Beamforming with LOFAR

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ASTRON

8th LOFAR Data School 2026

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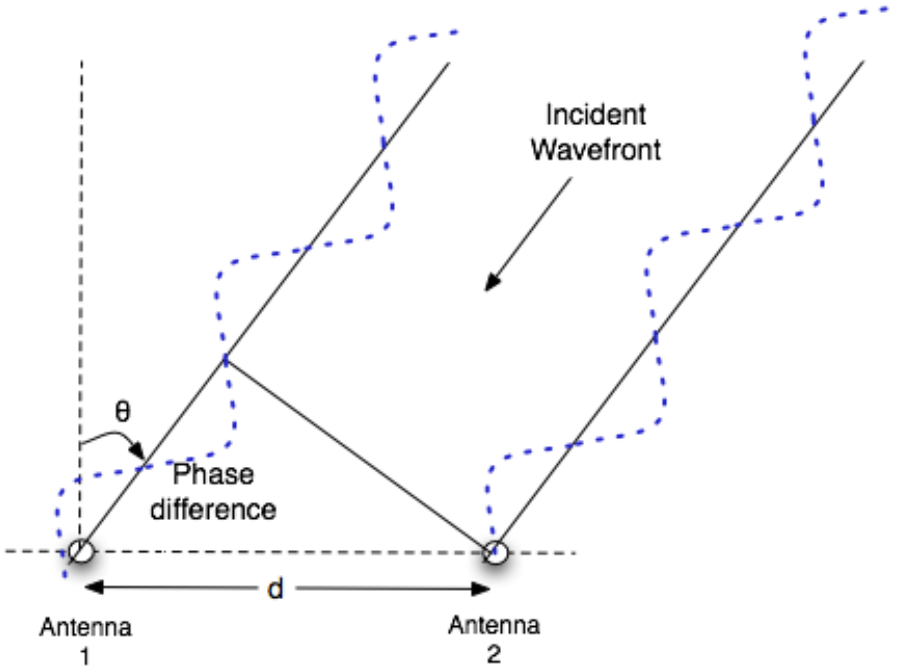
Beamforming in a nutshell

Q: What is beamforming?
A: Adding signals from different antennas in phase
(Note that correlation is a multiplication)

Q: Why beamform?
A: Increase sensitivity of your telescope

Also referred to as:

- coherent sum
- coherent addition
- phased array
- tied array



source: wikipedia

Using LOFAR as a single dish telescope

Interferometry

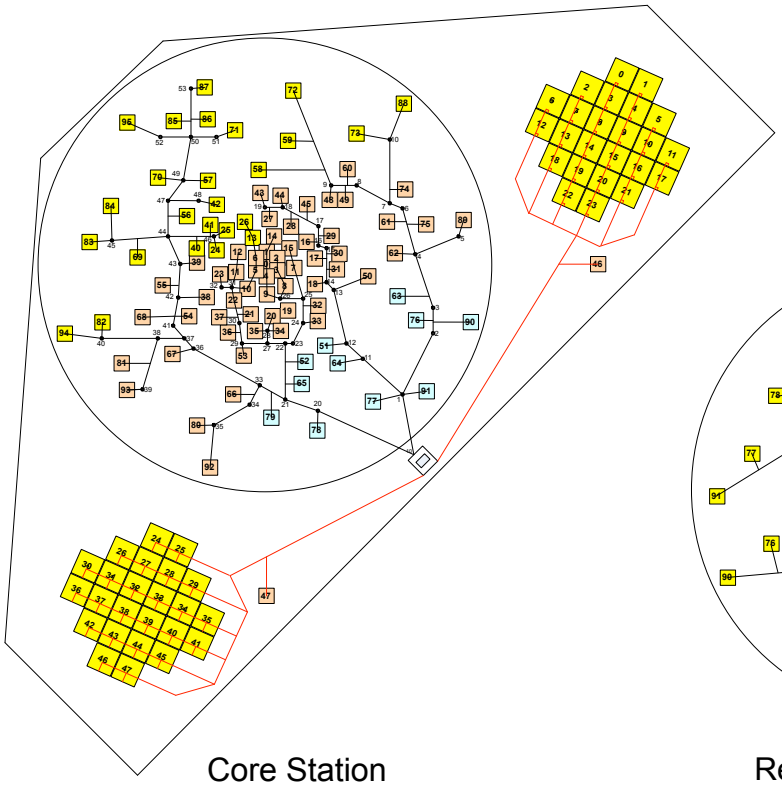
- correlates antenna signals
- high spatial resolution
- low time resolution

Beamforming

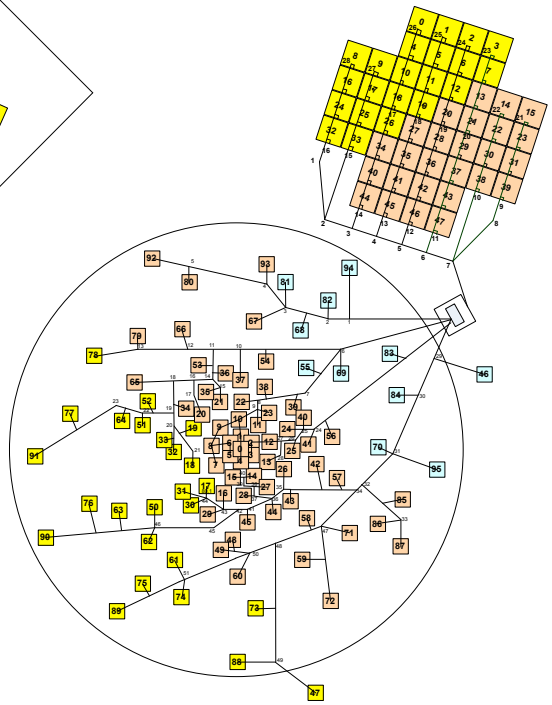
- adds antenna signals
- low spatial resolution
- high time resolution

- Beamforming trades spatial resolution for time resolution
- Much easier than interferometry; e.g. no phase/amplitude calibration, deconvolution etc. . .

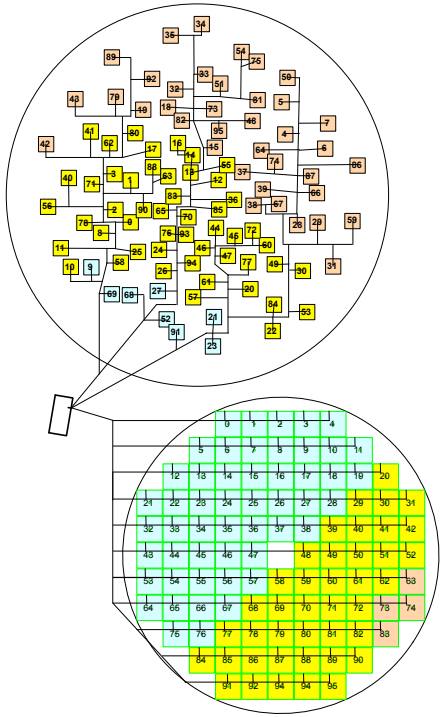
LOFAR stations (a review)



Core Station



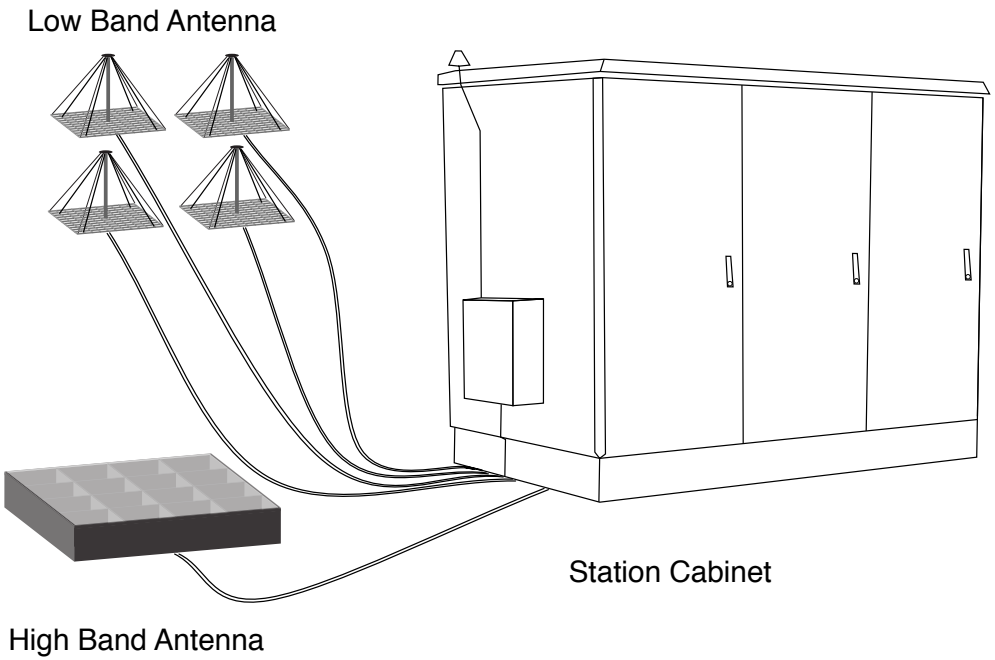
Remote Station

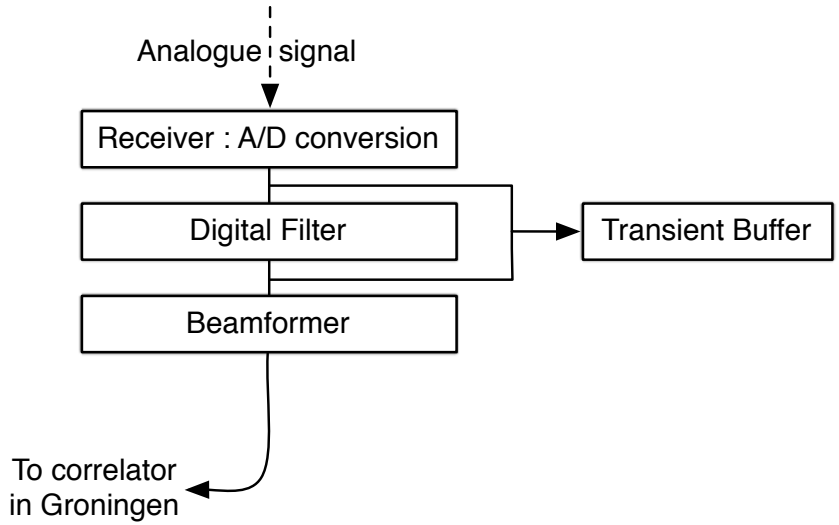


International Station

van Haarlem et al. 2013

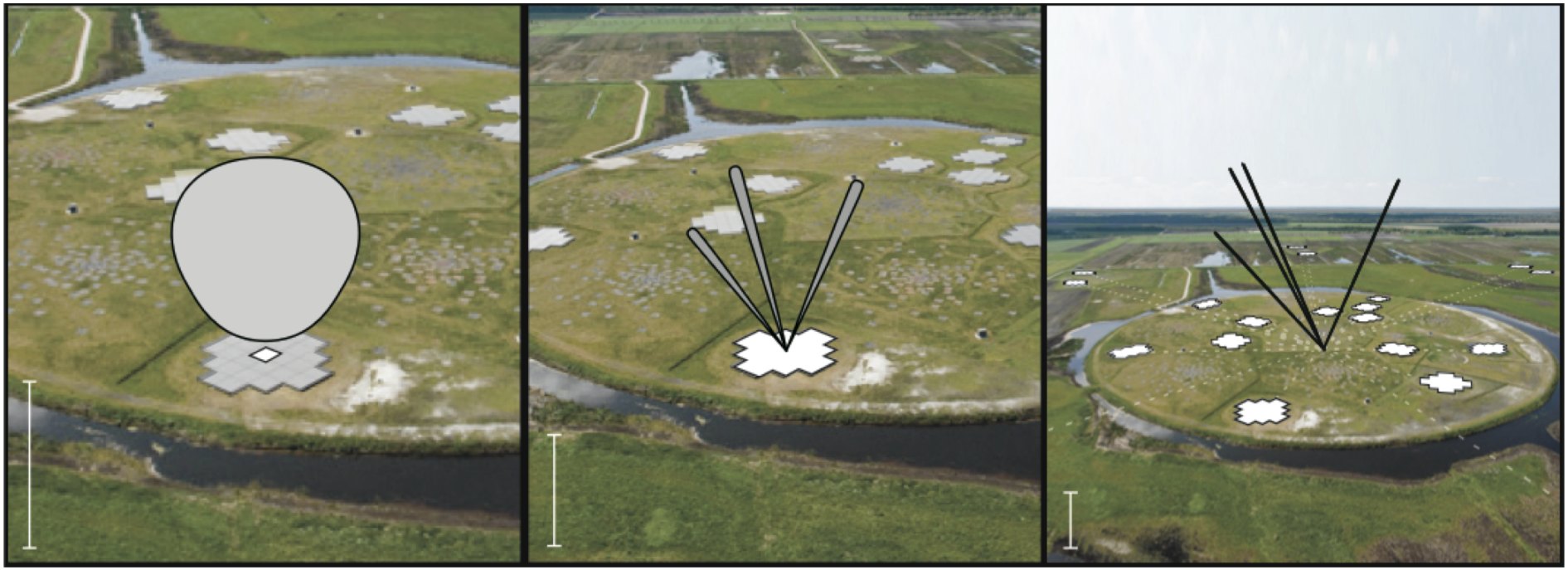
LOFAR stations (a review)





van Haarlem et al. 2013

Beam terminology



source: astron

Element beam
or
Tile beam

Station beam
or
Sub-array pointing (SAP)

Array beam
or
Tied-array beam (TAB)

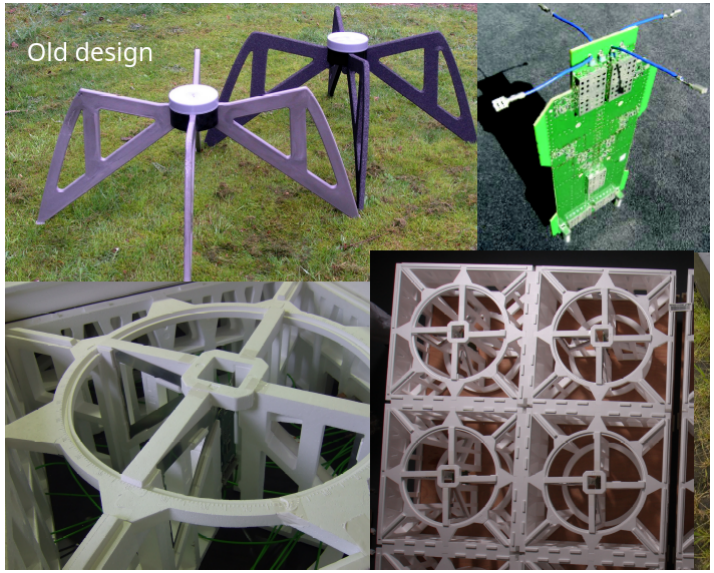
Tile beams



source: max planck

Tile beamforming:

