IONOSPHERE

M.Mevius

Netherlands Institute for Radio Astronomy

IONOSPHERE

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

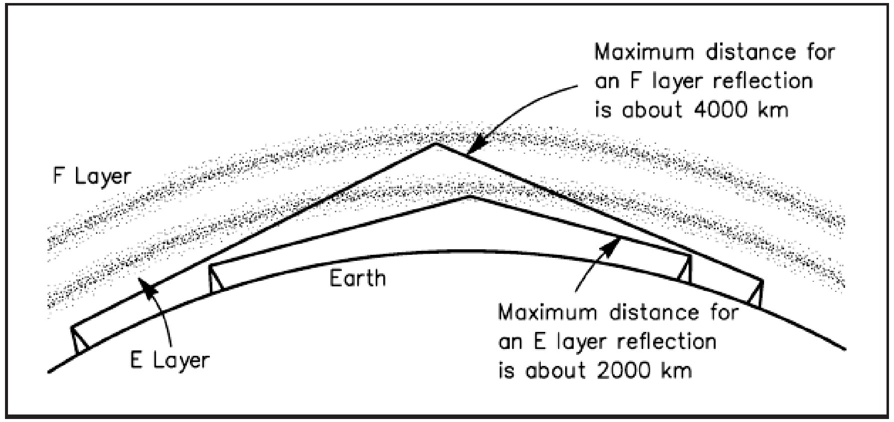

