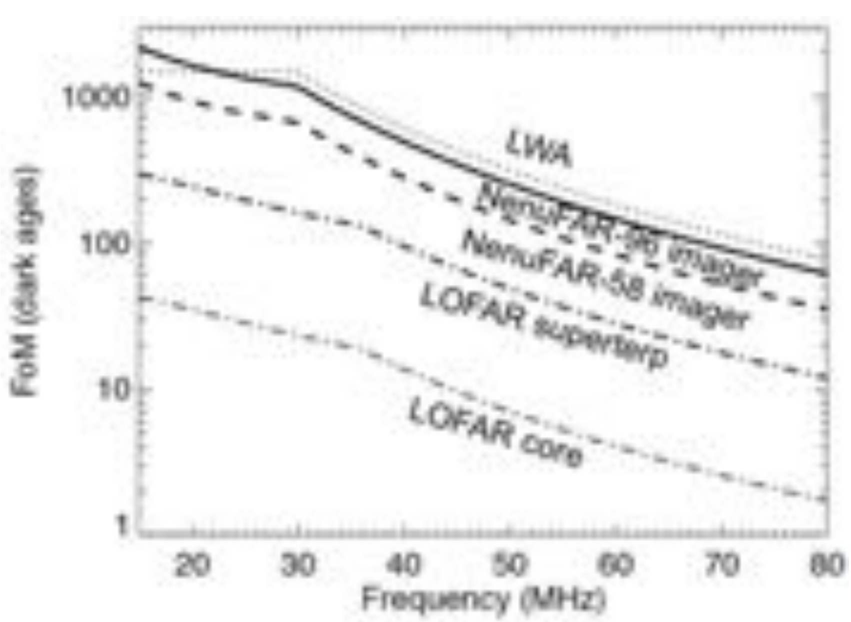
- Ages sombres/Aube cosmique *(SSI)*

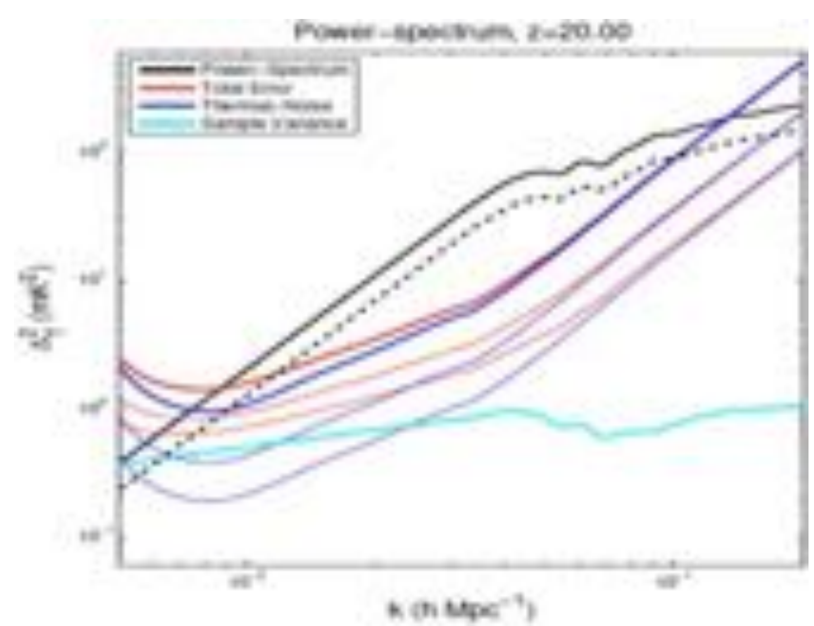






[Bowman et al. , Nature 2018]



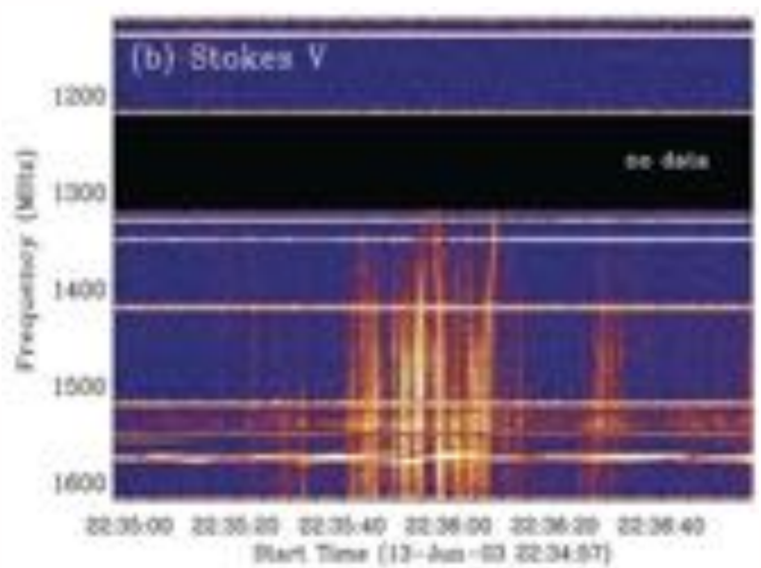


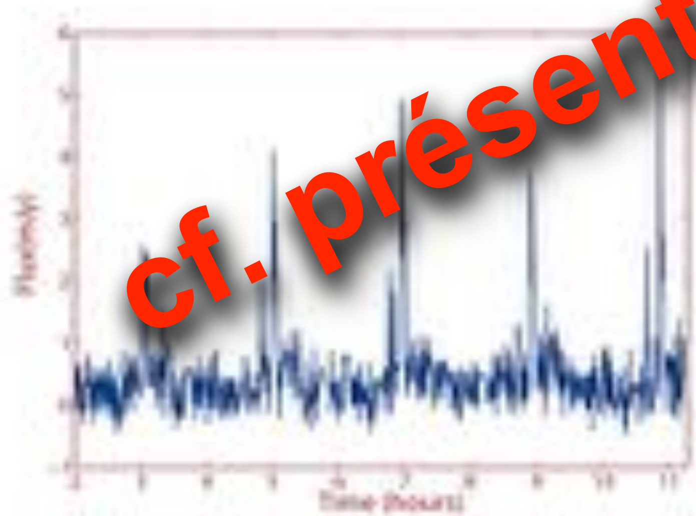
[Koopmans et al. 2015 ; Semelin et al., 2015]

La Science de NenuFAR

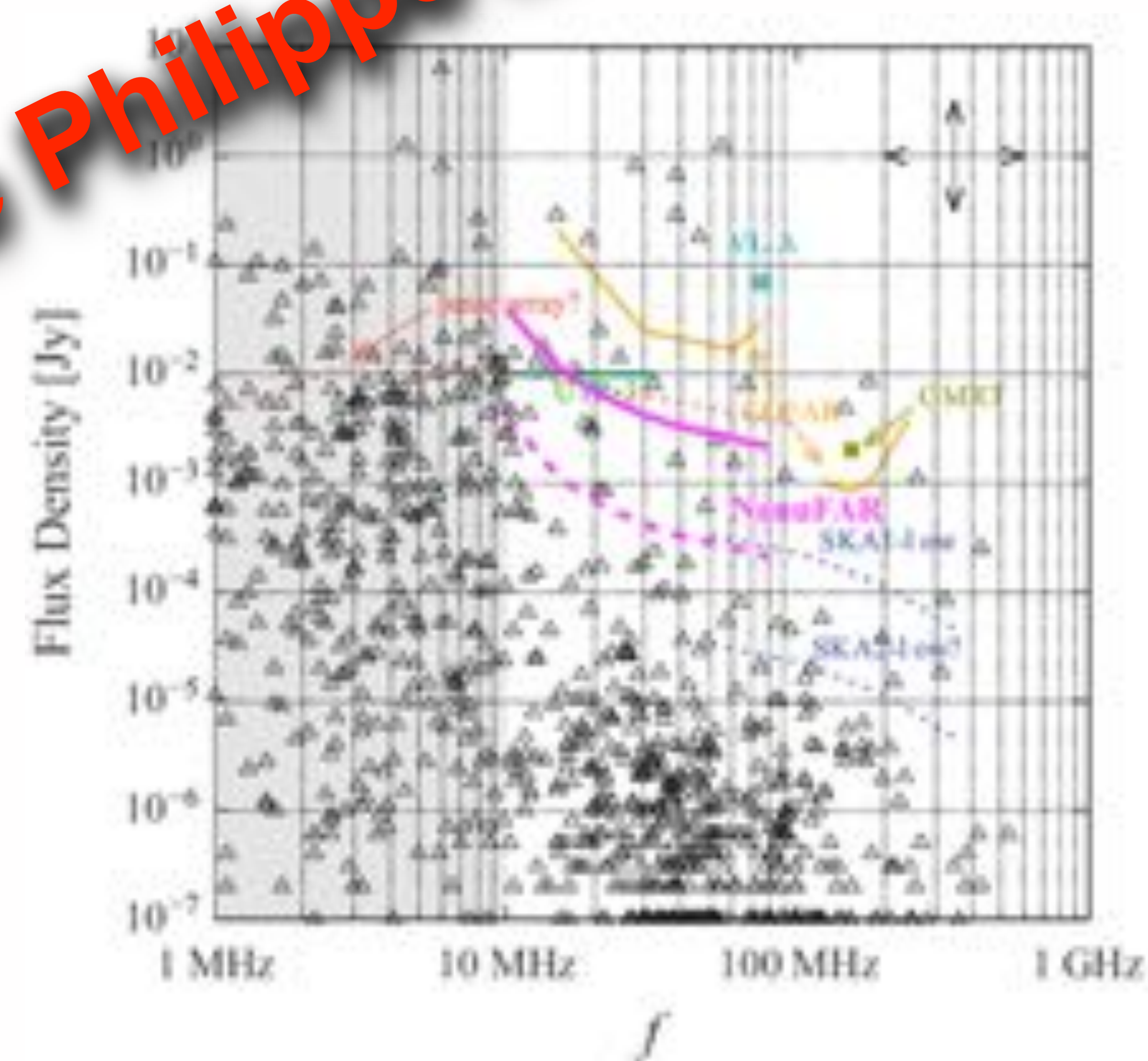
Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

- Étoiles, Planètes, Interactions *(SSI, SFI, SB)*





cf. présentation de Philippe ZARKA



[Osten et al., 2006, 2008 ; Hallinan et al., 2007, 2008, 2015]

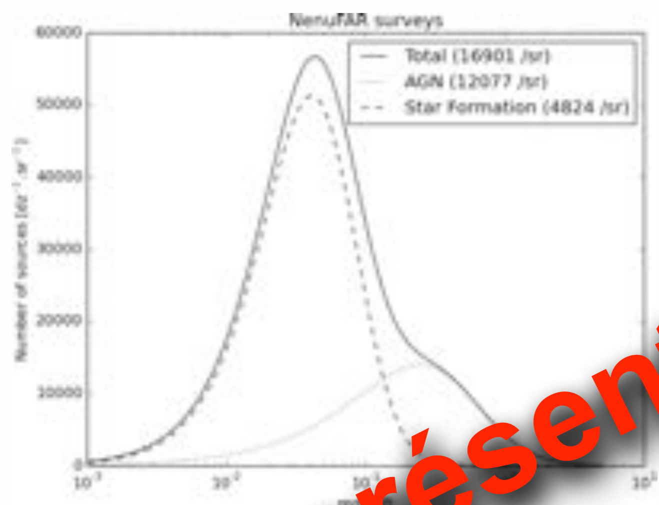
[Zarka et al., 2007, 2015; Grießmeier et al., 2007, 2011; Turner et al., 2017]