- Analog delay lines
- 5 bit delays of 0.5 ns
- HBA tiles only
- *Summator* combines 4×4 HBA dipoles
- $\lambda/D \sim 25^\circ$ for $\lambda = 2.2\,\mathrm{m}$, $D = 5\,\mathrm{m}$
- Updated once every few minutes



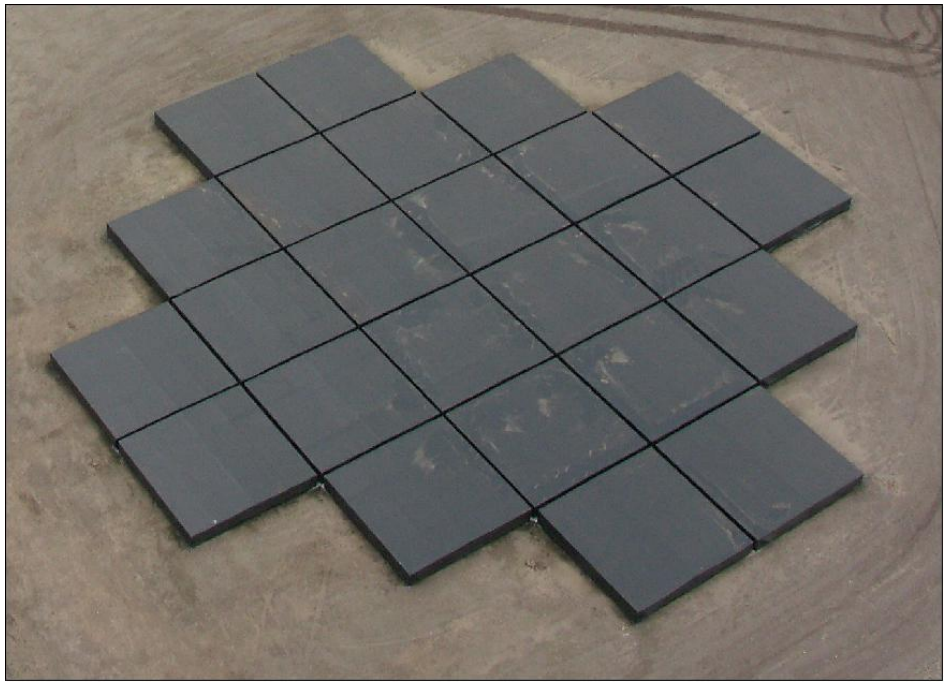
$$\Delta t = (1b_1 + 2b_2 + 4b_3 + 8b_4 + 16b_5) \times 0.5\,\mathrm{ns}$$

e.g. $11111 \rightarrow 15.5\,\mathrm{ns} = 4.65\,\mathrm{m}$, or $10110 \rightarrow 6.5\,\mathrm{ns} = 1.95\,\mathrm{m}$

Station beams (aka sub-array pointings)

Station beamforming:

- Digital signals from 48 HBA tiles or 48 LBA dipoles (96 dipoles for LOFAR2)
- Polyphase filter over 80 MHz (LOFAR1 only) or 100 MHz of bandwidth to 512 subbands
- 16 (LOFAR1 only) or 8 bit digital representation
- 244 (LOFAR1 only) or 488 beam/subband combinations (aka beamlets)
- Phase-rotation beamformer
- Updates every second



source: astron

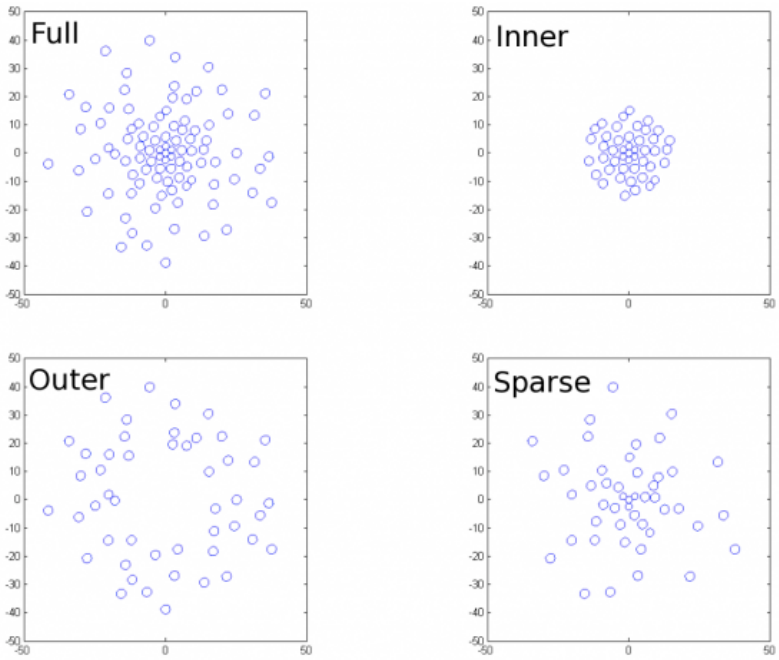
Stations configurations

LBA:

- **ALL:** All 96 dipoles (LOFAR2 only)
- **OUTER:** Outer 48 antennas
- **INNER:** Inner 48 antennas
- **SPARSE:** Sparse config
- **X or Y:** Single polarization from 96 antennas

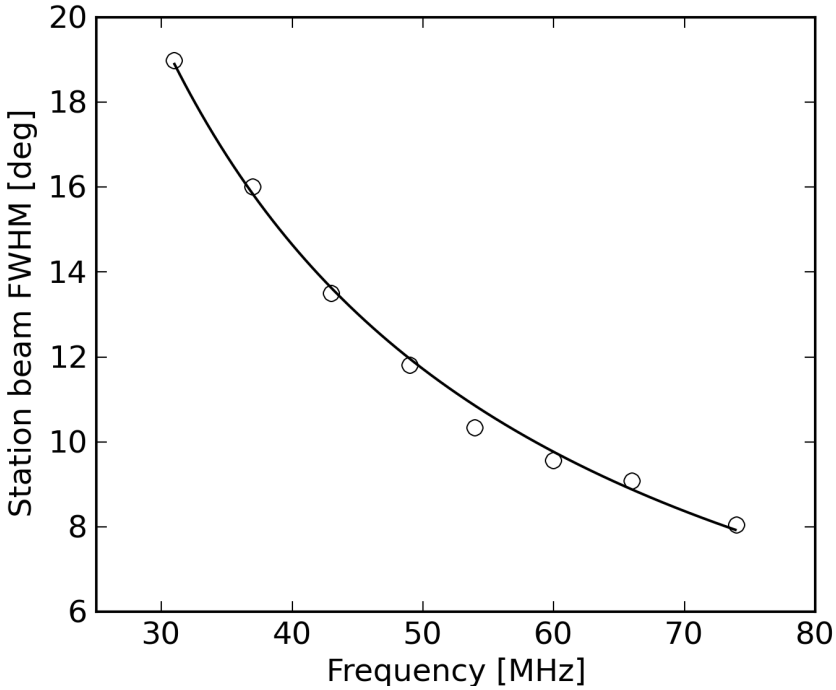
HBA:

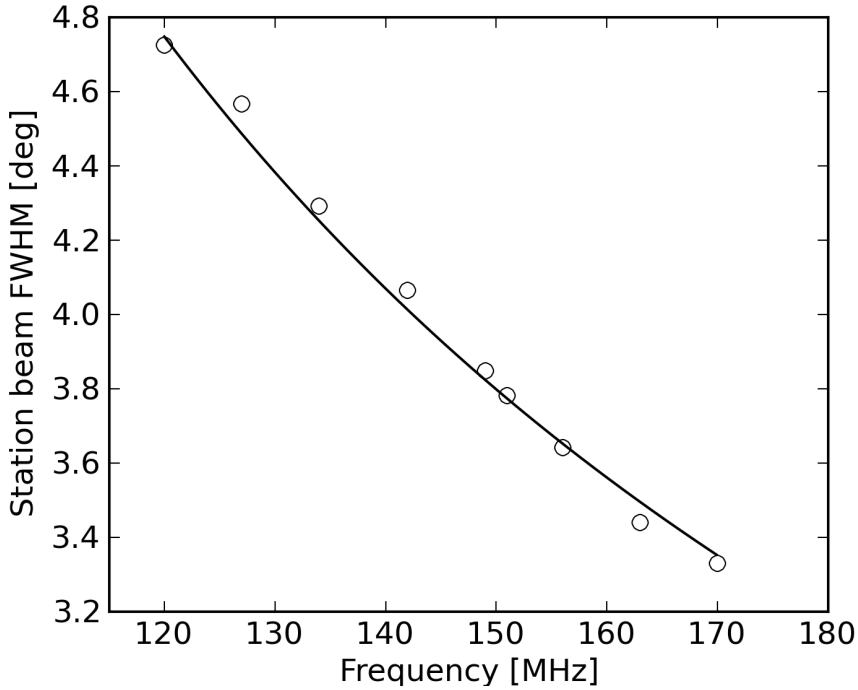
- **DUAL:** Substations separately
- ~~**JOINED:** Substations together~~
- **0 or 1:** Single sub-station (for Core stations)



source: astron

Station beam sizes





source: van Haarlem et al. (2013)

LBA_INNER and a single **HBA** core substation

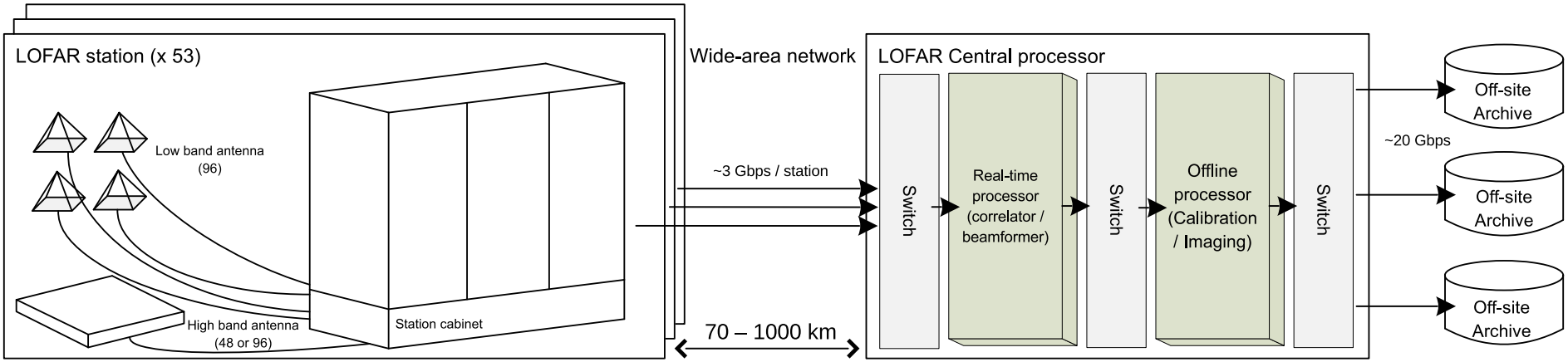
COBALT

COBALT: COrrellator and Beamformer Application for the LOFAR Telescope

- Using CPUs and GPUs
- Replaced Blue Gene in 2014
- Located in Groningen
- Hardware upgrade in 2019 (**COBALT2.0**)
- 11 nodes + 2 spare/testing
- Software upgrade in 2021
- **COBALT3:** Hardware and software upgrade in 2025-2026 (4 nodes with potenatial of future scalability)



COBALT signal path

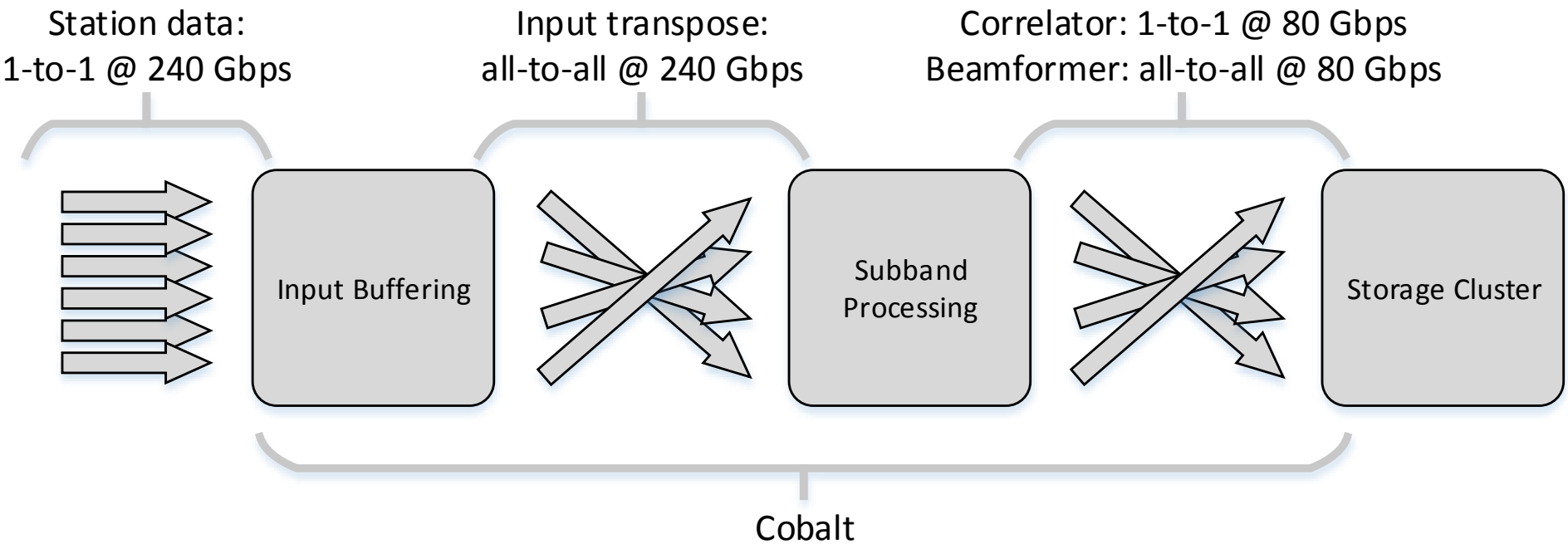


source: Broekema et al. (2018)

- 200 MHz clock, 195.3125 kHz channels, 5.12 μs samples
- ~~160 MHz clock, 156.250 kHz channels, 6.4 μs samples~~ (LOFAR1 only)

Data rate: 488 beamlets × 8 bits × 2 polarizations × 2 values per sample × 195312.5 samples s^{-1} = 3.05Gb s^{-1}.

