OPTICON RadioNet Pilot

ASTRON

JIVE
Joint Institute for VLBI
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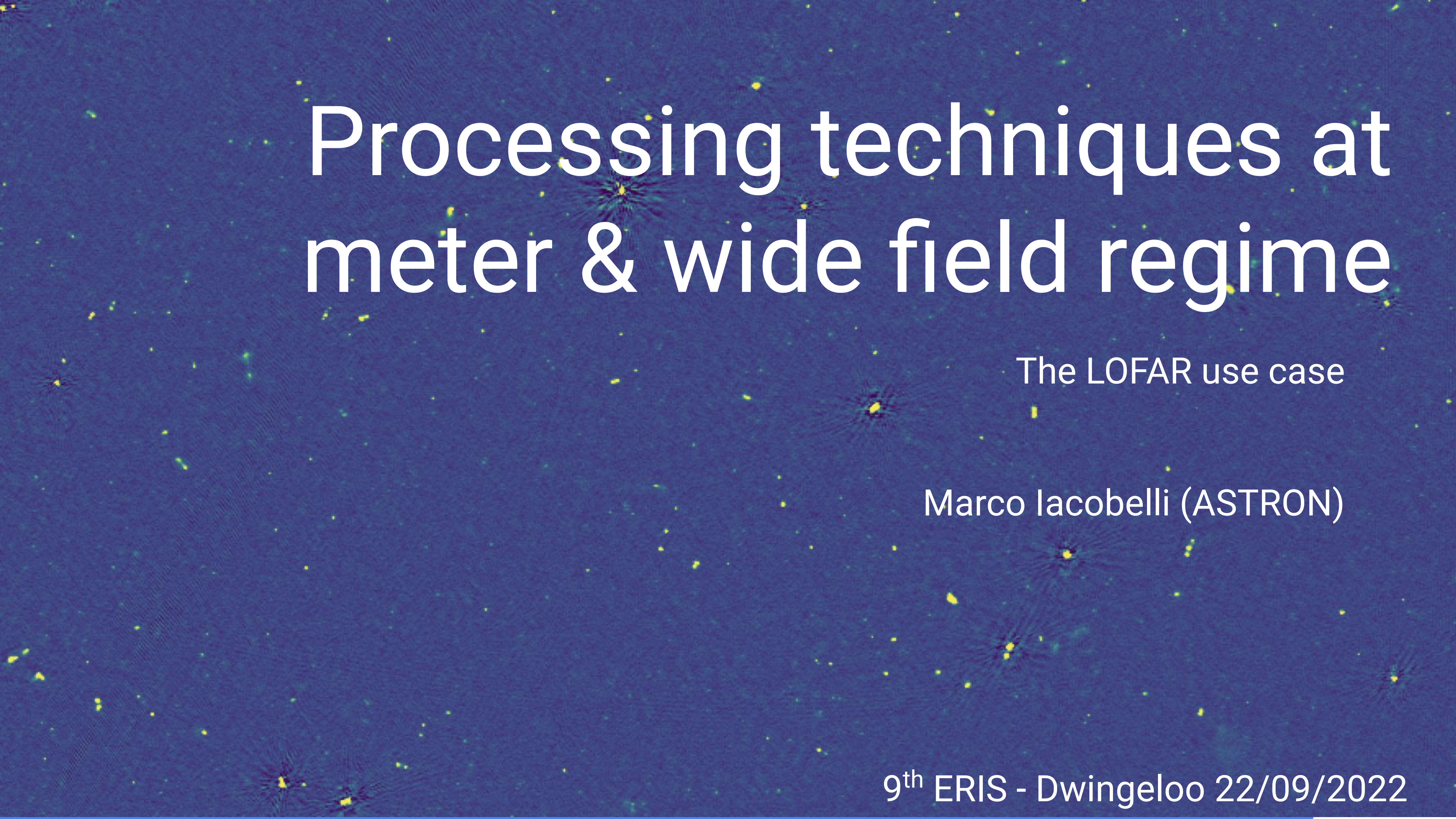
LOFAR

9th ERIS - Dwingeloo 22/09/2022



Processing techniques at meter & wide field regime

The LOFAR use case

Marco Iacobelli (ASTRON)

9th ERIS - Dwingeloo 22/09/2022

Outline

LOFAR overview

- A “next generation facility”
- The system

LOFAR data processing workflows

- DIE & DDE calibration/imaging in a nutshell
- Overview of available recipes

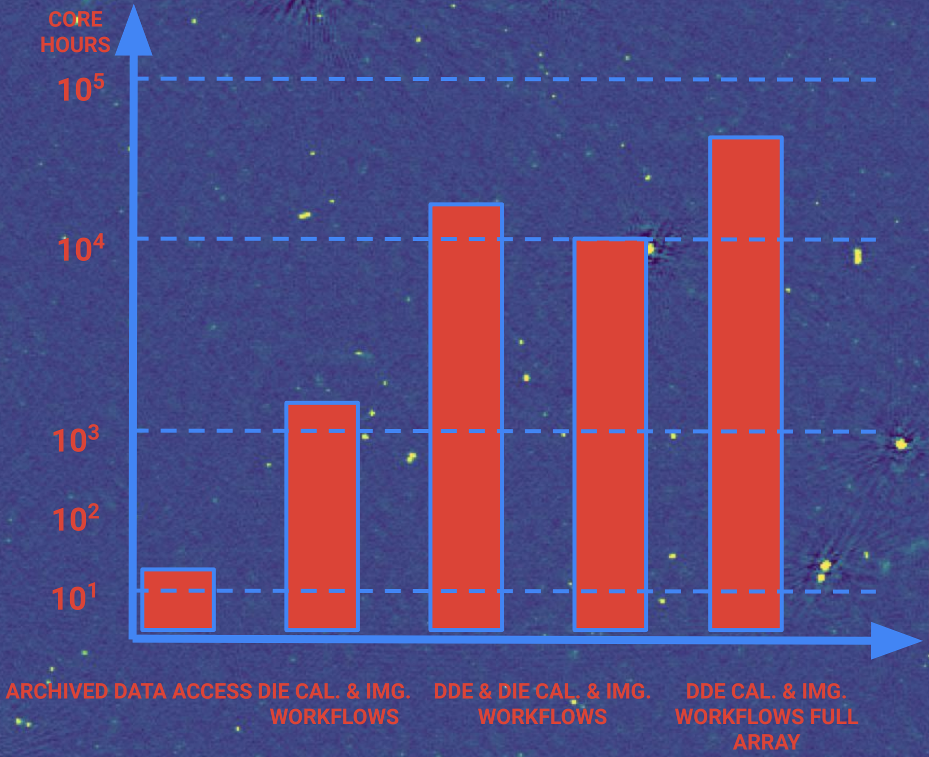
Tutorial handout

- Training datasets
- LOFAR processing software
- Training workflows (LINC / preFACTOR / FACTOR)

To get started

DATA ORIENTED TUTORIAL:

- LOFAR DATA PROPERTIES
- WORKING PRINCIPLES OF LOFAR PROCESSING TECHNIQUES
- HOW TO USE THESE



WHICH WORKFLOW(S) IS BEST FOR YOU TO TRY IN THIS TUTORIAL DEPENDS ON YOUR AVAILABLE COMPUTING RESOURCES

To get started

- Make a directory in your area to hold the
  - parset(s) + (eventually) config files
  - LINC / preFACTOR input data (16GB) & output (+8GB)
  - FACTOR input data (10GB) & output (+10GB)
- Open in your web browser the online view to the Grid Storage data repository and the full documentation
  - https://linc.readthedocs.io/en/latest/ for LINC / preFACTOR
  - https://www.astron.nl/citt/facet-doc/ for FACTOR

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A next-gen facility

- LOFAR is the most flexible, complex and data-intensive radio telescope currently in existence

- Generates huge amounts of data which requires a lot of supercomputing power and innovative data solutions

- Enables astronomers to investigate a large spectrum of science use cases (from cosmology to solar-physics)

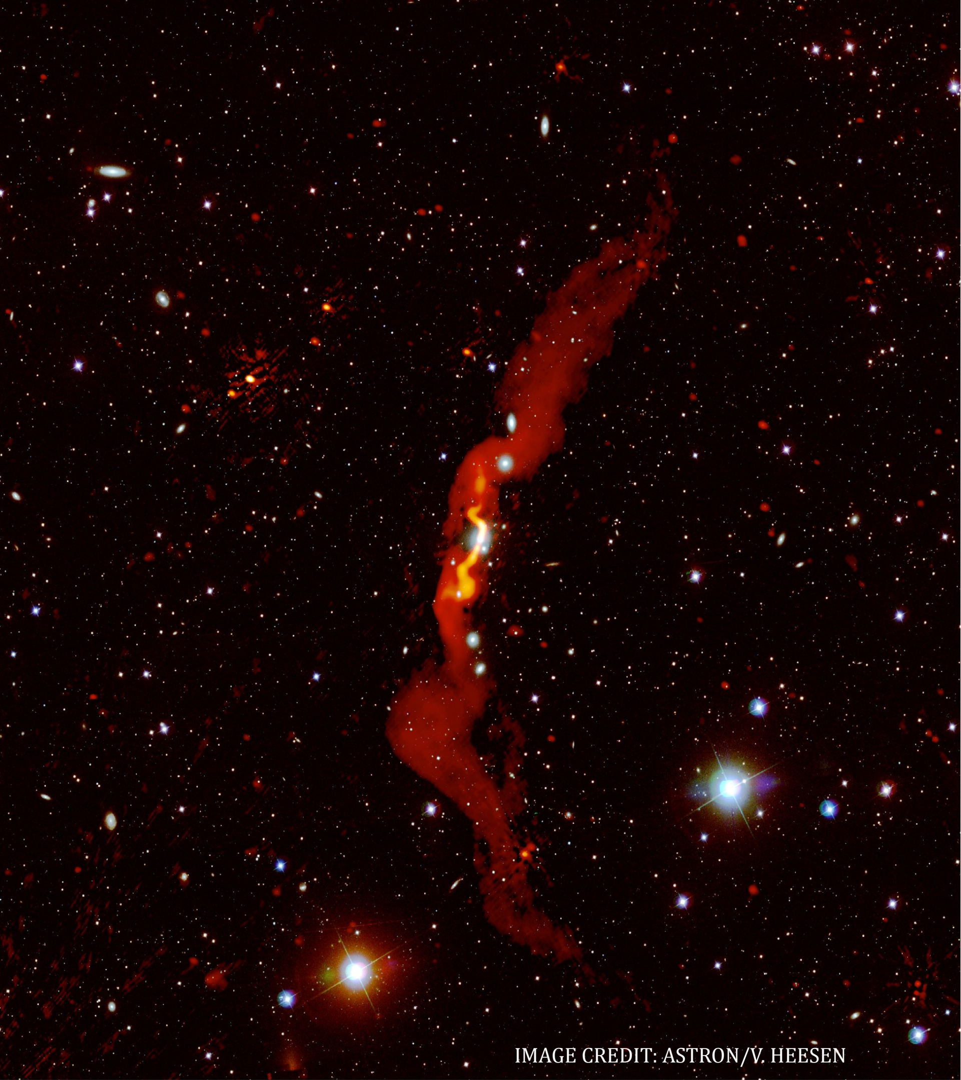

IMAGE CREDIT: ASTRON/V. HEESEN

A next-gen facility

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- Generates huge amounts of data which requires a lot of supercomputing power and innovative data solutions
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The LOFAR system: a distributed array

From day 1 Lecture J. Mc Kean . . .

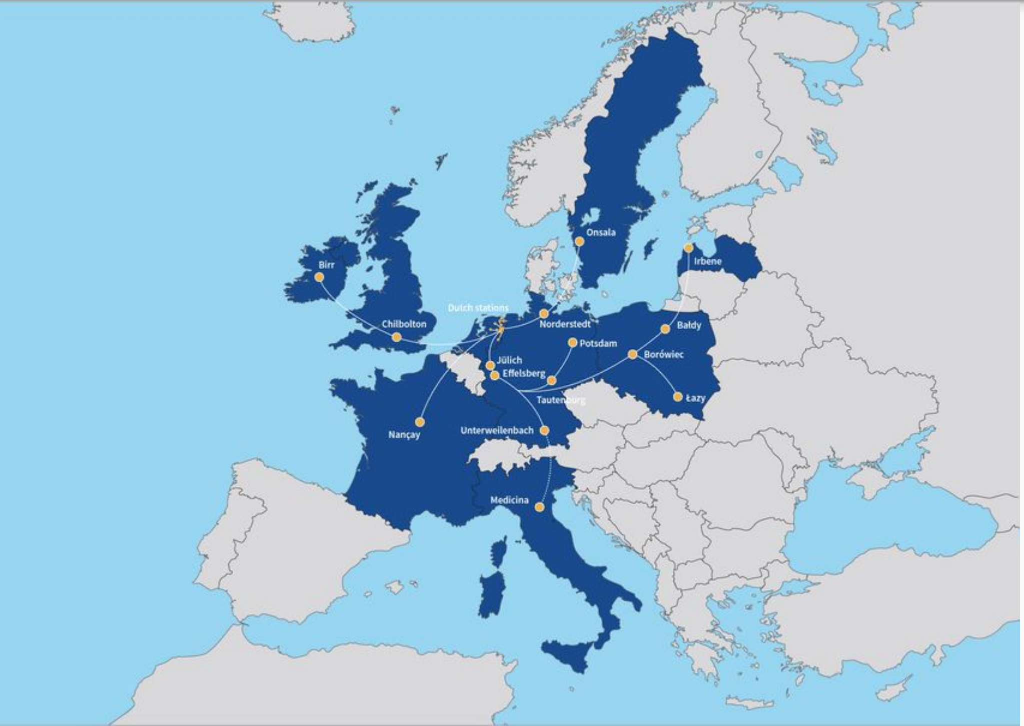
- Many science studies benefits from radio observing at low frequencies (<300 MHz). An additional benefit is the relatively large field-of-view, which can be several degrees in diameter.
- The lower limit in ground radio observing is set by the opacity of the Earth's atmosphere below 10–30 MHz (depending on the ionospheric conditions).
- The relationship between angular resolution (Θ) and the wavelength (λ) to telescope size (D) ratio requires LF observations to be performed with an interferometer to reach an angular resolution of (sub-) arcseconds.

Towards LF, the image background RMS increases (even faster than the flux density of an USS source) resulting in a relative loss of dynamic range. The increase in background RMS is typically the result of several effects (e.g., Thompson et al. 2001):

- (i) a high sky temperature from the Milky Way foreground,
- (ii) reduced telescope efficiency,
- (iii) wide-field imaging issues (e.g. the w-term, bandwidth & time averaging smearing),
- (iv) poorly constrained and variable antenna beam patterns on the sky (including pointing errors, beam squint),
- (v) radio frequency interference,
- (vi) ionospheric propagation effects.

Several of these effects can be removed or suppressed during data reduction if suitable algorithms are available.

The LOFAR system: a distributed array

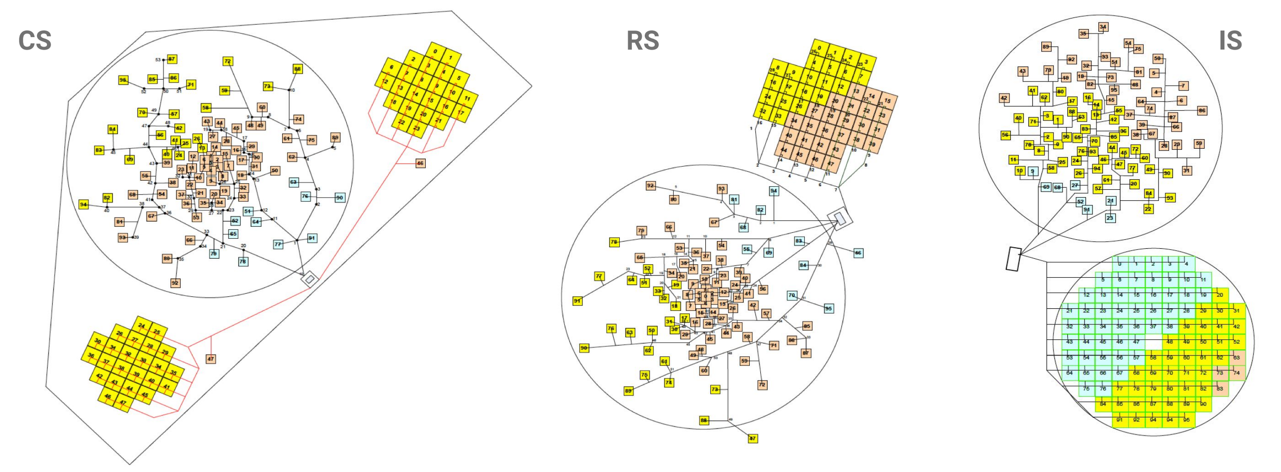


International LOFAR Telescope: 2 antennas type to cover the 10-240 MHz bandpass, grouped into 52 stations (38 NL+14 Europe)

- Tot. eff. collecting area **> 3x10^{5} m^{2}**, depending on ***ν*** & antenna config.
- With baselines of up to **~ 2x10^{3} km**, LOFAR has the unique capability of achieving sub-arcsecond resolution at ***ν*** < 200 MHz.
- Data rate & storage challenges (35 Tb/h of raw, correlated visibilities)
- An overview of the array and its stations is available here.

The LOFAR system: a distributed array

Different stations layout for different stations groups offering flexible array configurations



Core Stations (CS): a distribution of 24 stations located within a radius of 2 km, providing superb uv-coverage and sensitivity to detect extended and low-surface brightness emission from arcmin to degree angular scales. At the heart of the core, six stations are packed on a 320 m diameter island (the “Superterp”) to provide the shortest (O~10 m) baselines in the array and can also be combined to effectively form a single, large station to e.g. maximise the S/N on VLBI experiments.

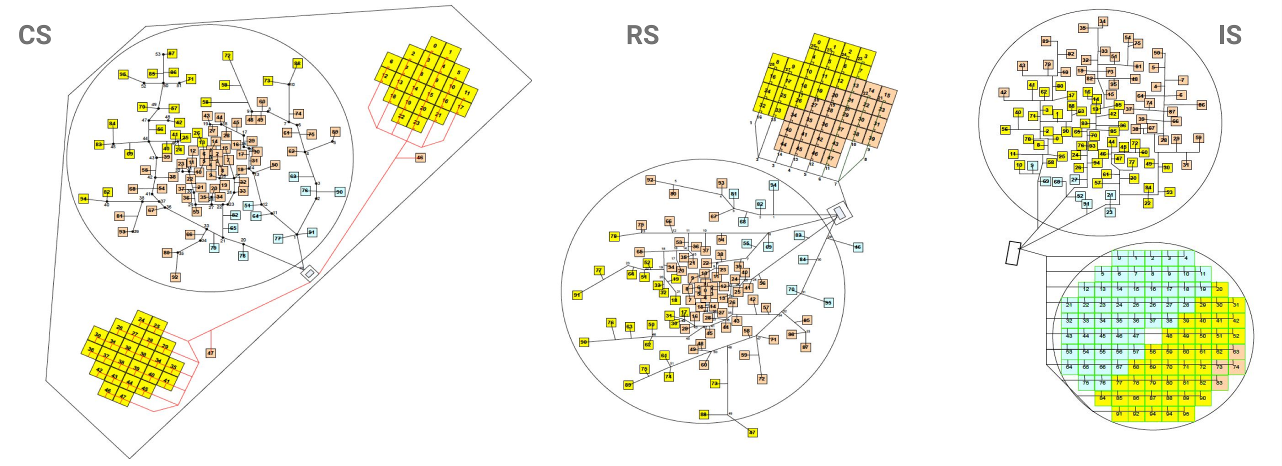
Remote Stations (RS): a distribution (beyond the "core") of 14 stations, arranged in an approximation to a logarithmic spiral distribution and extending out to a radius of 90 km.

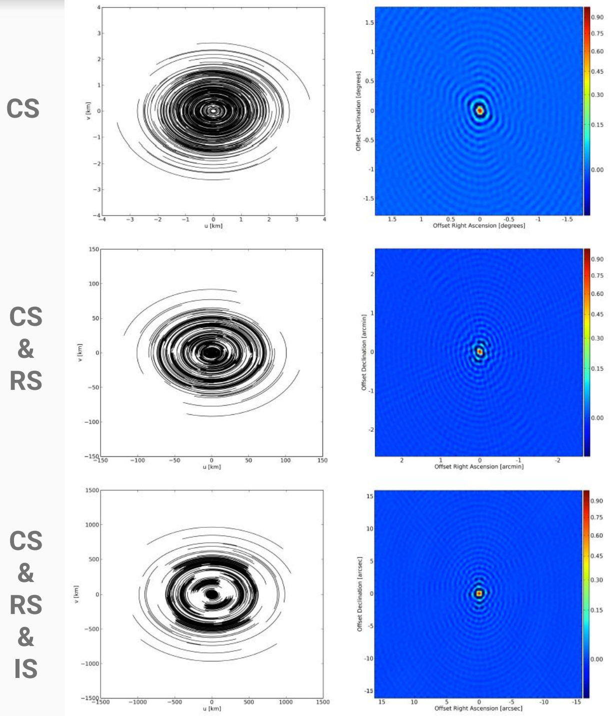
International Stations (IS): 14 stations across Europe enabling VLBI capabilities (<1” resolving power at ν>110MHz; O(1”) at ν<90 MHz.

The LOFAR system: a distributed array

Example of uv coverage plots (left) and synthesized beams (right) for different array configurations.

Source at dec +48; a 6 h track centered at LST; one point plotted every minute; uniform weighting and multi-frequency synthesis over the LBA frequency range 30-78 MHz.

