Ionospheric Effects

LOFAR data school 2024

M. Mevius

Ionosphere: imaging

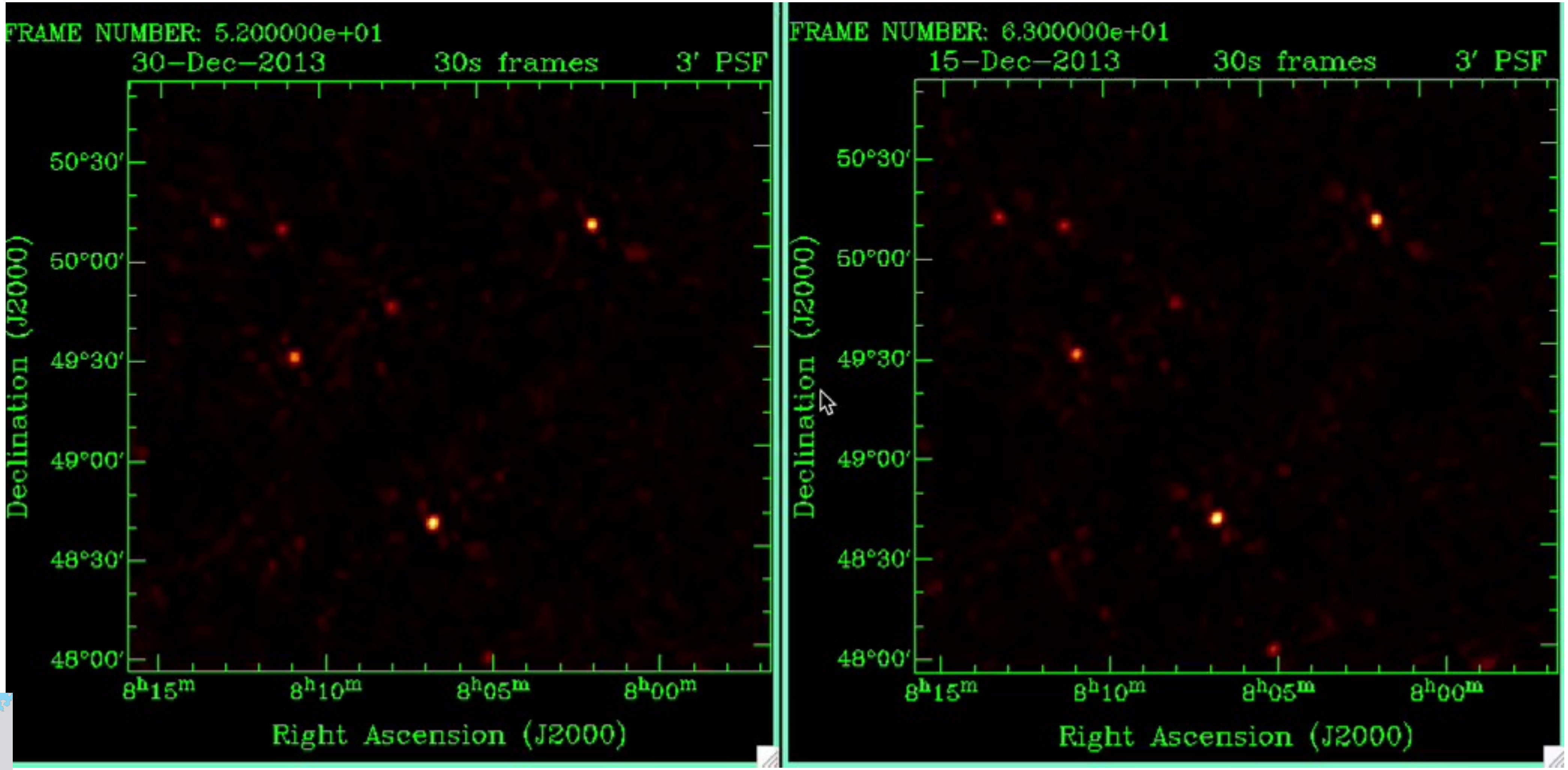
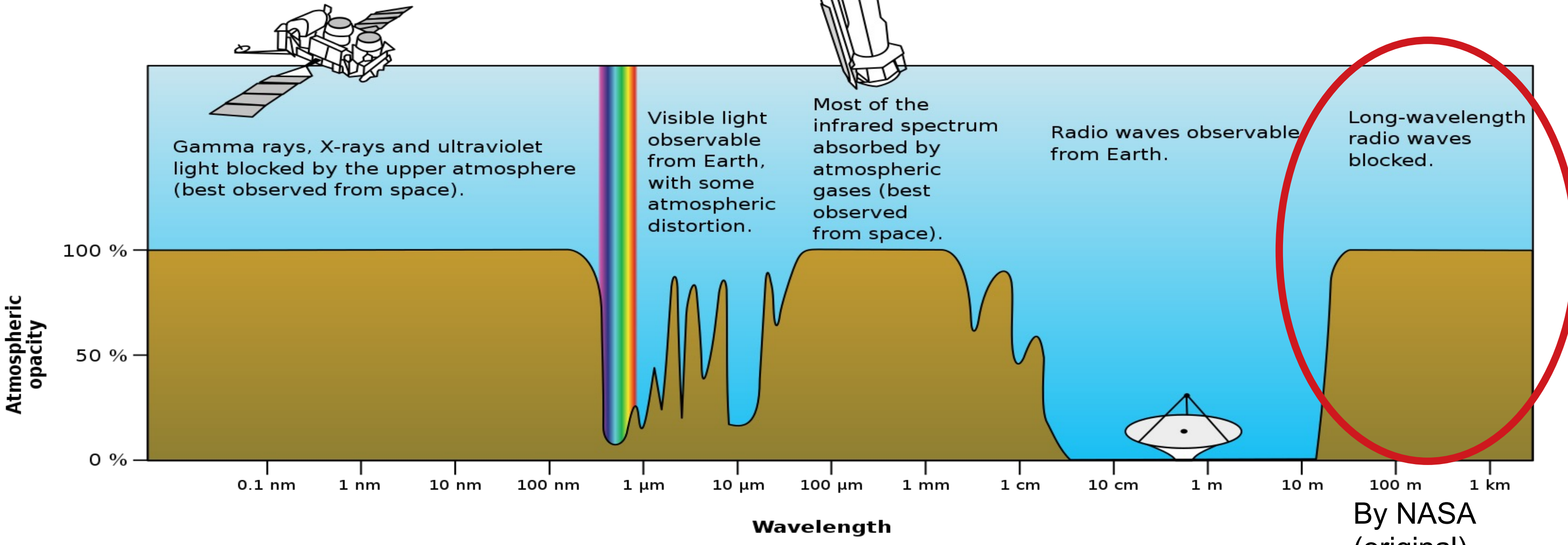


Image credit: G. de Bruyn

Ionosphere



By NASA (original)

What is it and why do we care?