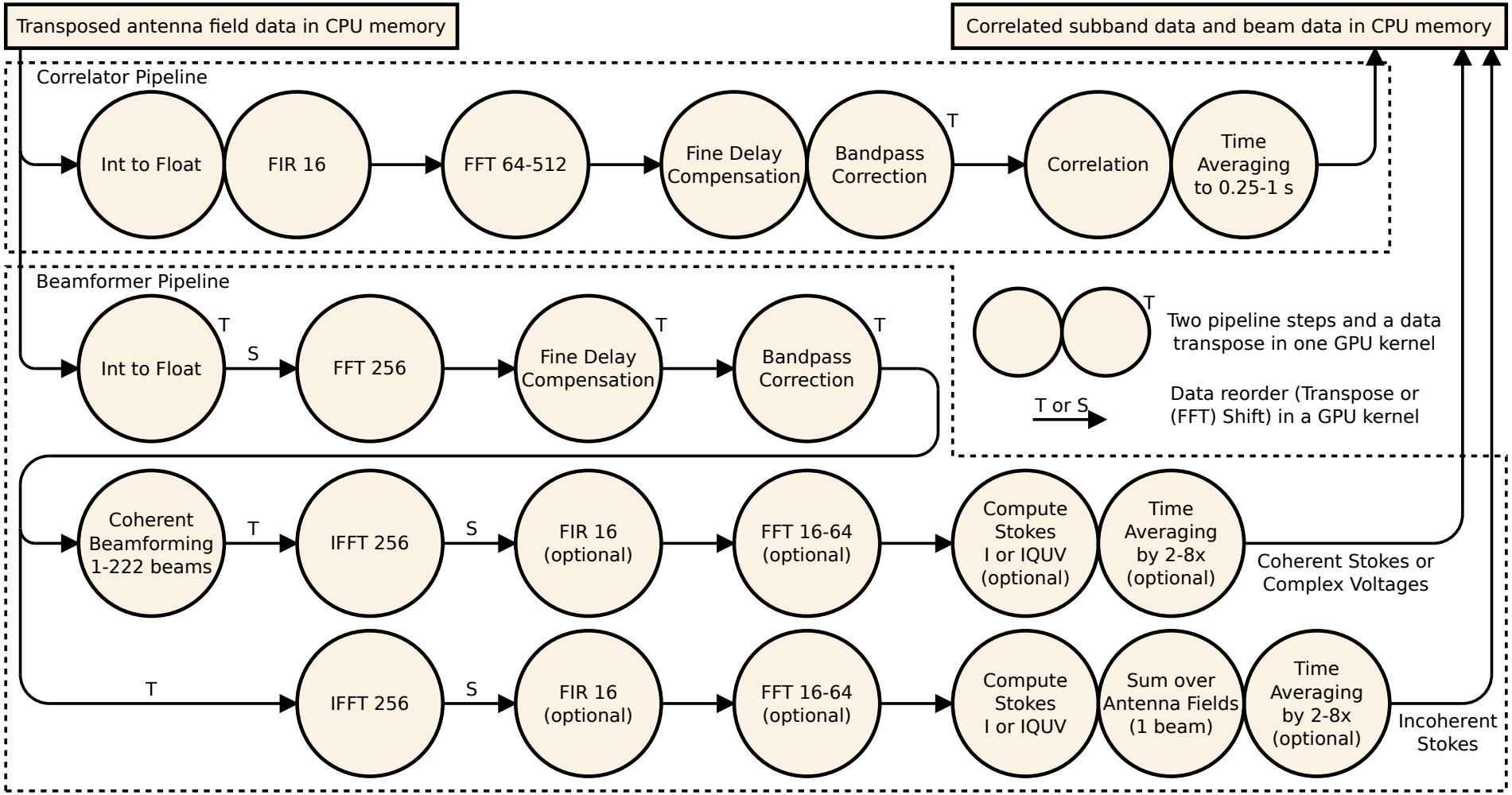
COBALT data flow



source: Broekema et al. (2018)

- **COBALT** designed to handle 80 stations at 3 Gb s^{-1}, 240 Gb s^{-1} total.

COBALT processing



source: Broekema et al. (2018)

COBALT Configuration (pipeline)

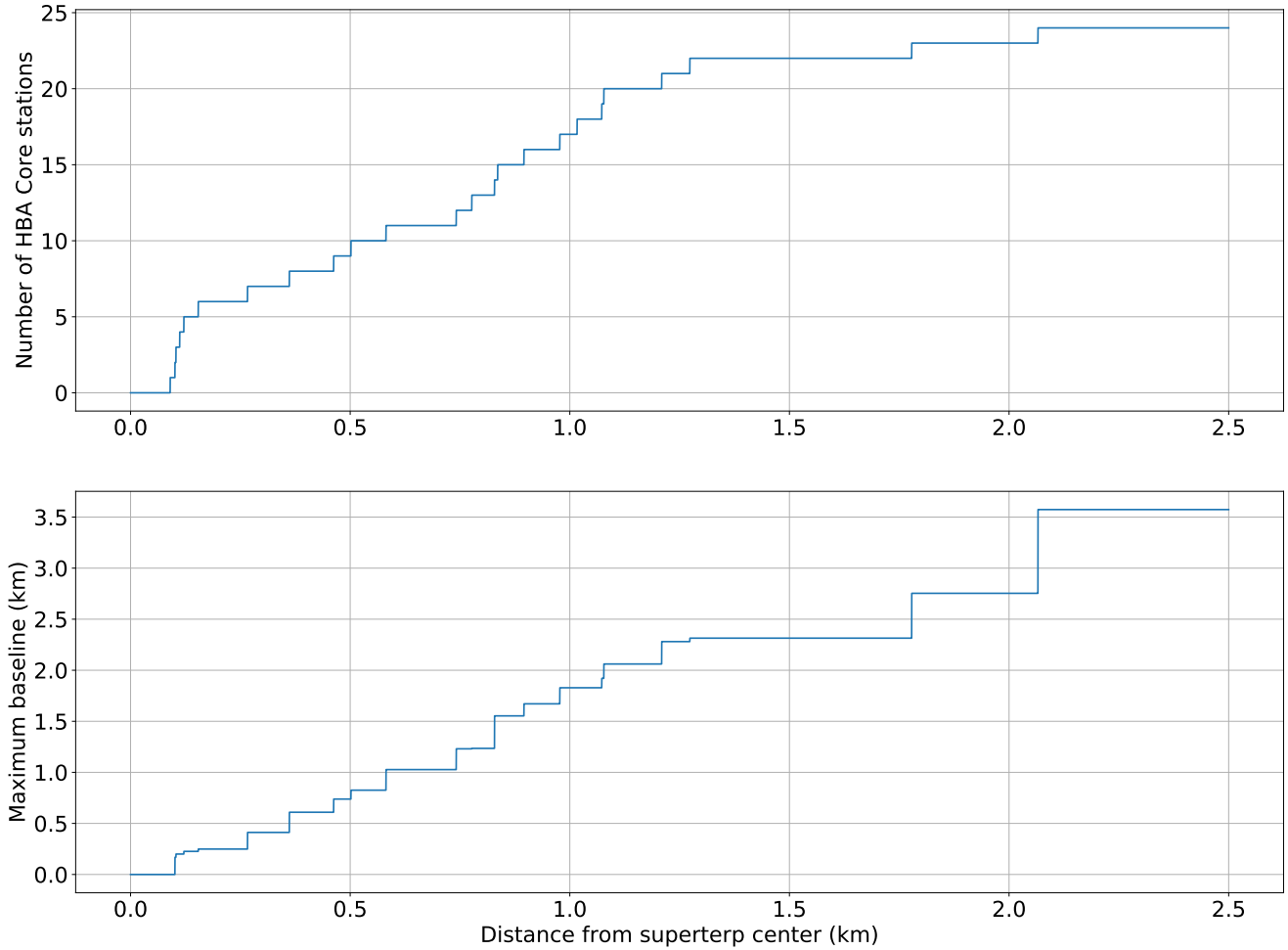
Many configurations to choose from:

- Choice of stations
- Coherent sum or incoherent sum
- Fly's eye (FE; each station independent)
- Observing mode: full Stokes (IQUV), Stokes I (I) or complex voltage (XXYY)
- Number of beams (tied-array rings)
- Sub-band selection
- Channels per subband (1, 16, 32, 64, 128, 512, 1024, 2048)
- Downsampling factor
- Quantization to 8 bit (LOFAR2 only)

LOFAR2:

Multiple configurations (or pipelines) are possible on the same data stream, n_{pipe}

Which stations? Sensitivity vs beamsize



$$S \propto N_{\text{station}} \text{ and } \theta \sim \lambda / D_{\max}$$

Coherent vs incoherent

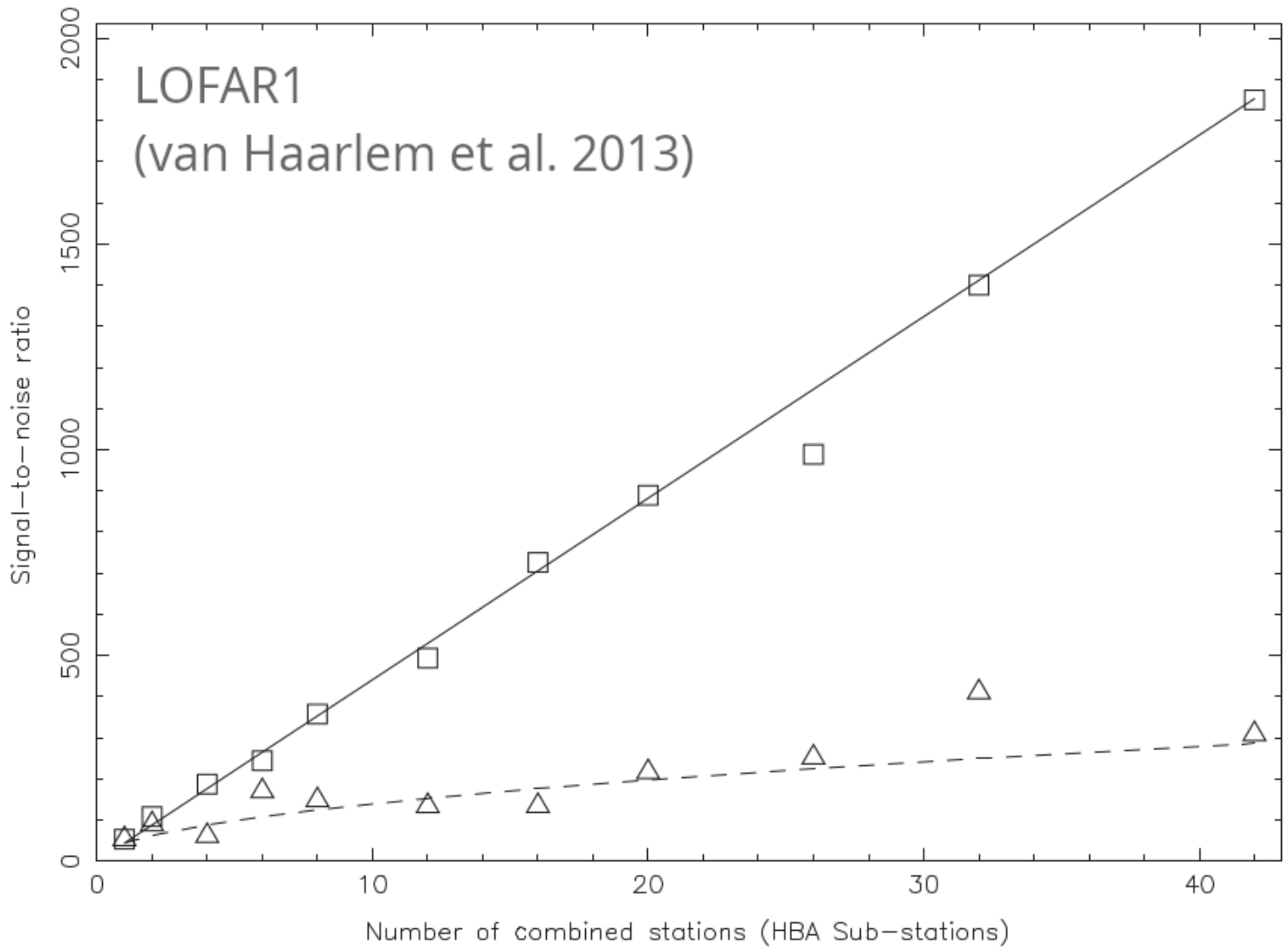
Coherent addition

- Sum *voltages (V)*
- Phase information retained
- $\mathrm{SNR} \propto N_{\mathrm{station}}$
- Tied-array beamsize
- Complex voltage (XXYY) or coherent Stokes (CS) output

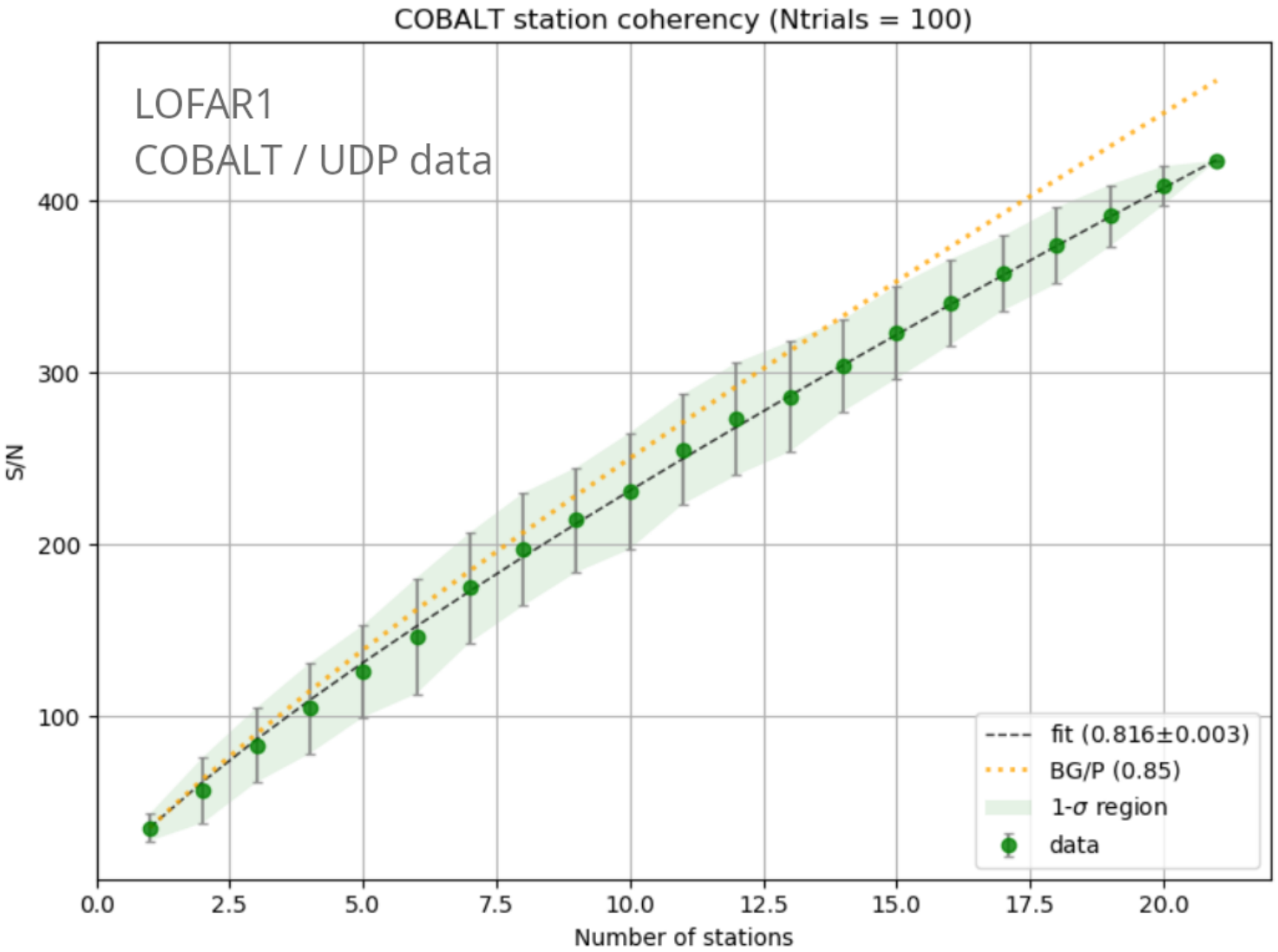
Incoherent addition

- Sum *powers P* ($P \propto V^2$)
- Phase information lost
- $\mathrm{SNR} \propto \sqrt{N_{\mathrm{station}}}$
- Station beamsize
- Incoherent Stokes (IS) output