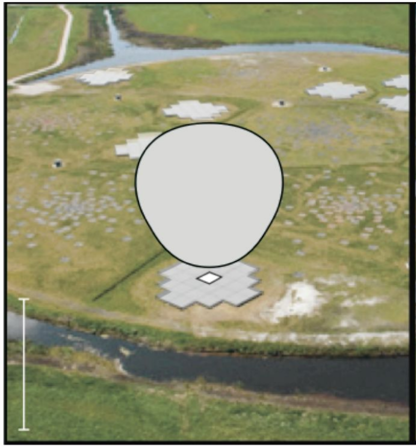




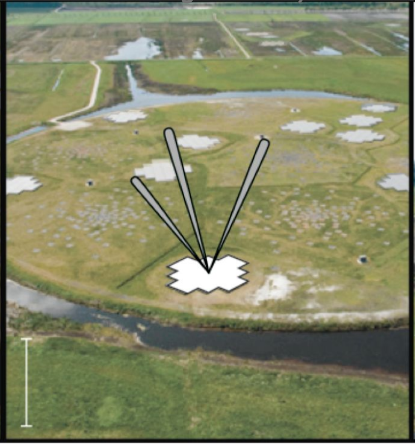
The LOFAR system: beam-forming

LOFAR uses a hierarchical beam-forming approach: first at tile / dipole (HBA/LBA) level, then station level, finally at array level

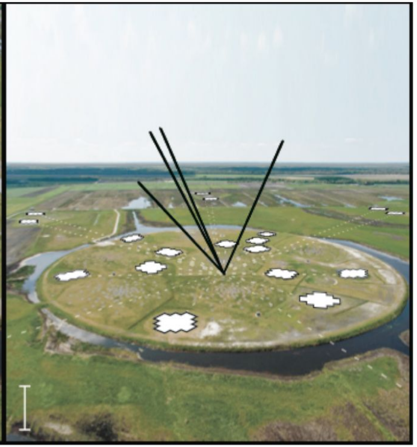
LBA Dipole & HBA tile beams



Station beams (or Sub Array Pointings - SAPs)



(Tied-)array beams



Dipole and Tile Beams

- The LBA 'dipole beam' covers the entire sky, but with a significant drop in sensitivity below about 30° elevation.
- A HBA tile contains 4x4 antennas combined with an analogue beam former before the data are sent to the station processor (RSP) boards. So a tile is sensitive to a smaller portion of the sky. This 'tile beam', (or 'analogue beam') has a FWHM beam width of 30-15 deg over the frequency range 110-240 MHz.

The LOFAR system: beam-forming

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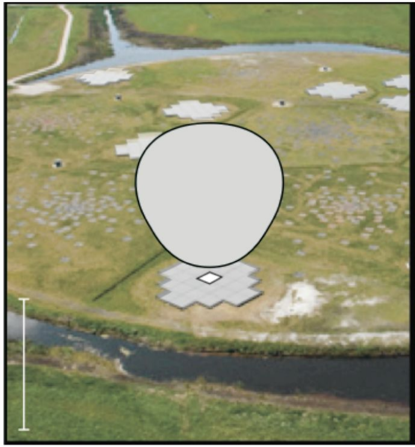
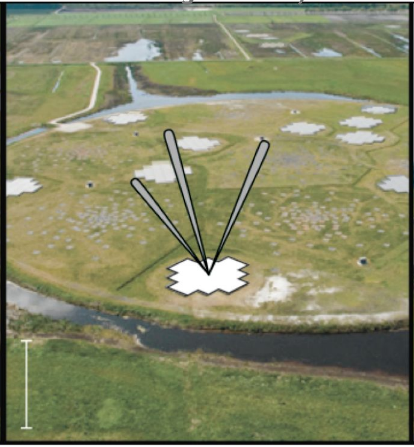
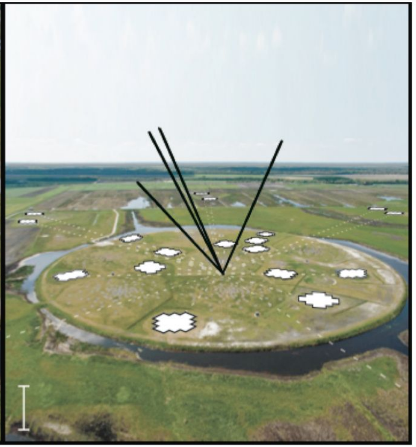
LBA Dipole & HBA tile beams



Station beams (or Sub Array Pointings - SAPs)



(Tied-)array beams

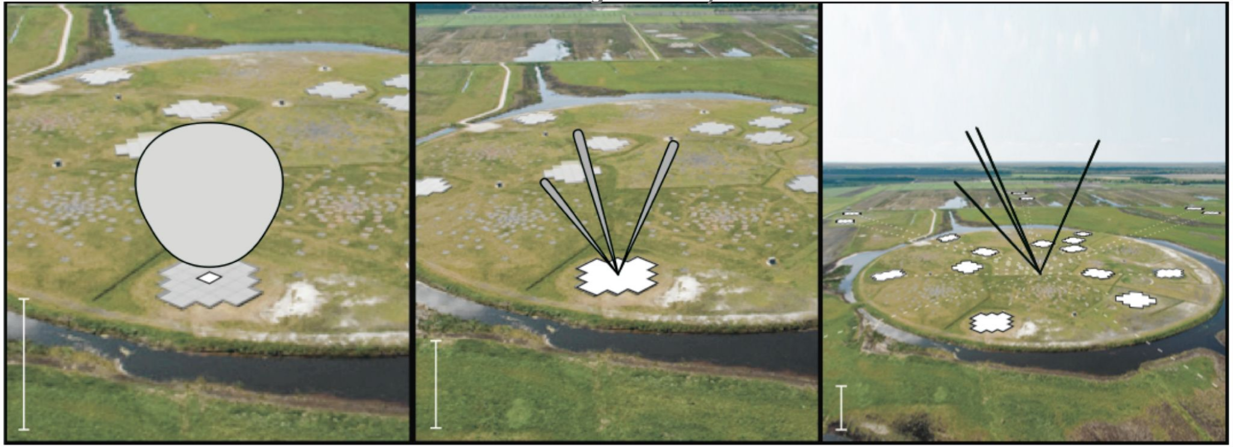


Station Beam or Sub-Array Pointing (SAP)

- A station beam is formed by combining (by appropriate phase-rotation) all the selected LBA antennas or HBA tiles in a given station to form a beam towards a specified direction.
- Beam-forming is done independently for each subband and the resulting beam is called a "beamlet". Multiple beamlets with the same pointing position are summed to produce beams with a large bandwidth. Thus the available bandwidth (up to 488 subbands in 8-bit mode) has to be distributed over all the specified station beams.
- Beams are calculated once per second, resulting in a gain variation of 0.3% for a station beam of 3 deg in diameter.

The LOFAR system: beam-forming

LOFAR uses a hierarchical beam-forming approach: first at tile / dipole (HBA/LBA) level, then station level, finally at array level



LBA Dipole & HBA tile beams

Station beams (or Sub Array Pointings - SAPs)

(Tied-)array beams

Array beams

- After forming a station beam towards a specified direction (say all 488 subbands in one SAP), the station data flows to the CEP to be processed by the correlator, the Graphical Processing Unit (GPU)-based Cobalt system.
- The real-time digital backend performs delay-tracking, separate each subband into up to 256 channels using a PPF and and FFT, compensate for the bandpass of the station and correlate (interferometry).
- The minimum real time integration time is ~0.5 s. Typically a time resolution of multiples of 1.006633 s is adopted.

The LOFAR system: frequency ranges & spectral resolution

A flexible selection of the total bandwidth, frequencies and spectral channel width is enabled by combining analogue & digital signal processing at station level and at the correlator.

FREQUENCY BAND [MHz]	SAMPLING CLOCK FREQUENCY [MHz]	ARRAY (ANTENNA TYPE)	NOTES
10-90	200	LBA	Dominant interference at ν<20 MHz during daytime.
30-90	200	LBA	LBA band with minimum level of interference.
110-190	200	HBA	HBA band with no digital audio stations; minimum level of interference.
170-230 | 210-250	160 | 200	HBA | HBA	HBA bands with high level of interference. Presence of many digital audio stations.

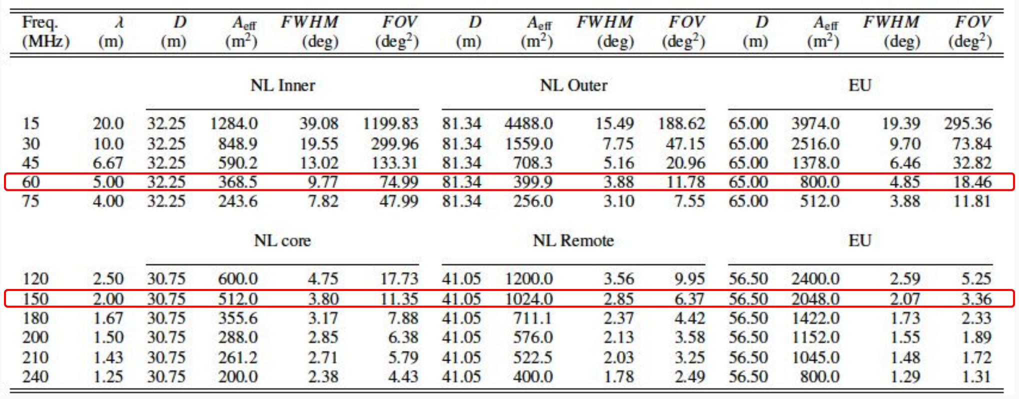
SAMPLING CLOCK FREQUENCY [MHz]	TOTAL BANDWIDTH [MHz]	SUB-BAND WIDTH [kHz]	CHANNEL WIDTH [Hz]
160	76.13	156.2500	610.352
200	95.16	195.3125	767.939

The LOFAR system: imaging capabilities

The Full Width Half Maximum (FWHM) of a Station beam is $\boxed{FWHM = \alpha_1 \times \frac{\lambda}{D}, \alpha_1 = 1.3,}$

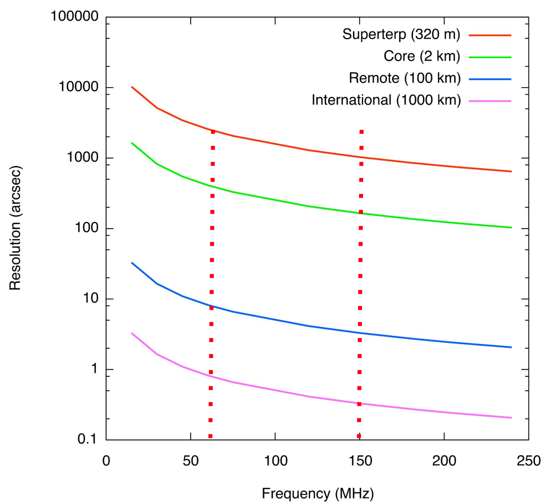
The Field of View (FoV) of a station is $\boxed{FoV = \pi \times (\frac{FWHM}{2})^2}$

Primary beams (FWHM) and Field of View (FoV) for different stations configurations.



Freq. (MHz)	λ (m)	D (m)	$A_{\rm eff}$ (m^2)	$FWHM$ (deg)	FOV (deg^2)	D (m)	$A_{\rm eff}$ (m^2)	$FWHM$ (deg)	FOV (deg^2)	D (m)	$A_{\rm eff}$ (m^2)	$FWHM$ (deg)	FOV (deg^2)
		NL Inner				NL Outer				EU			
15	20.0	32.25	1284.0	39.08	1199.83	81.34	4488.0	15.49	188.62	65.00	3974.0	19.39	295.36
30	10.0	32.25	848.9	19.55	299.96	81.34	1559.0	7.75	47.15	65.00	2516.0	9.70	73.84
45	6.67	32.25	590.2	13.02	133.31	81.34	708.3	5.16	20.96	65.00	1378.0	6.46	32.82
60	5.00	32.25	368.5	9.77	74.99	81.34	399.9	3.88	11.78	65.00	800.0	4.85	18.46
75	4.00	32.25	243.6	7.82	47.99	81.34	256.0	3.10	7.55	65.00	512.0	3.88	11.81
		NL core				NL Remote				EU			
120	2.50	30.75	600.0	4.75	17.73	41.05	1200.0	3.56	9.95	56.50	2400.0	2.59	5.25
150	2.00	30.75	512.0	3.80	11.35	41.05	1024.0	2.85	6.37	56.50	2048.0	2.07	3.36
180	1.67	30.75	355.6	3.17	7.88	41.05	711.1	2.37	4.42	56.50	1422.0	1.73	2.33
200	1.50	30.75	288.0	2.85	6.38	41.05	576.0	2.13	3.58	56.50	1152.0	1.55	1.89
210	1.43	30.75	261.2	2.71	5.79	41.05	522.5	2.03	3.25	56.50	1045.0	1.48	1.72
240	1.25	30.75	200.0	2.38	4.43	41.05	400.0	1.78	2.49	56.50	800.0	1.29	1.31

Effective angular resolution as a function of frequency for different array configurations.



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Introduction: DIE & DDE cal/img

(Some of the) challenges in LOFAR calibration & imaging

- Large data volumes [CAL]
- LOFAR beam(s) time dependent & difficult to model [CAL | IMG]
- Low S/N regime → calibration errors [CAL]
- Large FOV
    - Direction-dependent calibration approaches needed [CAL]
    - Large w-values [IMG]
    - Deconvolution complex [IMG]
- Large fractional bandwidth
    - Requires multi-frequency approaches [CAL | IMG]

Introduction: DIE & DDE cal/img

SYSTEMATIC EFFECT	AMPLITUDE / PHASE	FREQUENCY DEPENDENCY	DIRECTION DEPENDENT ?	TIME DEPENDENT ?
Instrumental noise	Amplitude & phase	$\propto f(\nu)$	No	Yes (random)
Clock drift	Phase	$\propto \nu$	No	Yes O(minutes)
Polarisation alignment	Phase	$\propto \nu$	No	No
Ionosphere (1st ord.) - dispersive delay	Phase	$\propto \nu^{-1}$	Yes	Yes O(seconds)
Ionosphere (2nd ord.) - Faraday rotation	Amplitude & phase	$\propto \nu^{-2}$	Yes	Yes O(seconds)
Ionosphere (3rd ord.)	Scalar	$\propto \nu^{-3}$	Yes	Yes O(seconds)
Ionosphere - Scintillation	Amplitude	$\propto f(\nu)$	Yes	Yes O(seconds)
Dipole beam & array factor	Amplitude & phase	$\propto f(\nu)$	Yes	Yes O(minutes)
Bandpass	Amplitude	$\propto f(\nu)$	No	No

Introduction: DIE cal

Direction-Independent Effects in LOFAR data are primarily caused by:

- The ionosphere → mostly phase effects (vary quickly in time)
  - Faraday rotation
- The instrumental effects → amplitude effects (vary slowly in time)
  - Polarisation alignment
  - Element beam
  - Bandpass
  - Clock drift

Direction-Independent calibration (mainly) attempts to correct for these effects

Introduction: DDE cal/img

Direction-Dependent Effects in LOFAR data are primarily caused by:

- The ionosphere → mostly phase effects (vary quickly in time)
  - Dispersive delays
- The LOFAR beam → mostly amplitude effects (vary slowly in time)
  - Dipole beam & array factor

