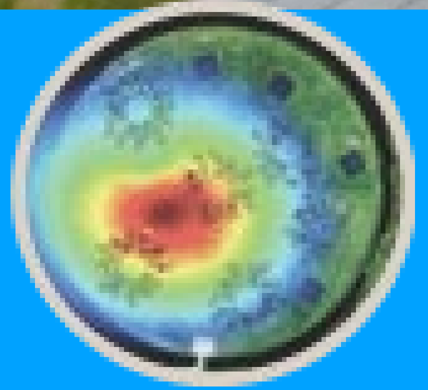
AST(RON
Netherlands Institute for Radio Astronomy

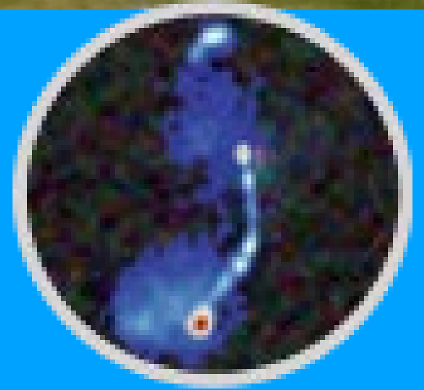
STELLAR

LOFAR

IONOSPHERIC EFFECTS

M. Mevius





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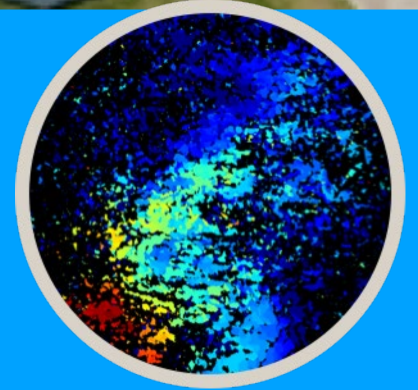


IONOSPHERE

What is the ionosphere 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

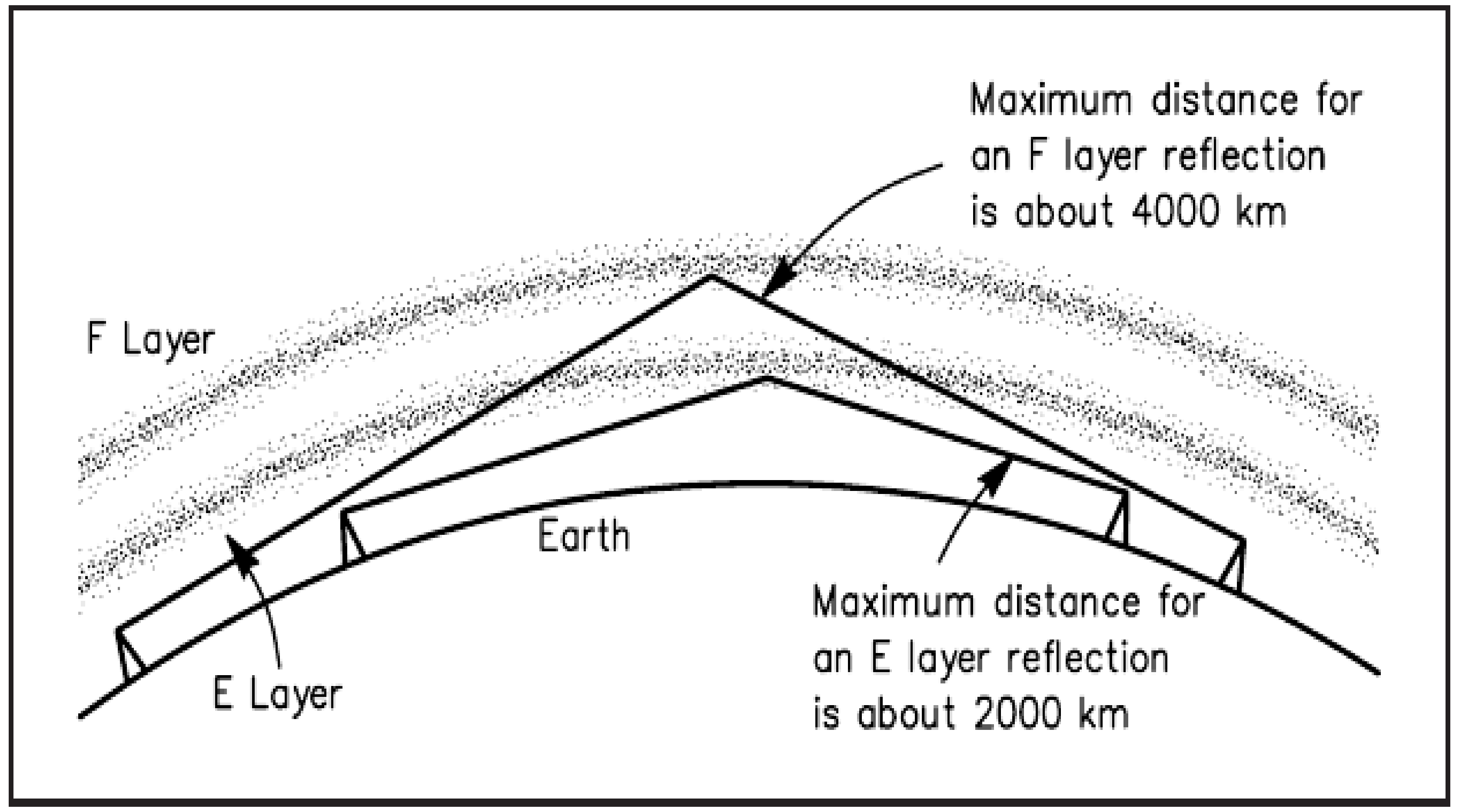
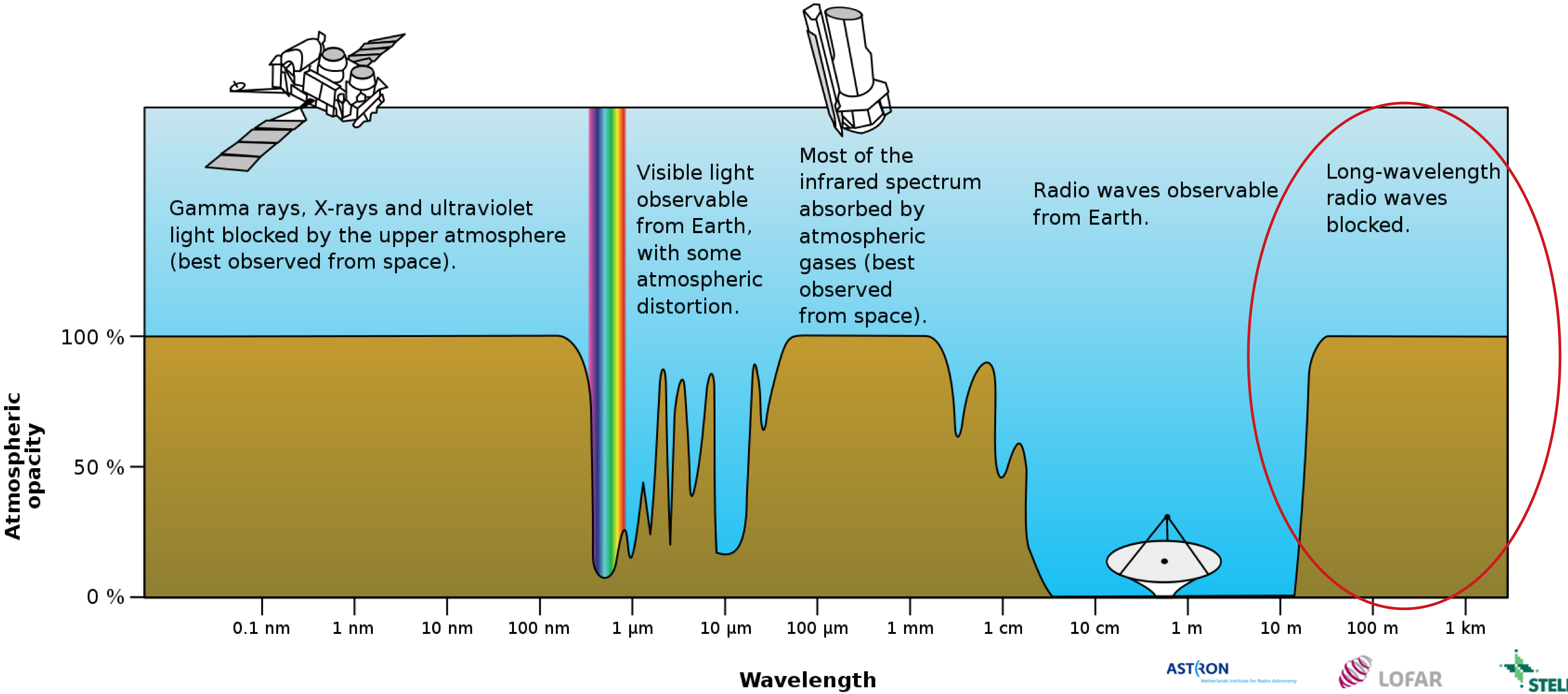


Figure 6—Signals reflected by the E and F layers.