Coherent vs incoherent



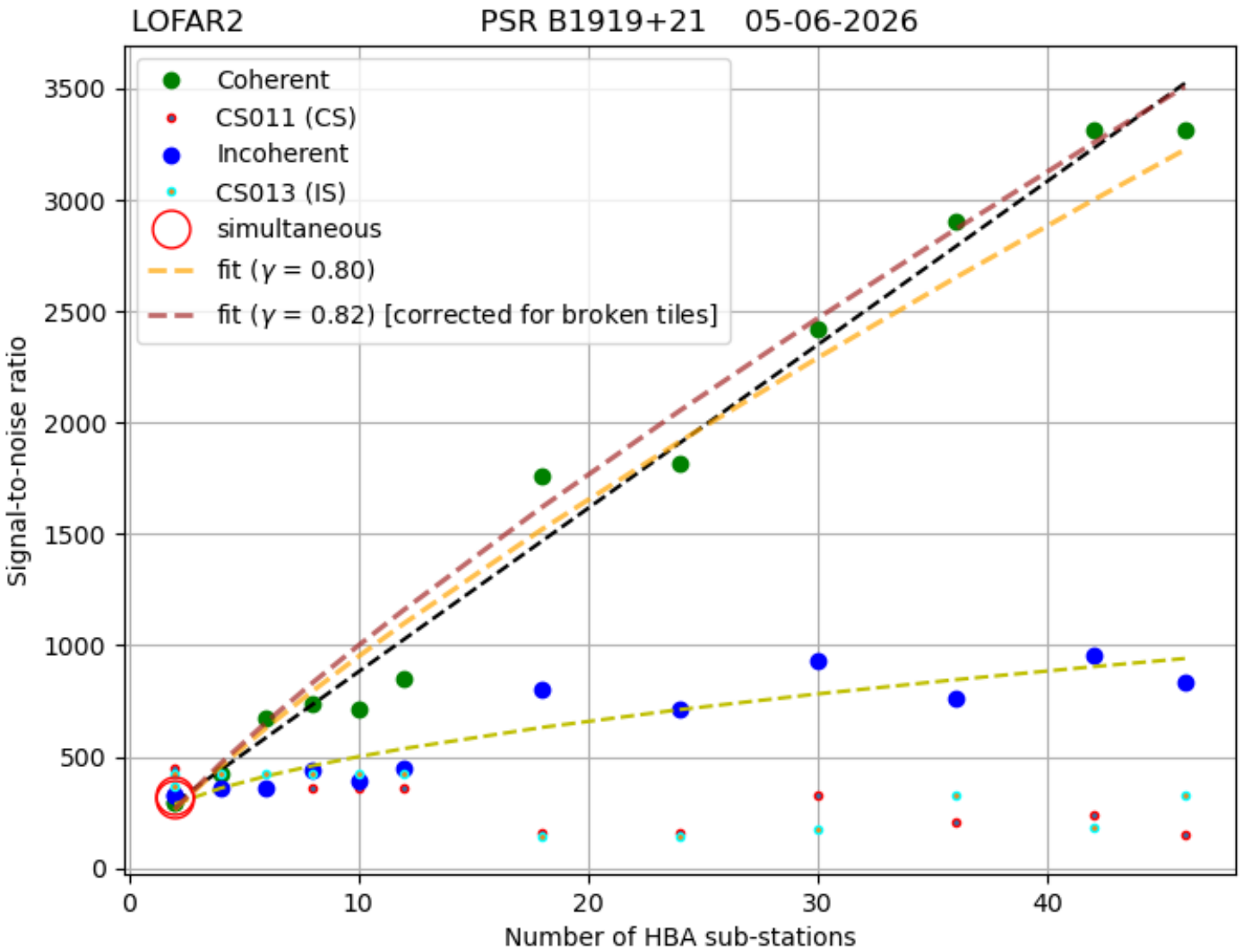
Core coherence (LOFAR1)



$S/N \propto N^{\gamma}$,
$\gamma < 1$

source: Kondratiev et al. (2016)

Core coherence (LOFAR2)



Complex voltages or Stokes parameters

Complex voltages (XXYY)

- Complex number for each polarization: $\vec{e} = e_x + ie_y$
- Two polarizations, so four values per sample
- Sampled at the Nyquist rate (5.12 μs for 200 MHz clock, ~~6.4 μs for 160 MHz clock~~)

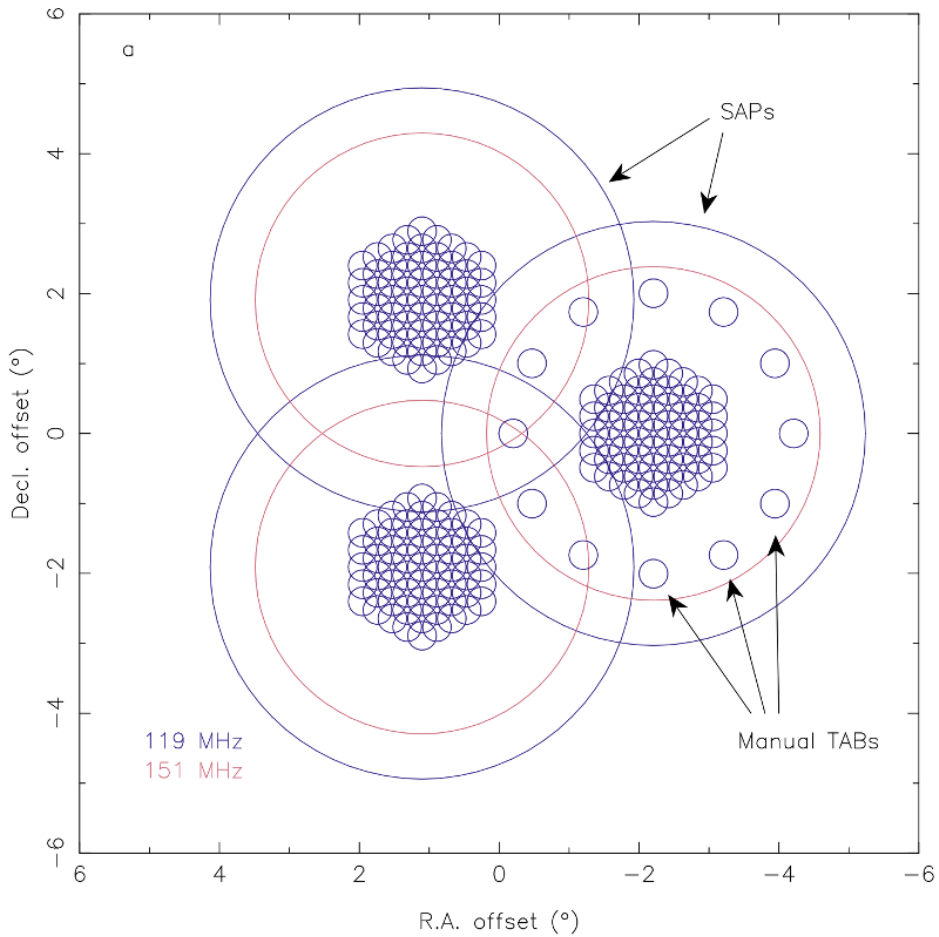
Stokes parameters (CS or IS)

- $I = \left\langle |e_x|^2 \right\rangle + \left\langle |e_y|^2 \right\rangle$
- $Q = \left\langle |e_x|^2 \right\rangle - \left\langle |e_y|^2 \right\rangle$
- $U = 2\mathrm{Re}\left|\left\langle e_y e_x^* \right\rangle\right|$
- $V = 2\mathrm{Im}\left|\left\langle e_y e_x^* \right\rangle\right|$
- Time averaging possible
- Can select *IQUV* or just *I*

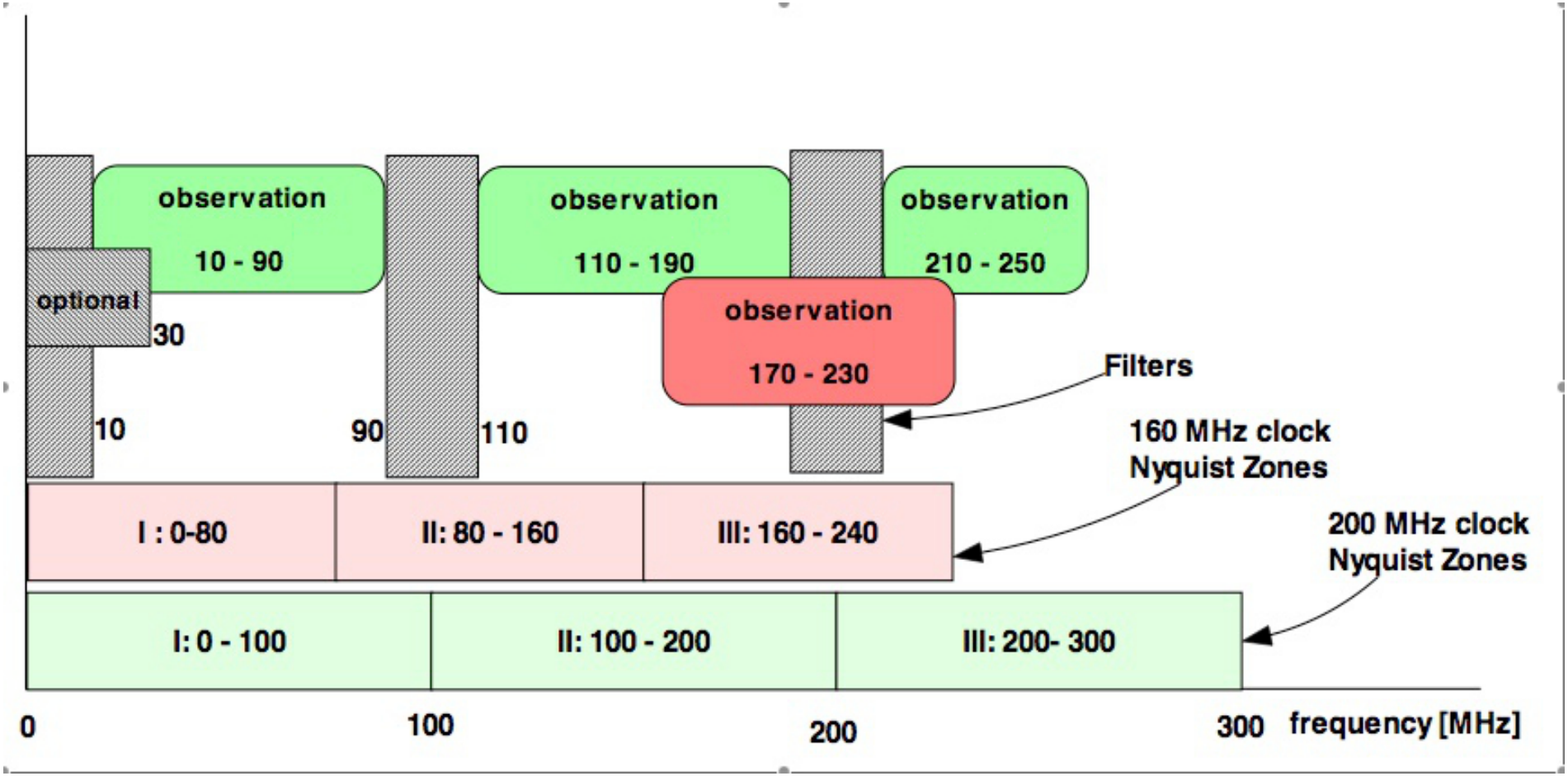
Number of beams?

Configuration options:

- Manual placement *or*
- hexagonal tied-array rings
- rings in α, δ coordinates
- 1, 7, 19, 37, 61, 91...
- Can be defined per sub-array pointing



Sub-band selection



source: astron

Sub-band selection

Configuration options:

- Sampler clock;
  $\nu_{\mathrm{clk}} = 200\,\mathrm{MHz}$ ~~or 160 MHz~~
- Nyquist zone; $n = 1$, 2 or 3
- Subband numbers;
  ~~$s = 0 \ldots 244$ for 16 bit, or~~
  $s = 0 \ldots 488$ for 8 bit

- subband $\rightarrow$ frequency:
  $\nu = (n - 1 + \frac{s}{512})\frac{\nu_{\mathrm{clk}}}{2}$
- frequency $\rightarrow$ subband:
  $s = \lfloor \frac{1024}{\nu_{\mathrm{clk}}}(\nu - \frac{(n-1)\nu_{\mathrm{clk}}}{2}) \rfloor$

Estimating data rates

$$r = n_{\text{beam}} \times n_{\text{sub}} \times n_{\text{chan}} \times n_{\text{value}} \times n_{\text{bit}} / (n_{\text{chan}} \times n_{\text{downsamp}} \times t_{\text{samp}})$$

- n_{beam}: beams
- n_{sub}: subbands
- n_{chan}: channels per subband
- n_{value}: values per sample
- n_{bit}: bits (32 by default, for LOFAR2 8 bit is possible)
- n_{downsamp}: downsampling factor
- t_{samp}: sampling time (5.12 µs ~~or 6.4 µs~~)

	t_{samp} (µs)	n_{beam}	n_{sub}	n_{chan}	n_{value}	n_{bit} (bit)	n_{downsamp}	r (Gbit s^{-1})
LOTAAS	5.12	222	162	16	1	32	6	37.5
MSP	5.12	7	200	1	4	32	1	35.0
Timing	5.12	1	400	1	4	32	1	10.0

Data rates here are for the **single** beamformer pipeline only.
If multiple, data rates from each must be summed together to get the total