Direction-Dependent calibration (mainly) attempts to correct for these effects

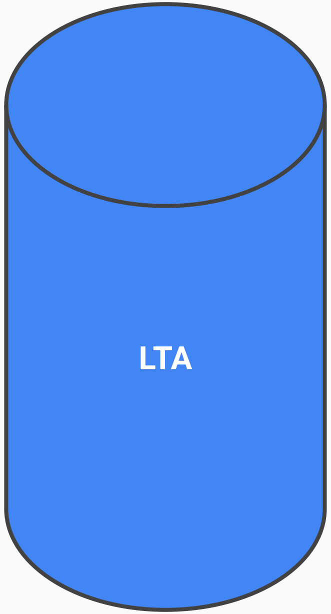
Introduction: available workflows

ARCHIVED
UNCALIBRATED DATA

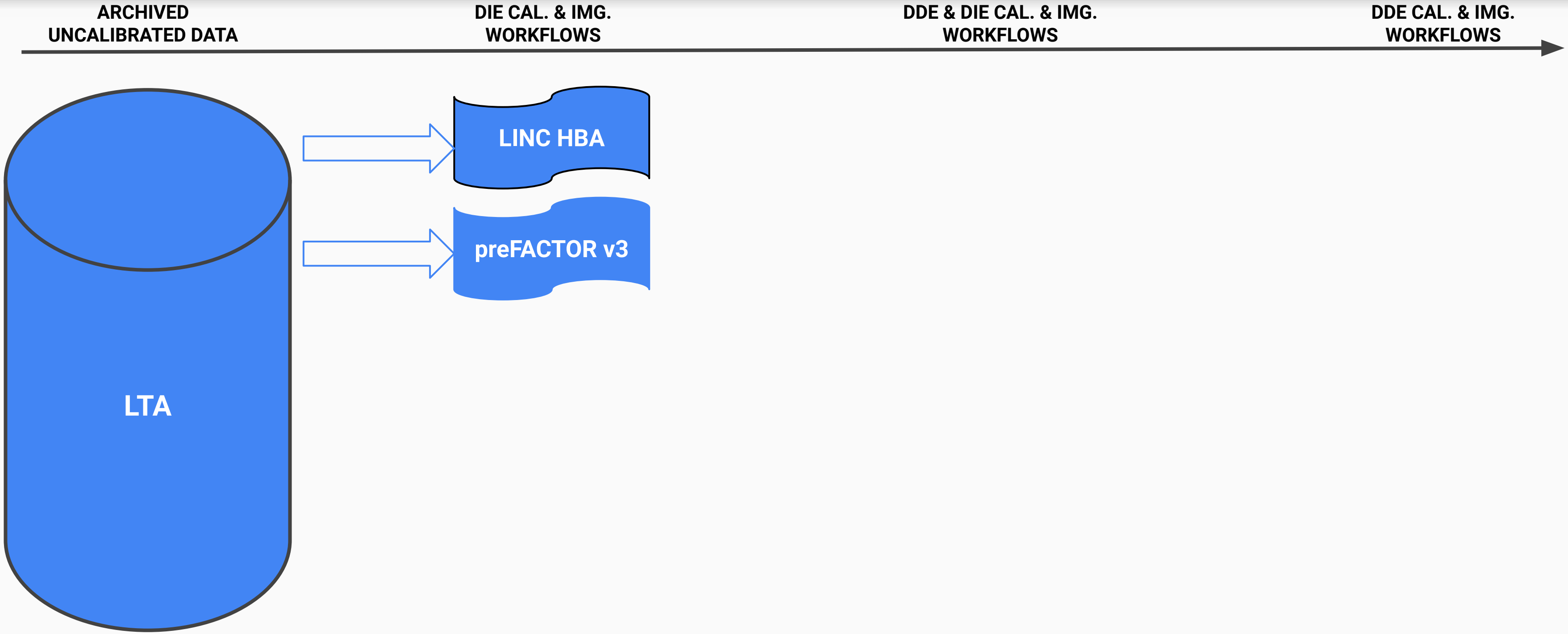
DIE CAL. & IMG.
WORKFLOWS

DDE & DIE CAL. & IMG.
WORKFLOWS

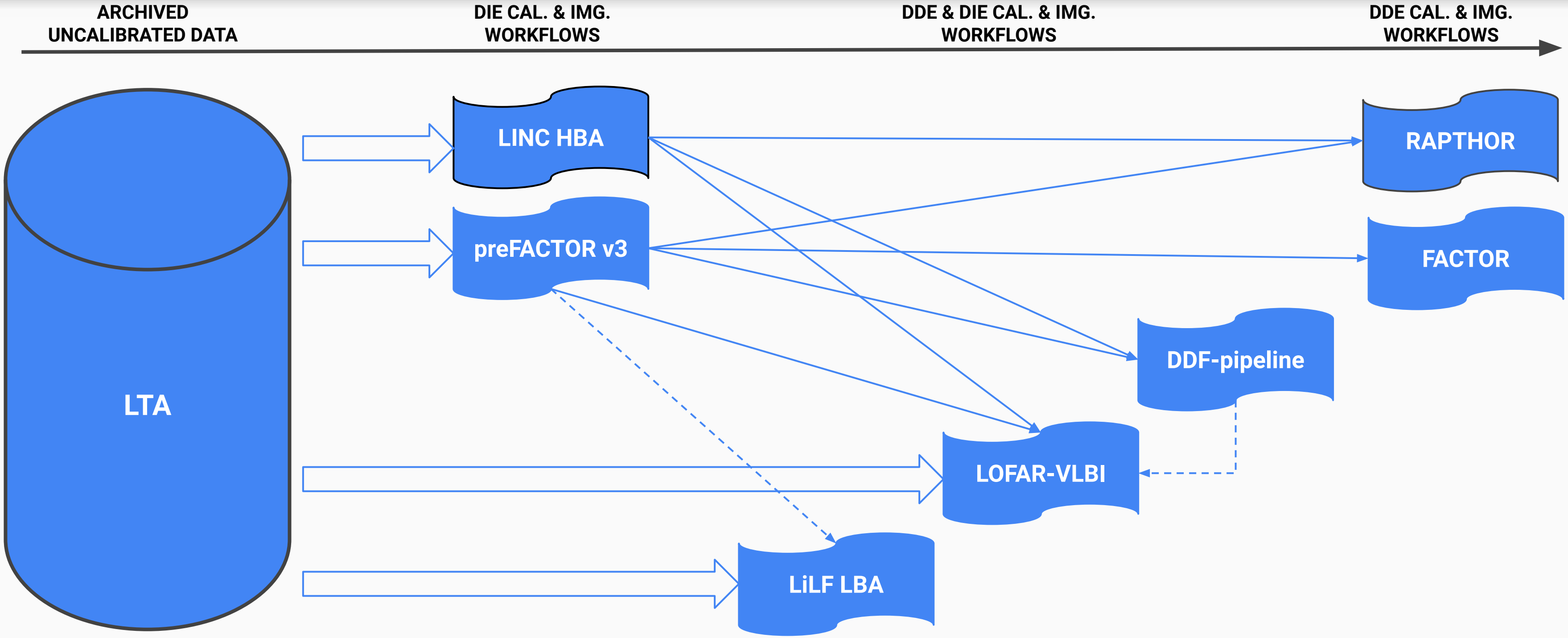
DDE CAL. & IMG.
WORKFLOWS



Introduction: available workflows



Introduction: available workflows


ARCHIVED UNCALIBRATED DATA
DIE CAL. & IMG. WORKFLOWS
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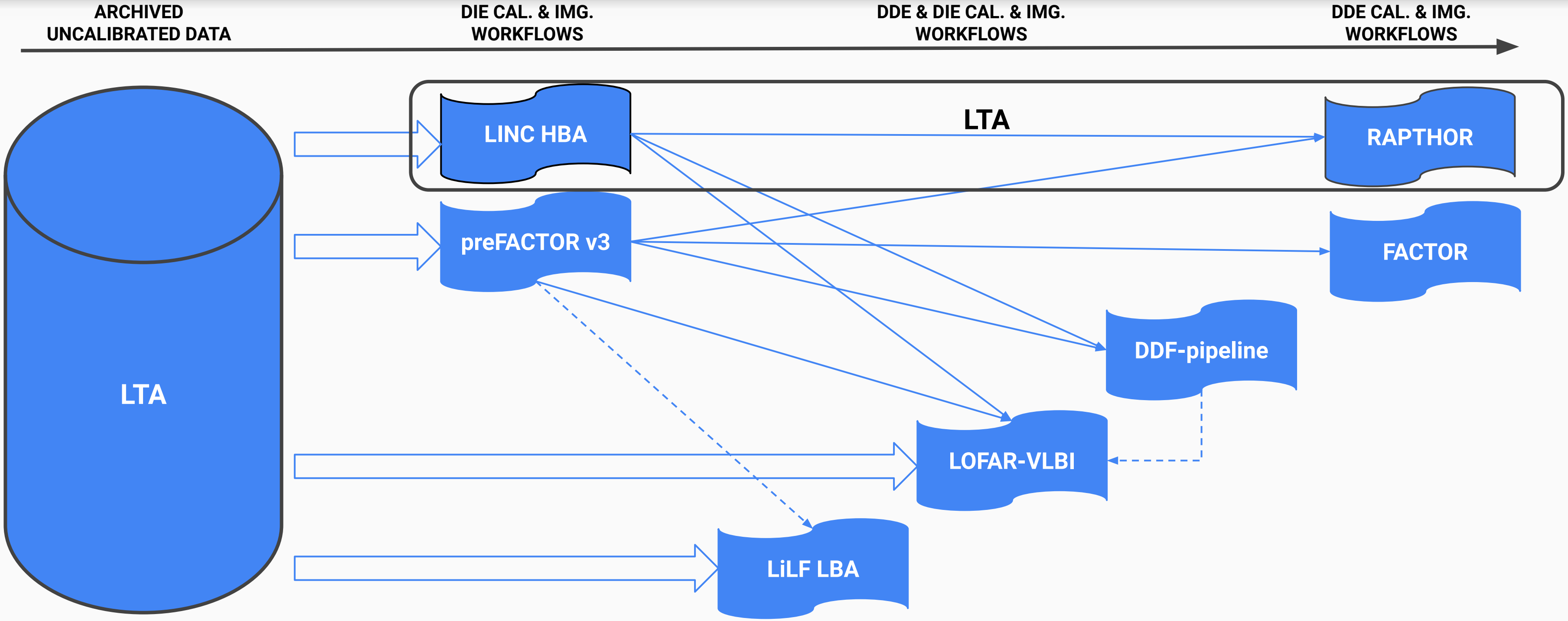
LTA
LINC HBA
preFACTOR v3
RAPTHOR
FACTOR
DDF-pipeline
LOFAR-VLBI
LiLF LBA

Introduction: available workflows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LOFAR-VLBI
LiLF LBA

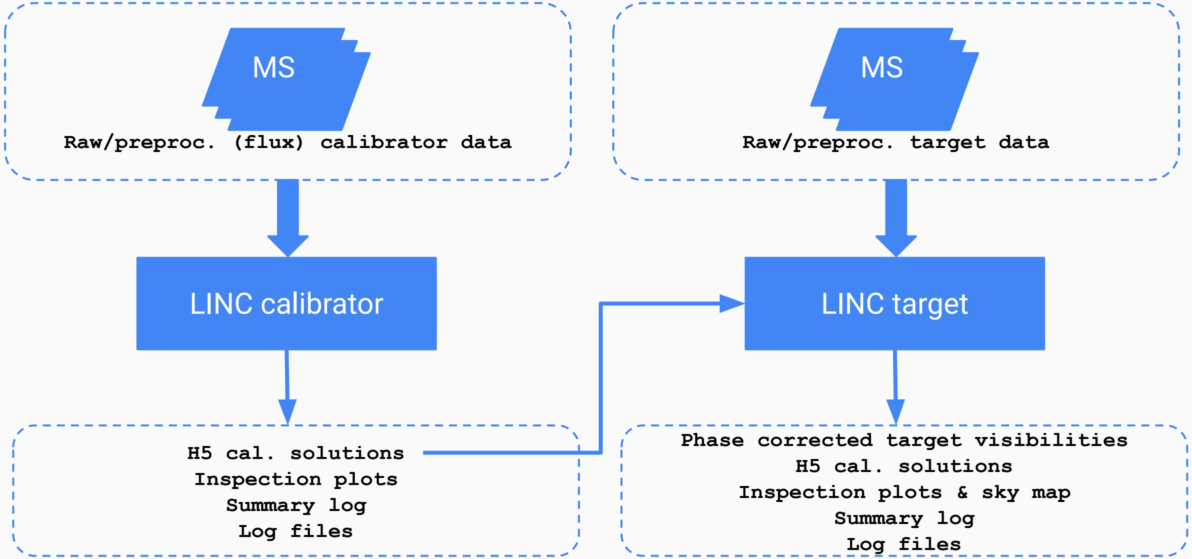
LINC (preFACTOR) workflows: an intro

LINC (preFACTOR) perform Direction-Independent cal. (& img.)

- Based on the unified-calibration scheme of de Gasperin et al. (2019)
- Supports multi-epoch datasets (interleaved or multiple nights)
- Designed to operate on HBA data (extension for LBA in progress)
- Prepare data to use any DDE calibration software (e.g. FACTOR, RAPTHOR, KillMS or LOFAR-VLBI)
- Main software packages used:
  - Default PreProcessing Pipeline (DPPP) to average, flag, calibrate, apply solutions
  - LOFAR Solution tools (LoSoTo) to analyse/extract parameters from calibration solutions

LINC (preFACTOR) workflows: an intro

LINC (preFACTOR) perform Direction-Independent cal. (& img.)



Pipeline consists of 2 workflows:

- LINC calibrator: processes the (flux) calibrator to derive DIE corrections.
- LINC target: Transfers the DIE corrections to the target; does phase self-calibration of the target.
- DIE calibrated target visibilities to be used for further DDE processing.

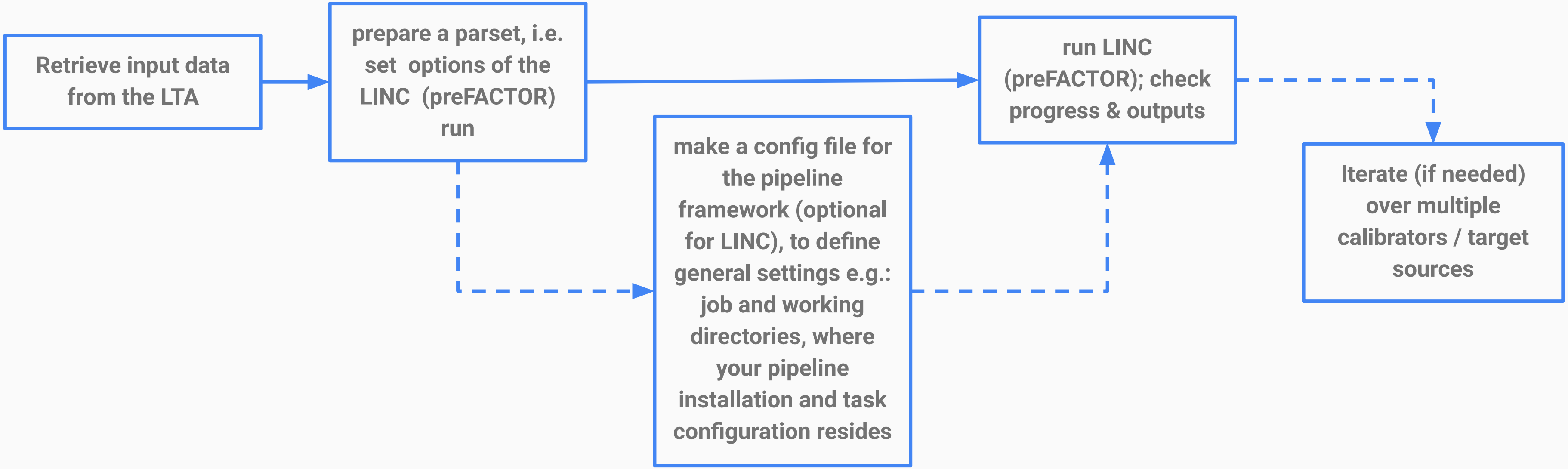
LINC (preFACTOR) workflows: an intro

LINC (preFACTOR) perform Direction-Independent cal. (& img.)

- preFACTOR uses LOFAR generic pipeline framework as backend:
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
  - Additional workflows → Init-Subtract to prepare data for FACTOR processing
- LINC uses CWL pipeline framework as backend:
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
  - Integrated Docker support

LINC (preFACTOR) workflows: an intro

Running LINC (preFACTOR) on a dataset generally involves the following basic steps:



Retrieve input data from the LTA

prepare a parset, i.e. set options of the LINC (preFACTOR) run

make a config file for the pipeline framework (optional for LINC), to define general settings e.g.: job and working directories, where your pipeline installation and task configuration resides

run LINC (preFACTOR); check progress & outputs

Iterate (if needed) over multiple calibrators / target sources

FACTOR workflow: an intro

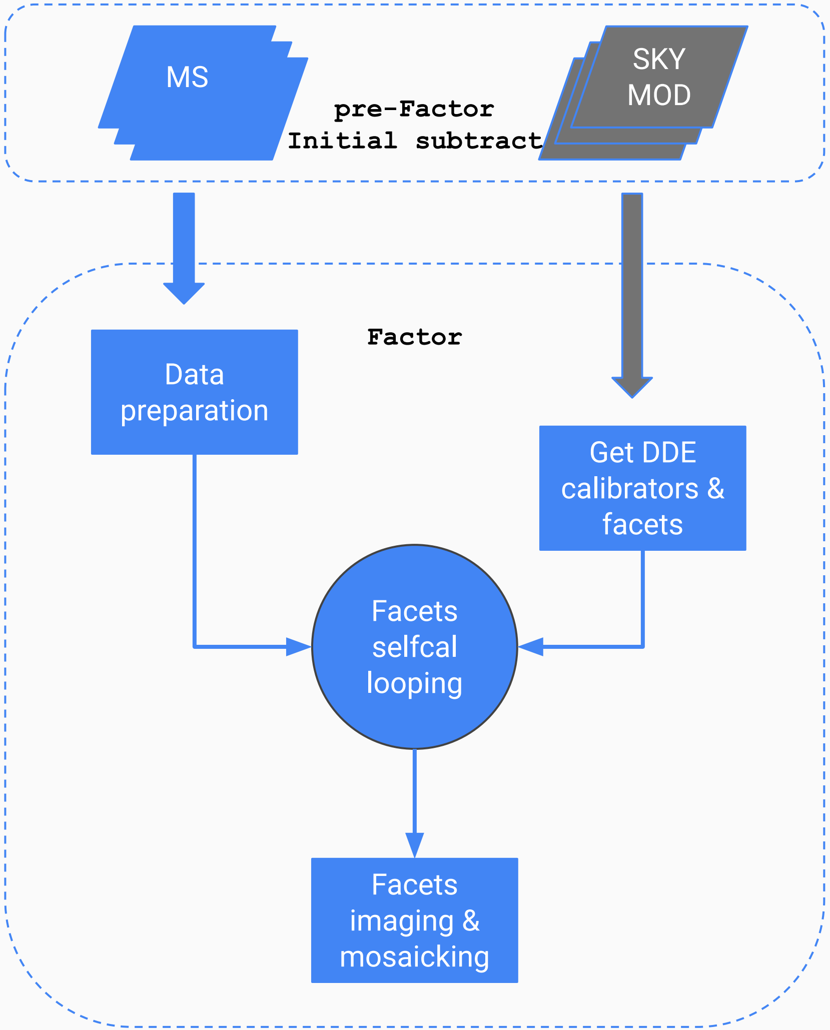
FACTOR performs Direction-Dependent calibration and imaging

- Based on the facet-calibration scheme of van Weeren et al. (2016)
- Supports multi-epoch datasets (interleaved or multiple nights)
- Designed to operate on HBA data only
- Recommended for targeted exposures
- Sub-optimal for:
  - full-field of view processing
  - very extended (e.g. >=1 deg) target sources (i.e. >1 facet needed)

FACTOR workflow: an intro

FACTOR performs Direction-Dependent calibration and imaging

- Uses Python for both backend and frontend:
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
- Available from GitHub at https://github.com/lofar-astron/factor
- Relatively modest resources required: 2 CPUs, 32 GB memory, 1TB of disk space

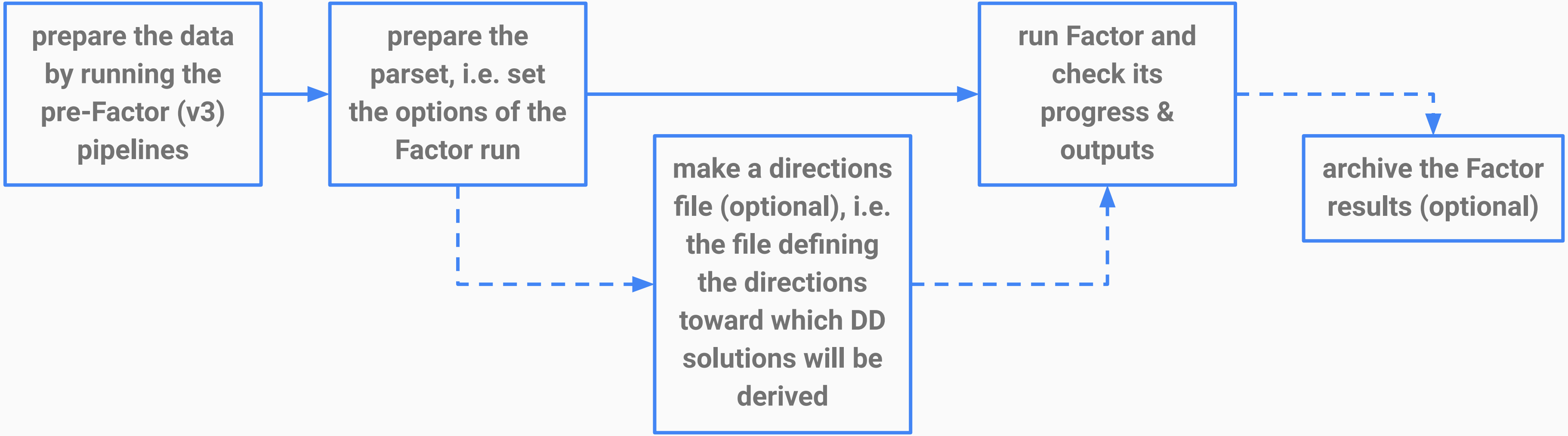


FACTOR workflow: an intro

- subtract best model of the sky (pre-FACTOR Initial-Subtract)
- divide field into facets based on bright DD calibrators
- cycle over facets:
  - add back the calibrator source
  - self calibrate the calibrator sources (`facetselfcal`)
  - add back the rest of the facet and apply calibration solutions
  - improve the subtraction with new model and calibration (`facetsub`)
- image the facets (`facetimage`)
- make a mosaic of all facets & correct for the primary beam attenuation (`fieldmosaic`)

FACTOR workflow: an intro

Using FACTOR on a dataset generally involves the following basic steps:



prepare the data by running the pre-Factor (v3) pipelines

prepare the parset, i.e. set the options of the Factor run

make a directions file (optional), i.e. the file defining the directions toward which DD solutions will be derived

run Factor and check its progress & outputs

archive the Factor results (optional)

LOFAR-VLBI workflow: an intro

LOFAR-VLBI performs full array Direction-(In)Dependent calib. & img.

- Based on the VLBI principles & LOFAR adapted scheme of Morabito et al. (2021)
- Supports multi-epoch datasets (interleaved or multiple nights)
- Designed to operate on HBA data (extension for LBA in progress)
- Recommended for targeted exposures
- Sub-optimal for:
    - full-field of view processing
    - faint (i.e. S/N<10) target sources away (i.e. >1.5deg) from the delay-calibrator

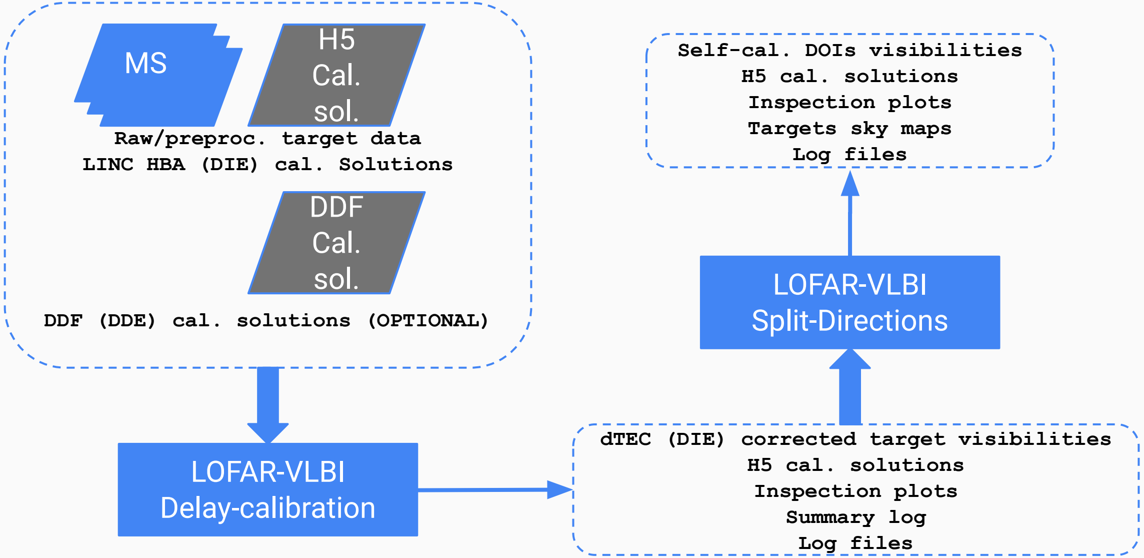
LOFAR-VLBI workflow: an intro

LOFAR-VLBI performs full array Direction-(In)Dependent calib. & img.

- Uses LOFAR generic pipeline framework as backend (a CWL version is in progress):
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
- Available from GitHub at https://github.com/lmorabit/lofar-vlbi
- Large resources required: 32 cores, 192 GB memory, >10TB of disk space

LOFAR-VLBI workflow: an intro

LOFAR-VLBI performs full array Direction-(In)Dependent calib. & img.



MS

H5 Cal. sol.

Raw/preproc. target data
LINC HBA (DIE) cal. Solutions

DDF Cal. sol.

