Beamforming with LOFAR

Vlad Kondratiev & Cees Bassa

ASTRON

April 17, 2024

Outline

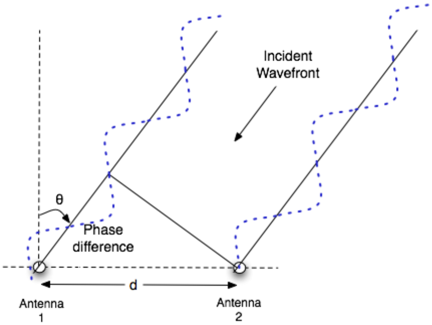
Beamforming in a nutshell

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

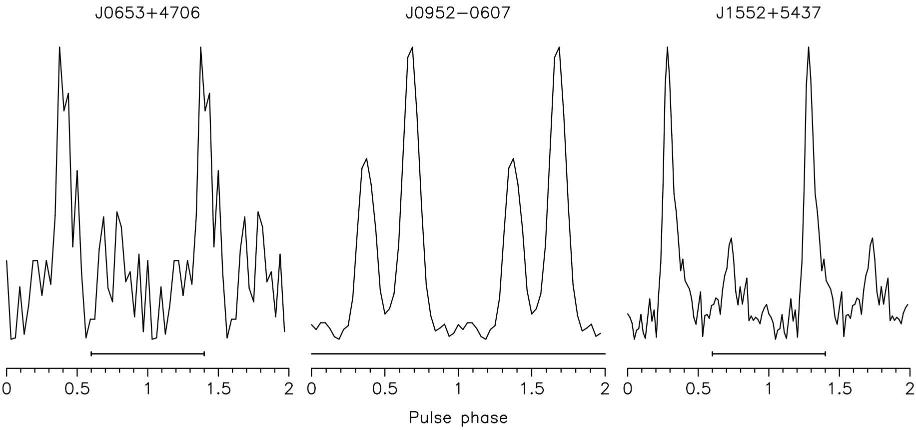
- correlates antenna signals
- high spatial resolution
- low time resolution

Beamforming

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

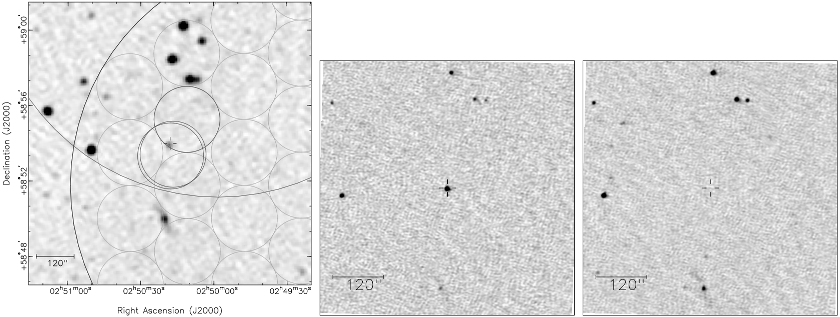
- Beamforming trades spatial resolution for time resolution
- Much easier than interferometry; e.g. no phase/amplitude calibration, deconvolution etc. . .

Some LOFAR beamforming results



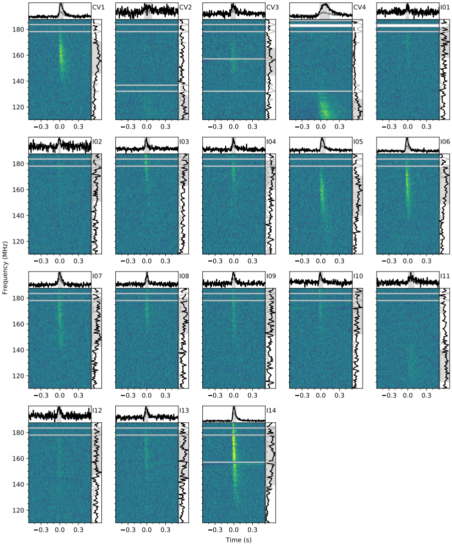
source: Bassa et al. (2017)