COBALT limits

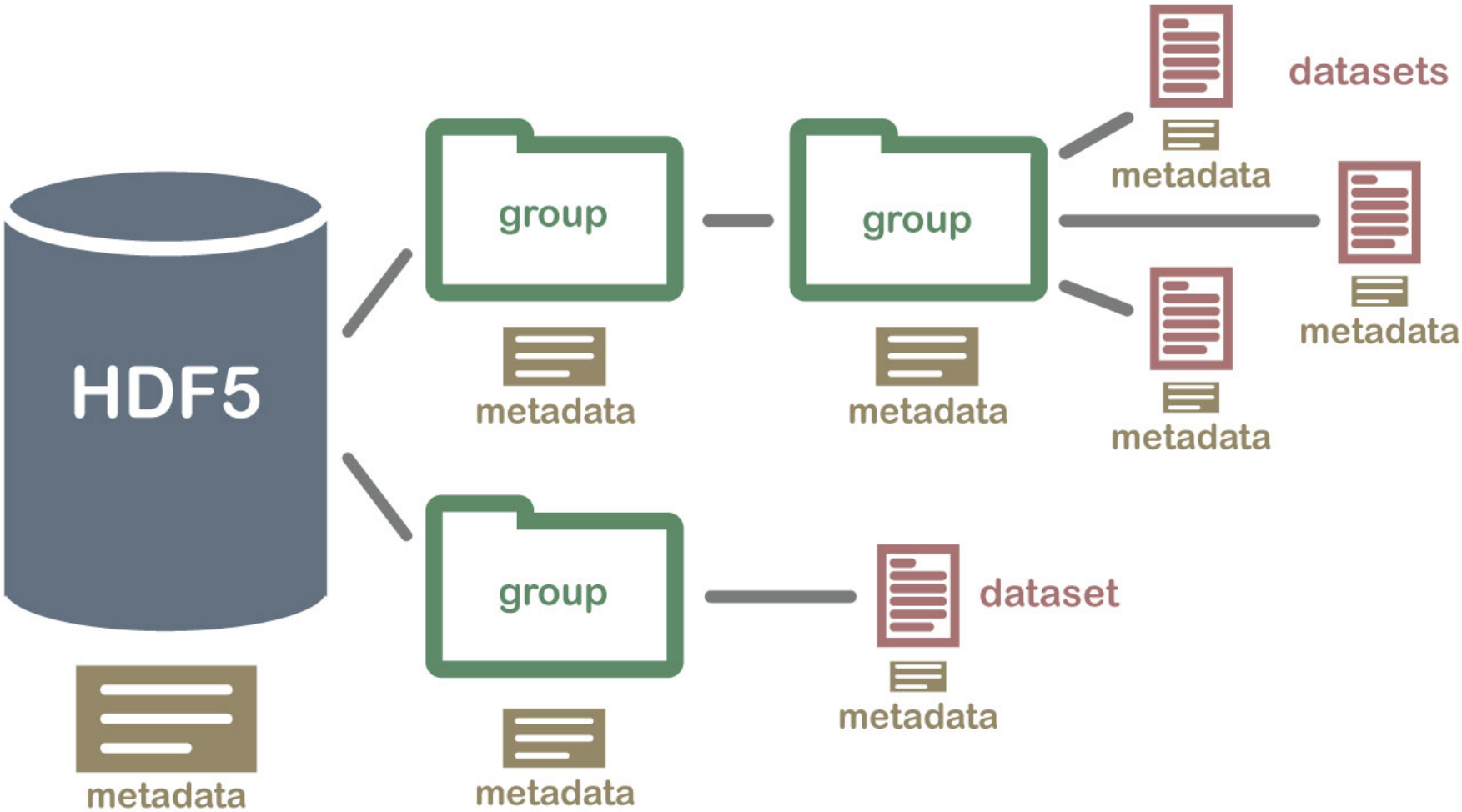
Limits:

- $r > 100\,\mathrm{Gbit\,s^{-1}}$
- Higher throughput if processing is parallel
- Combination of n_{pipe}, n_{station}, n_{sub}, n_{beam}, n_{chan}, n_{downsamp} can be fine tuned
- Contact SDCO for questions
- Offline and online tests can be performed
- Improved capabilities with COBALT 3.0 software (e.g. multicast data reception, TensorCore functionality)

```
ApplCtrl.application=CorrAppl
ApplCtrl.processes=[CorrProc]
ApplCtrl.resultfile=/opt/lofar/var/run/ACC_CCU001:OnlineControl[0]{666002}_CorrAppl_result.param
Cobalt.BeamFormer.CoherentStokes.nrChannelsPerSubband=16
Cobalt.BeamFormer.CoherentStokes.subbandsPerFile=512
Cobalt.BeamFormer.CoherentStokes.timeIntegrationFactor=6
Cobalt.BeamFormer.CoherentStokes.which=I
Cobalt.BeamFormer.IncoherentStokes.nrChannelsPerSubband=16
Cobalt.BeamFormer.IncoherentStokes.subbandsPerFile=512
Cobalt.BeamFormer.IncoherentStokes.timeIntegrationFactor=6
Cobalt.BeamFormer.IncoherentStokes.which=I
Cobalt.BeamFormer.coherentDedisperseChannels=false
Cobalt.BeamFormer.flysEye=false
Cobalt.BeamFormer.nrDelayCompensationChannels=256
Cobalt.BeamFormer.nrHighResolutionChannels=256
Cobalt.BeamFormer.stationList=[]
Cobalt.Correlator.integrationTime=1.00663
Cobalt.Correlator.nrBlocksPerIntegration=1
Cobalt.Correlator.nrChannelsPerSubband=16
Cobalt.Correlator.nrIntegrationsPerBlock=1
Cobalt.FinalMetaDataGatherer.database.host=sasdb.control.lofar
Cobalt.FinalMetaDataGatherer.database.name=
Cobalt.FinalMetaDataGatherer.database.port=
Cobalt.FinalMetaDataGatherer.database.username=
Cobalt.FinalMetaDataGatherer.enabled=true
Cobalt.Nodes=[ cbt001_0, cbt001_1, cbt002_0, cbt002_1, cbt003_0, cbt003_1, cbt004_0, cbt004_1, cbt005_0,
cbt005_1, cbt006_0, cbt006_1, cbt007_0, cbt007_1, cbt008_0, cbt008_1 ]
Cobalt.OutputProc.StaticMetaDataDirectory=/data/home/lofarsys/production/lofar_cobalt/etc
Cobalt.OutputProc.executable=outputProc
Cobalt.OutputProc.sshPrivateKey=
Cobalt.OutputProc.sshPublicKey=
Cobalt.OutputProc.userName=
Cobalt.PVSSGateway.host=ccu001
Cobalt.blockSize=196608
Cobalt.commandStream=file:/localhome/lofar/lofar_versions/LOFAR-Release-3_2_0/var/run/rtcp-666002.pipe
Cobalt.correctBandPass=true
Cobalt.correctClocks=true
Cobalt.delayCompensation=true
Cobalt.realTime=true
CorrAppl.CorrProc._executable=CN_Processing
CorrAppl.CorrProc._hostname=cbmmaster
CorrAppl.CorrProc._nodes=[]
CorrAppl.CorrProc._startstopType=bgl
CorrAppl.CorrProc.workingdir=/opt/lofar/bin/
CorrAppl._hostname=cbmmaster
CorrAppl.extraInfo=["PIC","Cobalt"]
CorrAppl.procesOrder=[]
CorrAppl.processes=["CorrProc"]
DRAGNET.Nodes=[ drg01, drg02, drg03, drg04, drg05, drg06, drg07, drg08, drg09, drg10, drg11, drg12, drg13,
drg14, drg15, drg16, drg17, drg18, drg19, drg20 ]
Observation.AnaBeam[0].angle1=6.096355752001689
Observation.AnaBeam[0].angle2=0.0
```

Beamformed COBALT output

HDF5: Hierarchical Data Format (version 5)



source: hdf group

COBALT BF filename convention

`L[nnnnnn[n]]_CP[ccc]_SAP[sss]_B[bbb[b]]_S[s]_P[ppp]_bf.{h5, raw}`

- **h5:** HDF5 header ($\sim$ 1 MB); contains header information
- **raw:** Raw data (many GBs); contains raw data
- **[nnnnnn[n]]:** Observation ID (ObsID or SASID), 6 or 7 digits (LOFAR1), or 7+ digits (LOFAR2)
- **[ccc]:** Cobalt Pipeline (CP) number for the beamforming (LOFAR2 only)
- **[sss]:** Sub-array pointing number (SAP)
- **[bbb[b]]:** Tied-array beam number, 3 digits for LOFAR1 and 4 digits for LOFAR2
- **[s]:** Stokes IQUV parameter or complex voltage identifier (real X, imag X, real Y, imag Y)
- **[ppp]:** Frequency part (multiple subbands in one file)

Example: `L2076263_CP000_SAP000_B0000_S3_P000_bf.h5`

Reading HDF5

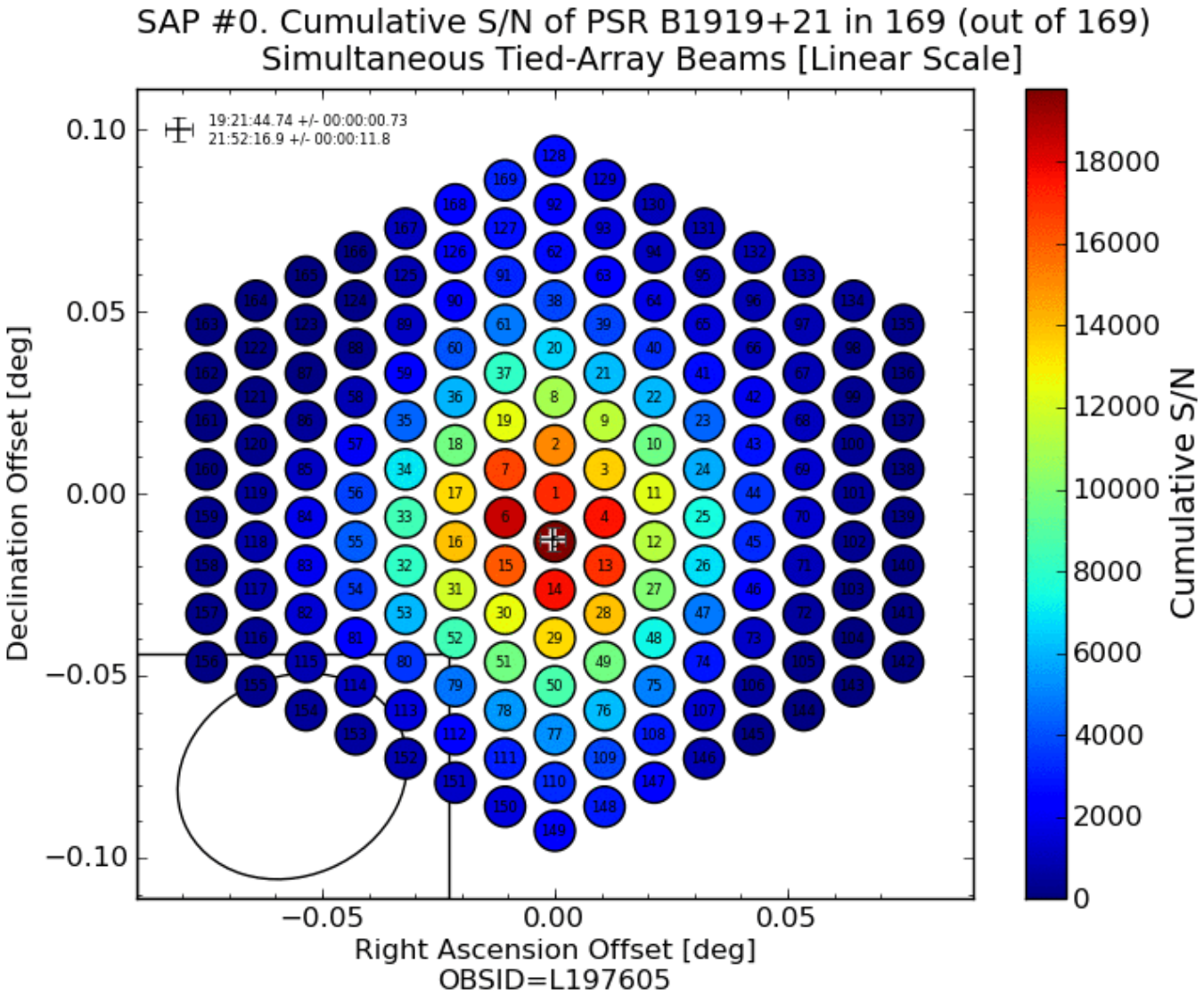
Options:

- `h5dump`, `h5ls` on linux command line to read header
- `h5py` python reader
- `pytables` python reader
- LOFAR DAL2.0 (Data Access Library) C++ library written by ASTRON `https://git.astron.nl/ro/dal2`
- DSPSR pulsar software `https://dspsr.sourceforge.net/`
- Plain old `fopen` on raw files (32 bit float or 8 bit char)

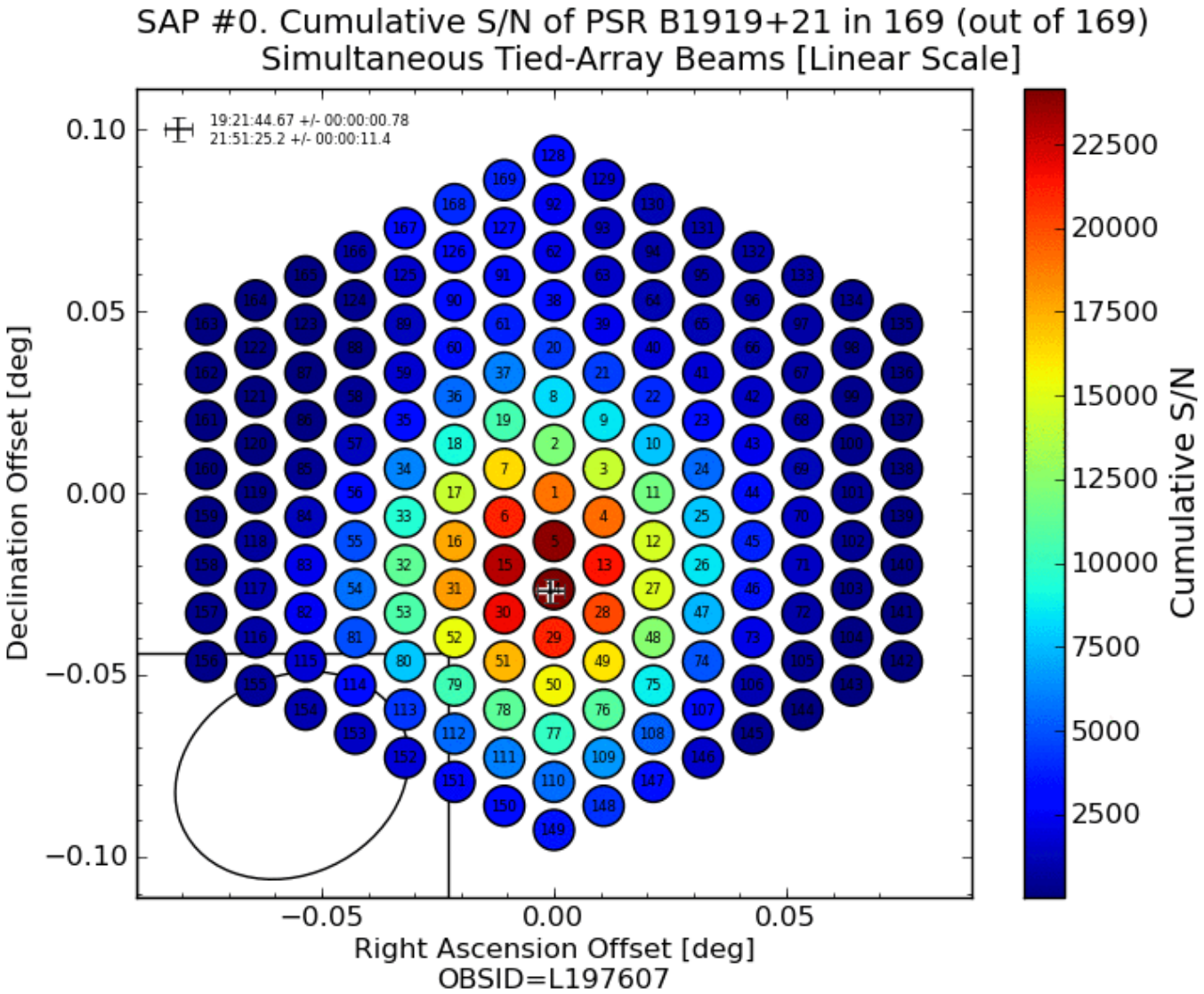


- `lofar_bf_h5info.py` from LOFAR2 Pulsar Folding pipeline – `https://git.astron.nl/RD/pulp2-cwl-folding`

