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Netherlands Institute for Radio Astronomy

Radio polarimetry with LOFAR

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Radio polarimetry at Low Frequency (LF):

- *<u>physics/instrumental</u>*

  Radio antennas are fundamentally polarized

  Understanding polarimetry improves your unpolarized calibration and imaging

- *<u>astrophysics</u>*

  Polarimetry required for certain astrophysical observations

** synchrotron emission ➔ B-field direction (indirectly strength) / Turbulence*
** Zeeman splitting ➔ B-field strength at source*
** Scattering/reflection ➔ electron densities in cool gas / Dust properties*
** Faraday rotation ➔ source / intervening plasma properties*

Radio Polarimetry at low frequency (LF)

- LF Instruments: Dishes and Dipoles → different polarimetric (beam) properties
- LF challenges: Confusion + Ionosphere + Radio Frequency Interference + Large Field of View + Wide Bandwidth
- Large Field of View + Wide Bandwidth → RM Synthesis

Radio polarimetry at LF: the LOFAR case

- ***LF Instruments: Dishes vs Dipoles → different polarimetric (beam) properties***

Electronic beamforming of dipole arrays:
* A single dipole sees the entire sky (element pattern)
* Station of dipoles can be combined to create station beams
* Multiple stations combined to create synthesized beams

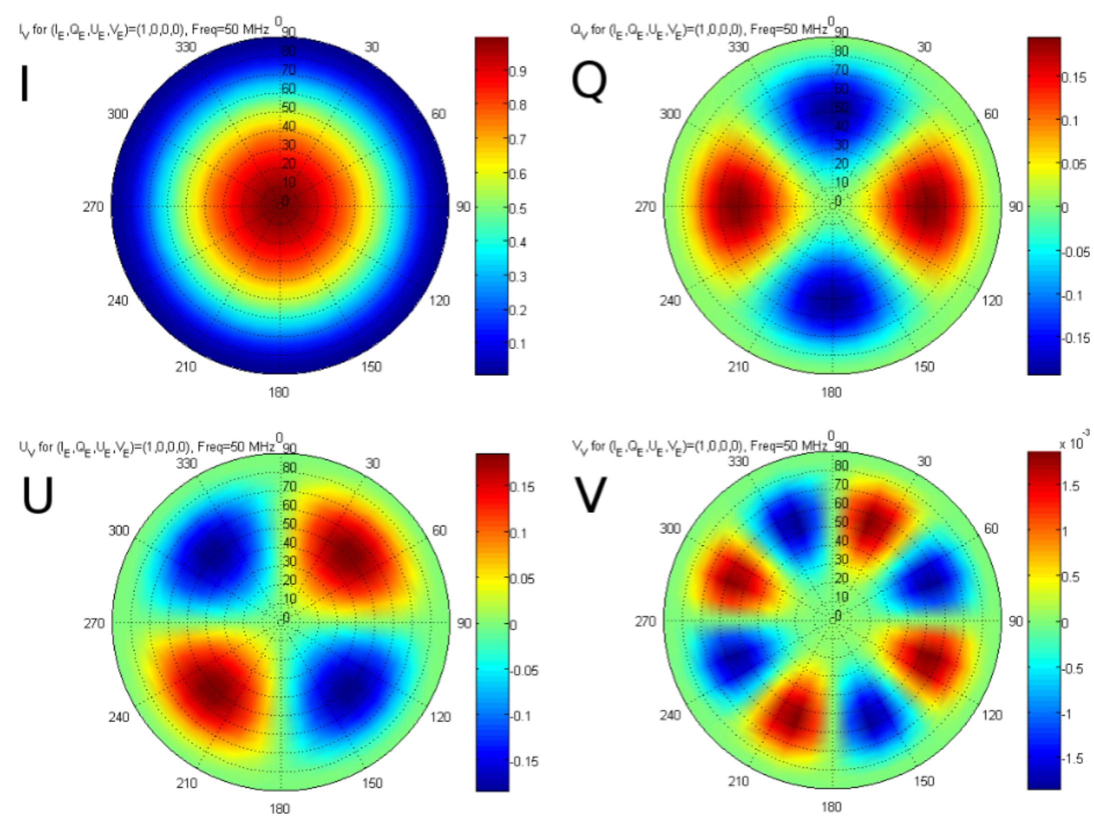
Dipole array beams:
* Changing Gain with Time → complicated beam pattern
* Projection effects of dipoles viewed out of the zenith → Change of polarimetric response on scales of the entire sky, instead of on scales of the station's beam

Polarimetry at LF & the LOFAR case

- ***LF Instruments: Dishes vs Dipoles → different polarimetric (beam) properties***

Because the digital beam is small compared to the element beam, the polarization response does not vary significantly across a station beam.

The beam is polarization dependent.

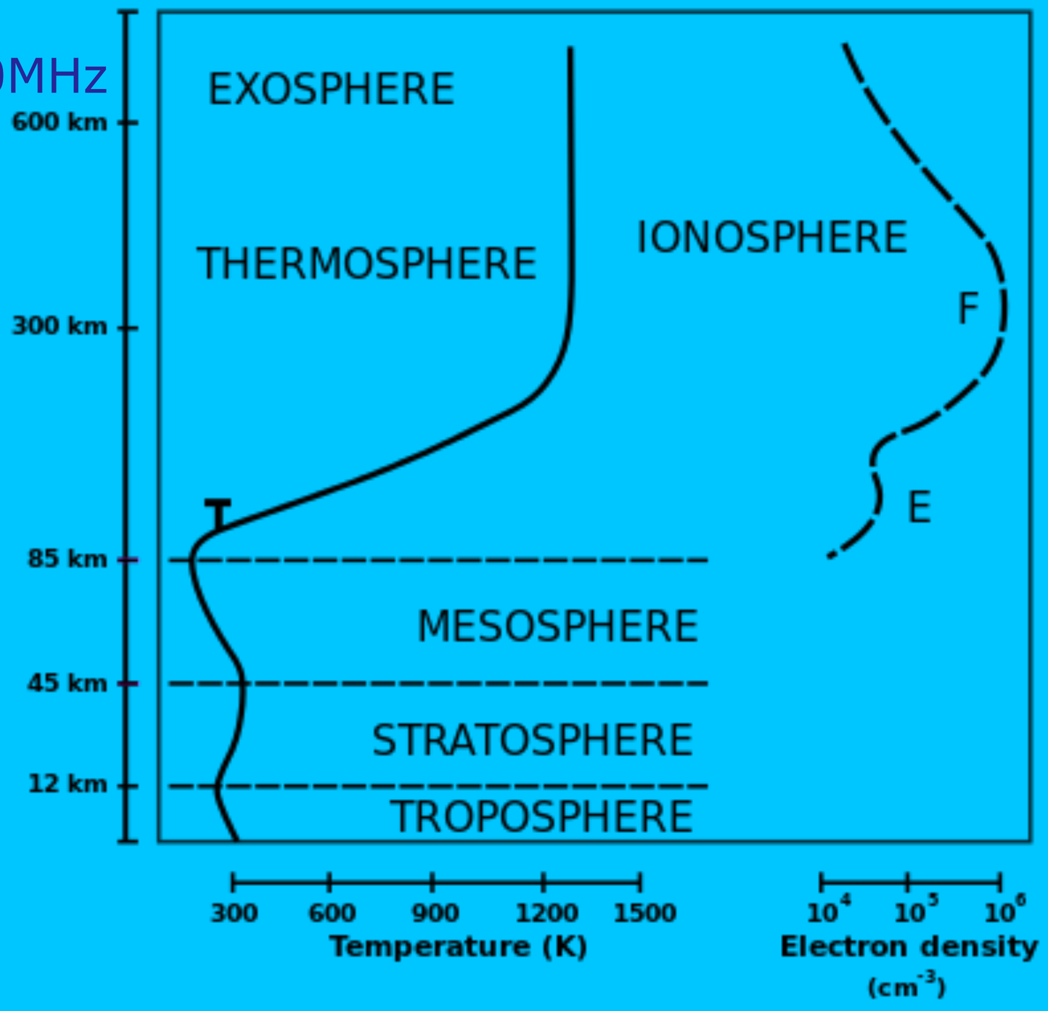


Calibrating the polarization response towards the pointing center is enough to obtain low leakage wide field maps

