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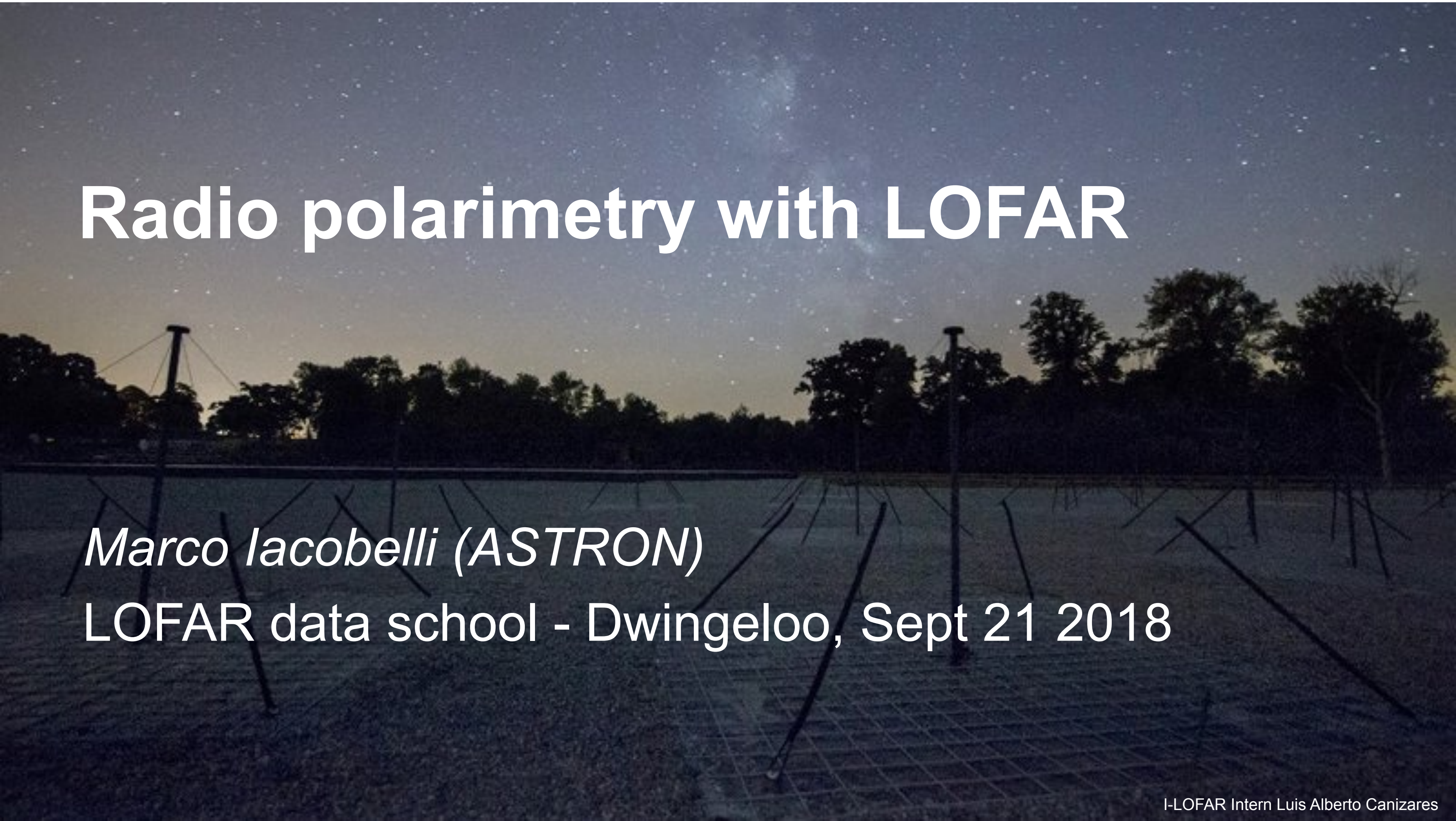
RadioNet

Netherlands Institute for Radio Astronomy



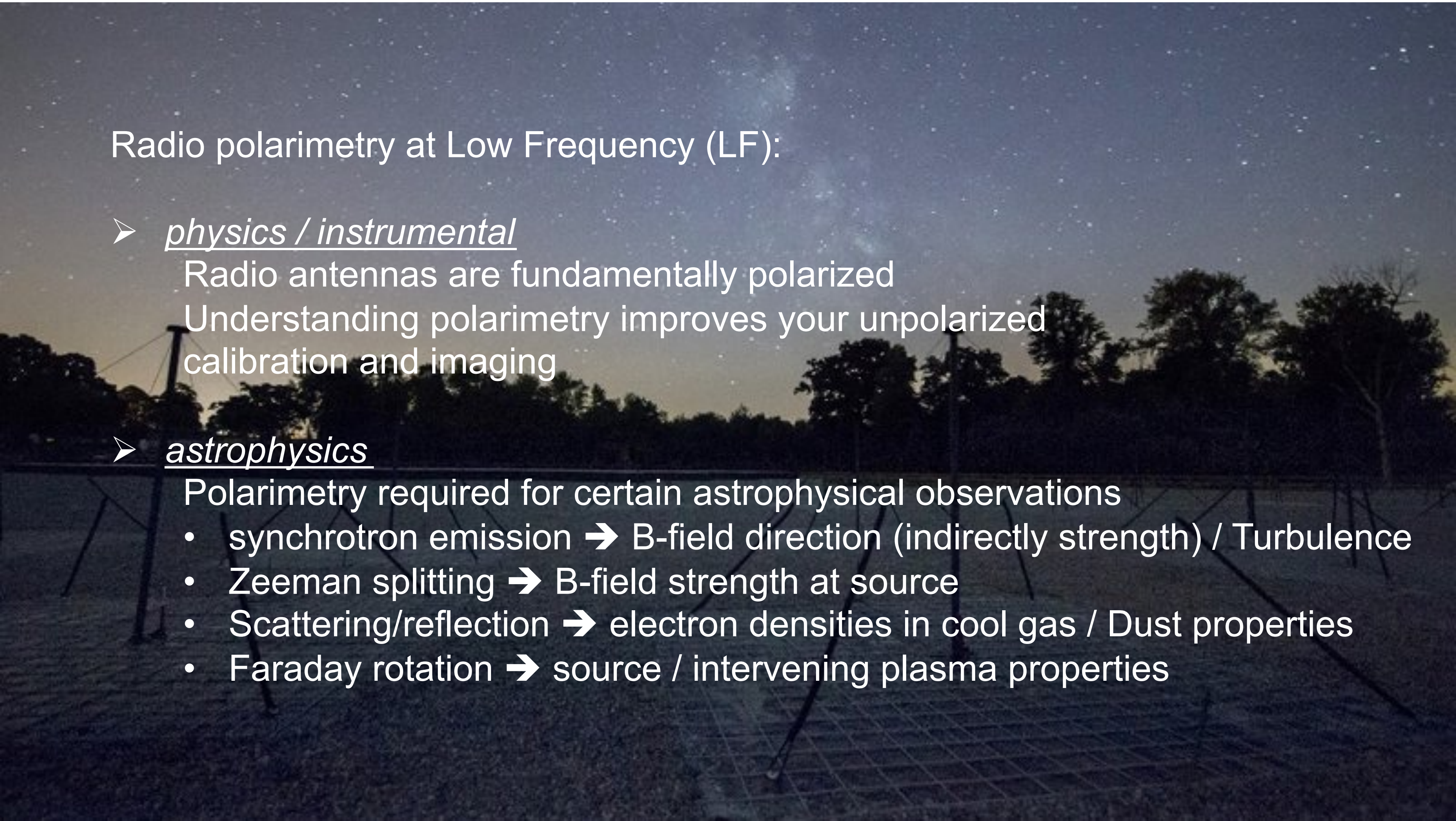
Radio polarimetry with LOFAR

Marco Iacobelli (ASTRON)

LOFAR data school - Dwingeloo, Sept 21 2018

I-LOFAR Intern Luis Alberto Canizares

Motivations



Radio polarimetry at Low Frequency (LF):