La Science de NenuFAR

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

cf. présentation de Mamta POMMIER

- Galaxies & halos *(LSS, SSI)*



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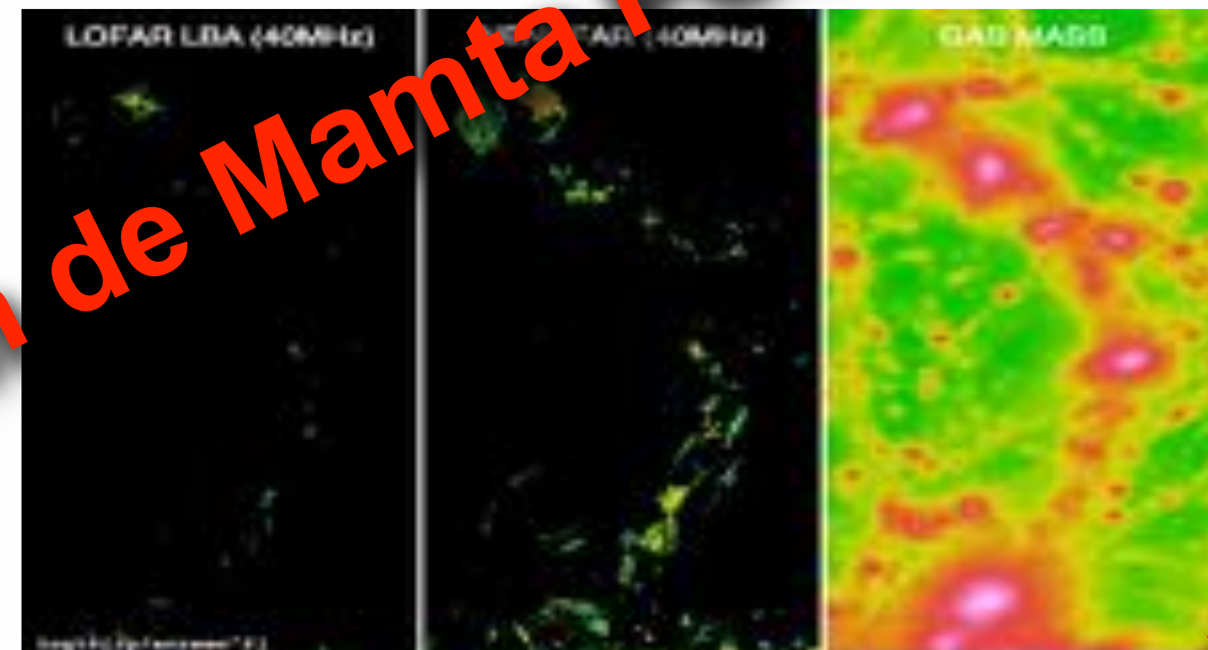

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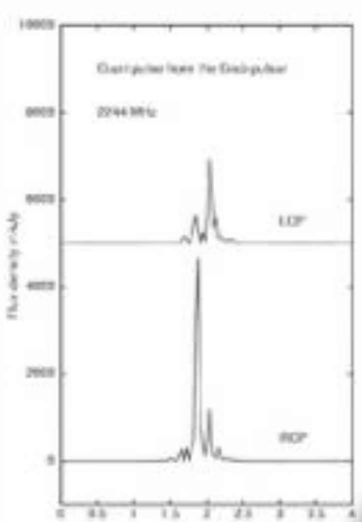
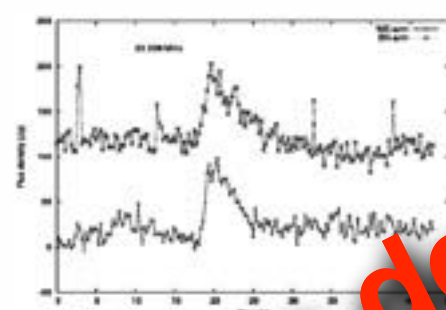
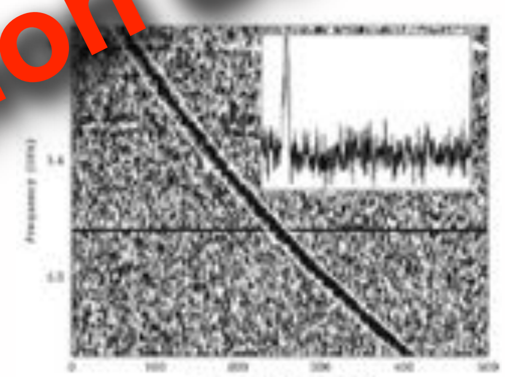
- Pulsars, RRAT, FRB *(SB)*

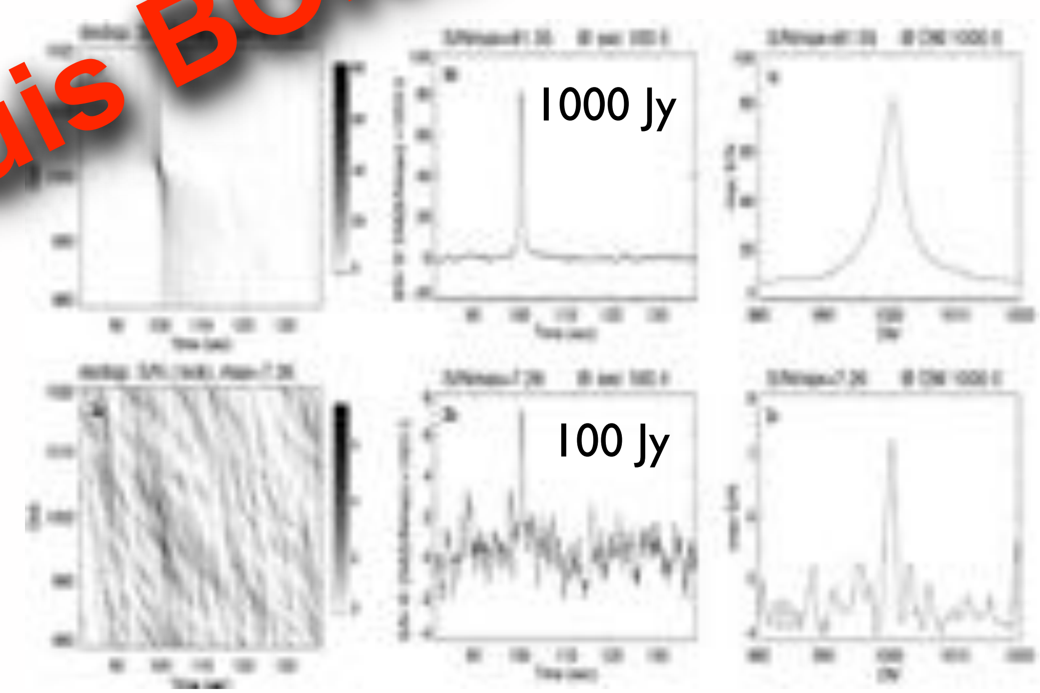
cf. présentation de Louis BONDONNEAU



Crab giant pulses [Popov et al.]





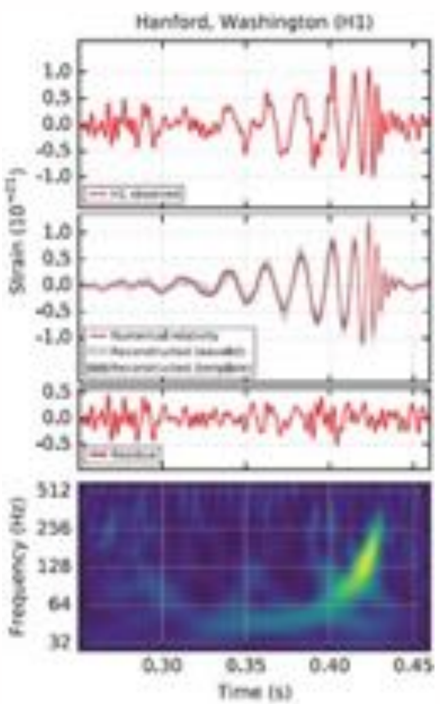


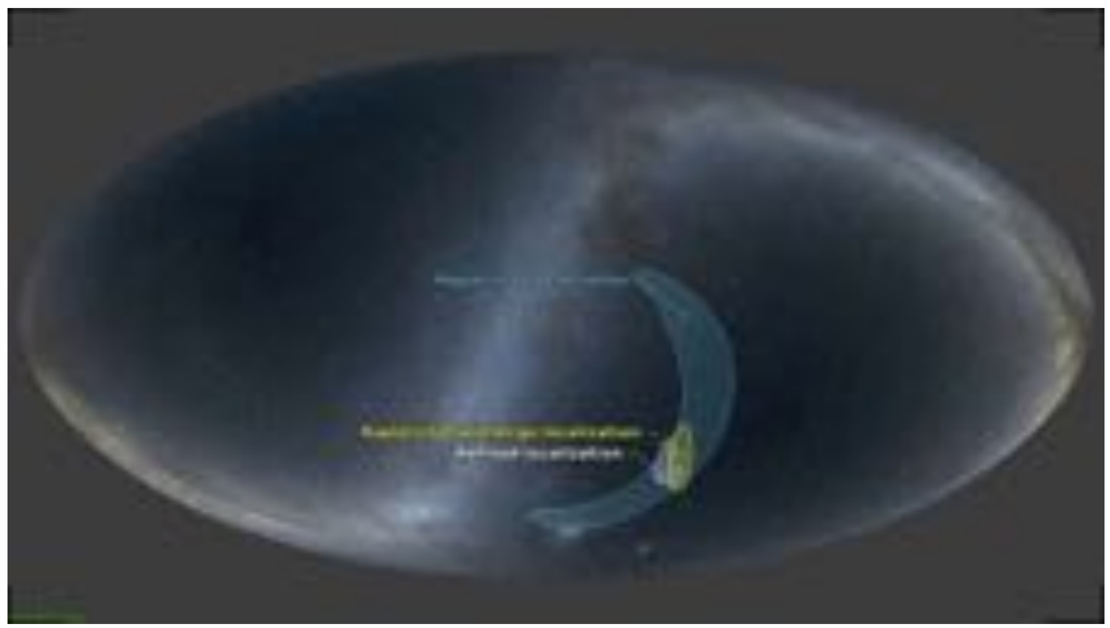
[Lorimer, 2007 ; Zarka & Mottez, 2016]