1950s formally defined as: “the part of the earth’s upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves” *Encyclopedia Britannica*

Ionized layer(s) in the upper atmosphere,

altitudes between 50 and 1000 km

Long distance radio transmission: bouncing via ionosphere

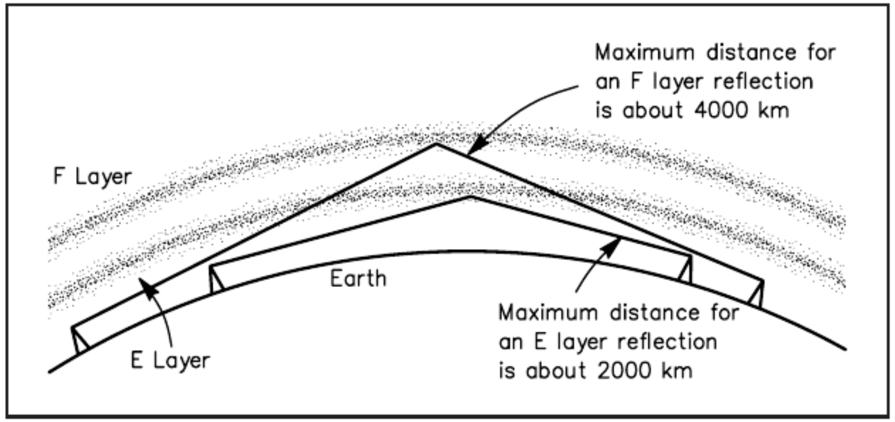
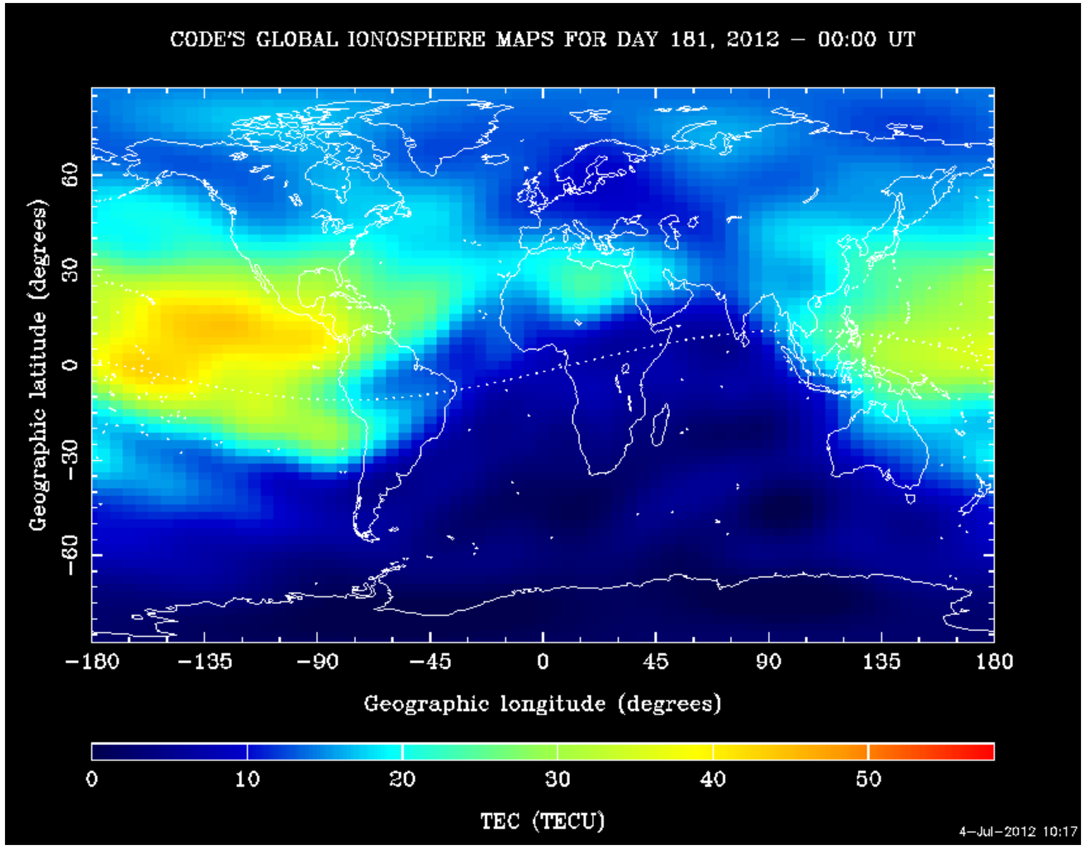


Figure 6—Signals reflected by the E and F layers.

Ian Poole, G3YWX

Electron Density

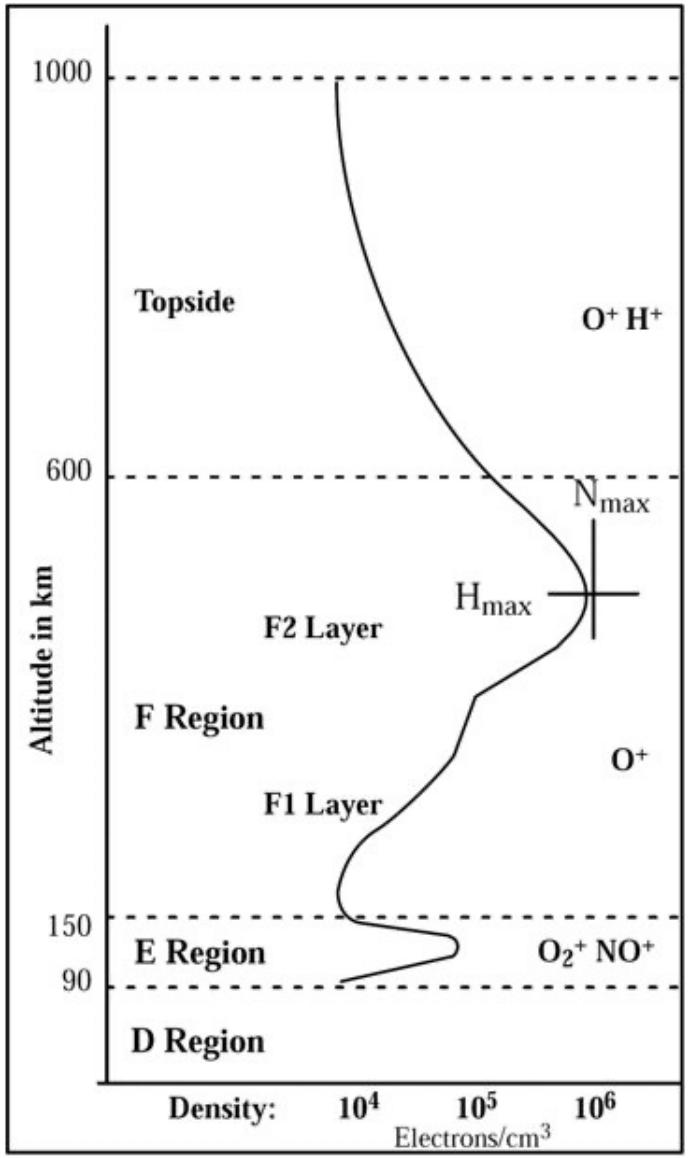
Electron density/Total integrate electron density (TECU: 10^{16} e^-/m^2)
Typical values @ 52° for integrated TEC along LOS: ~ 5(night) - 30(day) TECU



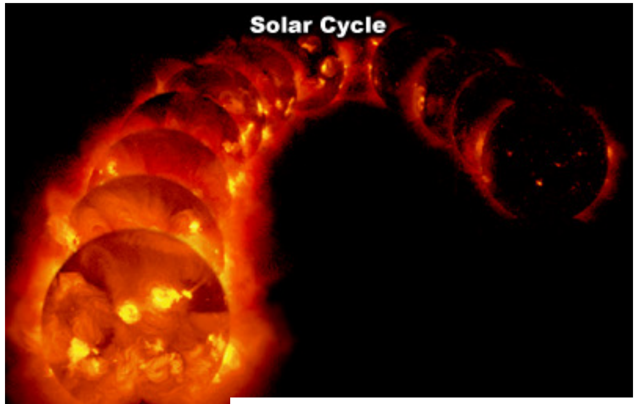
Ionization through solar radiation (X+EUV)
Recombination at night

Depth of radiation + Molecular densities + composition:
Layered structure
Maximum around 300 km (F-layer)

