Lecture 7

Calibration:

Science Data Processing

Lecturer: **Dr Vijay Mahatma** (vm462)

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Syllabus Overview

- Introduction to Big Data Radio Astronomy and Key Science Projects
  - Lecture 1: SKA Key Science Projects
  - Lecture 2: Brief history of radio astronomy and the SKA telescope
  - Lecture 3: The modern "large-N" radio interferometers
- Instrument simulations and design tools
  - Lecture 4: Intro into numerical methods for electromagnetic modelling
  - Lectures 5 and 6: Mutual coupling in antenna arrays
- Science Data Processing
  - Lecture 7: Calibration of radio observations
  - Lecture 8: Imaging techniques
  - Lecture 9: Advanced imaging techniques
  - Lecture 10: Time-domain radio astronomy
- Computing infrastructure
  - Lecture 11: Federation and scaling approaches for exascale data
  - Lecture 12: Data centre challenges and opportunities
- Advanced ML and Bayesian methods for data analysis and science extraction
  - Lecture 13: Nested sampling and MCMC
  - Lecture 14: Applications of Bayesian analysis
  - Lecture 15: Signal emulation for astrophysics and cosmology
  - Lecture 16: Simulation-based inference in astrophysics and cosmology

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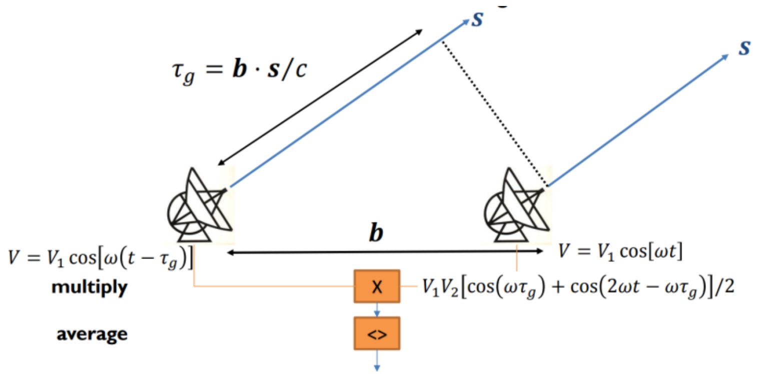
Mapping the radio sky

- In astronomy, we are interested in knowing the *angular distribution* of electromagnetic emission
- This means, we are interested in the *surface brightness* of the emission
    - Knowing how the brightness is distributed over the angular extent of the source (**how bright** and **where it is bright**)
- Modern radio interferometers measure complex visibilities (the interference pattern between pairs of antennas at a single unit of frequency and time):



$$R_c = \frac{[V_1 V_2 \cos(\omega \tau_g)]}{2} = \frac{\left[V_1 V_2 \cos\left(2\pi\nu \frac{\boldsymbol{b} \cdot \boldsymbol{s}}{c}\right)\right]}{c}$$

$$V = R_c - iR_s = Ae^{-i\phi}$$

how bright

where it is bright

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Mapping the radio sky

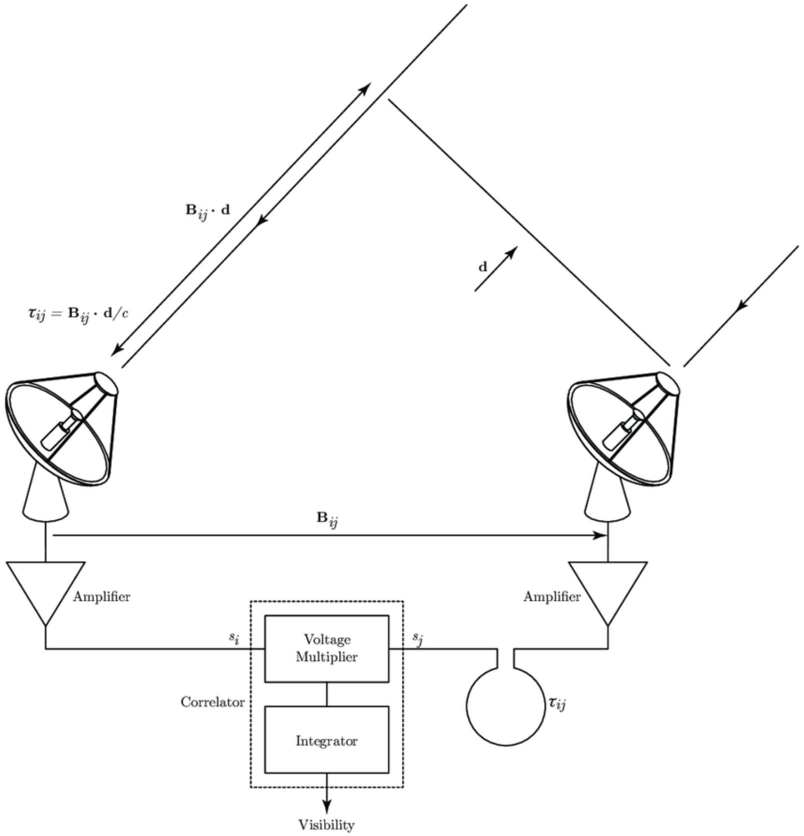
$$V = R_c - iR_s = Ae^{-i\phi}$$

how bright

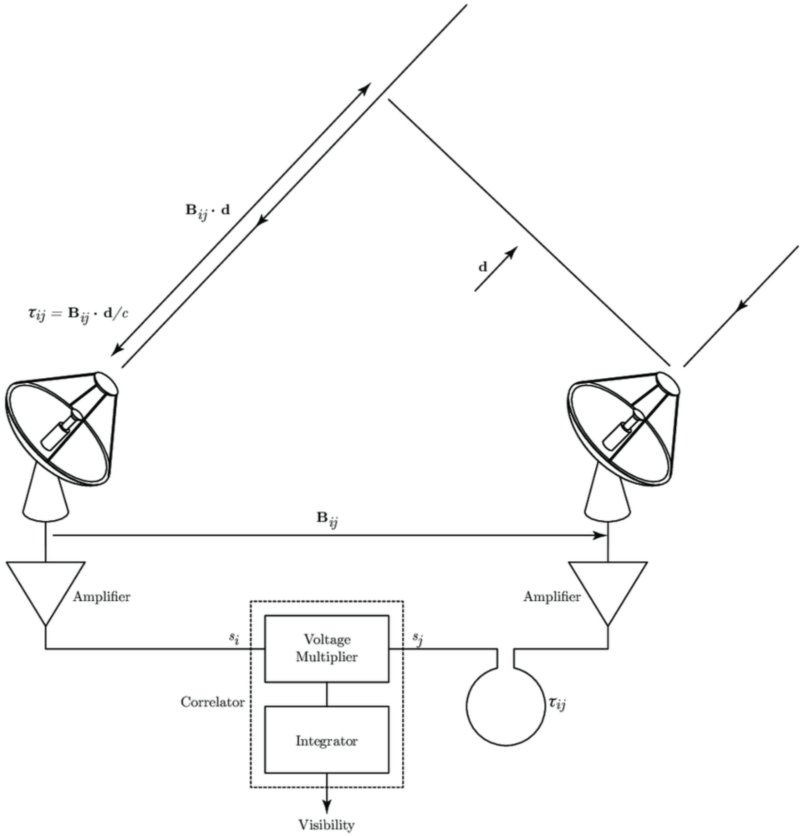
where it is bright

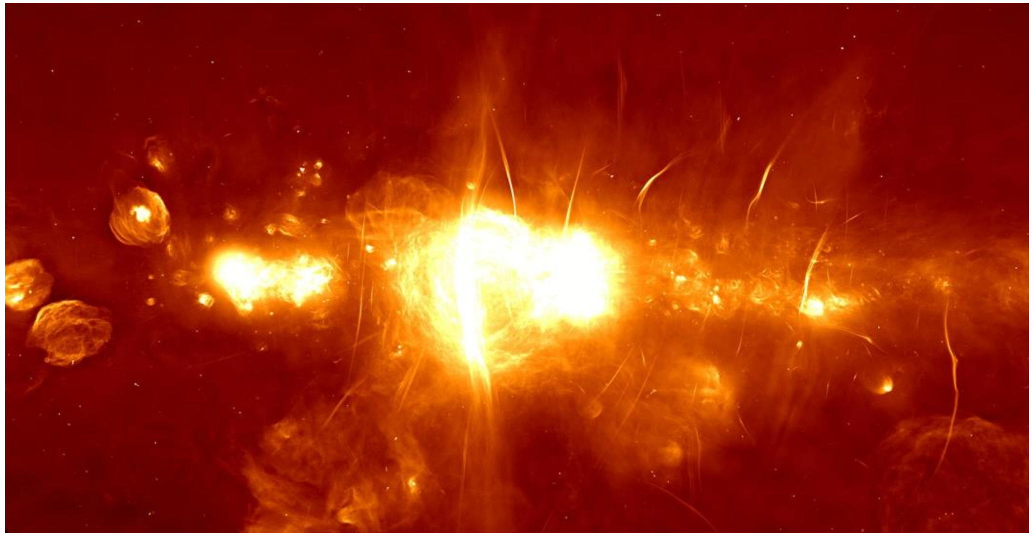
- The correlator outputs complex visibilities – for each pair of antennas, for each unit of frequency, for each unit of time, for each polarization (most dishes measure 4 polarizations)
- These form rows of data (currently called Measurement Set) that are sent to the scientists