Polarimetry at low frequency & the LOFAR case

- ***Ionosphere and ionospheric effects:***
  - Ionospheric Cutoff:

  Plasma opacity below ~10MHz

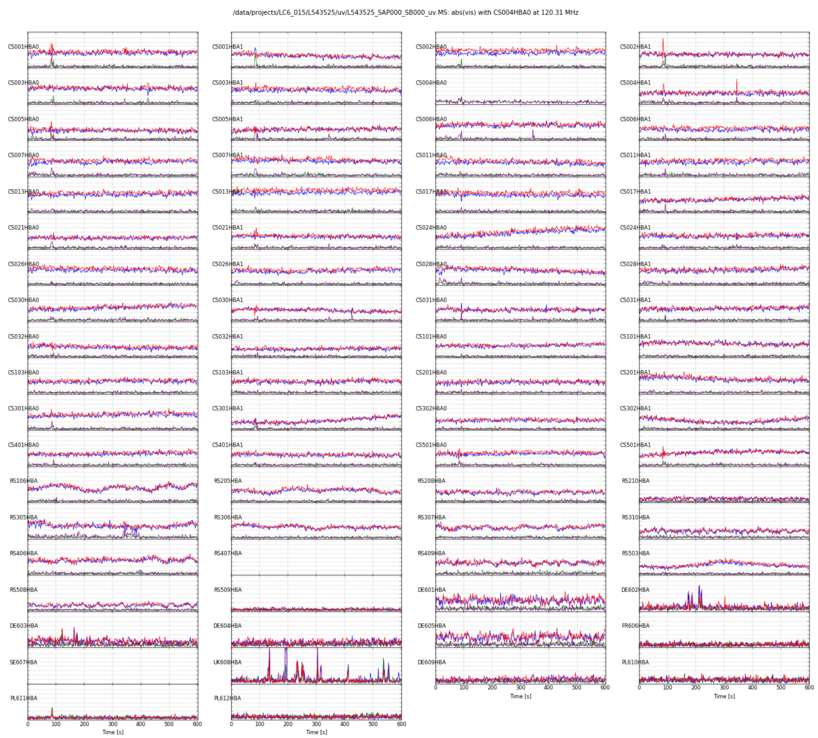


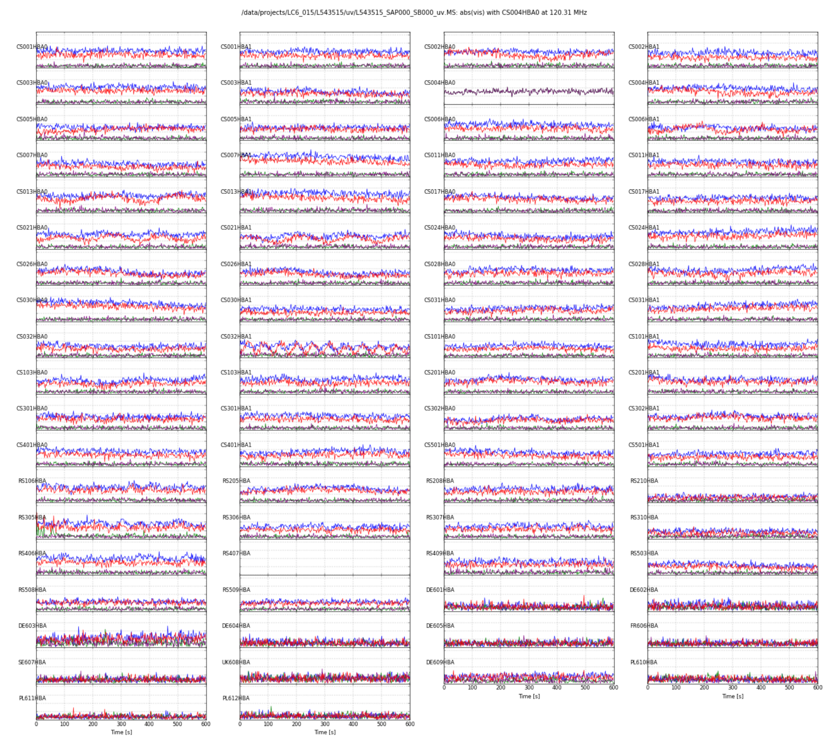
Polarimetry at low frequency & the LOFAR case

- ***Ionosphere and ionospheric effects:***
  - Disturbed Ionosphere:

    Scintillation

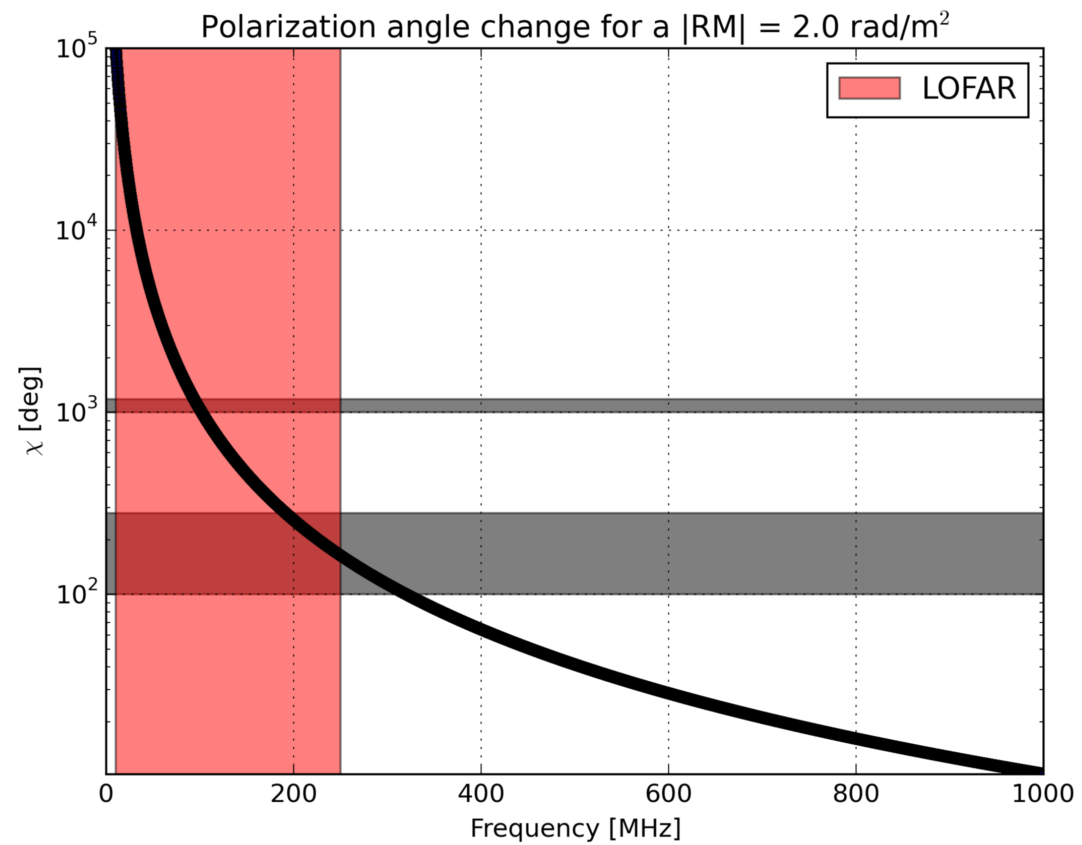
    Image distortion / Rapid position shift → on image plane





Polarimetry at low frequency & the LOFAR case

- ***Ionosphere and ionospheric effects:***
  - Ionospheric Cutoff:
    Plasma opacity below ~10MHz
  - Quiescent Ionosphere:
    Refraction
    Faraday Rotation