Some LOFAR beamforming results



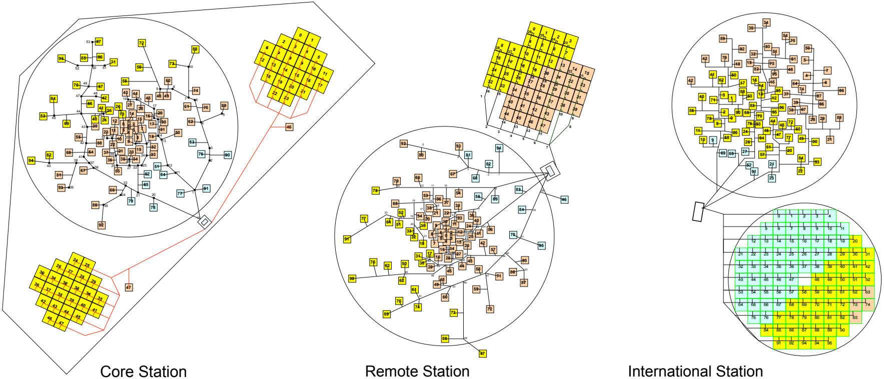
source: Tan et al. (2018)

Some LOFAR beamforming results



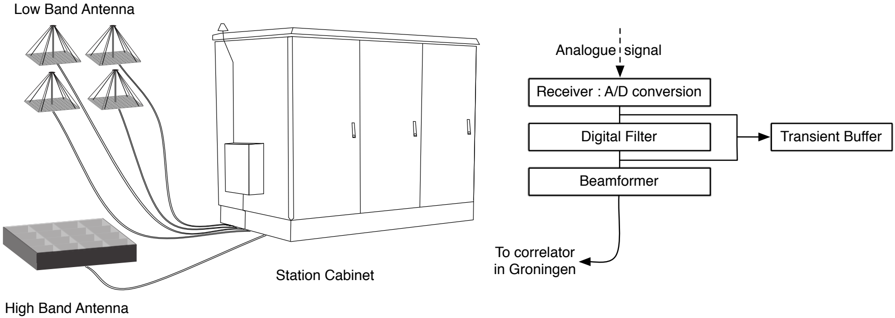
source: Pleunis et al. (2021)

LOFAR stations (a review)



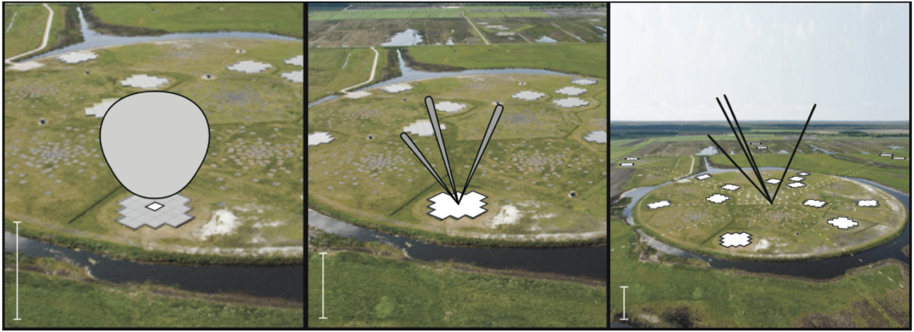
van Haarlem et al. 2013

LOFAR stations (a review)



van Haarlem et al. 2013

Beam terminology



source: astron

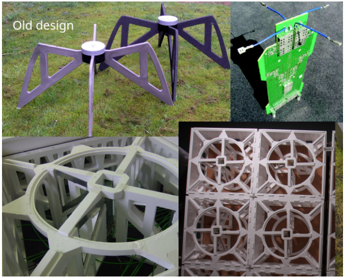
Element beam
or
Tile beam

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 $\lambda = 2.2$ m, $D = 5$ m
- Updated once every few minutes

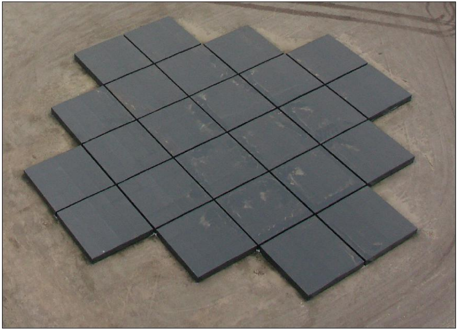
$$\Delta t = (1b_1 + 2b_2 + 4b_3 + 8b_4 + 16b_5) \times 0.5\,\text{ns}$$

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

Station beams (aka sub-array pointings

Station beamforming:

- Digital signals from 48 HBA tiles or 48 LBA dipoles
- Polyphase filter over 160 or 200 MHz to 512 subbands
- 16 or 8 bit digital representation
- 244 or 488 beam/subband combinations (aka beamlets)
- Phase-rotation beamformer
- Updates every second



source: astron

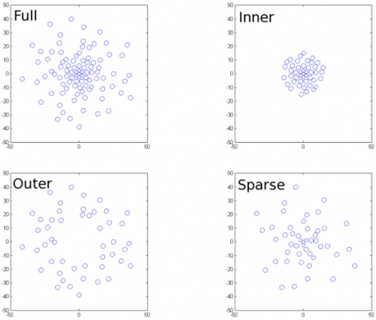
Stations configurations

LBA:

- **OUTER:** Outer 48 antennas
- **INNER:** Inner 48 antennas
- **SPARSE:** Sparse config
- **X or Y:** Single polarization from 96 antennas

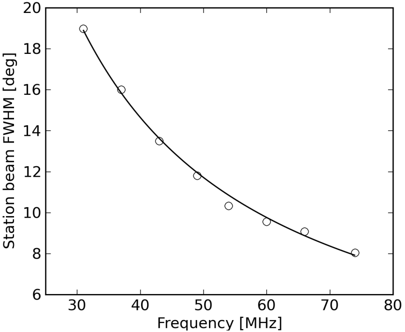
HBA:

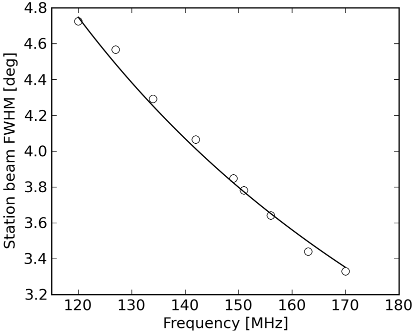
- **DUAL:** Substations separately
- **JOINED:** Substations together
- **0 or 1:** Single substation



source: astron

Station beam sizes





source: van Haarlem et al. (2013)

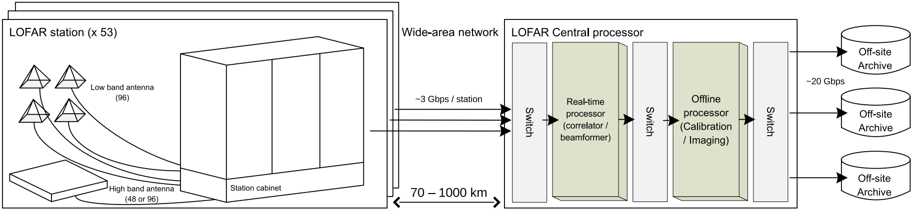
LBA_INNER and a single **HBA** core substation

COBALT

COBALT: COrrellator and **B**eamformer **A**pplication for the **L**OFAR **T**elescope

- 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

COBALT signal path

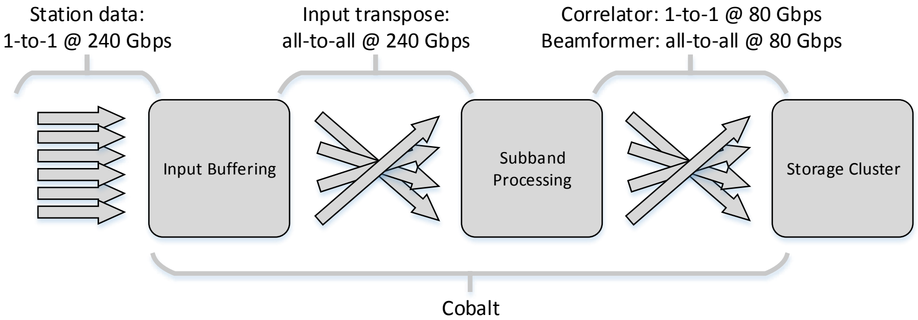


source: Broekema et al. (2018)

- 200 MHz clock, 195.3125 kHz channels, 5.12 μs samples
- 160 MHz clock, 156.250 kHz channels, 6.4 μs samples

Data rate: 244 beamlets × 16 bits × 2 polarizations × 2 values per sample × 195312.5 samples s^{-1} = 3.05Gb s^{-1}.