DDF (DDE) cal. solutions (OPTIONAL)

LOFAR-VLBI Delay-calibration

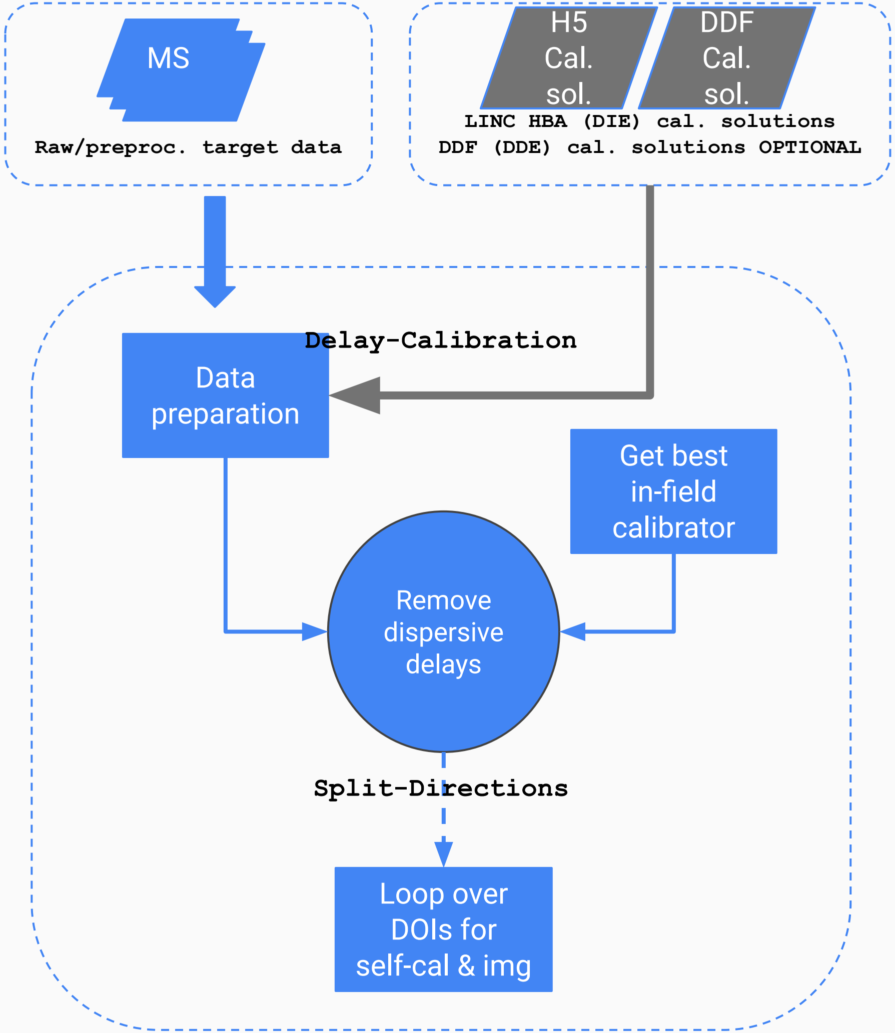
dTEC (DIE) corrected target visibilities
H5 cal. solutions
Inspection plots
Summary log
Log files

LOFAR-VLBI Split-Directions

Self-cal. DOIs visibilities
H5 cal. solutions
Inspection plots
Targets sky maps
Log files

Pipeline consists of 2 workflows:

- Delay-Calibration: processes the input data to find the best in-field calibrator and remove dispersive delays over the FoV.
- Split-Directions: phase shift over a set of directions of interest (DOIs); does phase self-calibration (amp & phases) & imaging.



LOFAR-VLBI workflow: an intro

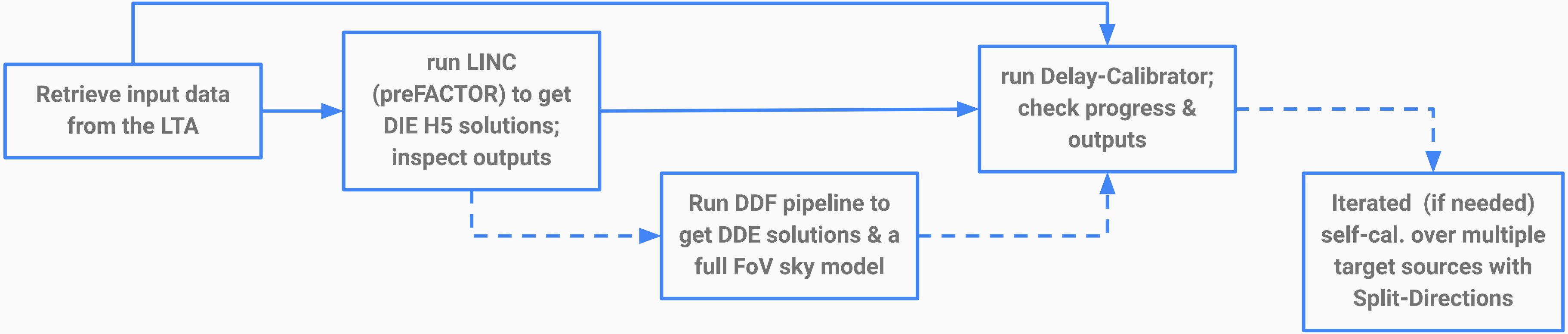
- apply solutions
- build a list of potential in-field calibrators
- for the best guessed in-field calibrator:
  - phase-shift to the direction
  - average time/freq
  - correct beam array-factor
  - combine CS into a ST & remove CS
- solve for dispersive delays (dTEC)

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\underbrace{\frac{d\phi}{d\nu}}_{\text{Delay}}\Delta\nu + \underbrace{\frac{d\phi}{dt}}_{\text{Rate}}\Delta t\right)$$

- apply delay calibrator solutions
- for the selected DOIs:
  - phase-shift to the direction
  - solve for residual dispersive delays
  - self-cal (amp.&phase) with imaging

LOFAR-VLBI workflow: an intro

Running LOFAR-VLBI on a dataset generally involves the following basic steps:



Retrieve input data from the LTA

run LINC (preFACTOR) to get DIE H5 solutions; inspect outputs

Run DDF pipeline to get DDE solutions & a full FoV sky model

run Delay-Calibrator; check progress & outputs

Iterated (if needed) self-cal. over multiple target sources with Split-Directions

DDF-pipeline workflow: an intro

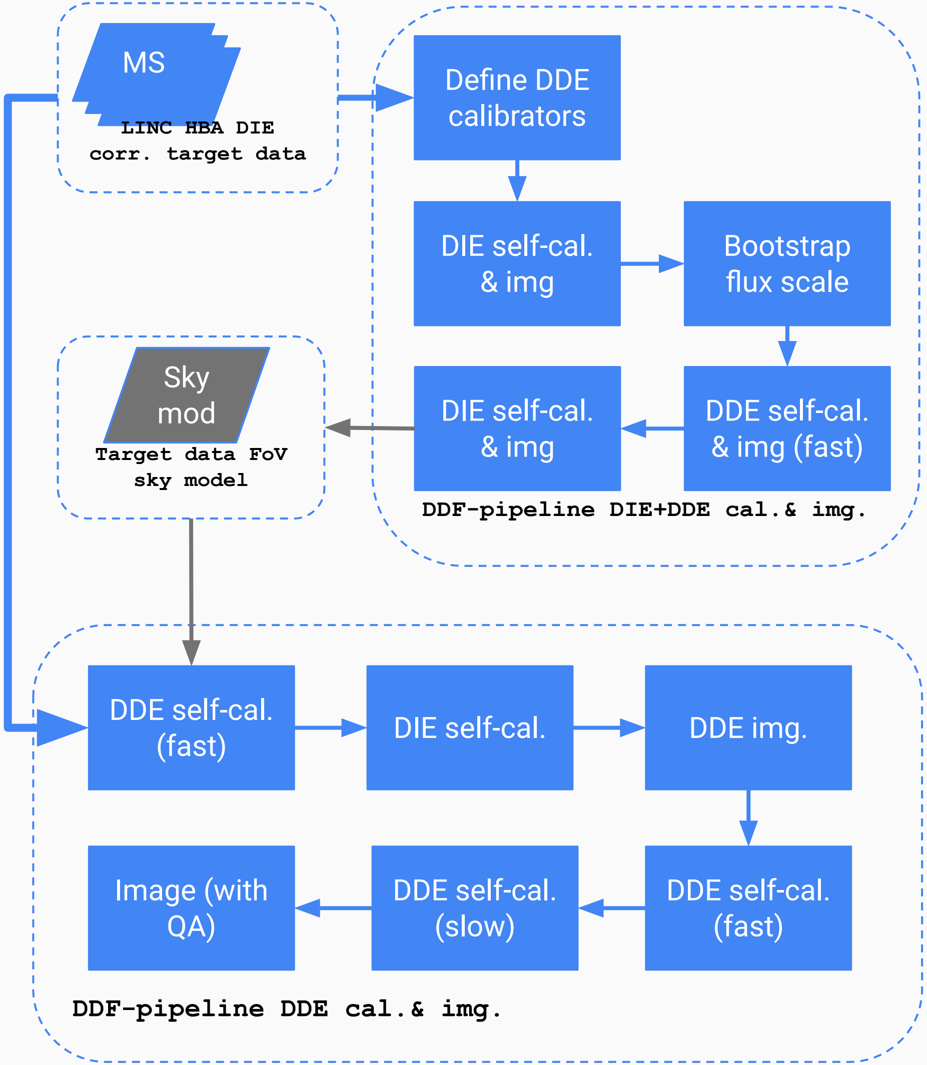
DDF-pipeline performs CS&RS array Direction-(In)Dependent calib. & img.

- Based on the calibration scheme of Tasse et al. (2021)
- Supports multi-epoch datasets (interleaved or multiple nights)
- Designed to operate on HBA data
- Recommended for full-field of view processing
- Sub-optimal for:
    - LBA processing

DDF-pipeline workflow: an intro

DDF-pipeline performs CS&RS array Direction-(In)Dependent calib. & img.

- Uses a Python for both backend and frontend:
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
- Available from GitHub at https://github.com/mhardcastle/ddf-pipeline
- Large resources required: 32 cores, 192 GB memory, 10TB of disk space



DDF-pipeline workflow: an intro

- Sub-dataset self-cal. & imaging:
  - Get DDE calibrators & facets
  - DIE self-cal. & imaging
  - DDE self-cal. (phase only) & img.
  - DIE self-cal. & imaging
  - Improved DIE solutions & sky model
- Full dataset self-cal. & imaging:
  - DDE+DIE self-cal.
  - DDE imaging
  - Fast DDE self-cal.
  - Slow DDE self-cal.
  - Full field imaging (& quality checks)

RAPTHOR workflow: an intro

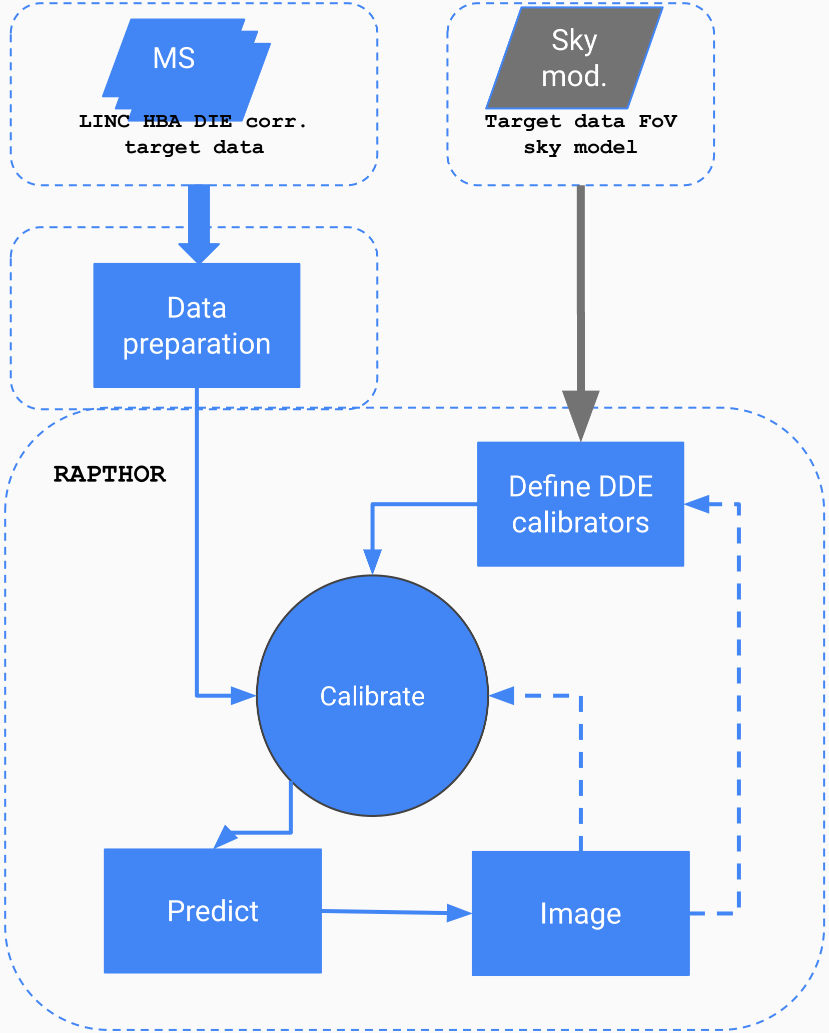
RAPTHOR performs CS&RS array Direction-(In)Dependent calib. & img.

- Based on the calibration scheme of de Gasperin et al. (2020)
- Supports multi-epoch datasets (interleaved or multiple nights)
- Designed to operate on HBA and LBA data
- Recommended for full-field of view processing
- Sub-optimal for:
    - very extended (e.g. >=1 deg) target sources (i.e. >1 facet needed)

RAPTHOR workflow: an intro

RAPTHOR performs CS&RS array Direction-(In)Dependent calib. & img.

- Uses a Python wrapper around CWL pipelines as backend:
  - The wrapper sets up & executes the pipelines as “operations” to perform the actual processing
  - Allows distribution over cluster nodes
  - Allows resuming of interrupted jobs
- Available from GitHub at https://git.astron.nl/RD/rapthor
- Large resources required: 20 cores, 192 GB memory, 1TB of disk space



RAPTHOR workflow: an intro

- Get list of DDE calibrators from sky model
  - Divide field into facets
- Iterative self-calibration:
  - Performed in multiple directions (facets) simultaneously
  - Each facet gets a single calibration solution
  - Fits smooth, 2-D screens to the calibration solutions
  - Screens are derived separately for each station
  - Full field imaging using smooth 2-D screens of corrections (to correct for DDE effects)
  - Get a sky model to (eventually) loop

Outline

LOFAR overview

A “next generation facility”

The system

LOFAR data processing workflows

DIE & DDE calibration/imaging in a nutshell

Overview of available recipes

Tutorial handout

Training datasets

LOFAR processing software

Training workflows (LINC / preFACTOR / FACTOR)

To get started

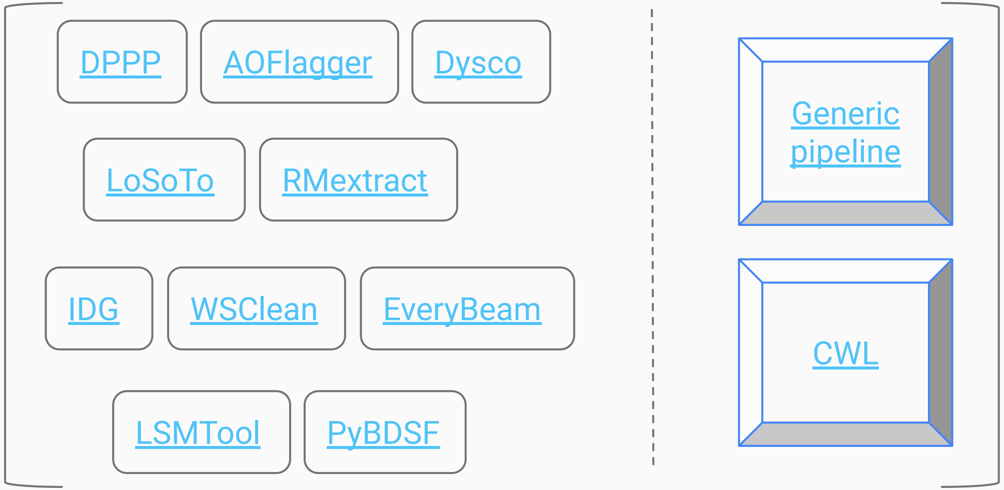
- Make a directory in your area to hold the
  - parset(s) + (eventually) config files
  - LINC / preFACTOR input data (16GB) & output (+8GB)
  - FACTOR input data (10GB) & output (+10GB)
- Open in your web browser the online view to the Grid Storage data repository and the full documentation
  - https://linc.readthedocs.io/en/latest/ for LINC / preFACTOR
  - https://www.astron.nl/citt/facet-doc/ for FACTOR

Input data

- Collect input data in a single directory
  - LINC / preFACTOR input data are:
    - 244 subbands (= 0.2 MHz) of a snapshot (10-min) HBA observation of the 3C48 calibrator source, averaged to 48.8 kHz and 2s per timeslot
  - FACTOR input data are:
    - 23 subband groups (= 2 MHz) of a snapshot (10-min) HBA observation of the PSR0329+54
    - Averaged after DIE calib. to 0.05 MHz per channel and 8 s per timeslot

LOFAR processing software

A landscape of customised software components and (currently) two pipeline frameworks to create workflows.



Use of software containers effective to enable:

- portability and interoperability,
- reproducibility and reusability

Available (mix of) options for pre-built containers:

- Docker and Singularity

For this tutorial, ASTRON repository `astronrd` on Docker hub to pull images

Preparing the parset / config files - LINC

- LINC configuration file
  - a JSON file with minimum required input the input data to be processed
  - to run a target pipeline the calibrator solution set must also be provided

```
{
     "msin": [
               {"class": "Directory", "path": "3C286/L228161_SB000_uv.MS"},
               {"class": "Directory", "path": "3C286/L228161_SB001_uv.MS"},
               . . .
               {"class": "Directory", "path": "3C286/L228161_SB099_uv.MS"}
          ],
     "cal_solutions": {"class": "File", "path": "cal_solutions.h5"}

}
```

Running LINC

- Enter a screen session

```
$ screen [+enter]
```

- Initialise your Docker (Singularity) environment, mounting your LINC directory

```
$ docker pull astronrd/linc
$ docker run --rm -it -v $PWD:$PWD astronrd/linc /bin/bash
$ cd <to>/<your>/<working dir>
```

- Run LINC in the screen session with the parset you made

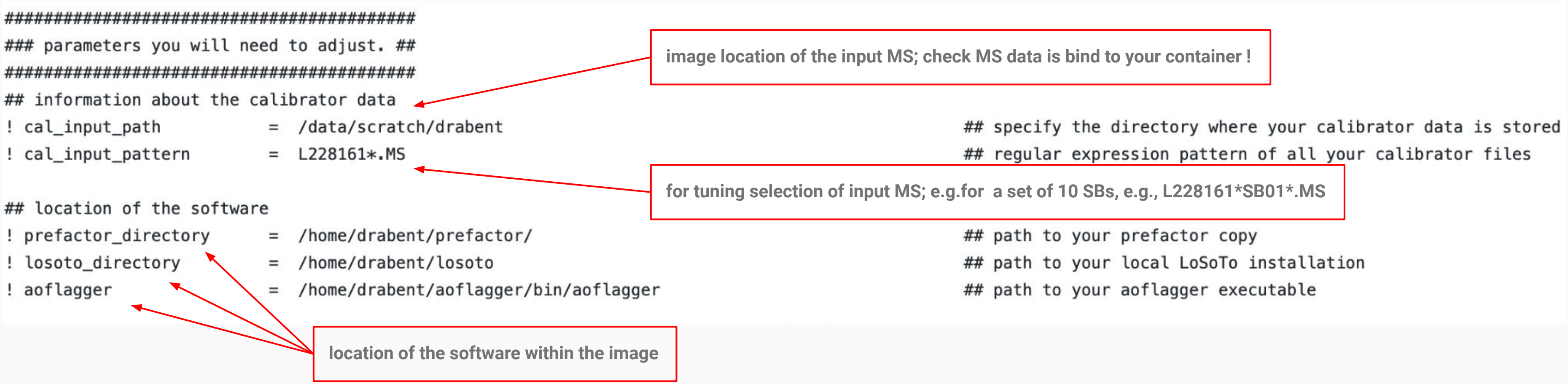
```
$ cwltool --preserve-entire-environment --outdir /<to>/<your>/<working dir>
--tmpdir-prefix /<to>/<your>/<tmp>/ --no-container
/usr/local/share/linc/workflows/HBA_calibrator.cwl LINC-calib.json
```

- Exit from the screen (CTRL-A CTRL-D)

Preparing the parset / config files - preFACTOR

preFACTOR parset & configuration files

- organised in sections; prefilled and to be adjusted
- mandatory sections are at the top & pipeline performance ones



```
##########################################
### parameters you will need to adjust. ##
##########################################
## information about the calibrator data
! cal_input_path            =  /data/scratch/drabent                                 ## specify the directory where your calibrator data is stored
! cal_input_pattern         =  L228161*.MS                                           ## regular expression pattern of all your calibrator files

## location of the software
! prefactor_directory       =  /home/drabent/prefactor/                              ## path to your prefactor copy
! losoto_directory          =  /home/drabent/losoto                                  ## path to your local LoSoTo installation
! aoflagger                 =  /home/drabent/aoflagger/bin/aoflagger                 ## path to your aoflagger executable
```

image location of the input MS; check MS data is bind to your container !