Polarimetry at low frequency & the LOFAR case

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Topics

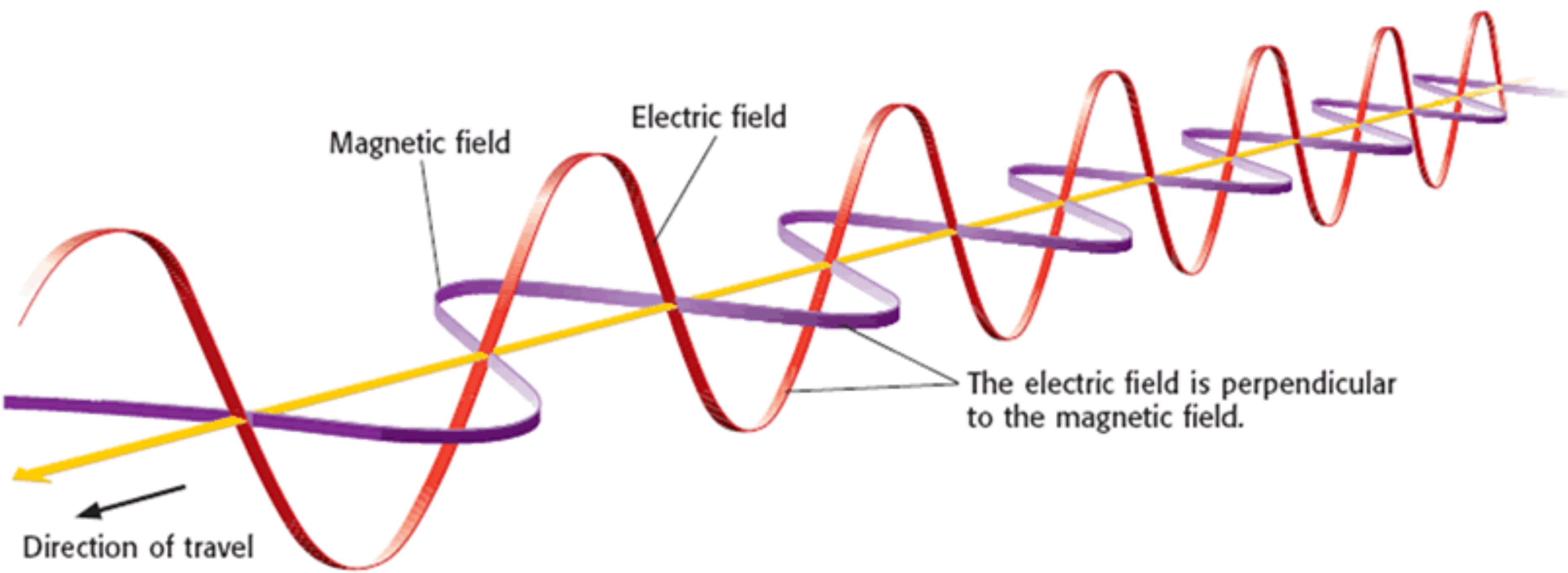
- ***Polarized EM waves***
  - different polarization states
- ***Stokes parameters***
  - an experimentally convenient description of the polarization state
- ***Radio polarimetry in practice***
  - Stokes visibilities
  - Jones matrices / antenna beam polarization
  - Faraday rotation / Ionospheric (differential) Faraday rotation / RM-synthesis

Polarized EM waves: a vector nature

k = direction of propagation, ***B*** = magnetic field, ***E*** = Electric filed

Antennas & detectors give ***k*** and ***E***

But ***E*** may rotate as function of *x* and *t* tracing an ellipse → **Polarization**



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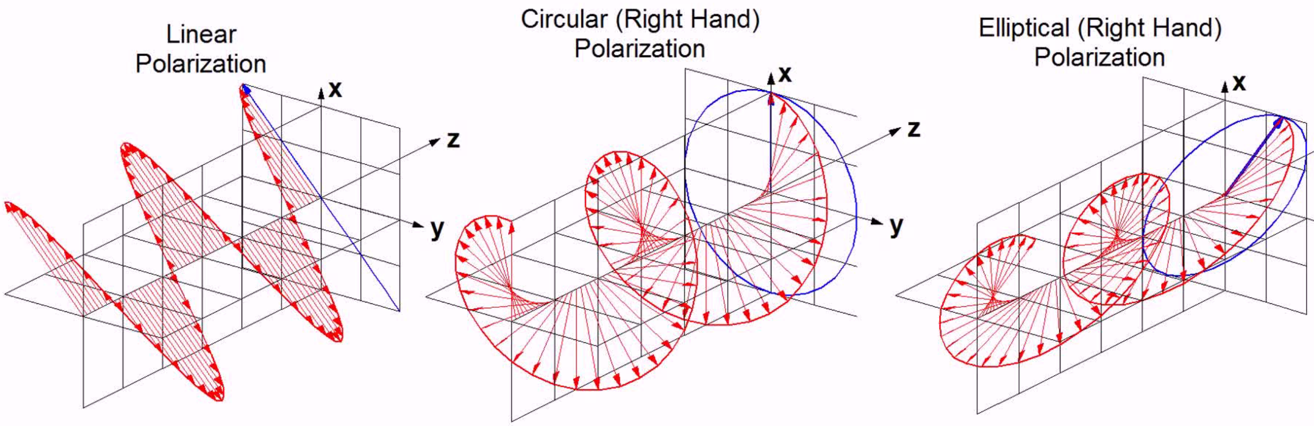

Polarized EM waves: a vector nature

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$\boldsymbol{E} = E_x\,\mathbf{e}_x + E_y\,\mathbf{e}_y$

$E_x = A_x \cos(2\pi\nu t + \delta_x)$

$E_y = A_y \cos(2\pi\nu t + \delta_y)$

$\delta_{xy} = \delta_y - \delta_x$ measure of ellipticity

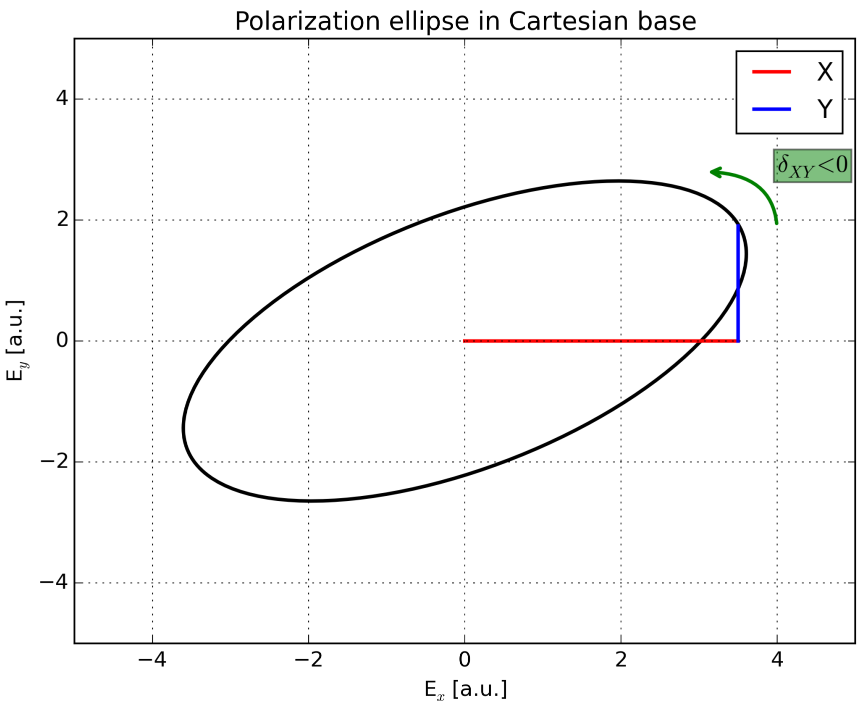
$\boldsymbol{E} = A_r\,\mathbf{e}_r + A_l\,\mathbf{e}_l$