Modern radio telescopes

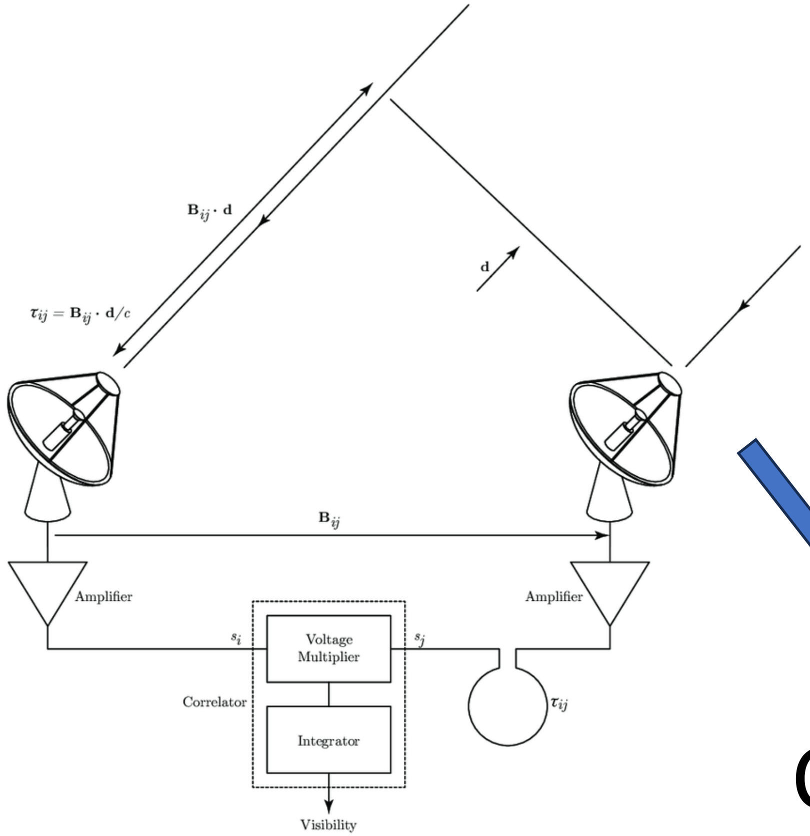


Modern radio telescopes

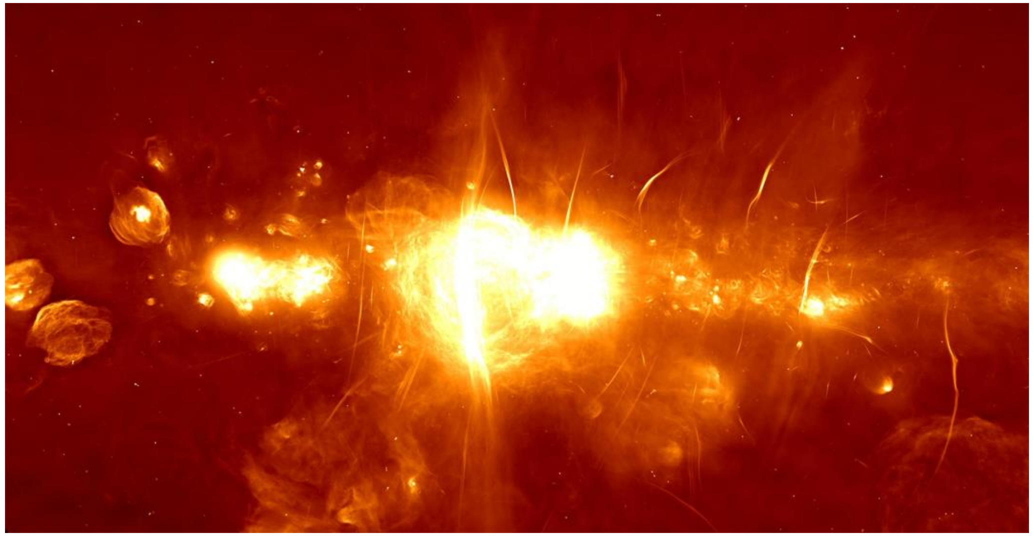




Modern radio telescopes



Calibration



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Calibration

- What is wrong with taking radio interferometer visibilities and making a map of the sky?

Calibration

- What is wrong with taking radio interferometer visibilities and making a map of the sky?
  - Changing weather/atmosphere/ionosphere can distort radio signals
  - Instrumental differences between antennas (dish imperfections, cable lengths, electronics)
  - The signals after correlation do not have physical units
  - Geometric delays between antennas not calculated perfectly
  - Bandpass filters not perfect
  - Telescope 'clocks' may not be perfect
  - Telescope 'beam' changes with time/frequency/where it points

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Calibration

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  - Telescope 'clocks' may not be perfect
  - Telescope 'beam' changes with time/frequency/where it points
- Calibration generally means to adjust the measurements of an instrument based on a standardized scale.
- For radio interferometers, this process tries to remove nasty effects on the measured visibilities, so that the radio observations become what we expected the interferometer to see

Calibration – general formalism

Antenna position correction

Antenna gain amplitude

Antenna gain phase

$$V'_{i,j}(u,v,\nu) = b_{ij}(u,v,t)\left[B_i(\nu,t)B_j^*(\nu,t)\right]g_i(t)g_j^*(t)V_{i,j}(u,v,\nu)e^{i[\theta_i(t)-\theta_j(t)]}$$

Observed visibility between antennas *i* and *j* (baseline coordinates u,v,w)

Bandpass filter correction

True visibility between antennas *i* and *j* (baseline coordinates u,v,w)

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Calibration – Jones formalism

$$\vec{V}_{ij} = \begin{pmatrix} XX & XY \\ YX & YY \end{pmatrix}$$

Jones matrix for antenna *i*

$$\vec{V}_{ij} = J_{ij} \vec{V}_{ij}^{\mathrm{IDEAL}}$$

where

$$J_{ij} = J_i \times J_j^*$$

observed visibility

ideal visibility

Combined Jones matrix

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Calibration – Jones formalism

$$\mathbf{V}_{pq} = \iint_{4\pi} \mathbf{J}_p(\sigma)\mathbf{B}(\sigma)\mathbf{J}_q^H(\sigma)d\Omega$$

Observed visibility between antennas p and q

True visibility between antennas p and q

Jones matrix

$\mathsf{J_i} = \mathsf{G_i}\ [\mathsf{H_i}]\ [\mathsf{Y_i}]\ \mathsf{B_i}\ \mathsf{K_i}\ \mathsf{T_i}\ \mathsf{F_i} = \mathsf{G_i}\ [\mathsf{H_i}]\ [\mathsf{Y_i}]\ (\mathsf{D_i}\ \mathsf{E_i}\ \mathsf{P_i})\ \mathsf{K_i}\ \mathsf{T_i}\ \mathsf{F_i}$

in which

$\mathsf{F_i}(\vec{\rho}, \vec{r_i})$	ionospheric Faraday rotation
$\mathsf{T_i}(\vec{\rho}, \vec{r_i})$	atmospheric complex gain
$\mathsf{K_i}(\vec{\rho}.\vec{r_i})$	factored Fourier Transform kernel
$\mathsf{P_i}$	projected *receptor* orientation(s) w.r.t. the sky
$\mathsf{E_i}(\vec{\rho})$	voltage primary beam
$\mathsf{D_i}$	position-independent *receptor* cross-leakage
$[\mathsf{Y_i}]$	commutation of *IF-channels*
$[\mathsf{H_i}]$	hybrid (conversion to circular polarisation coordinates)
$\mathsf{G_i}$	electronic complex gain (*feed*-based contributions only)

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Calibration – in practice

- How do we determine the Jones matrix/correction factors to calibrate our interferometer data?

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Calibration – in practice

- How do we determine the Jones matrix/correction factors to calibrate our interferometer data?
- Basic principle: have a model which is a well known representation of the radio source, and compare it to your observed visibilities – least squares fitting

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Calibration – in practice

- How do we determine the Jones matrix/correction factors to calibrate our interferometer data?
- Basic principle: have a model which is a well known representation of the radio source, and compare it to your observed visibilities – least squares fitting
- Let's say you want to calibrate your data to solve for the complex antenna gains:

$$V'_{i,j} = g_i g_j^* e^{i[\theta_i - \theta_j]} V_{i,j}^{\mathrm{model}}$$

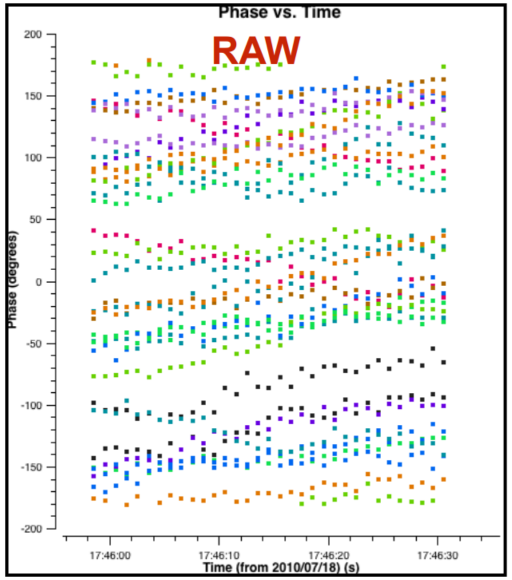
- Have the observed visibilities, predict the model visibilities. Find which correction factors are required to minimize the difference – one set of Jones matrices determined.
- Find all the Jones matrices, then do a single 2x2 matrix multiplication to the visibilities to calibrate.
- All about the model: need the most truth, but also should be representative of what the telescope would see (think about resolution)

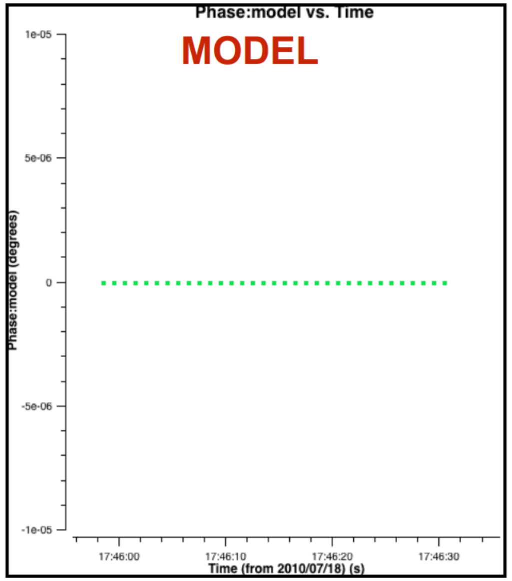
Calibration – where do we get the model

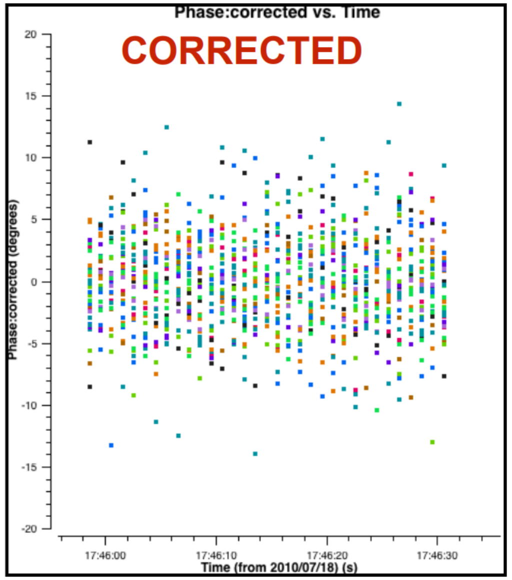
- A model is an astronomical source of known brightness and structure
- What type of object is the best model?

Calibration – choosing a model

- A model is an astronomical source of known brightness and structure
- What type of object is the best model?
  - Known brightness with the least amount of error
  - Point source – a point source observed at the phase center (dish pointing directly at it) has visibilities with zero phase (waves completely in phase).