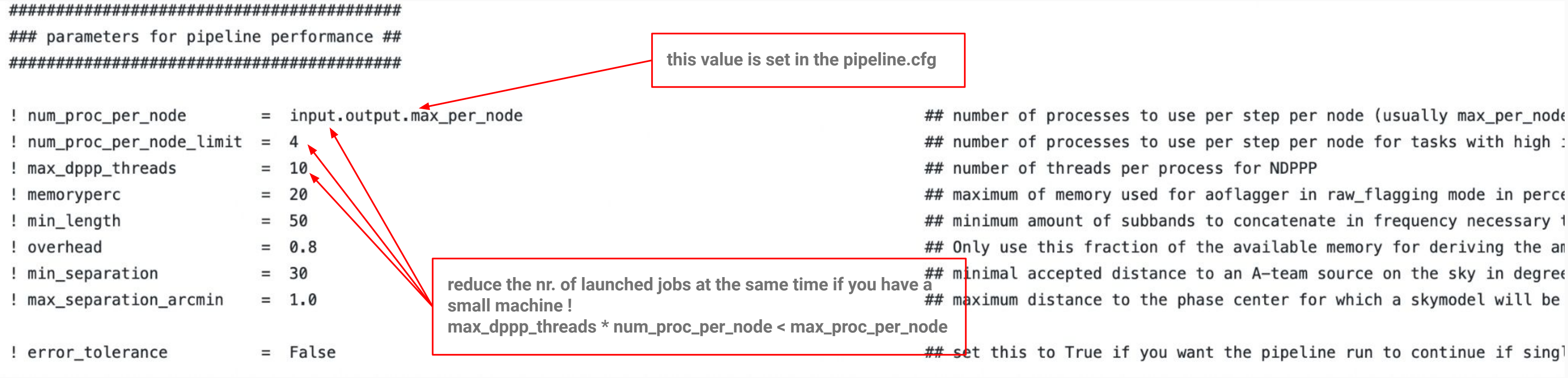
for tuning selection of input MS; e.g.for a set of 10 SBs, e.g., L228161*SB01*.MS

location of the software within the image

Preparing the parset / config files - preFACTOR

preFACTOR parset & configuration files

- organised in sections; prefilled and to be adjusted
- mandatory sections are at the top & pipeline performance ones



```
##########################################
### parameters for pipeline performance ##
##########################################

! num_proc_per_node         =  input.output.max_per_node                                 ## number of processes to use per step per node (usually max_per_node
! num_proc_per_node_limit   =  4                                                         ## number of processes to use per step per node for tasks with high i
! max_dppp_threads          =  10                                                        ## number of threads per process for NDPPP
! memoryperc                =  20                                                        ## maximum of memory used for aoflagger in raw_flagging mode in perce
! min_length                =  50                                                        ## minimum amount of subbands to concatenate in frequency necessary t
! overhead                  =  0.8                                                       ## Only use this fraction of the available memory for deriving the am
! min_separation            =  30                                                        ## minimal accepted distance to an A-team source on the sky in degree
! max_separation_arcmin     =  1.0                                                       ## maximum distance to the phase center for which a skymodel will be

! error_tolerance           =  False                                                     ## set this to True if you want the pipeline run to continue if singl
```

this value is set in the pipeline.cfg

reduce the nr. of launched jobs at the same time if you have a small machine !
max_dppp_threads * num_proc_per_node < max_proc_per_node

Preparing the parset / config files - preFACTOR

preFACTOR parset & configuration files

- organised in sections; prefilled and to be adjusted
- mandatory sections are at the top & pipeline performance ones

Many more parameters can be optimised under the sections

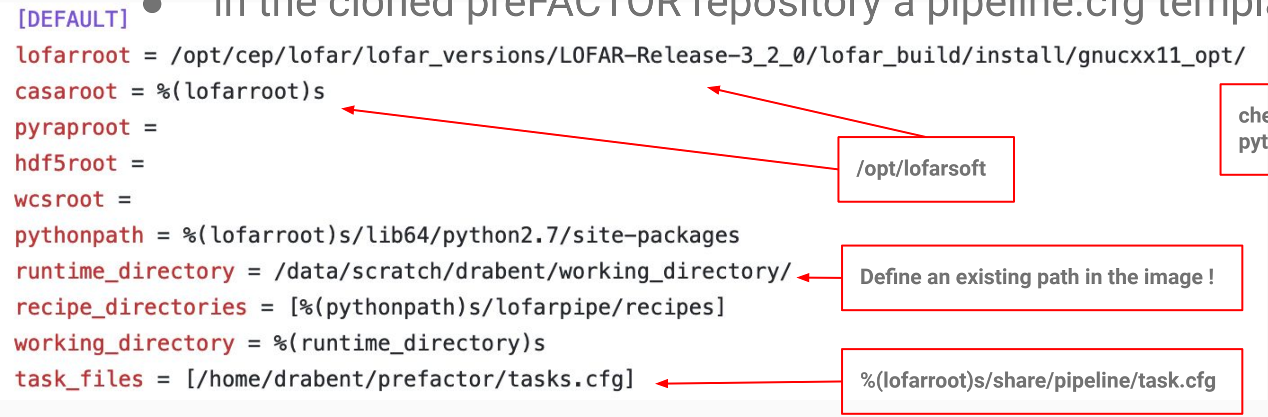
- `parameters you may need to adjust`
- `parameters you may want to adjust`

if issues are found when calibrating data !

Preparing the parset / config files - preFACTOR

preFACTOR parset & configuration files

- organised in sections; prefilled and to be adjusted
  `[DEFAULT], [layout], [cluster], [deploy], [logging], [feedback], [remote]`
- in the cloned preFACTOR repository a pipeline.cfg template is found



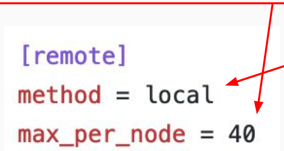
```
[DEFAULT]
lofarroot = /opt/cep/lofar/lofar_versions/LOFAR-Release-3_2_0/lofar_build/install/gnucxx11_opt/
casaroot = %(lofarroot)s
pyraproot =
hdf5root =
wcsroot =
pythonpath = %(lofarroot)s/lib64/python2.7/site-packages
runtime_directory = /data/scratch/drabent/working_directory/
recipe_directories = [%(pythonpath)s/lofarpipe/recipes]
working_directory = %(runtime_directory)s
task_files = [/home/drabent/prefactor/tasks.cfg]
```

/opt/lofarsoft

Define an existing path in the image !

%(lofarroot)s/share/pipeline/task.cfg

check resources
python3 -c 'import multiprocessing as mp; print(mp.cpu_count())'



```
[remote]
method = local
max_per_node = 40
```

run on a local machine

Running preFACTOR calibrator

- Enter a screen session

```
$ screen [+enter]
```

- Initialise your Docker (Singularity) environment (you may try the lds-img.sif)

```
$ singularity shell --bind /<your>/<dir>/,/<your>/<dir>/lds-img.sif
$ source /opt/lofarsoft/lofarinit.sh
$ cd <to>/<your>/<working dir>
```

load software environment first !

- Run preFACTOR in the screen session with the parset & config. file you made

```
$ genericpipeline.py -v -d Pre-Facet-Calibrator.parset -c pipeline.cfg
```

- Exit from the screen (CTRL-A CTRL-D)

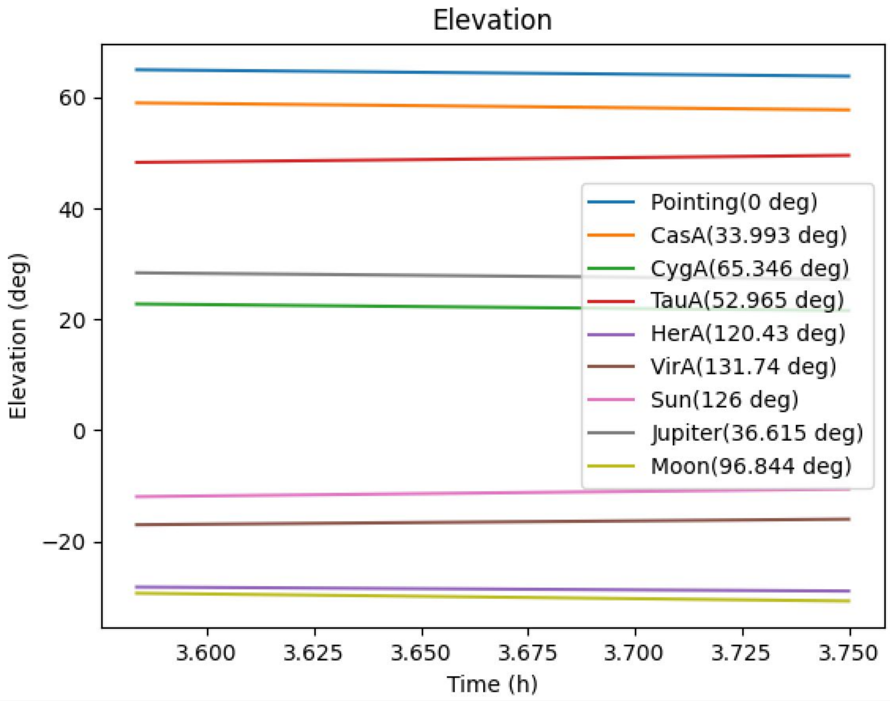
Running LINC / preFACTOR calibrator

The run makes tmp and final directories. Results (diagnostic plots & calibration solutions) are stored in the `--outdir` directory specified via the cwltool/toil command (LINC) or config. file (preFACTOR).

The (calibrator) pipeline derive DIE corrections following the correct order of distortions to be calibrated for. At each main step diagnostic plots are created.

Main steps are:

```
[data preparation]
     [correct for polarization alignment (PA)]
          [correct for Faraday Rotation (FR)]
               [correct for bandpass (BP)]
                    [correct for ionospheric disturbances (ion)]
```

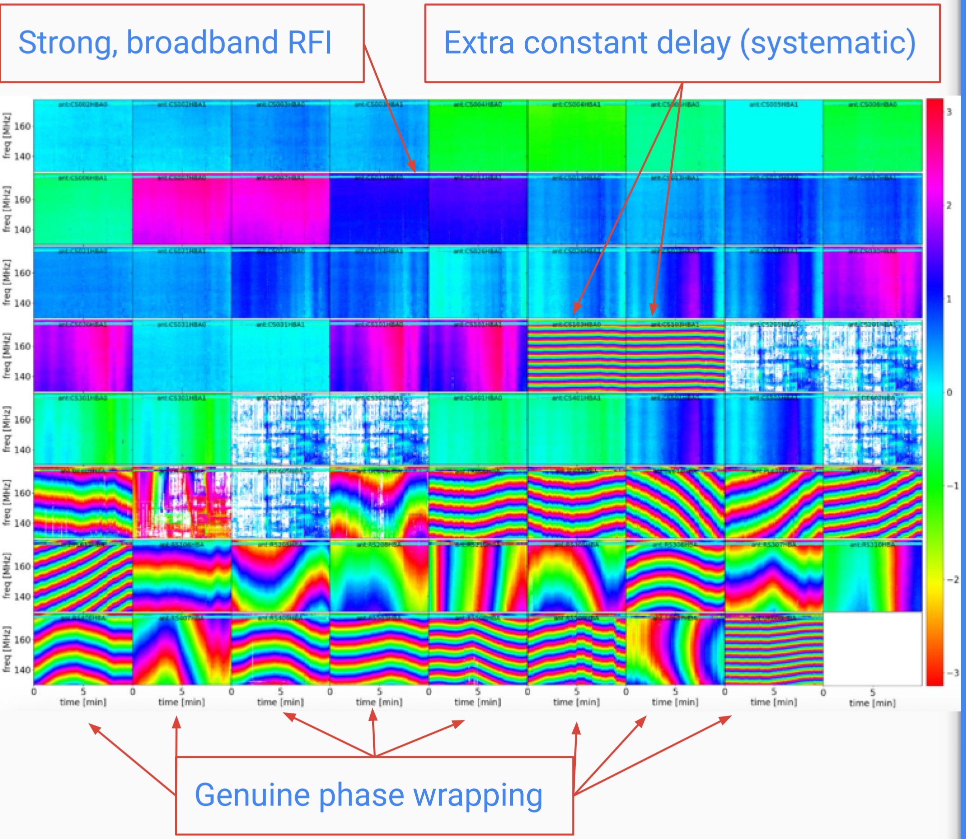


A-Team_elevation_calibrator.png

LINC / preFACTOR diagnostics

Data preparation step:

- determine suitable calibrator skymodel
- checking for nearby A-Team sources
- basic flagging (low elevation flagging, demix A-Team sources, wide-band statistical flagging) and averaging



Strong, broadband RFI

Extra constant delay (systematic)

Genuine phase wrapping

polalign_ph_polXX.png

LINC / preFACTOR diagnostics

Polarisation alignment (PA) step:

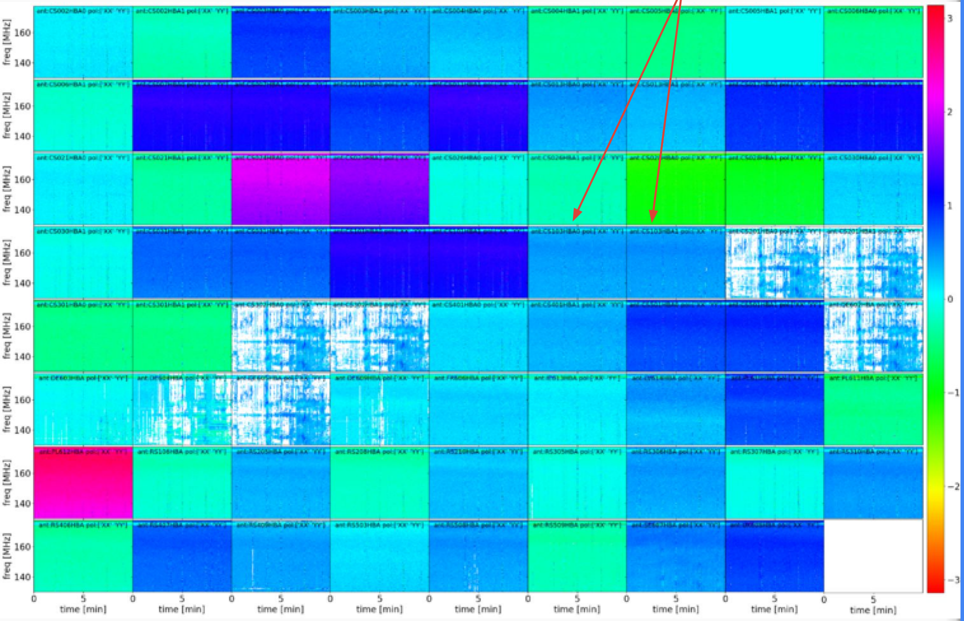
- Perform DIE phase-only calibration (diagonal terms + common rotation angle)
- Phase solutions processed in LoSoTo provide diagnostic plots:
  - **matrix plot of the phase solutions for the XX and YY polarization**
  - polalign_ph_poldif: matrix plot of the phase solutions from XX-YY
  - polalign: matrix plot of the derived polarization alignment between XX and YY

LINC / preFACTOR diagnostics

Polarisation alignment (PA) step:

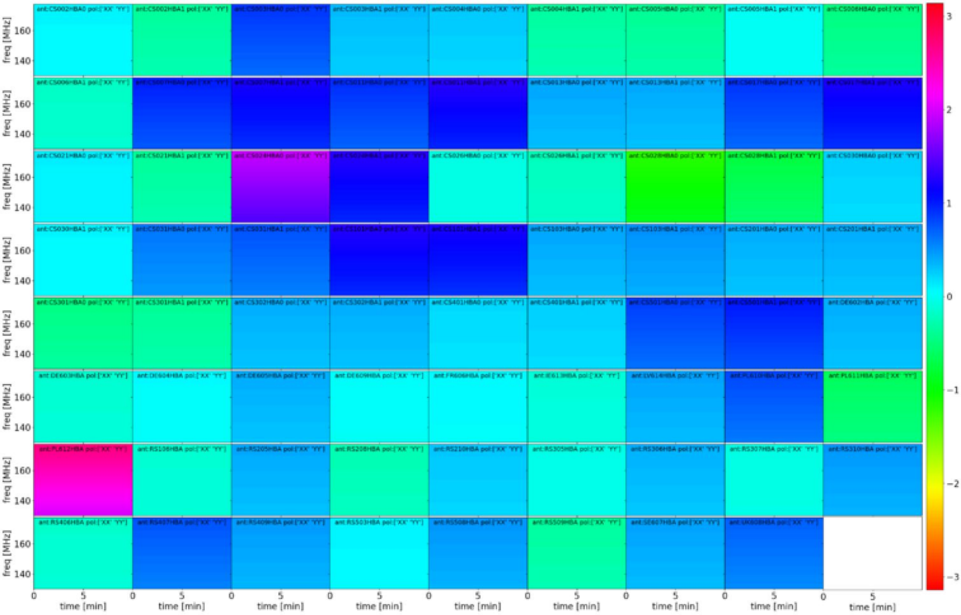
- Perform DIE phase-only calibration (diagonal terms + common rotation angle)
- Phase solutions processed in LoSoTo provide diagnostic plots:
  - matrix plot of the phase solutions for the XX and YY polarization
  - **matrix plot of the phase solutions from XX-YY**
  - matrix plot of the derived polarization alignment between XX and YY

Extra constant delay (systematic)



No time / frequency dependency left on diff phases

polalign_ph_poldif.png



No time / frequency dependency left on diff phases

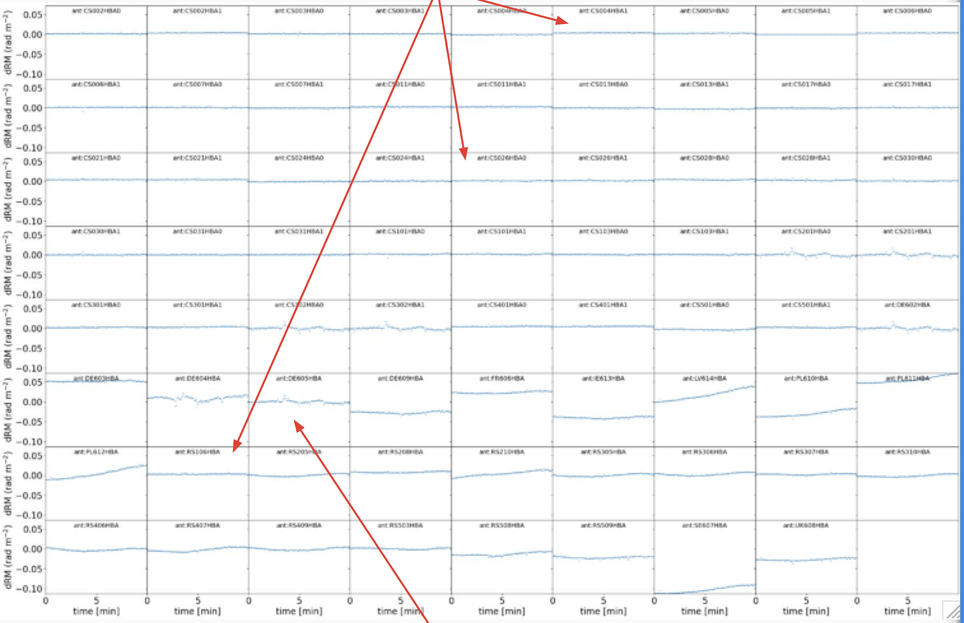
polalign.png

LINC / preFACTOR diagnostics

Polarisation alignment (PA) step:

- Perform DIE phase-only calibration (diagonal terms + common rotation angle)
- Phase solutions processed in LoSoTo provide diagnostic plots:
  - matrix plot of phase solutions for the XX and YY polarization
  - matrix plot of phase solutions from XX-YY
  - **matrix plot of the derived polarization alignment between XX and YY**

Flat dRM profile with no offset for short (<10km) baselines



High accuracy over a broad range of time scales !