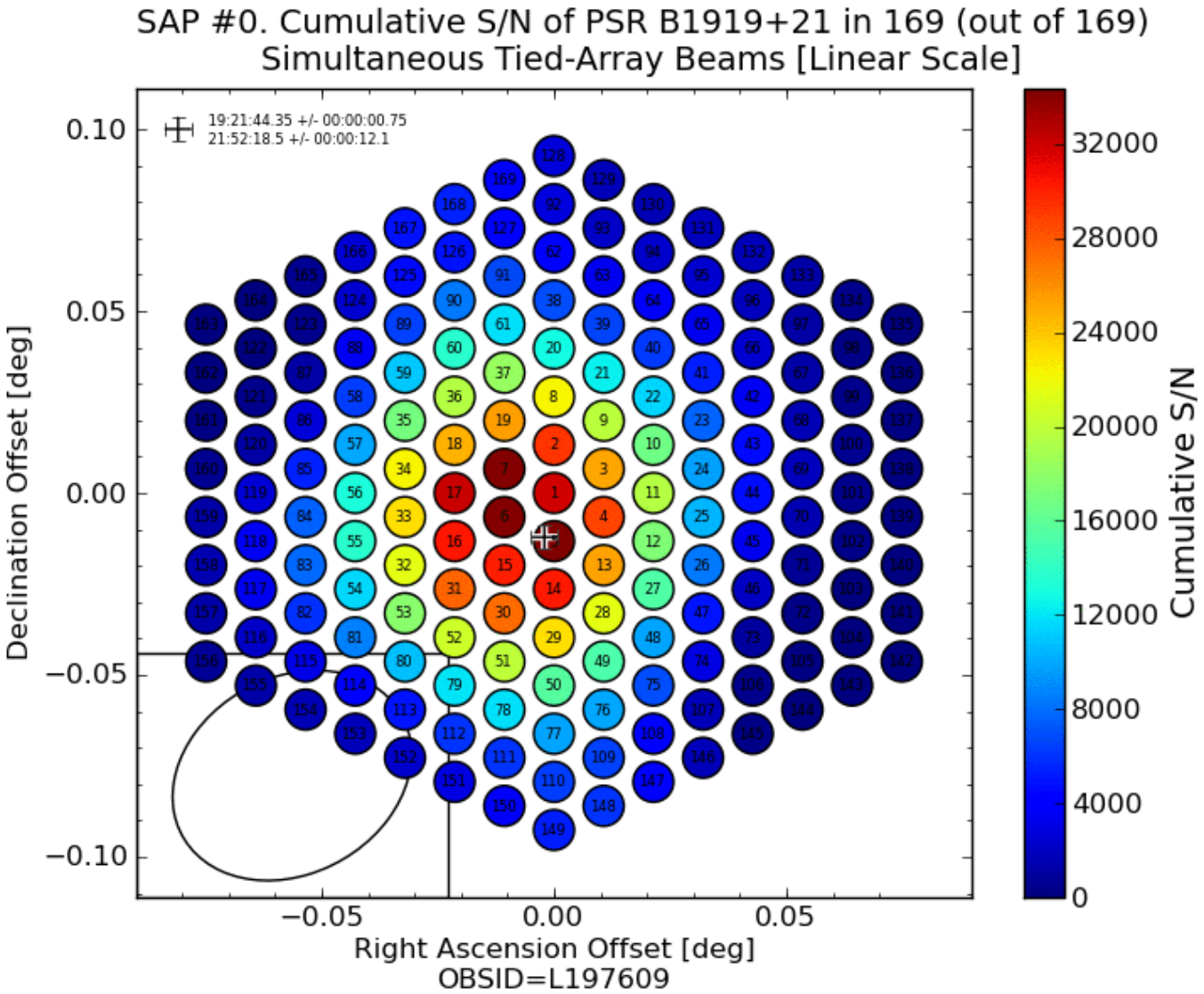
Impact of ionosphere



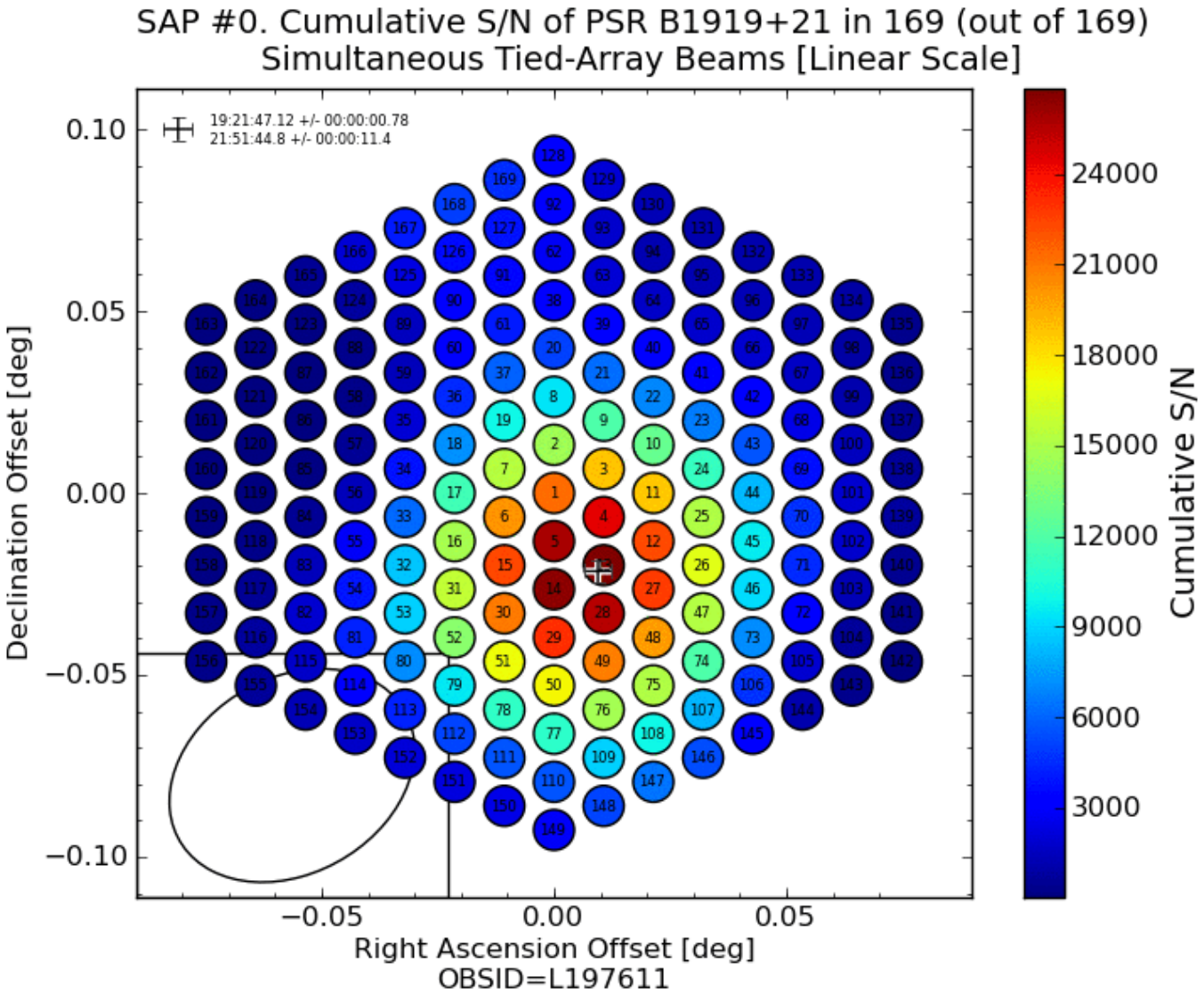
Impact of ionosphere



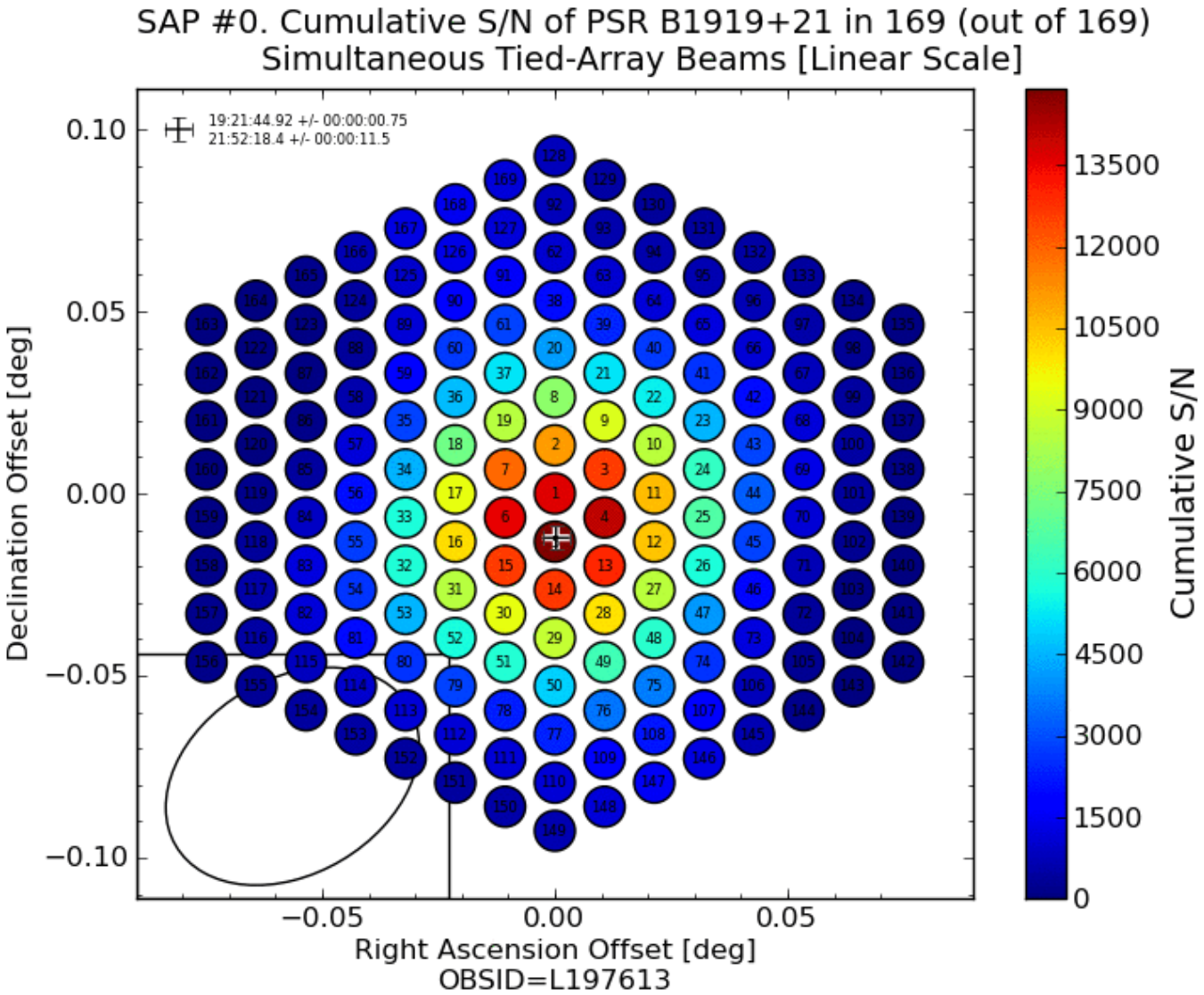
Impact of ionosphere



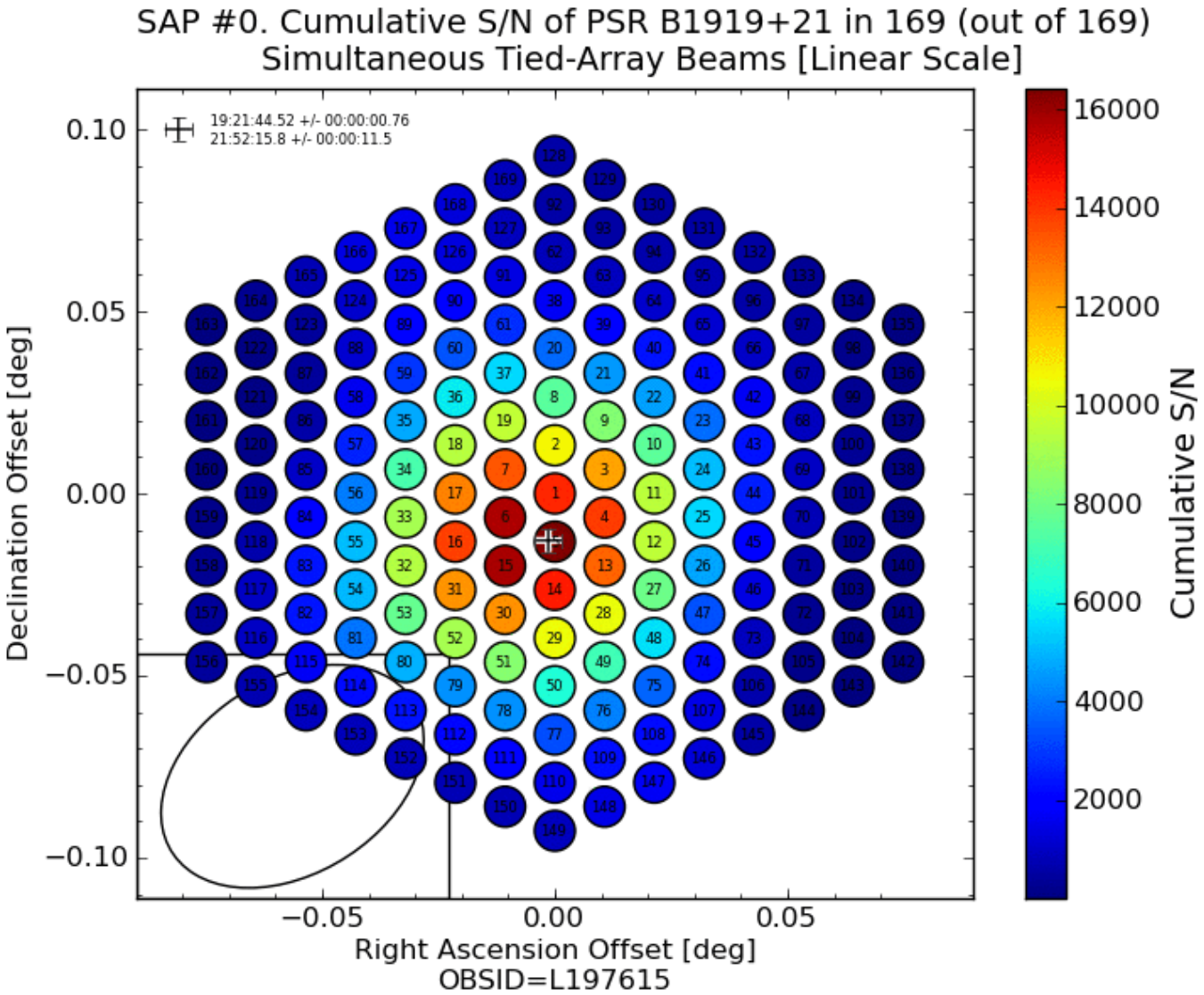
Impact of ionosphere



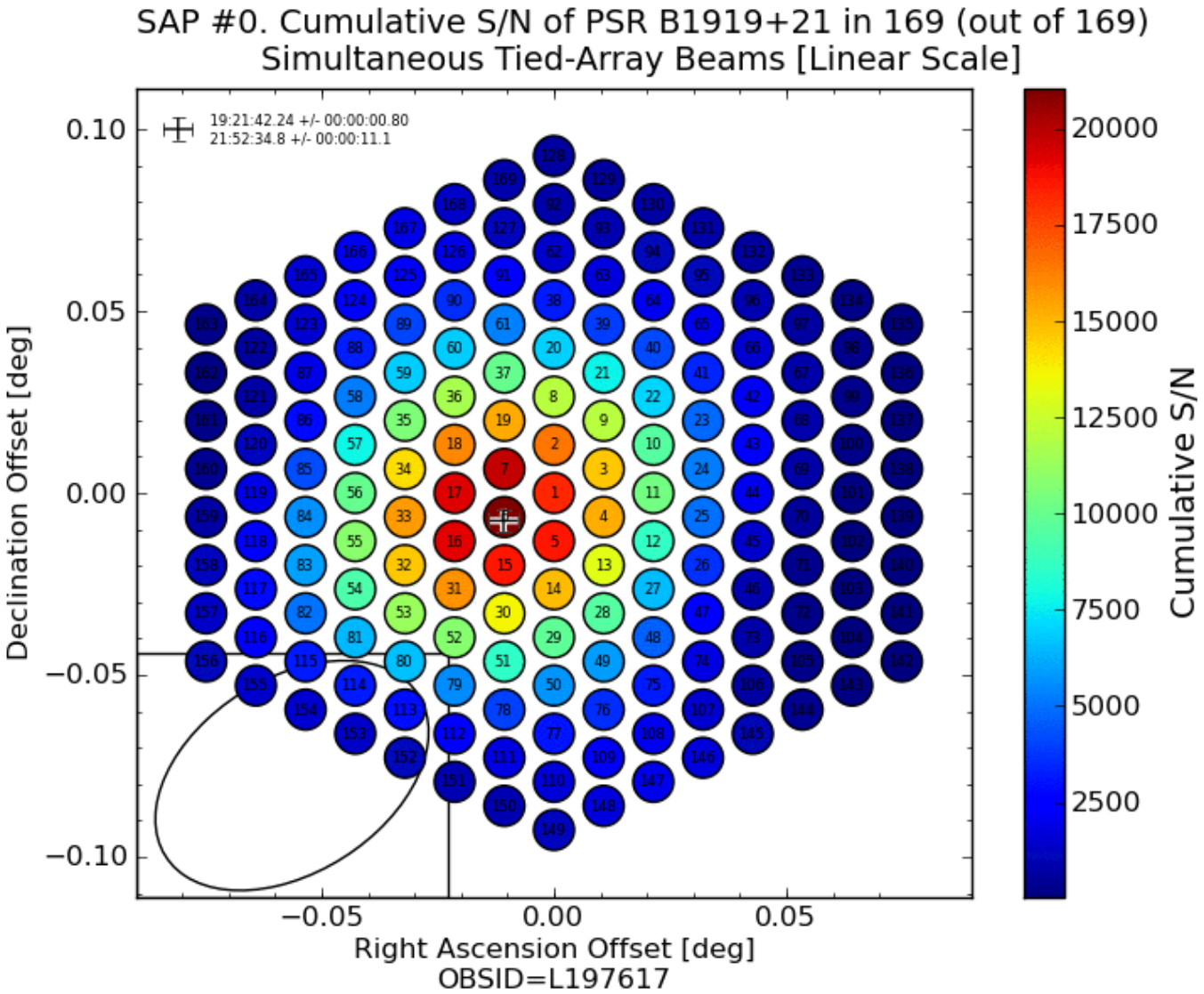
Impact of ionosphere



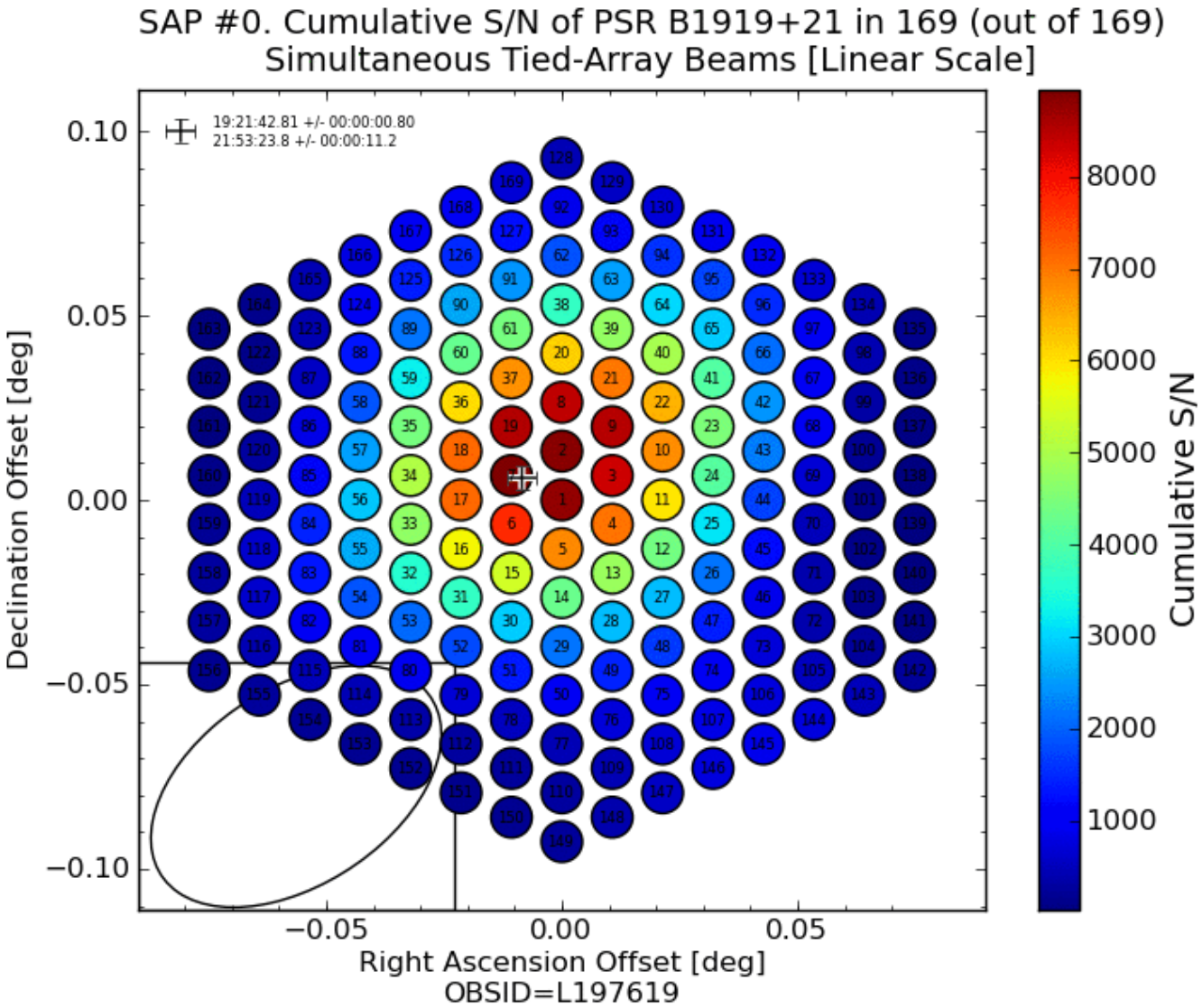
Impact of ionosphere