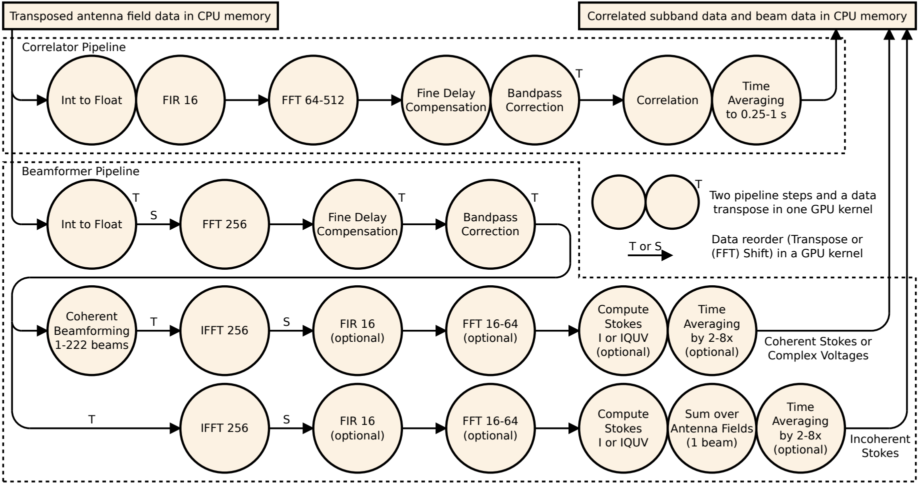
COBALT data flow



source: Broekema et al. (2018)

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

COBALT processing



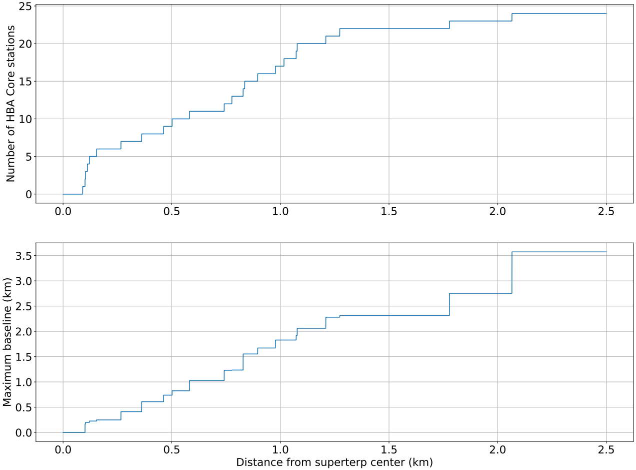
source: Broekema et al. (2018)

COBALT Configuration

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)
- Downsampling factor

Which stations? Sensitivity vs beamsize



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

Coherent vs incoherent

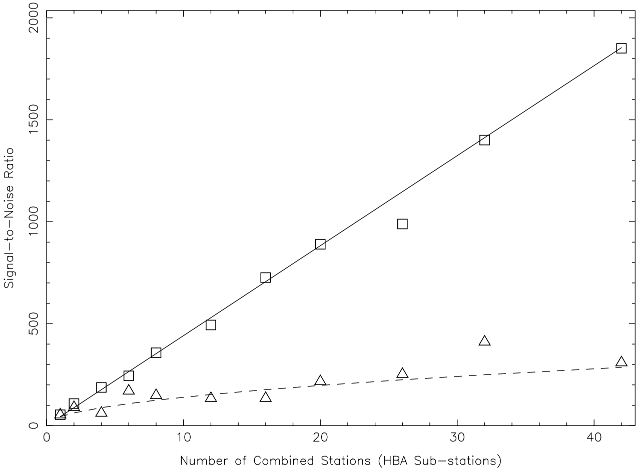
Coherent addition

- 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



source: van Haarlem et al. (2013)

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)

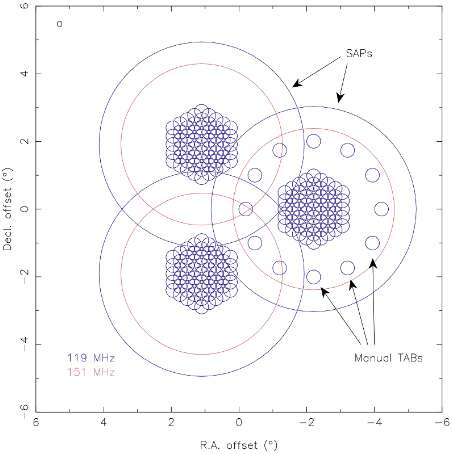
Stokes parameters (CS or IS)