Figure 6—Signals reflected by the E and F layers. Ian Poole, G3YWX

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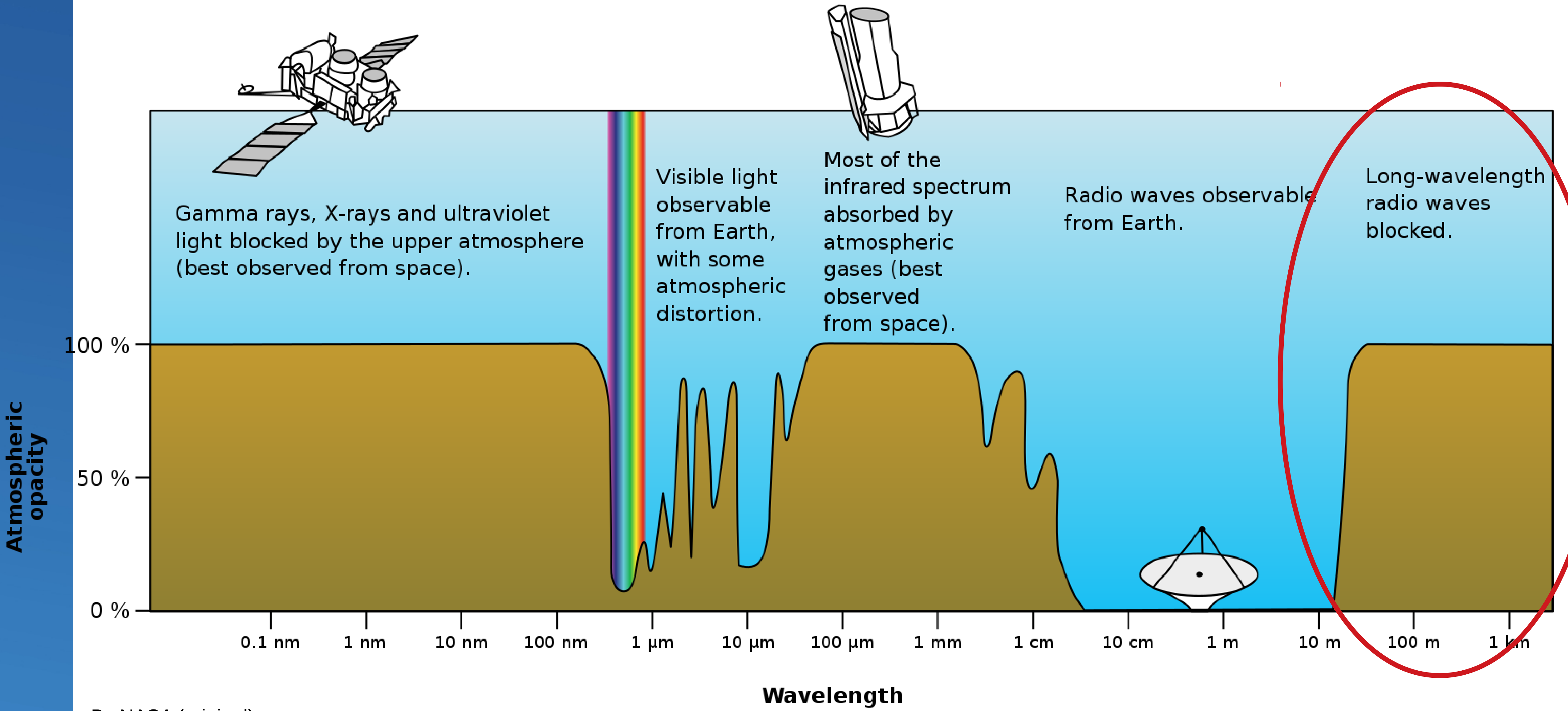
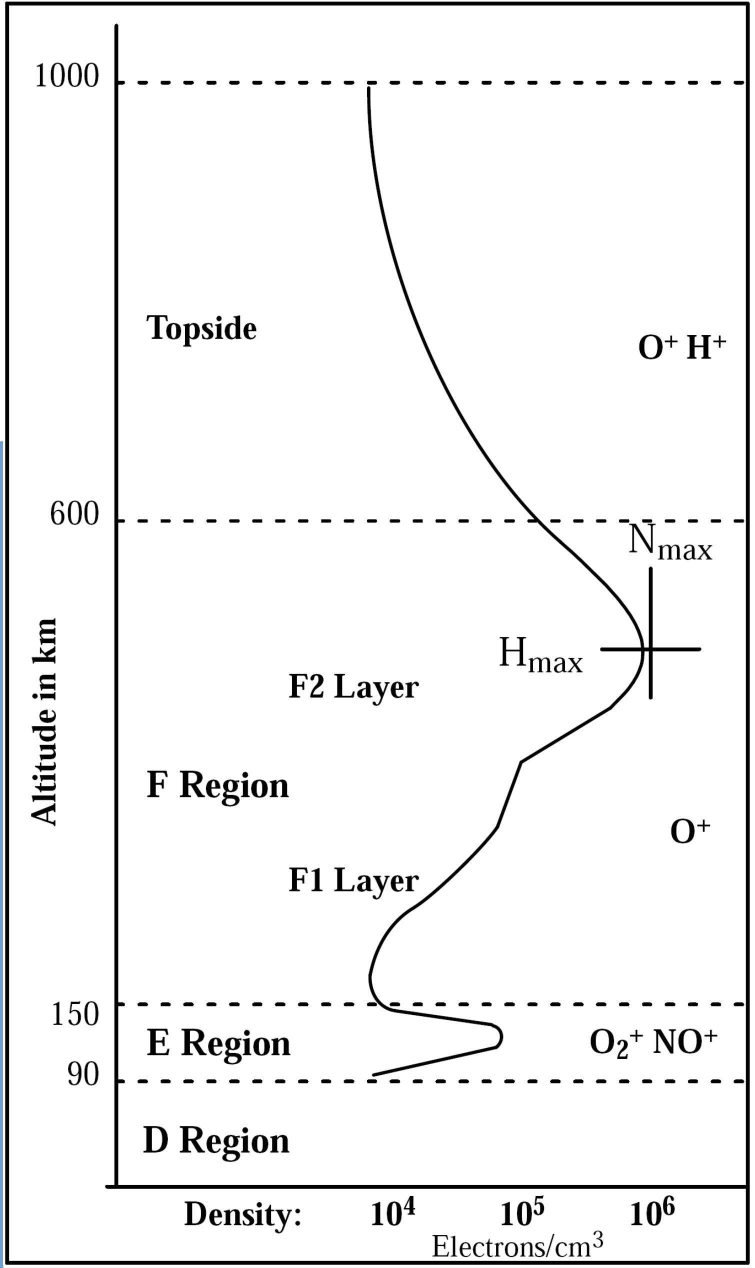