In many models thin screen approximation



Ionospheric Variability

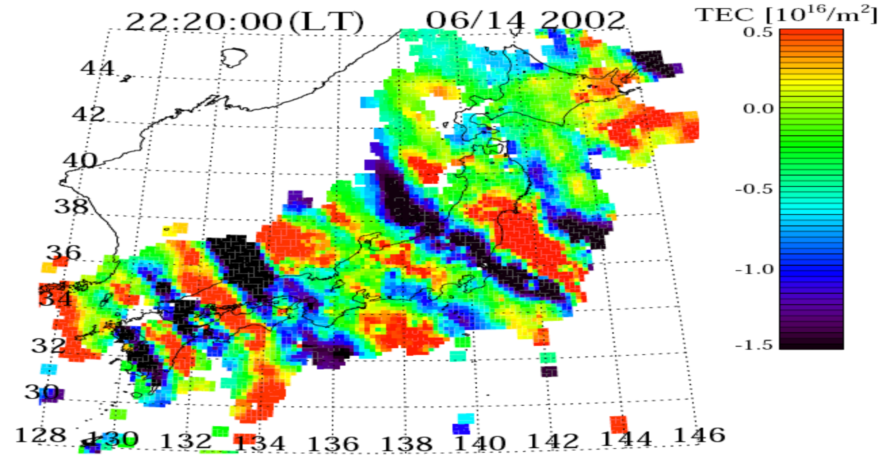


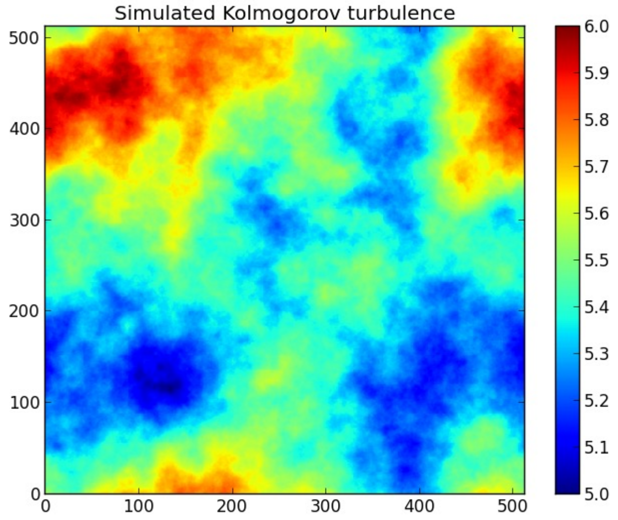
The ionosphere is highly dynamic:

- Ionization through solar radiation (UV+X-ray)
- Recombination at night
  - → diurnal pattern
  - large gradients @ dusk and dawn
- Solar activity cycle
- Space Weather events
- Scintillation (high turbulence):
  - (often) after sunset
- Pressure + composition lower atmosphere
- Traveling Ionospheric Disturbances (TIDs)

Small Scale Structures: Kolmogorov turbulence

- Structures moving with speeds ~ few 100 km/hr
- When observing: tracking through the ionosphere





Ionospheric Variability

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Small Scale Structures: Kolmogorov turbulence

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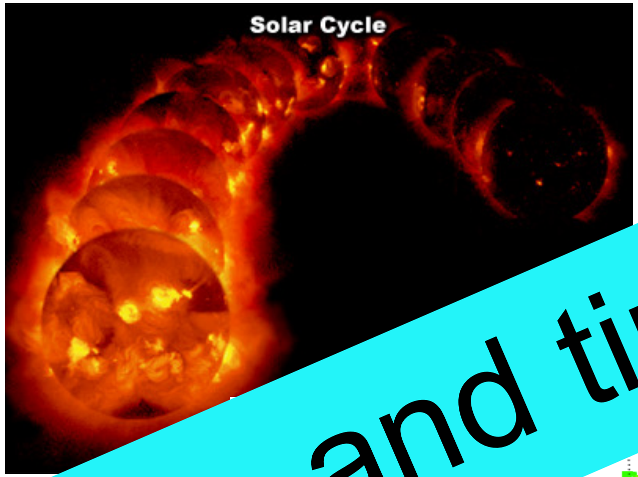
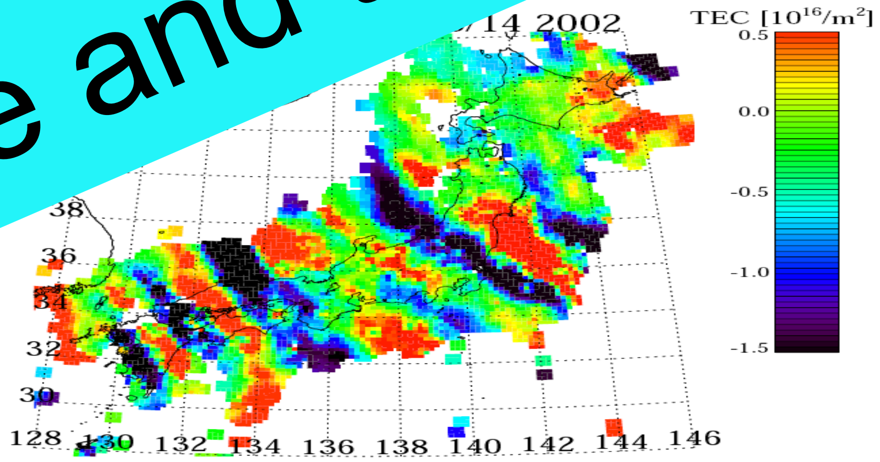
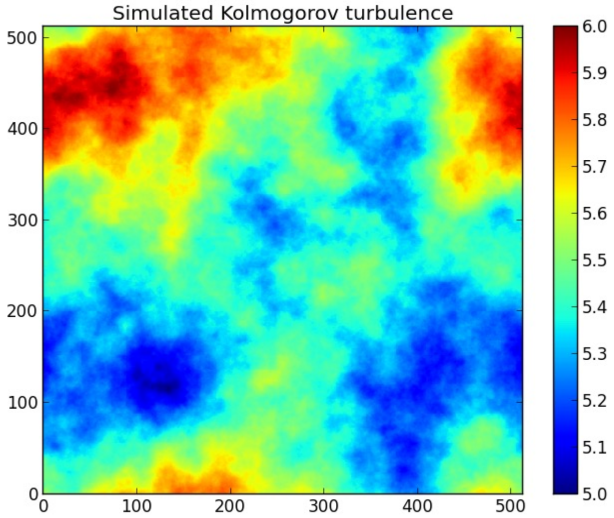
- When observing: tracking through the ionosphere

Varies a lot in space and time!







Electromagnetic Propagation

Total integrated propagation delay

$$\Phi_{\text{ion}} = -\frac{2\pi\nu}{c}\int_{\text{LoS}} (n-1)\ \mathrm{d}l.$$

Refractive index in ionized plasma

Approximation for frequencies well above the plasma frequency

$$n \approx 1 - \frac{q^2}{8\pi^2 m_e \epsilon_0}\cdot\frac{n_e}{\nu^2} \pm \frac{q^3}{16\pi^3 m_e^2 \epsilon_0}\cdot\frac{n_e B\cos\theta}{\nu^3} - \frac{q^4}{128\pi^4 m_e^2 \epsilon_0^2}\cdot\frac{n_e^2}{\nu^4} - \frac{q^4}{64\pi^4 m_e^3 \epsilon_0}\cdot\frac{n_e B^2(1+\cos^2\theta)}{\nu^4},$$

Appleton–Hartree equation (Taylor expansion)

Credits: F. de Gasperin

Electromagnetic Propagation

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Approximation for frequencies well above the plasma frequency

Refractive index in ionized plasma

$$n \approx 1 -$$

1st order: dispersive phase delay

$\Delta\phi = 8.45e9\ \mathrm{dTEC}/\nu$

2nd order: Faraday Rotation

3rd order

(LBA <50MHz)

$\Delta\phi \sim 1/\nu^3$

$$- \cancel{\frac{q^4}{64\pi^4 m_e^3 \epsilon_0} \cdot \frac{n_e B^2 (1 + \cos^2\theta)}{\nu^4}},$$