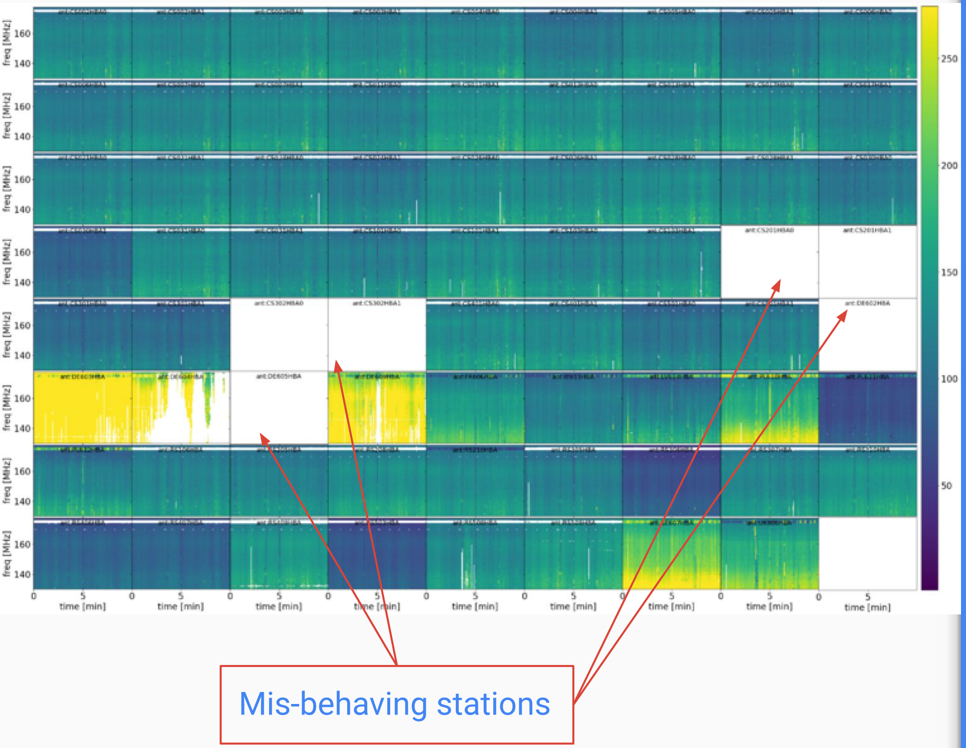
fr.png

LINC / preFACTOR diagnostics

Faraday Rotation (FR) step:

- Apply PA solutions & beam
- Perform DIE phase-only calibration (diagonal terms + common rotation angle)
- Phase solutions processed in LoSoTo provide diagnostic plot:
  - **matrix plot of the derived differential Rotation Measure from Faraday Rotation**

LINC / preFACTOR diagnostics



Mis-behaving stations

ampBFlag_polXX.png

Bandpass (BP) step:

- Apply PA sols. & beam & FR sols.
- Perform flagging & filtering on amp. sols. to reject bad/smooth good ones
- Perform DIE single scalar phase calibration
- Sols. transfer for IS for non-trusted calibrator sources
- Phase solutions processed in LoSoTo provide diagnostic plot:
  - **matrix plot of the amplitude solutions for the XX and YY polarisation after flagging**
  - matrix plot of the amplitude solutions for the XX and YY polarisation after flagging
  - matrix plot of the derived bandpass for XX and YY polarisations

LINC / preFACTOR diagnostics

Bandpass (BP) step:

- Apply PA sols. & beam & FR sols.
- Perform flagging & filtering on amp. sols. to reject bad/smooth good ones
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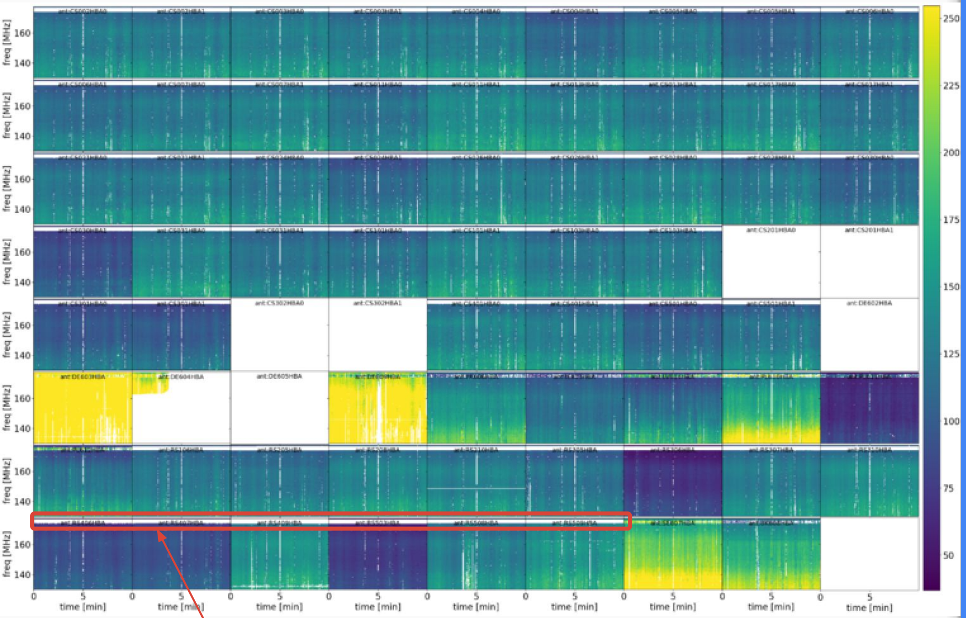
  - **matrix plot of the amplitude solutions for the XX and YY polarisation after flagging**
  - matrix plot of the derived bandpass for XX and YY polarisations

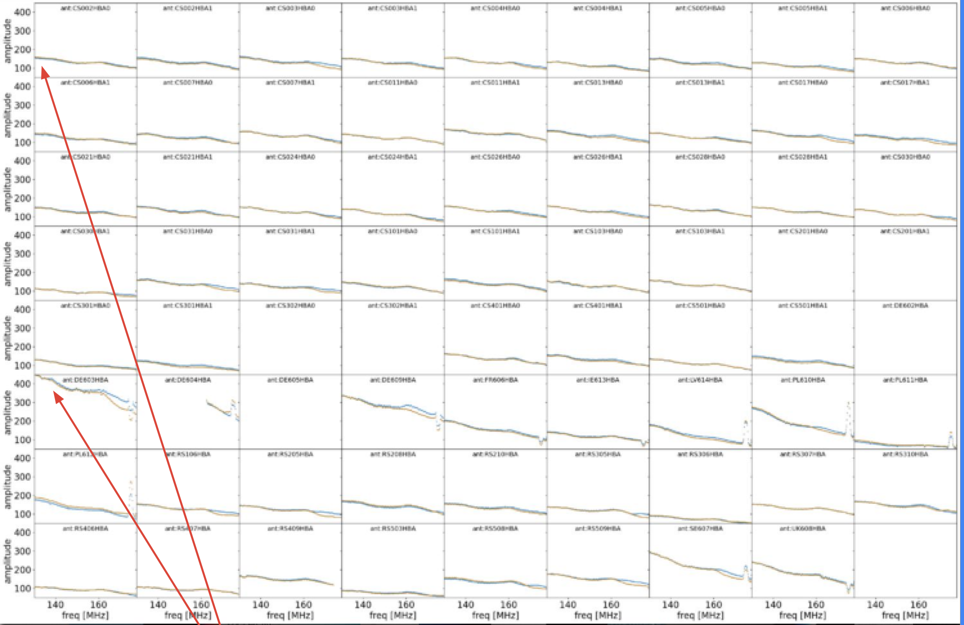
Removal of outliers scales down the amplitudes



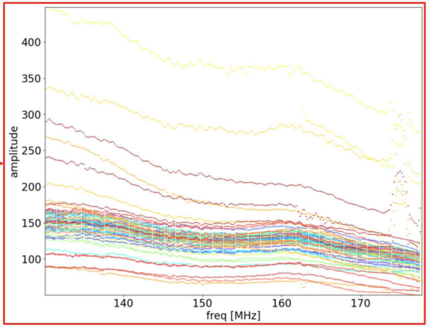
Strong, broadband RFI (DAB) around 175 MHz

ampAFlag_polXX.png

LINC / preFACTOR diagnostics



Different amplitude ranges for CS / RS /IS ! Check plots of the derived polarisation bandpasses for comparison

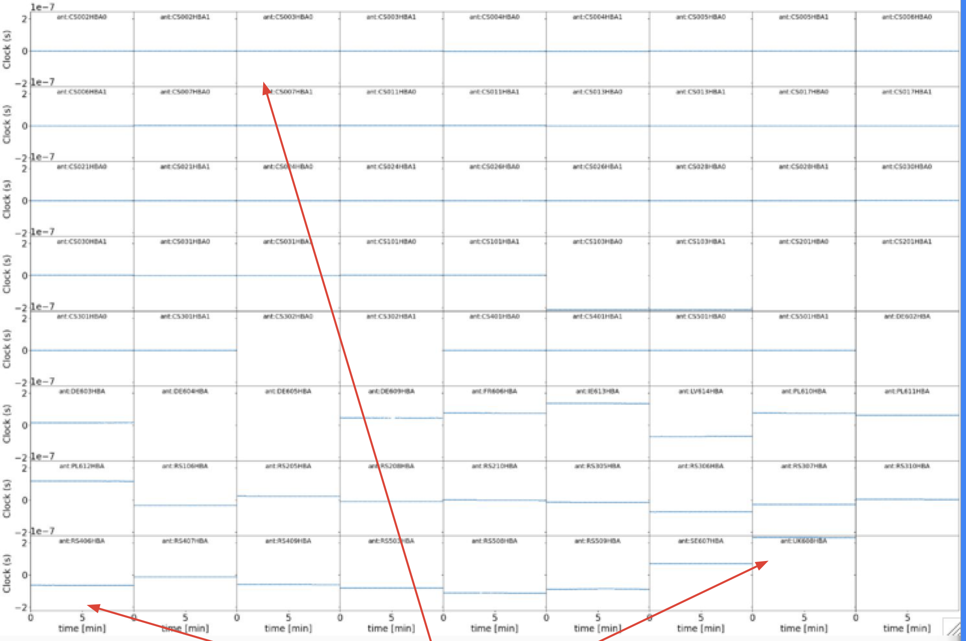


bandpass_time<JD>.png

Bandpass (BP) step:

- Apply PA sols. & beam & FR sols.
- Perform flagging & filtering on amp. sols. to reject bad/smooth good ones
- Perform DIE single scalar phase calibration
- Sols. transfer for IS for non-trusted calibrator sources
- Phase solutions processed in LoSoTo provide diagnostic plot:
    - matrix plot of the amplitude solutions for the XX and YY polarisation after flagging
    - matrix plot of the amplitude solutions for the XX and YY polarisation after flagging
    - **matrix plot of the derived bandpass for XX and YY polarisations**

$$\Delta\text{phase}(\nu, t) = \boxed{2\pi p_0(t)\nu} - \frac{8.448 \cdot 10^9 p_1(t)}{\nu}[\text{rad}]$$



No clock offsets for CS. Different clock offsets for RS /IS !

clock.png

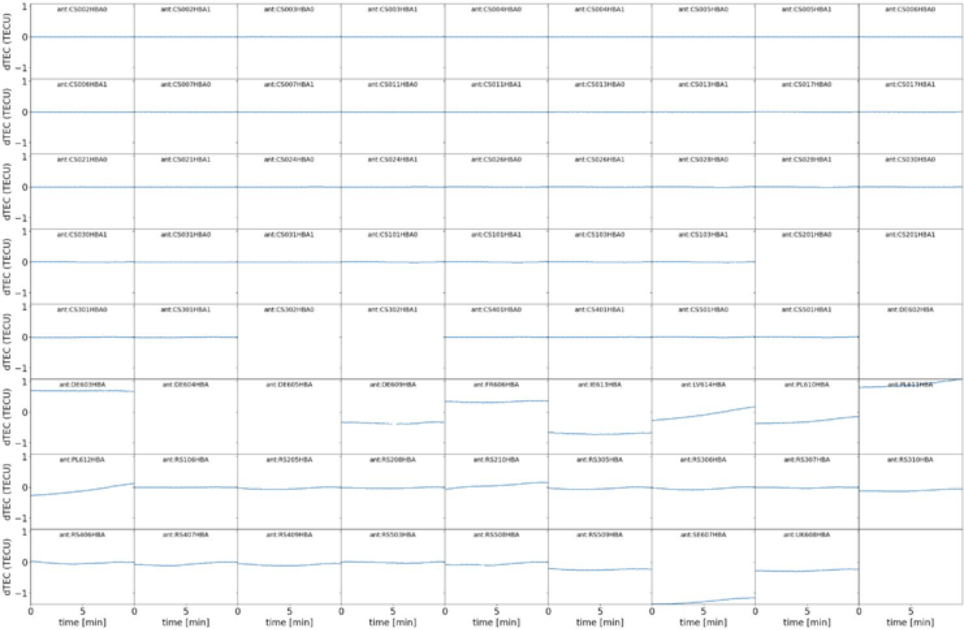
LINC / preFACTOR diagnostics

Ionospheric disturbances (Ion) step:

- Apply PA & bandpass sols., the element beam correction and the FR sols.
- Perform DIE single scalar phase calibration
- Phase solutions processed in LoSoTo provide diagnostic plot:
  - **matrix plot of the derived (instrumental) clock offsets [s]**
  - matrix plot of the derived differential TEC [TECU]
  - matrix plot of the residual phase solutions after the subtraction of the derived instrumental & ionospheric delays

LINC / preFACTOR diagnostics

$$\Delta\text{phase}(\nu, t) = 2\pi p_0(t)\nu - \boxed{\frac{8.448 \cdot 10^9 p_1(t)}{\nu}}[\text{rad}]$$

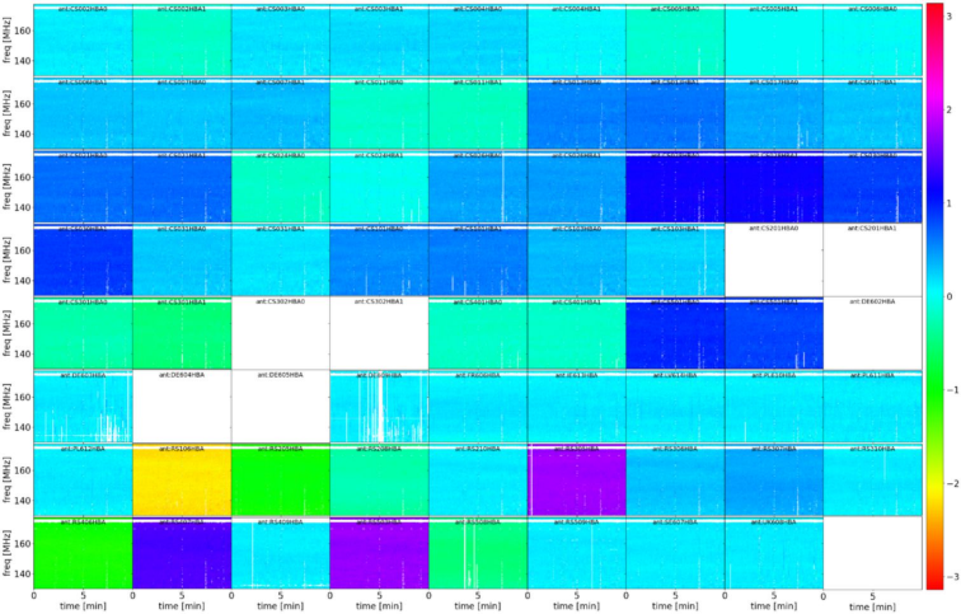


High accuracy over a broad range of time scales !

tec.png

Ionospheric disturbances (Ion) step:

- Apply PA & bandpass sols., the element beam correction and the FR sols.
- Perform DIE single scalar phase calibration
- Phase solutions processed in LoSoTo provide diagnostic plot:
  - matrix plot of the derived (instrumental) clock offsets [s]
  - **matrix plot of the derived differential TEC [TECU]**
  - matrix plot of the residual phase solutions after the subtraction of the derived instrumental & ionospheric delays



Only a phase offset left !

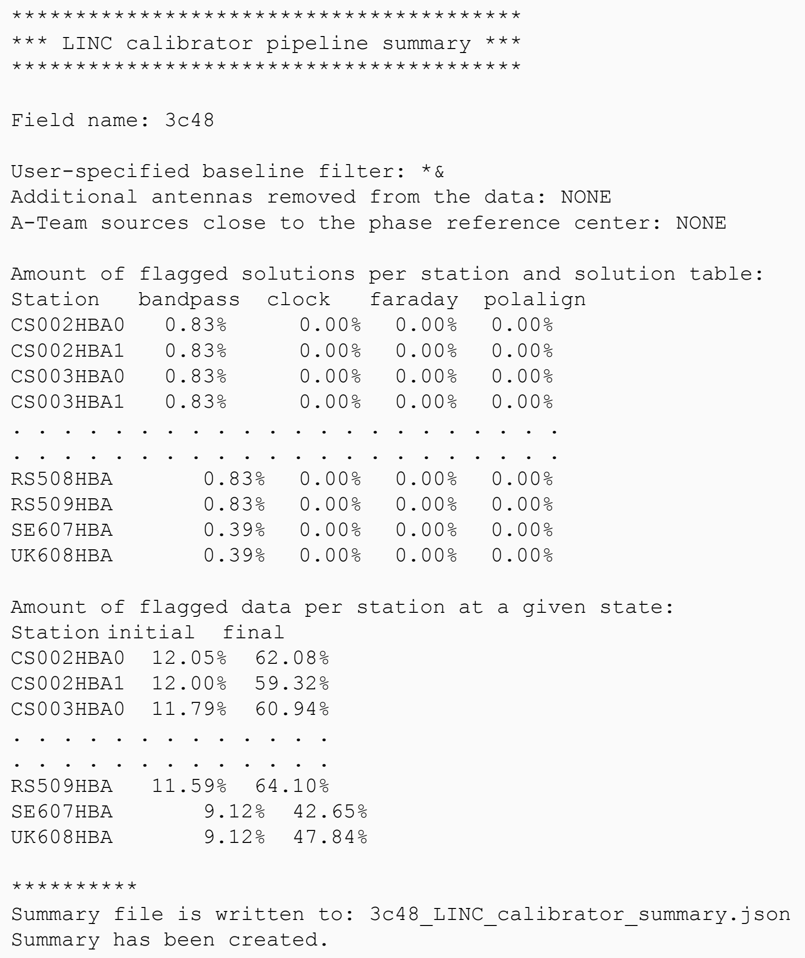
ion_ph-res.png

LINC / preFACTOR diagnostics

Ionospheric disturbances (Ion) step:

- Apply PA & bandpass sols., the element beam correction and the FR sols.
- Perform DIE single scalar phase calibration
- Phase solutions processed in LoSoTo provide diagnostic plot:
  - **matrix plot of the derived (instrumental) clock offsets [s]**
  - matrix plot of the derived differential TEC [TECU]
  - **matrix plot of the residual phase solutions after the subtraction of the derived instrumental & ionospheric delays**

LINC / preFACTOR diagnostics



```
****************************************
*** LINC calibrator pipeline summary ***
****************************************

Field name: 3c48

User-specified baseline filter: *&
Additional antennas removed from the data: NONE
A-Team sources close to the phase reference center: NONE

Amount of flagged solutions per station and solution table:
Station   bandpass  clock   faraday  polalign
CS002HBA0   0.83%      0.00%   0.00%   0.00%
CS002HBA1   0.83%      0.00%   0.00%   0.00%
CS003HBA0   0.83%      0.00%   0.00%   0.00%
CS003HBA1   0.83%      0.00%   0.00%   0.00%
. . . . . . . . . . . . . . . . . . . . . . .
. . . . . . . . . . . . . . . . . . . . . . .
RS508HBA       0.83%   0.00%   0.00%   0.00%
RS509HBA       0.83%   0.00%   0.00%   0.00%
SE607HBA       0.39%   0.00%   0.00%   0.00%
UK608HBA       0.39%   0.00%   0.00%   0.00%

Amount of flagged data per station at a given state:
Station initial  final
CS002HBA0  12.05%  62.08%
CS002HBA1  12.00%  59.32%
CS003HBA0  11.79%  60.94%
. . . . . . . . . . . . .
. . . . . . . . . . . . .
RS509HBA   11.59%  64.10%
SE607HBA       9.12%  42.65%
UK608HBA       9.12%  47.84%

**********
Summary file is written to: 3c48_LINC_calibrator_summary.json
Summary has been created.
```

logs/<calibrator source name>_summary.log

An overall calibration summary:

- User-specified baseline filter: *&
- Additional antennas removed from the data
- A-Team sources close to the phase reference center
- Amount of flagged solutions per station and solution table
- Amount of flagged data per station at a given state

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global], [calibration], [imaging], [directions], [cluster], [checkfactor], [<input ms>]`

- See http://www.astron.nl/citt/facet-doc/parset.html for a full description.
- An example parset that you can use as a basis for your reduction is available at https://www.astron.nl/citt/facet-doc/parset.html

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

```
[global] [calibration] [imaging] [directions] [cluster] [checkfactor] [<input ms>])
```

Section	Option	Value	Notes
global	dir_working	`/your/FactorTutorial/dir`	
global	dir_ms	`/your/FactorTutorial/dir`	
global	min_fraction_per_band	`0.8`	A large value set to maximise the S/N
global	use_compression	`True`	For less storage usage & faster processing

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global] [calibration] [imaging] [directions] [cluster] [checkfactor] [<input ms>])`

Section	Option	Value	Notes
calibration	max_selfcal_loops target_max_selfcal_loops	5 5	For faster processing
calibration	preaverage_flux_Jy	1.0	To maximise the S/N
calibration	multires_selfcal	True	To improve convergence of self-cal

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global] [calibration] [imaging] [directions] [cluster] [checkfactor] [<input ms>])`

Section	Option	Value	Notes
imaging	wsclean_nchannels_factor	2	For faster processing
imaging	fractional_bandwidth_selfcal_facet_image	0.75	Large bandwidth for a better subtraction
imaging	wsclean_use_idg idg_mode	True cpu	For faster processing

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global] [calibration] [imaging] [directions] [cluster] [checkfactor] [<input ms>])`

Section	Option	Value	Notes
directions	max_radius_deg	3	For faster processing
directions	flux_min_for_merging_Jy size_max_arcmin separation_max_arcmin flux_min_Jy	0.4 1.0 7.0 0.4	Constraints to select calibrators automatically (rule of thumb: bright and compact)
directions	minimize_nonuniformity	True	To make size of facets more uniform in size

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global] [calibration] [imaging] [directions] [cluster] [checkfactor] [<input ms>])`

Section	Option	Value	Notes
directions	faceting_radius_deg	`0.8`	For faster processing

directions	target_ra
	target_dec
	target_radius_arcmin
	target_has_own_facet
		`03h35m23.407`
		`+55d04m07.124`
		`4.0`
		`True`
			To specify a target area to ensure that a facet edge does not cross it. For this tutorial, we specify a region around a faint extended source

directions	minimize_nonuniformity	`True`	To make size of facets more uniform in size

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global]` `[calibration]` `[imaging]` `[directions]` `[cluster]` `[checkfactor]` `[<input ms>])`

Section	Option	Value	Notes
cluster	ncpu	`all`	Tune it based on your machine features !
cluster	wsclean_fmem	`0.9`	Tune it based on your machine features !
cluster	ndir_per_node	`1`	Tune it based on your machine features !