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Calibration – general strategy

- During a radio telescope observation, point your telescope at:
  - Your target source of interest
  - A well-known flux calibrator which has known brightness (direction-independent Jones matrices)
  - A phase calibrator – a bright point source somewhere near the target source (direction-dependent Jones matrices)

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Calibration – general strategy

```
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================================================================================
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Observation: EVLA
Data records: 9219600       Total elapsed time = 8970 seconds
   Observed from   05-Jul-2020/04:45:55.0   to   05-Jul-2020/07:15:25.0 (UTC)

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Calibration – general strategy

- 3 types (done in order)
    - **Direction-independent calibration**
        - Time-independent quantities – use a well-known astronomical object with known brightness
    - **Direction-dependent calibration**
        - Time-dependent quantities – use a bright point source nearby to your target
    - **Self-calibration**
- Determine all these corrections and store them in tables – before making an image apply all corrections to visibilities

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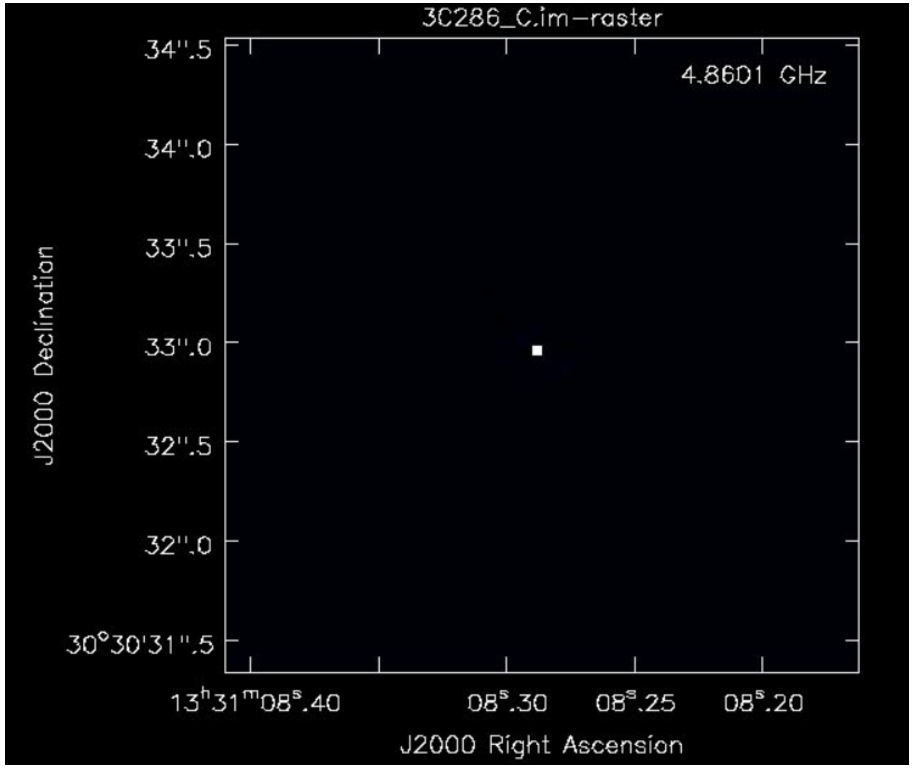
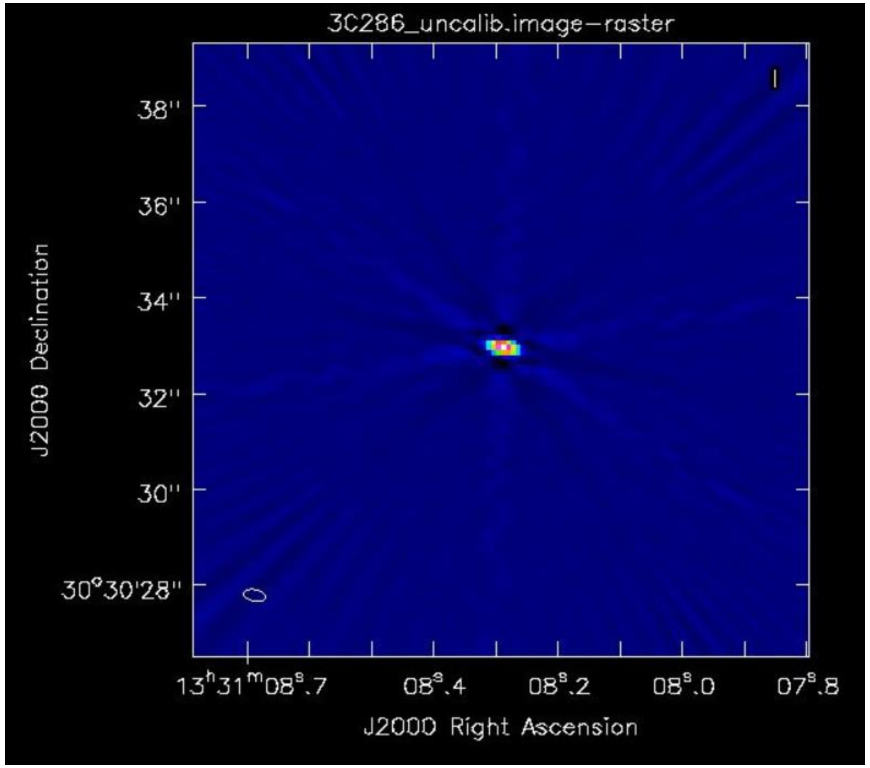
Calibration – general strategy

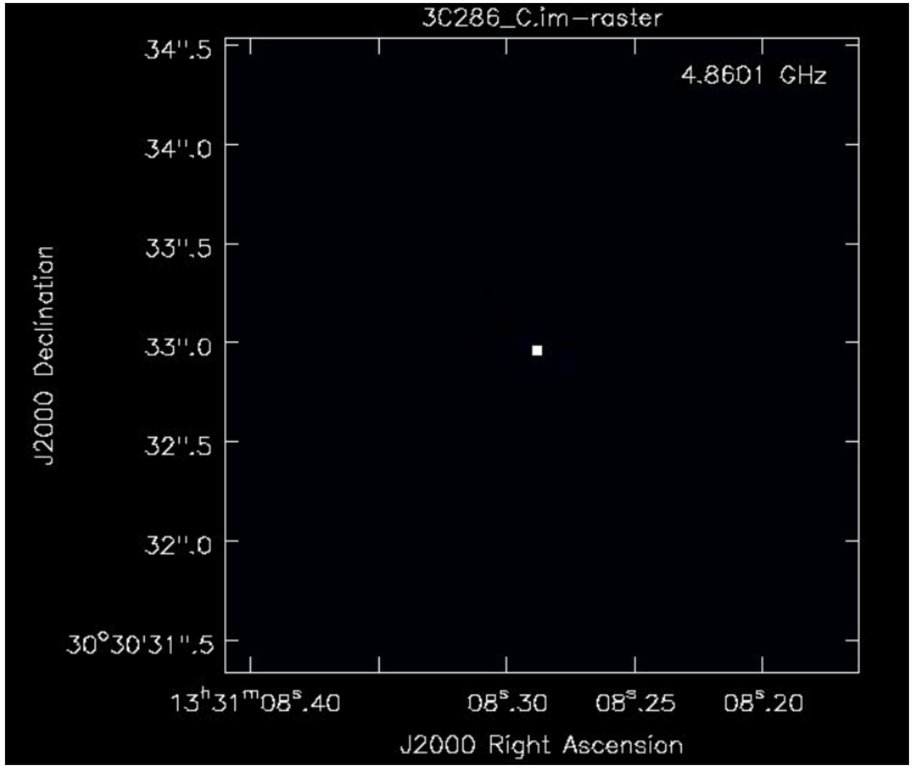


3C286 5 GHz model

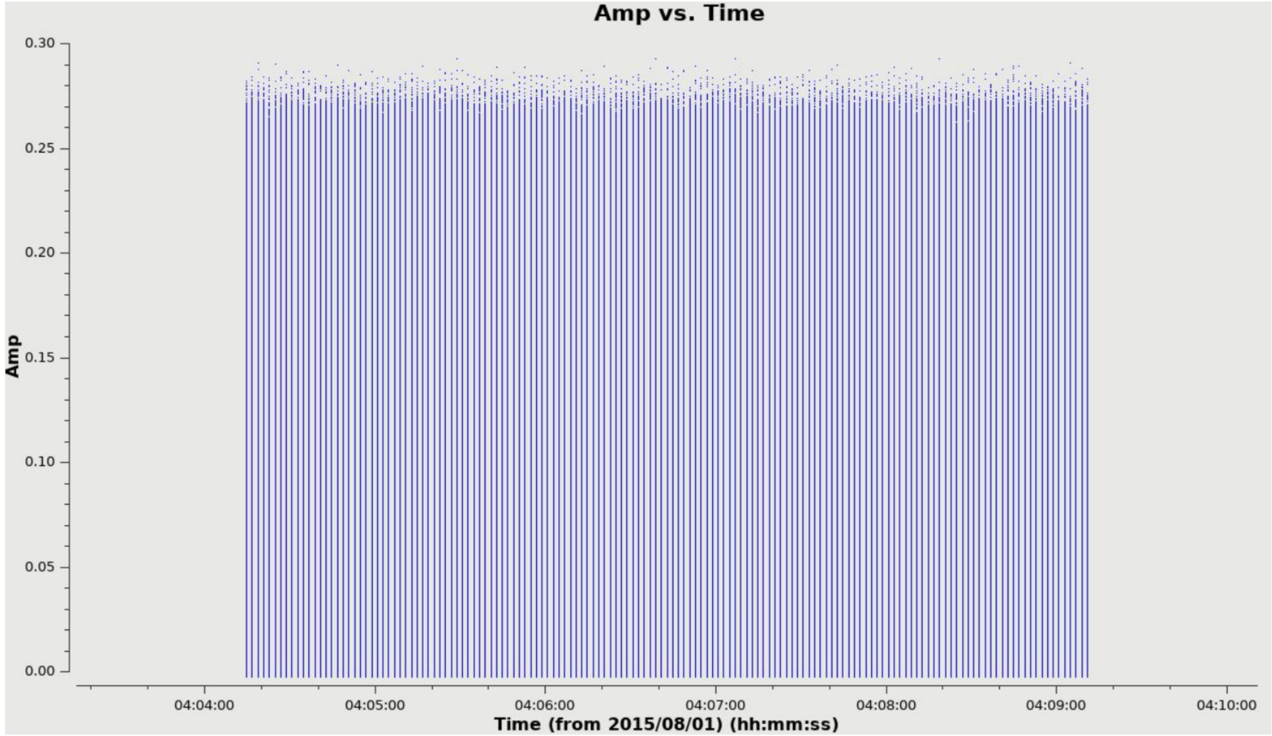


3C286 5 GHz VLA observation

Calibration – general strategy

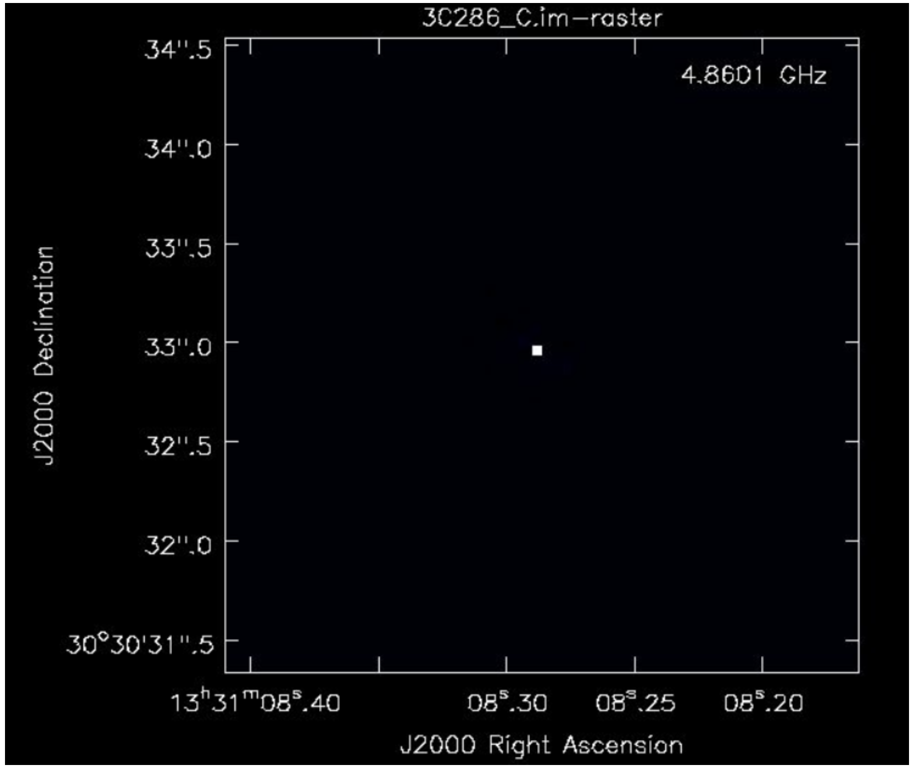


3C286 5 GHz model

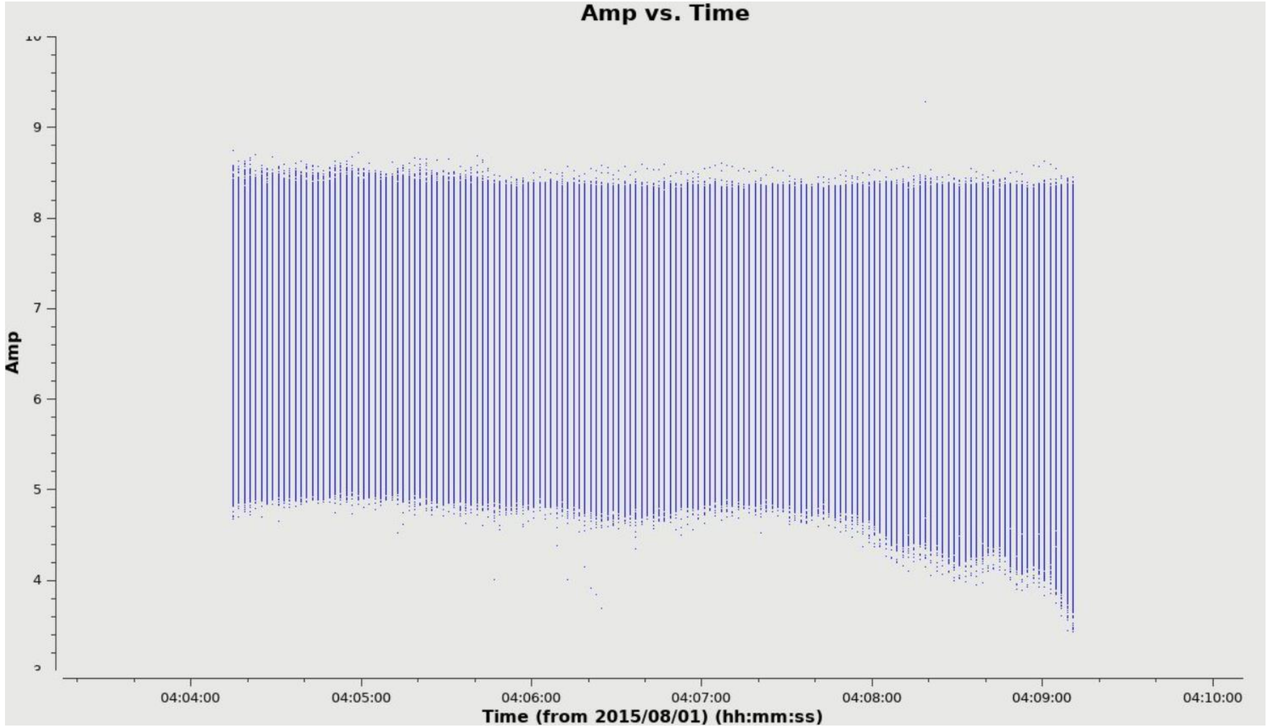


3C286 5 GHz VLA observation

Calibration – general strategy



3C286 5 GHz model



3C286 5 GHz VLA observation
Calibrated, with correct brightness units

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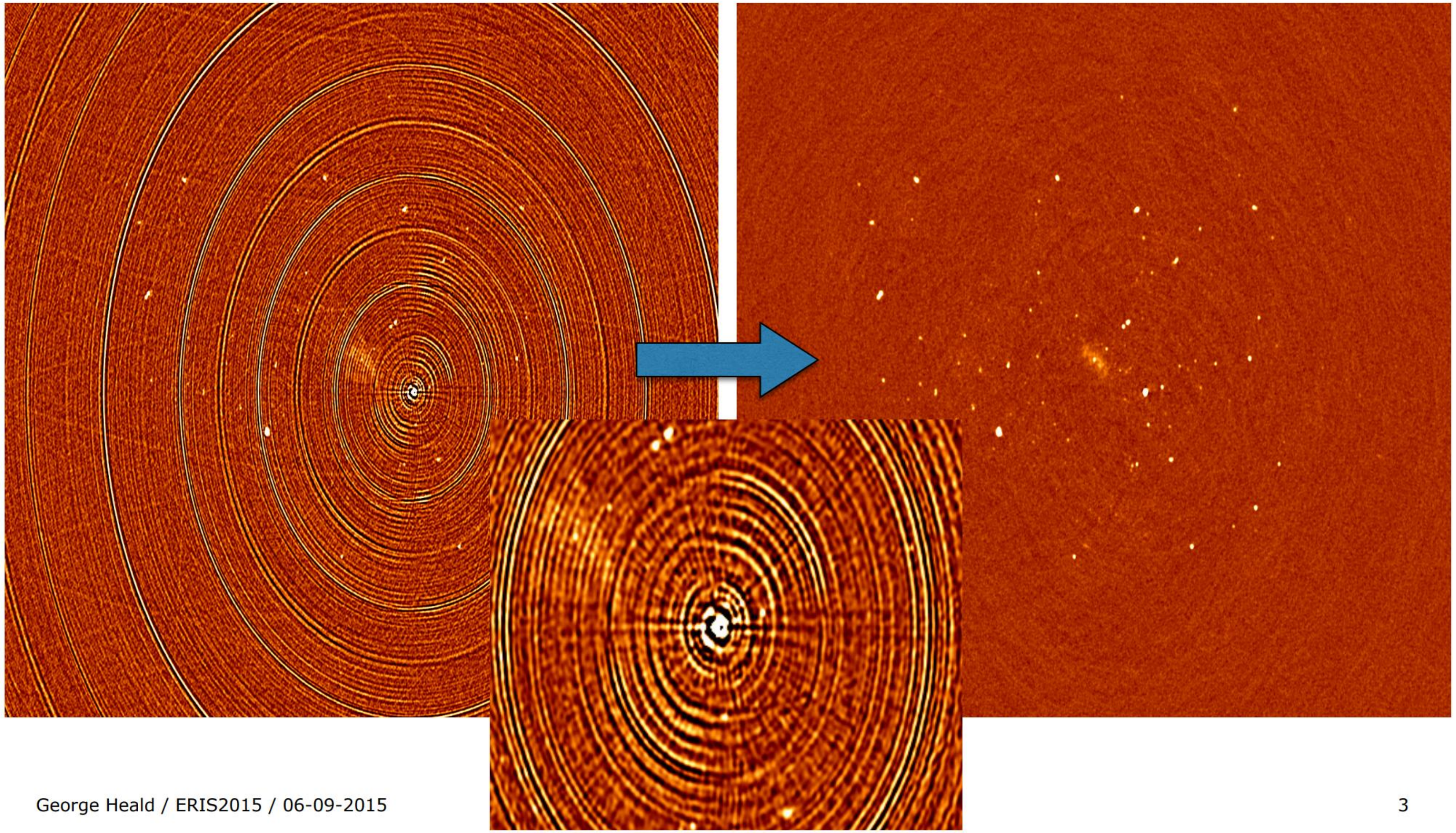
Calibration – general strategy



Proof that you can't simply image (take a Fourier transform of) visibilities straight after an observation – calibration is necessary for science quality

Self-calibration

- Is there more data processing to be done after calibration?
- The visibility amplitudes and phases should now be correct, no?

Self-calibration

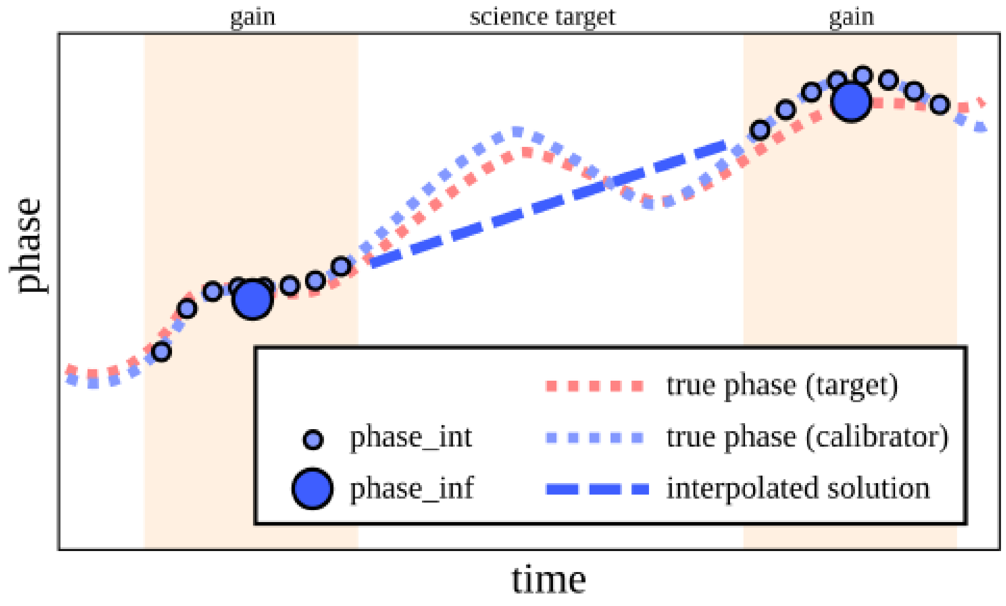
- Is there more data processing to be done after calibration?
- The visibility amplitudes and phases should now be correct, no?