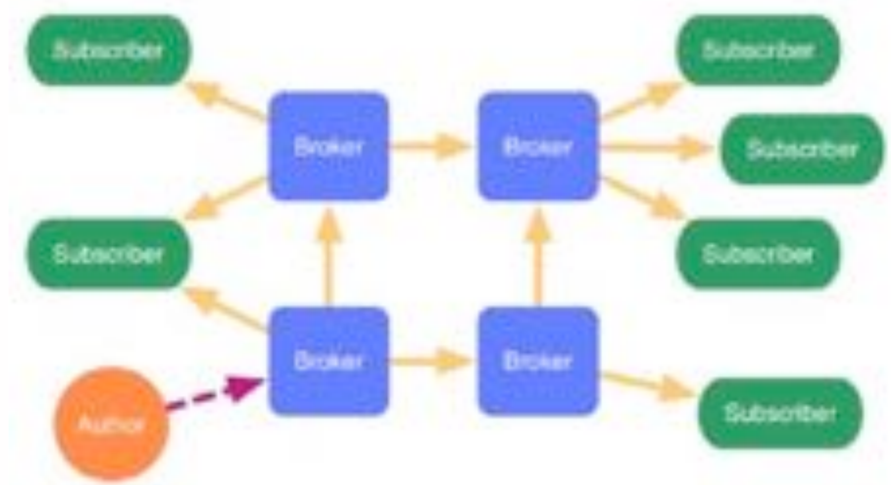
La Science de NenuFAR

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

- Contrepartie radio d'Ondes gravitationnelles *(SFI, SB)*

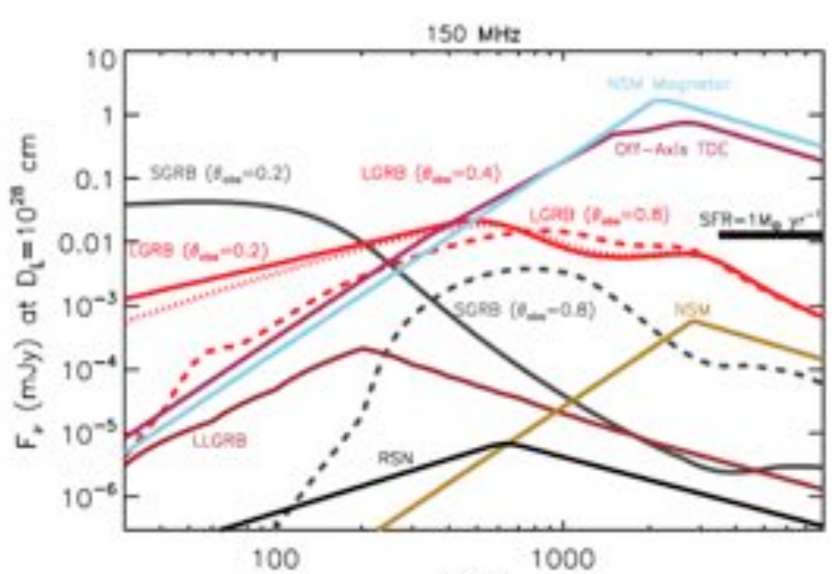




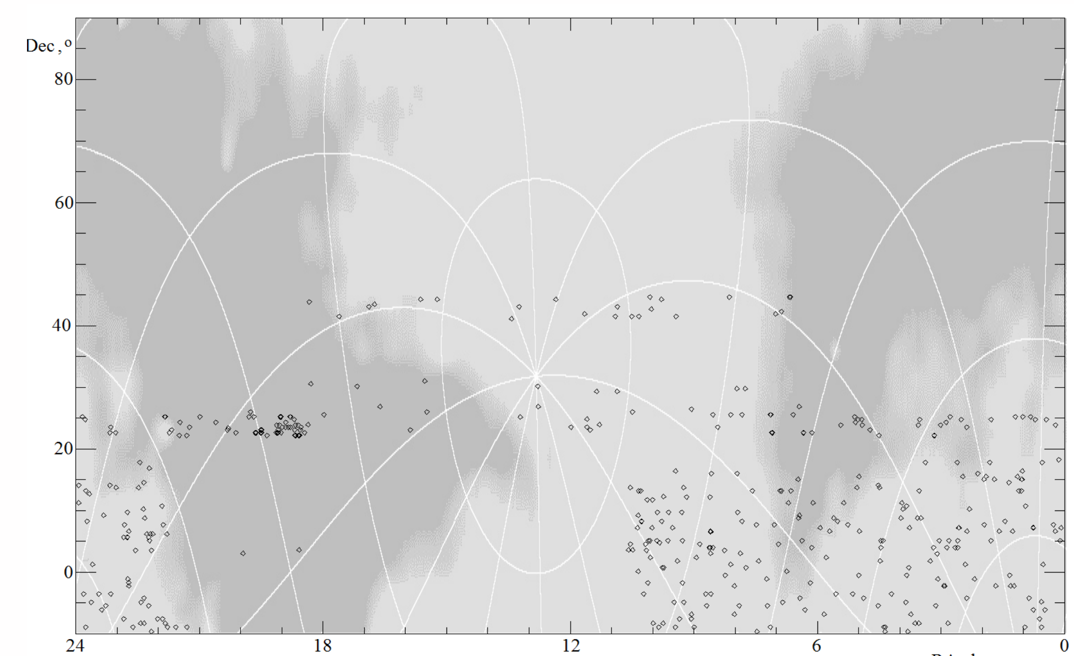


[LIGO-VIRGO coll., 2016, 2017]

- Transitoires lents / rapides *(SFI, SSI, SB)*



[Metzger et al., 2015]

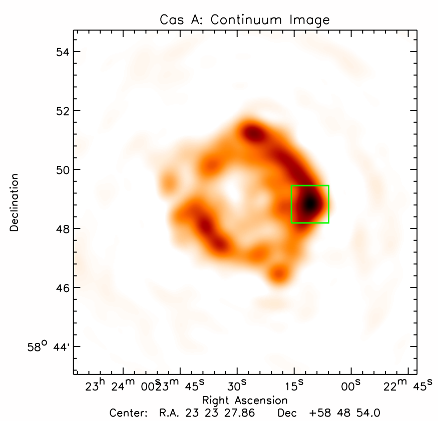


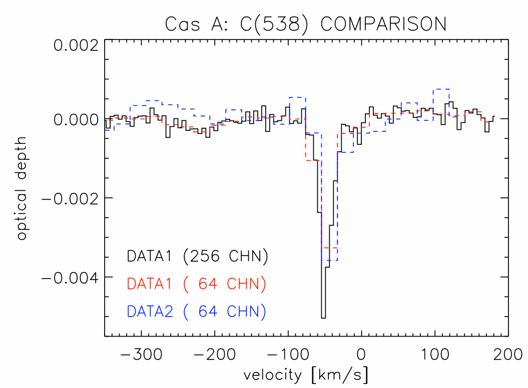
Part of UTR-2 transients survey ≤30 MHz
[Zakharenko, Vasylieva et al., 2015]

La Science de NenuFAR

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

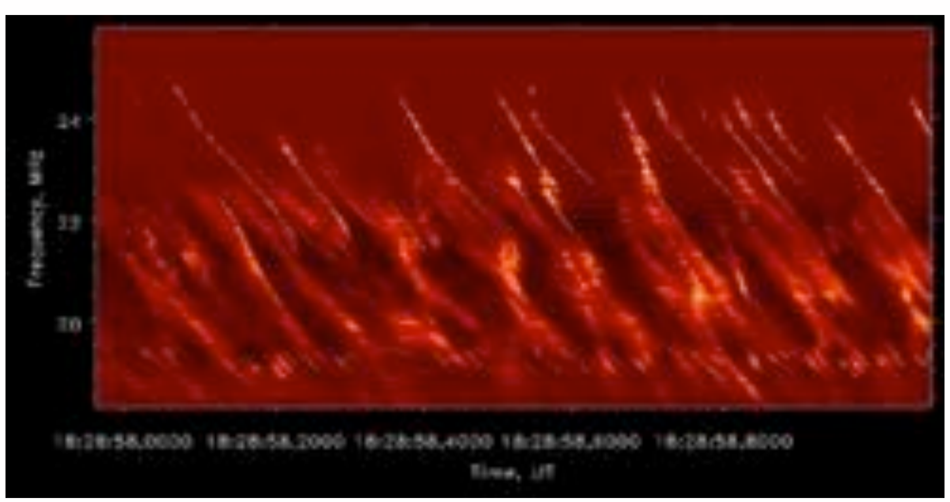
- RRL, Grains? *(SSI, SB)*





[Asgekar et al., 2013]

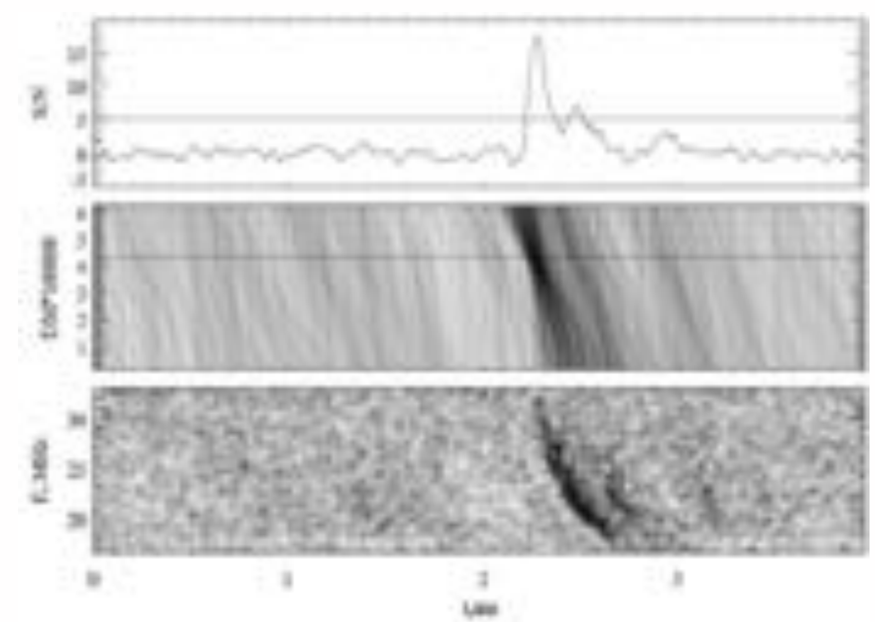
- Héliosphère: Soleil, Jupiter *(SFI, SB)*



[Ryabov et al., 2014]