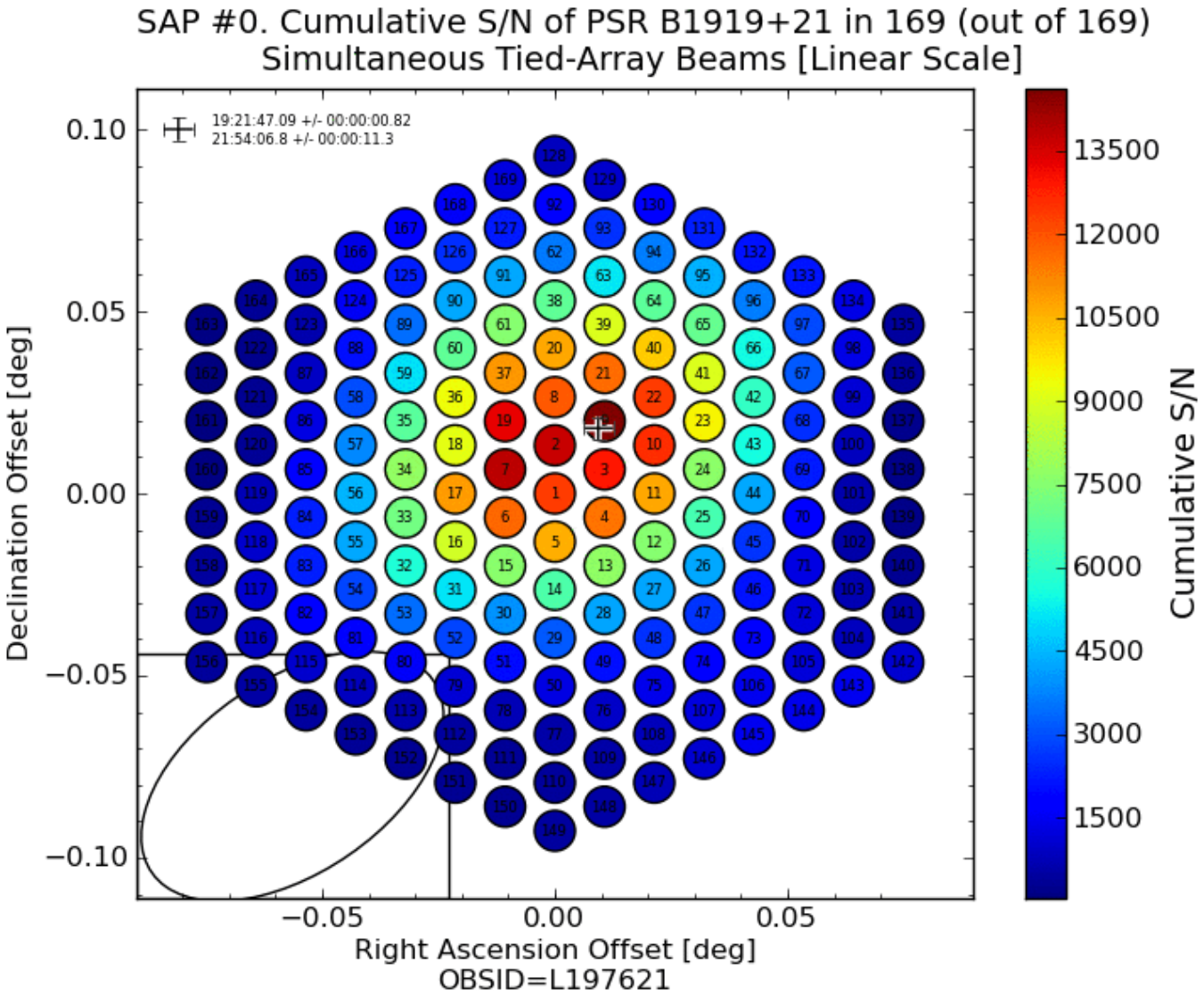
Impact of ionosphere



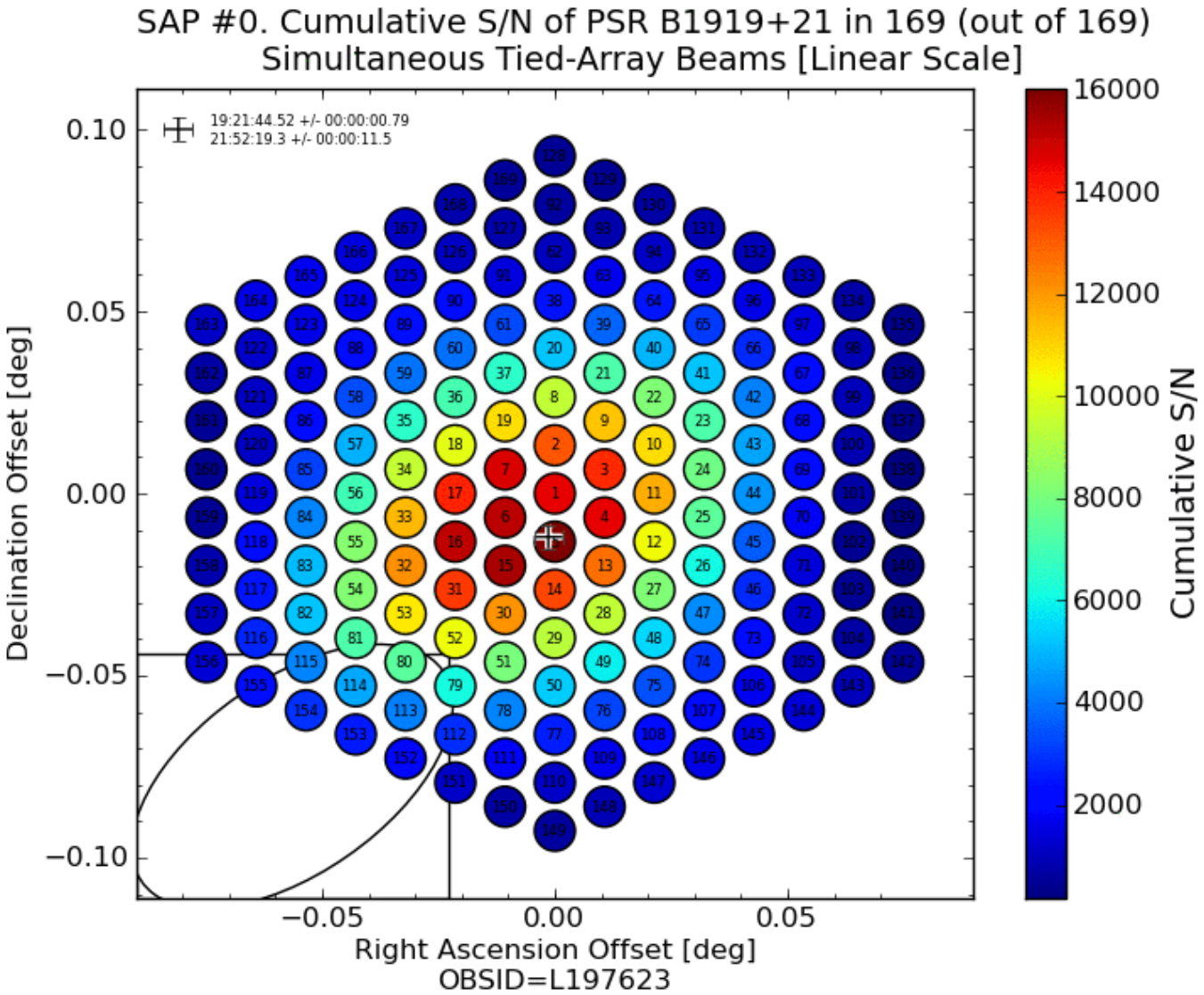
Impact of ionosphere



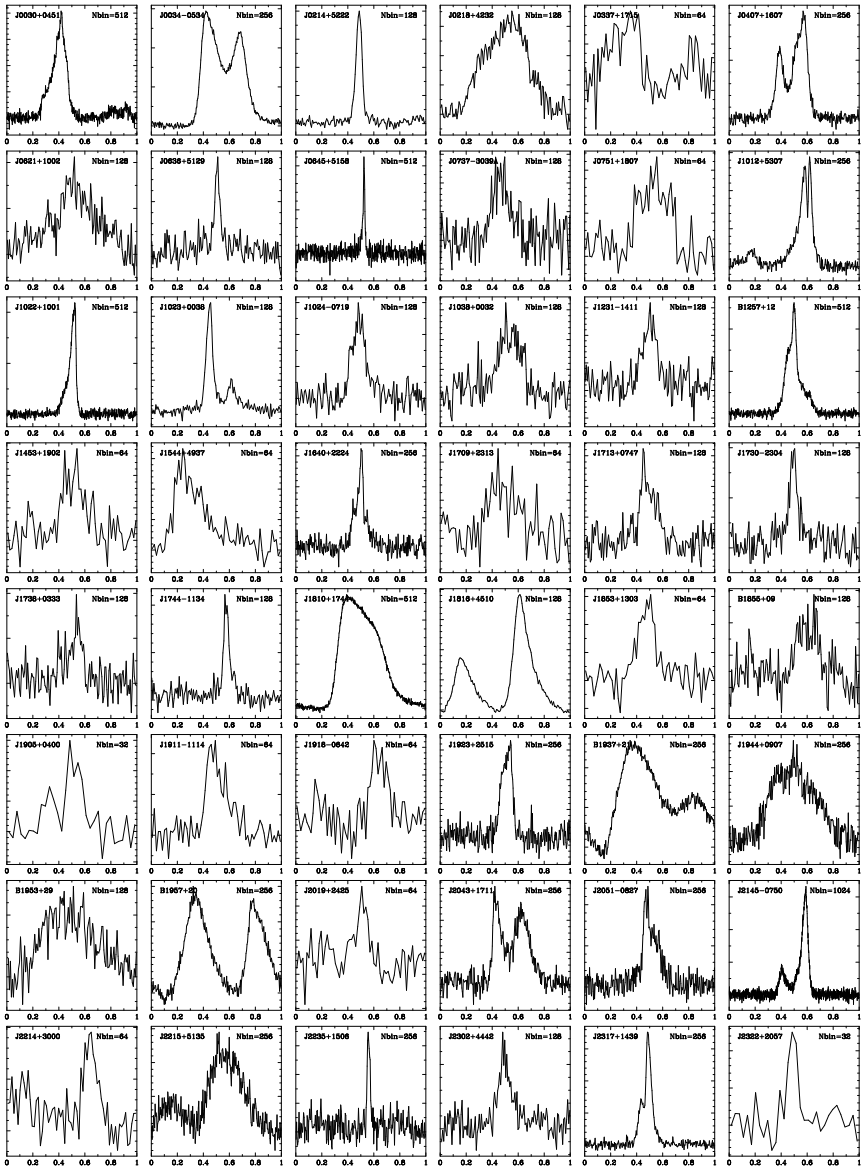
Impact of ionosphere



Impact of ionosphere



Some LOFAR beamforming results (1)

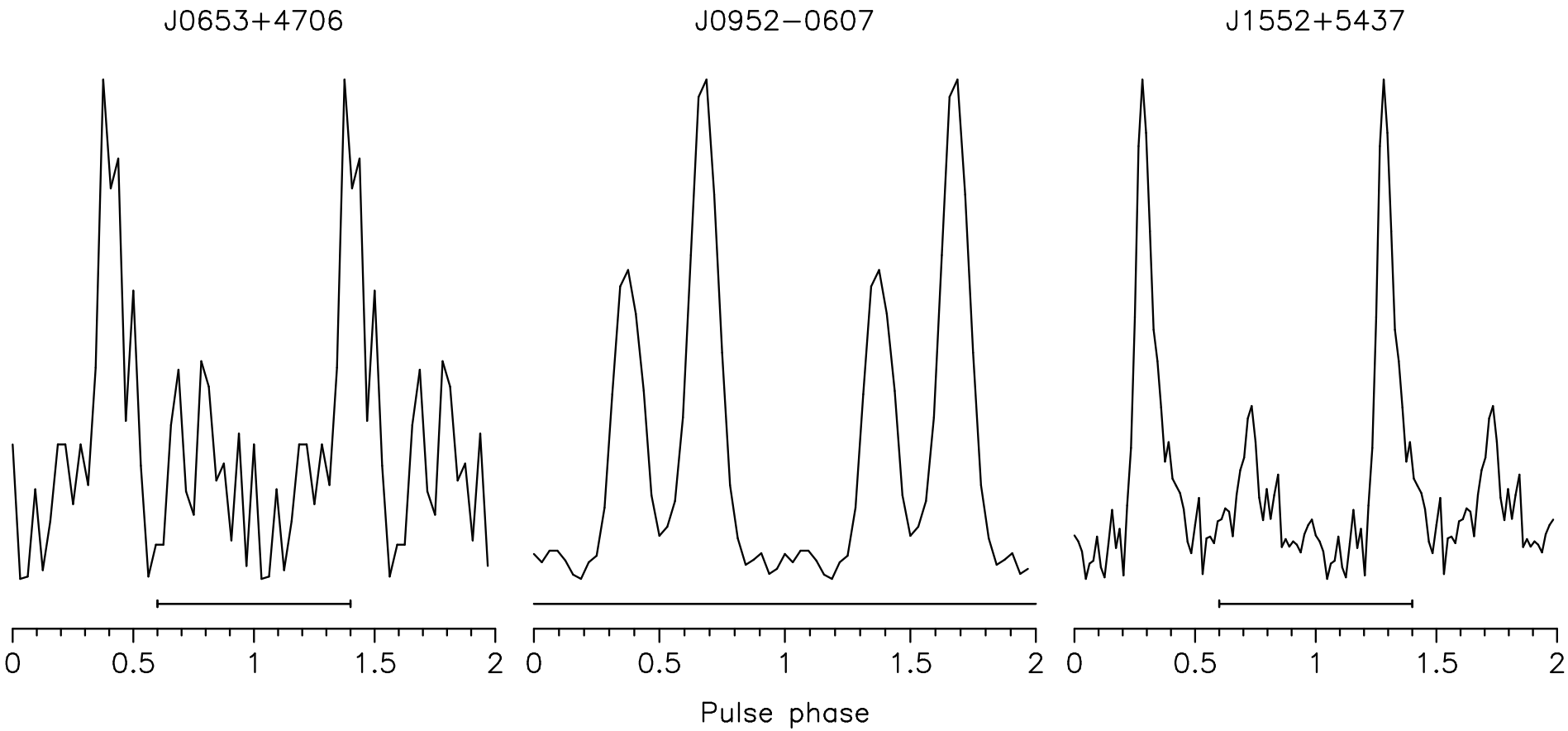


source: Kondratiev et al. (2016)

A LOFAR census of millisecond pulsars

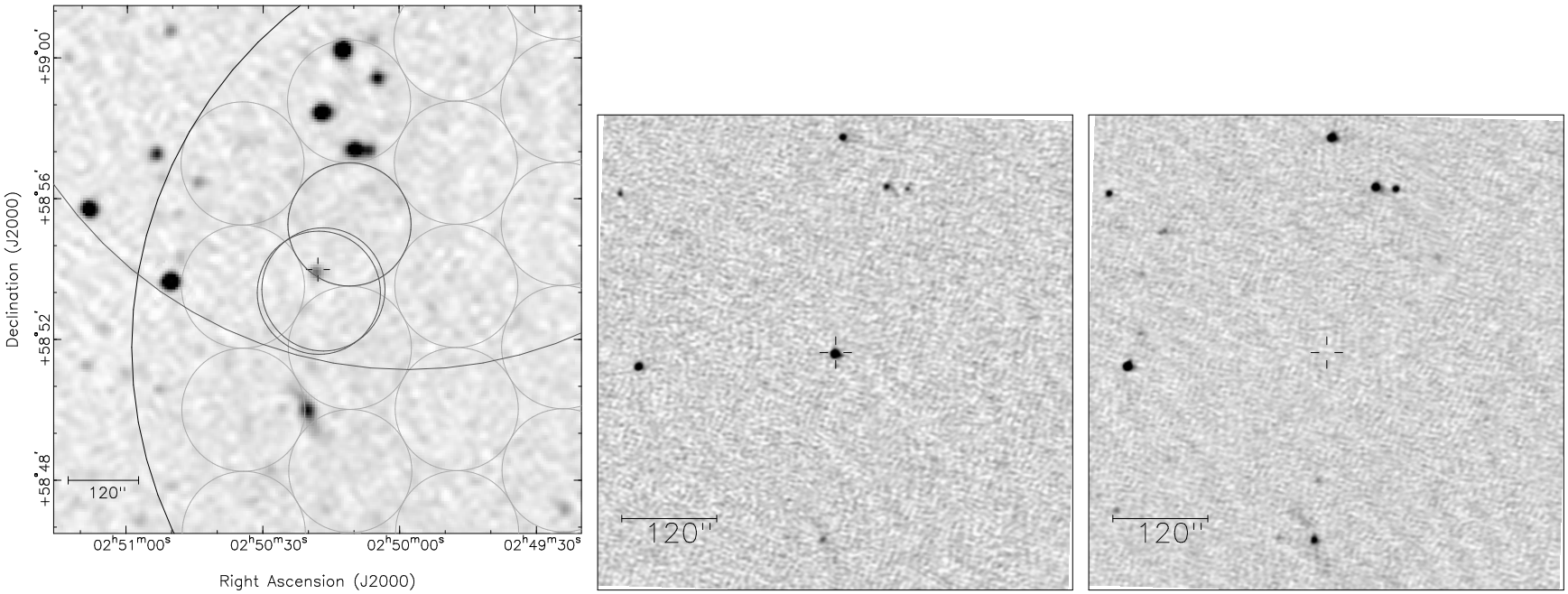