By NASA (original)

Measurements

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

- ionosonde: measure the structure of the different layers by investigating reflections of different wavelengths
- early radio astronomy
  - signals pass completely through
- incoherent scatter radar
- satellites + GPS receivers
  - GPS data online available
  - fit to GPS data of many stations also online: IONEX data
    - thin layer approximation
    - low time (1~2hr) and spatial (2.5 x2.5 degrees) resolution



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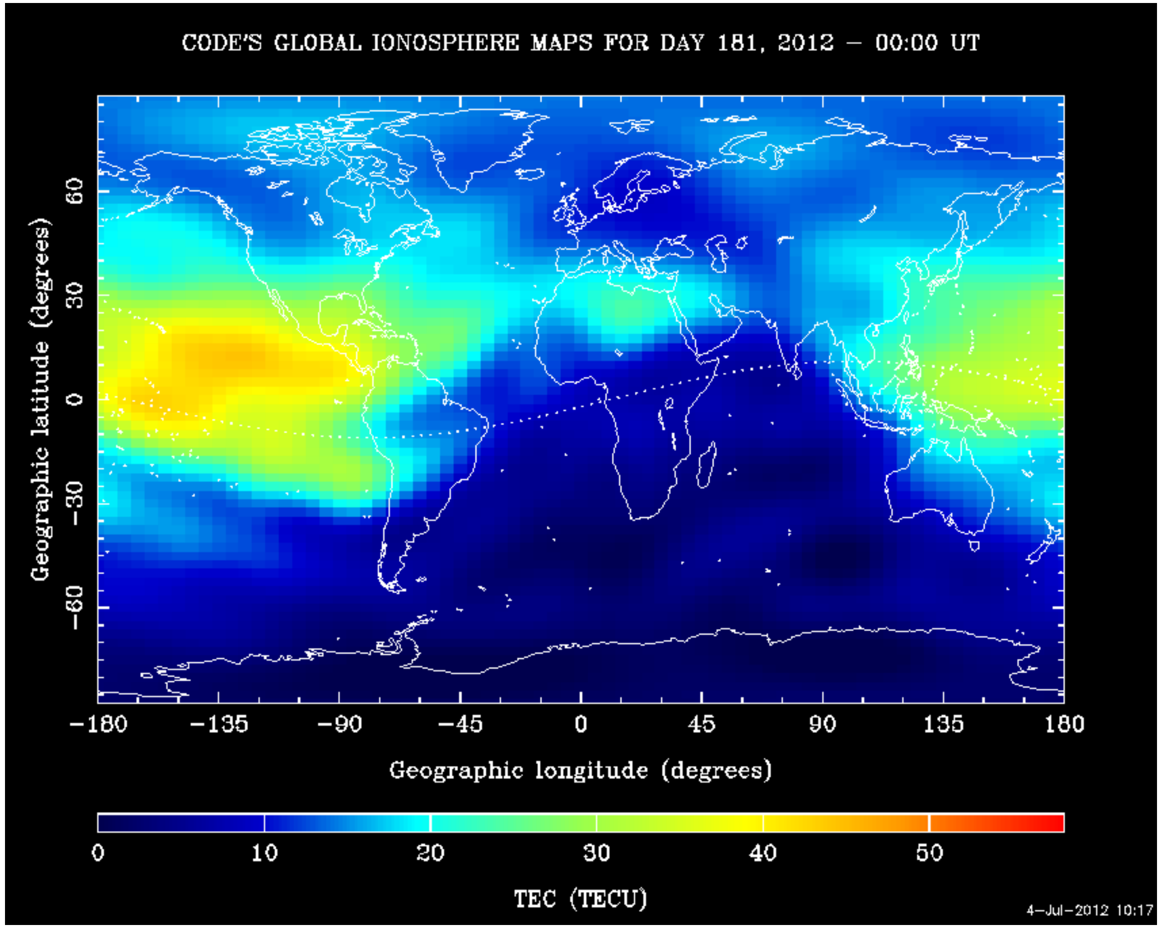
IONEX data (CODE)