Appleton–Hartree equation (Taylor expansion)

Electromagnetic Propagation

Calibration: Jones matrices

$$\begin{pmatrix} G_{xx} & G_{xy} \\ G_{yx} & G_{yy} \end{pmatrix} = \begin{pmatrix} cos(\alpha) & sin(\alpha) \\ -sin(\alpha) & cos(\alpha) \end{pmatrix} \cdot \begin{pmatrix} G_{xx} & 0 \\ 0 & G_{yy} \end{pmatrix}$$

Refractive index in ionized plasma

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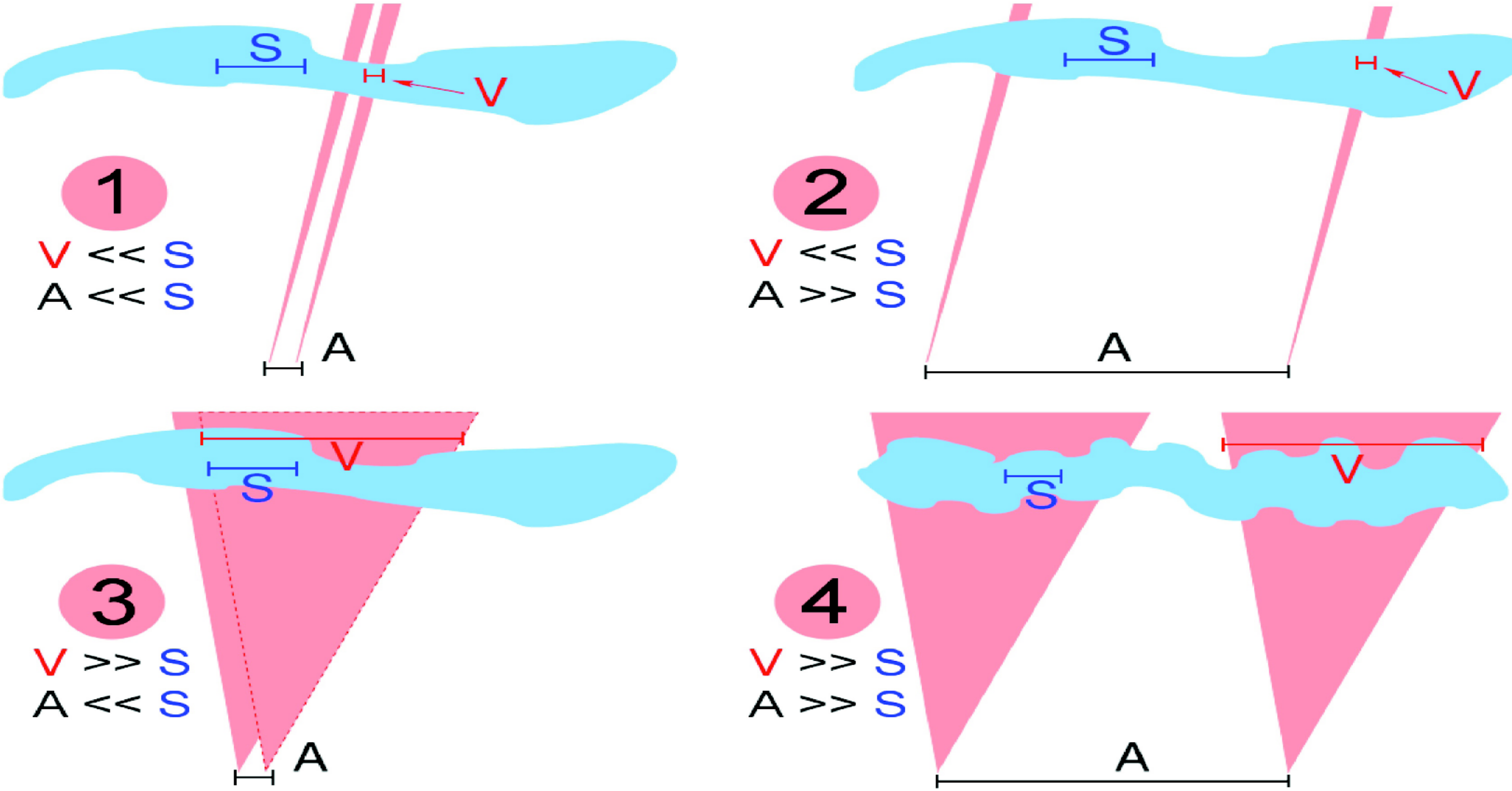
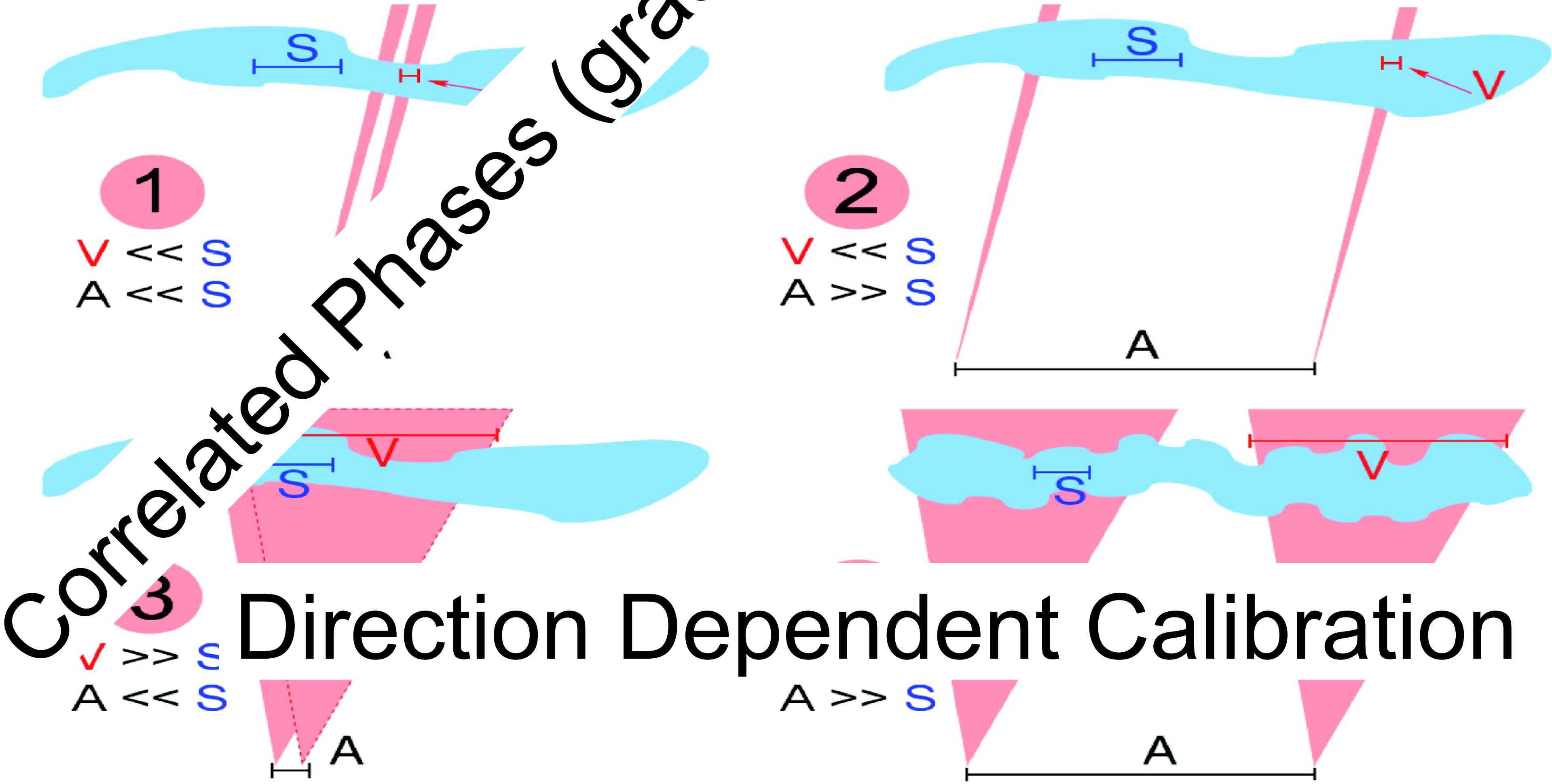
Phase effects