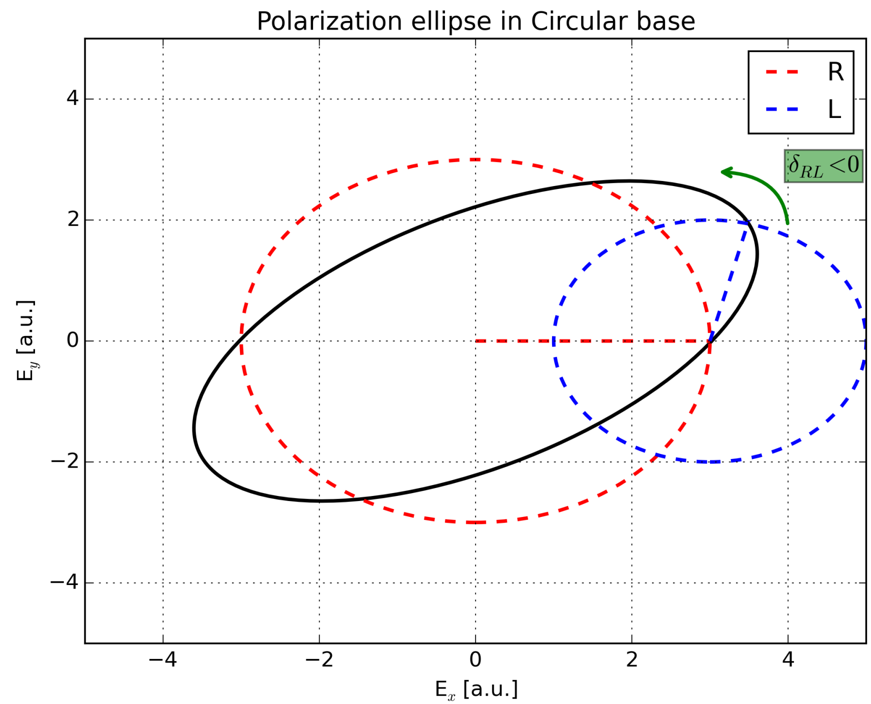
$\mathbf{e}_r = [\cos(2\pi\nu t + \delta_r), \sin(2\pi\nu t + \delta_r)]$

$\mathbf{e}_l = [\cos(2\pi\nu t + \delta_l), -\sin(2\pi\nu t + \delta_l)]$

$\delta_{rl} = \delta_r - \delta_l$ measure of ellipticity

$-\frac{1}{2}\,\delta_{rl}$ ➔ major axis position angle





Stokes parameters: a set of values to describe the polarization state

Polarization state described by a set of 4 parameters, e.g.: the semi-major and semi-minor axes of the polarization ellipse, its orientation and the sense of rotation.

The Stokes parameters → an alternative description of the polarization state experimentally convenient because each parameter corresponds to a sum or difference of measurable intensities.

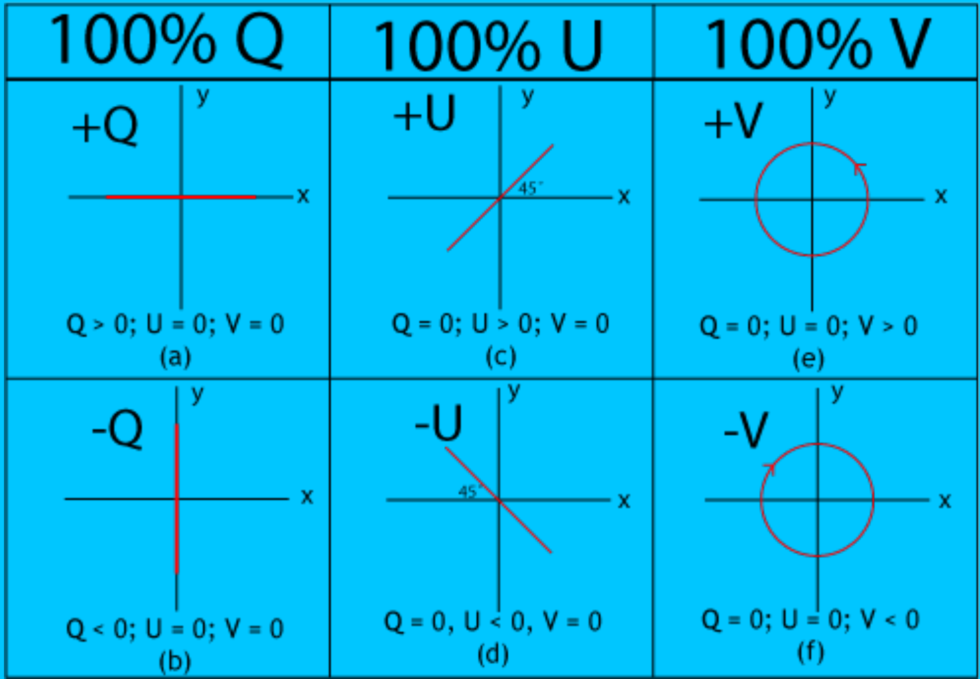
Polarization states:

1. Elliptical (general case)
2. Linear (degenerate case of 1.)
3. circular (degenerate case of 1.)

I → mean flux density

(Q,U) → linear polarization

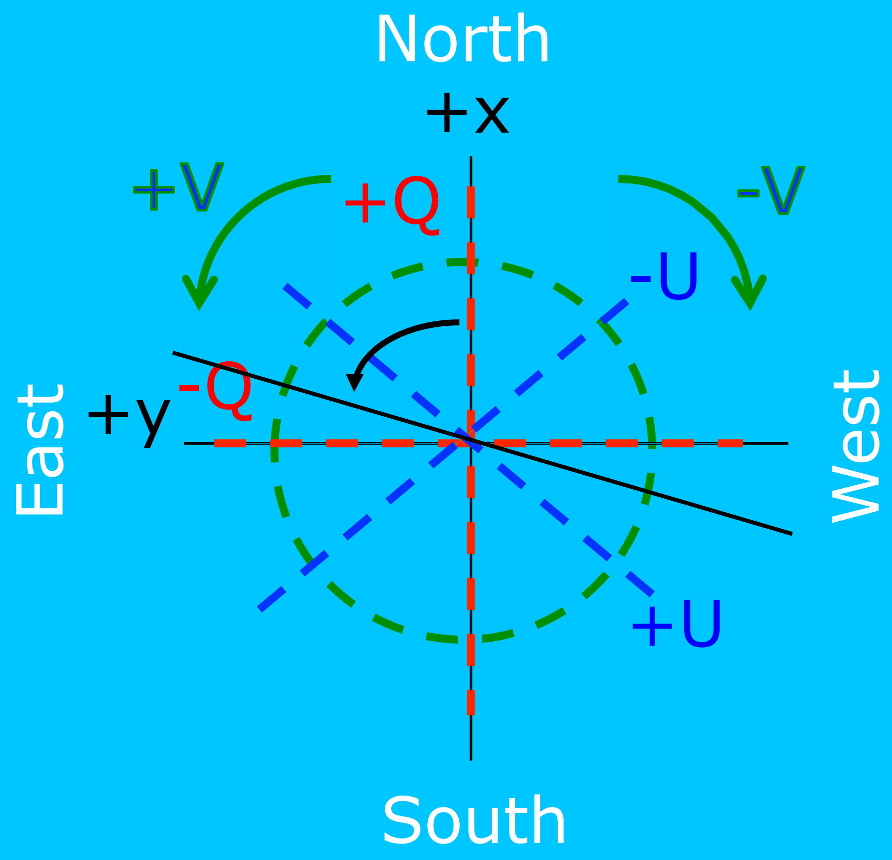
V → circular polarization



Stokes parameters: IAU convention

Polarization angle measurements are done North through East

North → +x East → +y



Stokes parameters: a set of values to describe the polarization state

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Polarization state described by e.g.: the semi-major and semi-minor axes of the polarization ellipse, its orientation, and the sense of rotation.

The Stokes parameters ➔ an alternative description of the polarization state experimentally convenient because each parameter corresponds to a sum or difference of measurable intensities.