  - No

Self-calibration

- Why is calibration not enough?

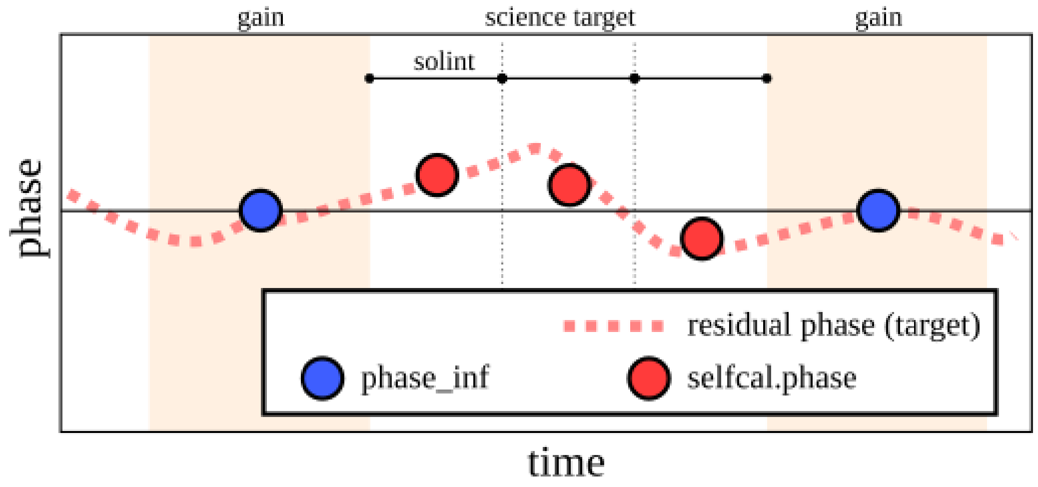
Self-calibration

- Why is calibration not enough?
  - Calibrators observed at a different time than the target – linear interpolation may be incorrect assumption
  - Calibrator models may not be perfect
  - Calibrators might not have enough S/N to follow tiny phase variations with time



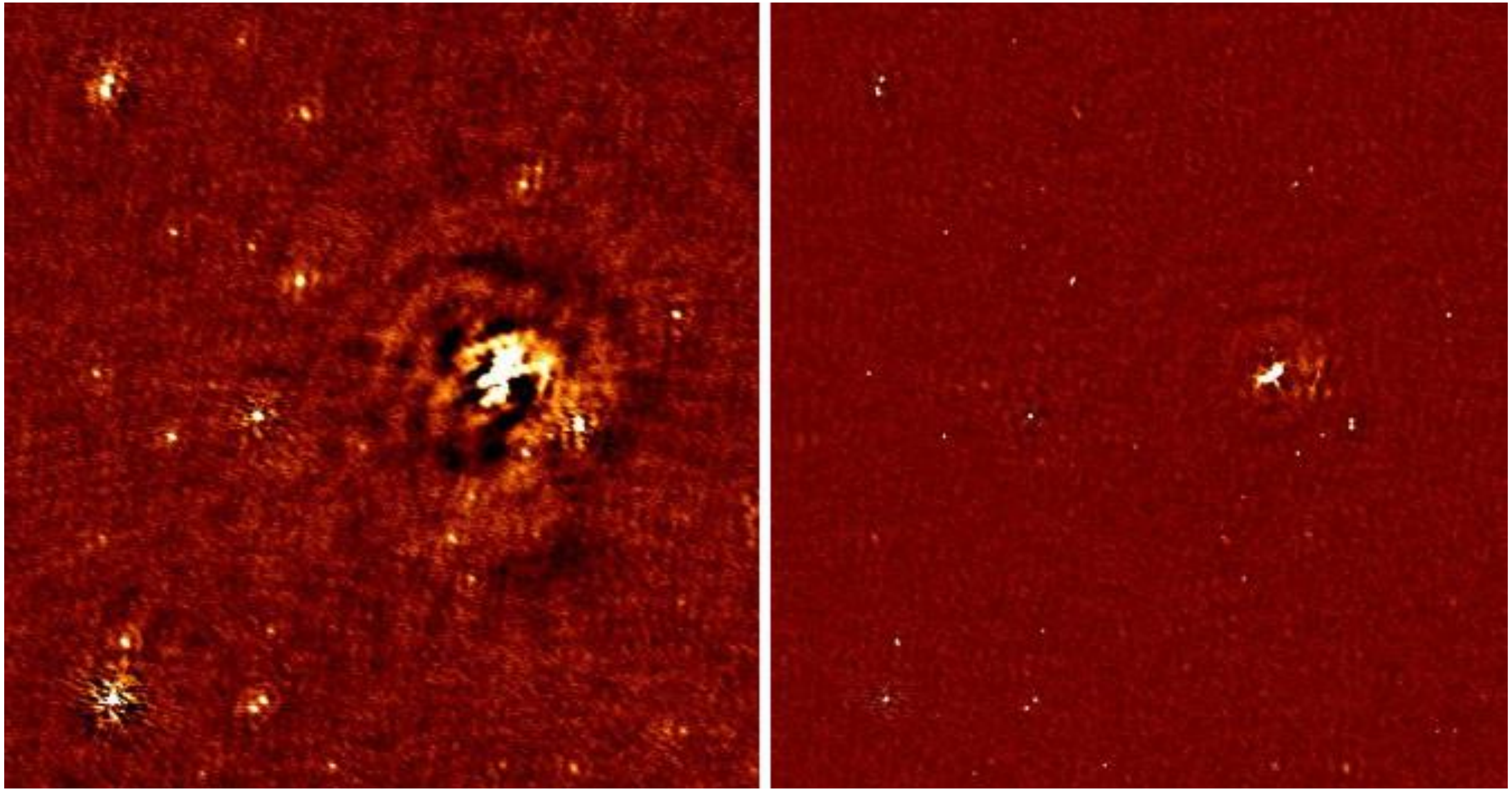
Self-calibration

- General idea
  1. Image your science target after calibration
  2. Take the brightest parts of those radio sources to generate a model
  3. Calibrate your data with that model (phase, amplitude)
  4. Image the new calibrated data
  5. Repeat from step 1

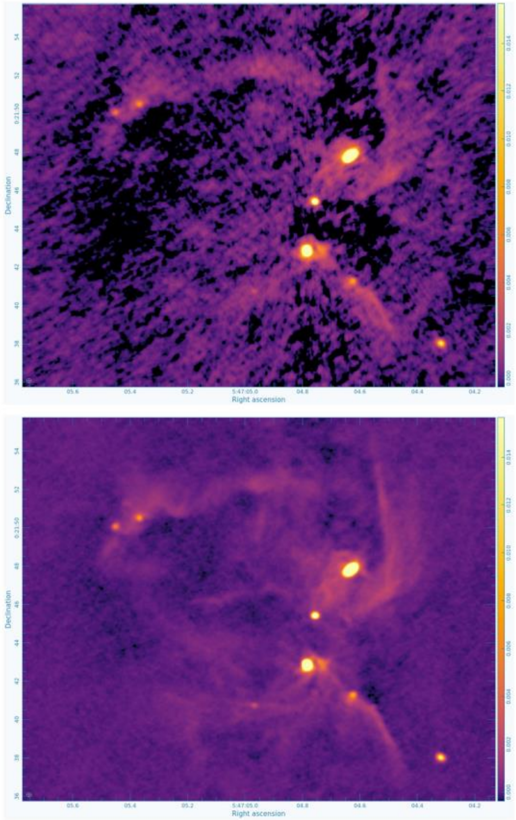


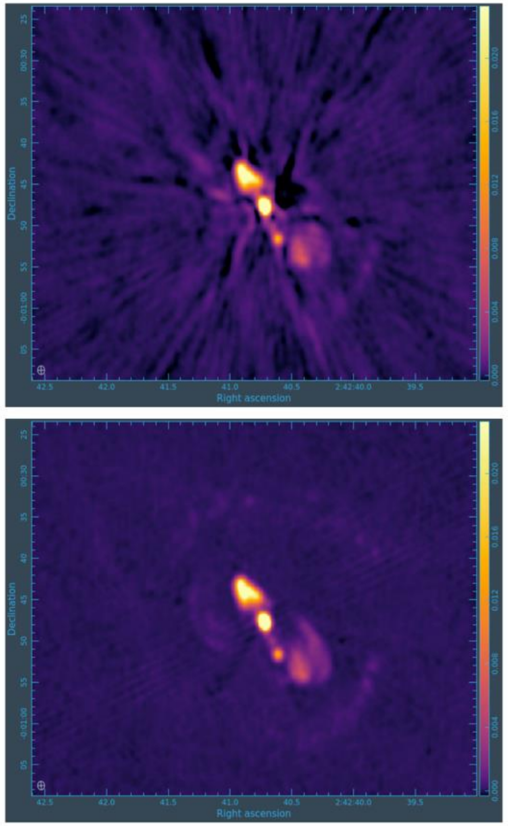
- Idea is that the model improves with every cycle

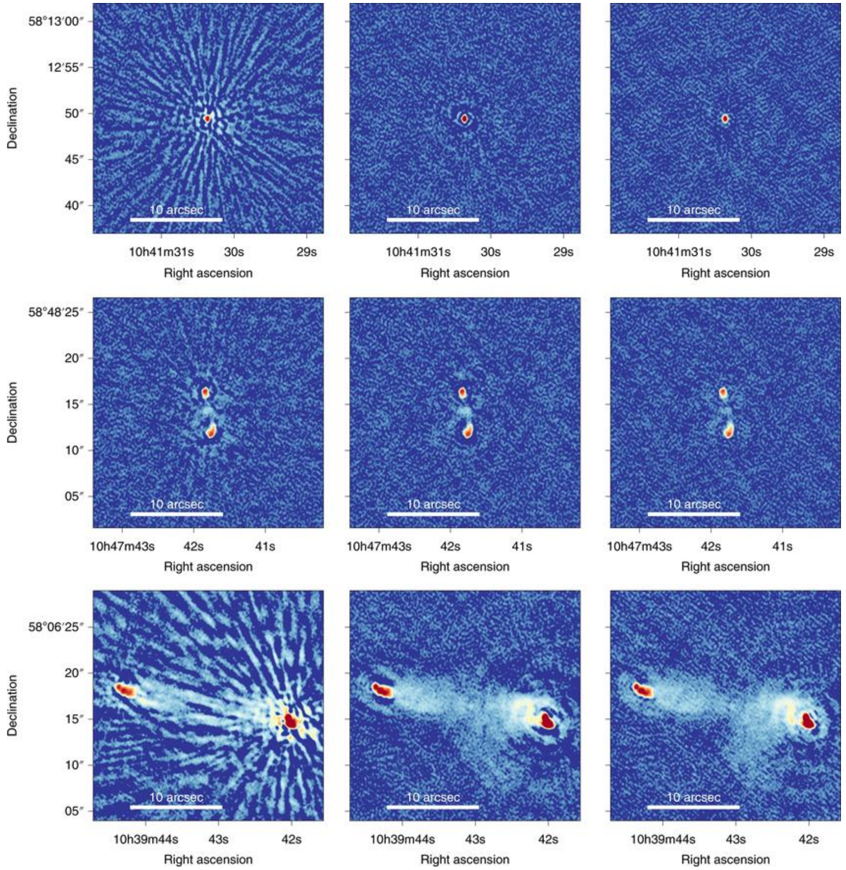
Self-calibration



Self-calibration







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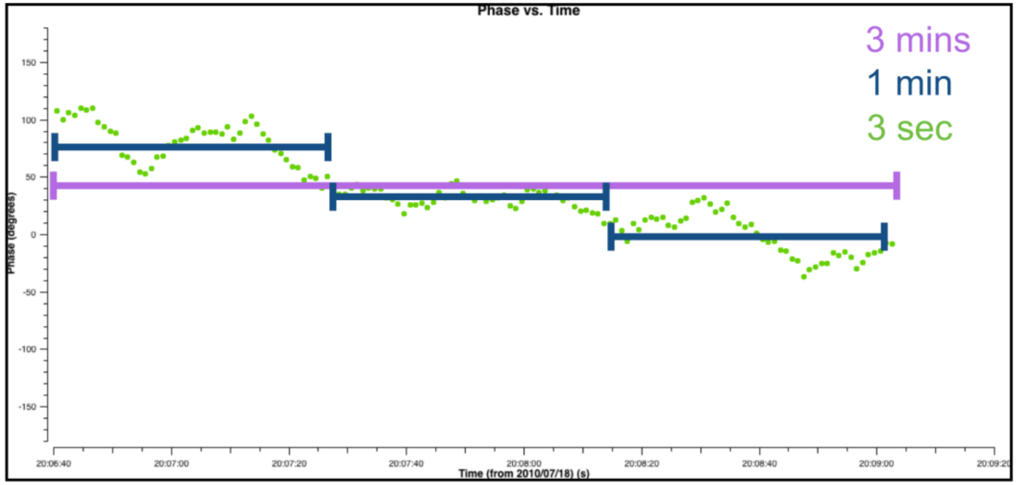
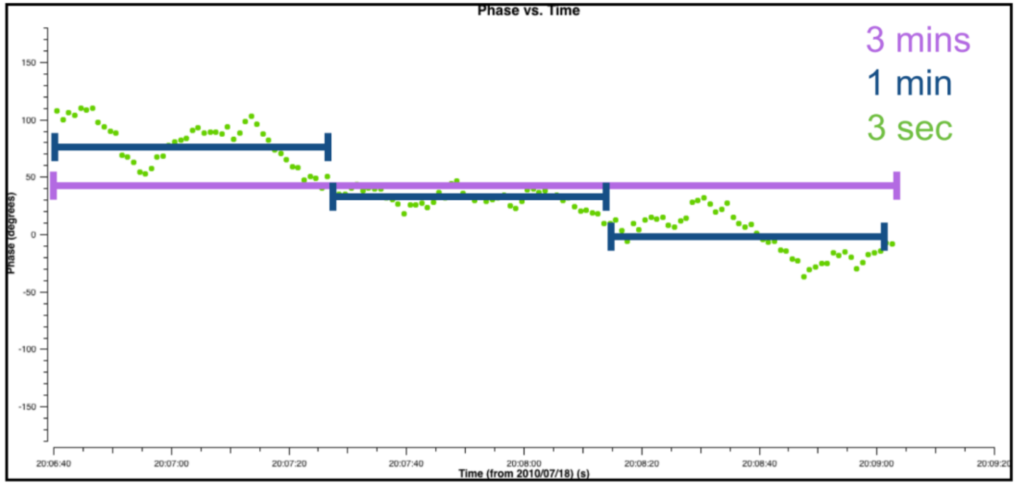
General remarks

- Jones matrix solutions are not static – several effects (e.g. the ionosphere are time, frequency, baseline, polarization dependent)
- We don't have one solution, but many, for each type