Ian Poole, G3YWX

Electromagnetic spectrum

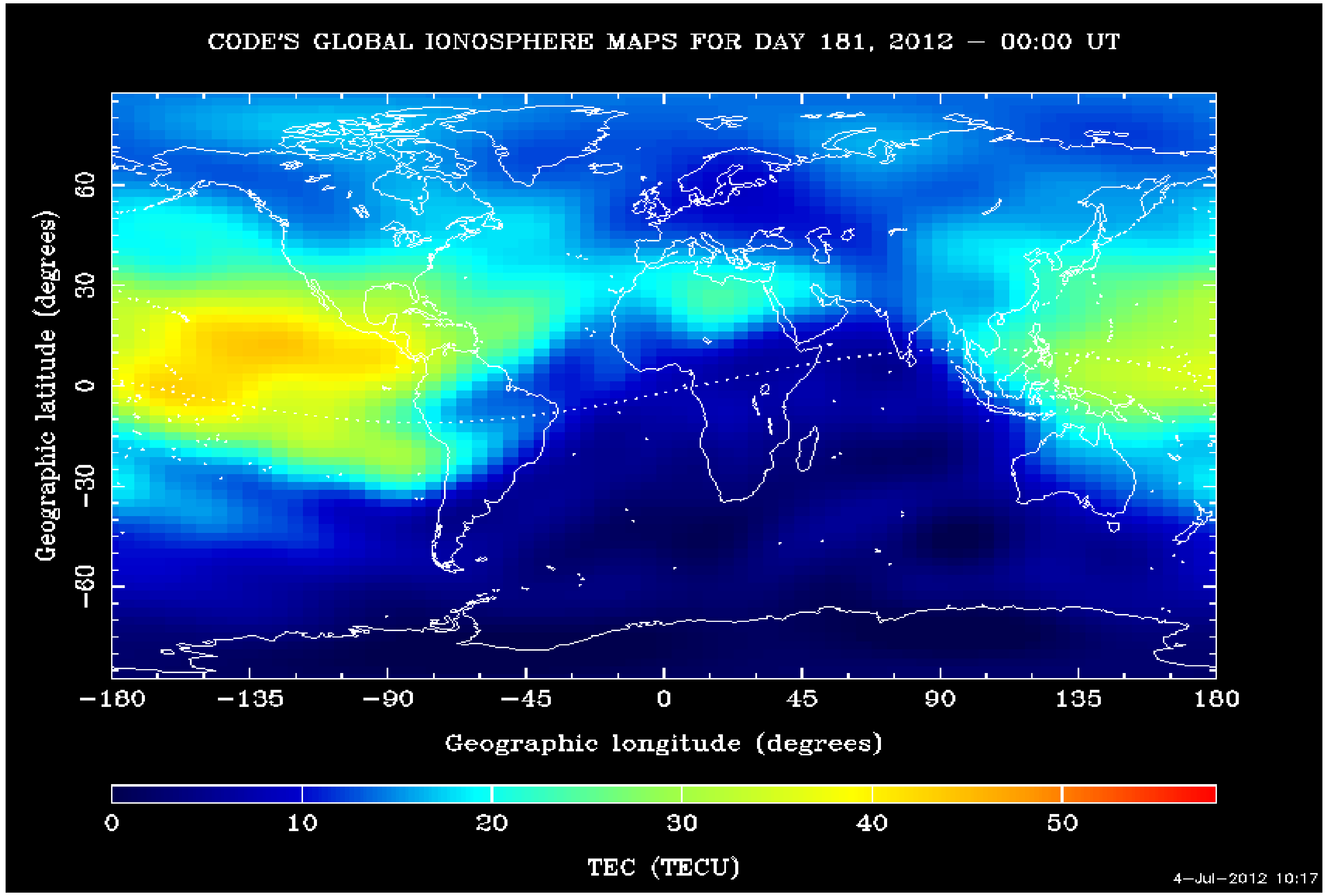


ASTRON LOFAR STELLAR

Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

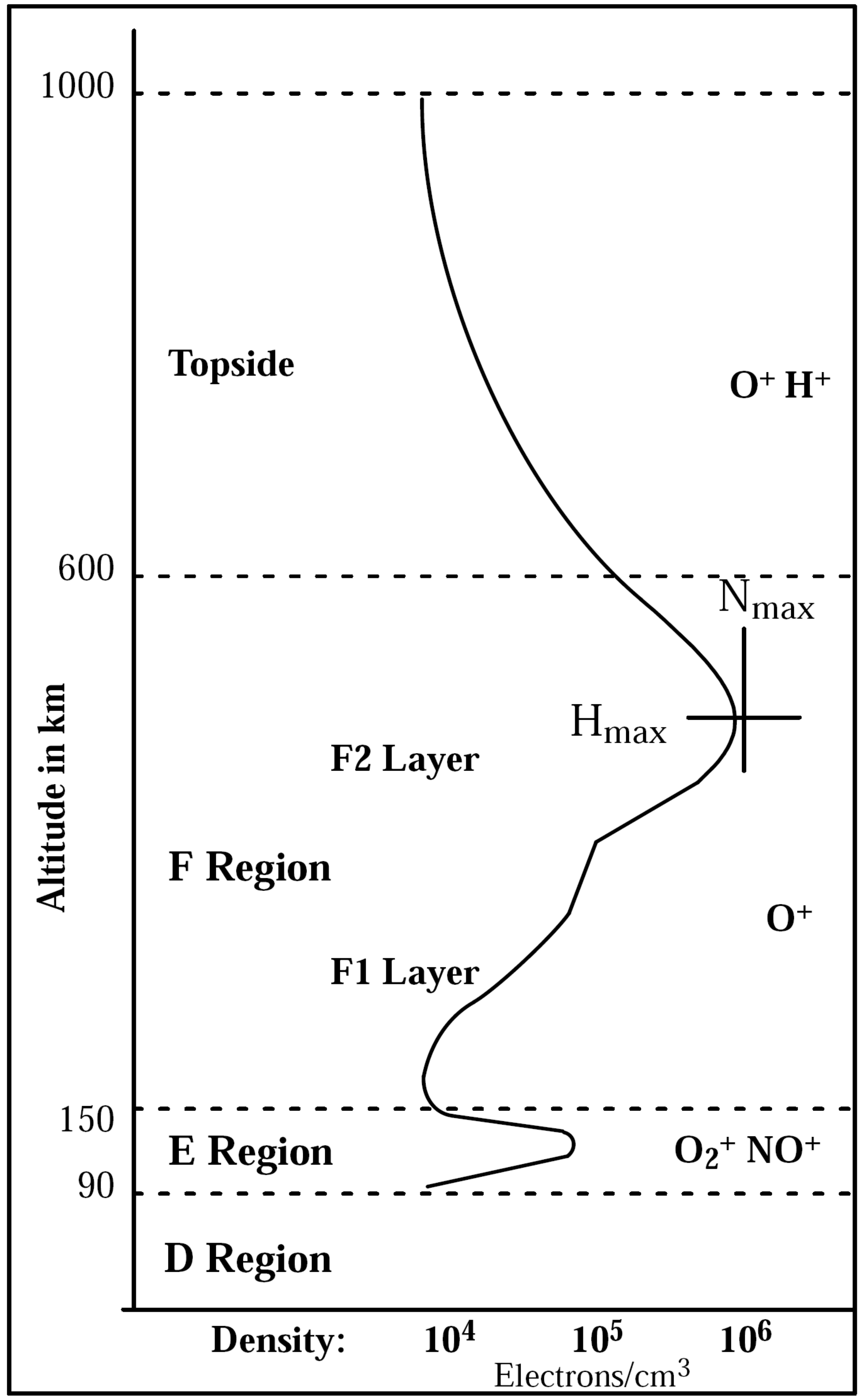
Measurements

Electron density/ Total integrated electron density
(TECU: 10^16 e-/m^2)



GPS data: online electron densitiy maps
thin layer approximation

Typical electron density profile

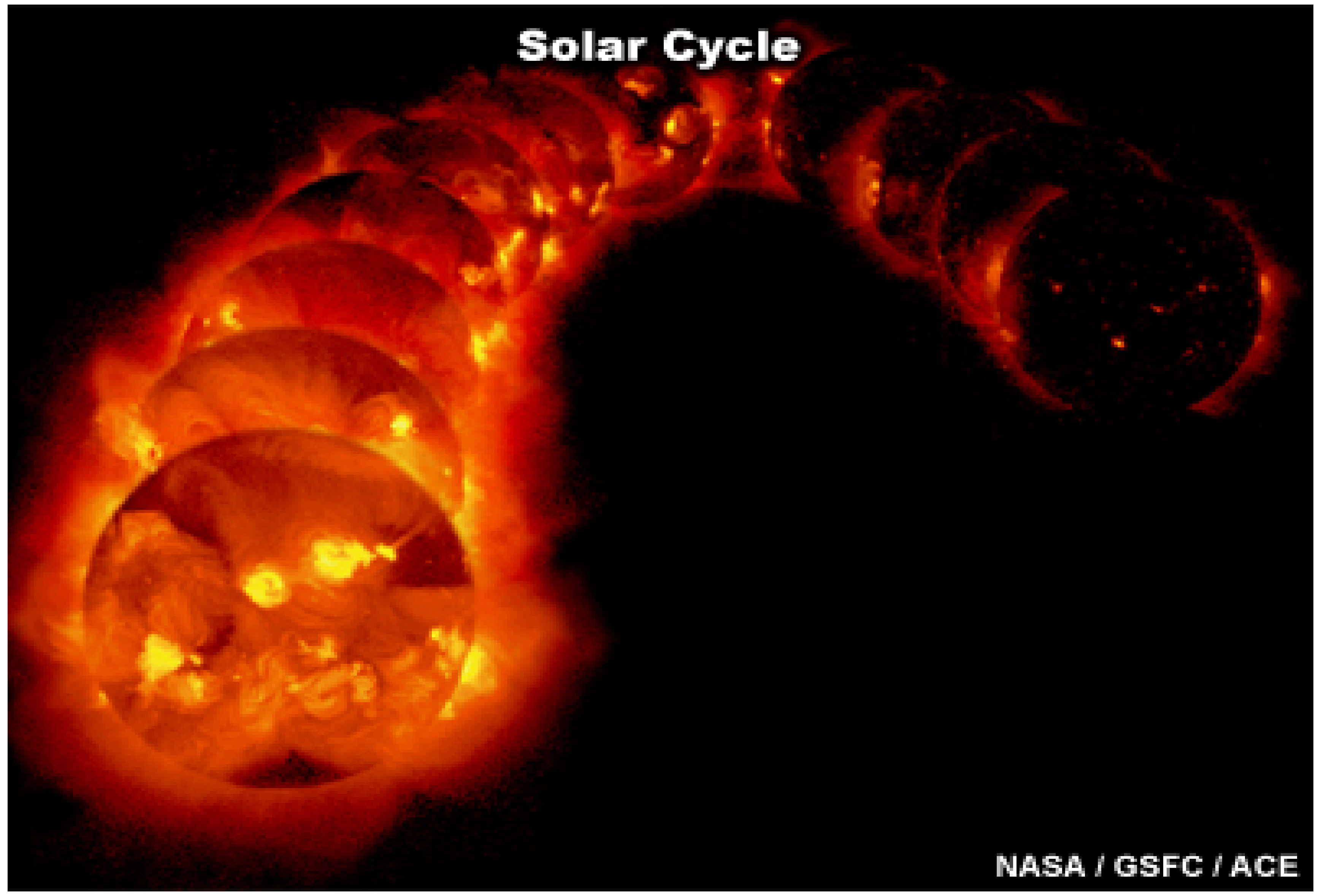


Variability

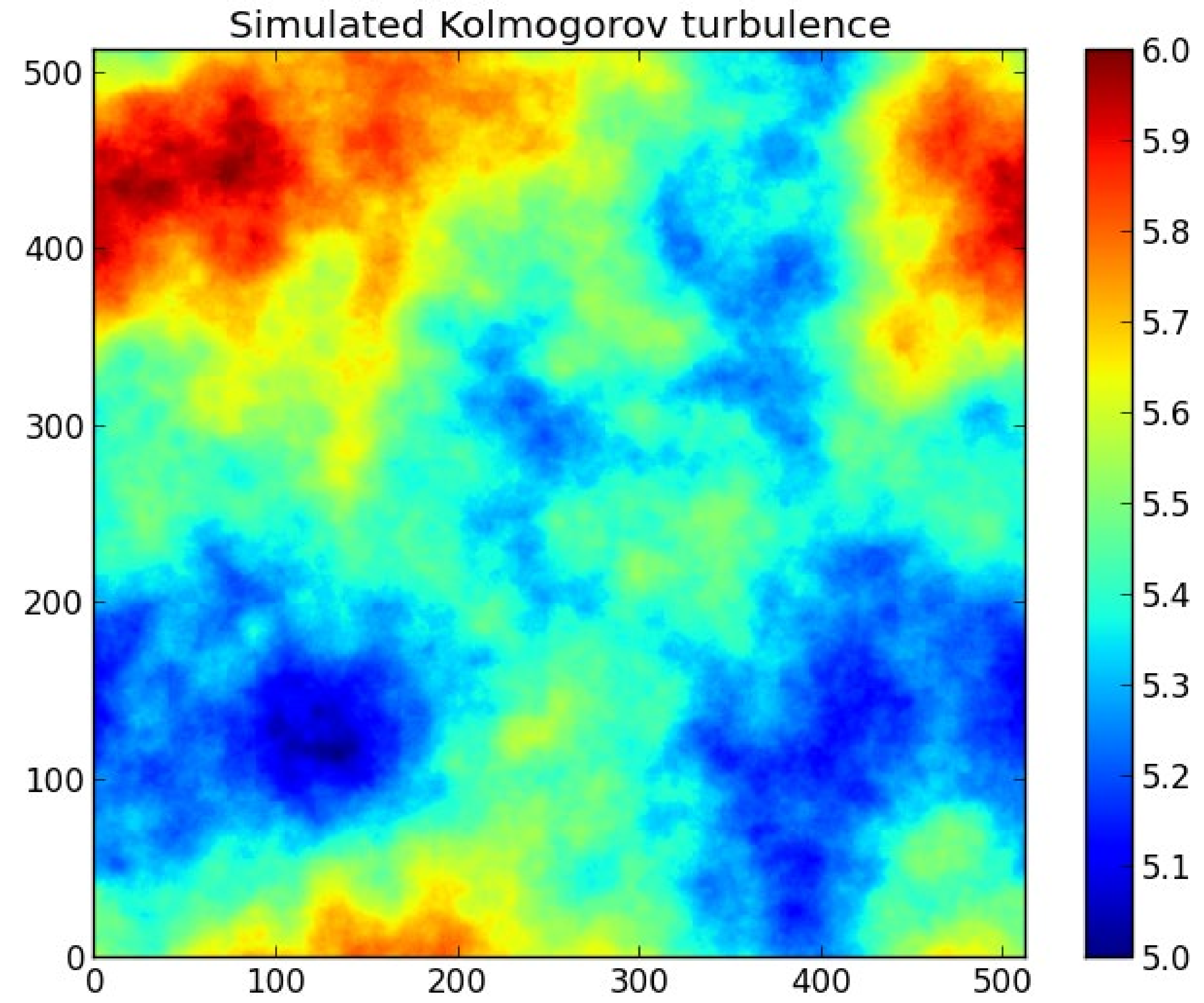
The ionosphere is highly dynamic:

- Ionization through solar radiation (UV+X-ray)
- Recombination at night
  - → diurnal pattern large gradients @ dusk and dawn
- Scintillation (high turbulence):(mostly) after sunset

Solar cycle



Turbulence



Traveling Ionospheric Disturbances (TIDs)

Small Scale Structures:

Kolmogorov turbulence

Structures moving with speeds ~ few 100 km/hr

When observing: tracking through the ionosphere

Wave like structures (TIDs)