Largest sample of millisecond pulsars (48) ever observed and detected with a single radio telescope below 300 MHz to date (Sep 2026)

Some LOFAR beamforming results (2)



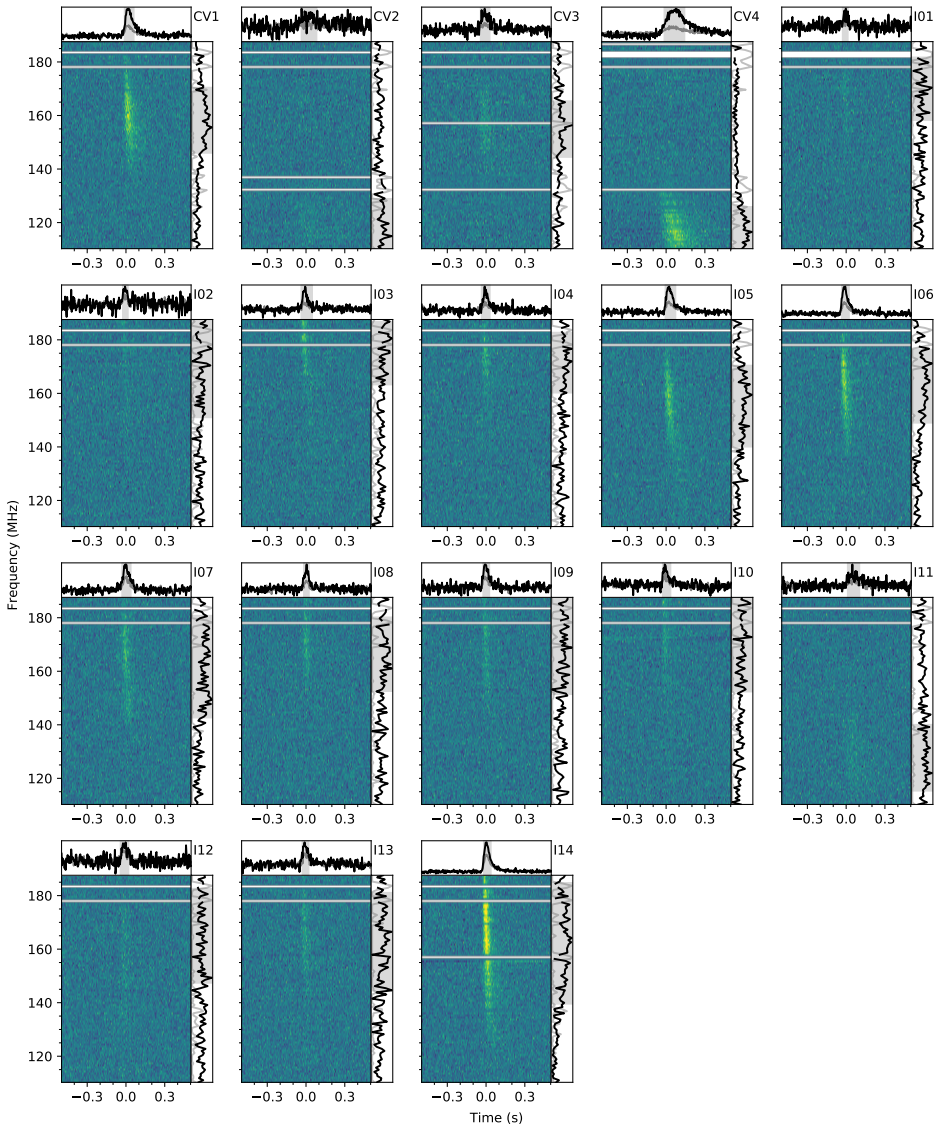
source: Bassa et al. (2017)

Some LOFAR beamforming results (3)



source: Tan et al. (2018)

Some LOFAR beamforming results (4)



source: Pleunis et al. (2021)