ASTRON

While we wait…

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Enter the code 7745 5582

The lecture will have many questions to help you understand the material better

ASTRON

Systematic effects in LOFAR data

Cristina-Maria Cordun

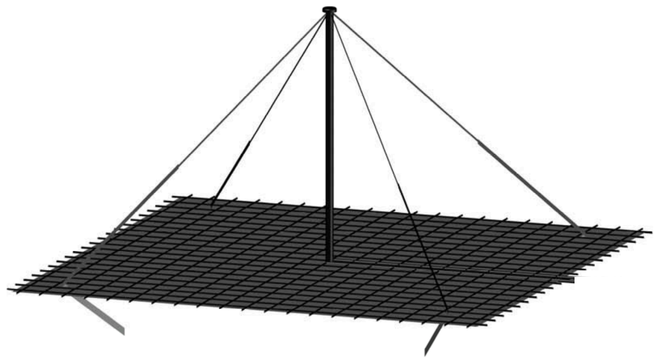



Credit: Zabet Ahmadi

What do we observe?

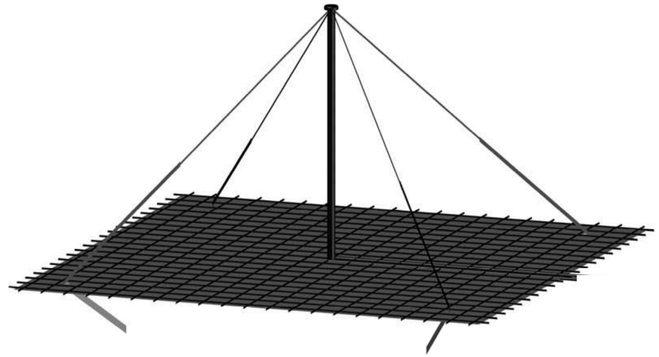
Voltage: complex numbers

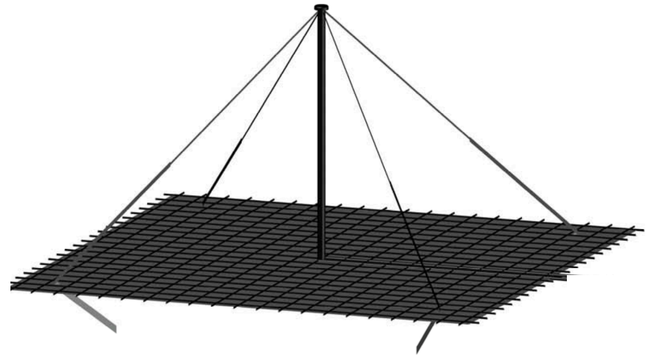
$$\vec{v}(\vec{r_1})$$



Visibility = correlation of voltages

$$\left\langle v(\vec{r}_1)\, v(\vec{r}_2)^{\dagger} \right\rangle \approx \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I_{\nu}(l,m) e^{-2\pi i(ul+vm)}\, dl\, dm$$



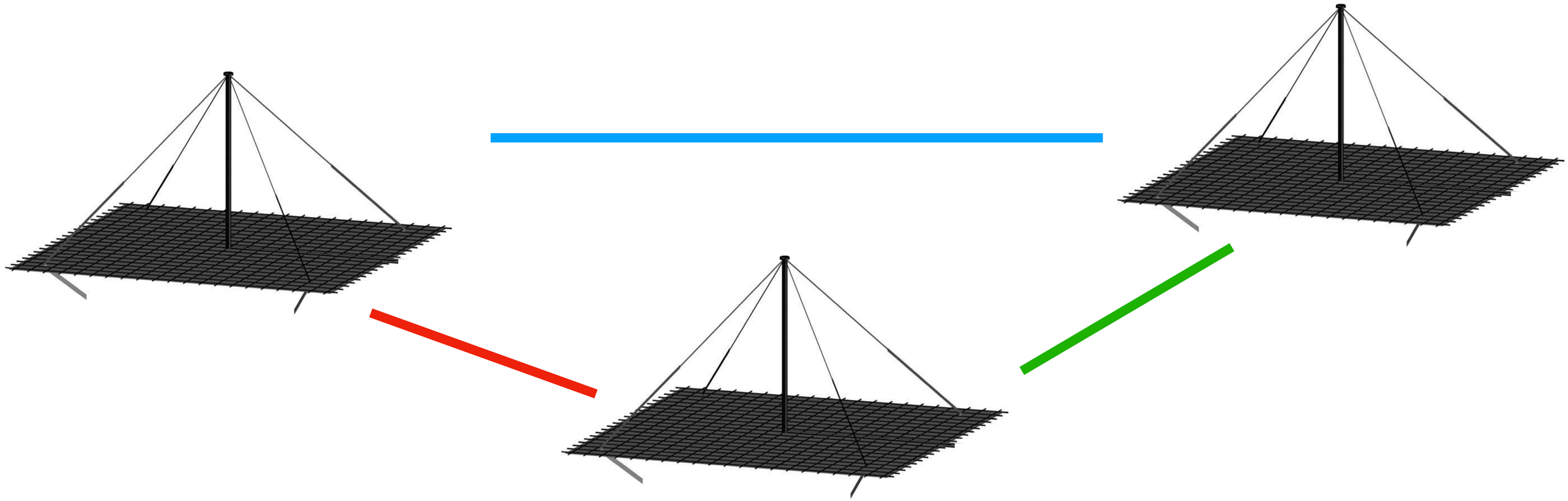


Questions

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3*5*2 = 30

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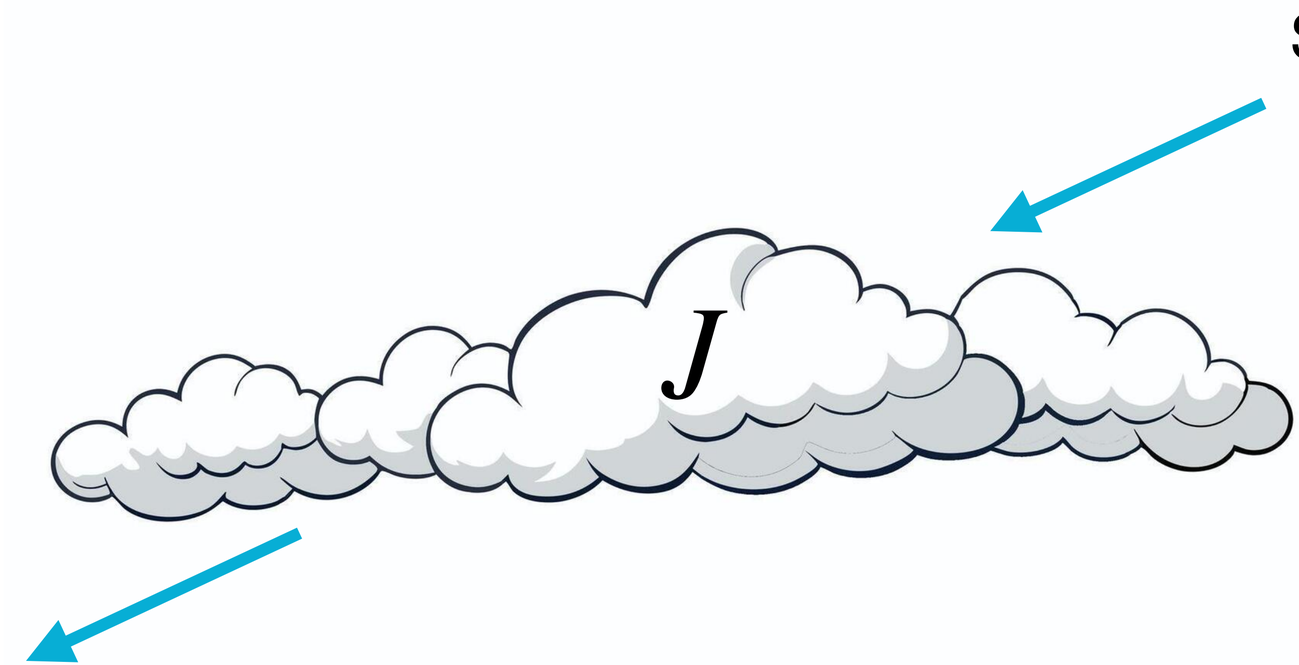
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N(N-1)/2

Signal to voltage

Source: Signal

$$\vec{e} = \begin{pmatrix} e_x \\ e_y \end{pmatrix}$$



Detector: Voltage

$$\vec{v} = \begin{pmatrix} v_x \\ v_y \end{pmatrix}$$

$$\vec{v} = J\vec{e} = \begin{pmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{pmatrix} \vec{e}$$

Jones matrices

- Each effect has its own Jones matrix
- Jones matrices are NOT commutative!

$$\vec{v} = \mathbf{J}_1\mathbf{J}_2\mathbf{J}_3\cdots\mathbf{J}_n\vec{e}$$
$$= \mathbf{J}\vec{e}$$

From voltages to visibilities

$$\vec{v}_1 = \mathbf{J}_1\vec{e} \qquad \text{and} \qquad \vec{v}_2 = \mathbf{J}_2\vec{e}$$

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From voltages to visibilities

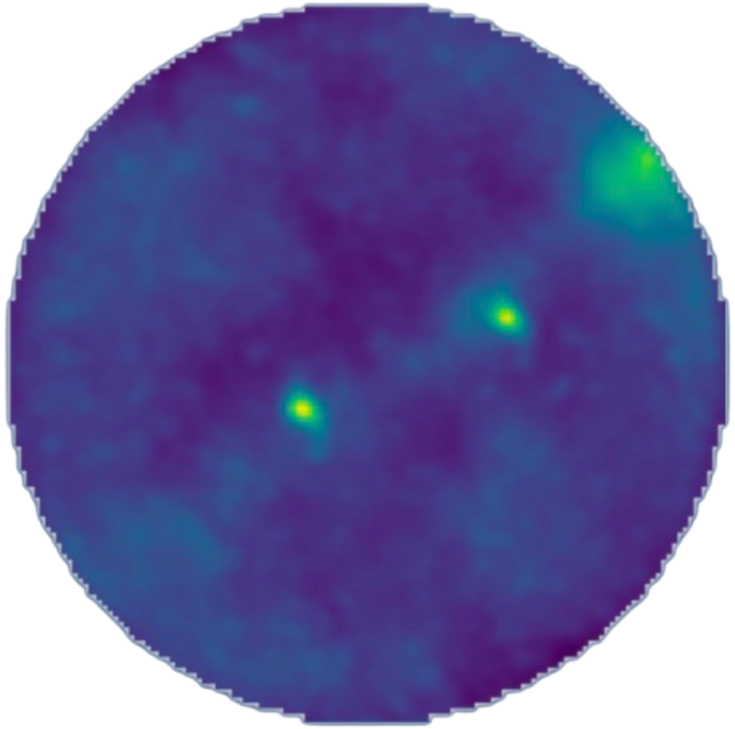
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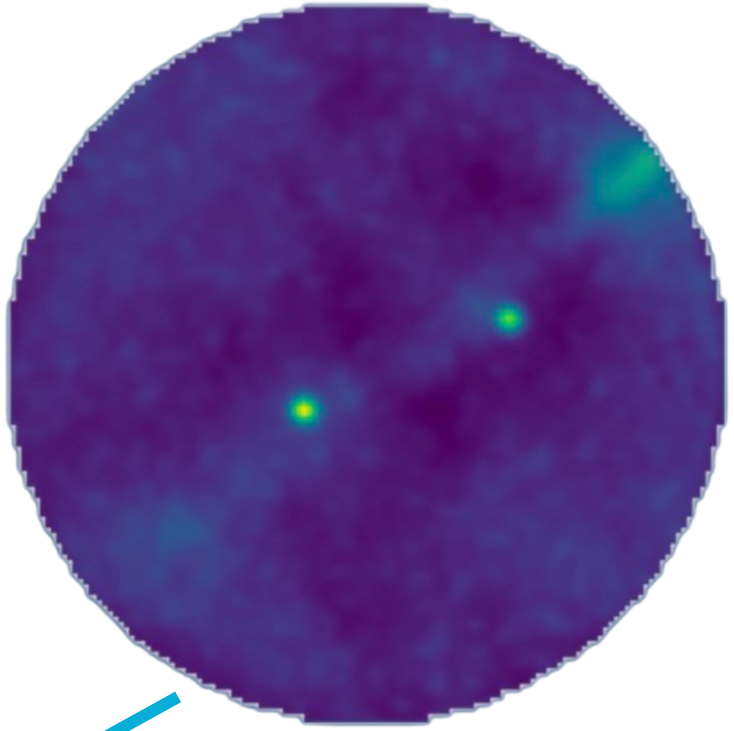
$$\mathbf{V}_{ij} = \mathbf{J}_i \mathbf{B}_{ij} \mathbf{J}_j^{\dagger}$$

Measured visibility between station i and station j

Why calibrate?