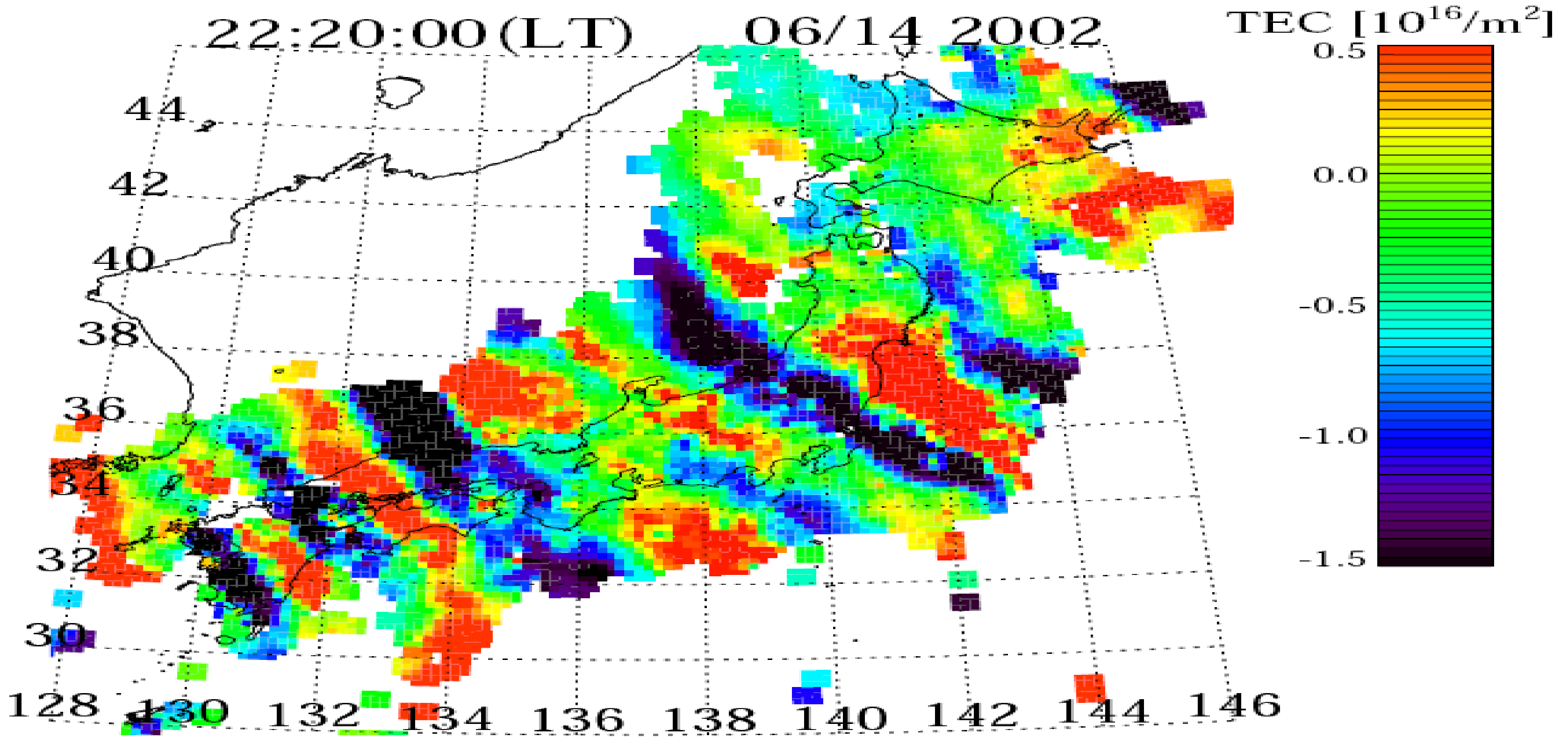


Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

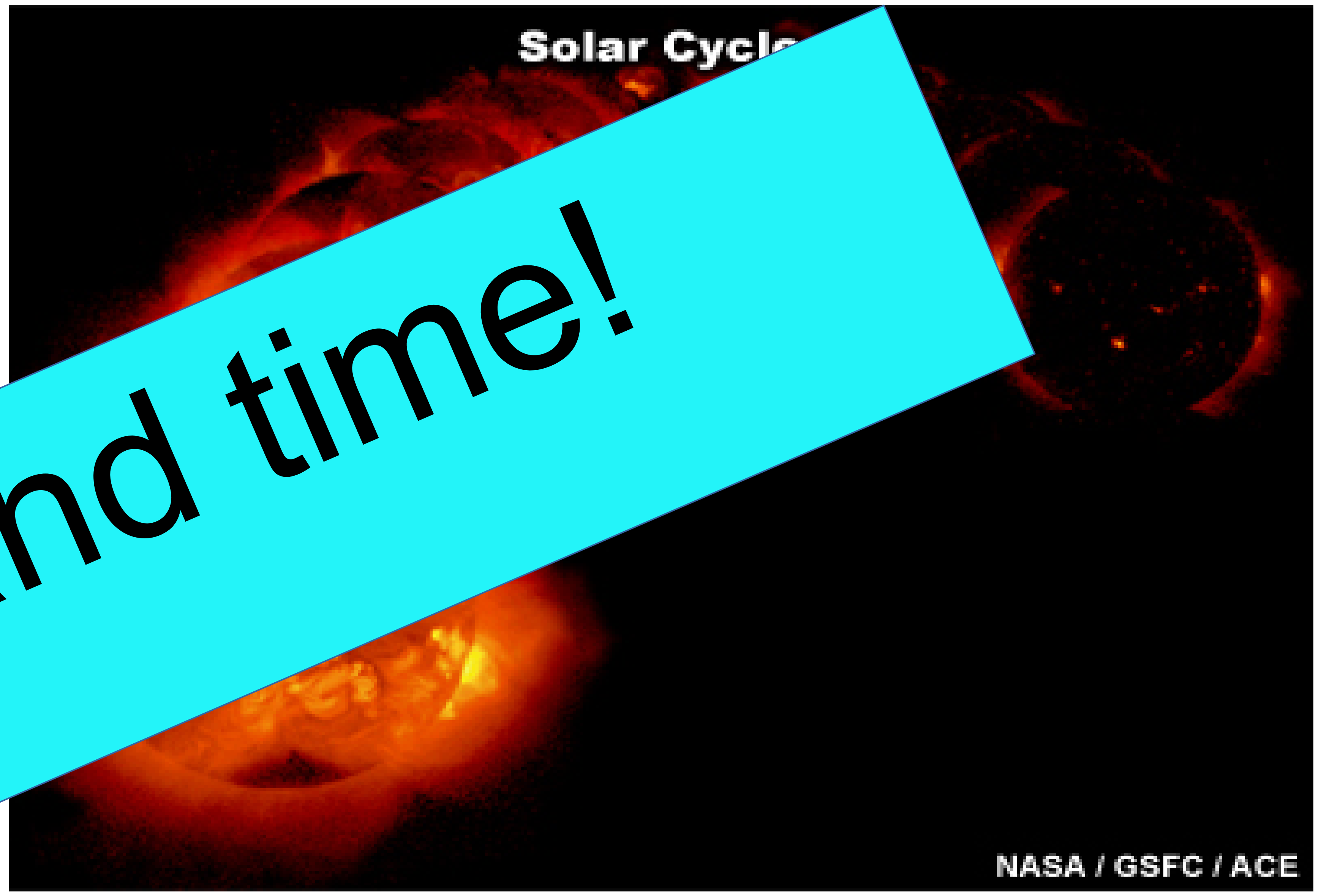
Variability

The ionosphere is highly dynamic:

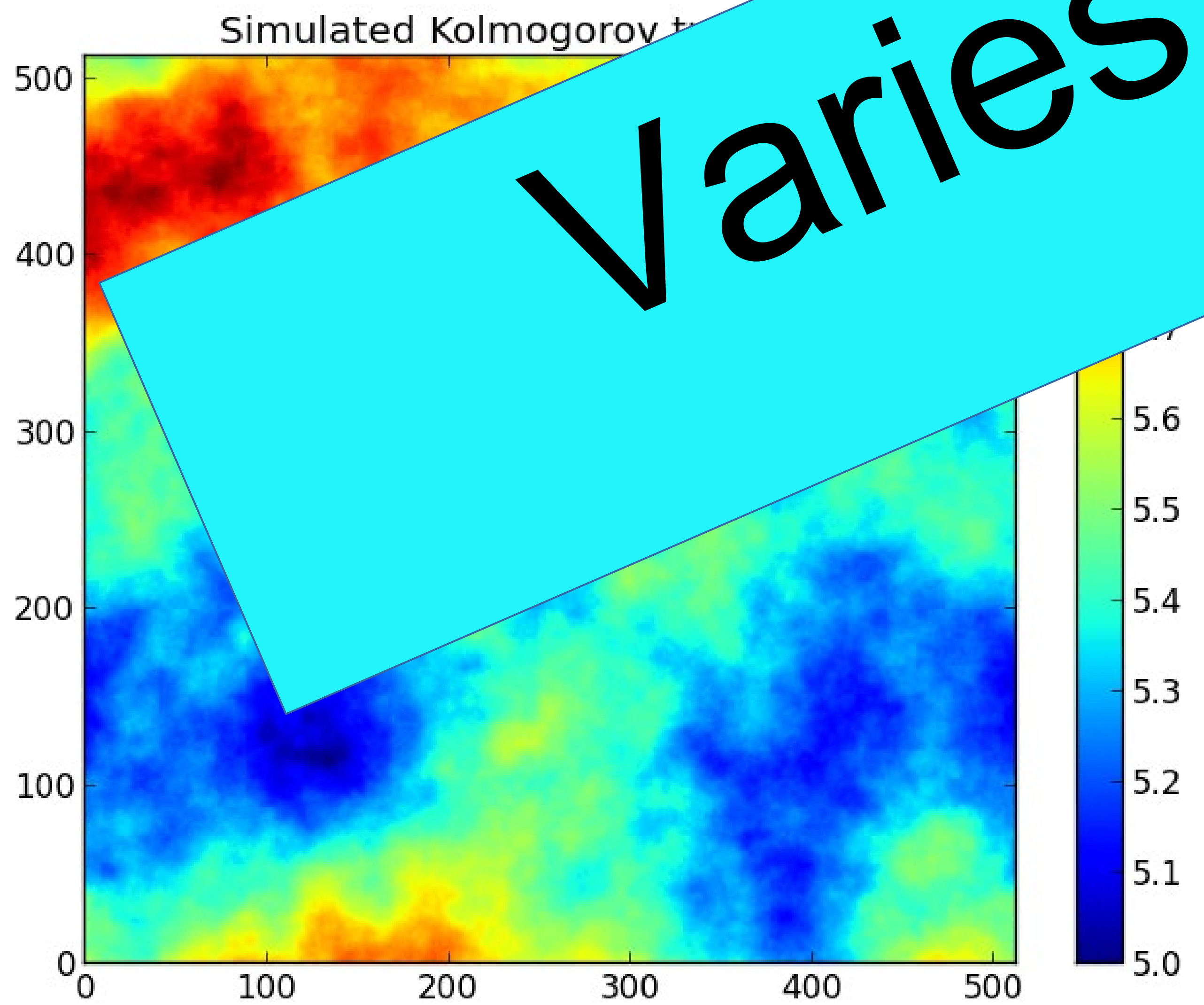
- Ionization through solar radiation (UV+X-ray)
- Recombination at night
  - → diurnal pattern large gradients @ dusk and dawn
- Scintillation (high turbulence):(mostly) after sunset

Varies a lot in space and time!

Solar cycle



Turbulence



IDs)

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olmogorov turbulence

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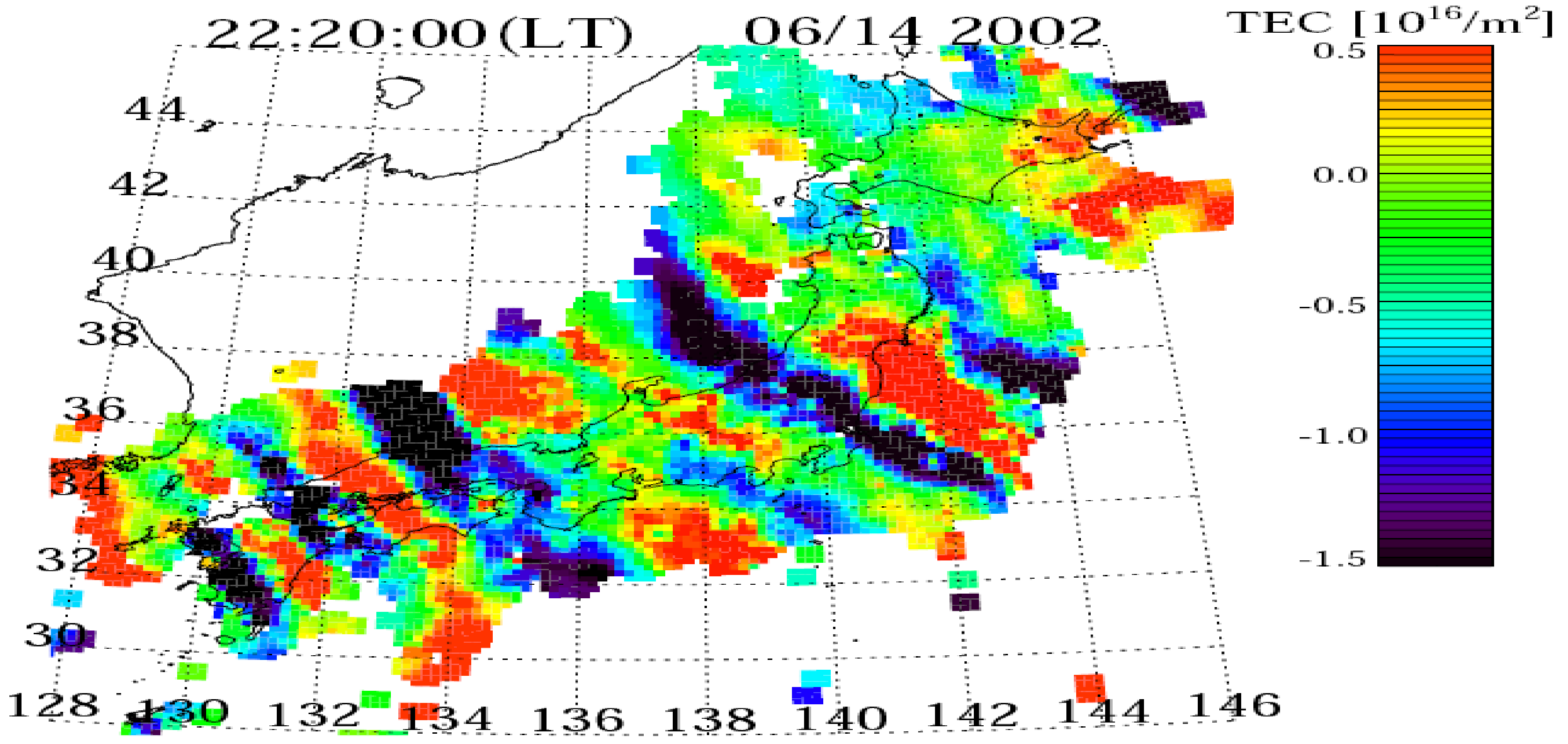