I ➔ total intensity, (Q,U) ➔ linear polarization, V ➔ circular polarization

Monochromatic wave fully polarized: $I^2 = Q^2 + U^2 + V^2$

$$\Psi = \frac{1}{2}\arctan(U,Q)$$

$$P = \sqrt{Q^2 + U^2}$$

$$p = \frac{\sqrt{Q^2+U^2}}{I}$$

$I = A_x^2 + A_y^2$

$Q = A_x^2 - A_y^2$

$U = 2A_xA_y \cos\delta_{xy}$

$V = -2A_xA_y \sin\delta_{xy}$

$I = A_r^2 + A_l^2$

$Q = 2A_rA_l \cos\delta_{rl}$

$U = -2A_rA_l \sin\delta_{rl}$

$V = A_r^2 - A_l^2$

Radio polarimetry in practice: Stokes visibilities vs sky images

Sky brightness

→

→

FT(Sky brightness): the visibilities

$I(u,v)=FT(I(l,m))$

$Q(u,v)=FT(Q(l,m))$

$U(u,v)=FT(U(l,m))$

$V(u,v)=FT(V(l,m))$

No mono-chromatic radiation approximation
Stokes parameters sampled in {time} / frequency

$$E_x = Re(A_x e^{2\pi i \nu t}) \quad E_y = Re(A_y e^{2\pi i \nu t} e^{i\delta_{xy}})$$

$$I = A_x^2 + A_y^2$$
$$Q = A_x^2 - A_y^2$$
$$U = 2A_x A_y \cos\delta_{xy}$$
$$V = -2A_x A_y \sin\delta_{xy}$$

⇒

$$I = \{E_x E_x^*\} + \{E_y E_y^*\}$$
$$Q = \{E_x E_x^*\} - \{E_y E_y^*\}$$
$$U = \{E_x E_y^*\} + \{E_y E_x^*\}$$
$$V = -i(\{E_x E_y^*\} - \{E_y E_x^*\})$$

Radio polarimetry in practice: Stokes visibilities vs sky images

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FT(Sky brightness): the visibilities

$I(u,v)=FT(I(l,m))$

$Q(u,v)=FT(Q(l,m))$

$U(u,v)=FT(U(l,m))$

$V(u,v)=FT(V(l,m))$

No mono-chromatic radiation approximation

Stokes parameters sampled in {time} / frequency

$E_r = Re(A_r e^{2\pi i\nu t}) \quad E_l = Re(A_l e^{2\pi i\nu t} e^{i\delta_{rl}})$

$I = A_r^2 + A_l^2$

$Q = 2A_rA_l \cos\delta_{rl}$

$U = -2A_rA_l \sin\delta_{rl}$

$V = A_r^2 - A_l^2$

⇒

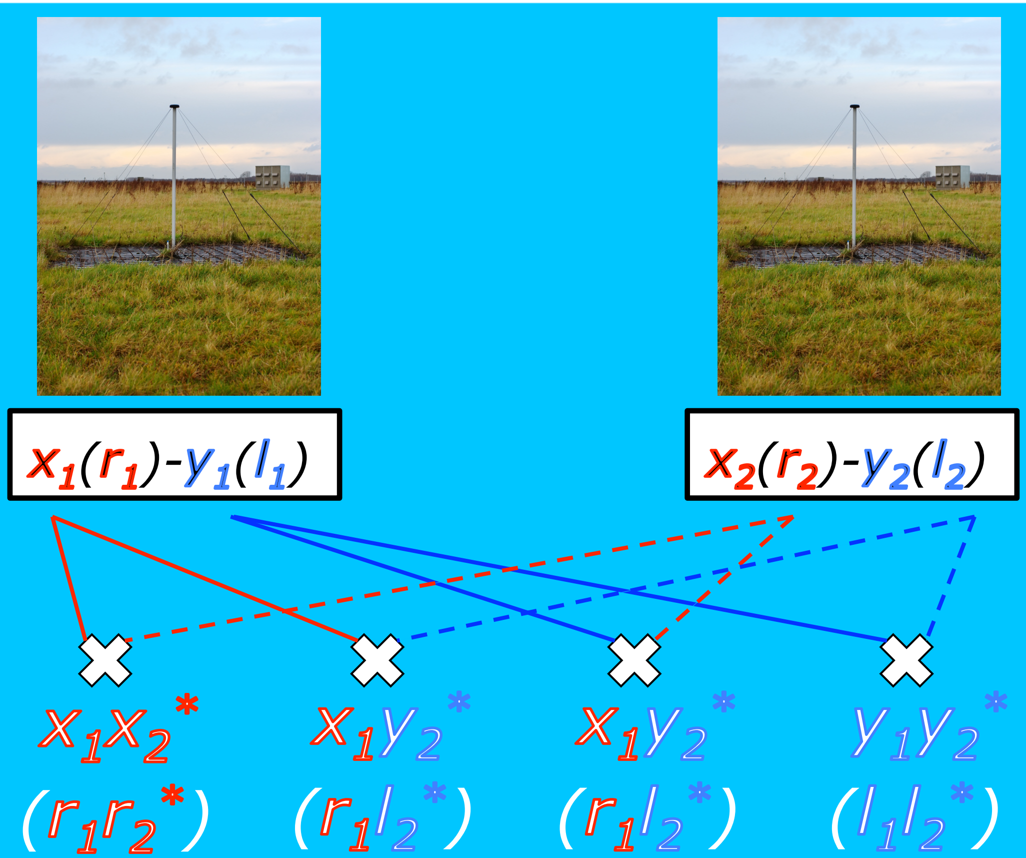
$I = \{E_r E_r^*\} + \{E_l E_l^*\}$

$Q = \{E_r E_l^*\} + \{E_l E_r^*\}$

$U = -i(\{E_r E_l^*\} - \{E_l E_r^*\})$

$V = \{E_r E_r^*\} - \{E_l E_l^*\}$

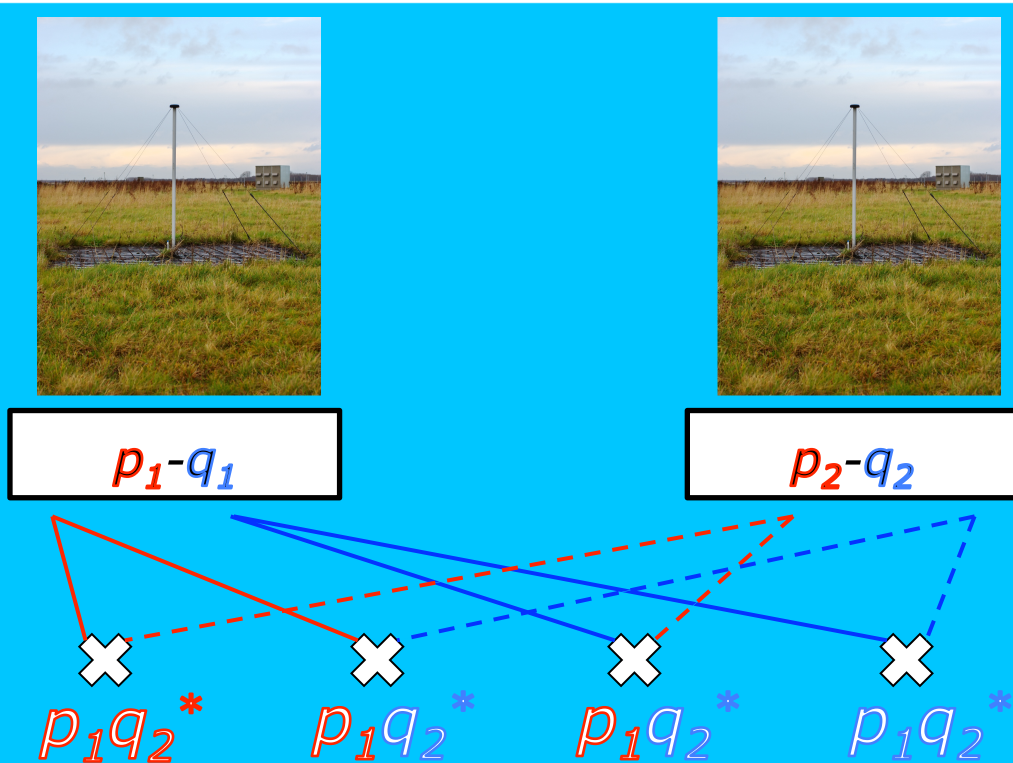
Radio polarimetry in practice: Stokes visibilities & correlators I



$$I(u,v)=\{x_1\, x_2^*\} + \{y_1\, y_2^*\}$$
$$Q(u,v)=\{x_1\, x_2^*\} - \{y_1\, y_2^*\}$$
$$U(u,v)=\{x_1\, y_2^*\} + \{y_1\, x_2^*\}$$
$$V(u,v)=-i(\{x_1\, y_2^*\} - \{y_1\, x_2^*\})$$

$$I(u,v)=\{r_1\, r_2^*\} + \{l_1\, l_2^*\}$$
$$Q(u,v)=\{r_1\, l_2^*\} + \{l_1\, r_2^*\}$$
$$U(u,v)=-i(\{r_1\, l_2^*\} - \{l_1\, r_2^*\})$$
$$V(u,v)=\{r_1\, r_2^*\} - \{l_1\, l_2^*\}$$