What we measure



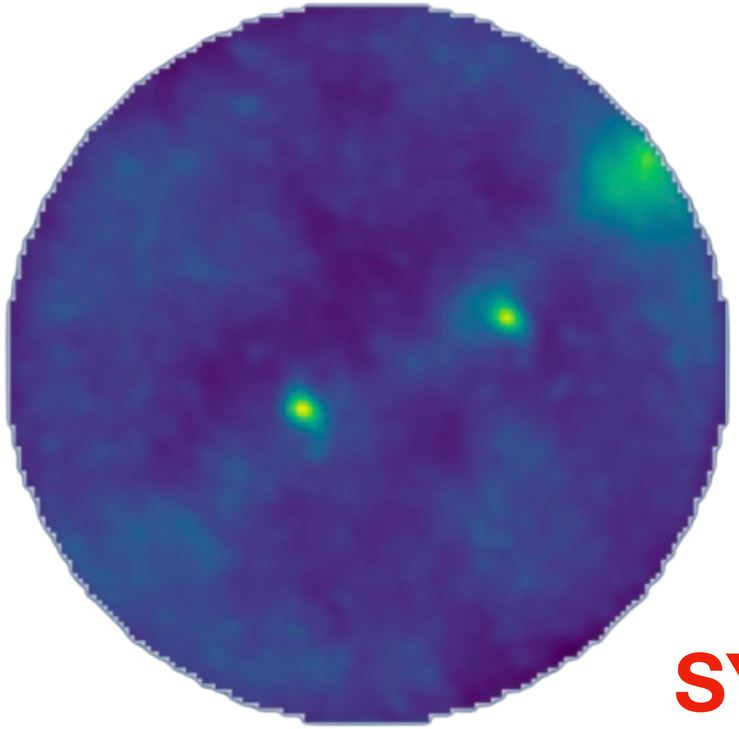
What we want

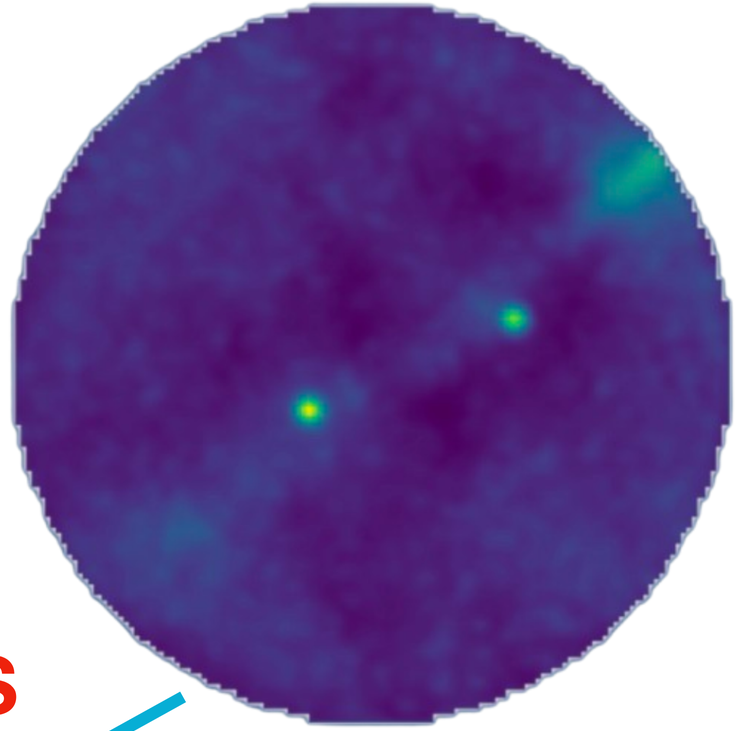
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Credit images:

David McKenna

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SYSTEMATICS

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$$\mathbf{V}_{ij} = \mathbf{J}_i \mathbf{B}_{ij} \mathbf{J}_j^{\dagger}$$

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In practice

- Start with a model of a known (bright) calibrator (M_{ij}) $\mathbf{V}_{ij} = \mathbf{J}_i \mathbf{M}_{ij} \mathbf{J}_j^{\dagger}$ $(first\ approx)$

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!!! All of this is for one time and frequency slot !!!

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  Jones matrices contain complex numbers (amplitude and phase), and you have 4 elements per matrix => 4 complex unknowns per station => N*4 complex unknowns

  (This is the most general case, see later why they are usually reduced)

Questions

- You are trying to find Jones matrices for N stations (one time and frequency slot). How many complex unknowns do you have?
- How many complex-valued equations do you have for N stations?

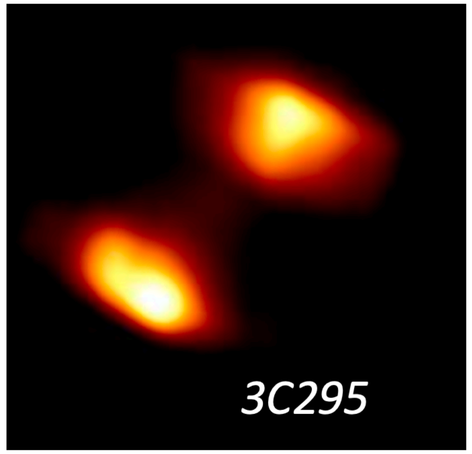
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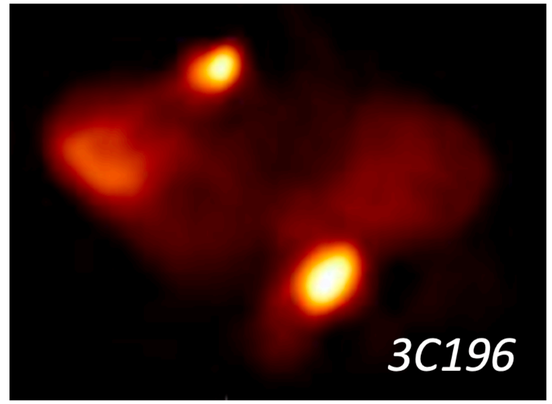
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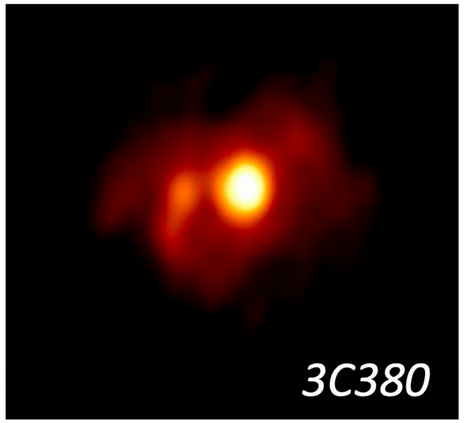
You have 4 equations per baseline (one for each visibility matrix element), so 4*N(N-1)/2 equations => 2N(N-1)

Calibrators

- They need to be:
  - Bright
  - Compact
  - Well known structure
  - Well-known fluxes (Scaife and Heald, 2012)







Different effects

Systematic effect	Type of Jones matrix[a]	Ph/Amp/ Both[b]	Frequency dependency	Direction dependent?	Time dependent?
Clock drift	Scalar	Ph	$\propto \nu$	No	Yes (many seconds)
Polarisation alignment	Diagonal	Ph	$\propto \nu$	No	No
Ionosphere – 1st ord. (dispersive delay)	Scalar	Ph	$\propto \nu^{-1}$	Yes	Yes (few seconds)
Ionosphere – 2nd ord. (Faraday rotation)	Rotation	Both	$\propto \nu^{-2}$	Yes	Yes (few seconds)
Ionosphere – 3rd ord.	Scalar	Ph	$\propto \nu^{-3}$	Yes	Yes (few seconds)
Ionosphere – scintillations	Diagonal	Amp	–	Yes	Yes (few seconds)
Dipole beam	Full-Jones	Both	–	Yes	Yes (minutes)
Bandpass	Diagonal	Amp	–	No	No

De Gasperin et al. (2019)

Different effects (Telescope vs iono)

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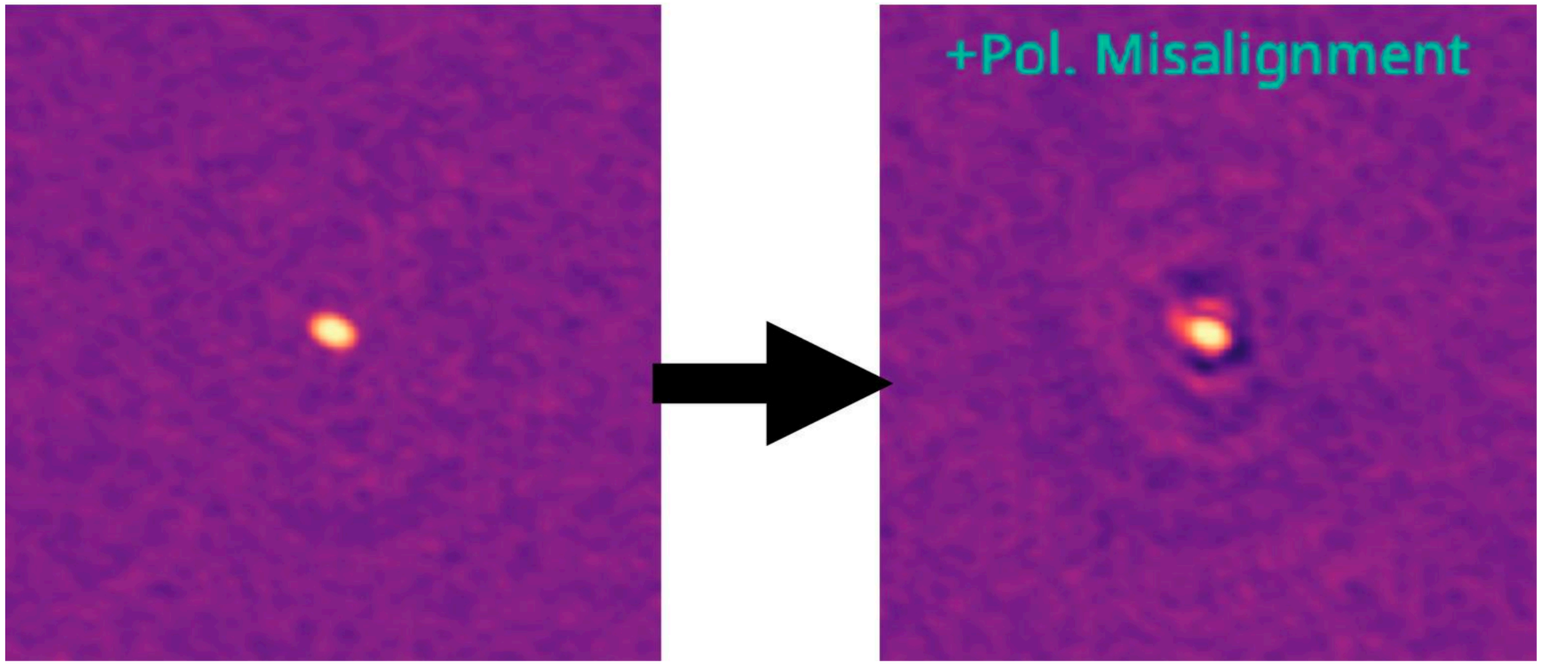
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TELESCOPE EFFECTS

Polarisation misalignment - what is it?

- Small delay between X and Y polarisation (from the station) - constant in time

$$J_i = \begin{pmatrix} ? & ? \\ ? & ? \end{pmatrix}$$

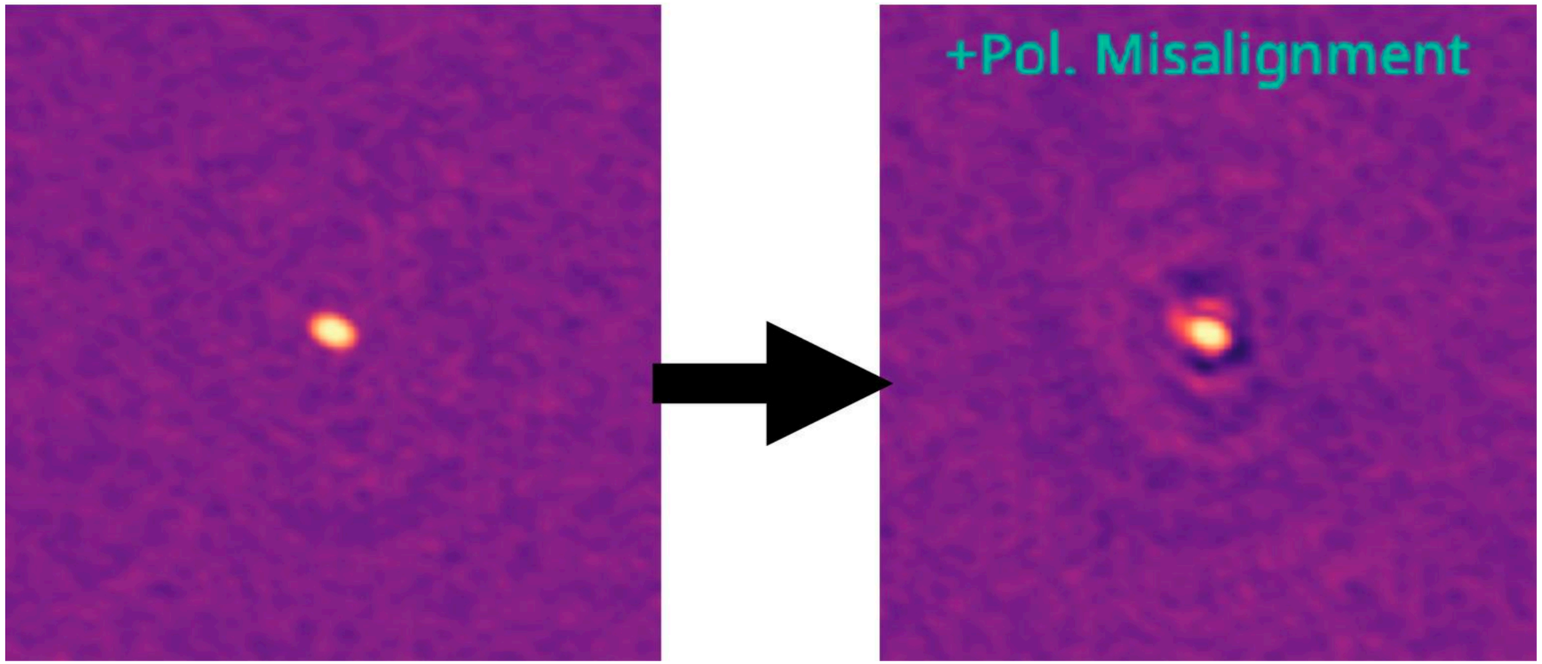


Polarisation misalignment - what is it?