Total Electron Content (TEC)

Typical values @ 52° for integrated TEC along LOS:
~5(night)- 50(day) TECU
(10^{16} e/m^2)

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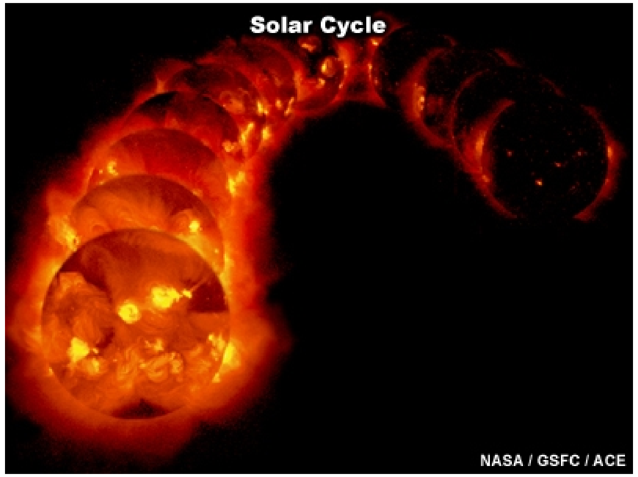
Ionospheric Variability

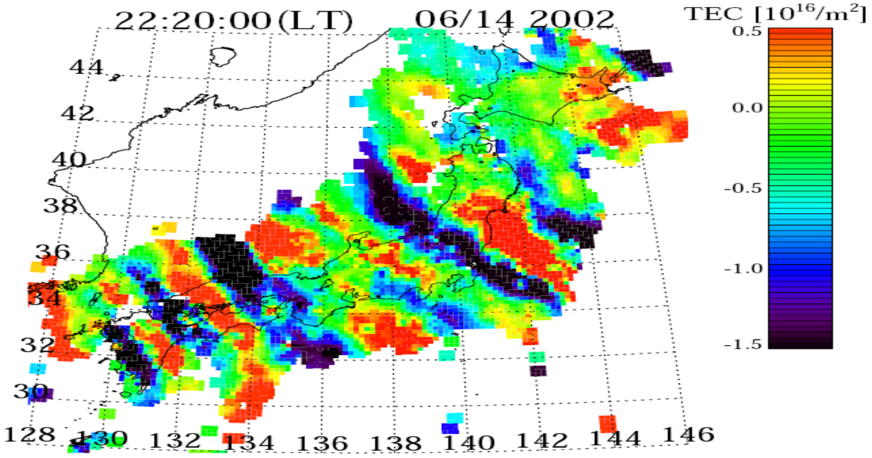
The ionosphere is highly dynamic:

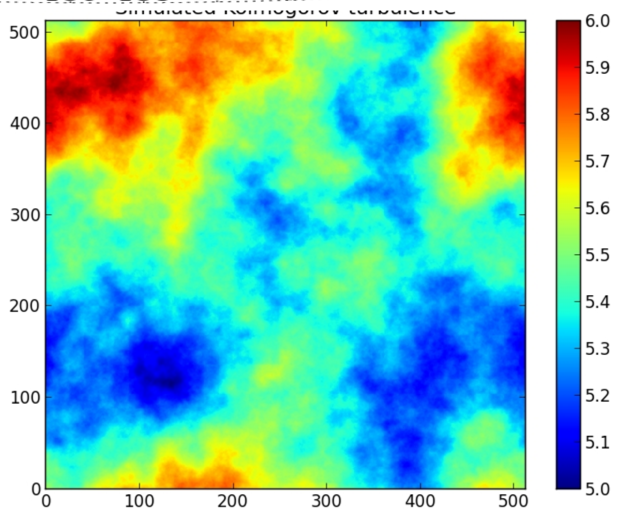
- Ionization through solar radiation (UV+X-ray)
- Recombination at night
  - → diurnal pattern
  - large gradients @ dusk and dawn
- Solar activity cycle
- Scintillation (high turbulence):
  - (mostly) after sunset
- Pressure + composition lower atmosphere
  - Traveling Ionospheric Disturbances (TIDs)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