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IONOSPHERIC EFFECTS

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

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

Appleton–Hartree equation (Taylor expansion)

IONOSPHERIC EFFECTS

Total integrated propagation delay

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

Refractive index in ionized plasma

$$n \approx$$

1st order: dispersive phase delay
$\Delta\varphi = 8.45e9\ \mathrm{dTEC}/\nu$

2nd order: Faraday Rotation

$$-$$

3rd order
(LBA <50MHz)
$\Delta\varphi \sim 1/\nu^3$

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

Appleton–Hartree equation (Taylor expansion)

Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

IONOSPHERIC EFFECTS

Calibration: Jones matrices

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

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Appleton–Hartree equation (Taylor expansion)

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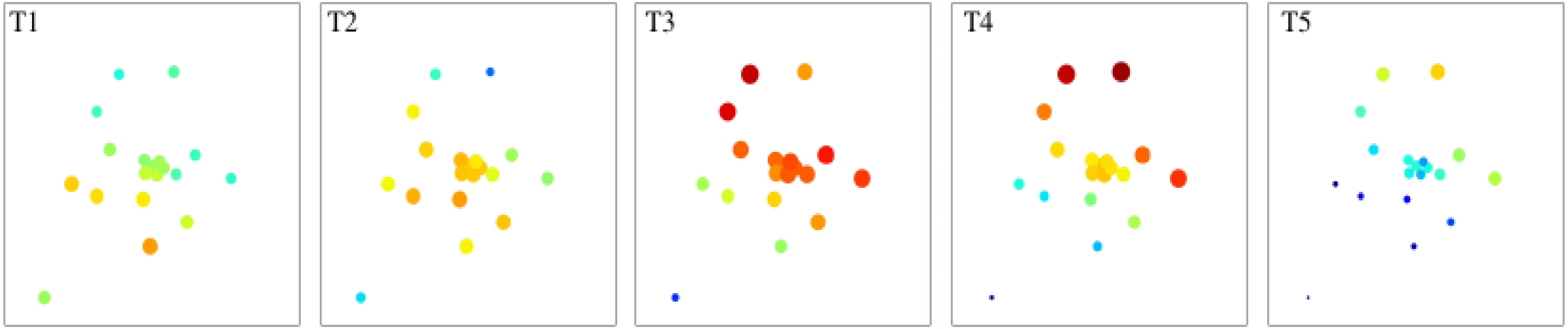
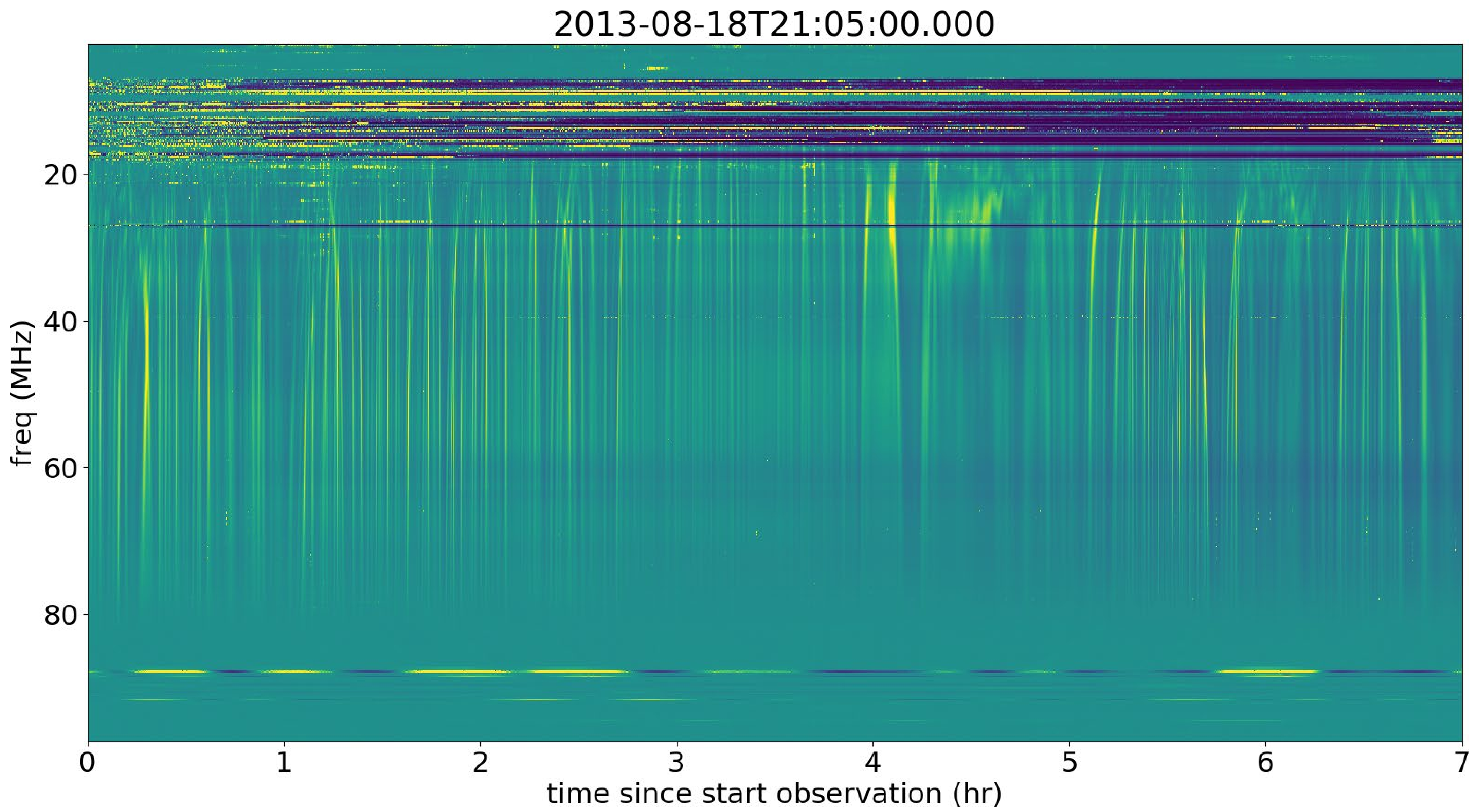
Other effects

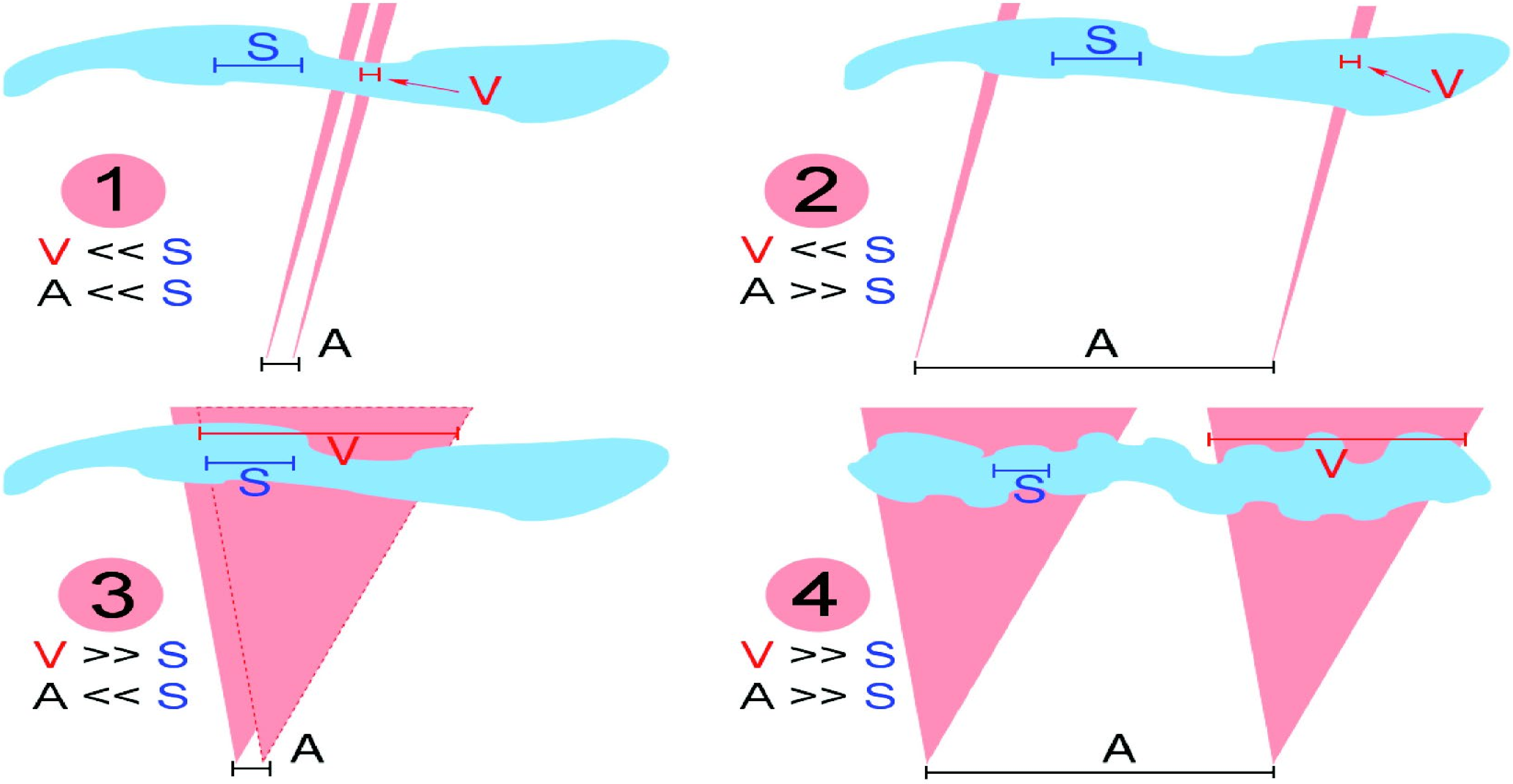




Amplitude scintillation

Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

Direction dependent effects



Lonsdale (2005)