- Small delay between X and Y polarisation (from the station) - constant in time

$$J_i = \begin{pmatrix} ? & 0 \\ 0 & ? \end{pmatrix}$$

The effect acts independently on X and Y; it does not mix the two polarisations.

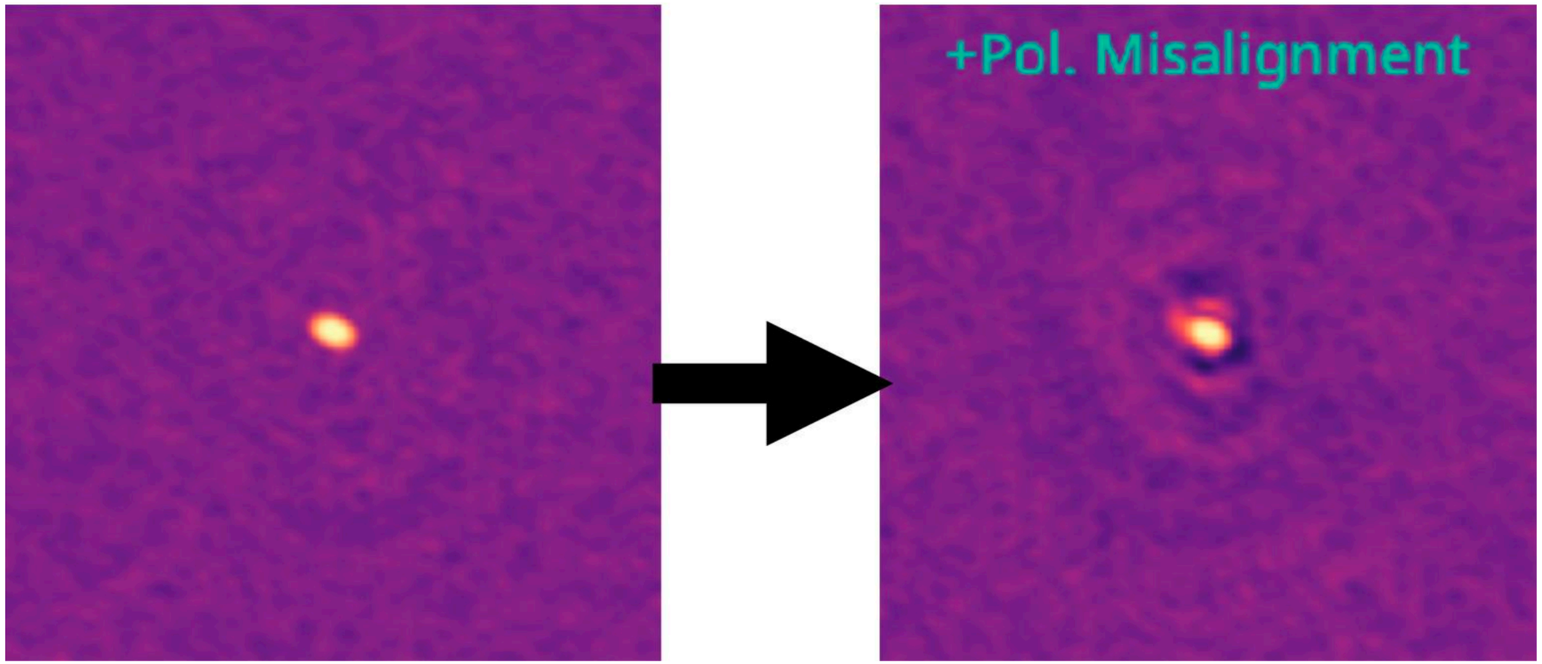


Polarisation misalignment - what is it?

- Small delay between X and Y polarisation (from the station) - constant in time

$$J_i = \begin{pmatrix} 1 & 0 \\ 0 & ? \end{pmatrix}$$

It's the delay between X and Y, so one of them is kept as reference (at 1)

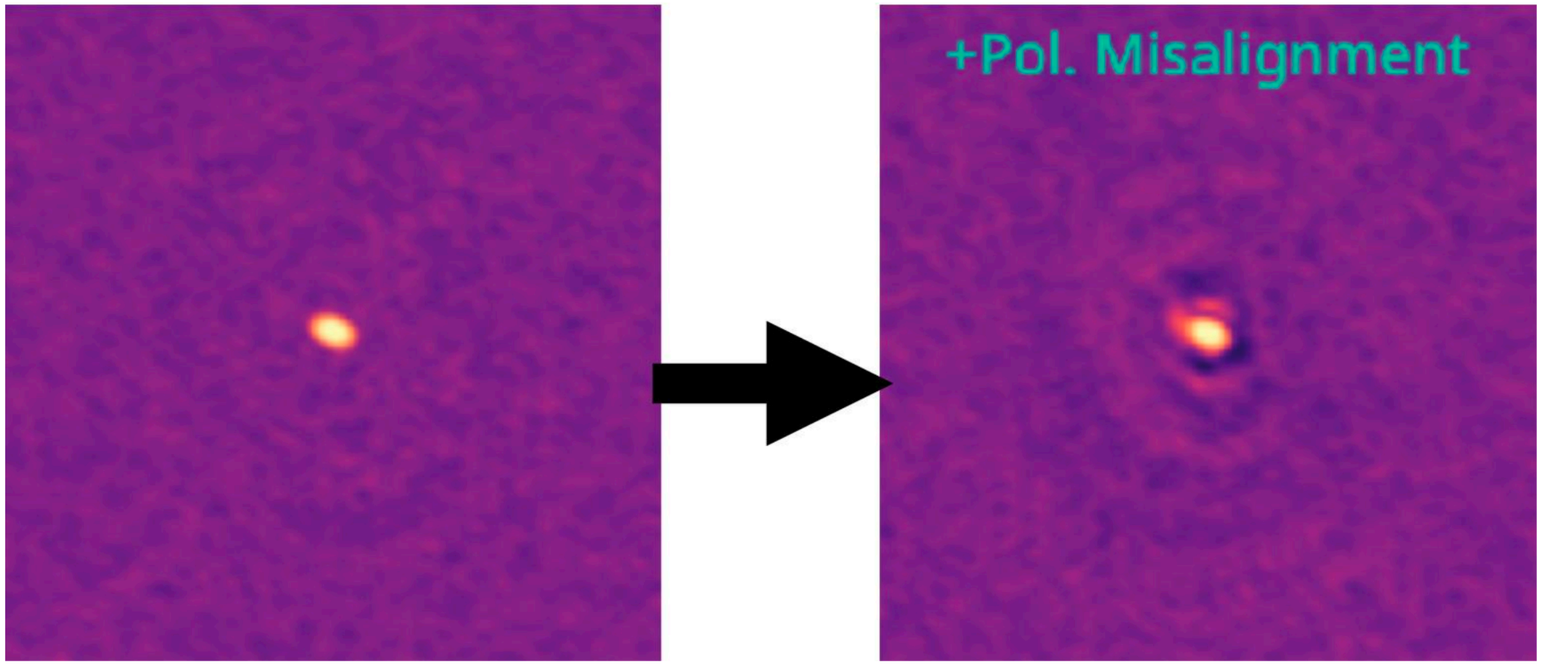


Polarisation misalignment - what is it?

- Small delay between X and Y polarisation (from the station) - constant in time

$$J_i = \begin{pmatrix} 1 & 0 \\ 0 & e^{2\pi i \nu \Delta t_{xy}} \end{pmatrix}$$

A delay (Δt) leads to a phase slope via $2\pi\nu\Delta t$



Polarisation misalignment - find solution

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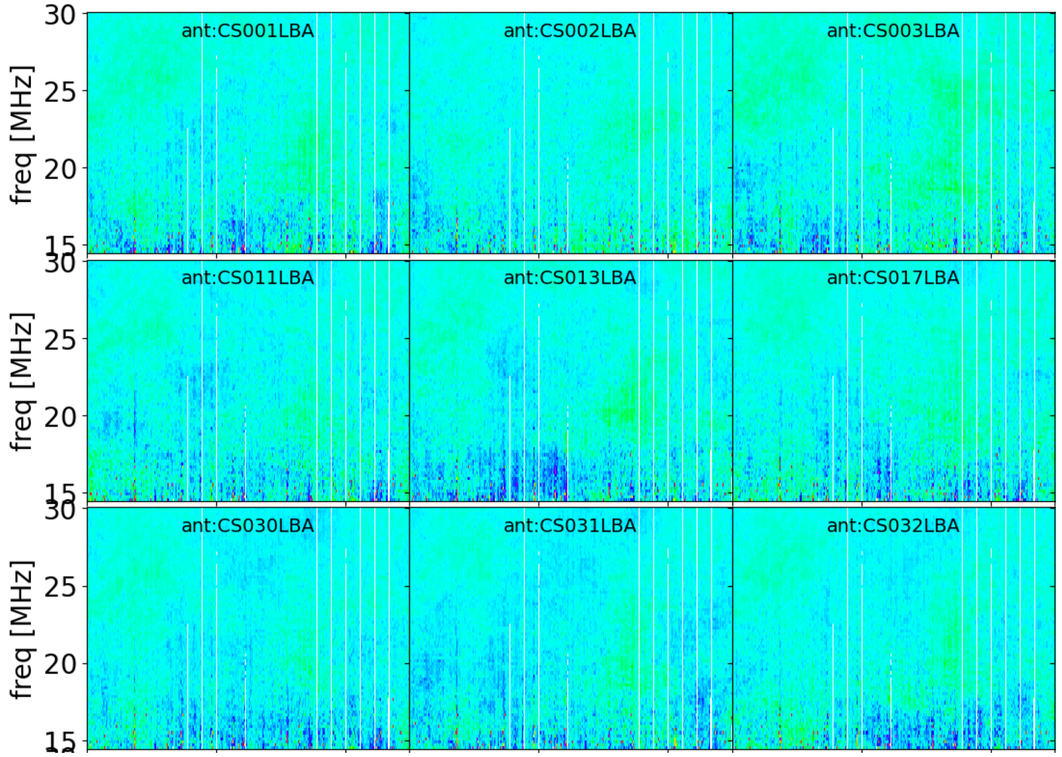
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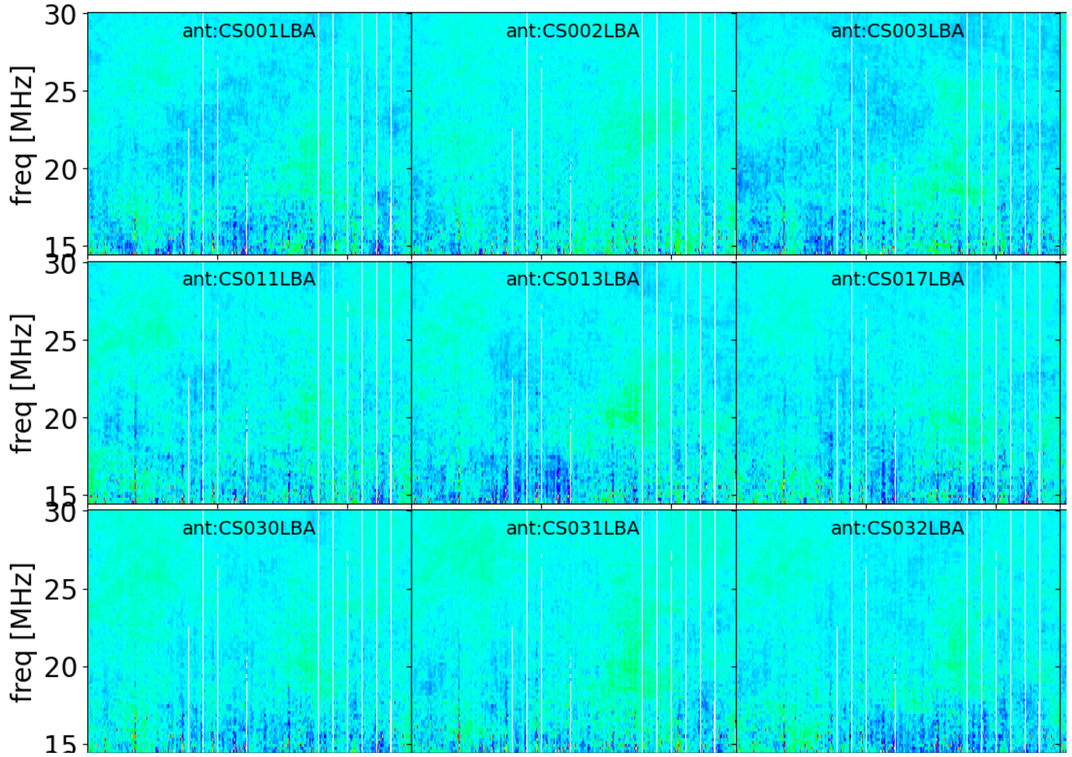
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  1 rotation angle + 2 phases = 3 unknowns per station