Radio polarimetry in practice: Stokes visibilities & correlators II



Signal editing by linear operators: Jones matrix and coherence matrix

$$\mathbf{e}_i = \begin{pmatrix} p_i \\ q_i \end{pmatrix}$$

$$\mathbf{E}_{ij} = \mathbf{e}_i \mathbf{e}_j^\dagger = \begin{pmatrix} p_i \\ q_i \end{pmatrix} (p_i^*, q_i^*)$$

$$\mathbf{E}_{ij} = \begin{pmatrix} p_i p_j^*, p_i q_j^* \\ q_i p_j^*, q_i q_j^* \end{pmatrix}$$

Radio polarimetry: signal editing & Jones matrices I

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Polarization state changes assumed to be linear ➔ corruptions described by linear operators as 2x2 complex valued matrices: the Jones matrices (***J***)

$$\mathbf{e}'_i = \mathbf{J}_i \mathbf{e}_i$$

Signal perturbation at correlator input *i*

$$\mathbf{E}'_{ij} = \mathbf{e}'_i \, \mathbf{e}'^{\dagger}_j = \mathbf{J}_i \mathbf{E}_{ij} \mathbf{J}^{\dagger}_j$$

Cross correlation of the corrupted signal: the measurement equation (baseline *i*-*j*)

$$\mathbf{E}_{ij} = \mathbf{J}_i^{-1} \mathbf{E}'_{ij} \mathbf{J}^{\dagger -1}_j$$

Inversion of the equation ➔ Calibration

$$\mathbf{J} = \mathbf{G} \; \mathbf{P} \; \mathbf{I}$$

Matrix product is not commutative: right to left!

Radio polarimetry: signal editing & Jones matrices II

Polarization state changes assumed to be linear → corruptions described by linear operators as 2x2 complex valued matrices: the Jones matrices (***J***)

A relevant case at LF: (Faraday or feed) rotation or Parallactic angle

Cartesian base

$$\mathbf{J} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

Circular base

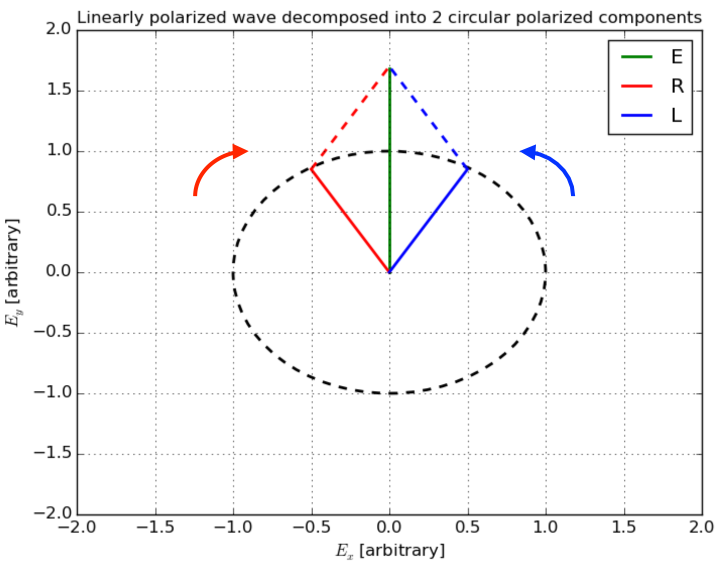
$$\mathbf{J} = \begin{pmatrix} \mathrm{e}^{+i\theta} & 0 \\ 0 & \mathrm{e}^{-i\theta} \end{pmatrix}$$

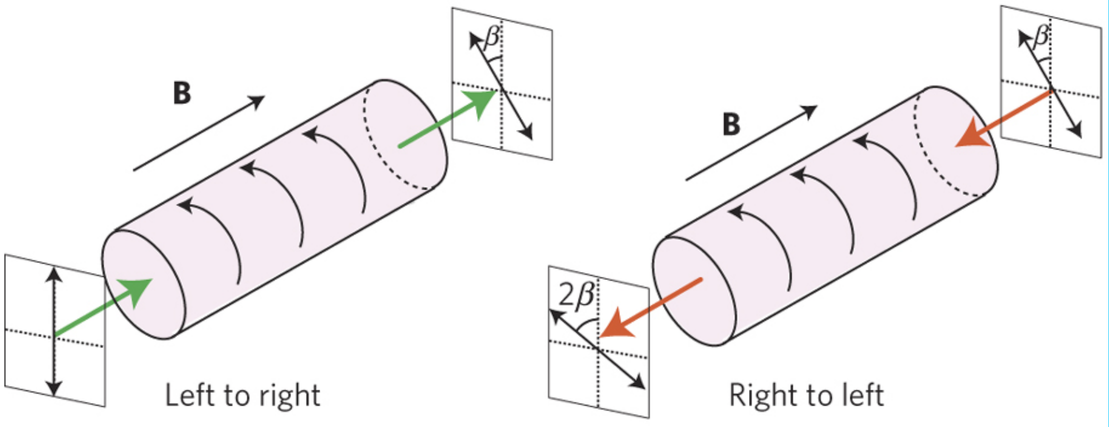
Choose the proper base!

To correct your LOFAR data for rotations / Parallactic angle use BBS software package

Radio polarimetry: Faraday rotation

Faraday rotation is a magneto-optical phenomenon → in a magnetized plasma, L and R circularly polarized waves propagates at slightly different speeds at different wavelengths (circular birefringence).





Frequency dependent delay:

IF:

- ✓ Linear dependence on λ^2 $\Psi(\lambda) = \Psi_0 + RM\lambda^2$ and $RM = \frac{\partial\Psi}{\partial\lambda^2}$

ELSE:

- ✓ Non linear dependence on λ^2 → Faraday depth $\phi = 0.81 \int_{source}^{observer} n_e \vec{B} \cdot d\vec{l}$