IONOSPHERIC EFFECTS

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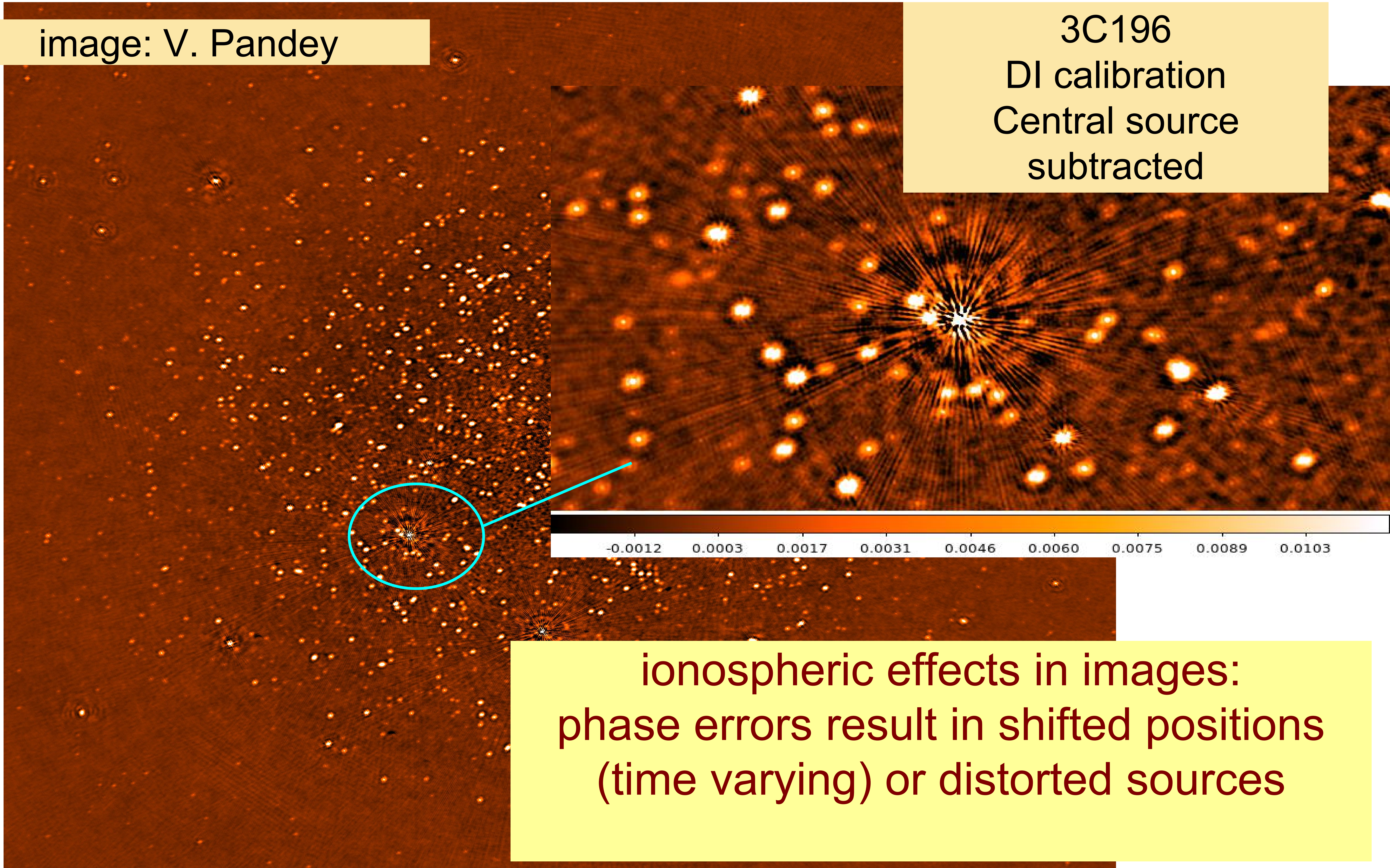
Appleton–Hartree equation (Taylor expansion)

Phase errors

image: V. Pandey



3C196
DI calibration
Central source
subtracted

ionospheric effects in images:
phase errors result in shifted positions (time varying) or distorted sources

Phase errors

interferometer measures phase differences:

- ionospheric delay only visible if the excess path length is different for signal at different receivers
- ionosphere is highly variable in space and time
- low frequency radio telescope sensitive to small ionospheric disturbances
  - with LOFAR HBA calibrator data we are able to measure ionospheric variations <0.001 TECU
  - orders of magnitude better than GPS
- differential integrated TEC of 0.2 TECU →
  - 1 full 2π rotation between 110-180 MHz (HBA)
  - 3.5 full 2π rotations between 40-80 MHz (LBA)

typical variation LOFAR (NL) 80 km: 0.5- 1TECU
within a single HBA beam: ~0.1 TECU

ASTRON Netherlands Institute for Radio Astronomy LOFAR STELLAR

Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

Clock/TEC separation (losoto tutorial this afternoon)

DI calibration phases contain different phase effects

@ LOFAR 2 dominant sources:

- drifting clock errors
- ionospheric phases

second order effects are cable reflections,beam and source model errors

Start from selfcal phases over wide frequency range.

Fit for A(clock) and B(TEC) in:

$$\Delta\phi(\nu) = A \cdot 2\pi\nu + B \cdot 8.4479745 \cdot 10^{9} / \nu$$

For LBA <40MHz third order term is also important!

LOSOTO operation CLOCKTEC

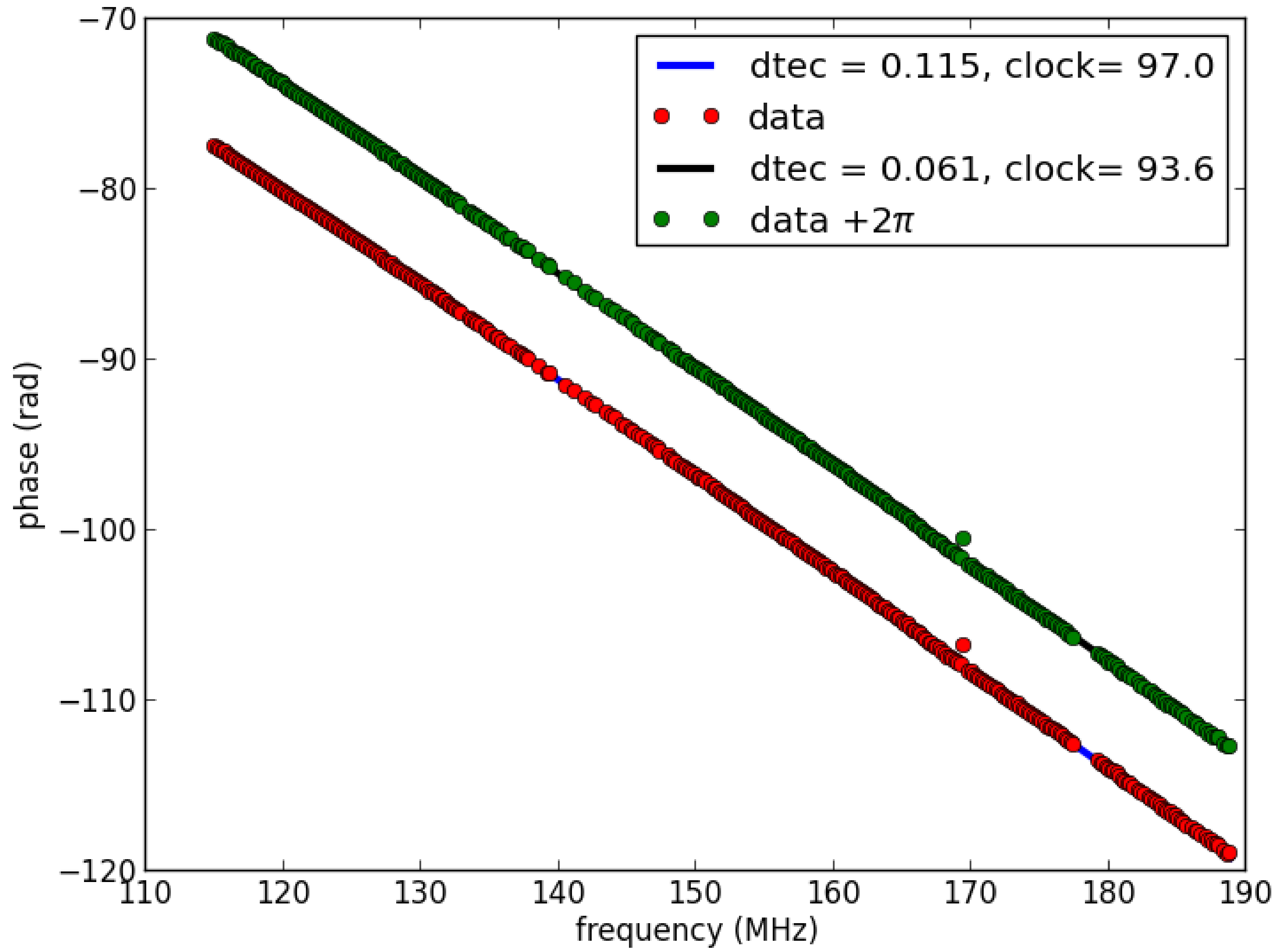
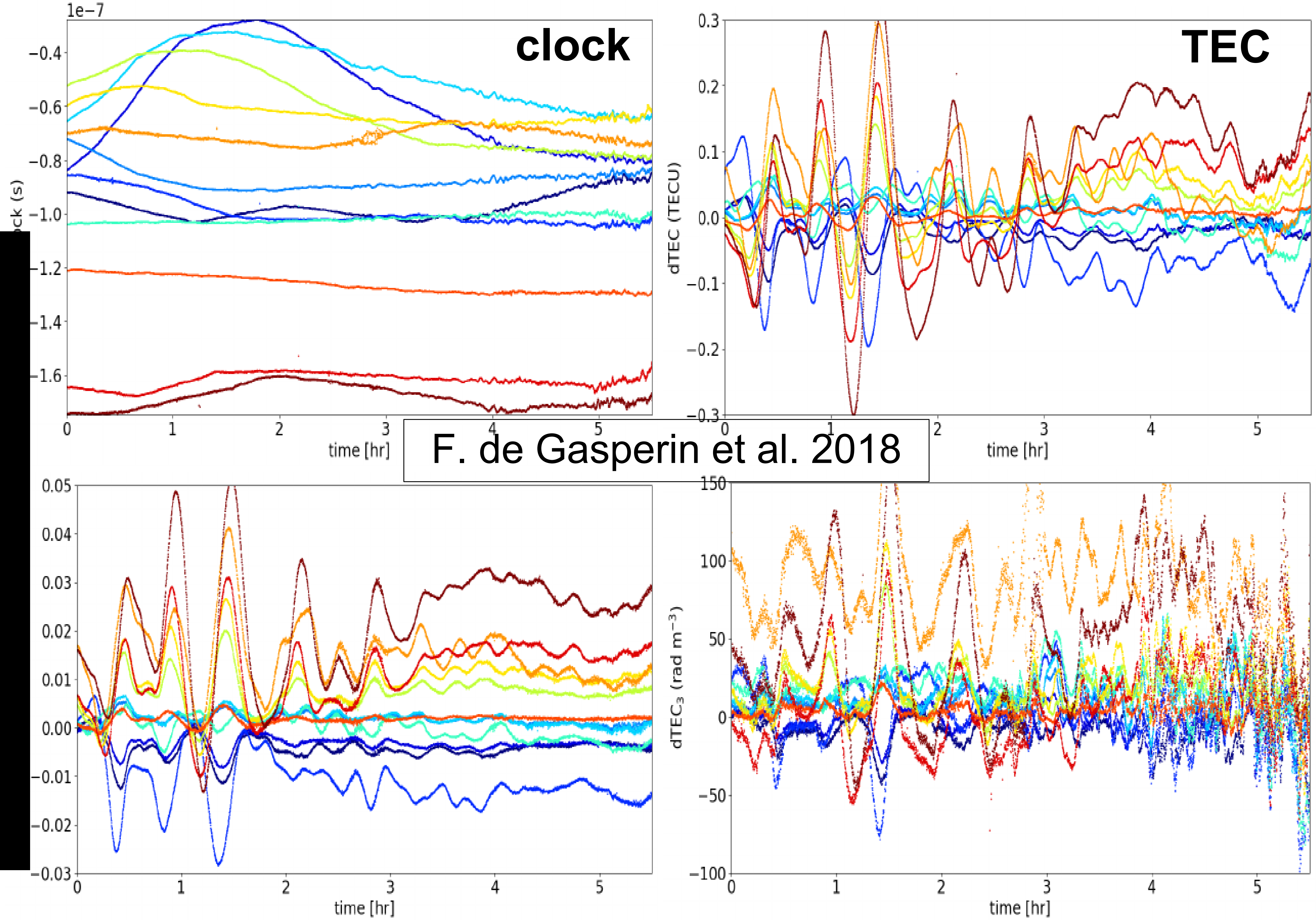


Image credits: A. Corstanje, F. Sweijen, C. van Eck, F. Zucca

Clock/TEC separation (losoto tutorial this afternoon)