Polarisation misalignment - solution

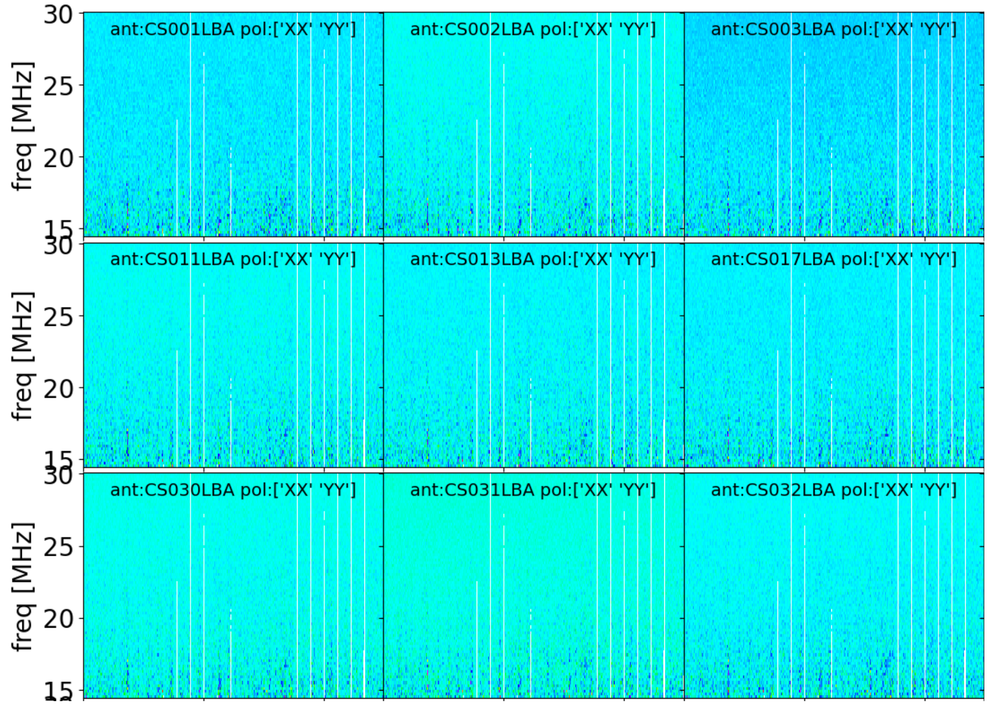
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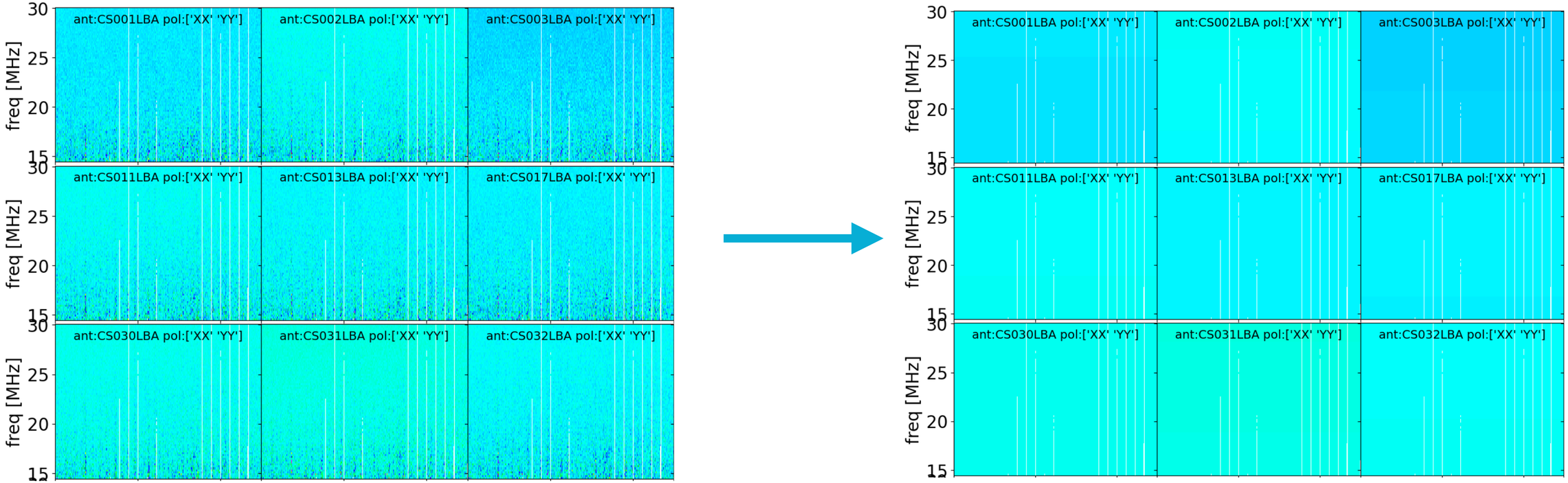
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!!! These can be done with LoSoTo library: POLALIGN function !!!

Polarisation misalignment - solution

- Now we have phase solutions for X and Y polarisation
- Subtract them (removes common ionospheric effects and delays)
- Avg in time (effect is constant in time) and fit a delay
- Apply solutions with DP3 ApplyCal

Primary Beam

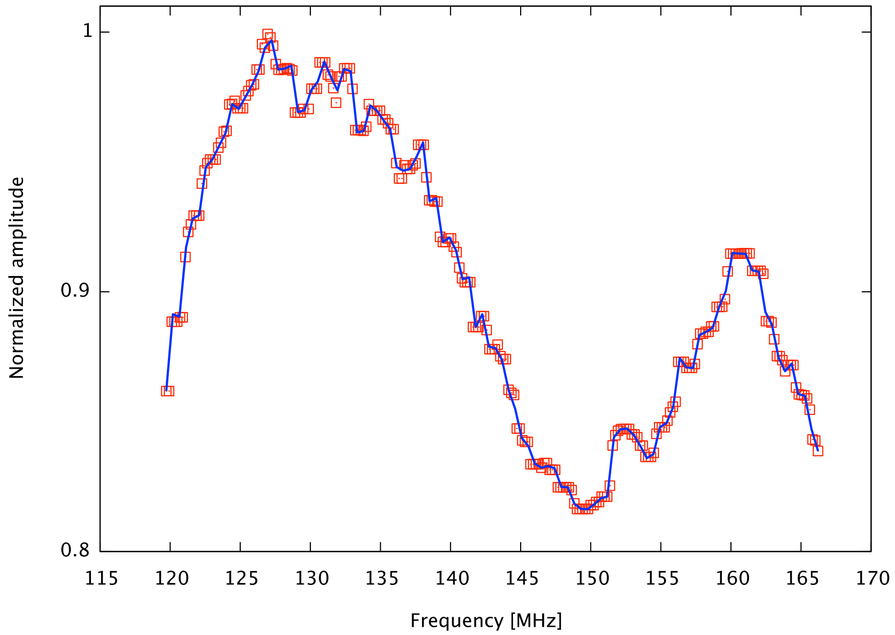
- The instrument's response
- It is direction dependent
- It is calculated with Everybeam
- You simply apply it with ApplyBeam of DP3
- Contains: array factor (complex scalar) and element beam (full-Jones)

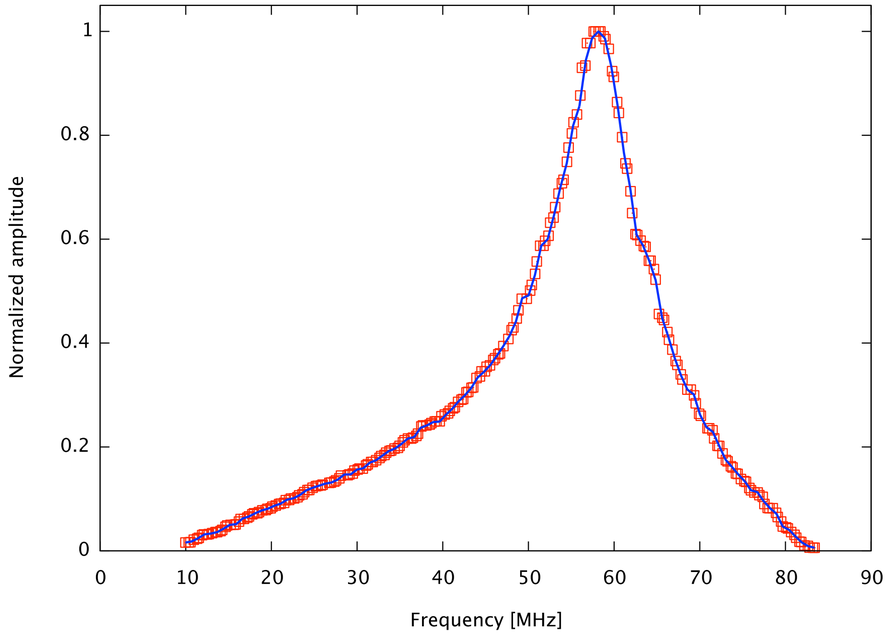
$$\mathbf{J}_{i,\mathrm{beam}} = a_{\mathrm{arr}} e^{i\phi_{\mathrm{arr}}} \begin{pmatrix} A_{xx} e^{i\phi_{xx}} & A_{xy} e^{i\phi_{xy}} \\ A_{yx} e^{i\phi_{yx}} & A_{yy} e^{i\phi_{yy}} \end{pmatrix}$$

Bandpass - what is it?

- Frequency dependence of instrument response
- Time independent
- Bandpass can be different for xx and yy pol