Radio polarimetry: Faraday rotation & Stokes Q,U parameters

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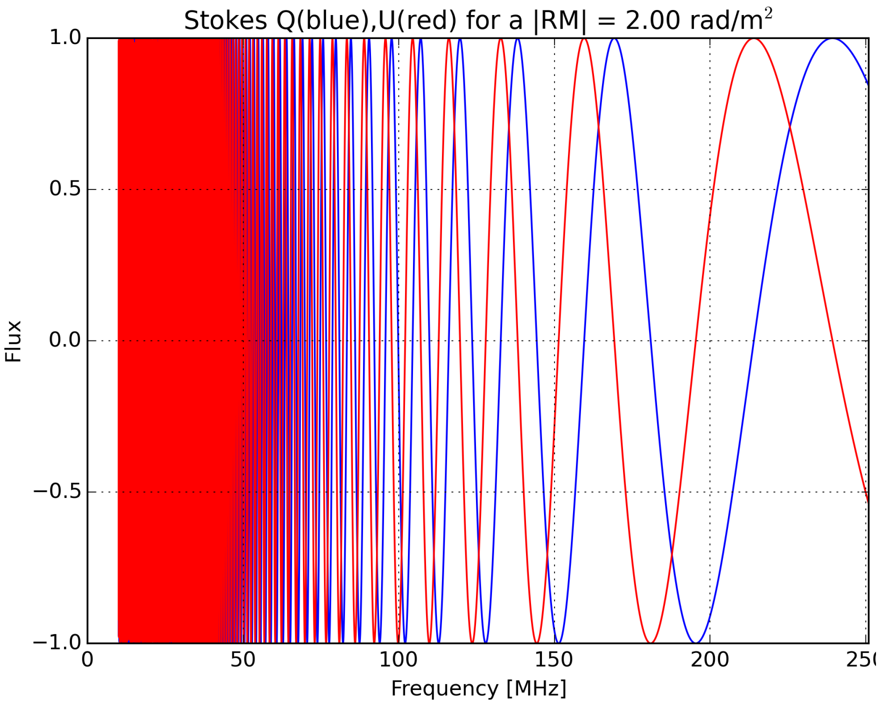
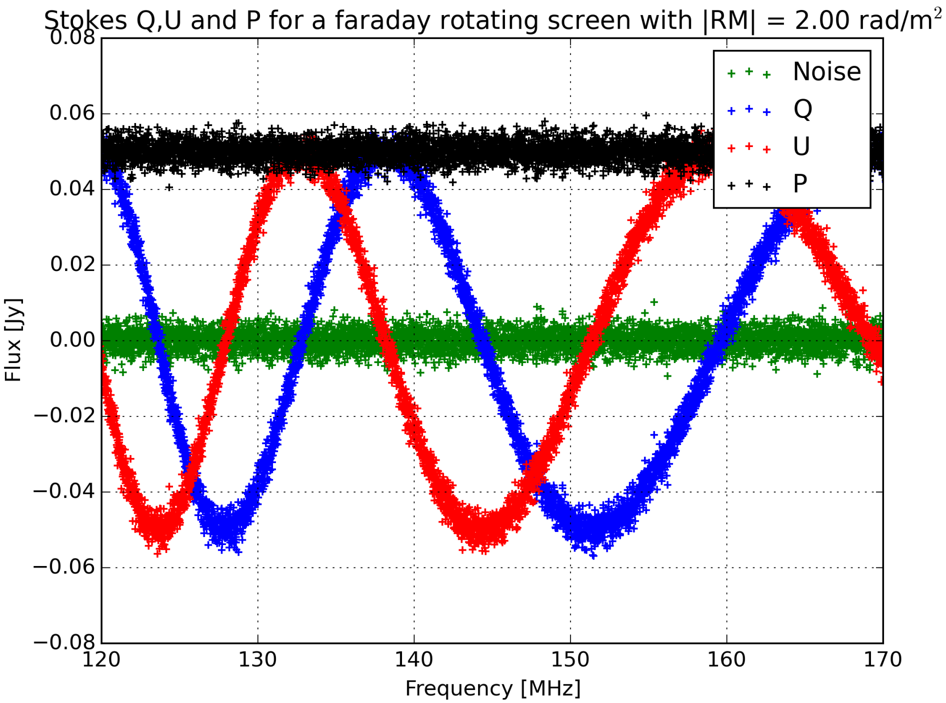
Faraday rotation imprints on Stokes Q,U ➔ fast rotation / band depolarization





When frequency averaging your LOFAR data the signal can completely depolarize. Carefully choose averaging factors for LBA and HBA polarimetry!

Radio polarimetry: Faraday rotation & Stokes parameters

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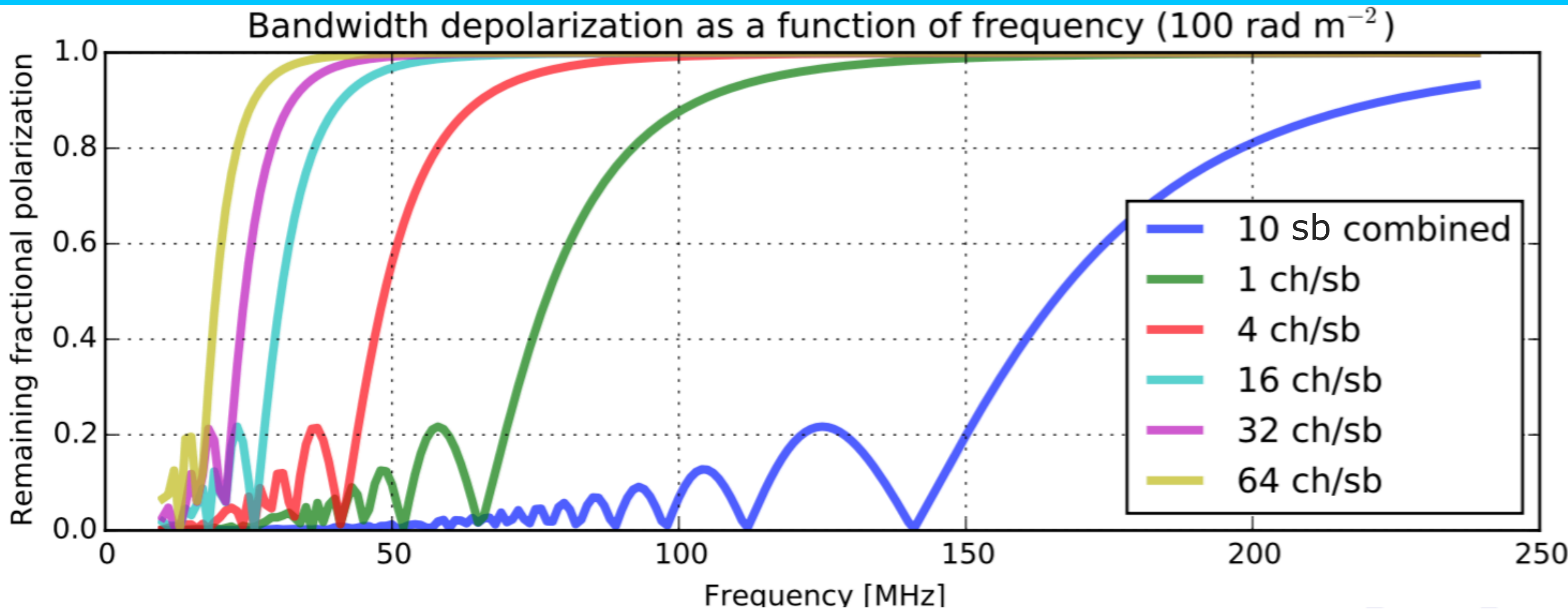
Faraday rotation imprints on Stokes Q,U ➔ fast rotation / band depolarization



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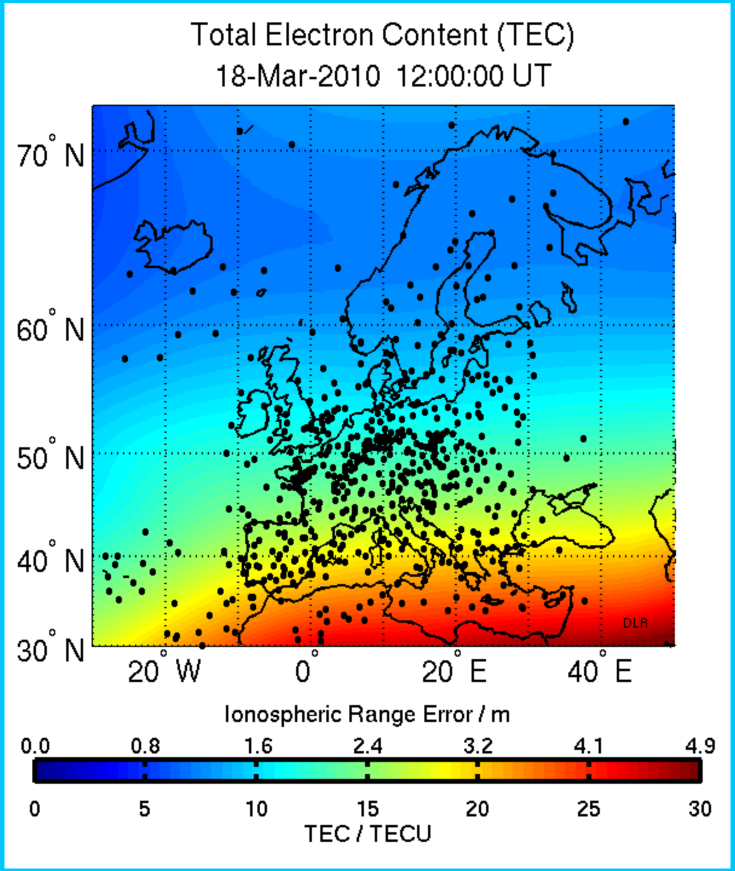
Radio polarimetry: Ionospheric Faraday rotation