Inspect your solutions



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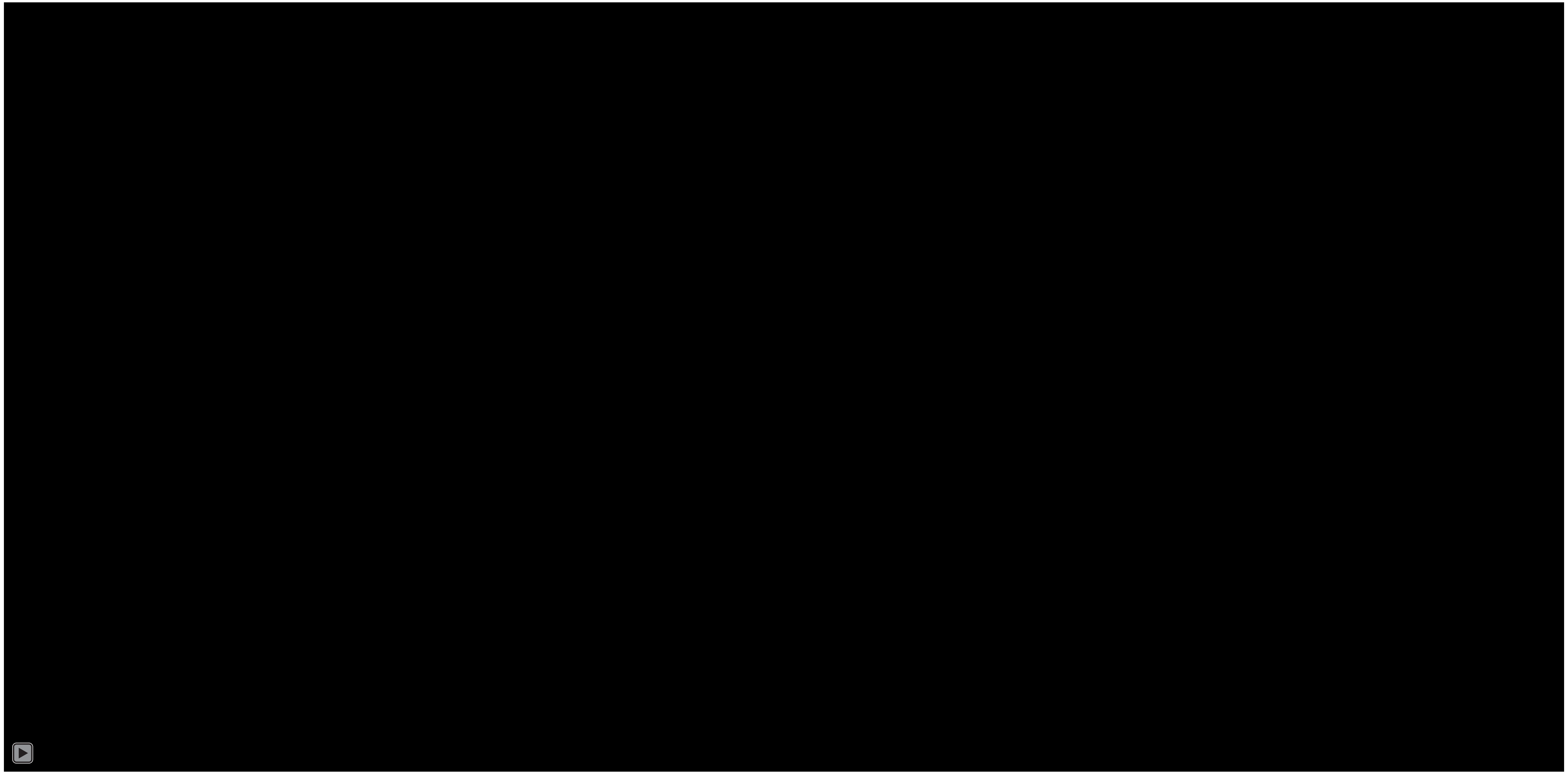
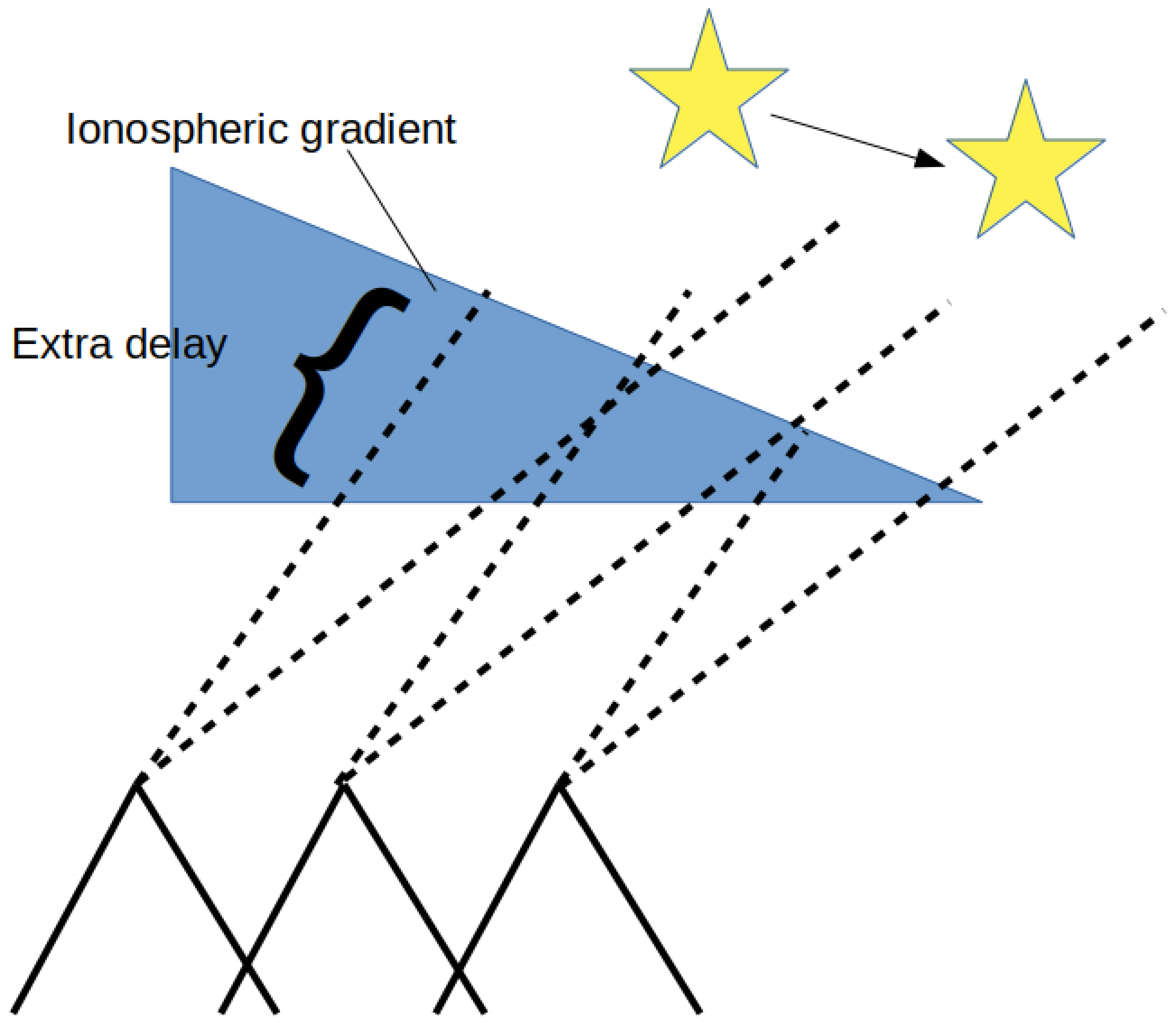
Position shifts

Ger de Bruyn



Position shifts



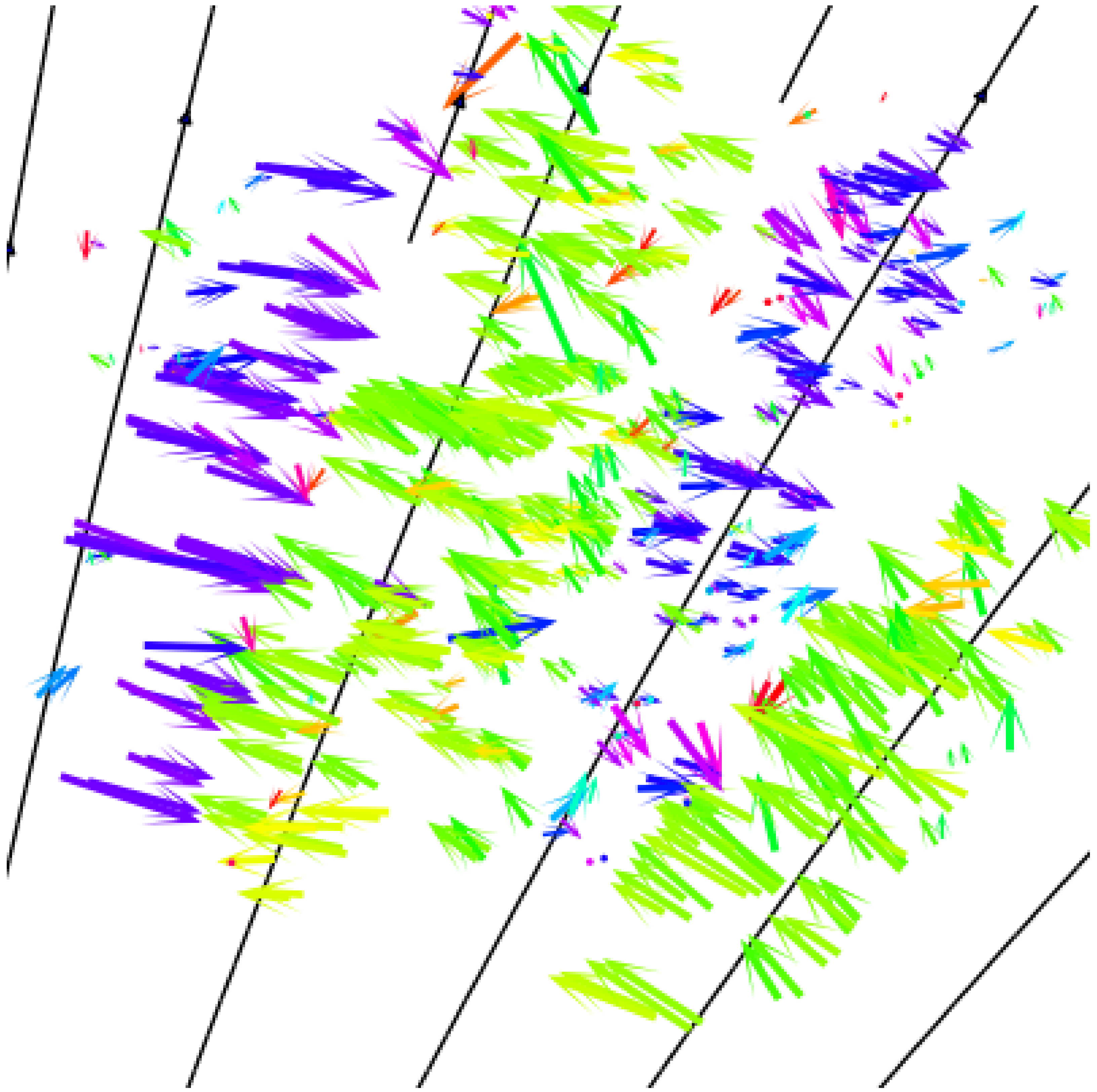
Linear TEC gradient over array mimics geometrical delay

Effective position shift of source in image

$$\Delta\theta = C/\nu^2 \, \nabla_\perp \, \mathrm{TEC}$$

Higher order TEC effects will distort the source in the image plane

7 HBA beam analysis
1minute snapshot
Color/arrow angle/size of position shift
Lines: projected magnetic field lines



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6th LOFAR Data School

IONOSPHERIC EFFECTS

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Appleton–Hartree equation (Taylor expansion)

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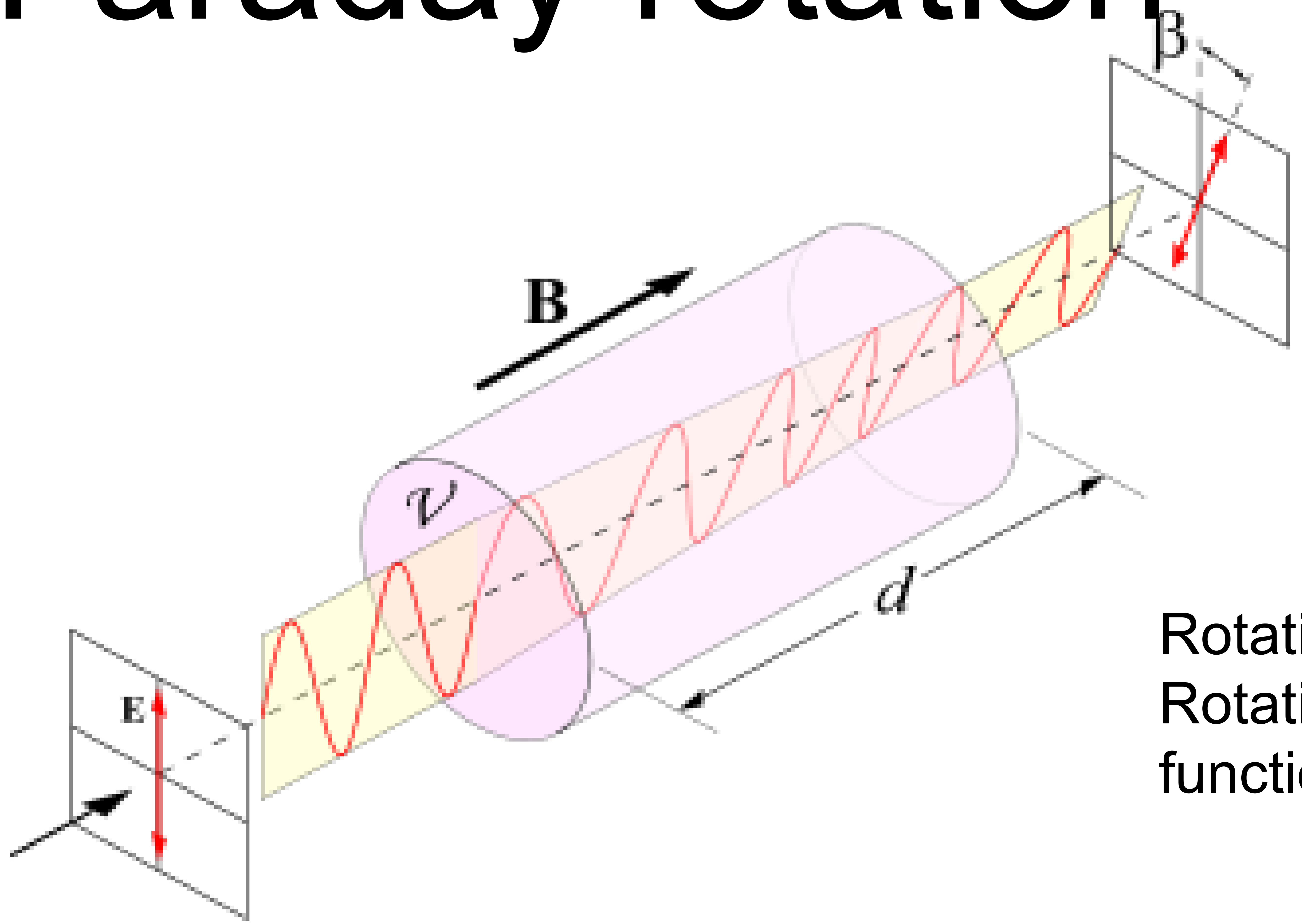
Faraday rotation