Structures moving with speeds ~ few 100 km/hr

When observing: tracking through the ionosphere







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Recombination at night
→ diurnal pattern
large gradients @ dusk
Solar activity cycle
Scintillation (h
(m   set
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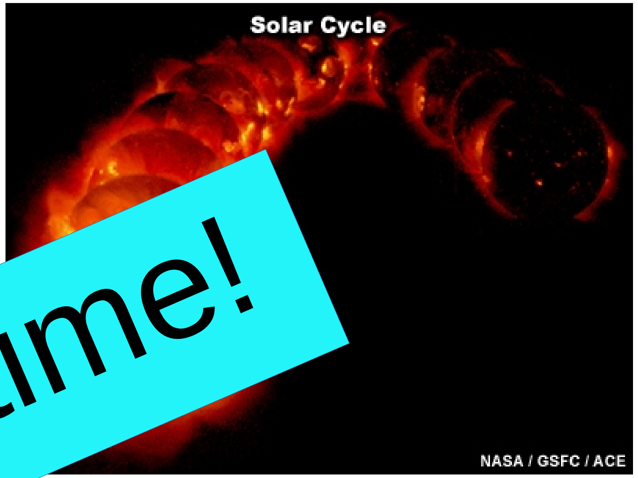
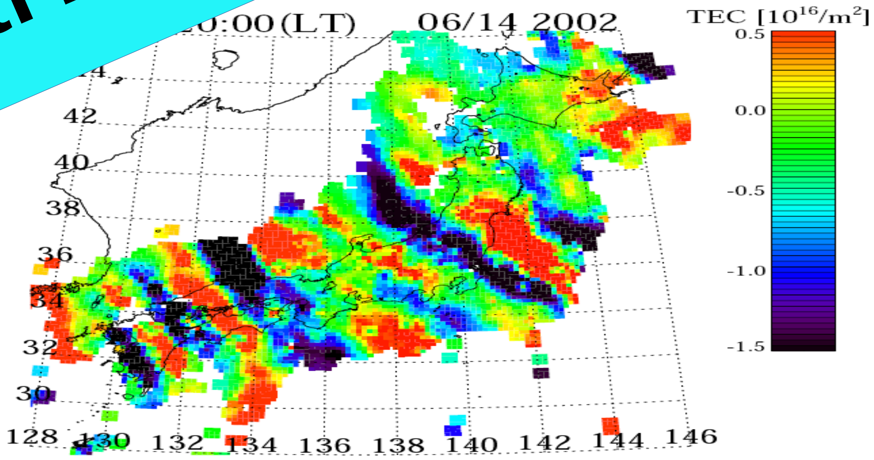
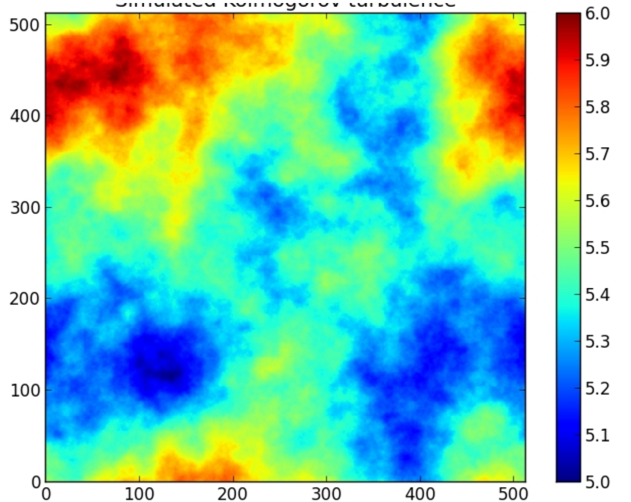
                    Ionospheric Disturbances (TIDs)
Sma   Scale Structures: Kolmogorov turbulence