- *physics / instrumental*

  Radio antennas are fundamentally polarized

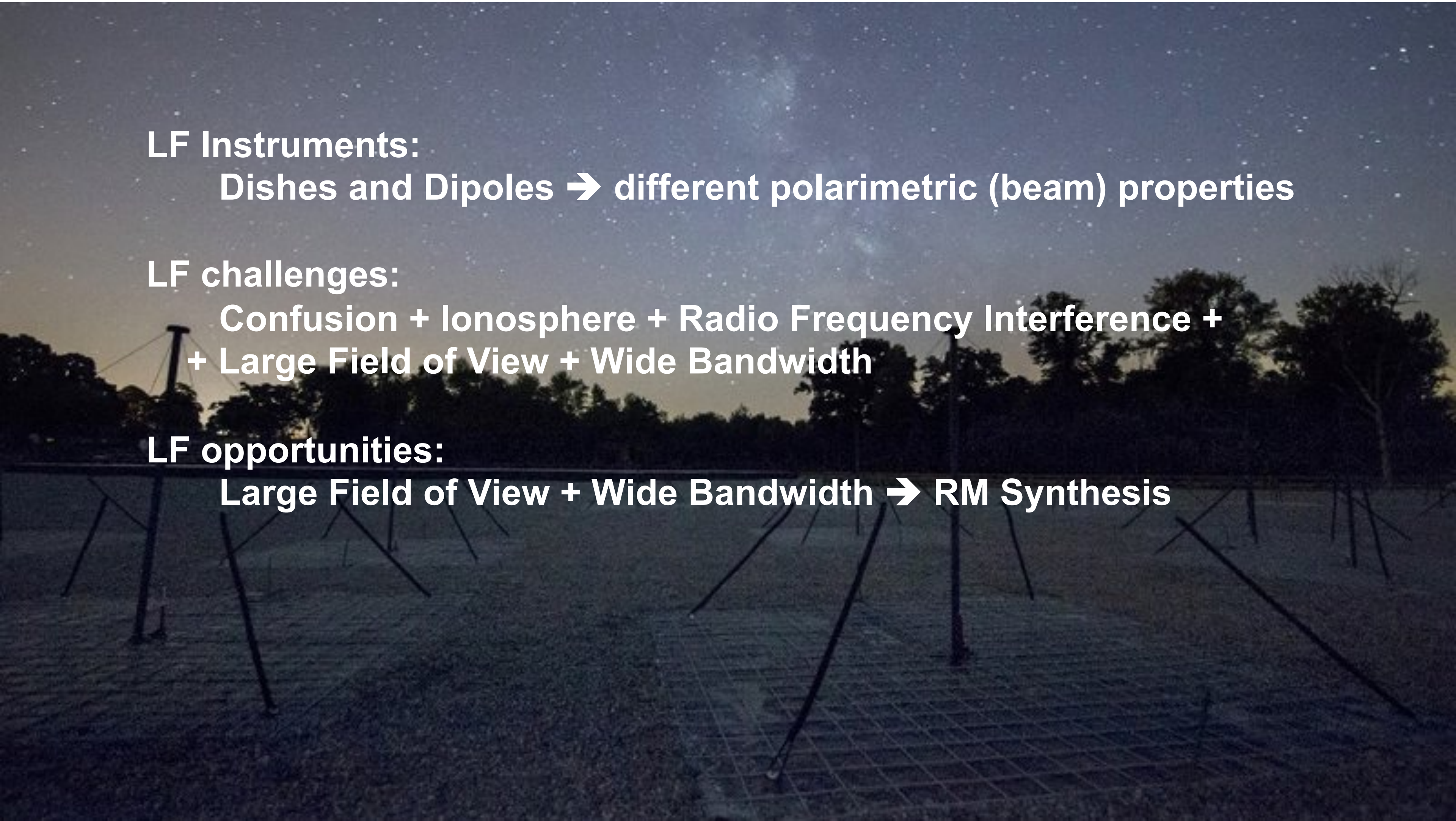
  Understanding polarimetry improves your unpolarized calibration and imaging

- *astrophysics*

  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

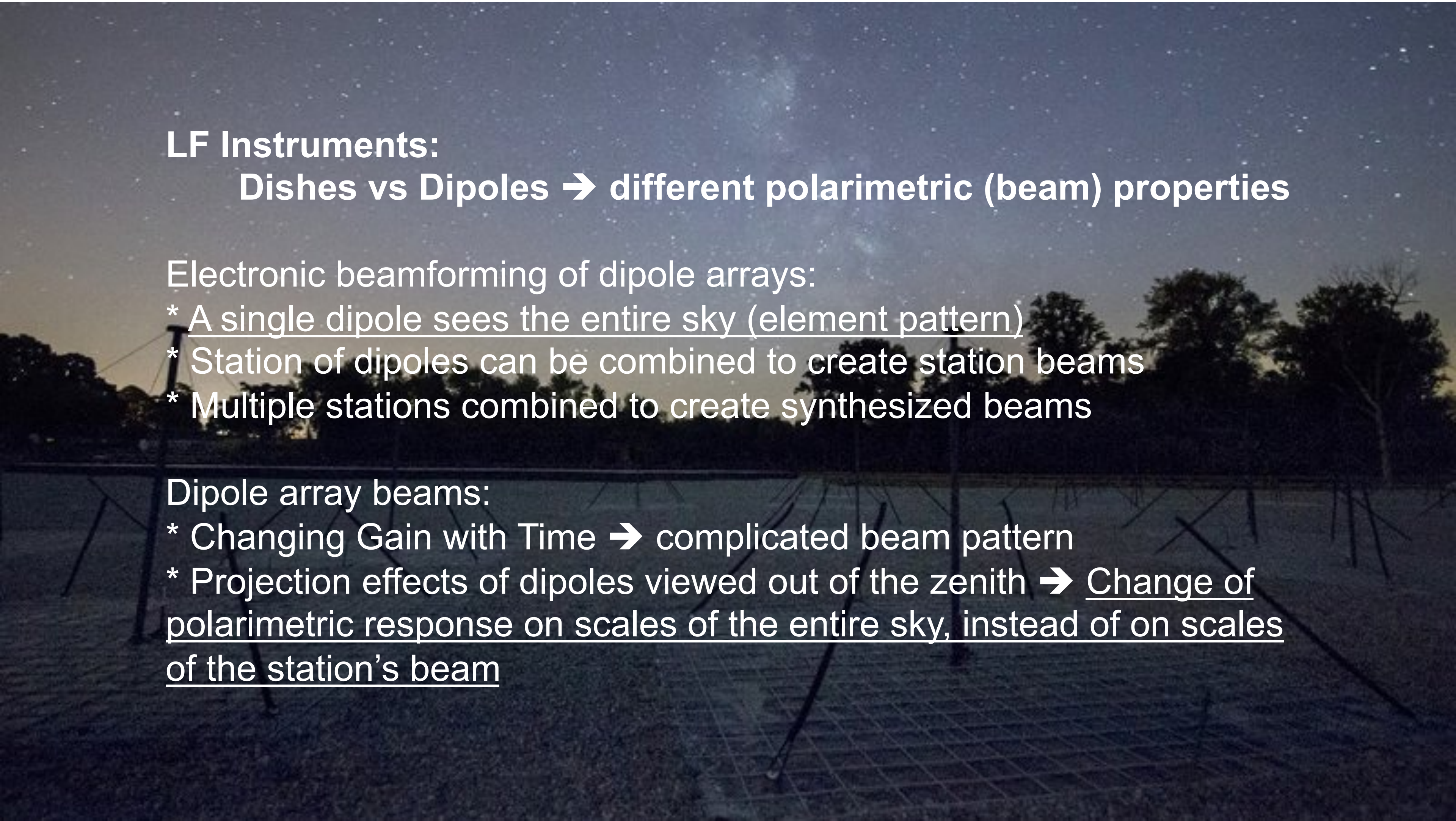
LF challenges:

Confusion + Ionosphere + Radio Frequency Interference +
+ Large Field of View + Wide Bandwidth

LF opportunities:

Large Field of View + Wide Bandwidth → RM Synthesis

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

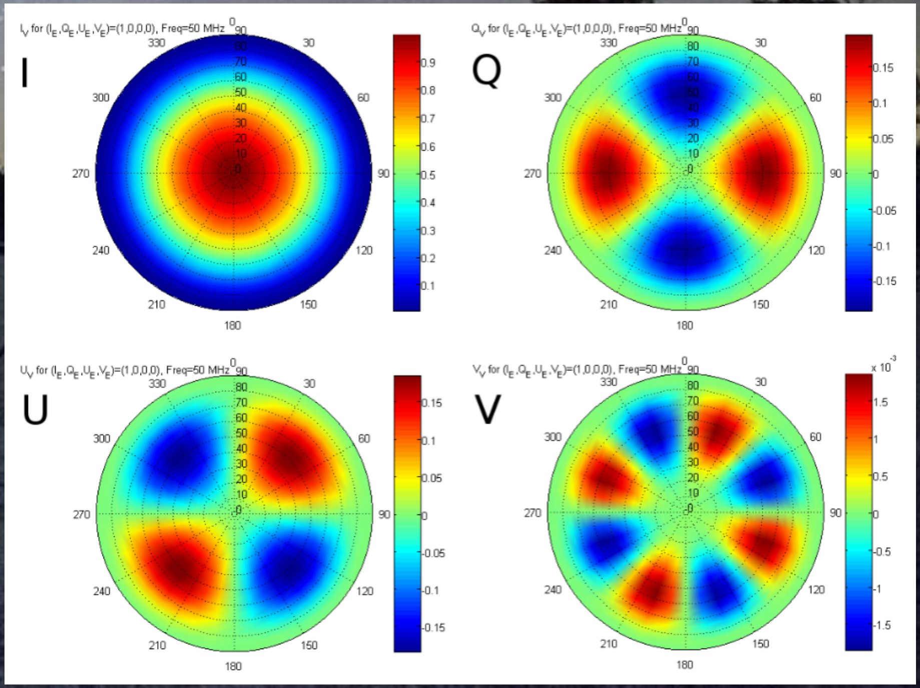
LF Instruments:

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



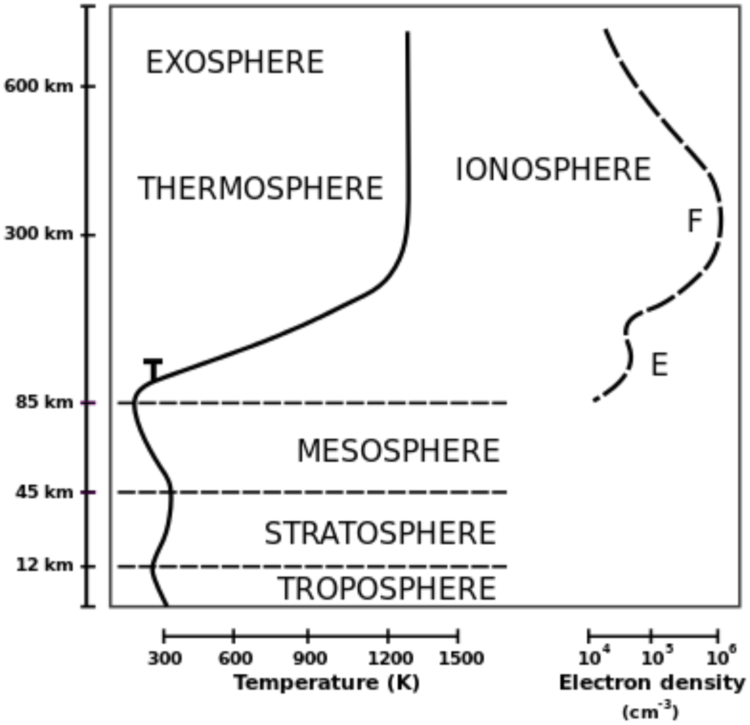
Polarimetry at LF: the LOFAR case

LF challenges:

Ionosphere and ionospheric effects

Ionospheric Cutoff:

- Plasma opacity below ~10MHz



Polarimetry at LF: the LOFAR case

LF challenges:

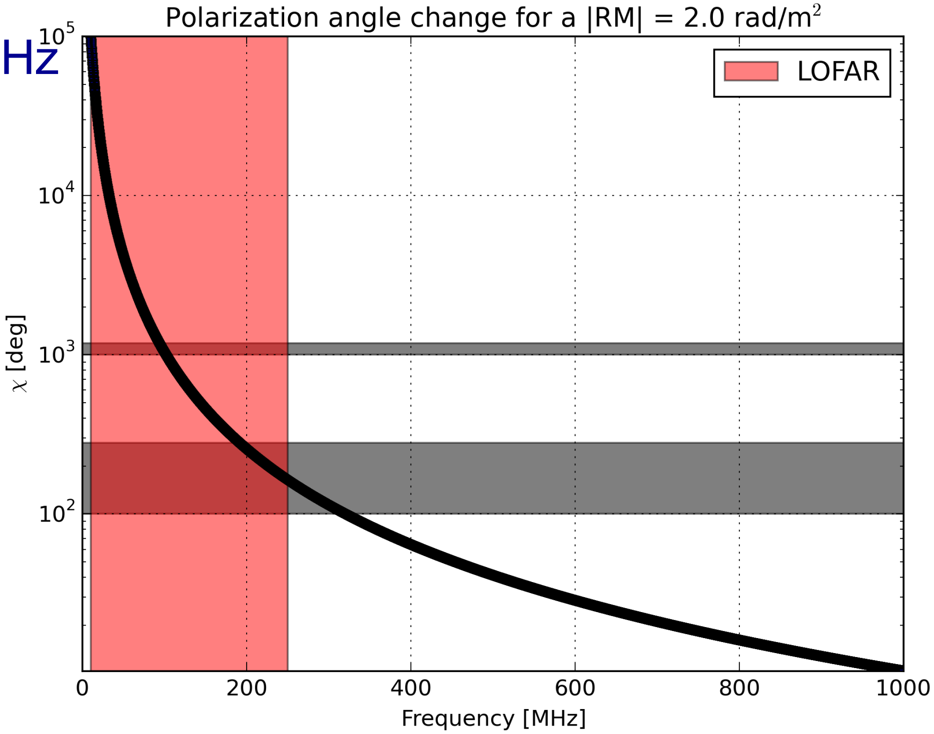
Ionosphere and ionospheric effects

Ionospheric Cutoff:

- Plasma opacity below ~10MHz

Quiescent Ionosphere:

- Refraction
- Faraday Rotation



Polarimetry at LF: the LOFAR case

LF challenges:

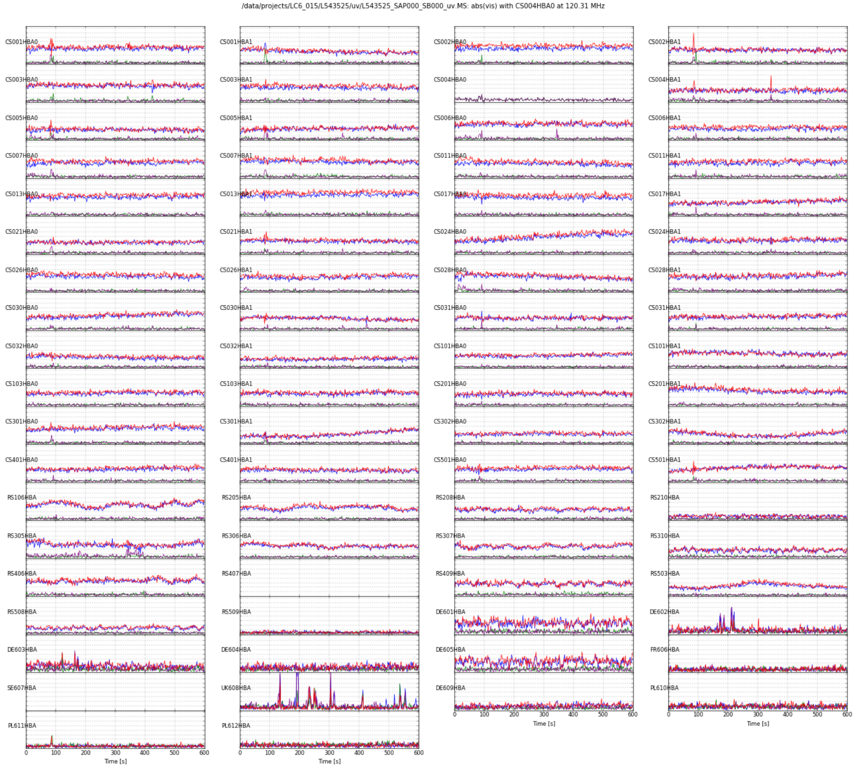
Ionosphere and ionospheric effects

Disturbed Ionosphere:

- Scintillation ➔ on uv plane
- Scintillation ➔ on image plane

  Image distortion

  Rapid position shift



Polarimetry at LF: the LOFAR case

LF challenges:

Ionosphere and ionospheric effects

Disturbed Ionosphere:

- Scintillation ➔ on uv plane
- Scintillation ➔ on image plane
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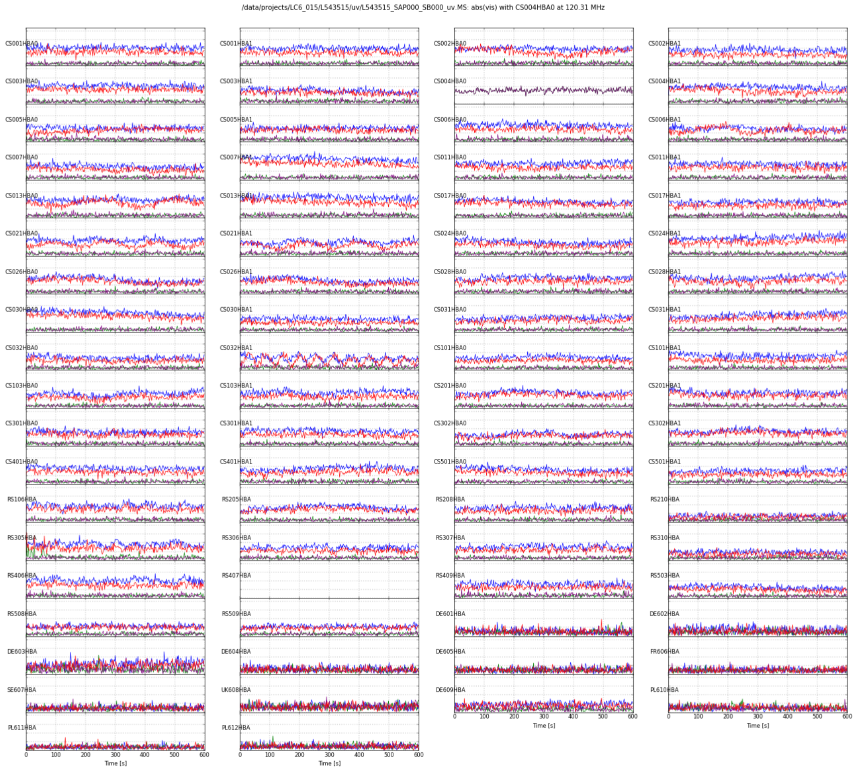
  Rapid position shift



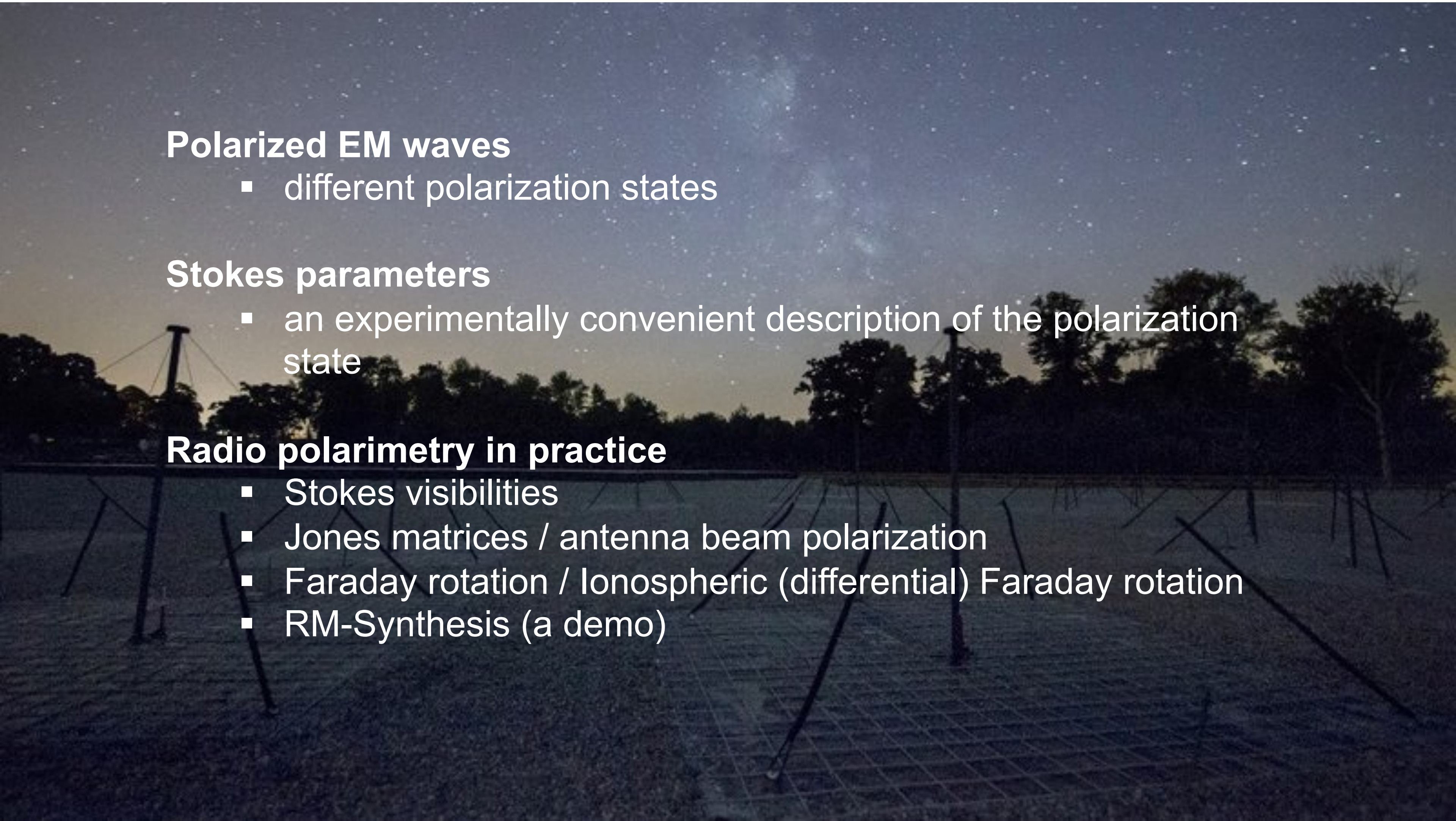
Polarimetry at LF: the LOFAR case

LF challenges:

Ionosphere and ionospheric effects

- Ionospheric Cutoff:
  - Plasma opacity below ~10MHz
- Quiescent Ionosphere:
  - Refraction
  - Faraday Rotation
- Disturbed ionosphere:
  - Scintillation / Rapid position shifts

TOPICS



Polarized EM waves

- different polarization states

Stokes parameters

- an experimentally convenient description of the polarization state

Radio polarimetry in practice

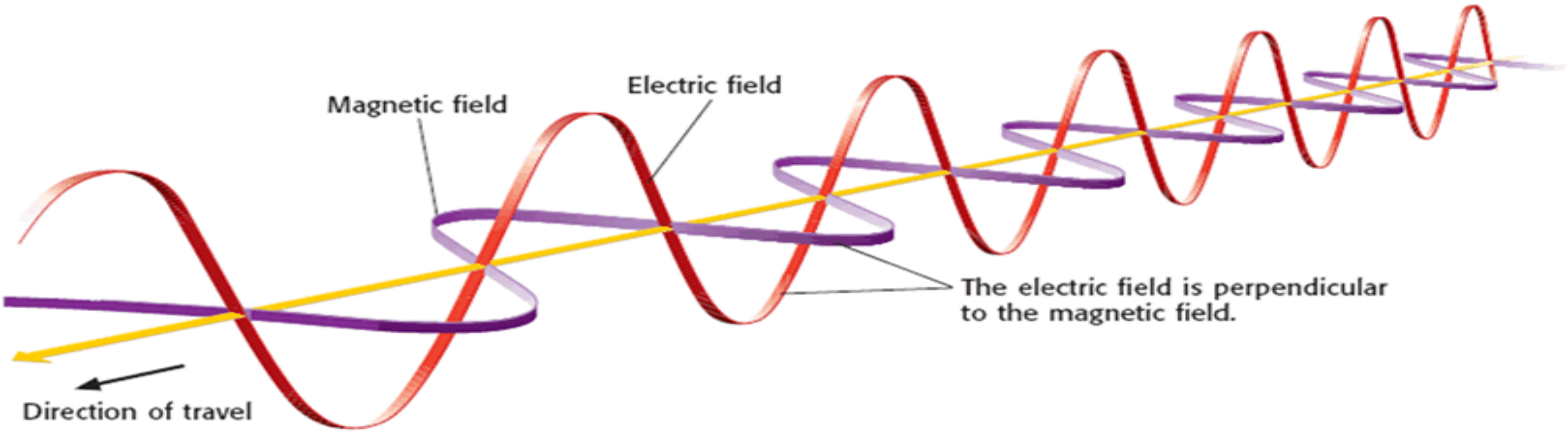
- Stokes visibilities
- Jones matrices / antenna beam polarization
- Faraday rotation / Ionospheric (differential) Faraday rotation
- RM-Synthesis (a demo)

Polarized EM waves: a vectorial 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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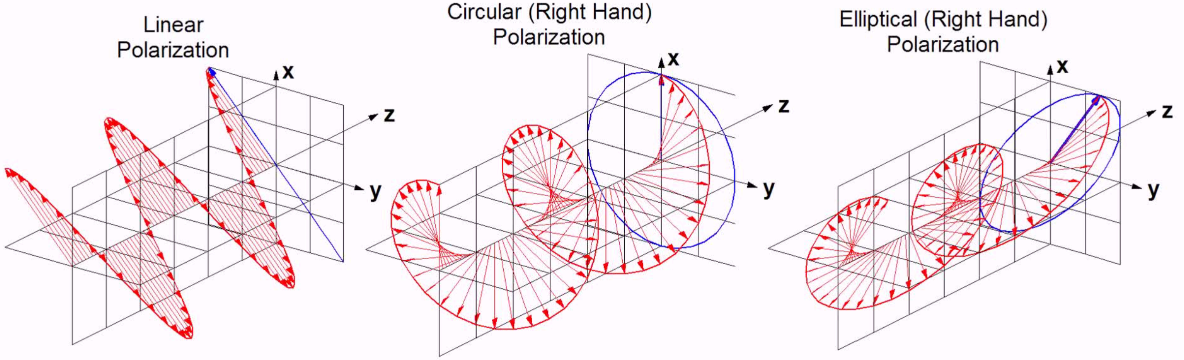
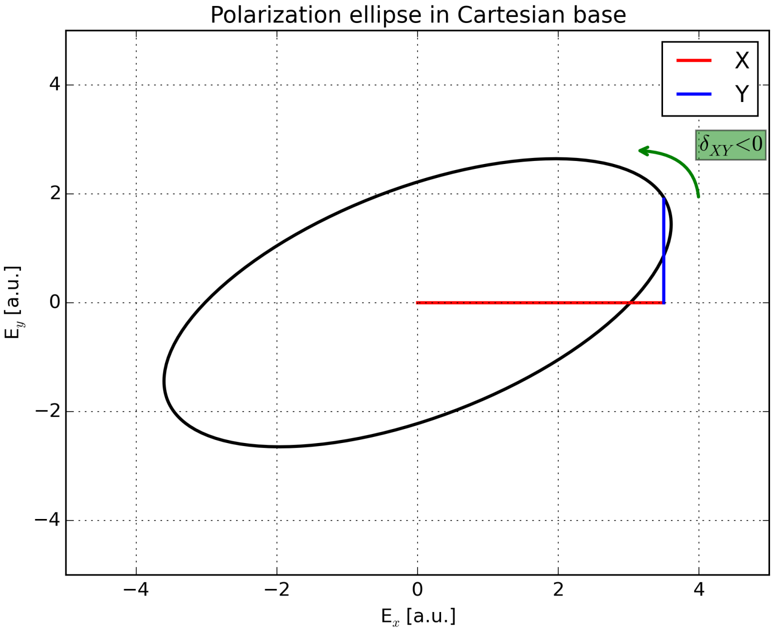
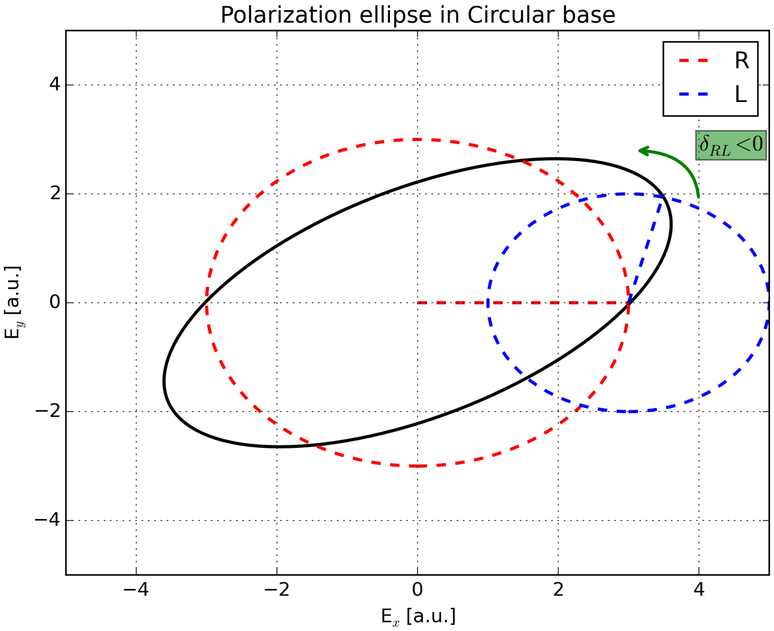


Polarized EM waves: a vectorial nature

$\boldsymbol{E} = E_x\,\mathbf{e}_x + E_y\,\mathbf{e}_y$
$E_x = A_x \cos(2\pi\nu t + \delta_x)$
$E_y = A_y \cos(2\pi\nu t + \delta_y)$
$\delta_{xy} = \delta_y - \delta_x$ 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


Polarization ellipse in Cartesian base


Polarization ellipse in Circular base

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.