In the presence of a magnetic field:
- different refractive index for right and left circularly polarized waves
  - phase shift between right and left circular components
  - equivalently:

Rotation of linearly polarized components
Rotation Measure (RM) defines rotation angle as function of frequency

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

Differential Faraday Rotation

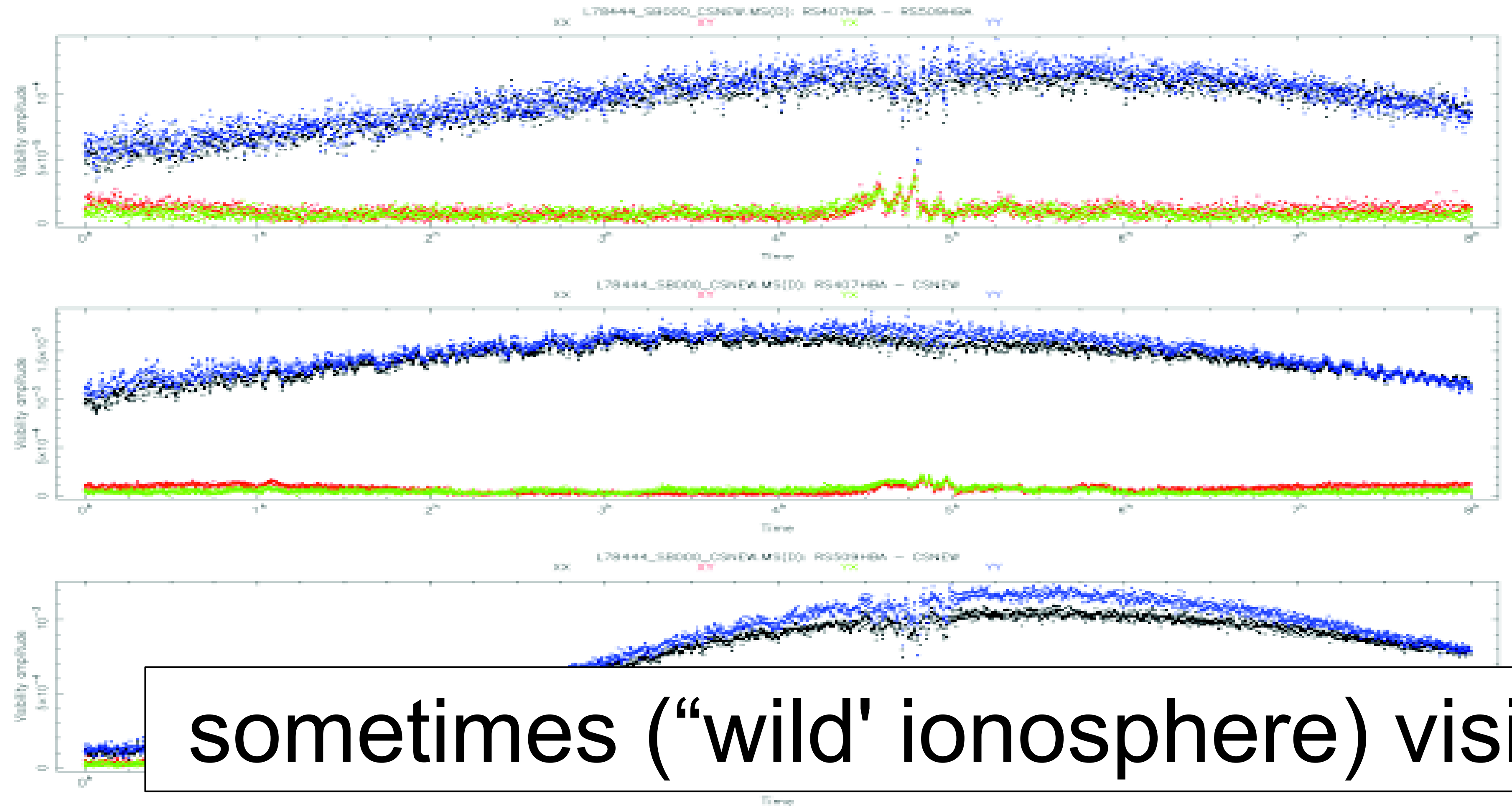
Thin layer approximation: RM_{iono} = $TEC \cdot B_{||}$
Different LOS: dTEC and $dB_{||}$ → dRM

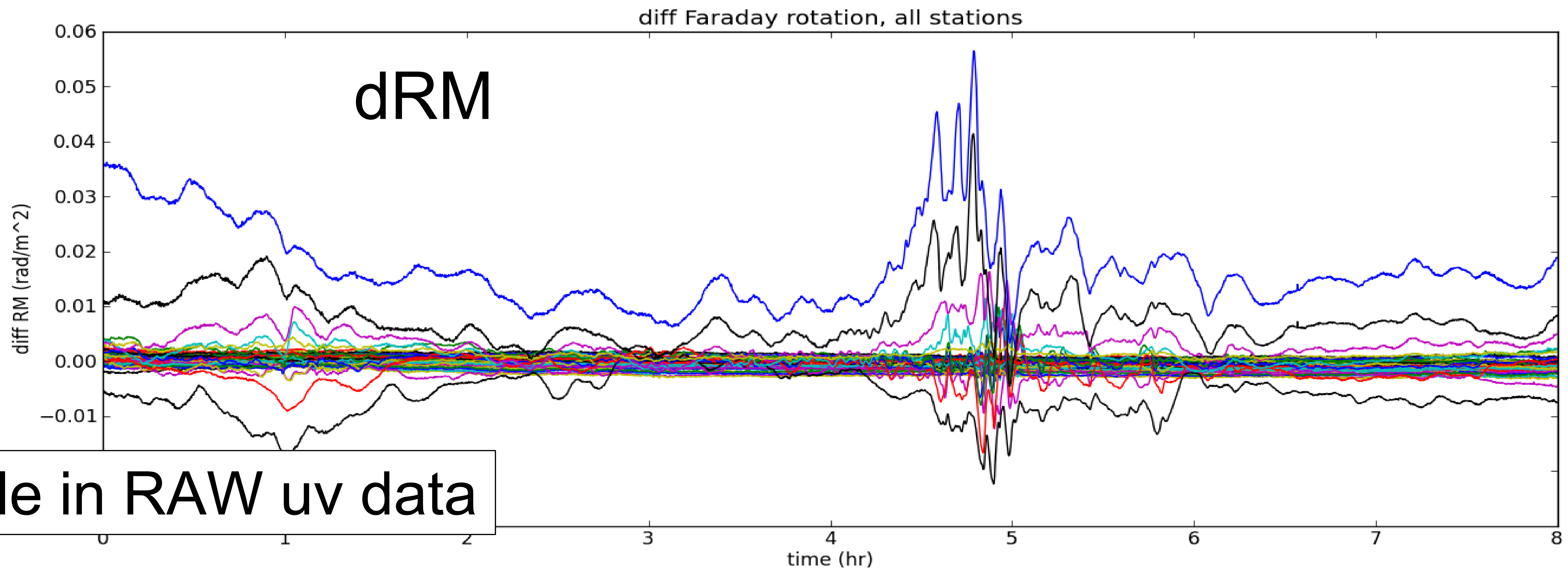
Rotation of the signal from XX,YY to XY,YX due to different Faraday rotation angles for different antennas

HBA: small rotation most of the time
LBA: 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





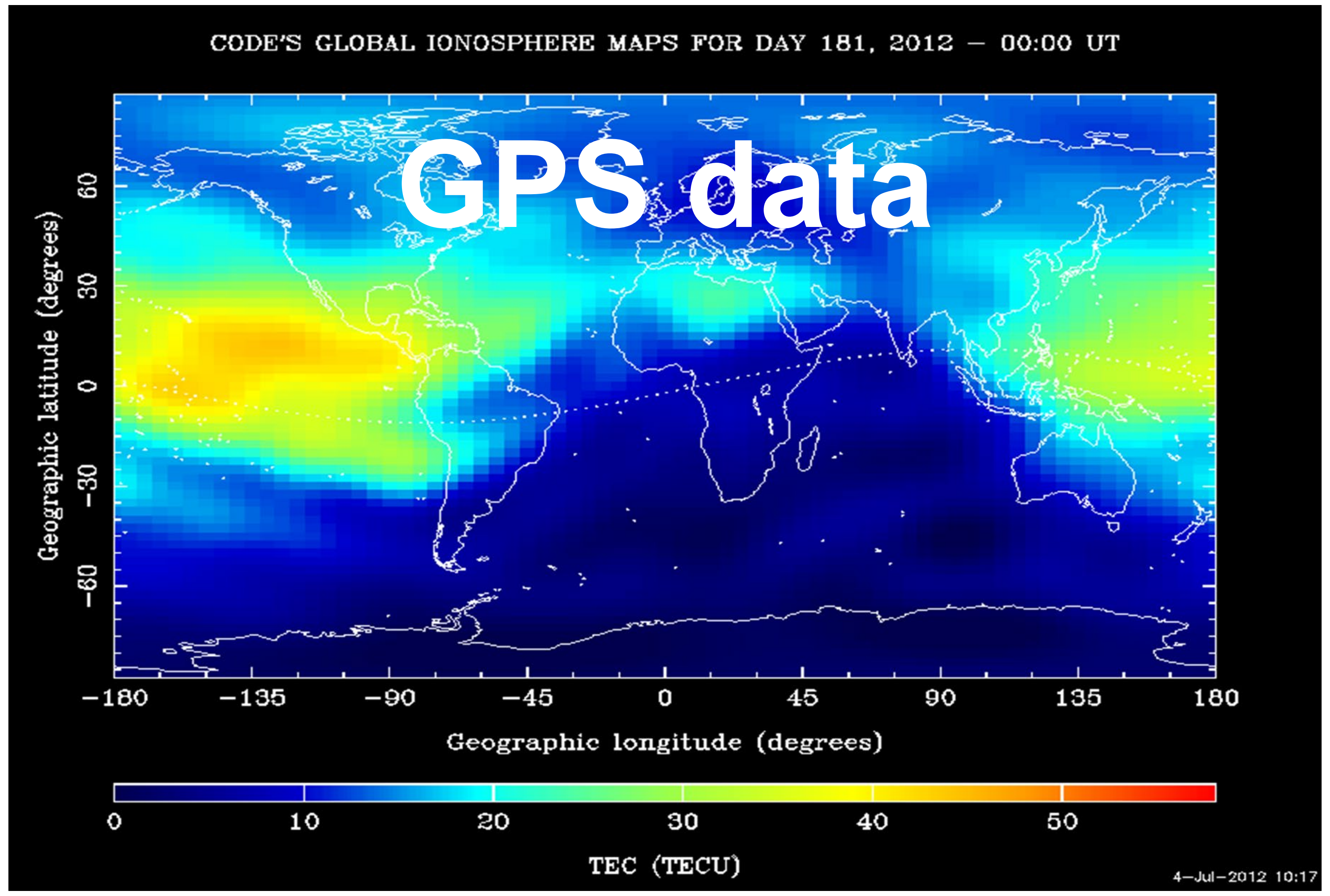
sometimes (“wild' ionosphere) visible in RAW uv data