$$J_i = \begin{pmatrix} ? & ? \\ ? & ? \end{pmatrix}$$

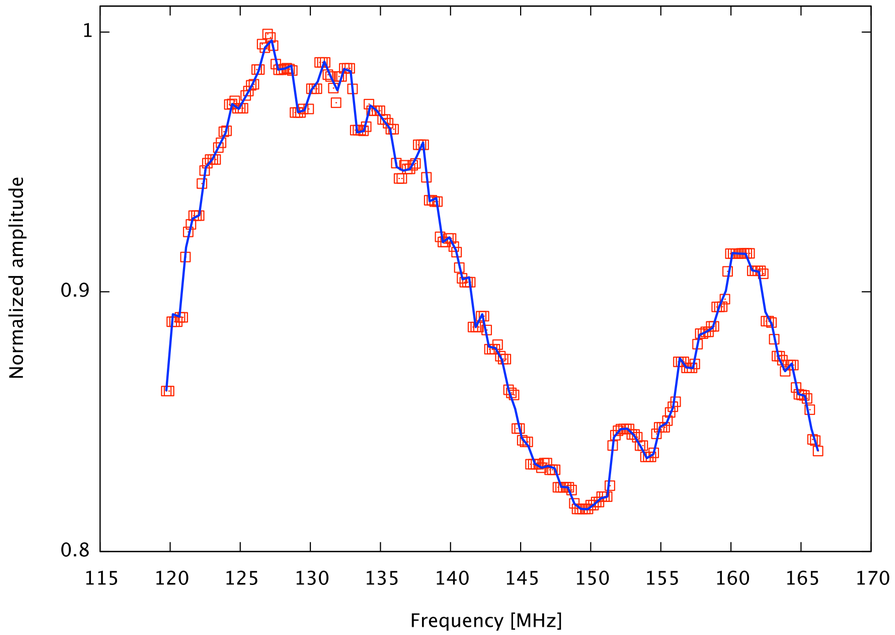


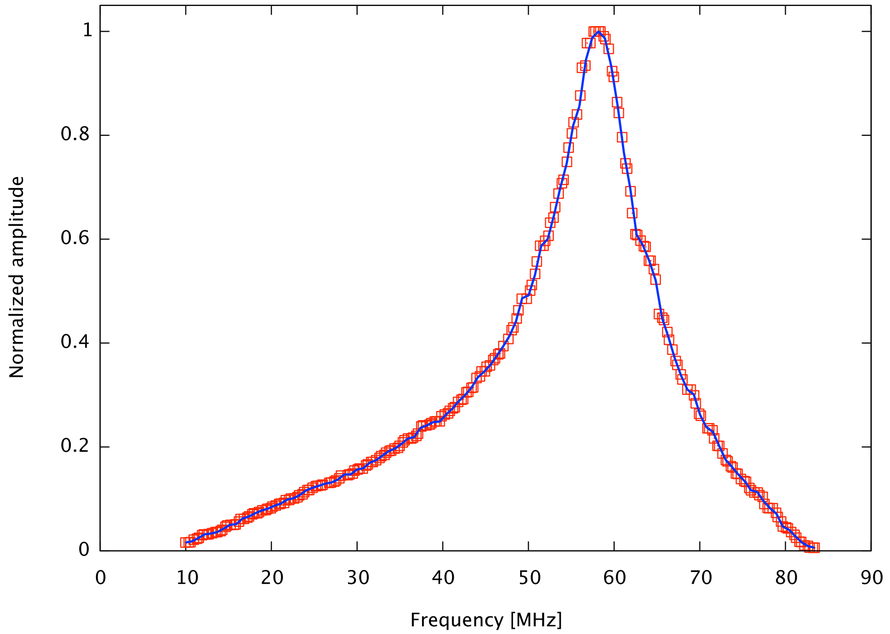


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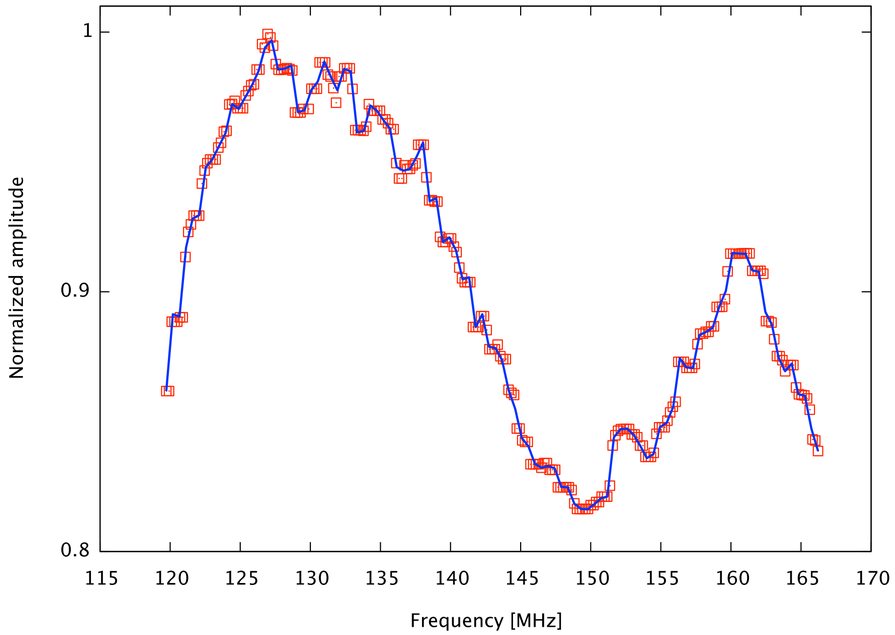
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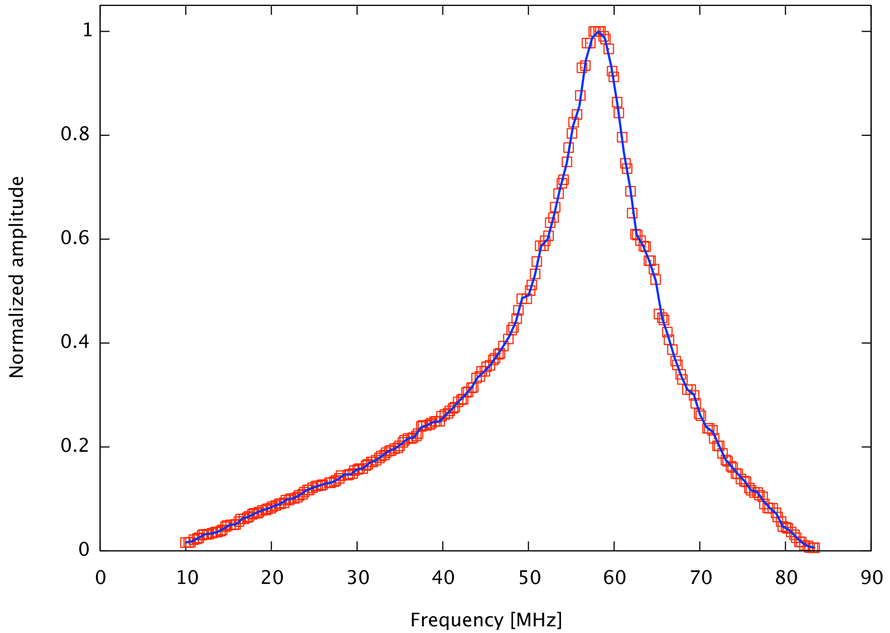




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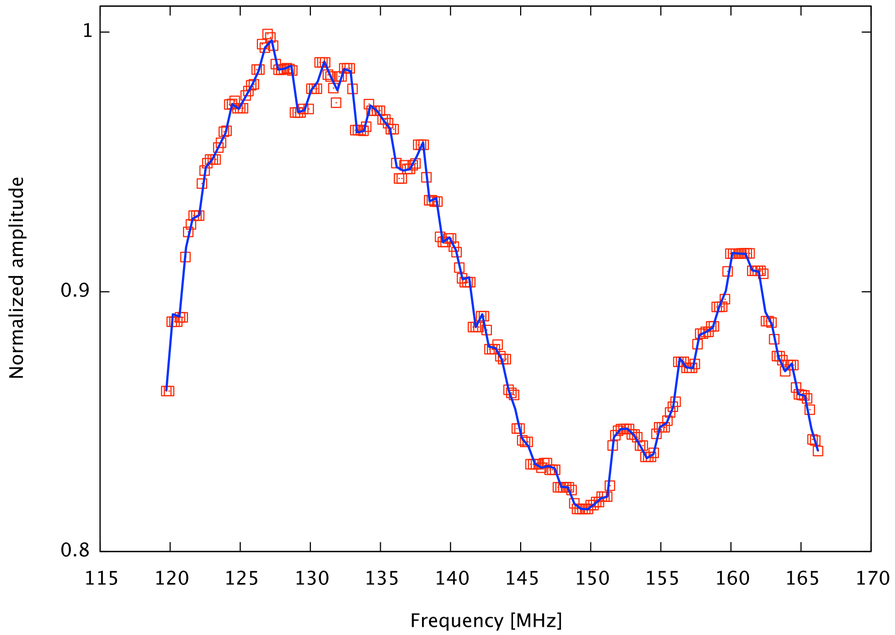


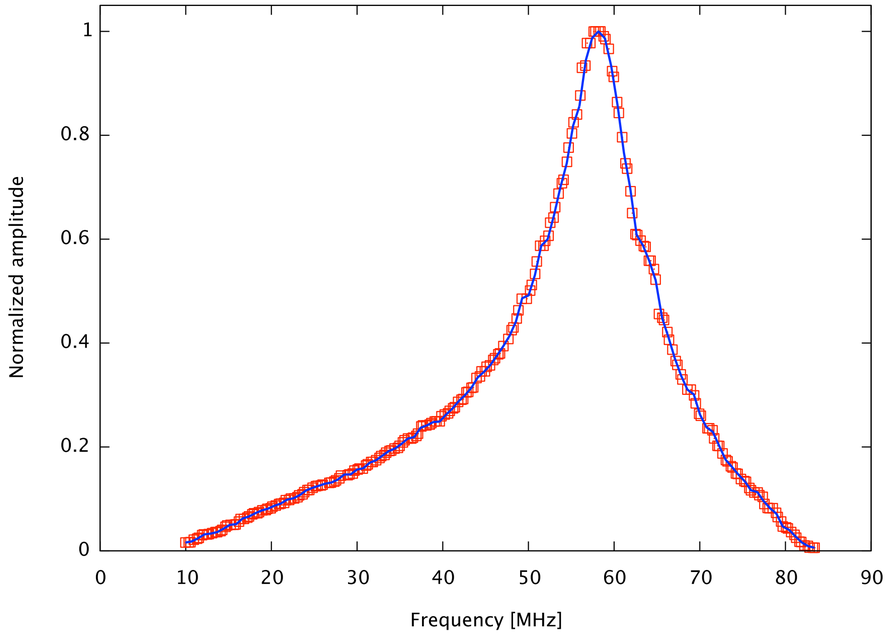


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2 amplitudes = 2 unknowns





Bandpass - find solution

- Use DP3 solver in scalaramplitude/diagonal/diagonalamplitude mode (which one?)

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Bandpass - NOTE

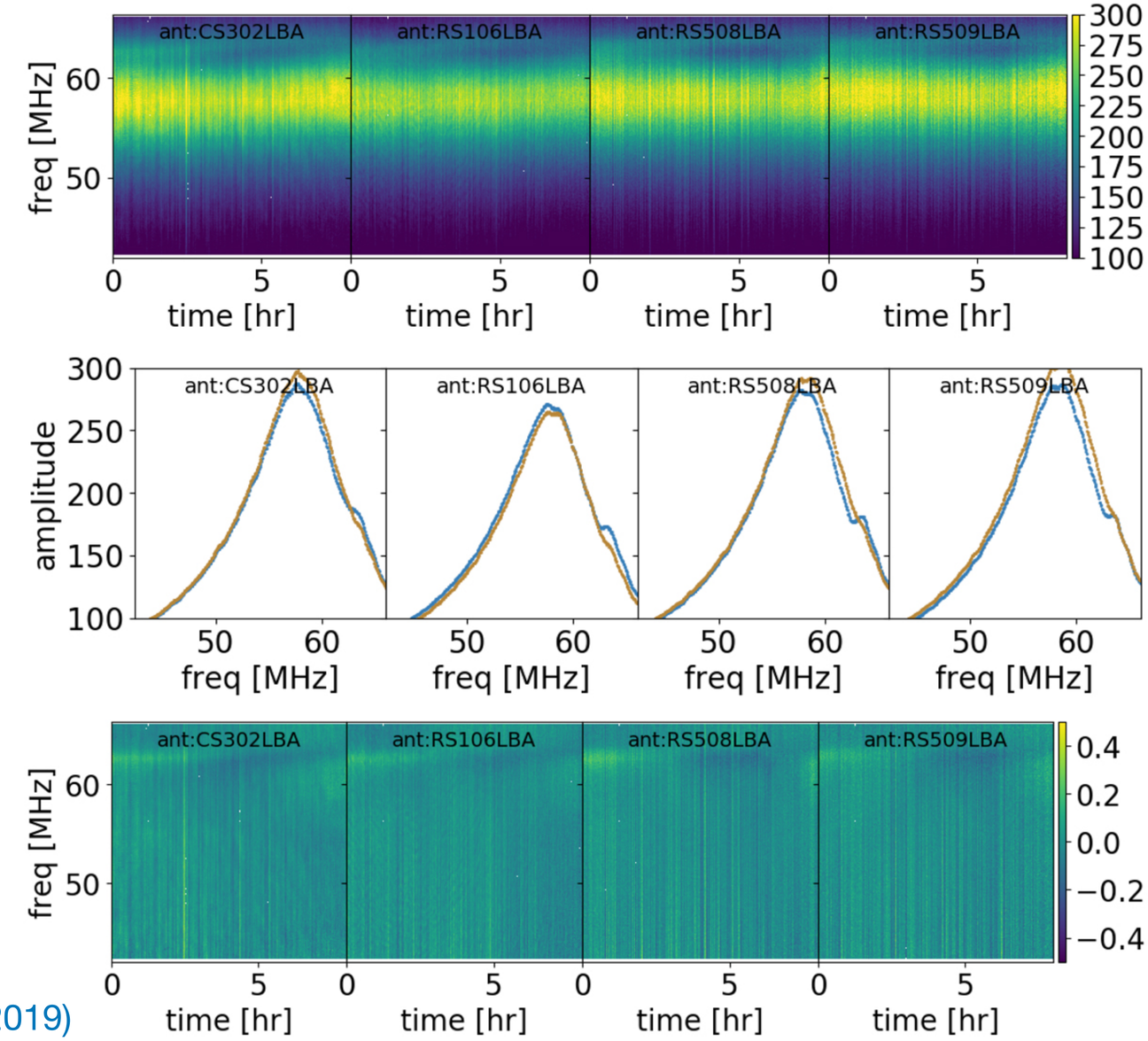
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$$J_i = \begin{pmatrix} A_{xx}e^{i\phi_{xx}} & 0 \\ 0 & A_{yy}e^{i\phi_{yy}} \end{pmatrix}$$

In practice we use diagonal because the amplitudes are very sensitive to any phase residual error, so it's best to not force the phases to be 0.