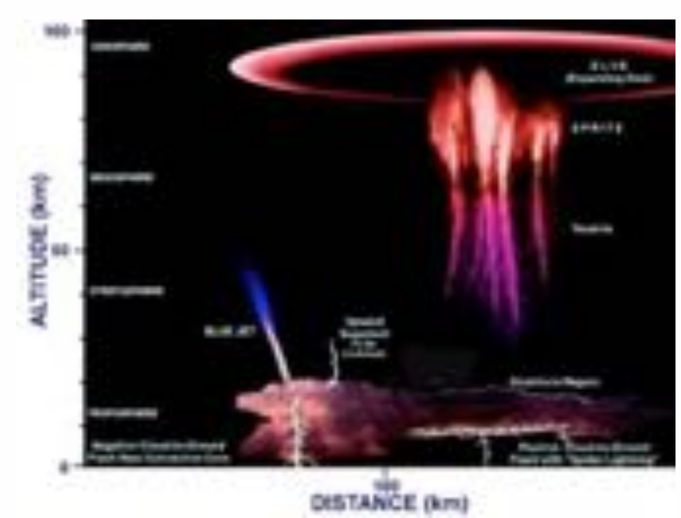
- SETI *(SB)*

- Éclairs d'orages planétaires *(SFI, SB)*



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

- Terre: Éclairs/Sprites, TLEs *(SFI, SB)*



Commissioning + Calibration *(Recette + Étalonnage)*

- Quantification sensibilité
- Simulation complète instrument + GSM

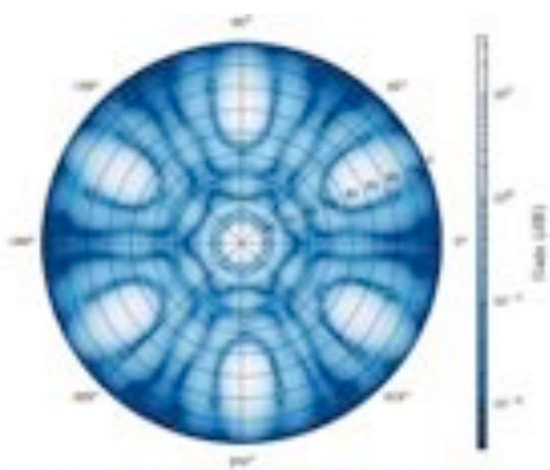
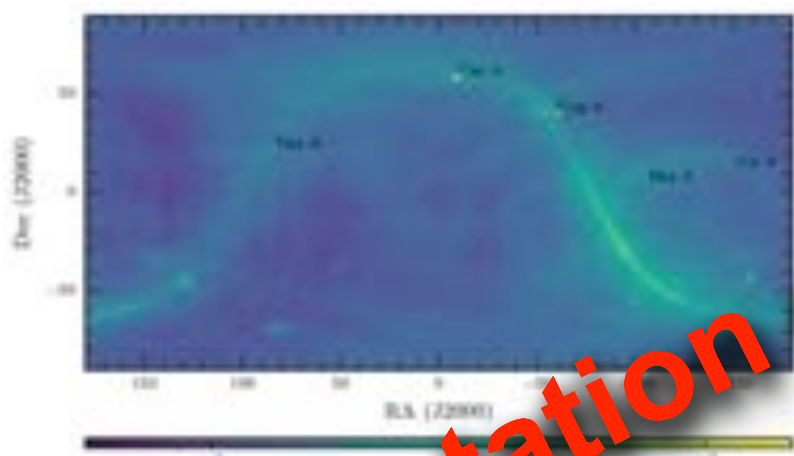
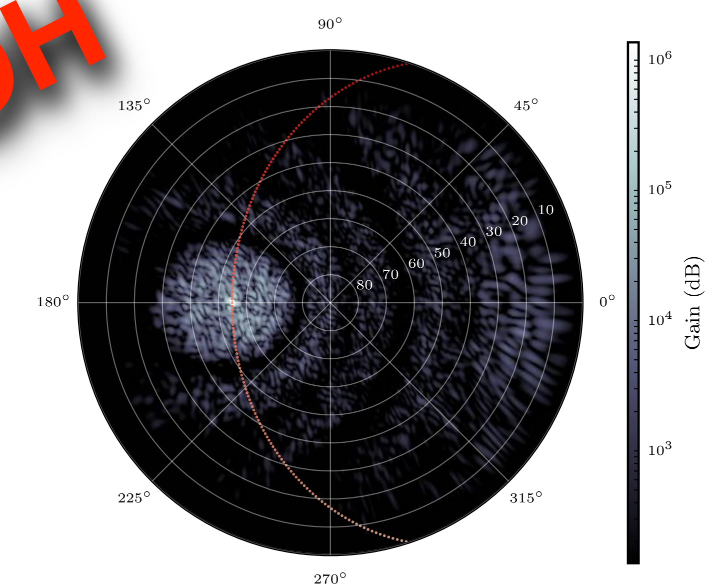


Figure 3: Gain pattern of the Mini-Array 0 (with the 88° offset angle). North is at 0°, East at 90° in azimuth.





cf. présentation d'Alan LOH

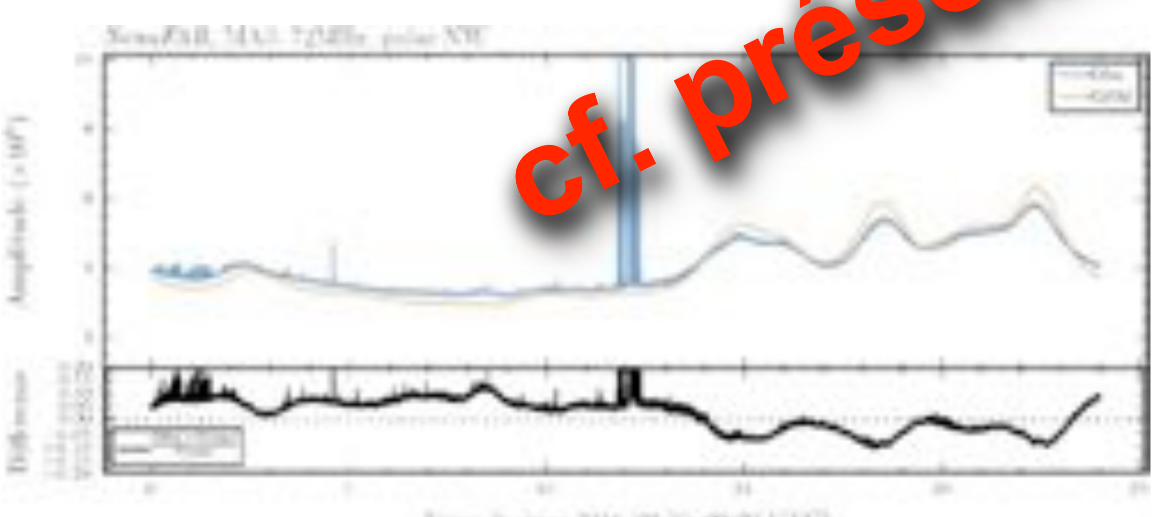
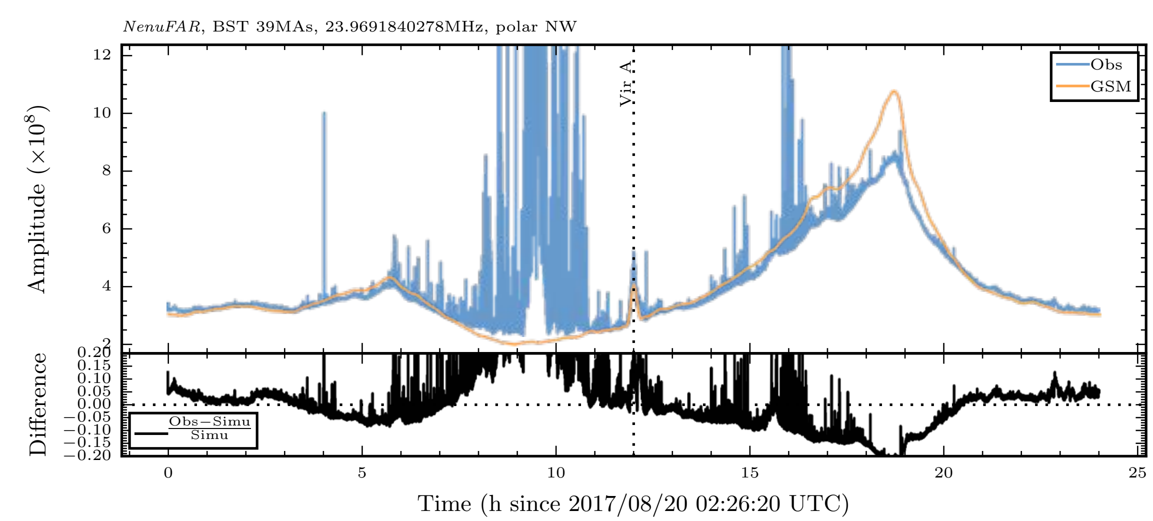
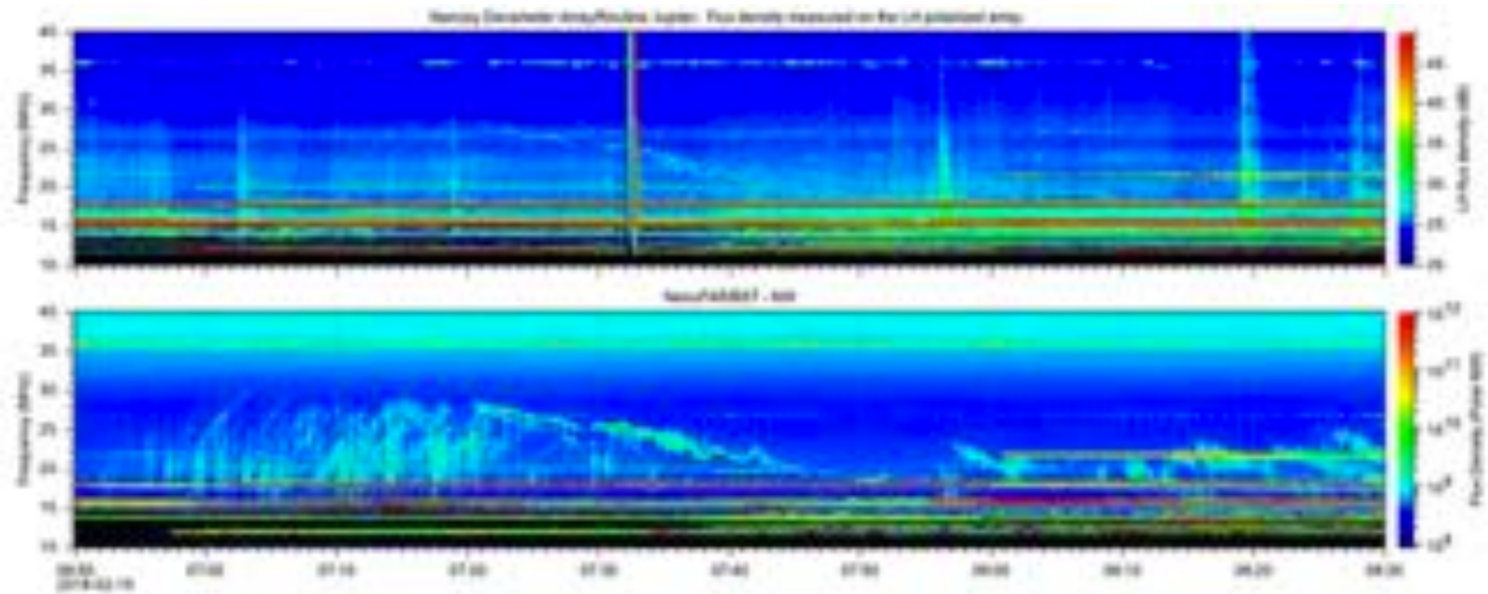