Preparing the parset / config files - FACTOR

The parset is divided into sections to control and specify the workflow:

`[global]` `[calibration]` `[imaging]` `[directions]` `[cluster]` `[checkfactor]` `[<input ms>])`

Section	Option	Value	Notes
checkfactor	facet_viewer	`ds9`	
checkfactor	ds9_load_regions	`False`	Set to True for inspection
checkfactor	image_display	`eog`	

Running FACTOR

First calibrate data against DIE

- input MS files (uv data) consist of concatenated bands of e.g. 10 subbands each (i.e. = 2 MHz); typical observations will have 24 bands (= 48 MHz total)

After calibration, the Initial-subtract pre-FACTOR pipeline must be run to:

- image the field at medium and low resolution to make initial sky models
- subtract these models of the sources from the uv data

```
L644395_SB000_uv_12BAF0A46t_163MHz.pre-cal.merge

L644395_SB000_uv_12BAF0A46t_163MHz.pre-cal.ms
```

Running FACTOR

- Enter a screen session . . . because the expected pipeline runtime is ~2.5 days!

```
$ screen [+enter]
```

- Initialise your Docker environment, mounting your FACTOR directory

```
$ docker pull astronrd/factor:eris2022
$ docker run --rm -it -v $PWD:$PWD astronrd/factor:eris2022 /bin/bash
$ source /opt/lofarsoft/lofarinit.sh
$ cd <to>/<your>/<working dir>
```

- Run FACTOR in the screen session with the parset you made

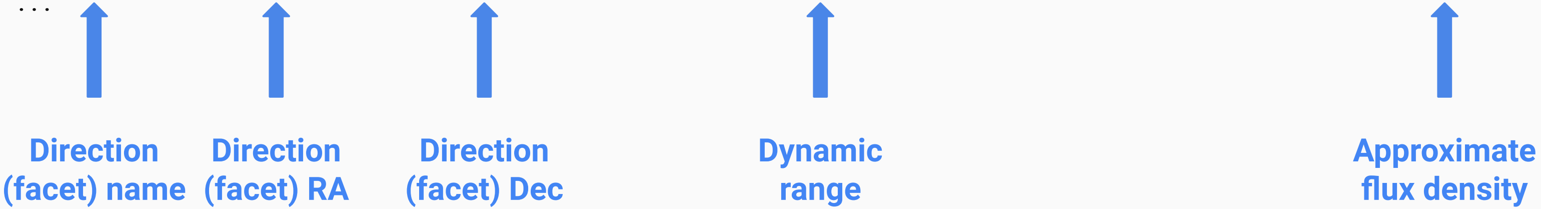
```
$ r
```

- Exit from the screen (CTRL-A CTRL-D)

The directions (facets) file

FACTOR records selected DDE calibrators in a file called `factor_directions.txt`

```
$ more factor_directions.txt
# name position atrous_do mscale_field_do cal_imsize solint_ph solint_amp dynamic_range region_selfcal region_facet
peel_skymodel outlier_source cal_size_deg cal_flux_mJy

# LSMTool history:
...

facet_patch_41 3h27m31.1093s,55d21m30.5782s empty empty 0 0 0 LD empty empty empty False 0.1050687533 36442.853868
facet_patch_35 3h29m52.7506s,53d32m43.7471s empty empty 0 0 0 LD empty empty empty False 0.0128485275297 10059.9407256
facet_patch_22 3h36m28.7034s,53d38m56.1925s empty empty 0 0 0 LD empty empty empty False 0.0112901740997 8669.60507632
facet_patch_40 3h28m11.8884s,55d09m08.5092s empty empty 0 0 0 LD empty empty empty False 0.0110088789021 7315.00279903
...
```



Direction (facet) name

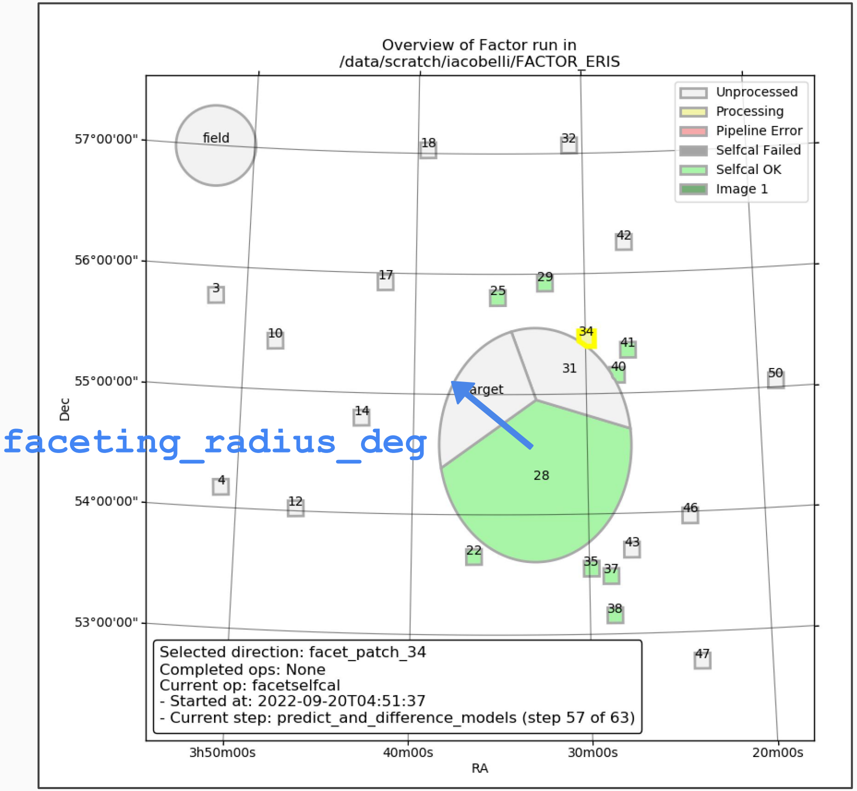
Direction (facet) RA

Direction (facet) Dec

Dynamic range

Approximate flux density

The directions (facets) file: editing



```
Selected direction: facet_patch_34
Completed ops: None
Current op: facetselfcal
- Started at: 2022-09-20T04:51:37
- Current step: predict_and_difference_models (step 57 of 63)
```

faceting_radius_deg

FACTOR divides the field into facets (one for each DDE calibrator) inside of `faceting_radius_deg` (under the `[directions]` section of the parset).
Outside of this radius, boxes are used instead (to speed up processing).

Directions can be:

- added or removed to improve facet layout
- reordered (e.g., in order to process only a subset of directions)

Other, advanced options can be activated on a per-direction basis (see online doc)

Warning

- after the first direction has completed for a run, changes to the facet layout will result in incorrect results!

Check DDE calibrators & facets

- When the `factor_directions.txt`file is made, enter the docker container

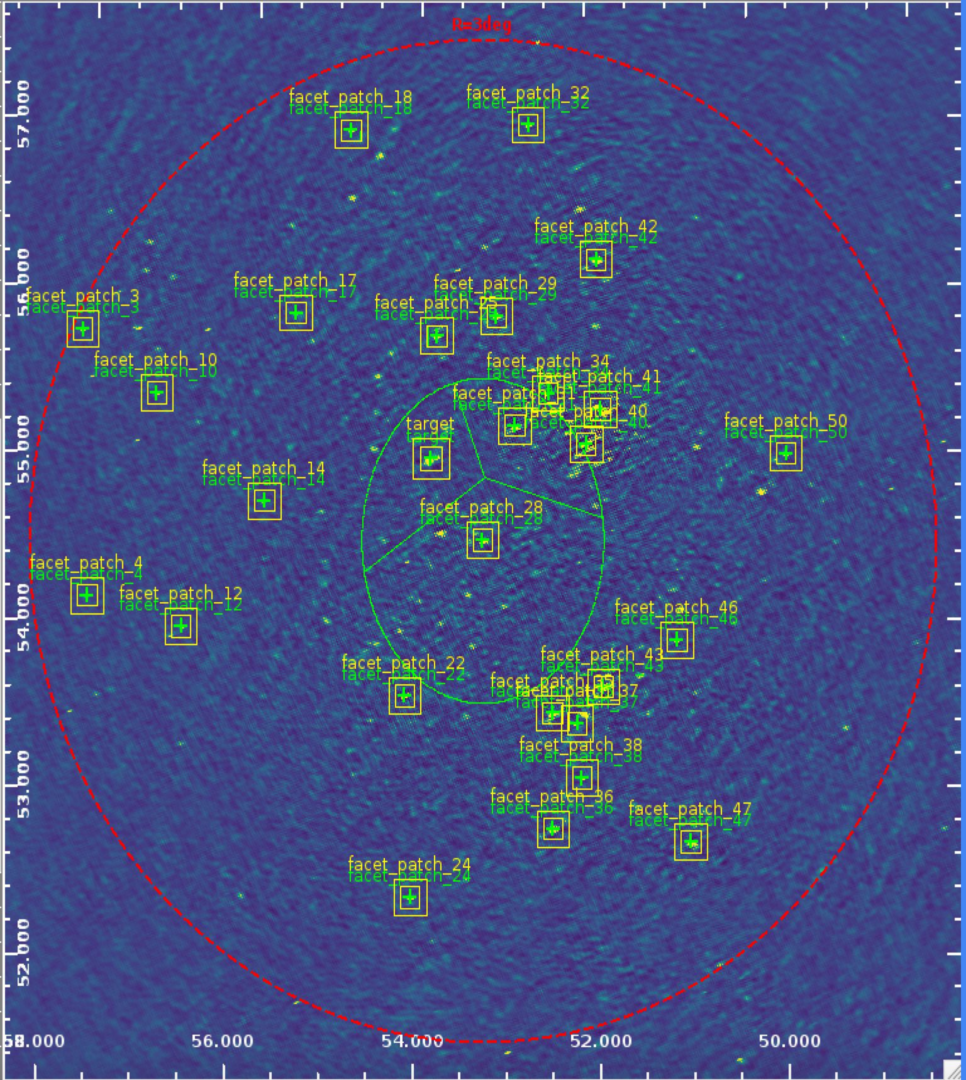
```
$ docker run --rm --net=host -it -v $PWD:$PWD -v $HOME/.Xauthority:/root/.Xauthority -e DISPLAY
astronrd/factor:eris2022 /bin/bash
```

```
$ cd <to>/<your>/<working dir>
```

- Load in `ds9` (1) the provided wide-field image of the field (obtained by the Initial Subtract FACTOR pipeline) and (2) FACTOR auxiliary `*.reg` files (see next slide)

```
$ ds9 L644395_SB000_uv_12BAF0A46t_163MHz.pre-cal.wsclean_high-image.fits
```

- Next check the progress of the run (see Lecture notes under “Running Factor”)



Verification of DDE calibrators

To check pre-selected calibrators and facets use auxiliary files saved in `/your/FactorTutorial/dir/regions`:

- load a wide-field image of the field in `ds9` (e.g., one made by the Initial Subtract pre-Factor pipeline)
- load (under the "Region" menu) files named
  - `calimages_ds9.reg`
  - `facets_ds9.reg`

Warning

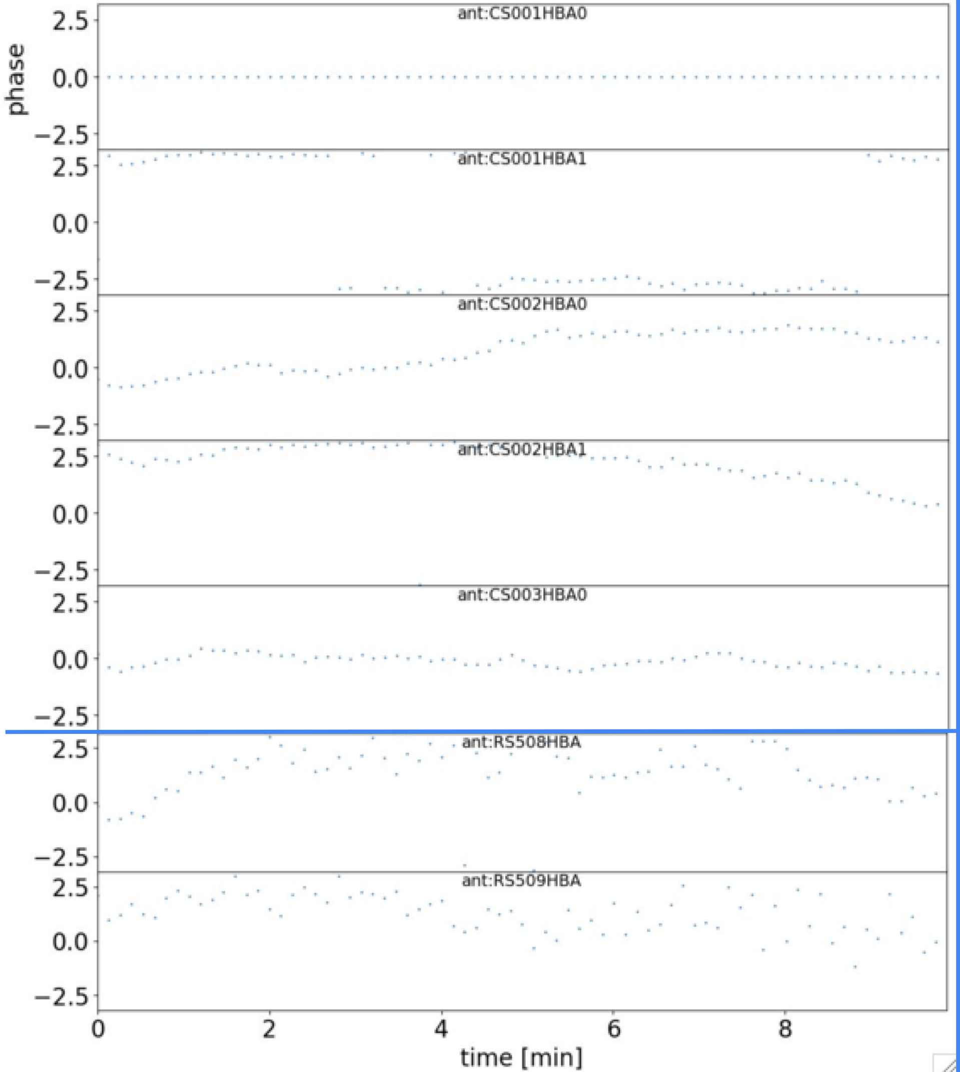
- To check & edit DDE calibrators list set in the **`[global]`** section of the parset `interactive=True`

The selfcal strategy

Selfcal is done on each calibrator to improve its model and DDE corrections

FACTOR minimizes the number of free parameters solved for during selfcal in order to avoid overfitting:

- **Fast phases (TEC)**: one solution every ~10–20 seconds and ~10 MHz to track rapid changes due to ionosphere
- **Slow gains (amp+phase)**: one solution every ~10–20 minutes and ~2 MHz to correct for beam effects

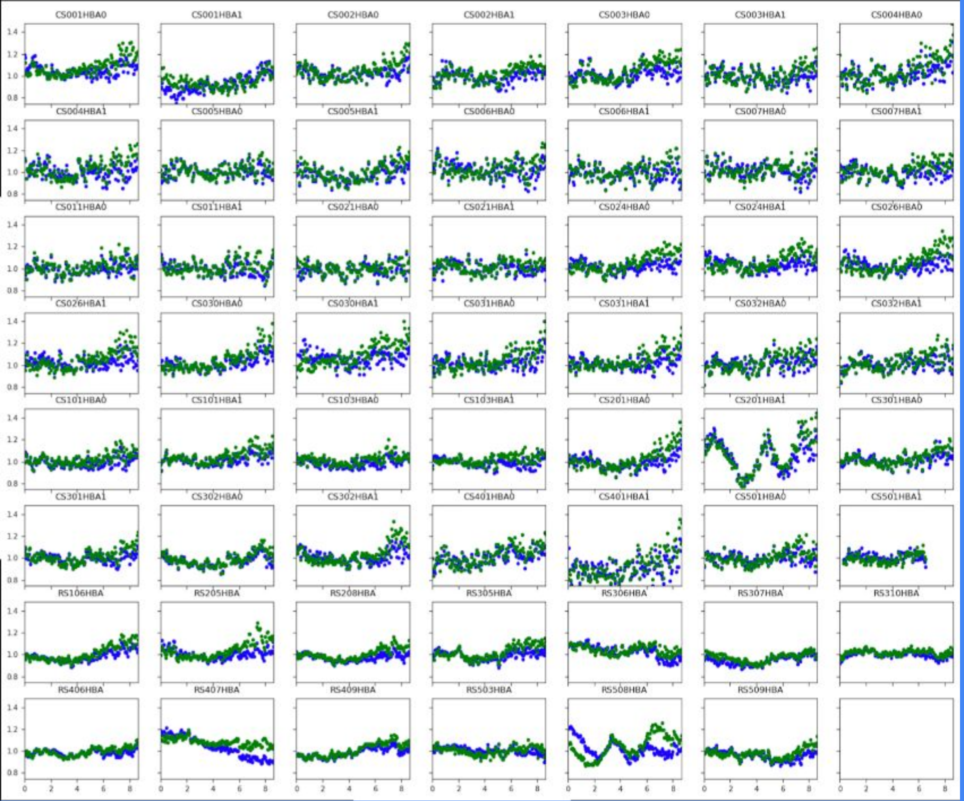


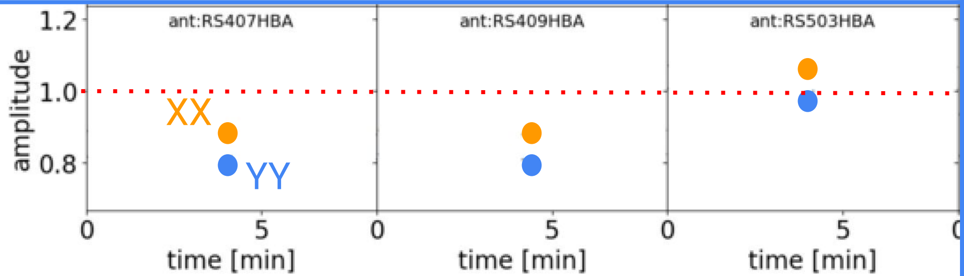
The selfcal strategy

TEC (from fast-phases): correction for ionospheric errors

- Tracking of phase changes has different S/N for different DDE calibrators as well as stations
  - ○ The brightest and compact the DDE calibrator is the better results expected
- Quicker phase changes expected for stations further away from the reference one
- Noisy periods or jumps indicate problems !

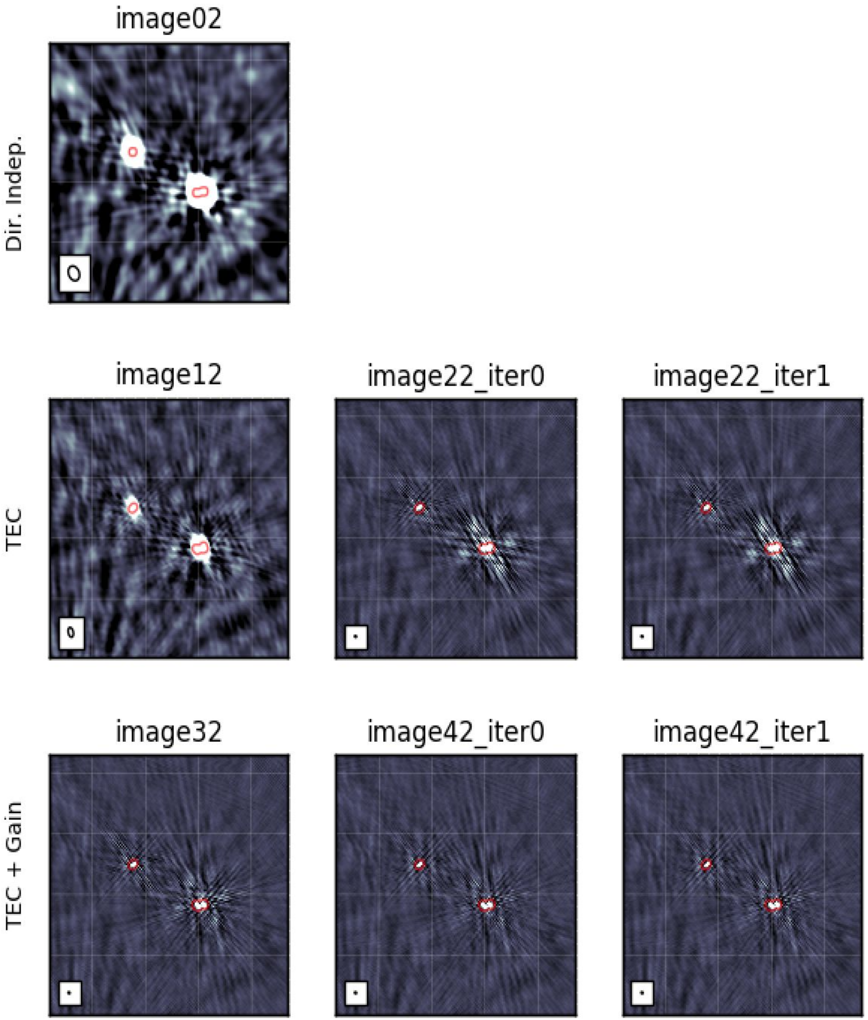
The selfcal strategy





Amplitudes (from slow-gains): correction for beam effects

- Tracking of amplitude changes has different S/N for different DDE calibrators as well as stations
  - ○ The brightest and compact the DDE calibrator is the better results expected
- Amplitude correction values for XX and YY should be close to 1; systematic deviations suspicious:
  - ○ resolved source structure,
  - ○ Instrumental systematics



The selfcal strategy

Results of iterative selfcal (DIE, TEC, amplitude and TEC) corrections on the image plane are provided as useful diagnostic per DDE calibrator (see next section)

Running FACTOR

Once FACTOR has started, you can check the progress of a run with the `checkfactor` tool:

```
$ docker run --rm --net=host -it -v $PWD:$PWD -v $HOME/.Xauthority:/root/.Xauthority
-e DISPLAY astronrd/factor:eris2022 /bin/bash
$ checkfactor <your factor>.parset
    INFO - factor:progress - Plotting directions...
    INFO - factor:progress - Left-click on a direction to select it and see its current state
    INFO - factor:progress - Right-click on a direction to deselect it
    INFO - factor:progress - (In both cases, pan/zoom mode must be off)
    INFO - factor:progress - Press "c" to display calibrator selfcal images for selected direction
    INFO - factor:progress - Press "i" to display facet image for selected direction
    INFO - factor:progress - Press "v" to display facet verify image for selected direction
    INFO - factor:progress - Press "t" to display TEC solutions for selected direction
    INFO - factor:progress - Press "g" to display Gain solutions for selected direction
    INFO - factor:progress - Press "u" to update display (display is updated automatically every minute)
    INFO - factor:progress - Press "h" to repeat these instructions on this terminal
```