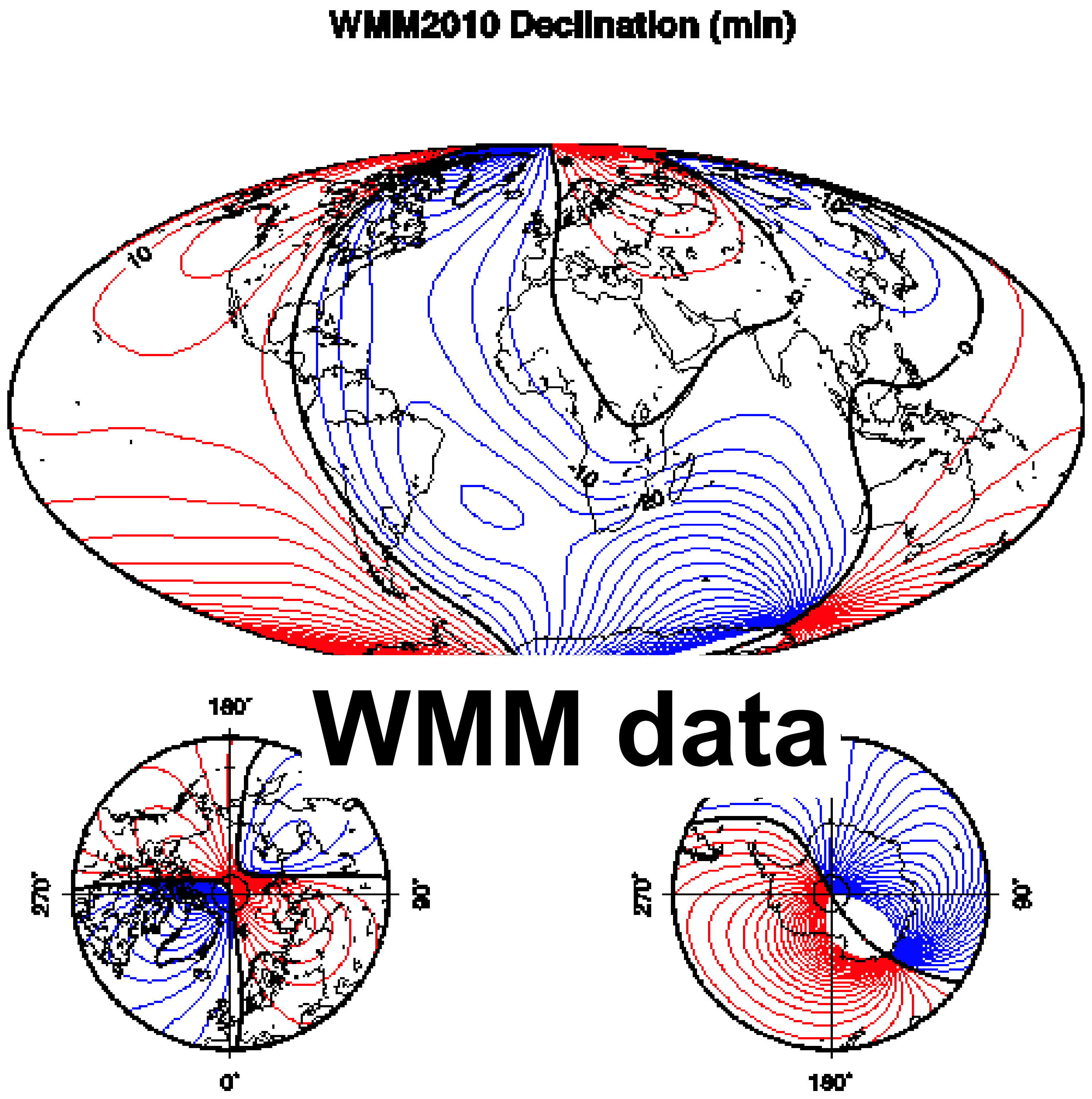
Faraday rotation (RMextract)

Polarized emission

Time variability of ionospheric Faraday rotation causes depolarization

Model RM_{iono} by combining geomagnetic and ionospheric models





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

Install using option: --add-lofar-utils

Execute:

createRMh5parm.py –MSfiles <MS> --h5parm <h5parm_file>

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

Generates h5parm with "rotationmeasure" to be used with DPPP (ApplyCal)

Implemented in prefactor

ASTRON LOFAR STELLAR

Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

Faraday rotation (RMextract)

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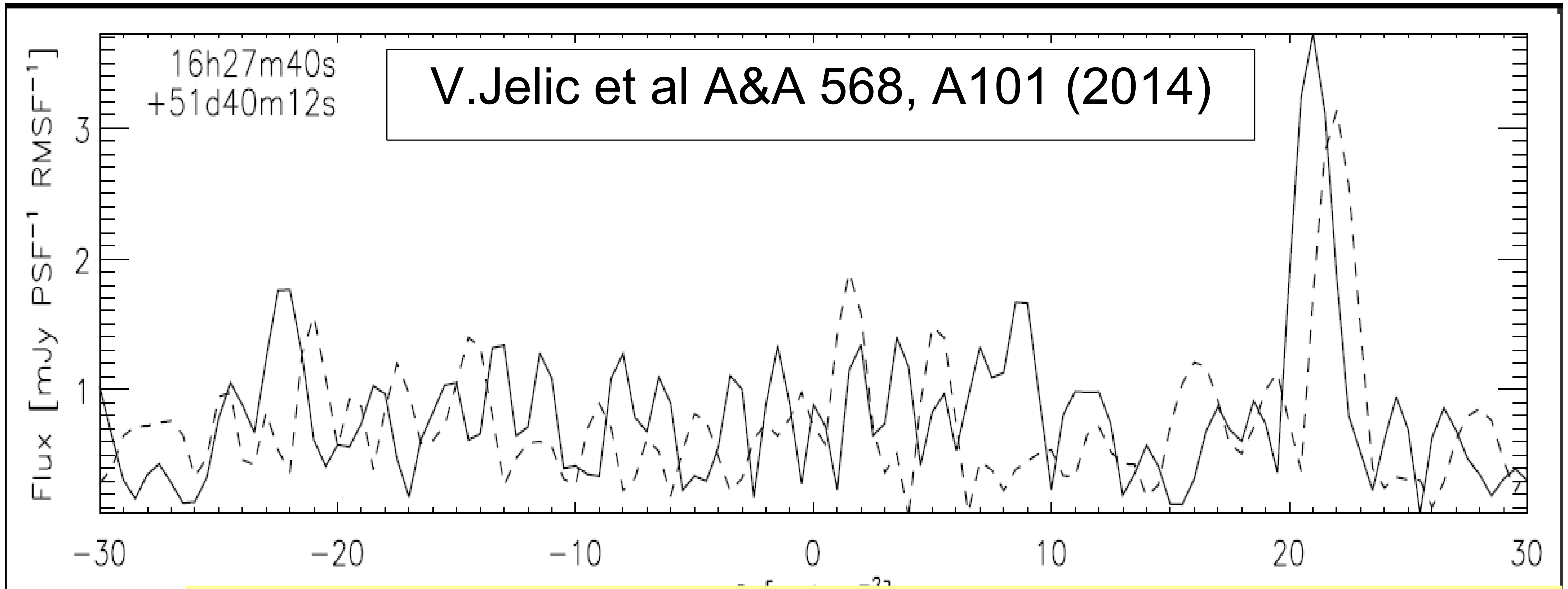
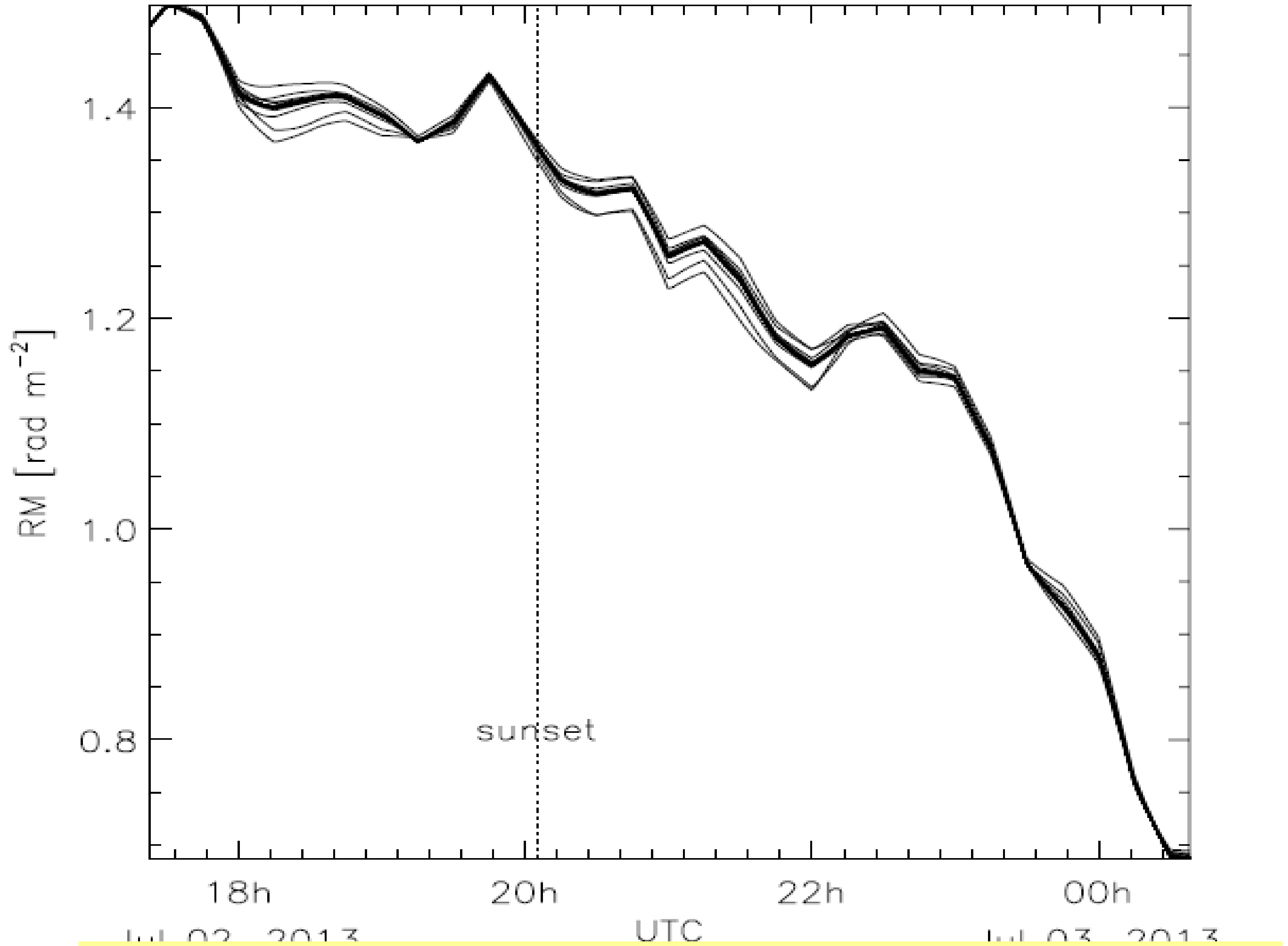
Polarized emission



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



Ionospheric RM corrections versus time

https://github.com/lofar-astron/RMextract
Install using option: --add-lofar-utils
Execute:
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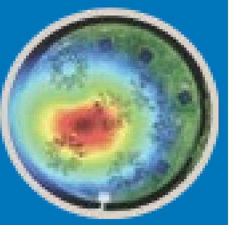
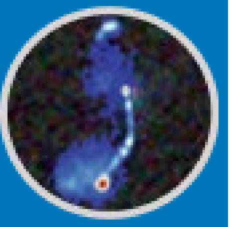
Image credits: A. Corstanje, F. Sweijen, C. Van Eck, P. Zucca

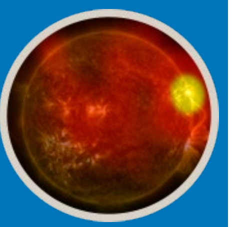
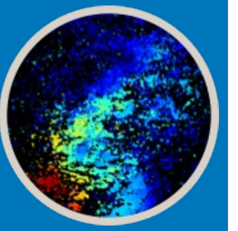
Faraday rotation (RMextract)

Direct access to RM values (e.g for beamformed (pulsar) data)

RMextract/examples/example_getRM.py

```
import RMextract.getRM as gt
from astropy.time import Time

t = Time('2010-01-01T00:00:00',format='isot',scale ='utc')
starttime = t.mjd*24*3600.  # getRM still wants MJD time in seconds (casacore definition)
endtime = starttime + 3600. # one hour of data
statpos = [3826577.1095  ,461022.900196, 5064892.758] #LOFAR CS002LBA (center) , ITRF xyz in meters
pointing=[ 2.15374123,  0.8415521 ] #3C196  Ra, Dec in radians

RMdict = gt.getRM(ionexPath='./IONEXdata/', radec=pointing, timestep=100, timerange = [starttime, endtime], stat_positions=[statpos,])

times=RMdict['times']
RM = RMdict['RM']['st1']

print ("TIME(mjd)     RM (rad/m^2)")
for tm,rm in zip(times,RM):
    print ("%5.2f        %1.3f"%(tm/(3600*24.),rm))
```

Thin layer approximation
More advanced models (using profiles) also available

Calibration Strategies

- Calibration strategies of the ionospheric distortions depends on your science goal
- In general:
  - dispersive delay requires high frequency resolution
  - time variability requires high time resolution
    - TID timescales ~ 15 min
    - moving turbulence: smaller amplitude but faster variations
  - spatial variability requires direction dependent calibration
  - #of degrees of freedom
- In practice S/N can complicate above
  - Calibrator phases cannot always directly be applied to target field due to spatial variations

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 (RMextract)