Bandpass - solution

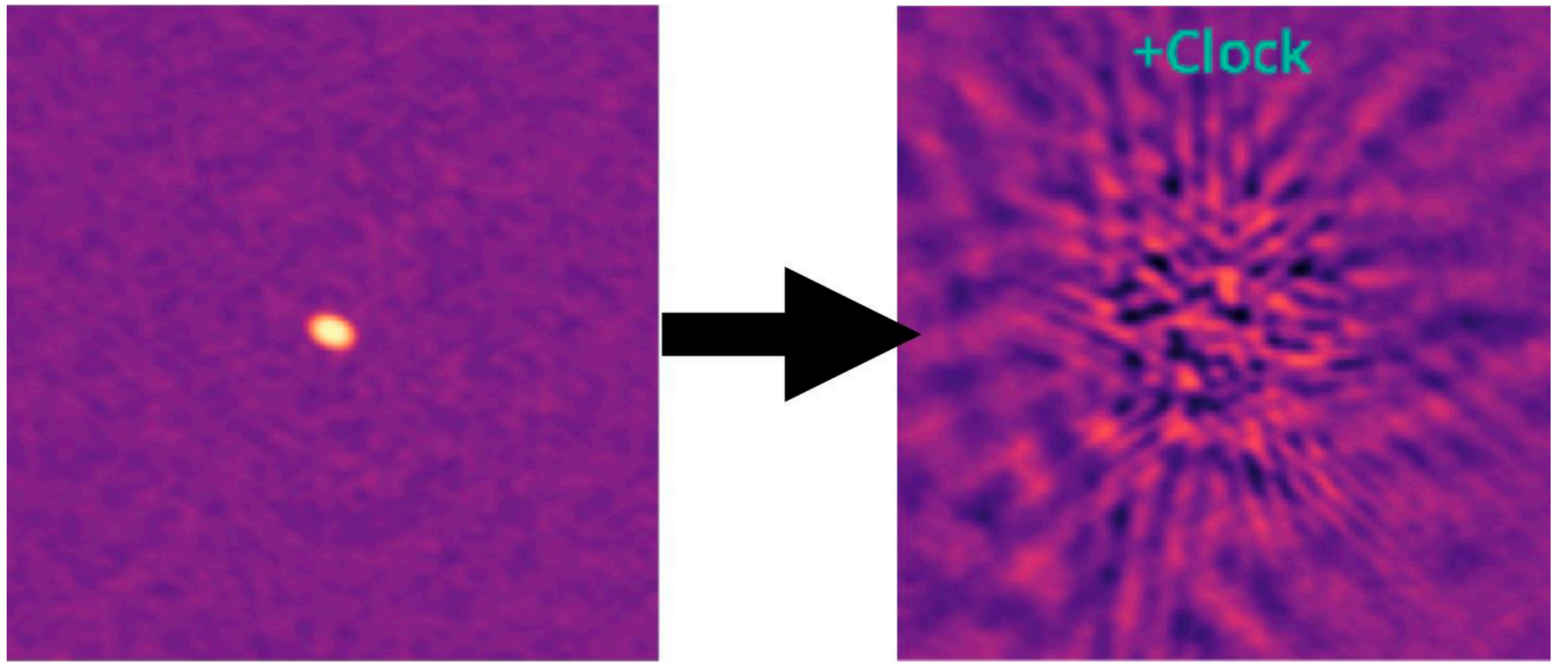
- Take the amplitude solution
- Smooth in time (with LoSoTo Smooth function)
- Apply with DP3 ApplyCal



De Gasperin et al. (2019)

Clock drift - what is it?

- There can be a physical delay between the stations



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- In LOFAR2, this delay is up to 10ns for CS AND RS, and up to 500ns for IS
- A delay induces a phase slope

$$J_i = \begin{pmatrix} ? & ? \\ ? & ? \end{pmatrix}$$

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1 phase = 1 unknown

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- Use DP3 solver in scalarphase/diagonal/diagonalphase mode (which one?)

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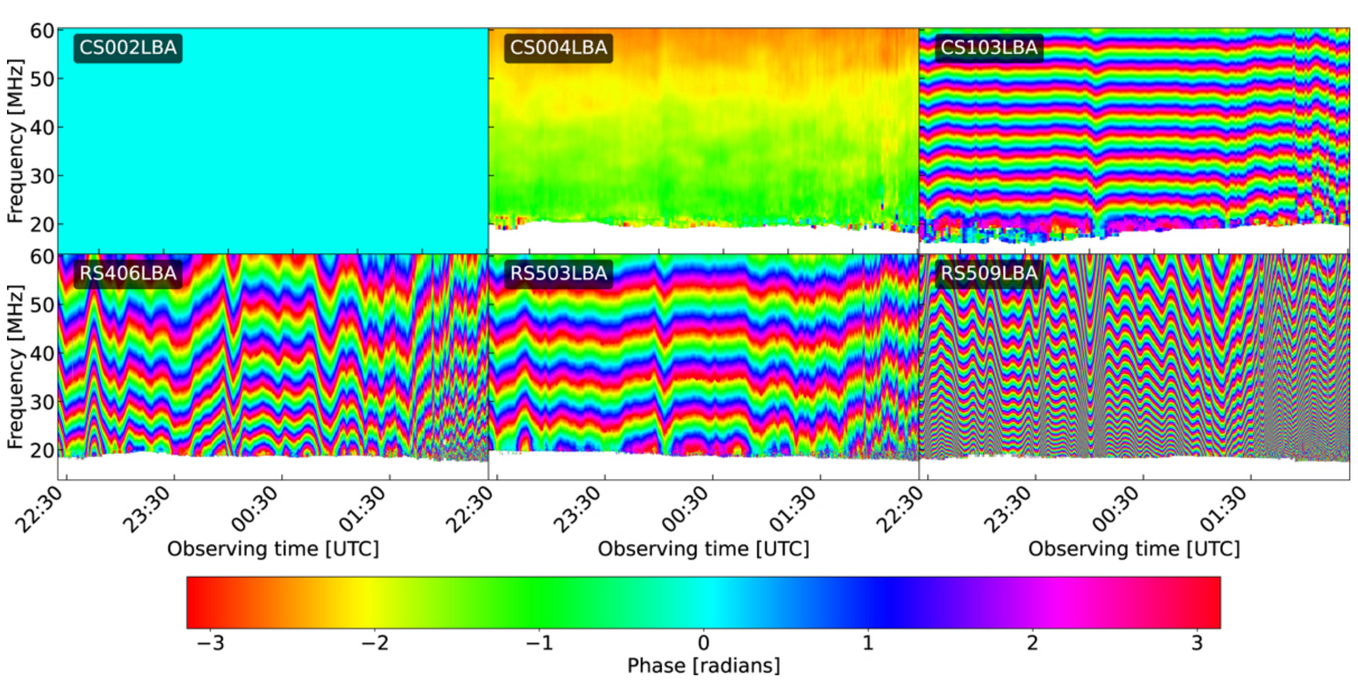
Clock drift - solution

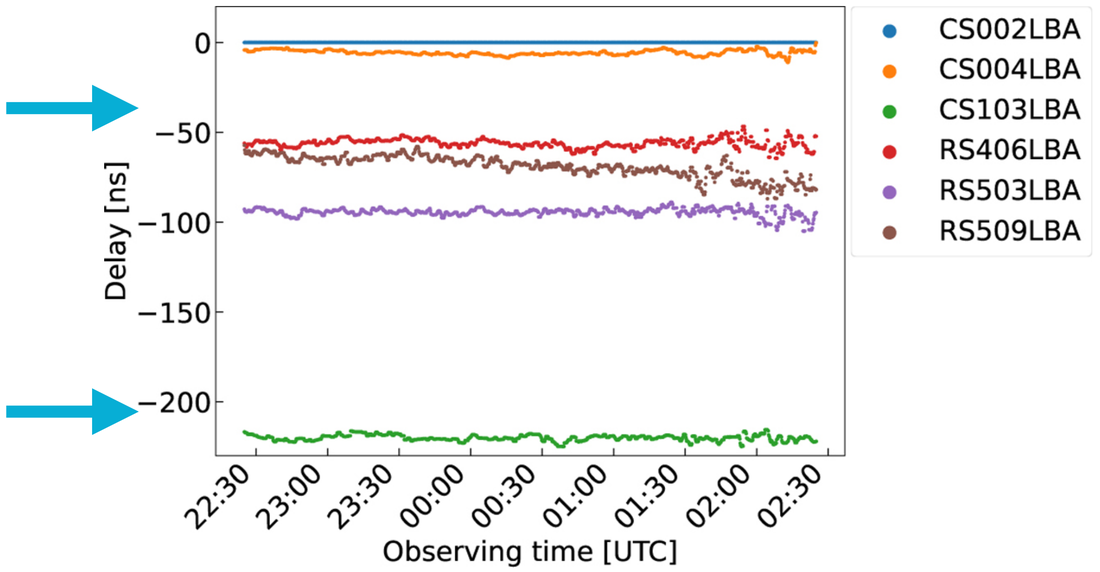
- This is where things get complicated…
- Phase solutions contain both effects of the clock drift and the ionosphere

$$J_i = \begin{pmatrix} e^{2\pi i \nu \Delta t} & 0 \\ 0 & e^{2\pi i \nu \Delta t} \end{pmatrix} \quad \text{becomes} \quad J_i = \begin{pmatrix} e^{i(2\pi \nu \Delta t + iono)} & 0 \\ 0 & e^{i(2\pi \nu \Delta t + iono)} \end{pmatrix}$$

Clock drift - solution

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- We need to separate them (can be done with LoSoTo clocktec or https://git.astron.nl/RD/clocktec)





Clock drift - solution

- This is where things get complicated…
- Phase solutions contain both effects of the clock drift and the ionosphere
- We need to separate them (can be done with LoSoTo clocktec or https://git.astron.nl/RD/clocktec)
- Apply only delays with DP3 ApplyCal

IONOSPHERIC EFFECTS

Ionosphere - what is it?

- Encyclopedia Britannica: “the part of the Earth’s upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves”
- In short: Magnetized layer of the atmosphere which perturbs radio waves
- Between 50 and 1000 km

Ionosphere - phase perturbation

- Remember: a physical delay Δt adds a phase slope of $\phi_t = 2\pi\nu\Delta t$
- The ionosphere adds its own phase perturbation of $\phi_{iono} = -\frac{2\pi\nu}{c}\int_{LoS}(n-1)dl$, where n is the refractive index

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  $\phi_{iono} = -\frac{2\pi\nu}{c}\int_{LoS}(n-1)dl$, where n is the refractive index
- If we perform a Taylor expansion for n, we obtain

$$n \approx 1 - \frac{q^2}{8\pi^2 m_e \epsilon_0}\cdot\frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \epsilon_0}\cdot\frac{n_e B\cos\theta}{\nu^3} - \frac{q^4}{128\pi^4 m_e^2 \epsilon_0^2}\cdot\frac{n_e^2}{\nu^4}$$

n_e - electron density

B - magnetic field

$cos\theta$ - angle between wave propagation direction and B

Ionosphere - simplified

- $\phi_{\text{iono}}(\nu) = C_{\text{TEC}}\frac{N_e}{\nu} \pm \frac{\text{RM}}{\nu^2} + C_3\frac{N_{e,3rd}}{\nu^3}$ C_{TEC}, C_3 - constants

- $N_e = \int_{\text{LoS}} n_e \, dl$ Total electron content (TEC)

- $\text{RM} = \frac{e^3}{8\pi^2\epsilon_0 m_e^2 c^3} \int_{\text{LoS}} n_e B \cos\theta \, dl$ Rotation measure (why rotation?)

- $N_{e,3rd} = \int_{\text{LoS}} n_e^2 \, dl$ 3rd order TEC (only below 40 MHz)

Ionosphere - Differential Faraday

- $\phi_{\text{iono}}(\nu) = C_{\text{TEC}}\frac{N_e}{\nu} \pm \frac{\text{RM}}{\nu^2} + C_3\frac{N_{e,3rd}}{\nu^3}$
- Requires a rotation matrix because of Earth's magnetic field

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Ionosphere - Differential Faraday