Ionization (day) vs recombination (night): 1 TEC Unit = 10^{12} el/cm^2



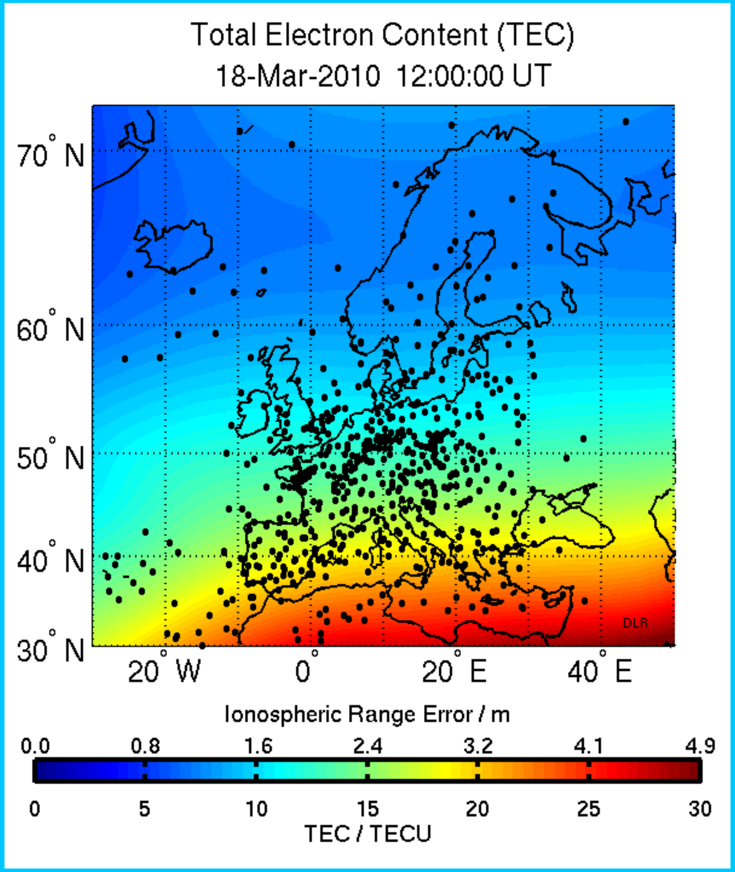
Typically daily variations up to ±5 rad m^{-2}
If not corrected, variations cause depolarization when combining data from long day/night runs.

Typical accuracies are of the order of 0.2 rad m^{-2}, which is good enough for the HBA but not for the LBA.

To correct your LOFAR data for ionospheric Faraday rotation use RMextract package ➔ createRMParmdb script

Radio polarimetry: Ionospheric differential Faraday rotation

Ionization (day) vs recombination (night): 1 TEC Unit = 10^{12} el/cm^2



Stations apart >10 km see different ionosphere, i.e. different amounts of ionospheric Faraday rotation.

During cross correlation Stokes I leakages into Stokes V and viceversa.

For LOFAR, differential Faraday rotation becomes important at baselines of only a few tens of km in the LBA and at the longer in the HBA.

To correct your LOFAR data for differential ionospheric RM use BBS package → solve for diagonal gains and a common rotation angle

Radio polarimetry: Faraday rotation Measure synthesis

A Fourier transform between Φ and λ^2 space: $P(\lambda^2) \rightarrow F(\Phi)$

$$\mathrm{P} = \mathrm{Q} + \mathrm{i}\mathrm{U} = \mathrm{p}\mathrm{I}\mathrm{e}^{2i\Psi} \quad + \quad \Psi(\lambda) = \Psi_0 + RM\lambda^2 \quad + \quad \phi \equiv RM$$

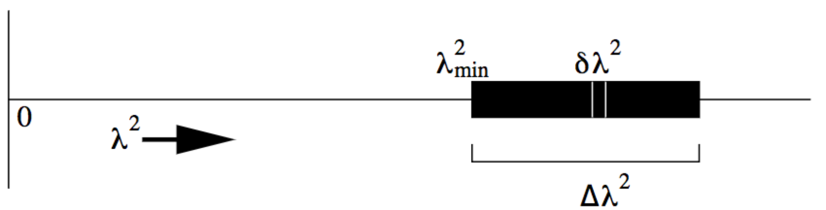
$$P(\lambda^2) = W(\lambda^2) \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi$$

W(λ²): the ***sampling (window) function***

F(Φ): the ***Faraday dispersion function***

By inverting, a finite point spread function (the ***Rotation Measure Spread Function***) is obtained!

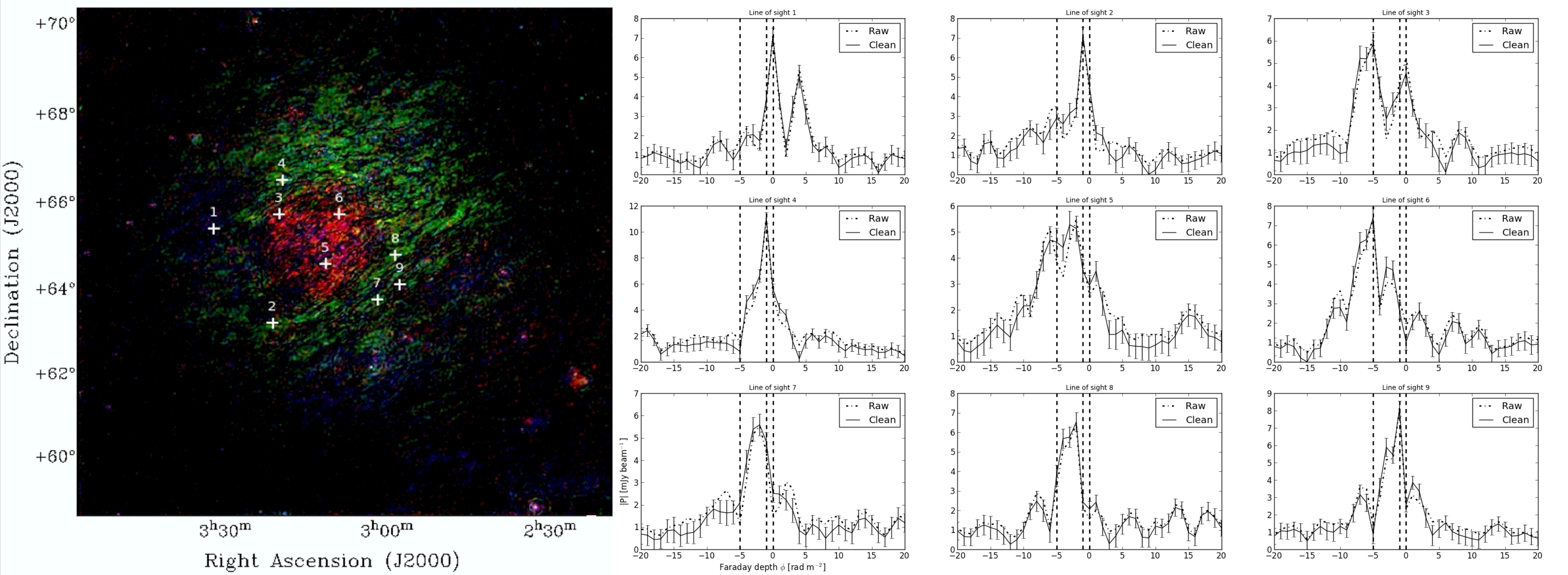
3 instrumental parameters fix the output of RM synthesis



Radio polarimetry: Faraday rotation Measure synthesis

A Fourier transform between Φ and λ^2 space: $P(\lambda^2) \rightarrow F(\Phi)$

In practice … the reconstructed ***Faraday dispersion function***



To apply RM synthesis to your LOFAR data use PYRMSINTH or RM-SYINTHESIS packages (github)