Lonsdale (2005)

Phase effects

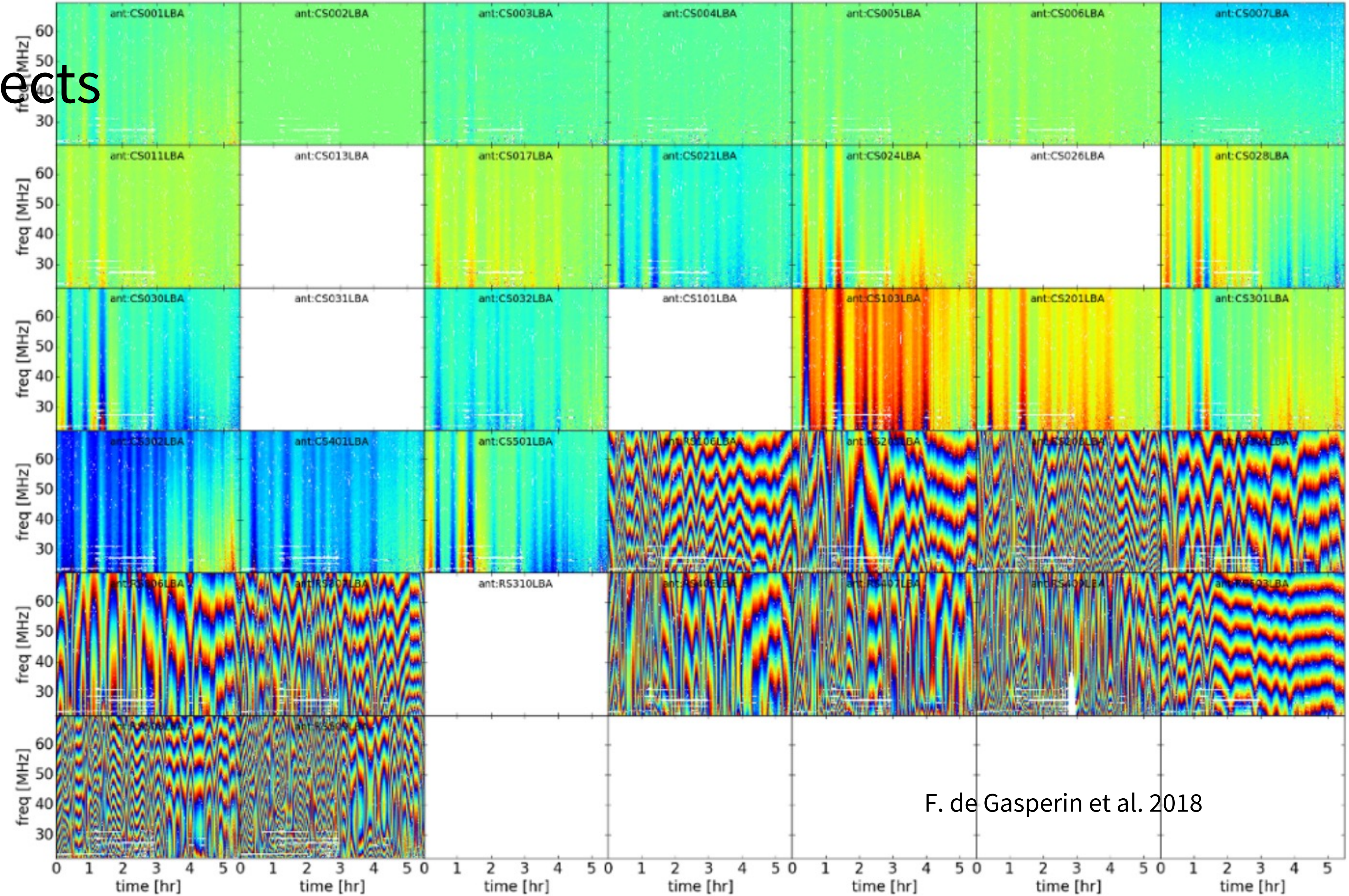


Correlated Phases (gradients)

Direction Dependent Calibration

Lonsdale (2005)

Phase effects

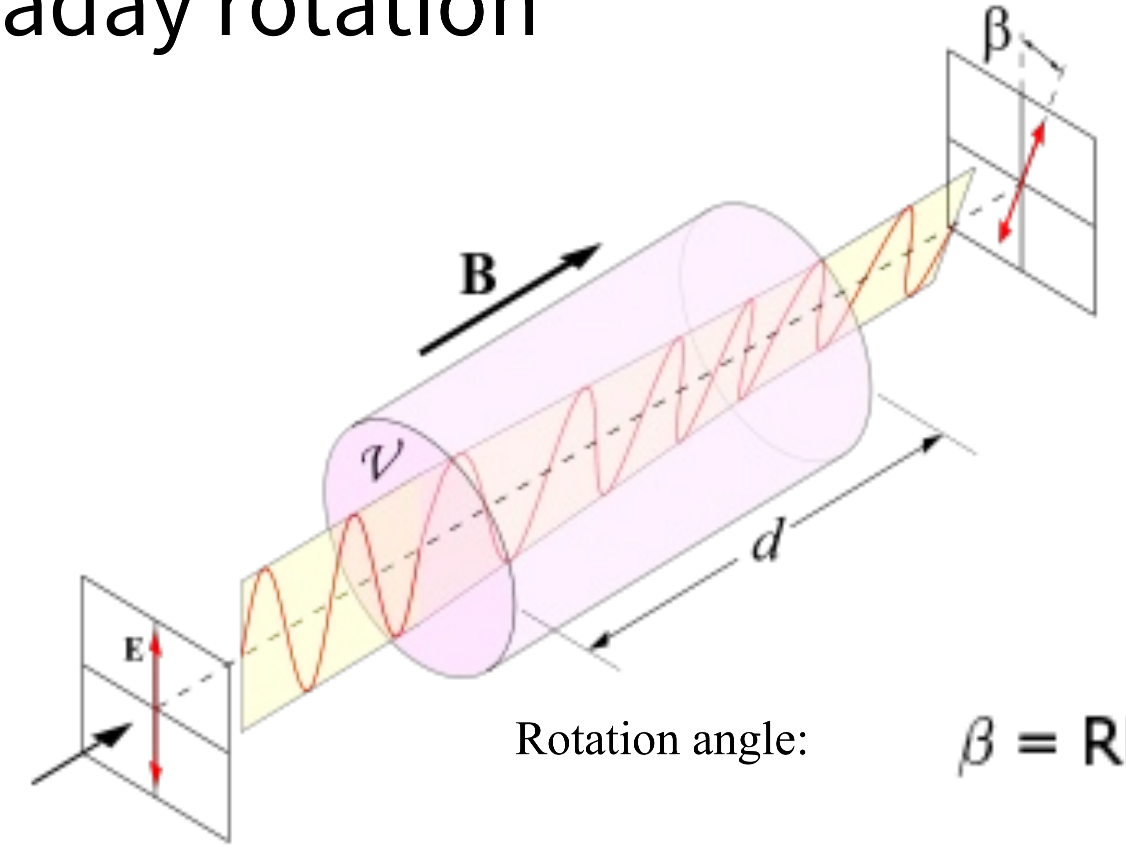


F. de Gasperin et al. 2018

Polarisation Effects

See Polarimetry Lecture (M. Brentjens) on Wednesday

Faraday rotation



Plasma + magnetic field:
phase shift between right and left circular components

Equivalently:
Rotation of linearly polarized components

Rotation angle:

$$\beta = \mathrm{RM}\,\nu^{-2}\ ,\ \mathrm{RM} = \frac{e^3}{8\pi^2\epsilon_0 m^2 c^3}\int_0^d n_e(s)B_{||}(s)ds$$