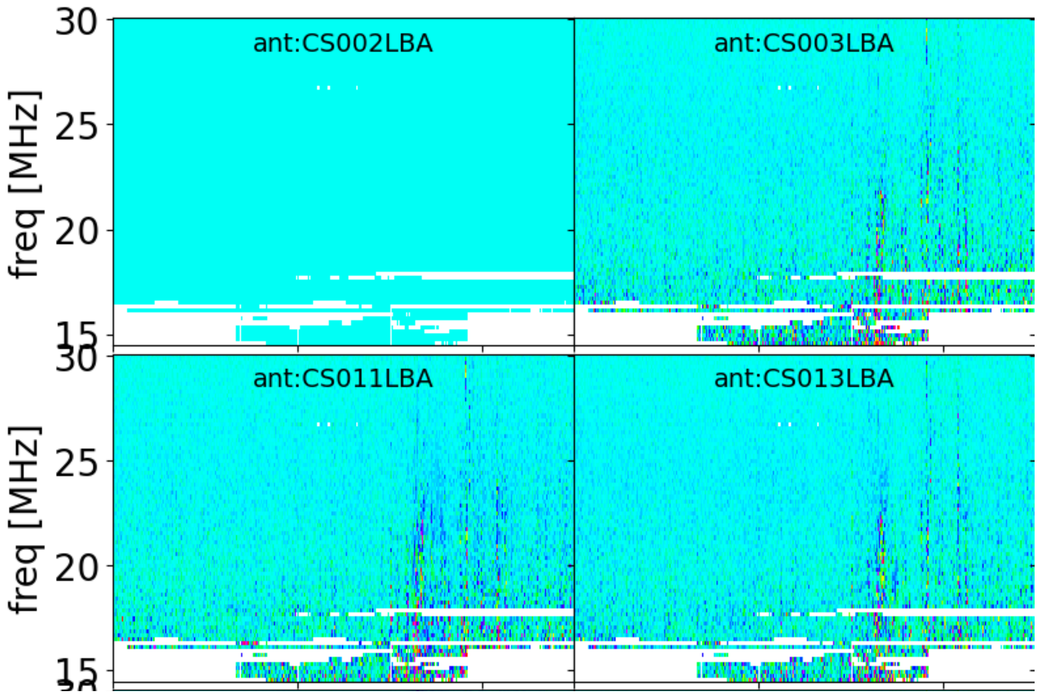
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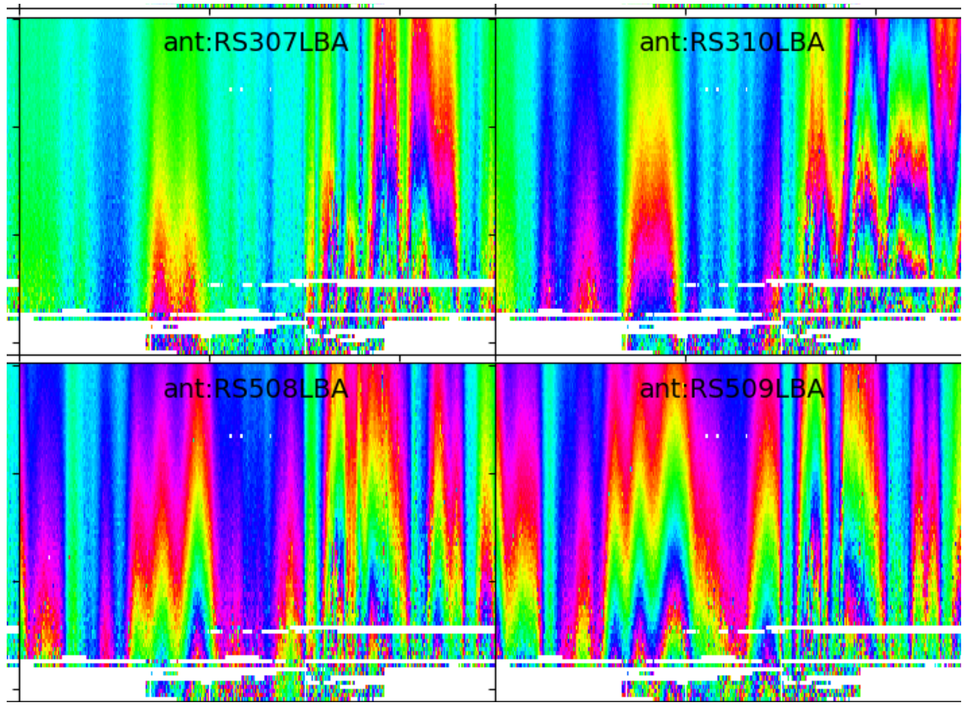
$$\text{RM} = \frac{e^3}{8\pi^2\epsilon_0 m_e^2 c^3}\int_{\text{LoS}} n_e B\cos\theta\, dl$$

$$J_i = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix}, \text{ where } \beta = RM\ \nu^{-2}$$

Ionosphere - Differential Faraday - solution

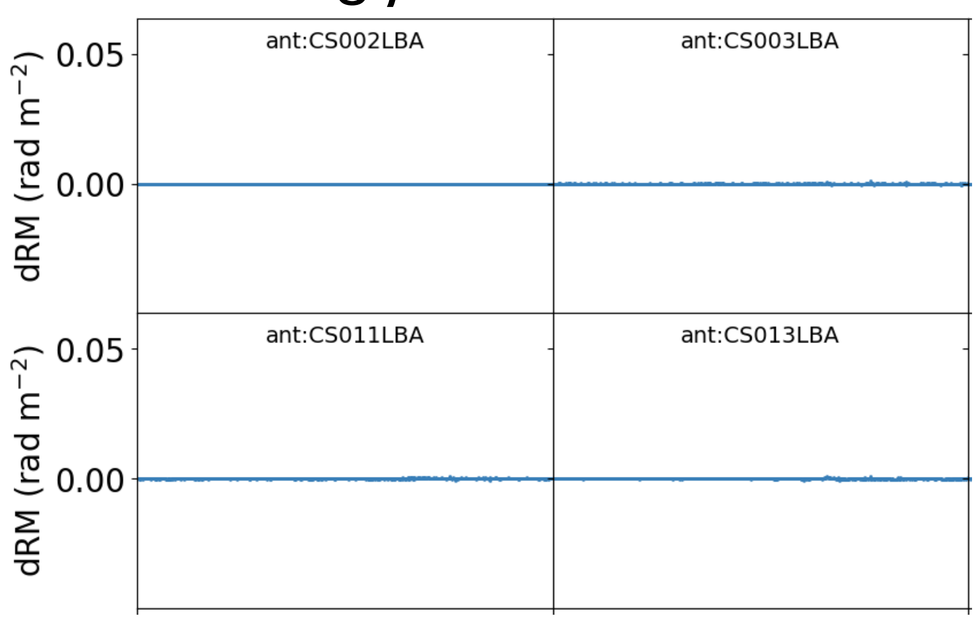
- Use DP3 solver in rotation+diagonal mode
- Look at the rotation angle

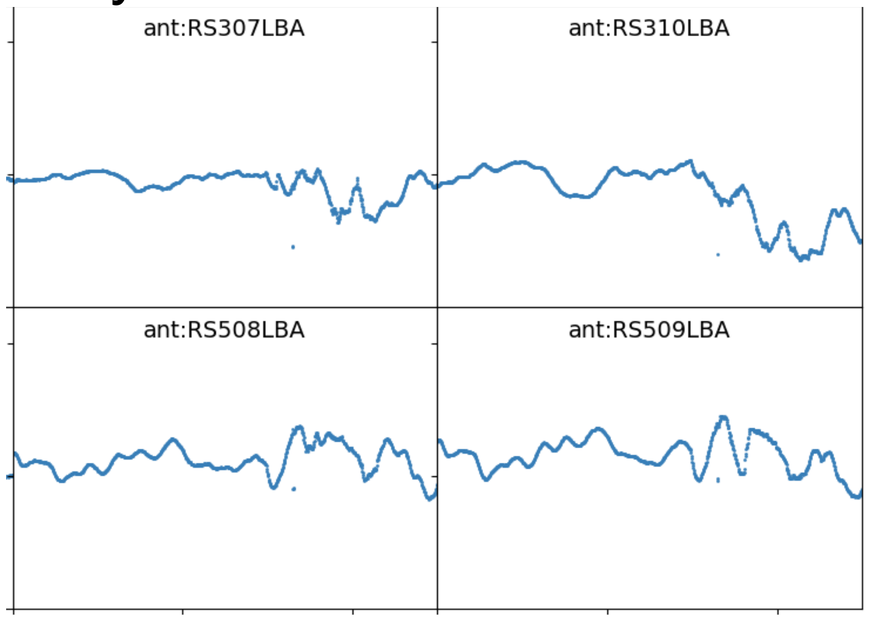




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- Find RM using $\beta = RM\ \nu^{-2}$ - LoSoTo faraday function





Ionosphere - Differential Faraday - solution

- Use DP3 solver in rotation+diagonal mode
- Look at the rotation angle
- Find RM using $\beta = RM\ \nu^{-2}$ - LoSoTo faraday function
- Apply with DP3 ApplyCal

Ionosphere - Scalar effects

- $\phi_{\mathrm{iono}}(\nu) = C_{\mathrm{TEC}}\frac{N_e}{\nu} \pm \frac{\mathrm{RM}}{\nu^2} + C_3\frac{N_{e,3rd}}{\nu^3}$
- These are linear effects

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$$J_i = \begin{pmatrix} e^{i\phi_{iono}} & 0 \\ 0 & e^{i\phi_{iono}} \end{pmatrix} = e^{i\phi_{iono}} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Ionosphere - Scalar effects - solution

- Use DP3 solver in scalarphase/diagonal/diagonalphase mode (which one?)

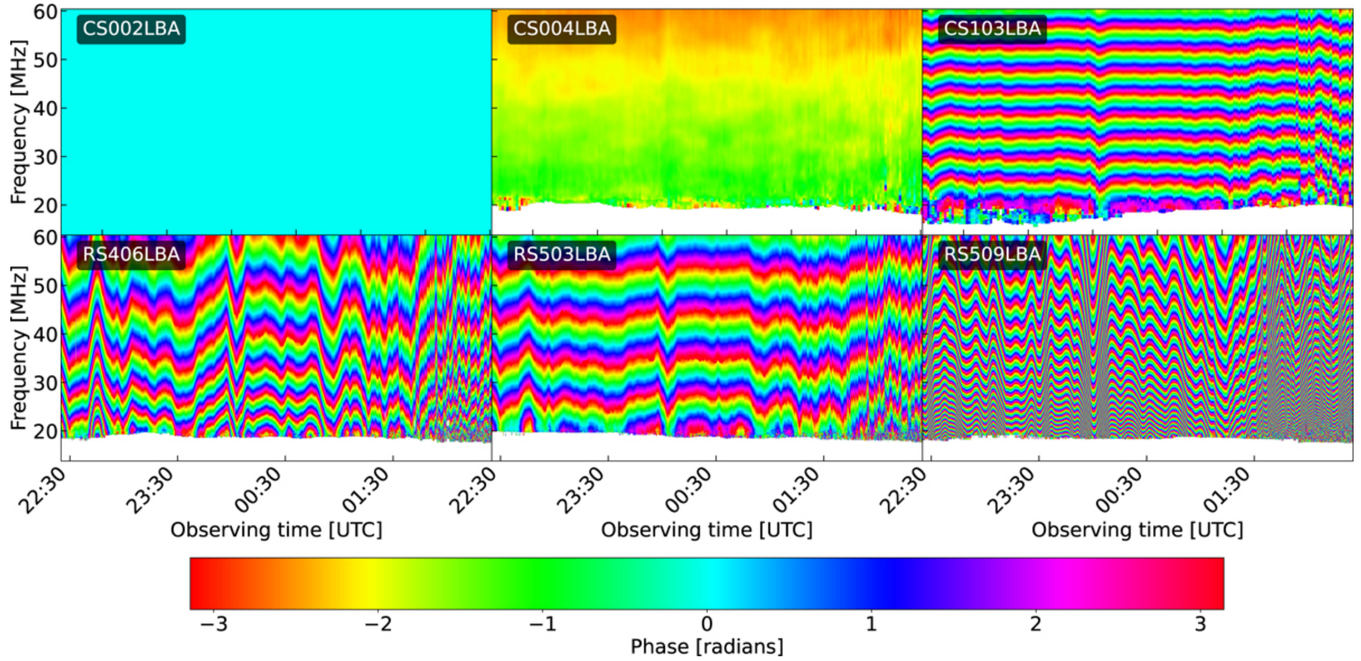
Ionosphere - Scalar effects - solution

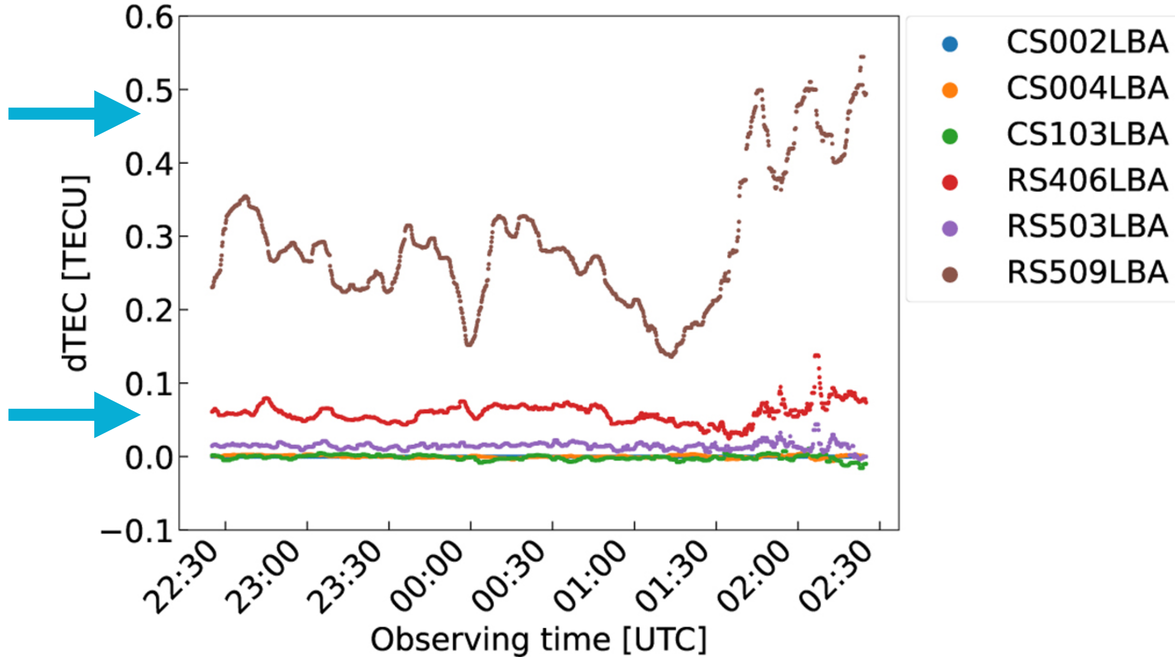
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Ionosphere - Scalar effects - solution