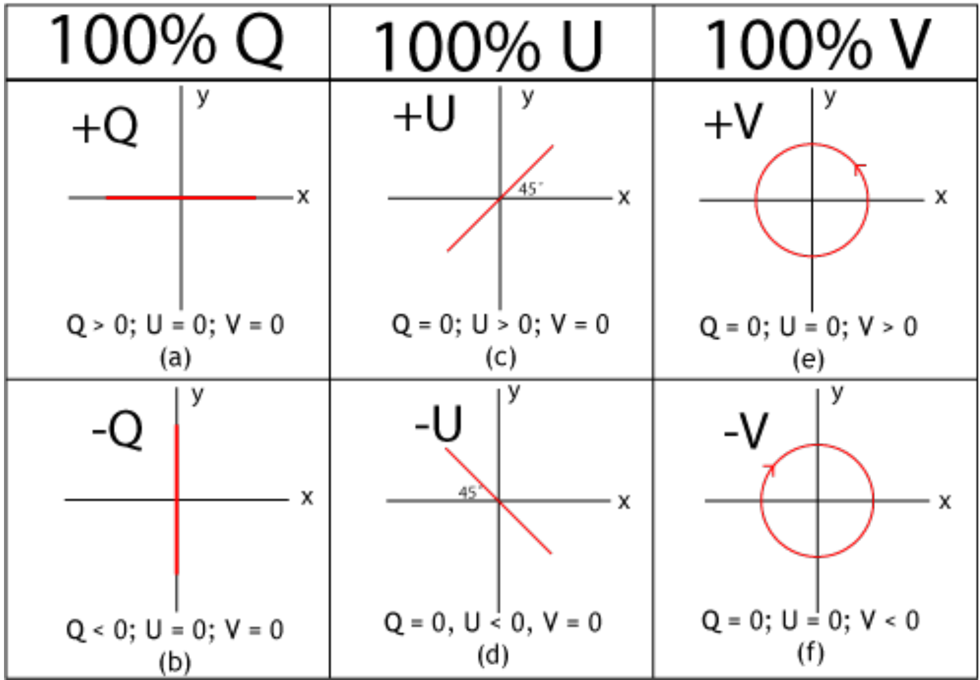
Polarization states:

1 Elliptical (general case)
2 Linear (degenerate case of 1)
3 Circular (degenerate case of 1)

I➔ mean flux density

(Q,U)➔ linear polarization

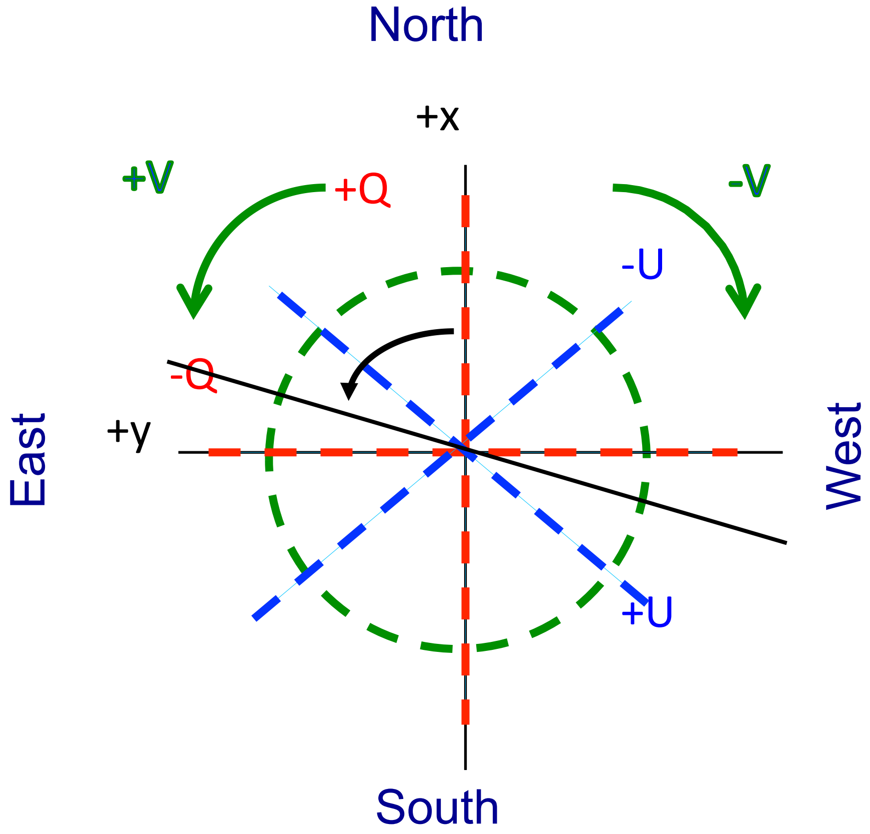
V➔ circular polarization



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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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: $I^2 = Q^2 + U^2 + V^2$

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

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

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

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

$$I = A_r^2 + A_l^2$$
$$Q = 2A_rA_l \cos\delta_{rl}$$
$$U = -2A_rA_l \sin\delta_{rl}$$
$$V = A_r^2 - A_l^2$$

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

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

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

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

Radio polarimetry in practice: Stokes visibilities vs sky images

Sky brightness

➔

➔

FT(Sky brightness):
the visibilities
$I(u,v)=FT(I(l,m))$
$Q(u,v)=FT(Q(l,m))$
$U(u,v)=FT(U(l,m))$
$V(u,v)=FT(V(l,m))$

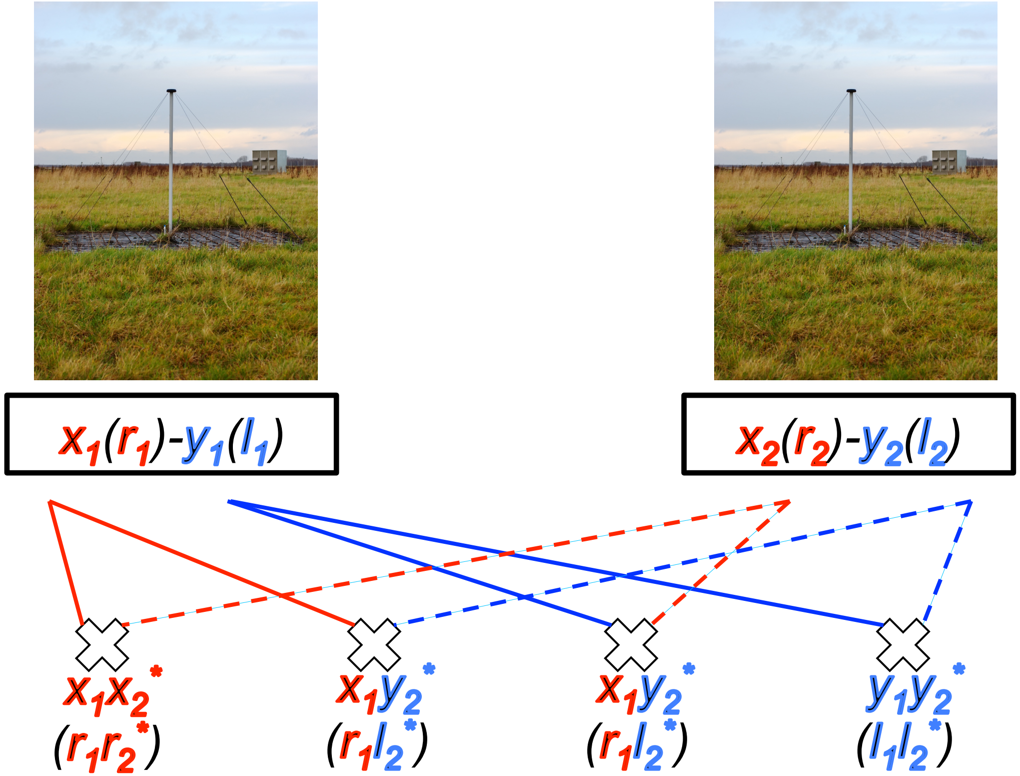
No mono-chromatic radiation approximation
Stokes parameters sampled in {time} / frequency

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

$$I = A_r^2 + A_l^2$$
$$Q = 2A_rA_l \cos\delta_{rl}$$
$$U = -2A_rA_l \sin\delta_{rl}$$
$$V = A_r^2 - A_l^2$$