Image credits: wikimedia commons

Differential Faraday Rotation

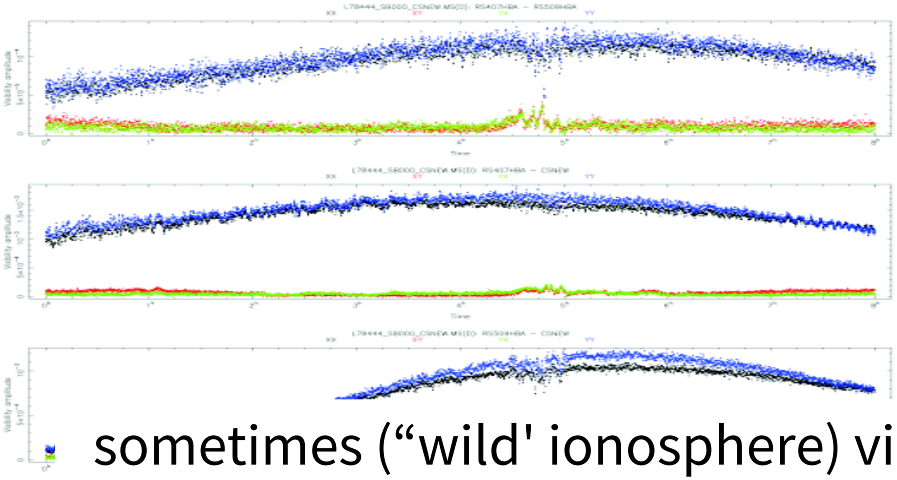
Thin layer approximation: $RM_{iono} = TEC \cdot B_{||}$
Different LOS: dTEC and $dB_{||} \rightarrow$ dRM
Rotation of the signal from XX,YY to XY,YX due to different Faraday rotation angles for different antennas

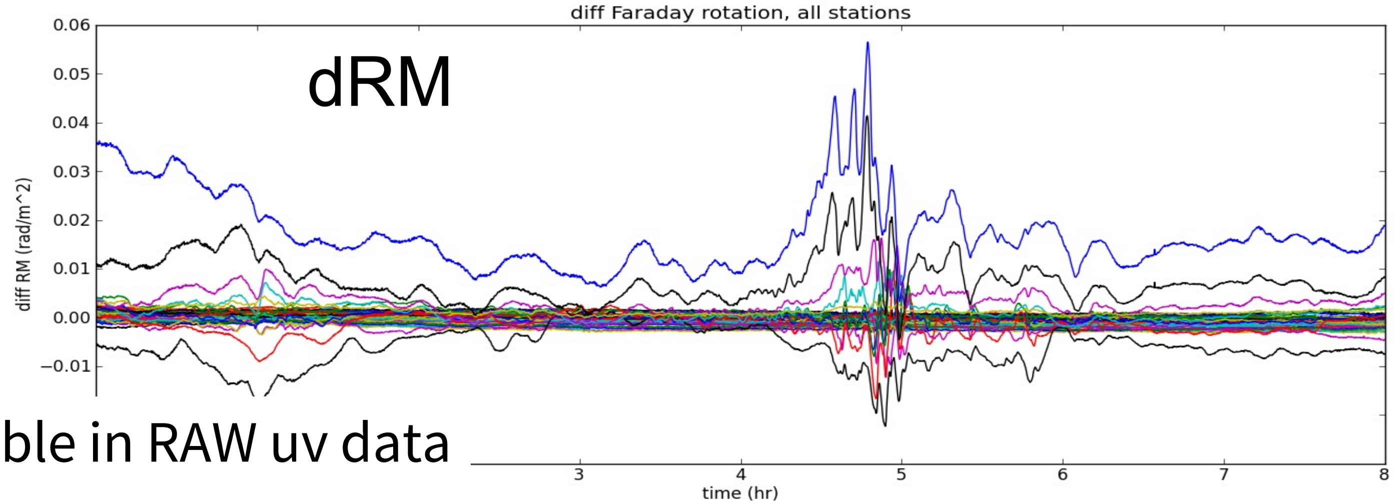
>100MHz: small rotation most of the time
<100MHz: significant effect

Selfcal: either

- solve full polarization matrix
- diagonal gains + 1 rotation matrix
- convert to circular polarization:

difference in R and L phases gives Faraday rotation angle





- sometimes (“wild' ionosphere) visible in RAW uv data

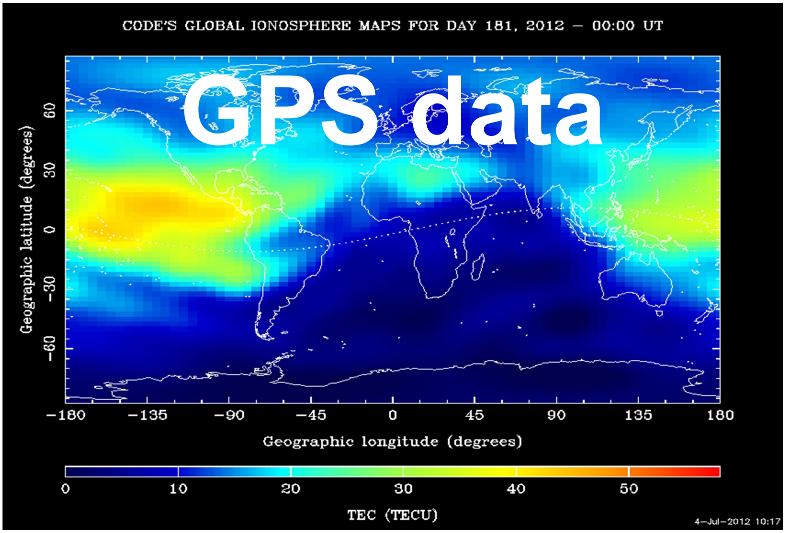
Faraday rotation: Polarised emission

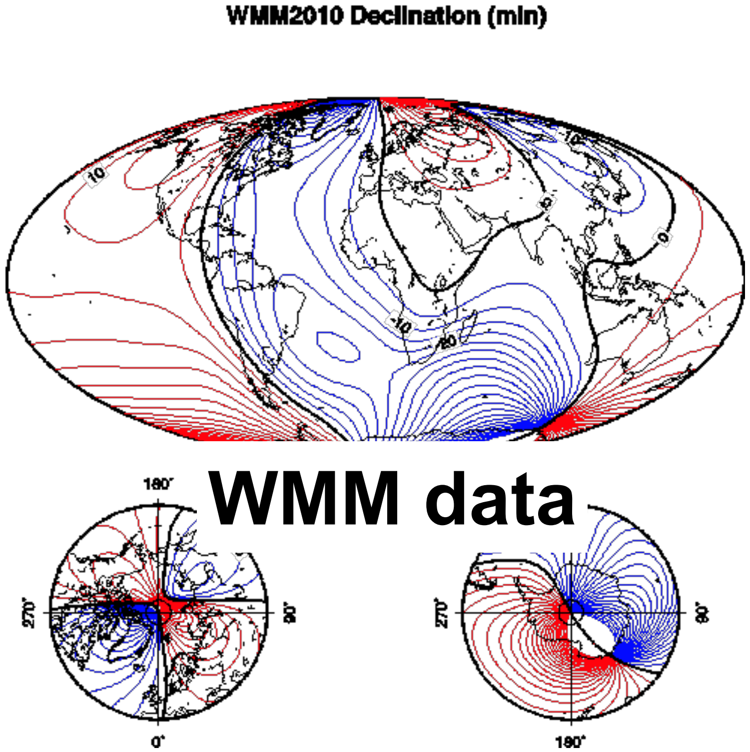
Polarized emission

Time variability of ionospheric Faraday rotation causes depolarization

Model RM_{iono} by combining geomagnetic and ionospheric models

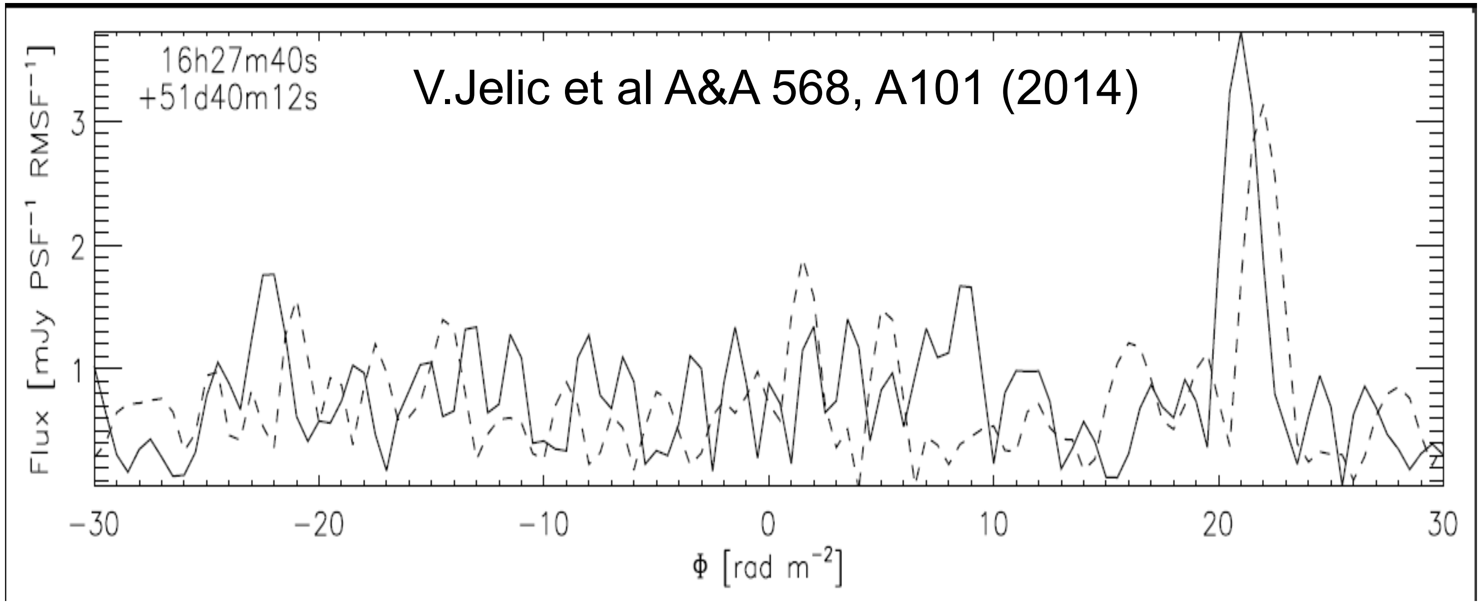
Eg: https://github.com/lofar-astron/RMextract



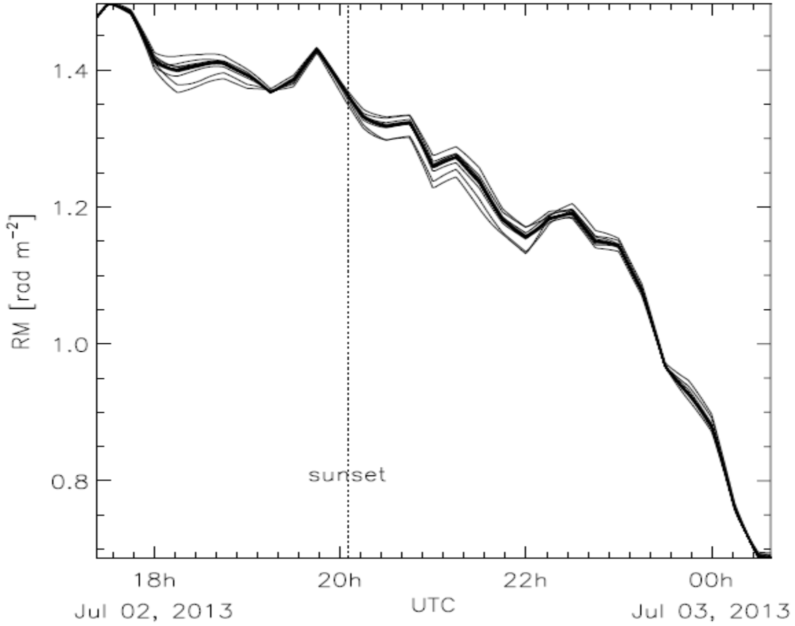


Thin layer approximation: $RM_{iono} = TEC \cdot B_{||}$

Faraday rotation: Polarised emission



V.Jelic et al A&A 568, A101 (2014)



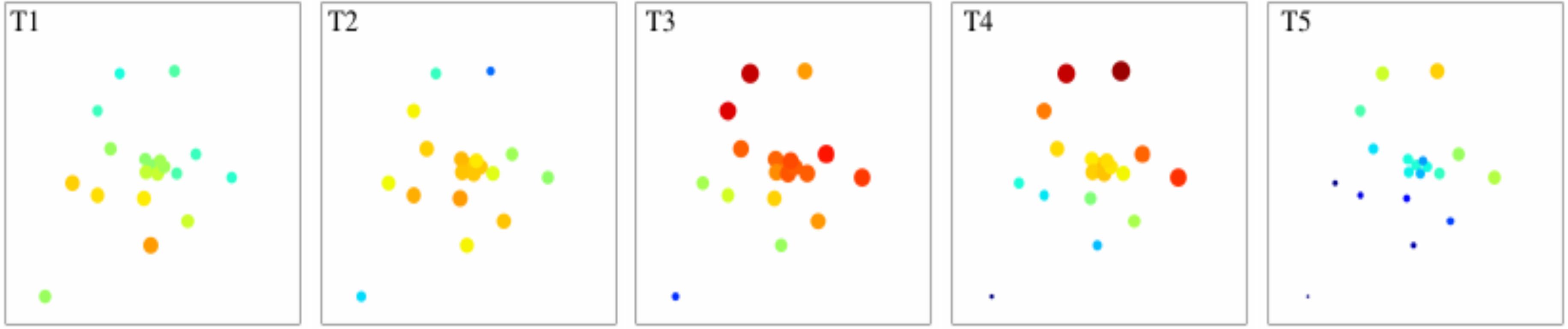
Polarized Flux before (dashed) and after (solid) RM correction