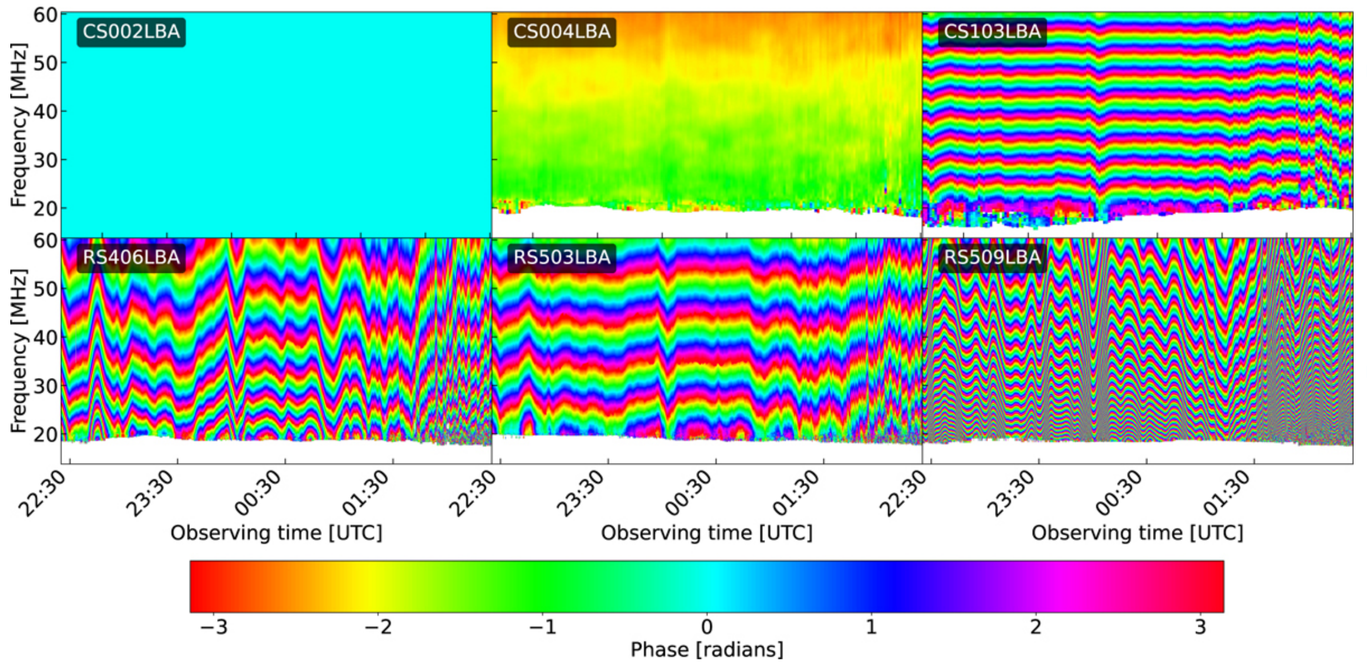
- Use DP3 solver in scalarphase/diagonal/diagonalphase mode (which one?)
- Remember! If the delays between stations are not corrected for, we find the effects of both these delays and the ionosphere. They can be separated

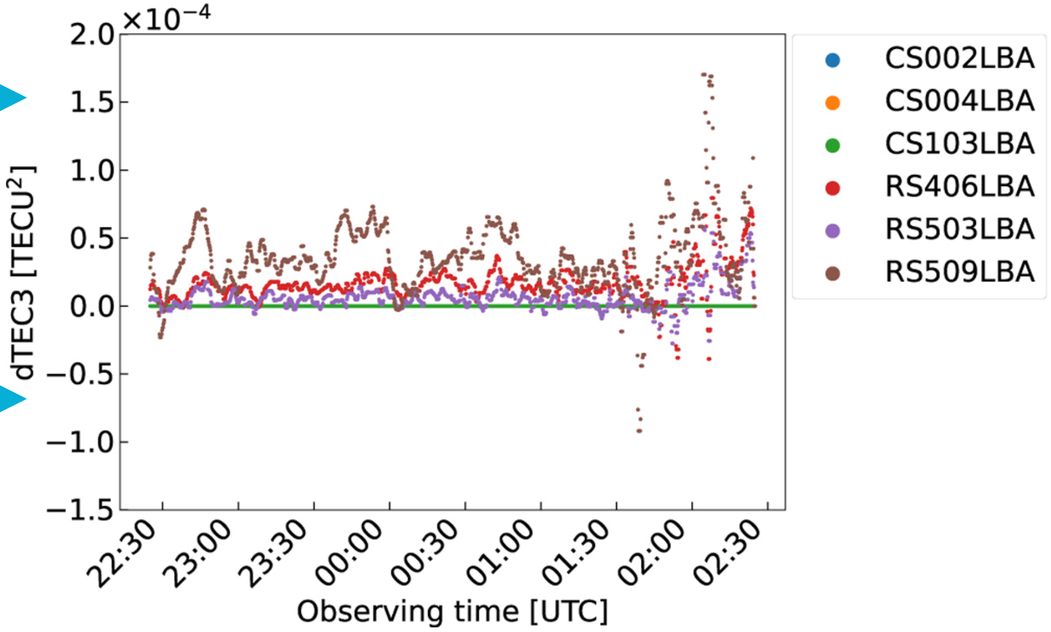




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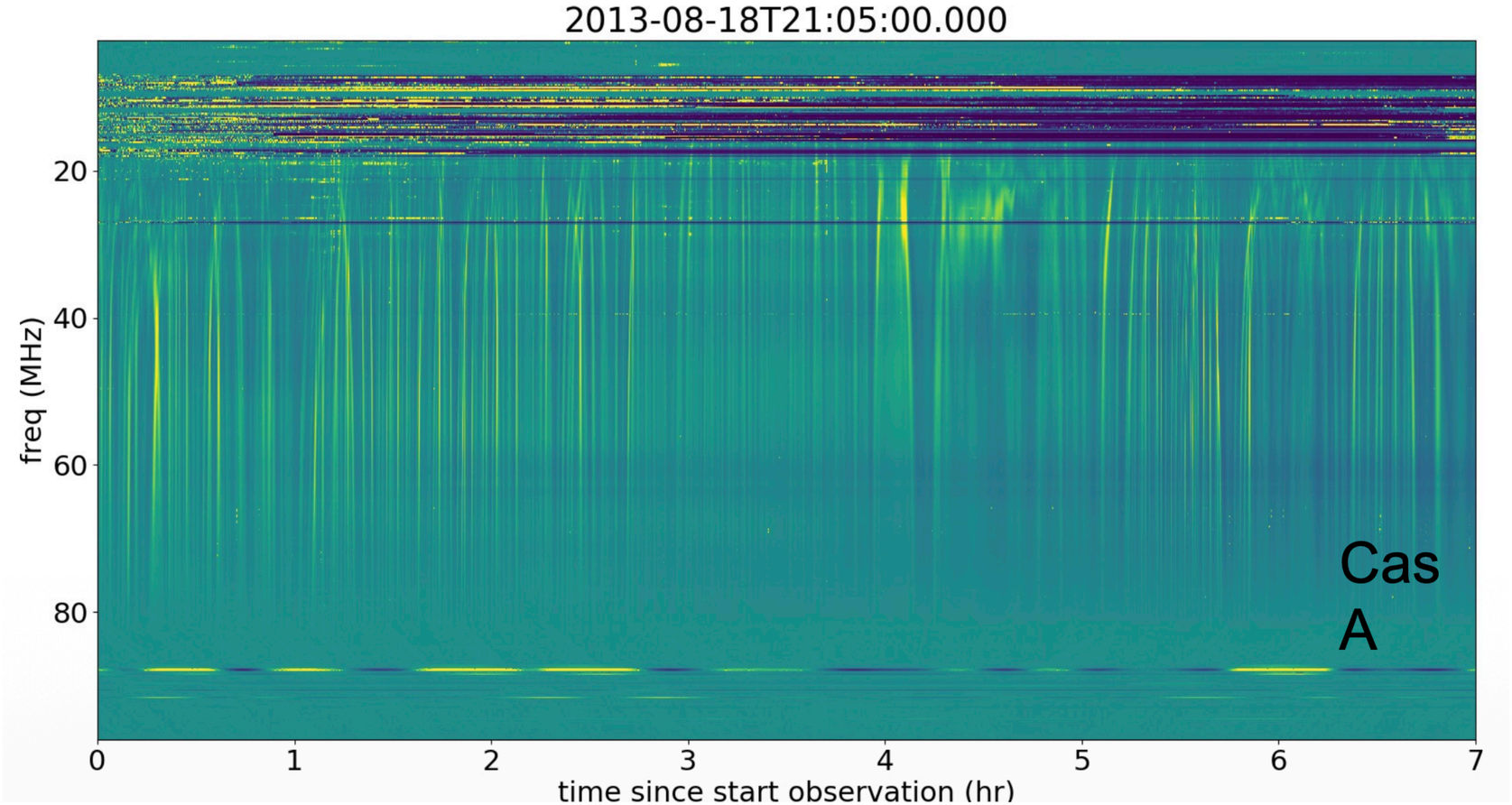


Ionosphere - Scalar effects - solution

- Use DP3 solver in scalarphase/diagonal/diagonalphase mode (which one?)
- Remember! If the delays between stations are not corrected for, we find the effects of both these delays and the ionosphere. They can be separated
- If the delays are corrected for, then we find ONLY the effects of the ionosphere (see selfcal lecture tomorrow morning)

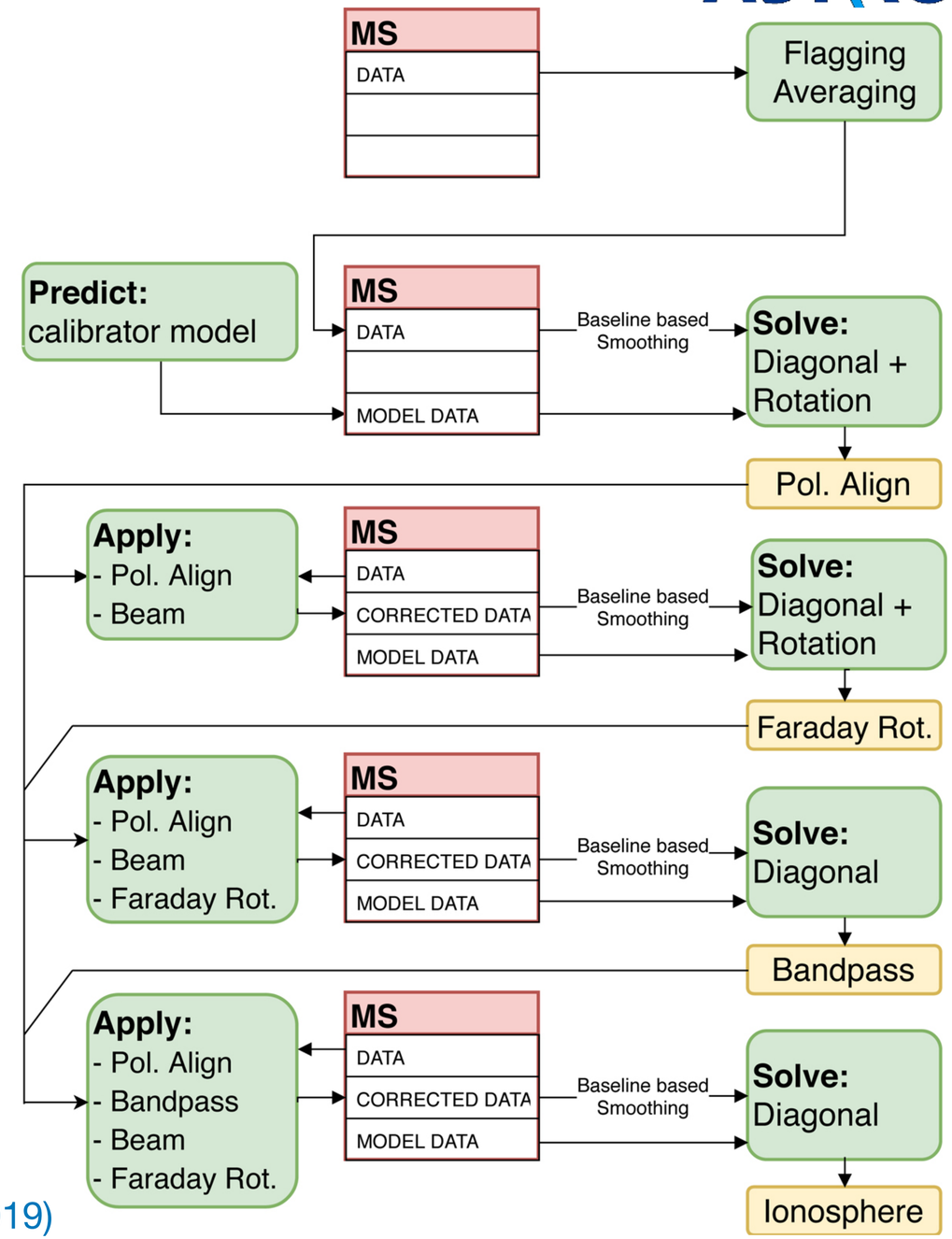
Ionospheric scintillations

- Amplitude effects - very rare for HBA, more often in the LBA
- Short variations in time



Overview of all effects

- This is the order you should apply them
- Always apply the previous effect before calculating a new one
- !!! They are not commutative !!!



De Gasperin et al. (2019)

Useful places to find information

- DP3 manual - https://dp3.readthedocs.io/en/stable/

- LoSoTo documentation - https://github.com/revoltek/losoto/releases