- Determining solution intervals in time, frequency etc depends on many things – how bright your calibrator is, how well behaved the ionosphere is during the observation.
- Errors at any step (e.g. incorrect model, poor choice of solution interval) will lead to the snowball effect and a poor image. Rubbish in=rubbish out



General remarks

- Calibration is an over-determined problem
- We have N antennas to calibrate, but there are N(N-1)/2 unique baselines (data points)
- When N>3, we have a lot more constraints than unknowns: improved accuracy and reliability
- But this increases computational complexity
    - Imagine doing regression fitting (getting all antenna visibility phases and amplitudes from all its baselines) over 10 solution intervals in time and 10 solution intervals in frequency for each antenna, multiplying all the Jones matrices and applying them to a 10 TB dataset



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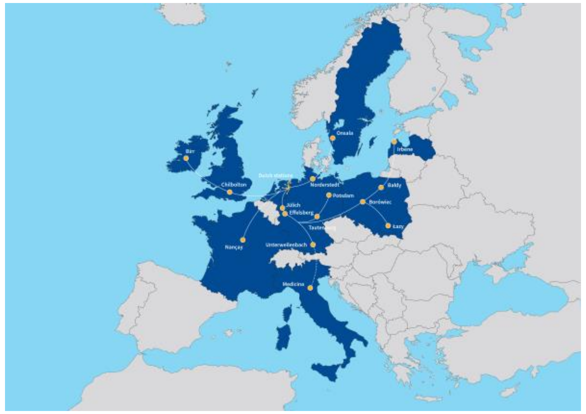
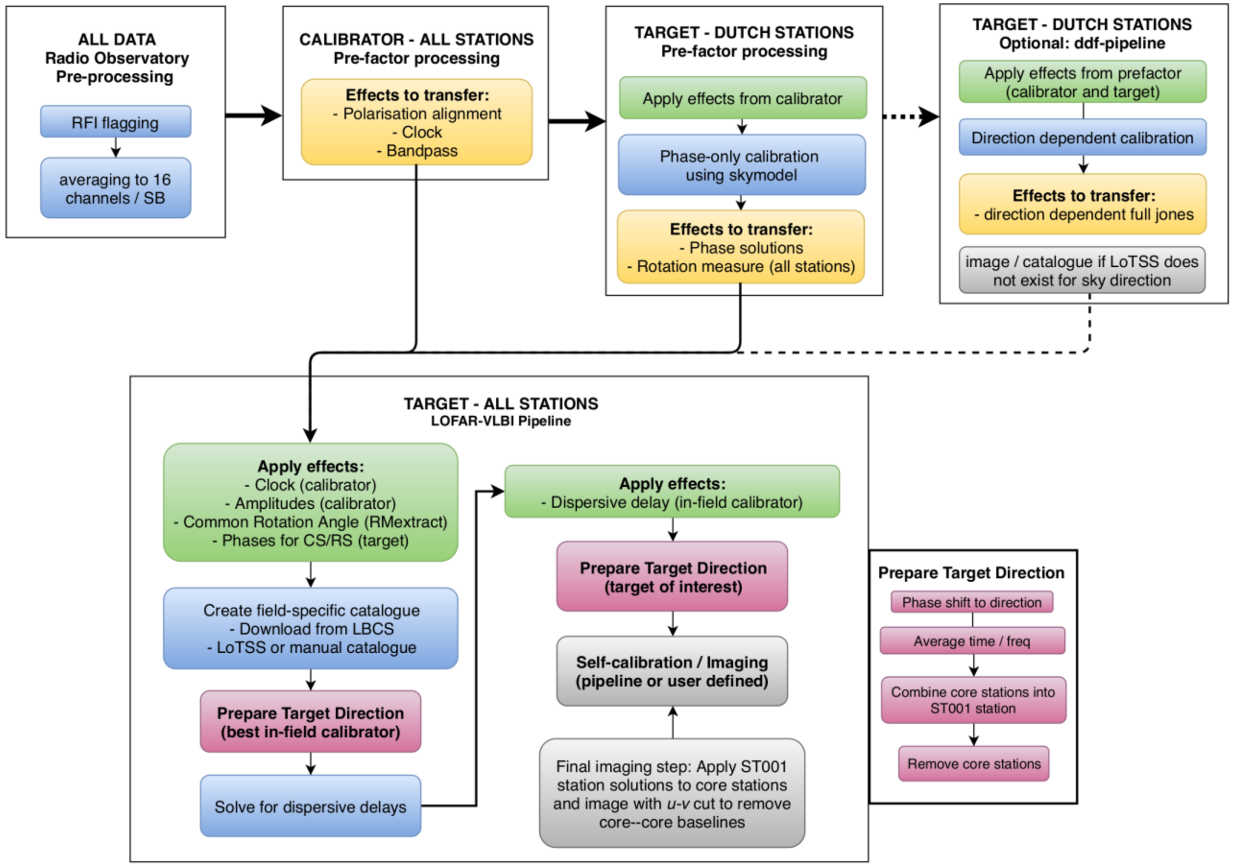
Modern calibration pipelines





Morabito+22

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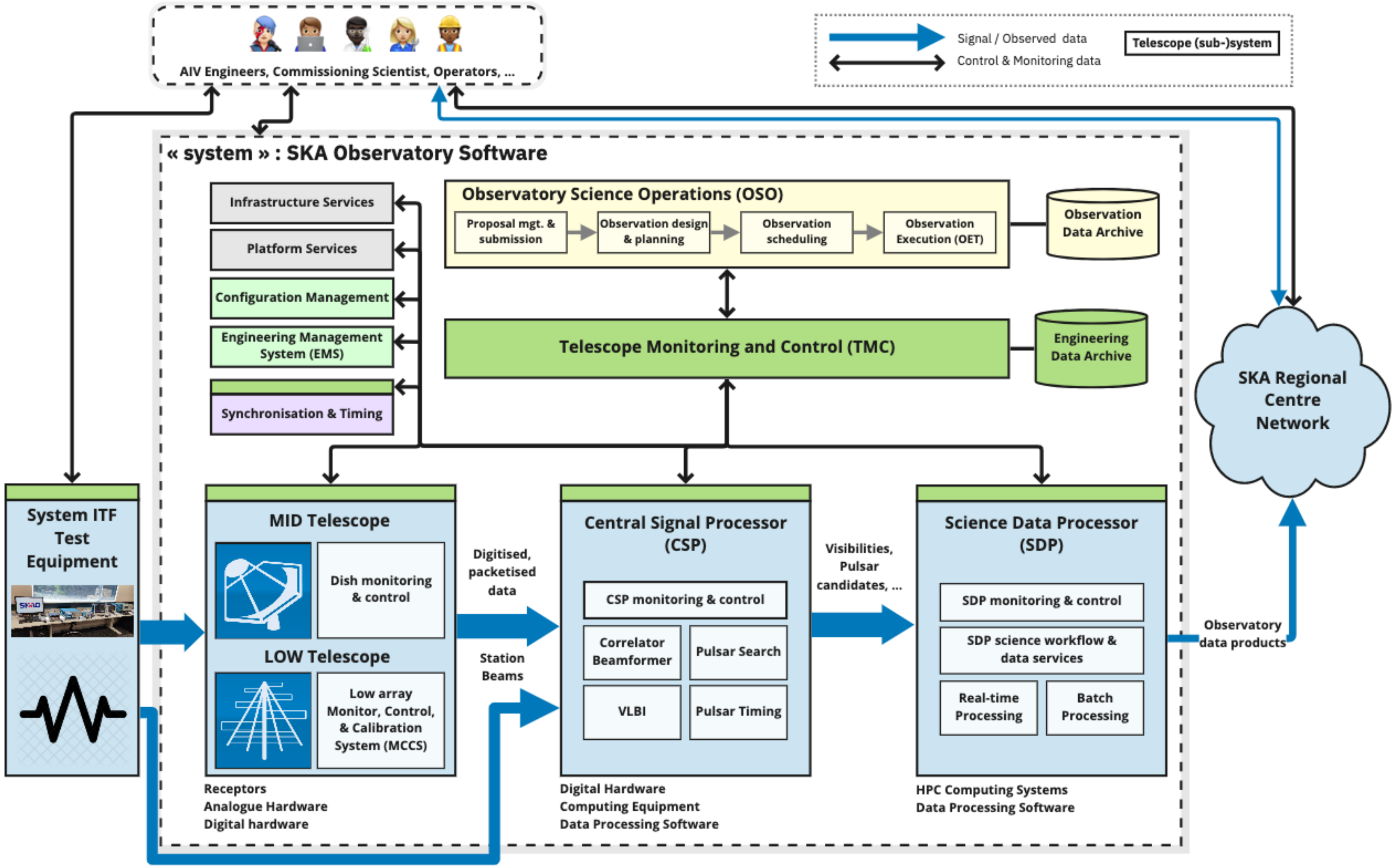
SKA system overview



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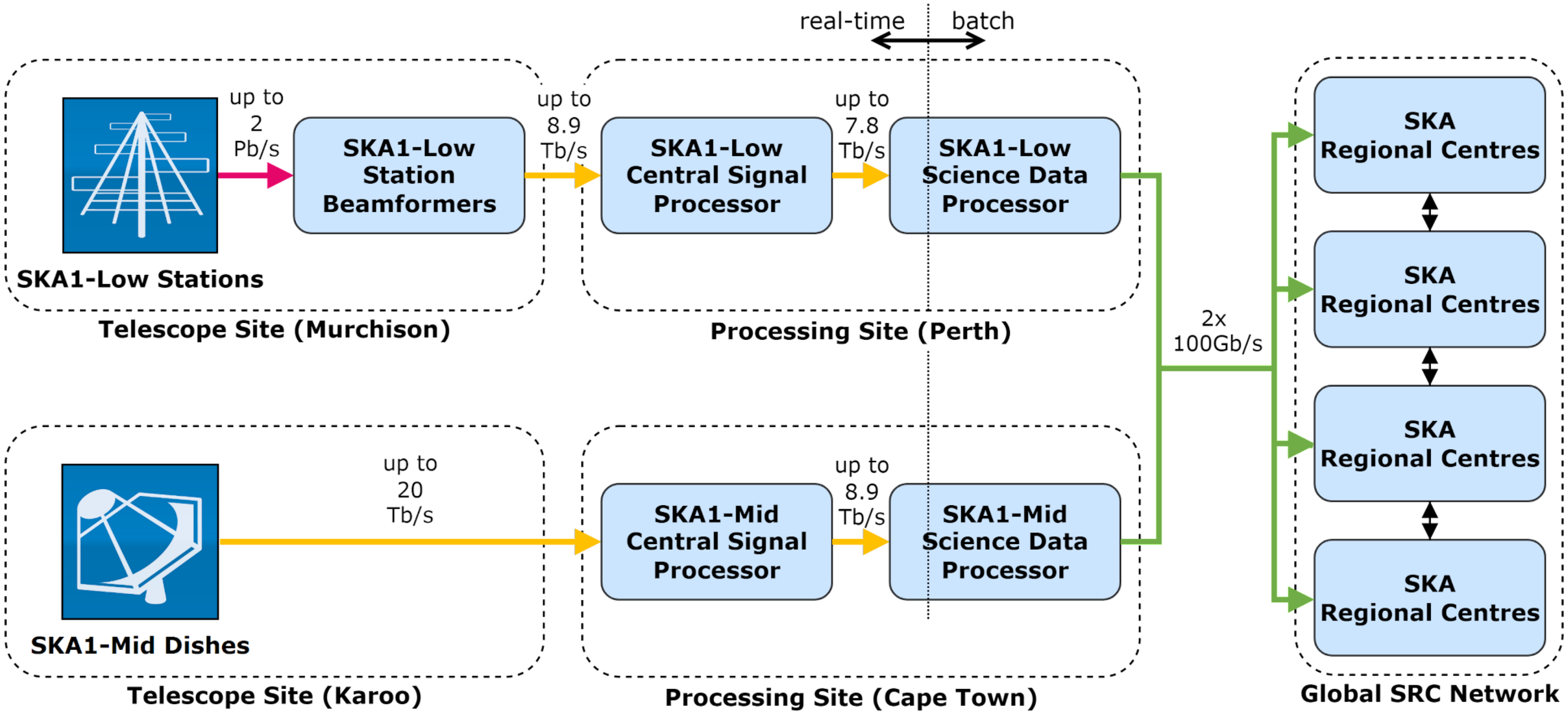