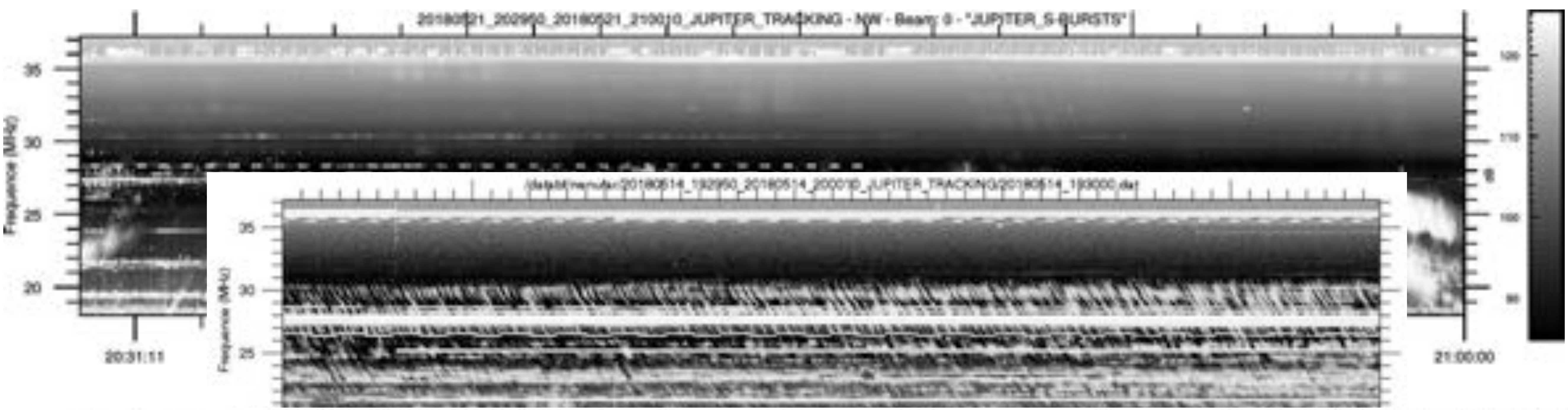
Figure 4: Time profile at 72 MHz of the Mini-Array 0 during the zenith observation on 2016 October 15 and simulation using a 88° offset angle.

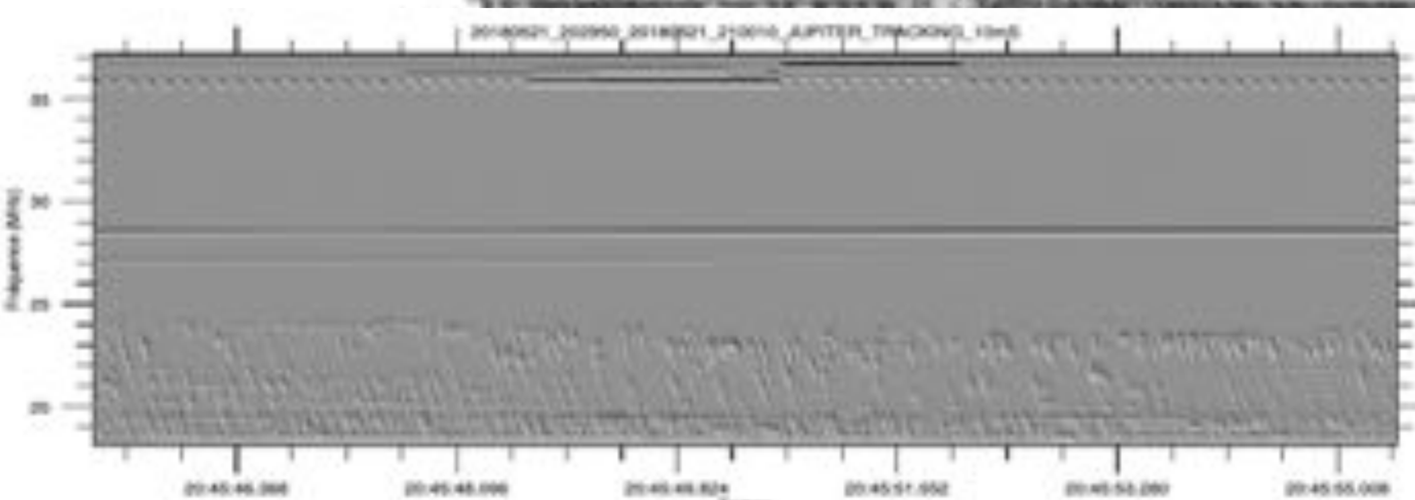


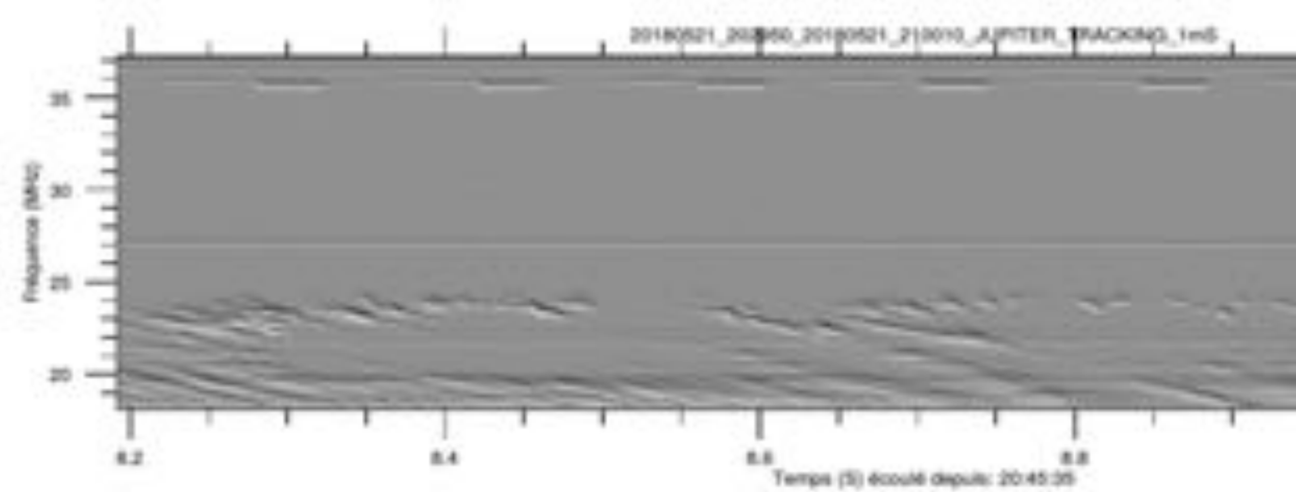
Commissioning

- Quantification sensibilité
- Simulation complète instrument + GSM
- Tests sur Jupiter