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

Radio polarimetry in practice: Stokes visibilities & correlators I



$x_1(r_1)$-$y_1(l_1)$

$x_2(r_2)$-$y_2(l_2)$

$x_1x_2^*$ $(r_1r_2^*)$

$x_1y_2^*$ $(r_1l_2^*)$

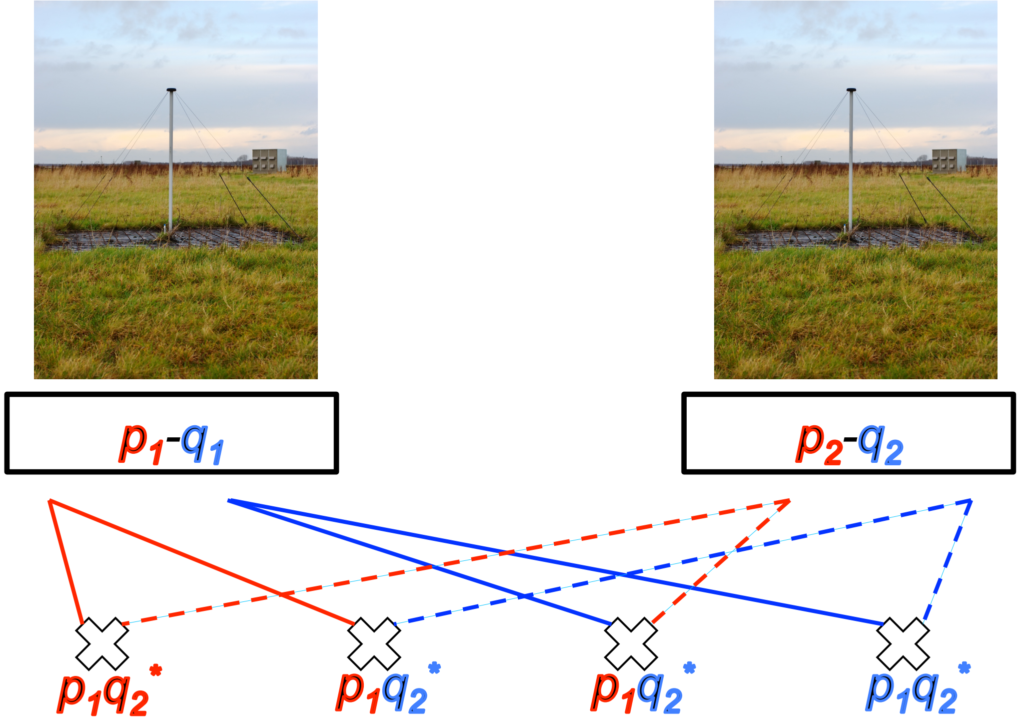
$x_1y_2^*$ $(r_1l_2^*)$

$y_1y_2^*$ $(l_1l_2^*)$

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

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

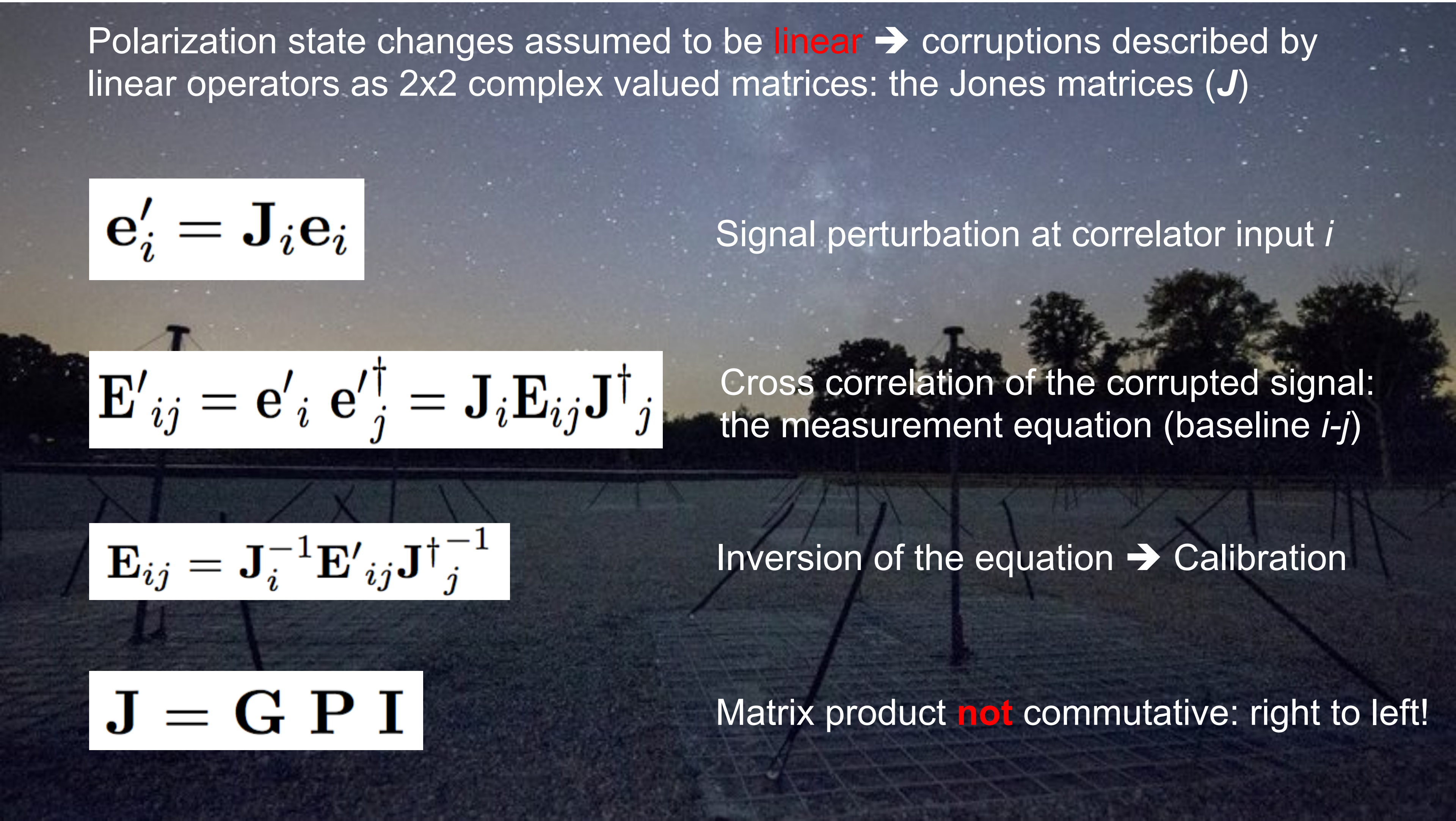
Radio polarimetry in practice: Stokes visibilities & correlators II



Signal editing by linear operators: Jones matrix and coherence matrix

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

Radio polarimetry: signal editing & Jones matrices I



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*)

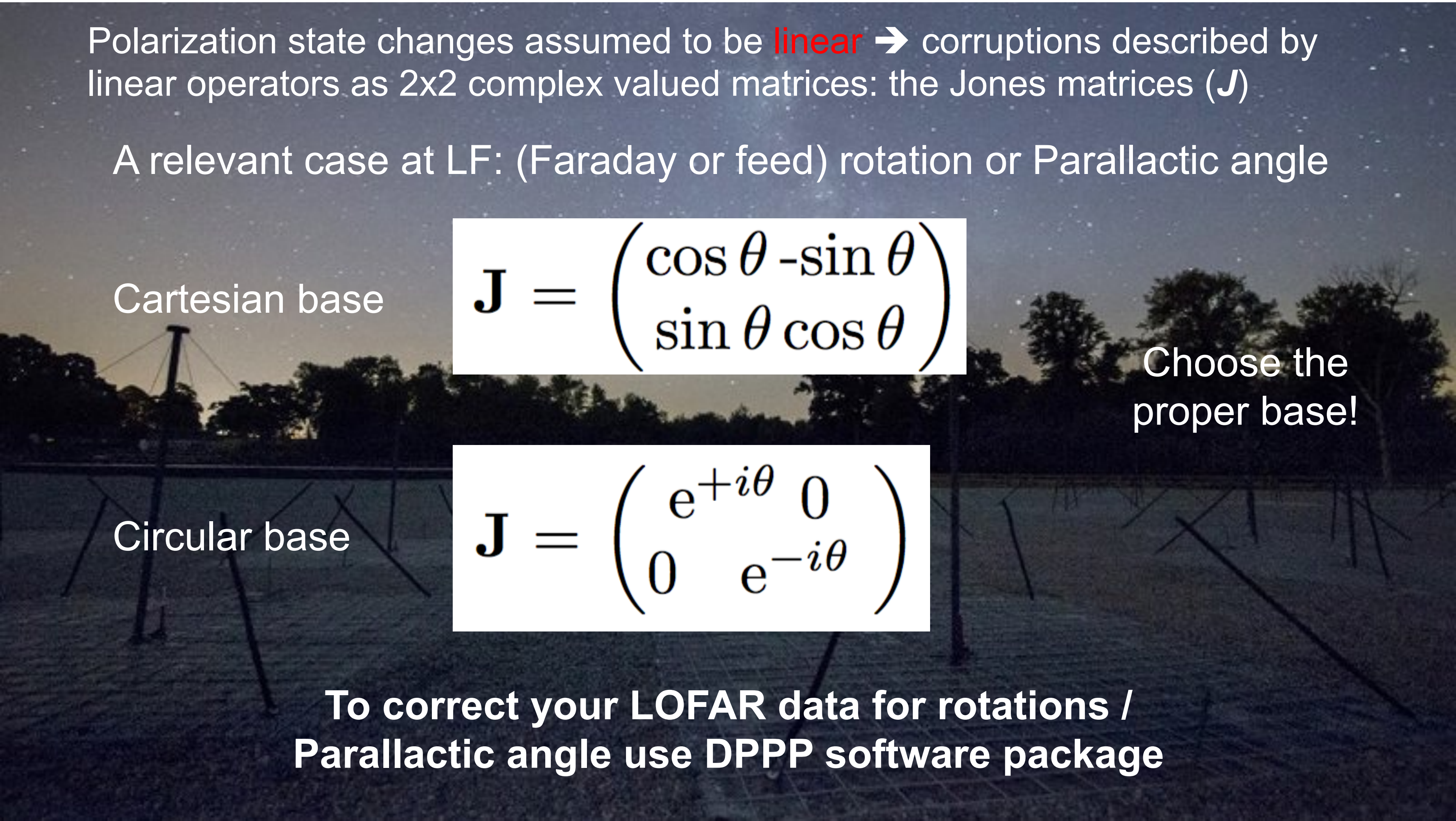
$$\mathbf{E}_{ij} = \mathbf{J}_i^{-1} \mathbf{E}'_{ij} \mathbf{J}^{\dagger}{}_j^{-1}$$

Inversion of the equation ➔ Calibration

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

Matrix product **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

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

Choose the proper base!

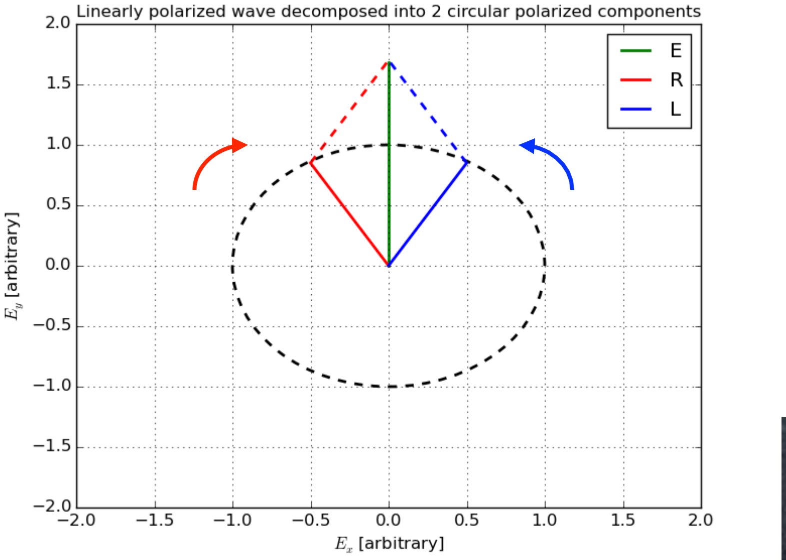
Circular base

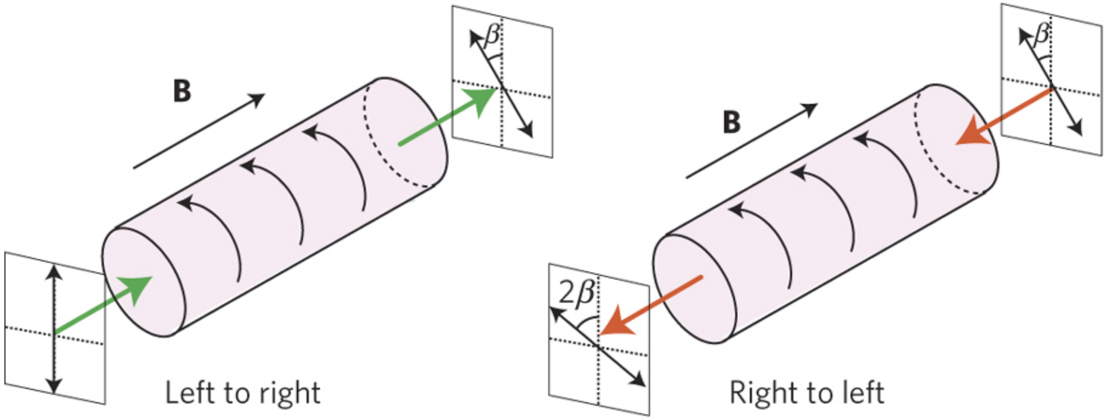
$$\mathbf{J} = \begin{pmatrix} \mathrm{e}^{+i\theta} & 0 \\ 0 & \mathrm{e}^{-i\theta} \end{pmatrix}$$