SKA system overview



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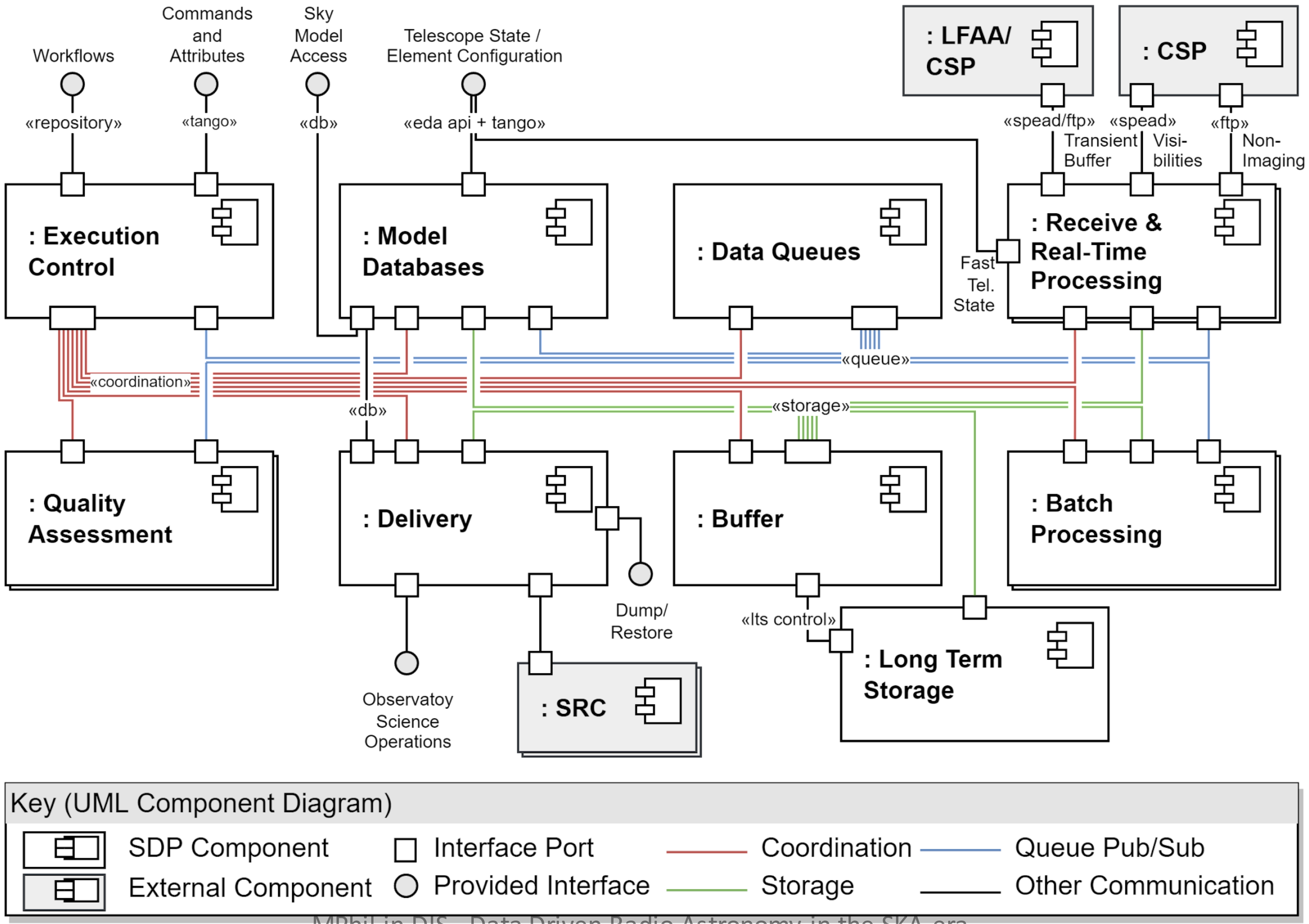
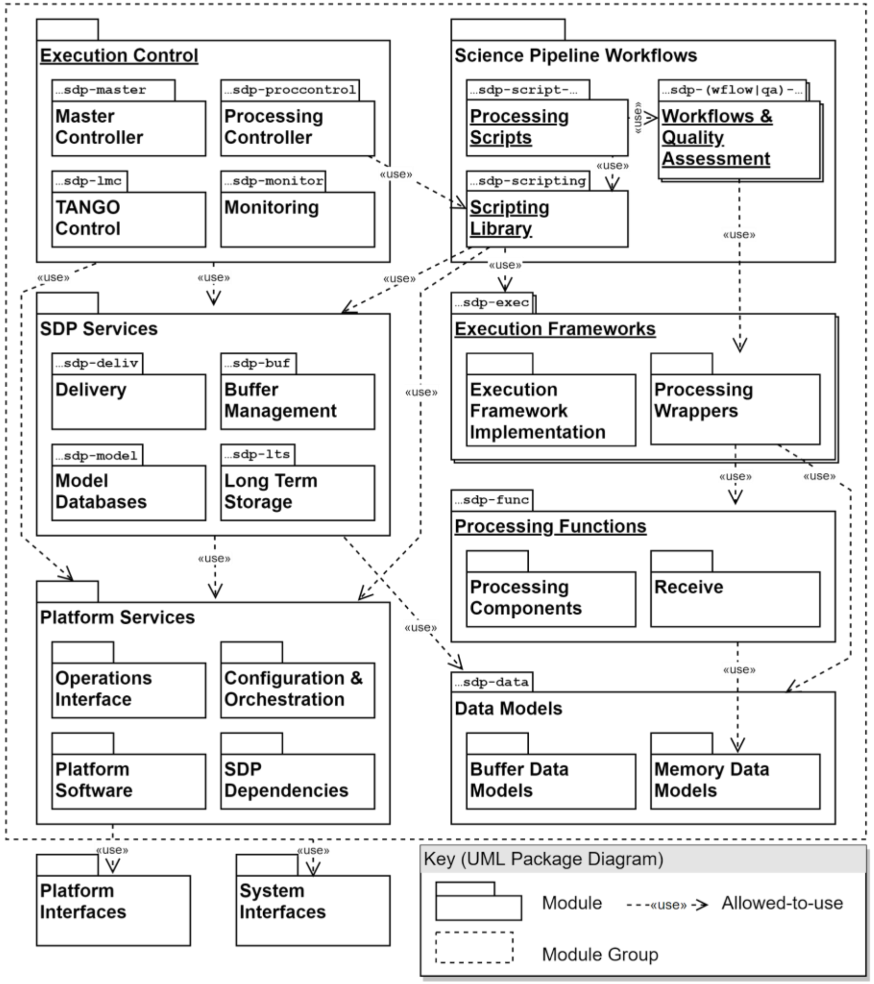
SKA Science Data Processor (SDP)



SKA Science Data Processor (SDP)



The problem of scalability

- Storage
  - > 700 Pb of data archived per year
- Compute processing
  - Typical complexity ~ 10 Pflops/s, mostly for calibration and self-calibration
  - Compute node storage limited to < 1 Tb – cannot keep data in memory for more than a few s
  - Images will be 10s of Tb – we need to process these in memory for self-cal. Remember every visibility affects every image pixel and vice versa. We need to go from visibilities <-- FT --> images multiple times for self-calibration, while doing the calibration, for every observation.
- I/O
  - Continuous stream of 0.4 Tb/s for calibration and imaging
  - 35 Pb/day expected throughput of the SKA -- $10m a day
- Solution?

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- Solution?
  - Distributed computing

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The problem of scalability

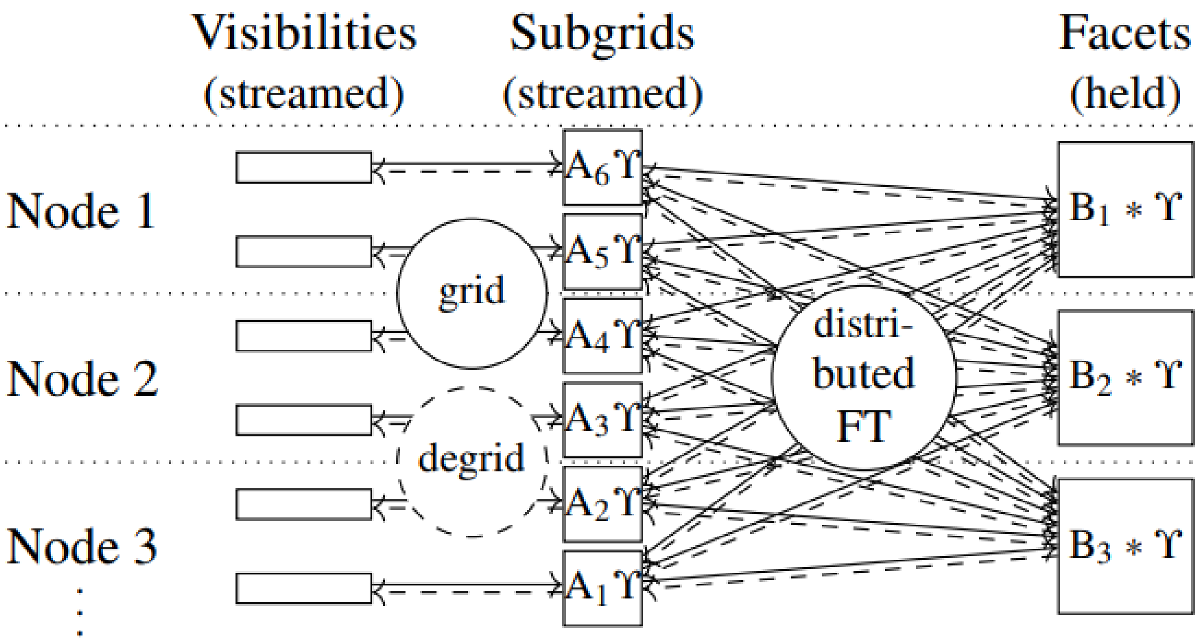
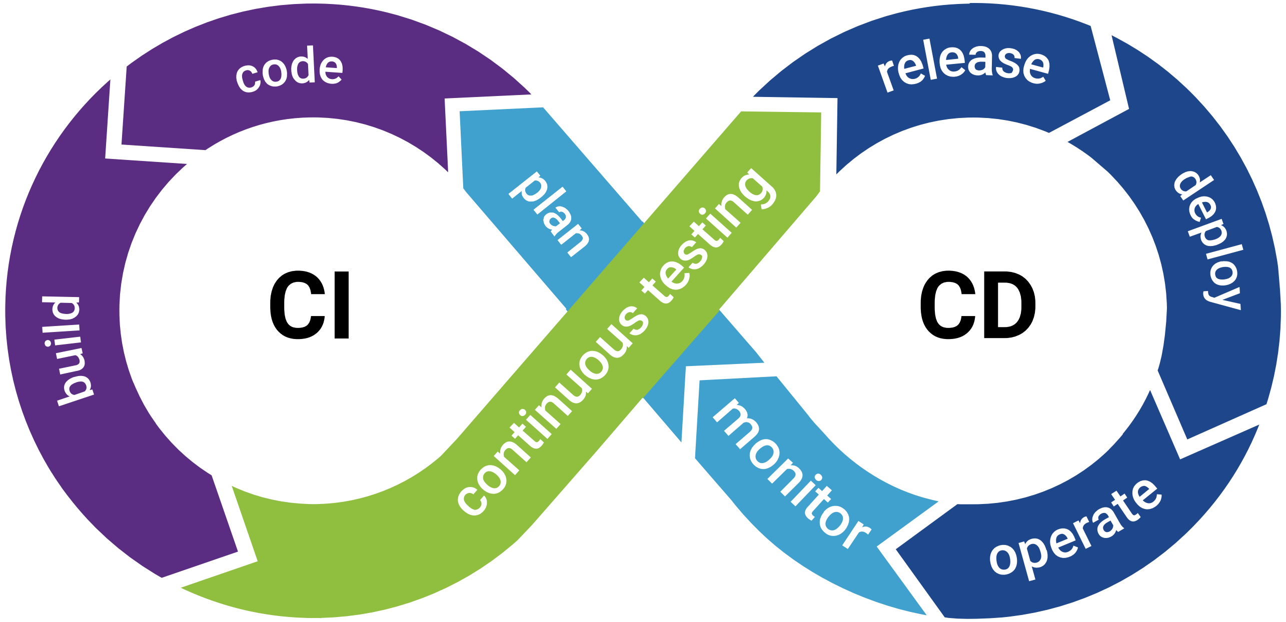


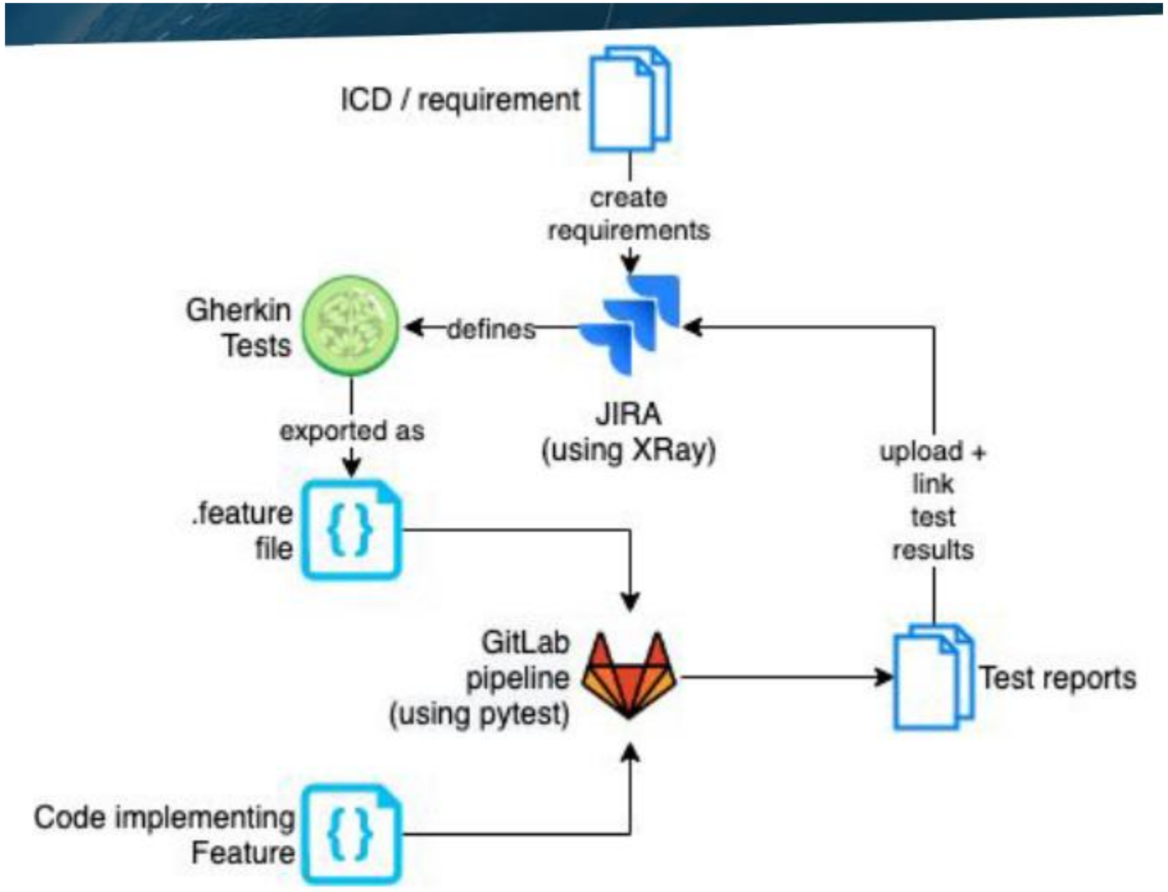
Fig. 1: Distribution Concept sketch – grid visibilities to sub-grids, accumulate contributions to facets using our algorithm (dashed: backwards direction – extract contributions from facets, then degrid visibilities from sub-grids)

Wortmann+21

SKA Science Data Processor practices: CI/CD



SKA Science Data Processor practices: BDD



SKA Science Data Processor practices: Containerization

- Containers are a manifestation of a collection of features of a Linux kernel and the OS, typically launched by an Engine such as Singularity or Docker
- Allows you to have software, environments, applications stored in a single container, so that dependencies and versions are controlled – faster for running calibration pipelines that use a lot of software.

SKA Science Data Processor practices: Unit/integration tests

- Unit tests test the functionality of a small unit of a large piece of code (e.g. a Python function that reads visibilities)
- Fast, agile code development requires such testing to ensure the overall codebase is clean and compiles whenever changes are made (e.g. changing calibration methods)
- Integration tests test the whole software module created, ensuring the system is compliant against functional requirement
- SKA SDP functions are unit and integration tested before they are released as working code.