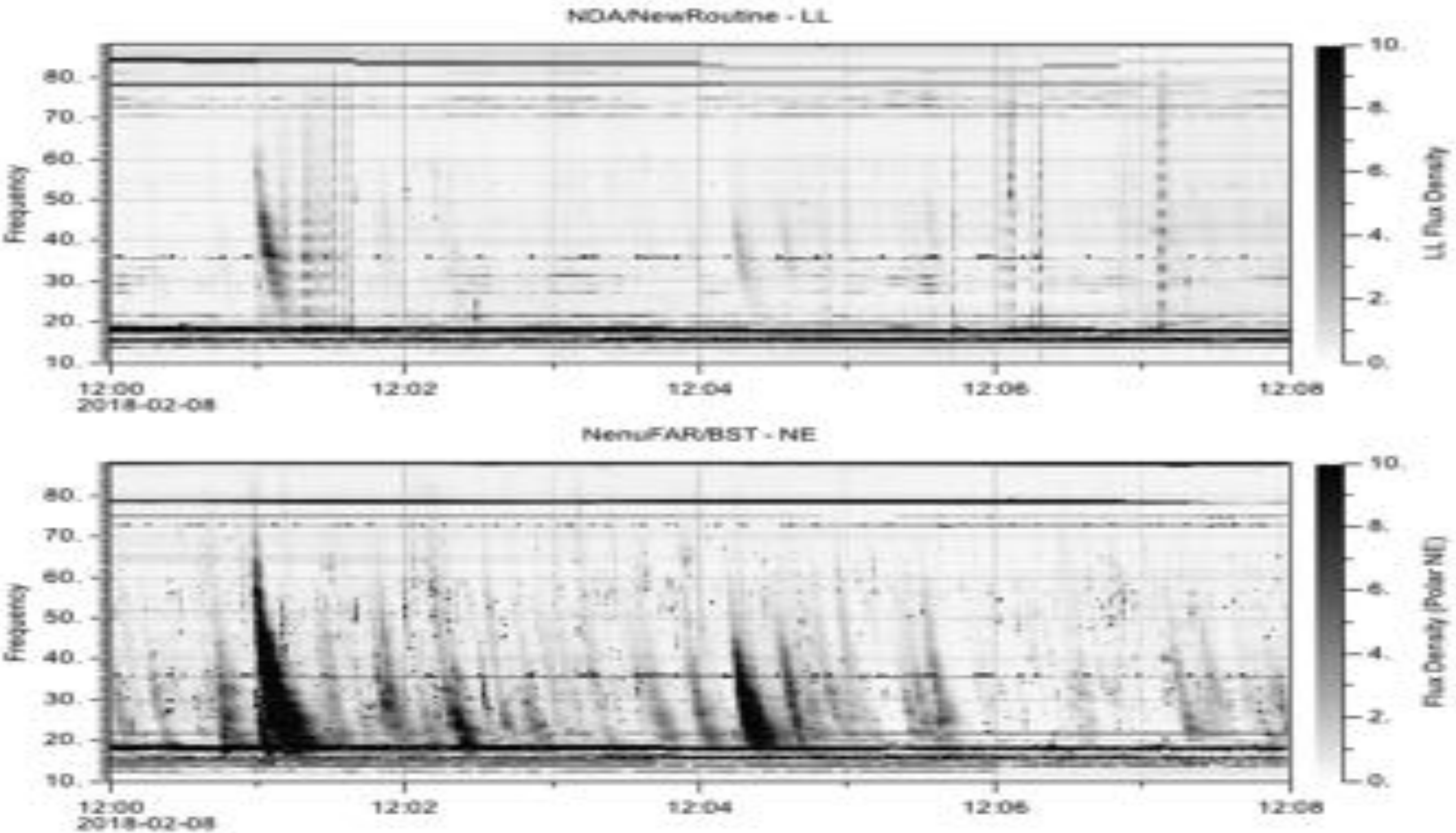






Commissioning

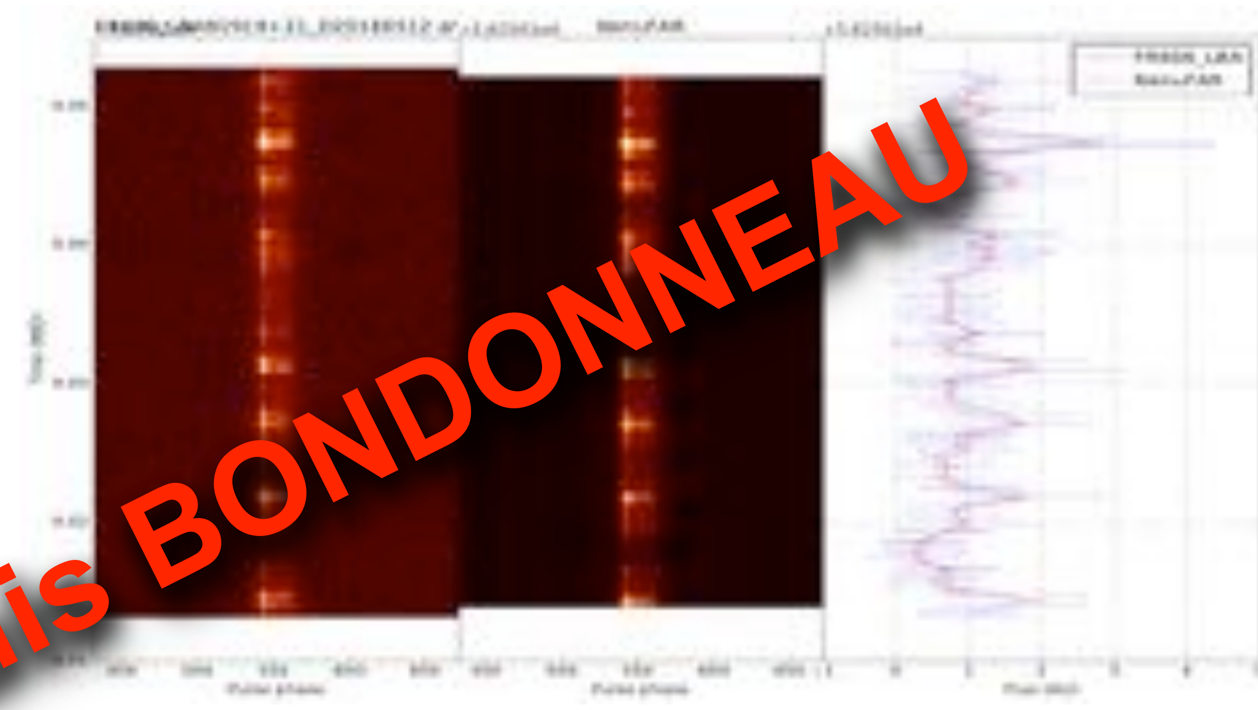
- Quantification sensibilité
- Simulation complète instrument + GSM
- Tests sur Jupiter et le Soleil



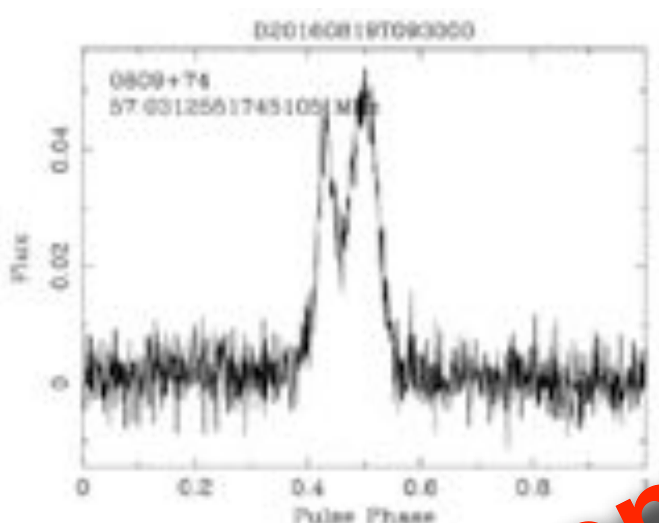
Commissioning + Calibration

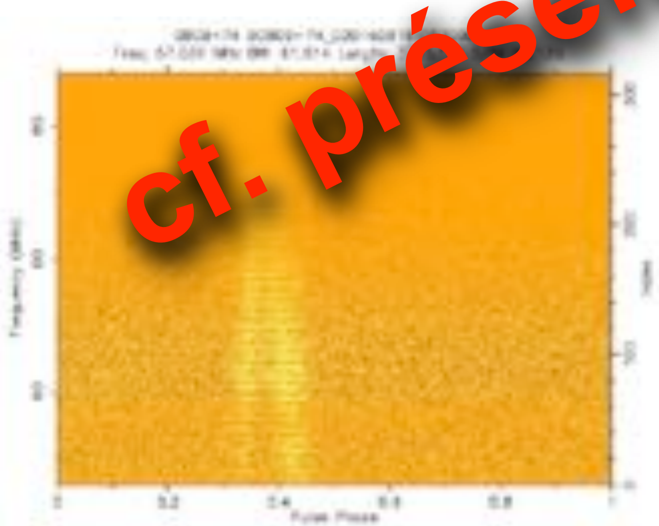
- Quantification sensibilité
- Simulation complète instrument + GSM
- Tests sur Jupiter et le Soleil
- **Observations de pulsars**

UnDySPuTeD + 40 MR

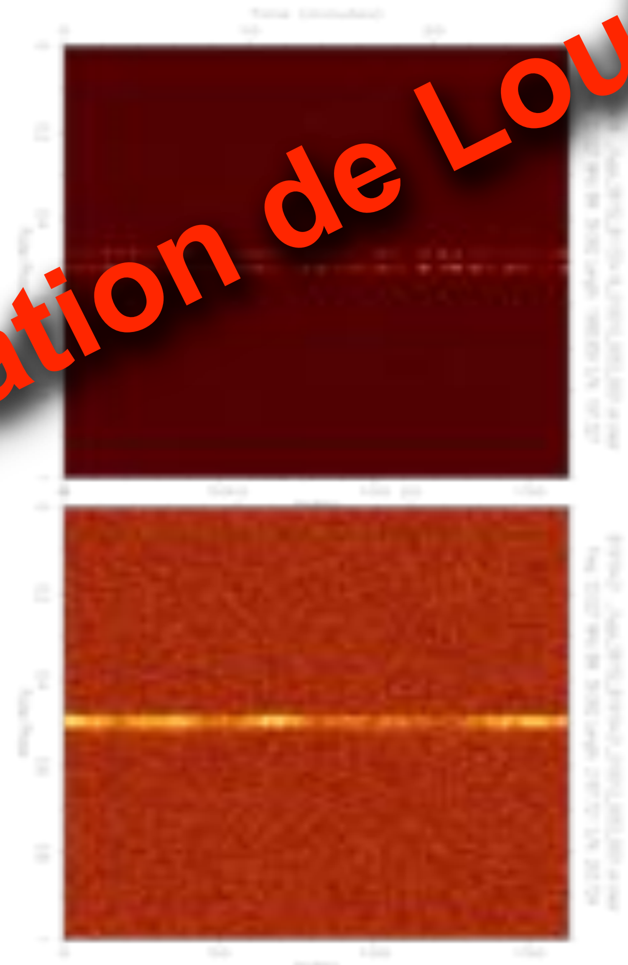


FR606 + 15 MR





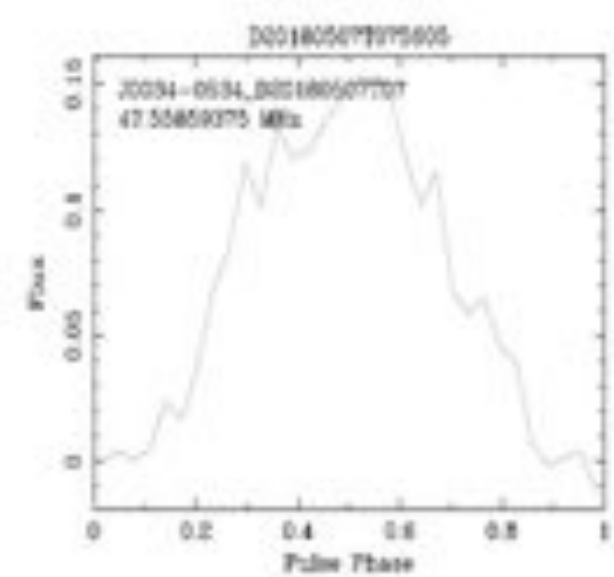
Single pulse detections



cf. présentation de Louis BONDONNEAU

A 58 MHz:
SNR NenuFAR / LOFAR-FR606 (calibré) ~ 3
SNR NenuFAR / LOFAR-FR606 (non calibré) ~ 7

Pulsar milliseconde

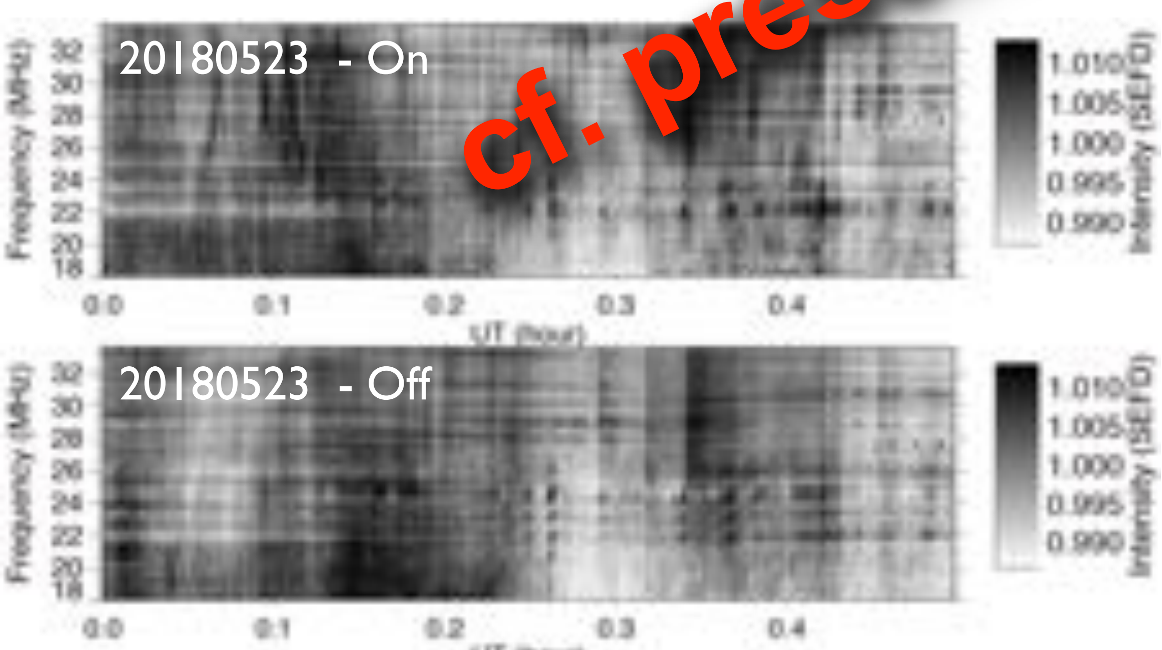


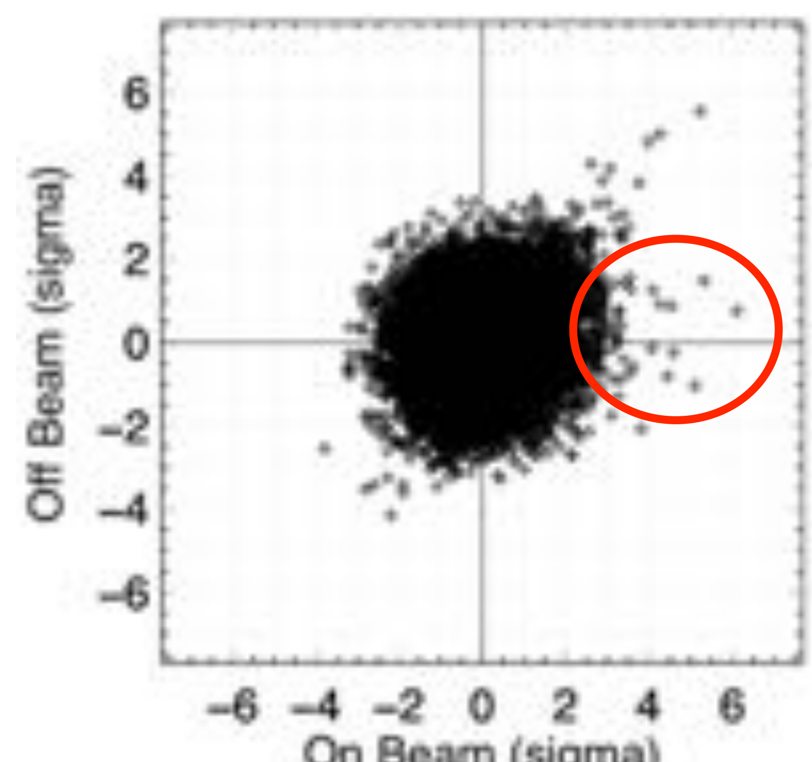
Commissioning

- Quantification sensibilité
- Simulation complète instrument + GSM
- Tests sur Jupiter et le Soleil
- Observations de pulsars
- **Eclairs d'orages de Saturne**