To correct your LOFAR data for rotations / Parallactic angle use DPPP 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

$$RM = \frac{\partial\Psi}{\partial\lambda^2}$$

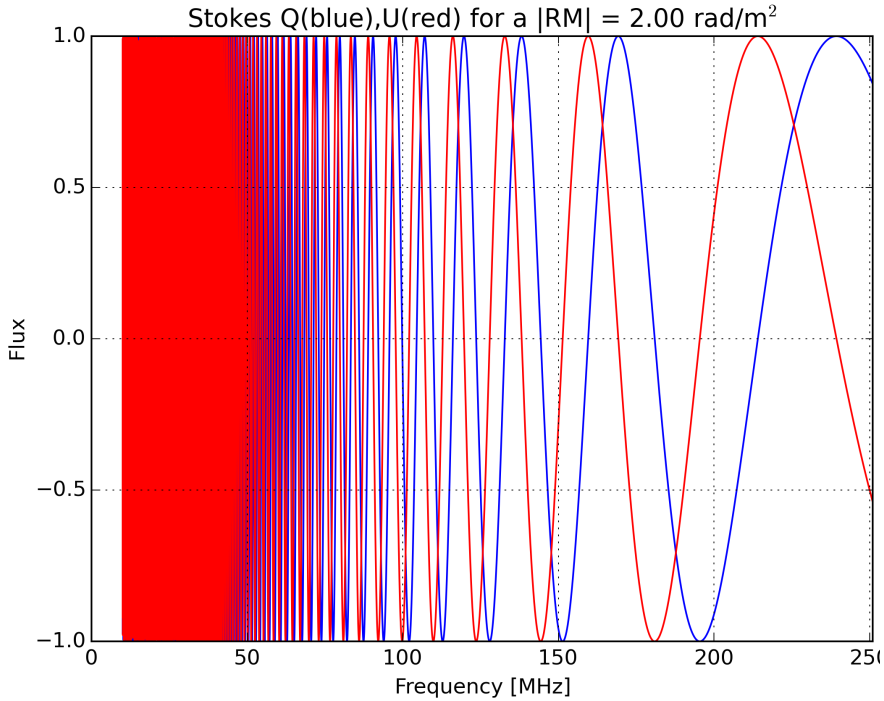
ELSE:

- ✓ Non linear dependence on λ^2 ➔ Faraday depth

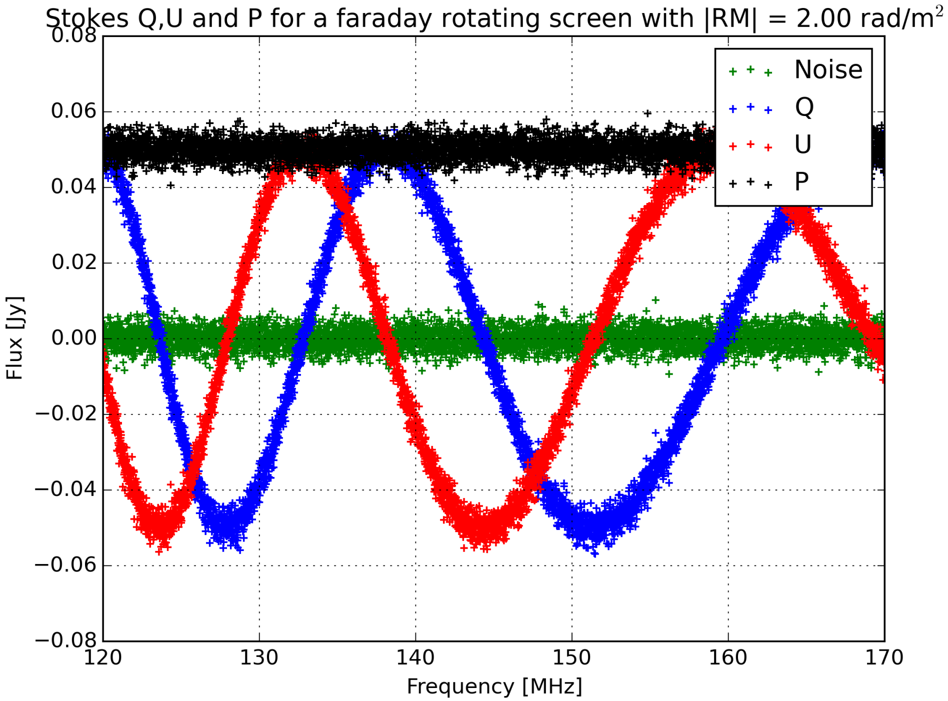
$$\phi = 0.81\int_{source}^{observer} n_e \vec{B}\cdot d\vec{l}$$

Radio polarimetry: Faraday rotation & Stokes Q,U parameters

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



Stokes Q(blue),U(red) for a |RM| = 2.00 rad/m^2

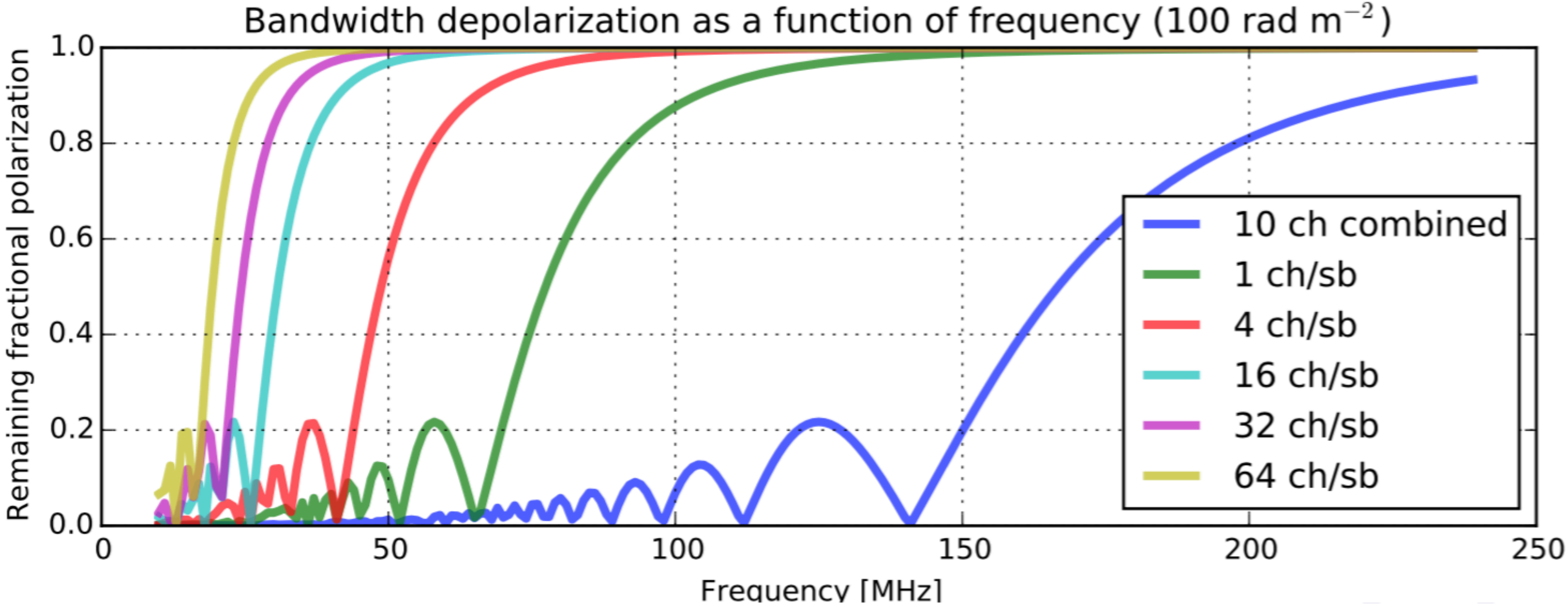


Stokes Q,U and P for a faraday rotating screen with |RM| = 2.00 rad/m^2

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 Q,U parameters

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 Q,U parameters

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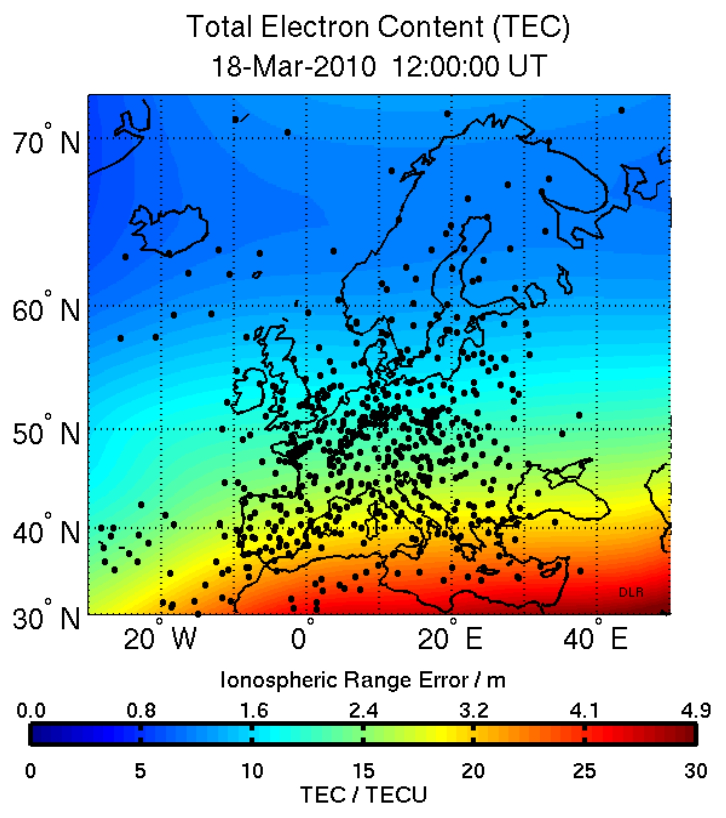
Ionization (day) vs recombination (night): 1 TEC Unit = 10^{12} el/cm^2