Ionospheric RM corrections versus time

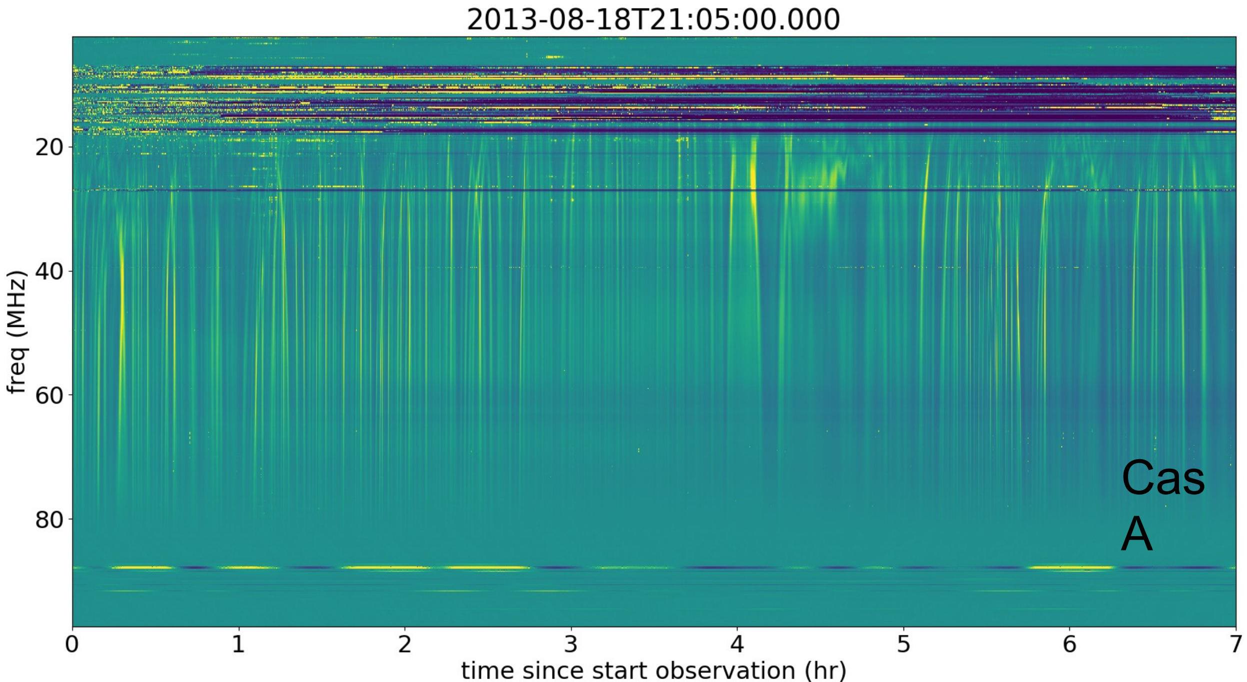
Thin layer approximation: $\mathbf{RM_{iono} = TEC \cdot B_{||}}$

Amplitude Effects

Amplitude solutions LOFAR CORE (3km)



F. de Gasperin et al. 2018



Amplitude scintillation:

Due to lensing effect (Fresnel scale: ~2 km @LOFAR)

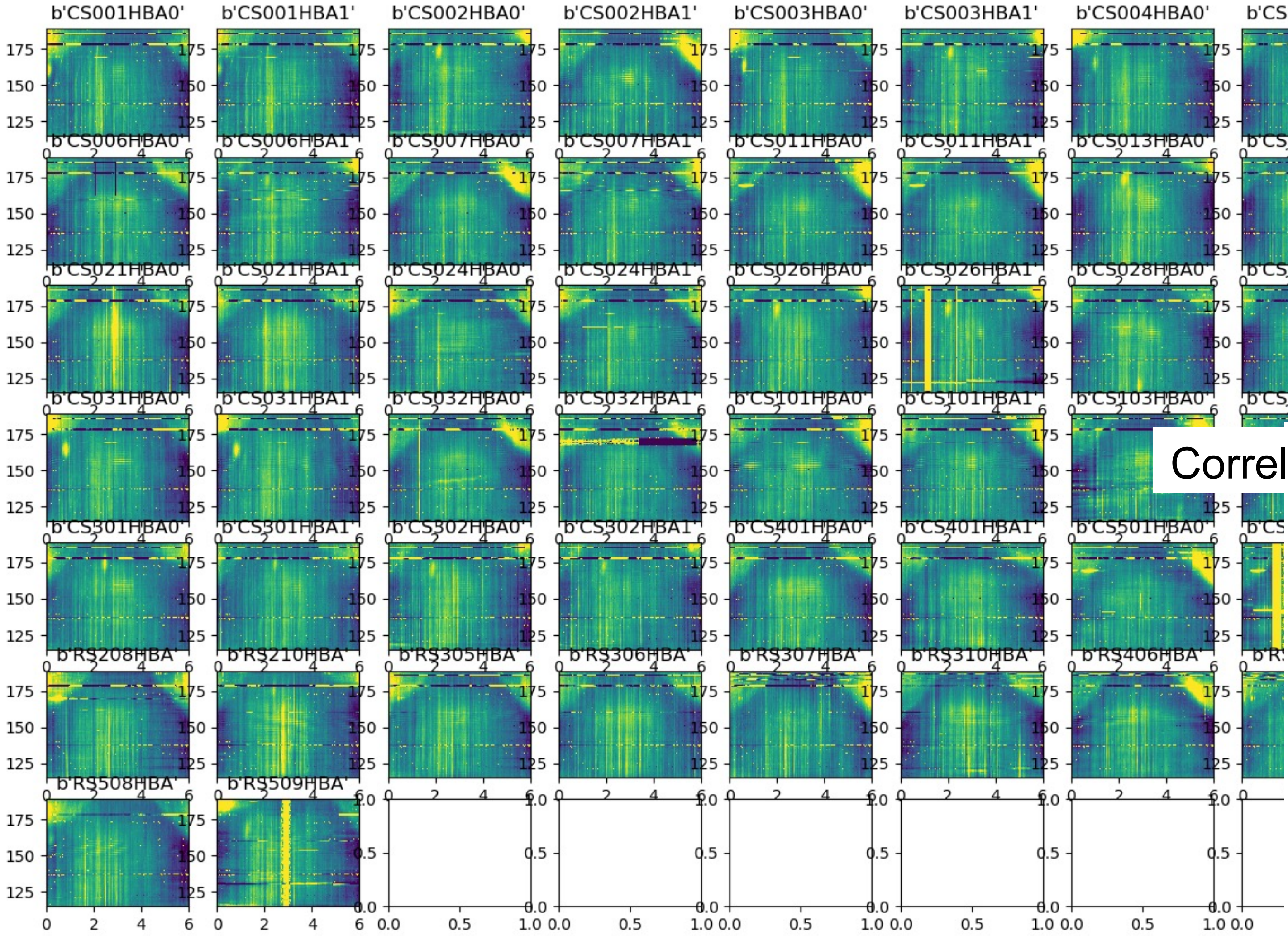
Rapid varying station amplitudes

DI calibration

FOV variations?

Excellent diagnostic tool for ionospheric conditions

Characterization of the ionosphere: Autocorrelations of the calibrator (3C196, HBA)



Correlate CS data (<3km) to find delays → velocity

Single snapshot, baseline dx, dy, delay (color)

Conclusion

- When doing radio astronomy @ low frequencies, you cannot ignore the ionosphere
- Mainly phase effect
- Variations in time, frequency and space
- You need to choose your calibration strategy well
  - Time, frequency solution interval
  - Transfer of calibrator solutions not sufficient → selfcal on target
- Rapid DD phase calibration necessary in many cases
- Polarised emission can be precorrected for ionospheric Faraday rotation using external data

Tutorial

- Download lofim.def, put it in an empty directory cd to that directory
- Start docker: sudo service docker start
- Check: docker ps
    - If you get permission denied : try sudo chmod 666 /var/run/docker.sock
- Build image: docker build -t lofim_soft -f lofim.def ./ (this will take about an hour!)

Hopefully these first steps were already completed

- cd to directory with notebooks and materials (ionospheric_effects)
- Run image with docker: run -it -v $PWD:/data -p 8000:8000 lofim_soft
- cd /data && jupyter lab --ip 0.0.0.0 --port 8000 --no-browser --allow-root
- Open browser: open link from terminal
- Start notebook (Ionospheric Phase Effects.ipynb)