After a short time, a window should appear showing the facet layout

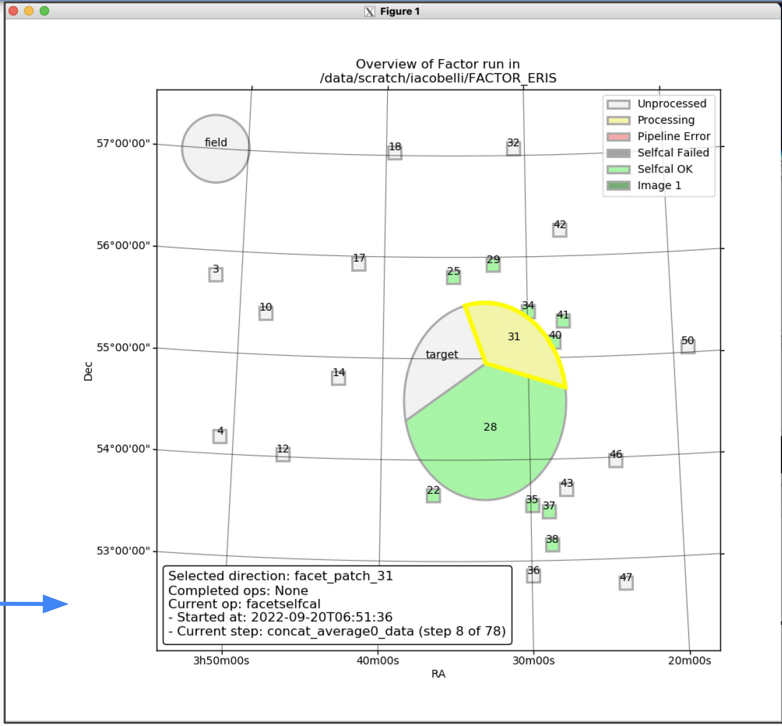
Running FACTOR

Click on a facet

- yellow: the one being processed
- green: the one completed

Hit the “c” key to see the calibrator images made during selfcal

Summary of processing for selected facet



```
Selected direction: facet_patch_31
Completed ops: None
Current op: facetselfcal
- Started at: 2022-09-20T06:51:36
- Current step: concat_average0_data (step 8 of 78)
```

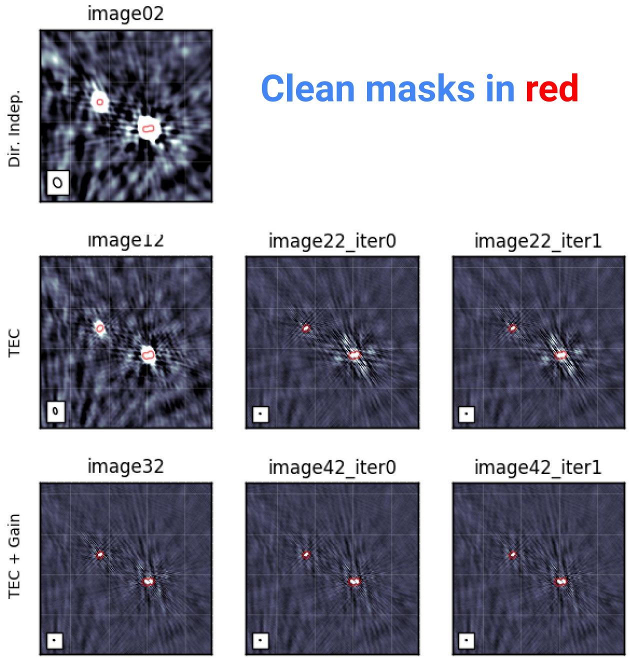
Running FACTOR

Click on a facet

- yellow: the one being processed
- green: the one completed

Hit the “c” key to see the calibrator images made during selfcal

Image before any direction dependent calibration



Clean masks in red

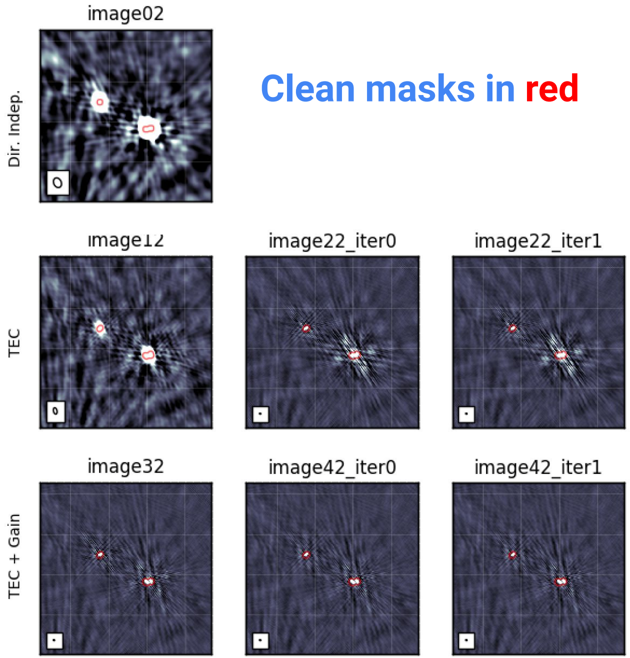
Running FACTOR

Click on a facet

- yellow: the one being processed
- green: the one completed

Hit the “c” key to see the calibrator images made during selfcal

Images after fast phases calibrations



Clean masks in red

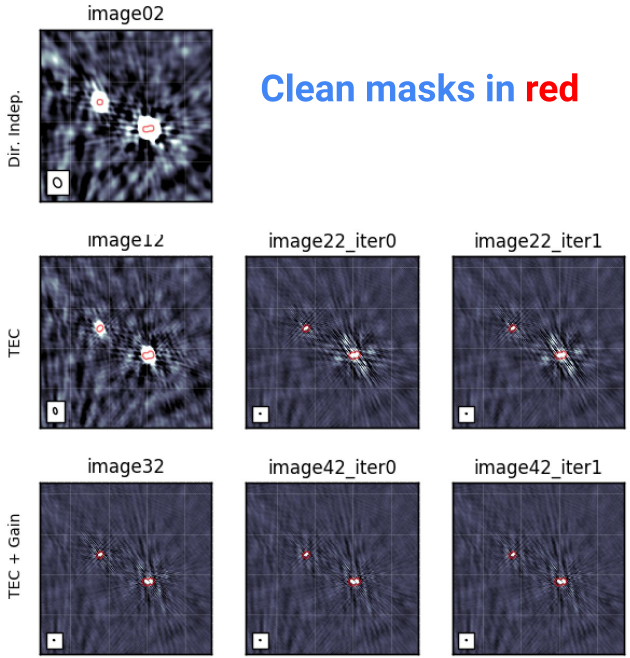
Running FACTOR

Click on a facet

- yellow: the one being processed
- green: the one completed

Hit the "c" key to see the calibrator images made during selfcal

Images after slow gain calibrations →



Clean masks in red

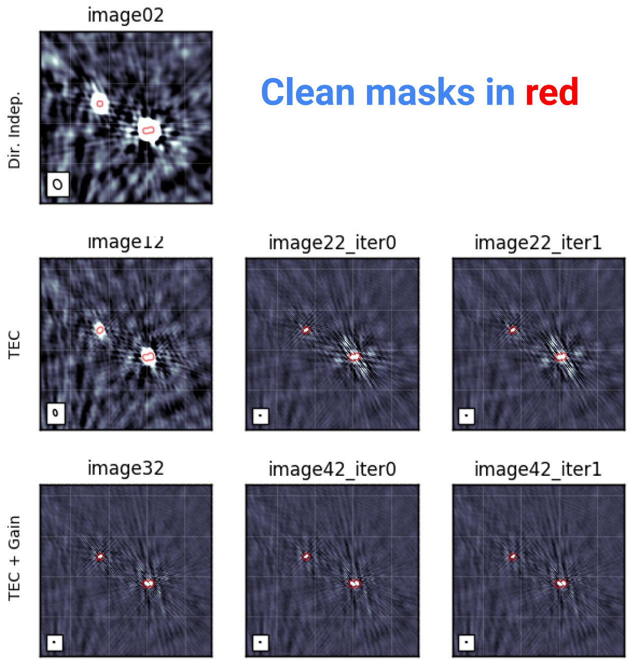
Running FACTOR

Click on a facet

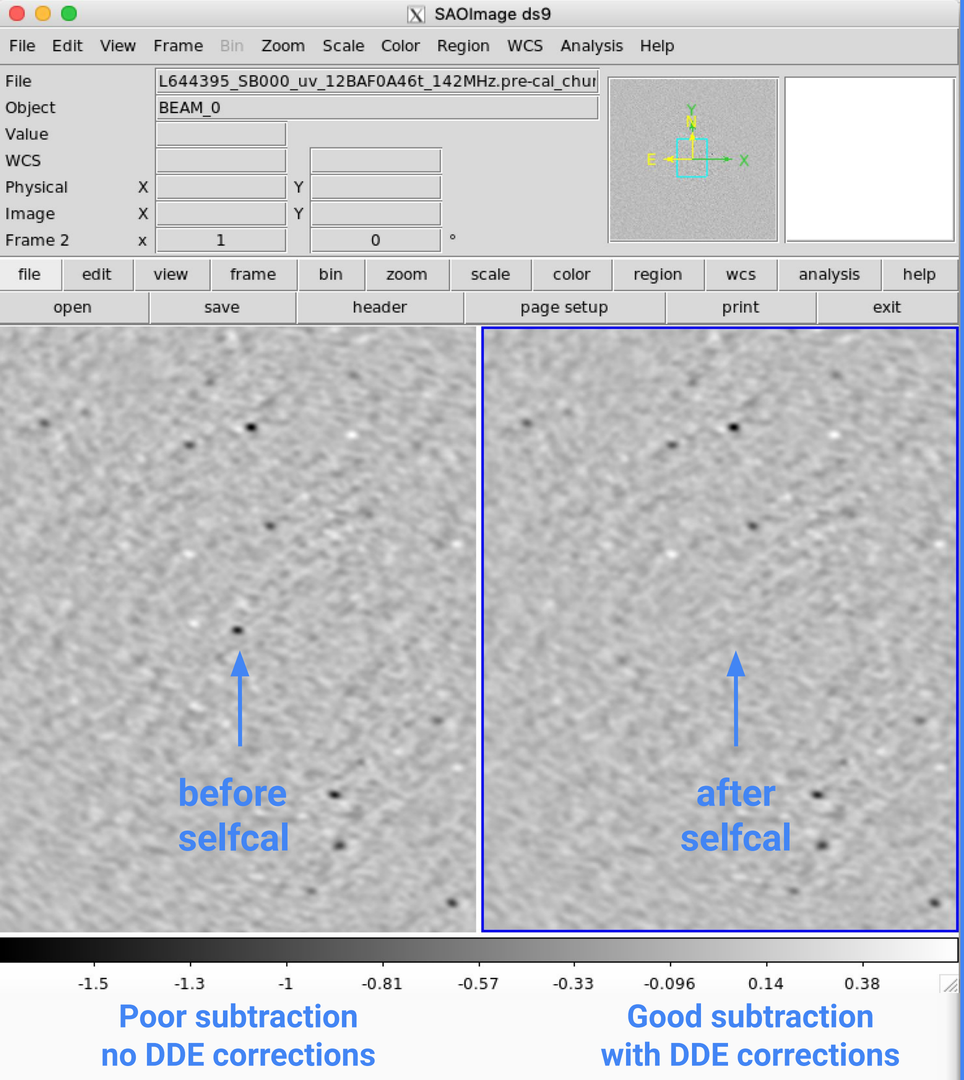
- yellow: the one being processed
- green: the one completed

Hit the "`c`" key to see the calibrator images made during selfcal

The tutorial run setup was with `max_selfcal_loops = 5`
FACTOR stops after no more improvement is seen !



Clean masks in red


SAOImage ds9
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
file edit view frame bin zoom scale color region wcs analysis help
open save header page setup print exit
Y N E X
-1.5 -1.3 -1 -0.81 -0.57 -0.33 -0.096 0.14 0.38

File L644395_SB000_uv_12BAF0A46t_142MHz.pre-cal_chu

Object BEAM_0

Value

WCS

Physical X Y

Image X Y

Frame 2 x 1 0 °

before selfcal

after selfcal

Poor subtraction no DDE corrections

Good subtraction with DDE corrections

Running FACTOR

Click on a facet

- yellow: the one being processed
- green: the one completed

Hit the “v” key to open the selfcal verification (i.e. the residual, source subtracted) images in ds9 (the facetselfcal operation must be finished first). This may take a few seconds..

Running FACTOR

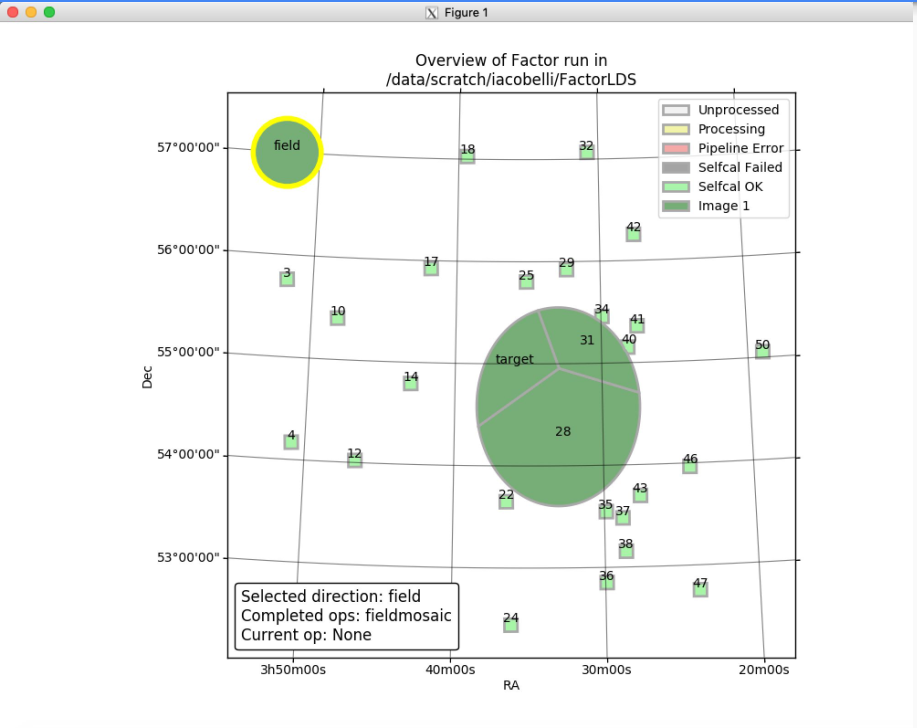


Figure 1

Overview of Factor run in /data/scratch/iacobelli/FactorLDS

- ⬜ Unprocessed
- 🟨 Processing
- 🟥 Pipeline Error
- ▨ Selfcal Failed
- 🟩 Selfcal OK
- 🟩 Image 1

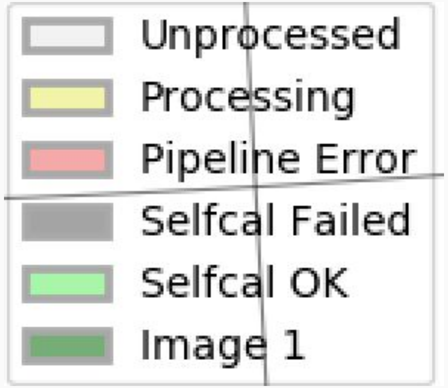
Selected direction: field
Completed ops: fieldmosaic
Current op: None

Once selfcal has completed for all the facets, FACTOR re-images each facets using the full bandwidth.

- These are the final images, but must be corrected for the primary beam attenuation !

Once reimaging is completed, FACTOR will mosaic the images together and correct them for the primary beam

Running FACTOR



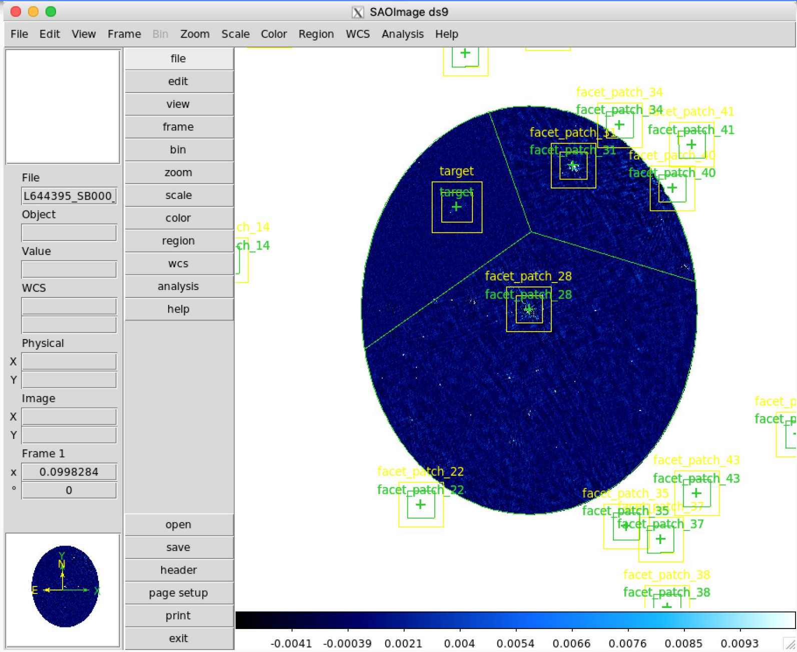
For each facet FACTOR makes one or more images, as set by the WSClean imaging parameters in the **`[imaging]`** section of the parset, e.g.

```
facet_cellsize_arcsec = [ 1.5, 5.0]

facet_robust          = [-0.5, -1.0]

facet_taper_arcsec    = [ 0.0, 15.0]

facet_min_uv_lambda      =   [80.0,
80.0]
```

Running FACTOR

Select the “field” direction (in the top-left corner)

- Hit the “`i`” key to list the available field images
- Hit the “`1`” key to open the full- resolution image in `ds9` (this may take a few seconds...)



File: L644395_SB000_

Frame 1

x 0.0998284

° 0

Facets regions can be loaded:

- via the `[checkfactor]`section of the parset.
- via the `ds9` “Region” menu (in `Factor_output/regions/facets_ds9.reg`)

Running FACTOR

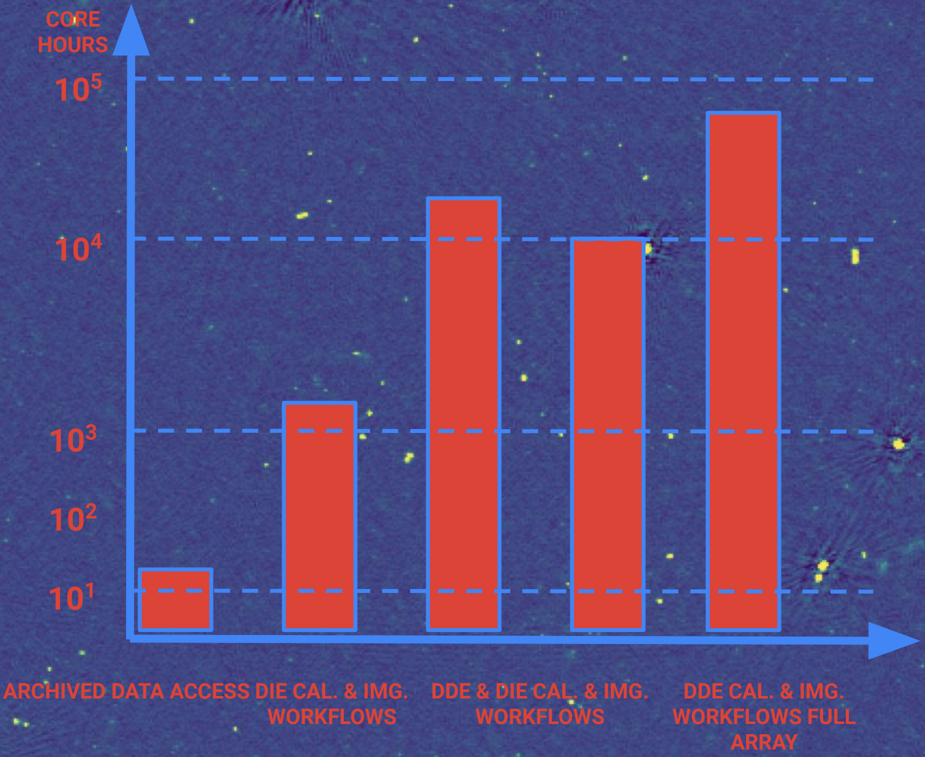
Two mosaics are made for each set of imaging parameters:

- Non-primary-beam corrected (“flat noise”), loaded by checkfactor (for inspection) `Factor_output/results/fieldmosaic/field/*.correct_mosaic.`**`pbcut`**`.fits`
- Primary-beam corrected image needed for flux measurements: `Factor_output/results/fieldmosaic/field/*.correct_mosaic.`**`pbcor`**`.fits`

Due to problems with the LOFAR beam model, the flux scale can be off by up to 15%. A check against e.g. TGSS catalog can be done.

Running . . .

TIME FOR FOLLOW UP QUESTIONS !



CURIOUS TO LEARN MORE ABOUT LOFAR DATA PROCESSING? CHECK ADDITIONAL ONLINE MATERIAL

9th ERIS - Dwingeloo 22/09/2022