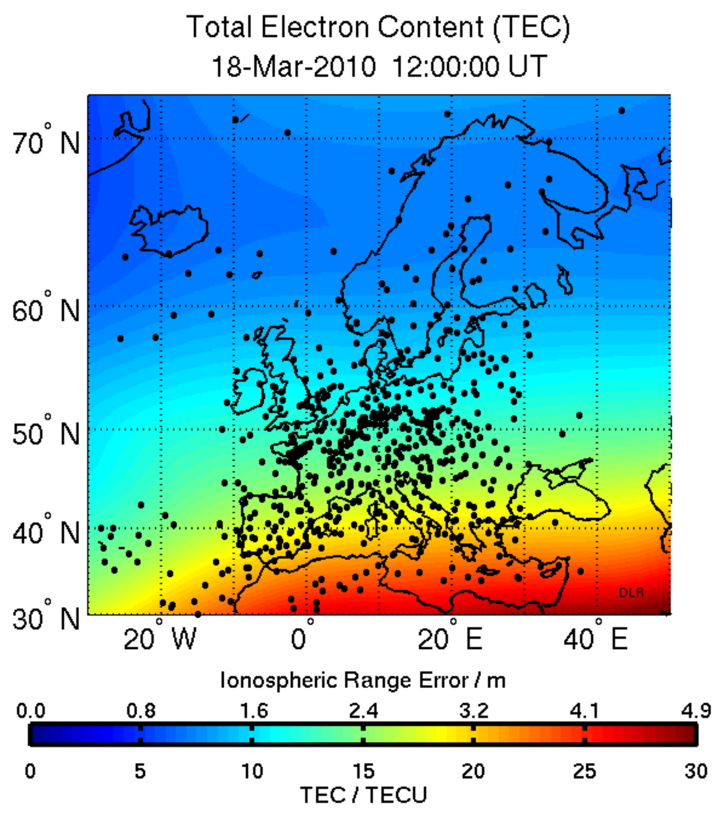
Typically daily variations up to ±5 rad m^{-2} If not corrected, variations cause depolarization when combining data from long day/night runs.

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 (see L7 by MM)

Radio polarimetry: Faraday rotation & Stokes Q,U parameters

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 DPPP package → solve for diagonal gains and a common rotation angle

Radio polarimetry: Faraday rotation Measure synthesis

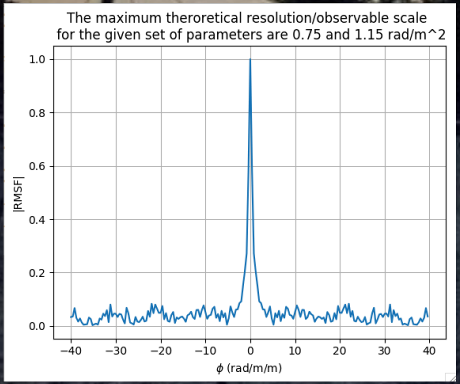
A Fourier transform between Φ and λ^2 space: $P(\lambda^2)$ ➔ $F(\Phi)$

$$\mathrm{P} = \mathrm{Q} + \mathrm{iU} = \mathrm{pIe}^{2i\Psi} \quad + \quad \Psi(\lambda) = \Psi_0 + RM\lambda^2 \quad + \quad \phi \equiv RM$$

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

$W(\lambda^2)$: the ***sampling (window) function***

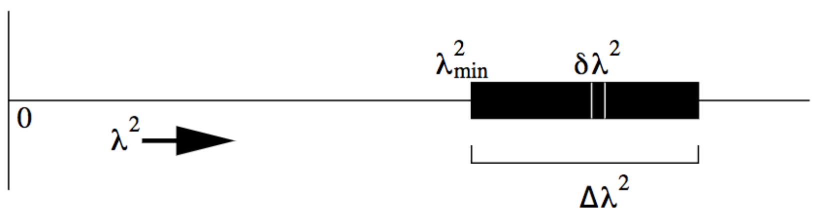
$F(\Phi)$: the ***Faraday dispersion function***



The maximum therоretical resolution/observable scale for the given set of parameters are 0.75 and 1.15 rad/m^2

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

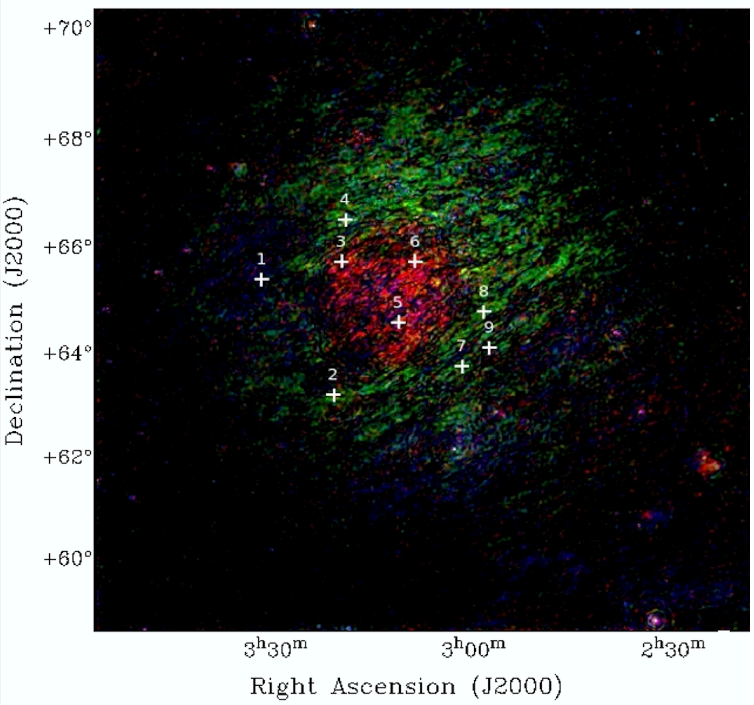
3 instrumental parameters fix the output of RM synthesis

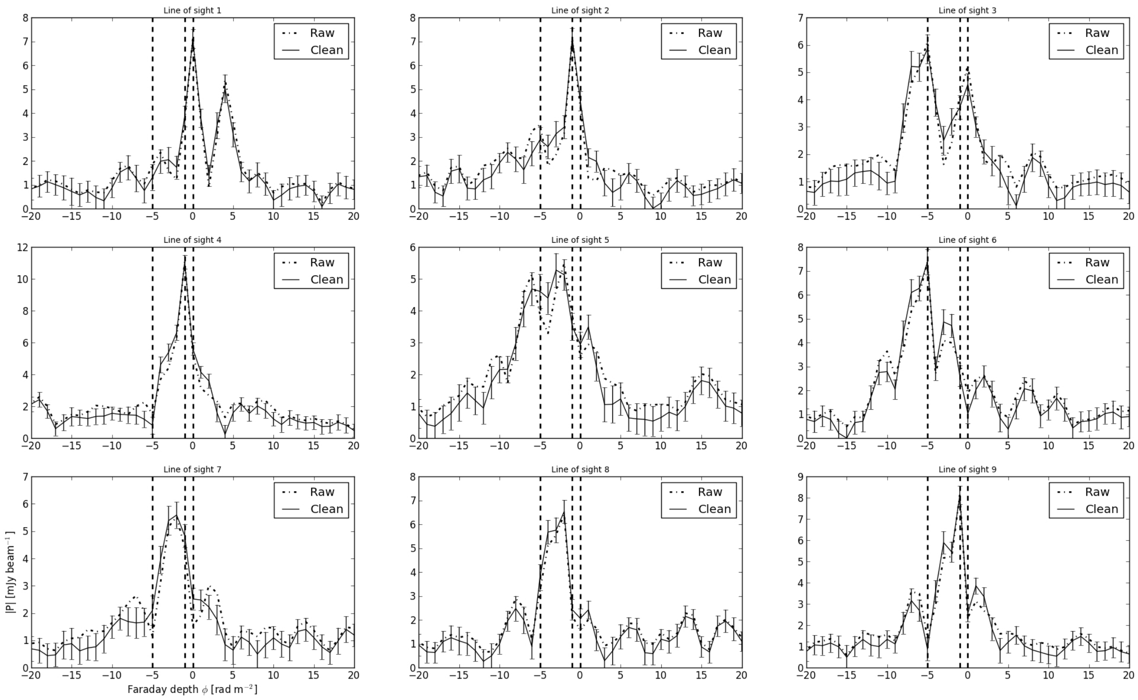


Radio polarimetry: Faraday rotation Measure synthesis

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

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





Several codes available to run RM synthesis to your LOFAR: cuFFS , pyrmsynth , rm-synthesis

Marco Iacobelli – 5th LOFAR data school
Dwingeloo 21th Sept 2018

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