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

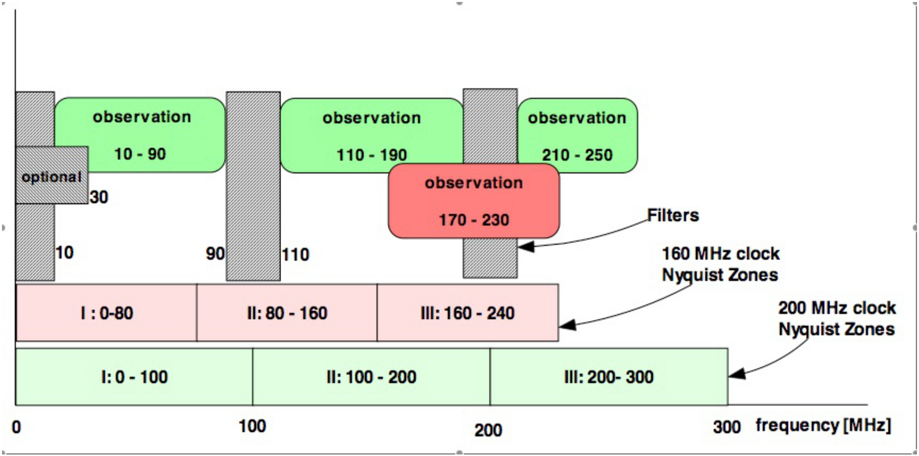
Number of beams?

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;
  $\nu_{\rm clk} = 200\,\text{MHz}$ or $160\,\text{MHz}$
- 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 → frequency:
  $\nu = \left(n - 1 + \frac{s}{512}\right)\frac{\nu_{\rm clk}}{2}$
- frequency → subband:
  $s = \left\lfloor \frac{1024}{\nu_{\rm clk}}\left(\nu - \frac{(n-1)\nu_{\rm clk}}{2}\right)\right\rfloor$

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)
- 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

COBALT limits

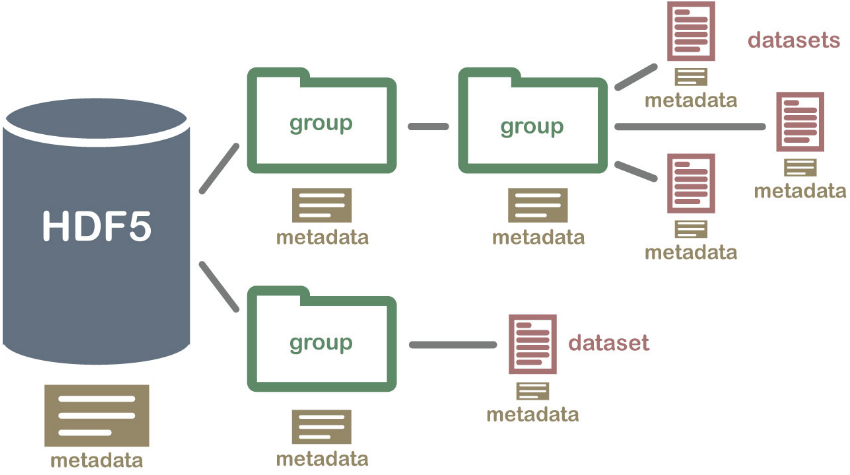
Limits:

- $r < 80\,\mathrm{Gbit\,s^{-1}}$
- Higher throughput if processing is parallel
- Combination of 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 2.0 software


```
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]]_SAP[sss]_B[bbb]_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
- **[sss]:** Sub-array pointing number (SAP)
- **[bbb]:** Tied-array beam number
- **[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: `L650501_SAP000_B002_S2_P010_bf.h5`

Reading HDF5

Options:

- h5dump, h5ls on linux command line to read header
- h5py python reader (will use in tutorials)
- pytables python reader
- LOFAR-DAL (Data Access Library) C++ library written by ASTRON https://github.com/nextgen-astrodata/DAL
- DSPSR pulsar software https://dspsr.sourceforge.net/
- Plain old fopen on raw files (32 bit float or 8 bit char)

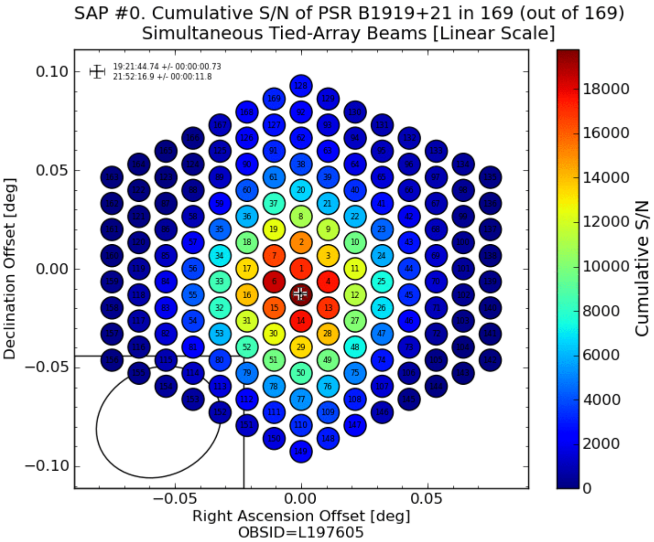
Redigitizing HDF5 complex voltages

`digitize.py` by Marten van Kerkwijk

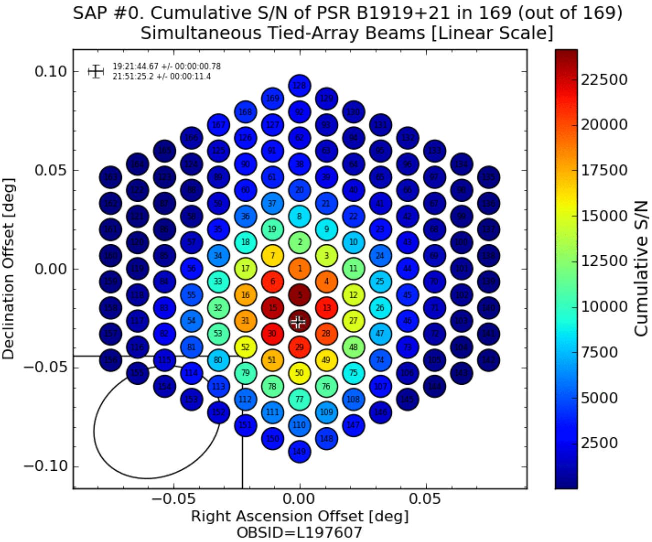
- Convert 32 bit float to 8 bit integers (256 levels)