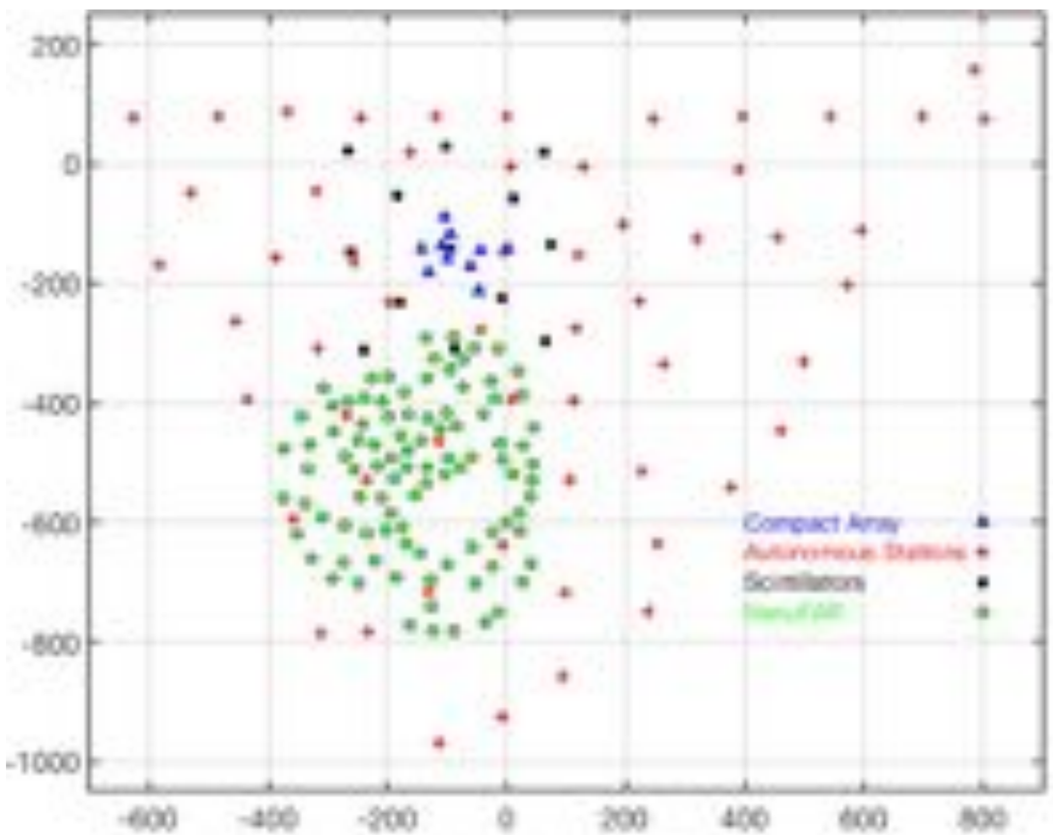
(observations On/Off 2018/04/28 - 05/30)

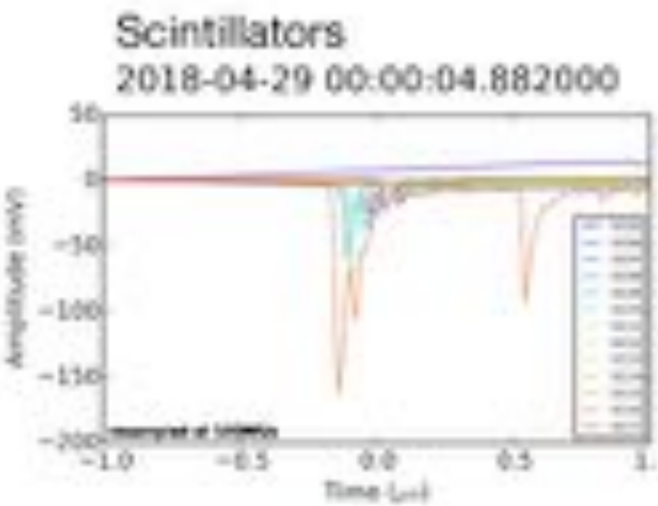
cf. présentation d'Alan LOH



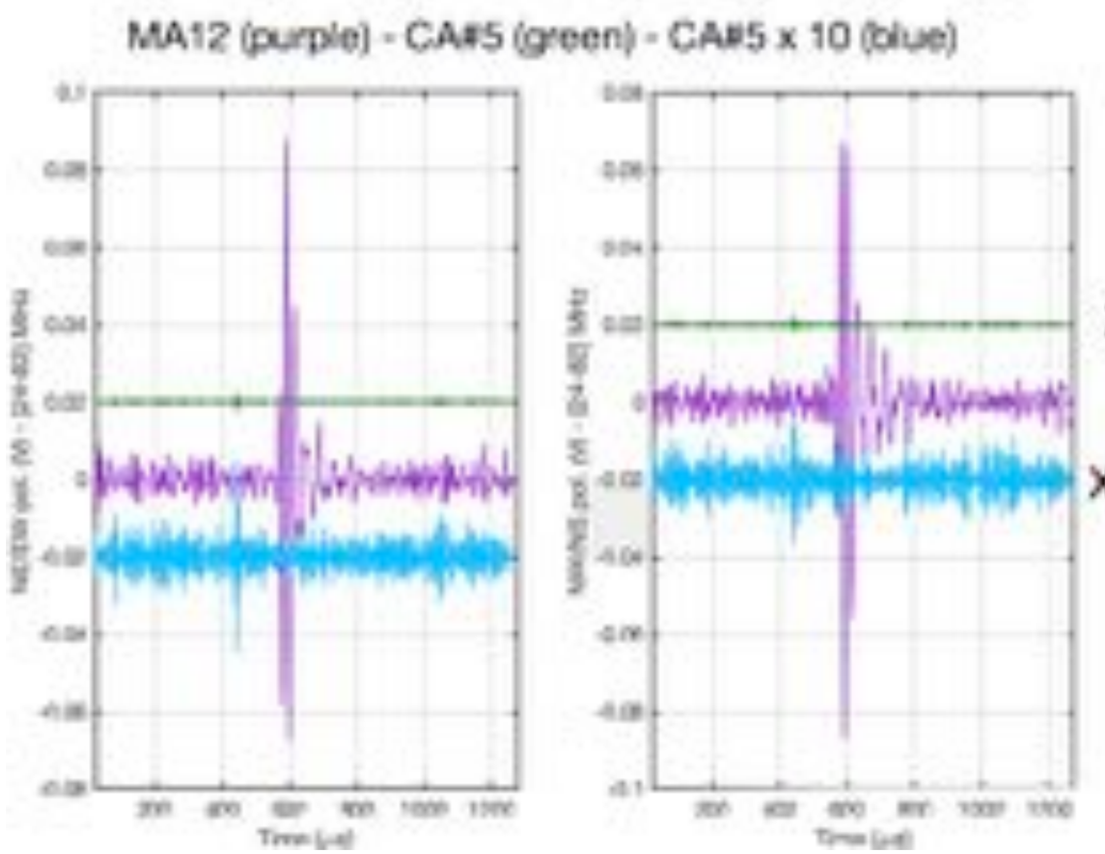


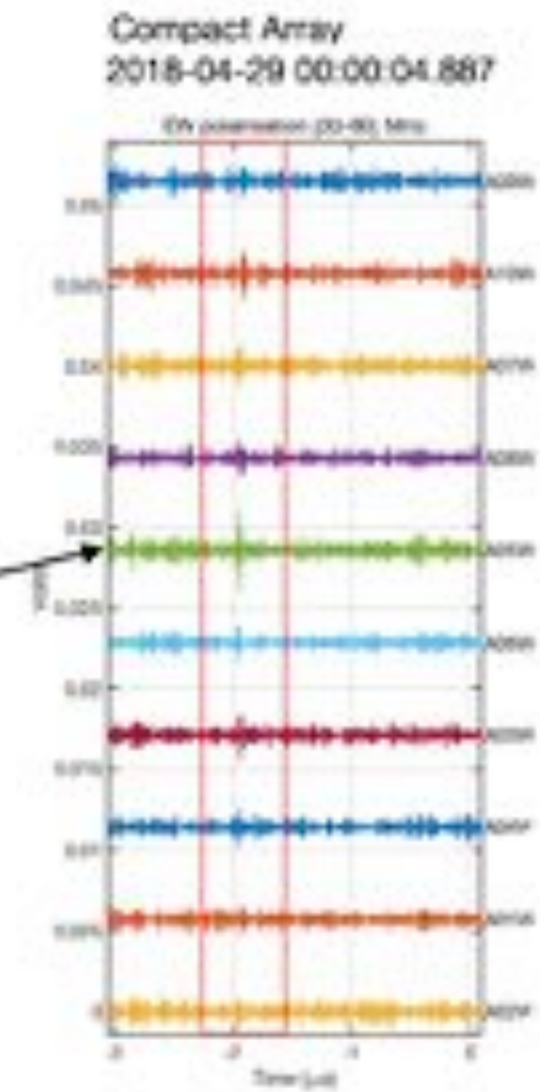
Commissioning

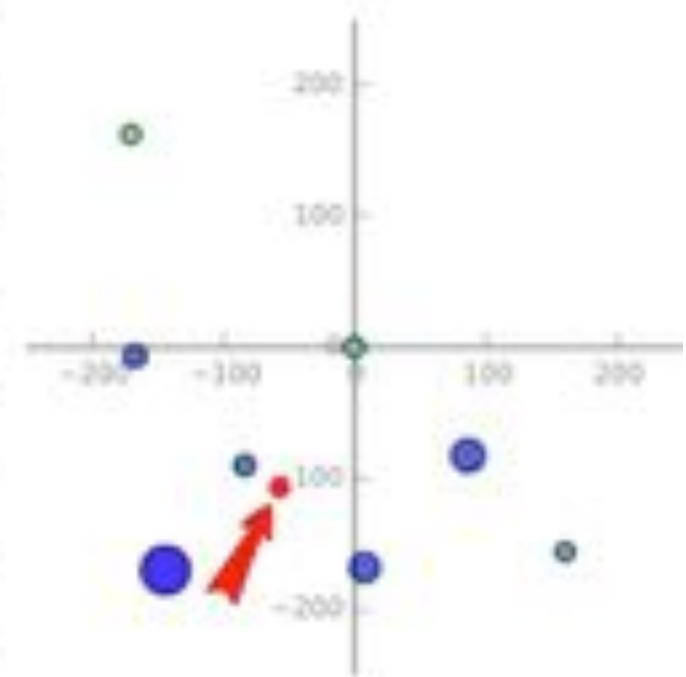




First detection of a cosmic ray event with NenuFAR - MA 12 and CODALEMA





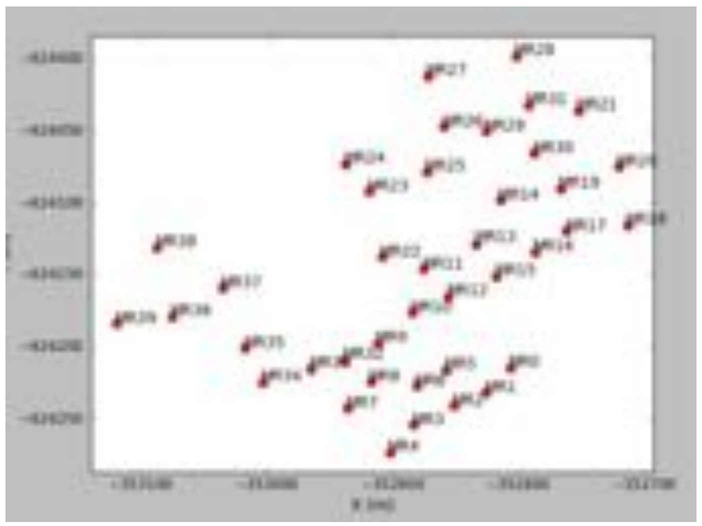


Commissioning + Calibration

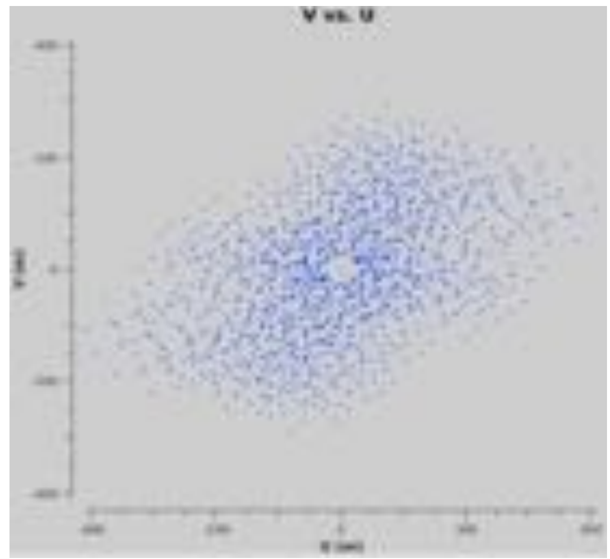
1ère image → étalonnage

Observation du 29/03/2018 9h10 TU

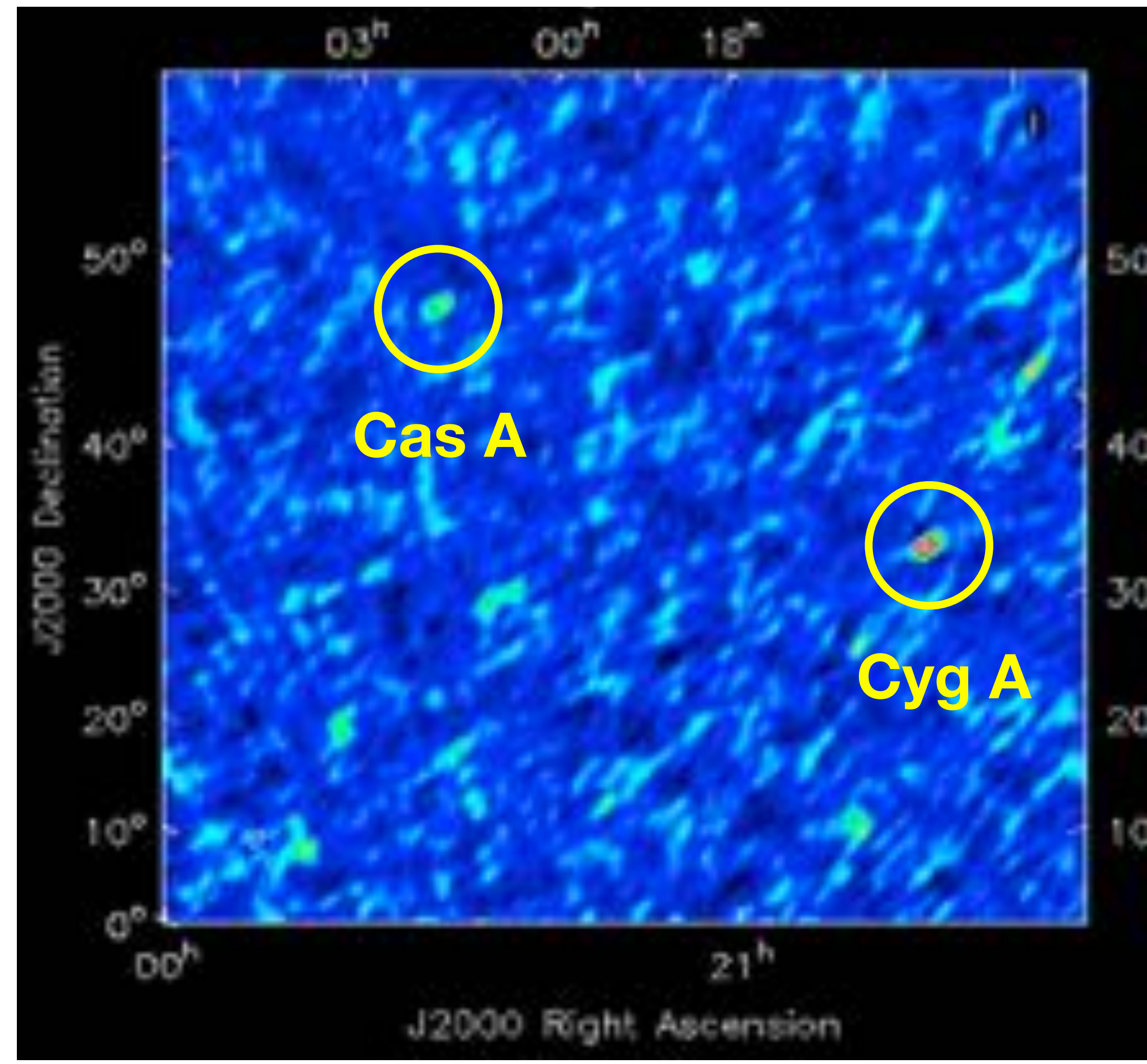
Interféromètre NenuFAR à 40 MR



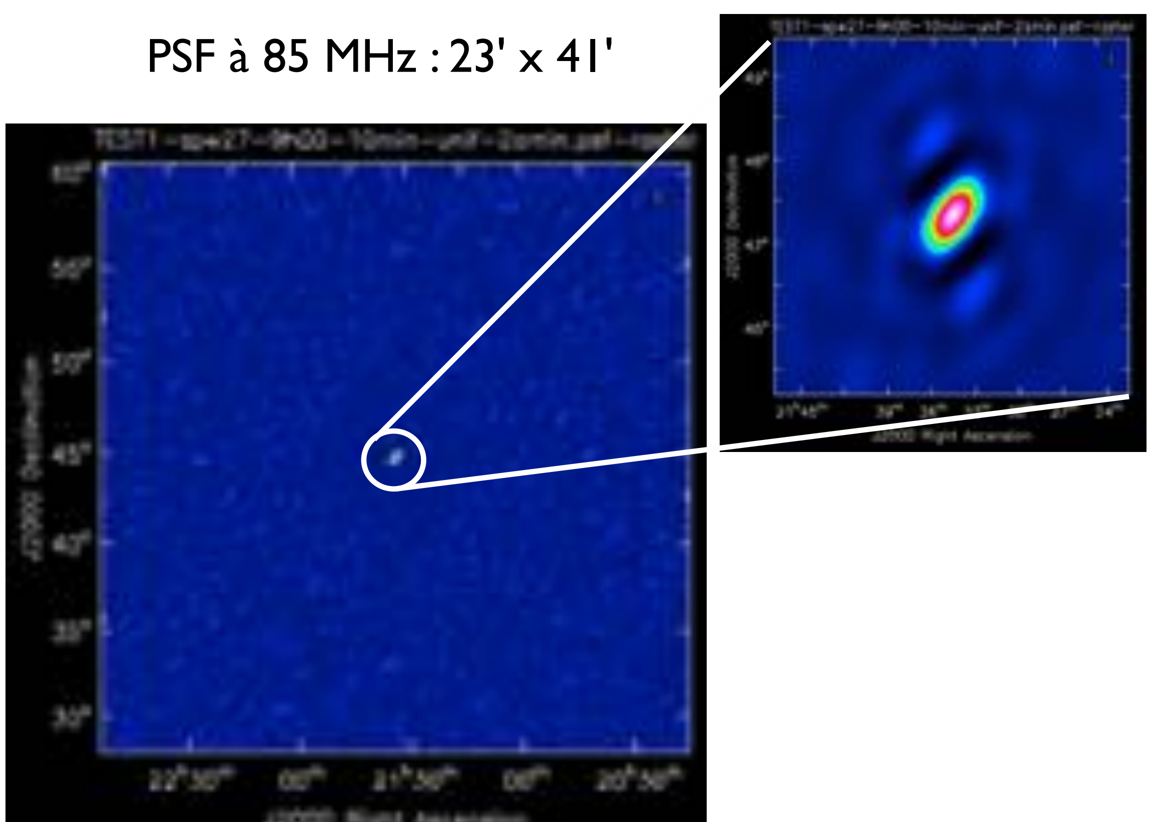
Couvertures instantanée des fréquences spatiales



1ère image *non calibrée*



PSF à 85 MHz : 23' x 41'



Étalonnage en cours ...

En bref ...

- Coût total non consolidé : ~5.9 M€ M€ *(80% acquis)*
- Petite équipe de commissioning *(~3.5 ETP)*
- SKA(-Low) pathfinder (2014)
- NenuFAR ∈ SO3 LOFAR → IR MESRI
- Projet d'art: "Le Dôme"

- Key Scientific Projects → formation à partir de l'automne 2018
- Early science (Beamformer autonome + LSS) → à partir de l'automne 2018
- Atelier NenuFAR : "Data & Early Science" → ≤ fin 2018
- Inauguration printemps 2019 (NRI 2020)