- Only to be used on complex voltages (XXYY)
- $4\times$ decrease in file size
- Stores scales and offsets in new HDF5 files
- Option offered as part of PULsar Pipeline

`https://github.com/mhvk/scintellometry/blob/master/scintellometry/lofar/digitize.py`

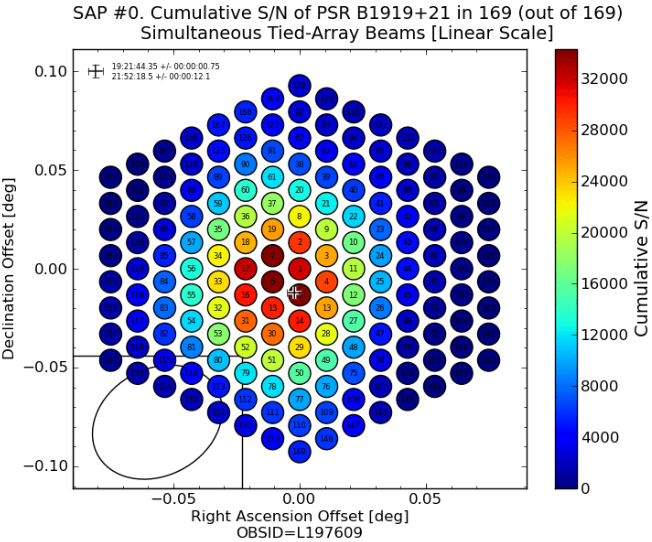
Impact of ionosphere



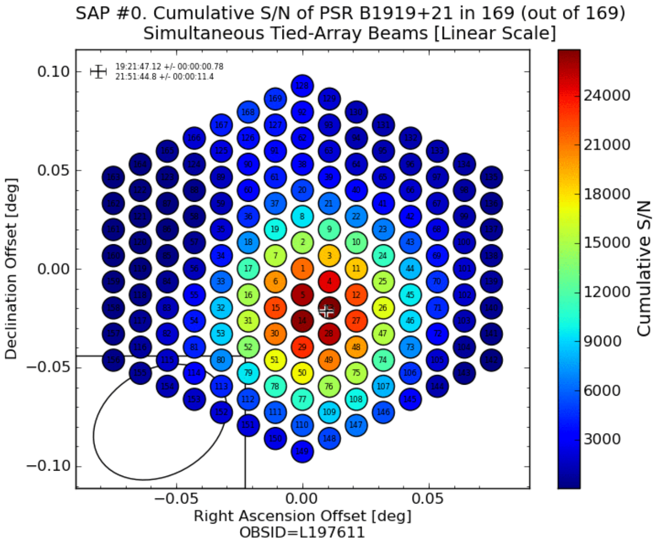
Impact of ionosphere



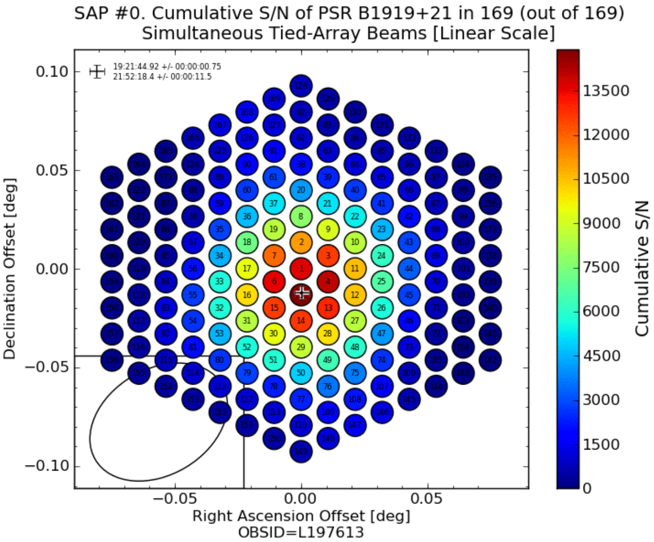
Impact of ionosphere



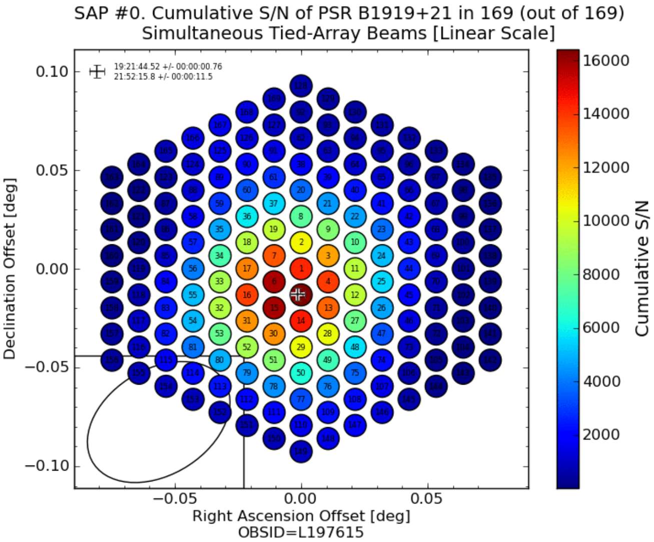
Impact of ionosphere



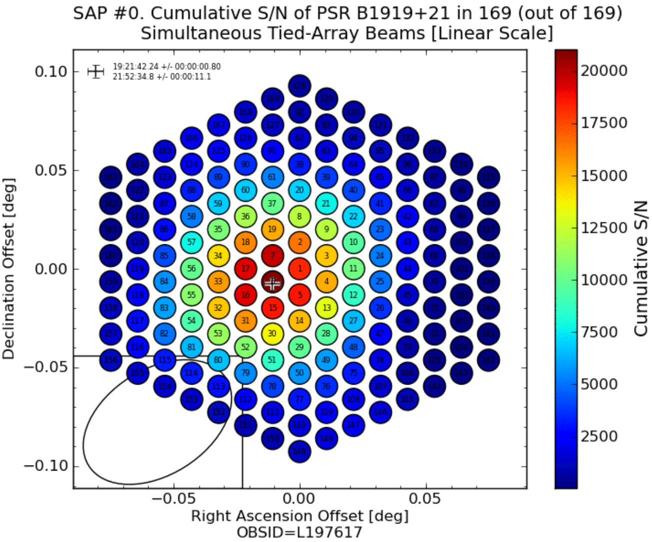
Impact of ionosphere



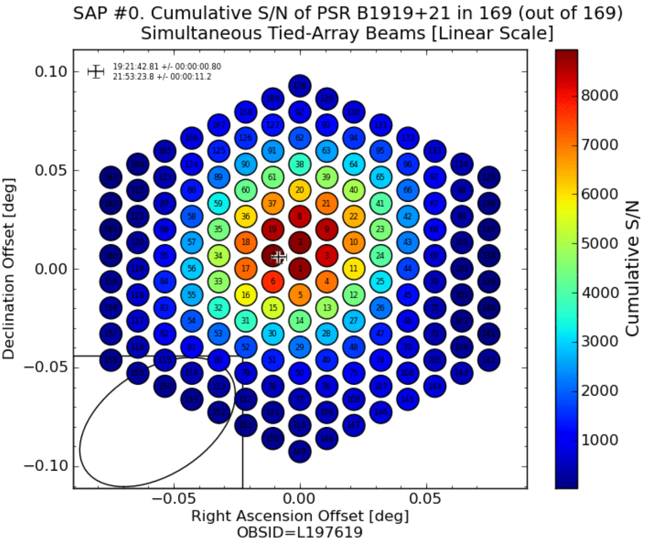
Impact of ionosphere



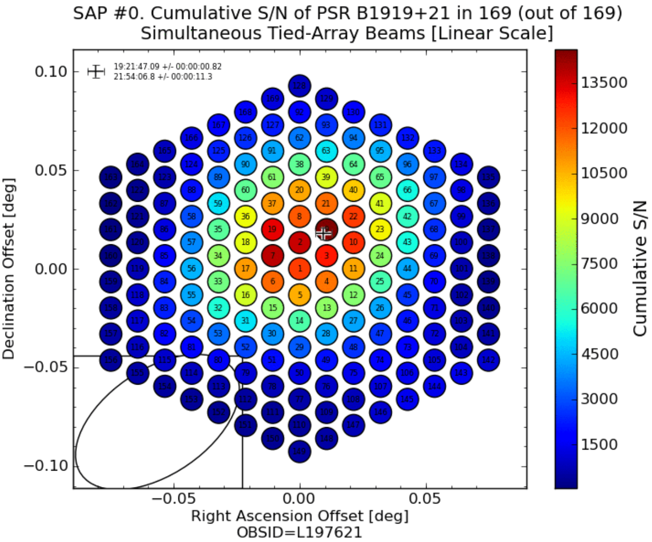
Impact of ionosphere



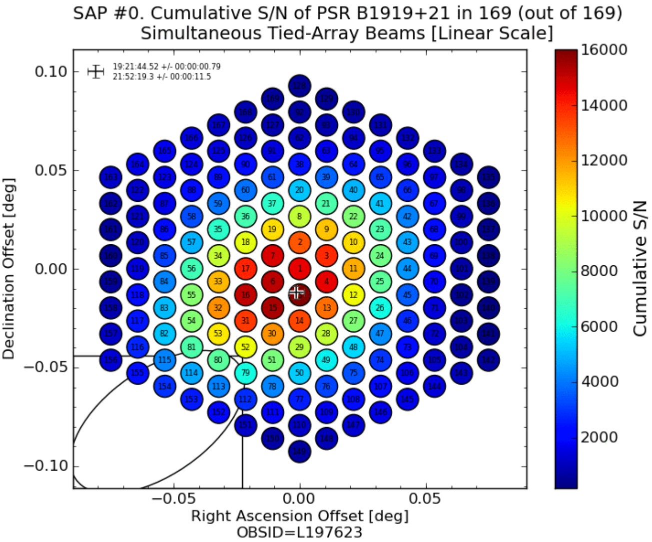
Impact of ionosphere



Impact of ionosphere



Impact of ionosphere



Tutorial: Beamformed data inspection (1)

Goal: read and inspect beamformed COBALT output

Requirements: `git` to download the notebooks, and `Python 3`, `jupyter` with `numpy`, `matplotlib` and `h5py` **OR use prepared singularity container (next slide)**

- **Installing python & jupyter:** Download and install `Anaconda 3` from `www.anaconda.com`
- **Installing h5py:** `pip3 install h5py`
- **Downloading notebooks:**
  `git clone https://github.com/cbassa/lofar_bf_tutorials.git`
- **Downloading HDF5 data:**
  `https://filesender.surf.nl/?s=download&token=853e3a55-c26f-4c0e-a6c1-a7ef8eafec28` (link is valid until April 23, 2024)

Tutorial: Beamformed data inspection (2)

Goal: read and inspect beamformed COBALT output

Requirements: use prepared singularity container `lofar-bf-lds2024.sif`

- **Download from:**
  `https://filesender.surf.nl/?s=download&token=5a6894bb-eec9-4c2b-a5f8-e87daedbf6a1` (link is valid until April 22, 2024)
- both notebooks and data are available:
  - **tutorials:** `/usr/local/src/lofar_bf_tutorials`
  - **data:** `/usr/local/src/lofar_bf_tutorials/data`
- start container with: `singularity shell lofar-bf-lds2024.sif`
- test the container for GUI applications: `xeyes`