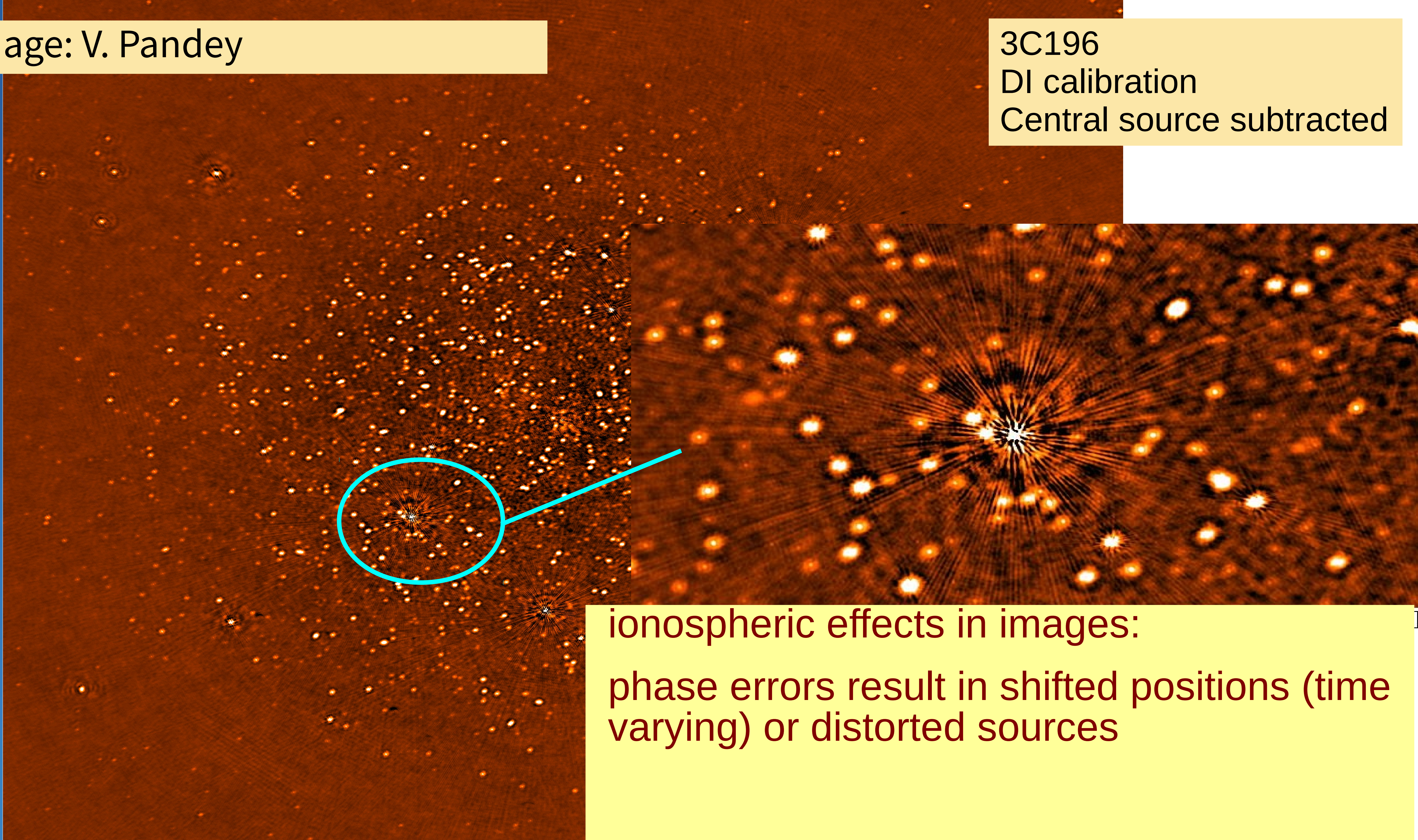
Varies a lot in space and time!

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









ionospheric effects in images:

phase errors result in shifted positions (time varying) or distorted sources

Electromagnetic Propagation

F. de Gasperin et al. 2018

Total LOS integrated propagation delay

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

Refractive index in ionized plasma

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

Approximation for frequencies well above the plasma frequency

$\alpha = RM \cdot \lambda^2$

Calibration: in M.E., 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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Total integrated propagation delay

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

1st order: dispersive phase delay
Δϕ = 8.45e9 dTEC/ν

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

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

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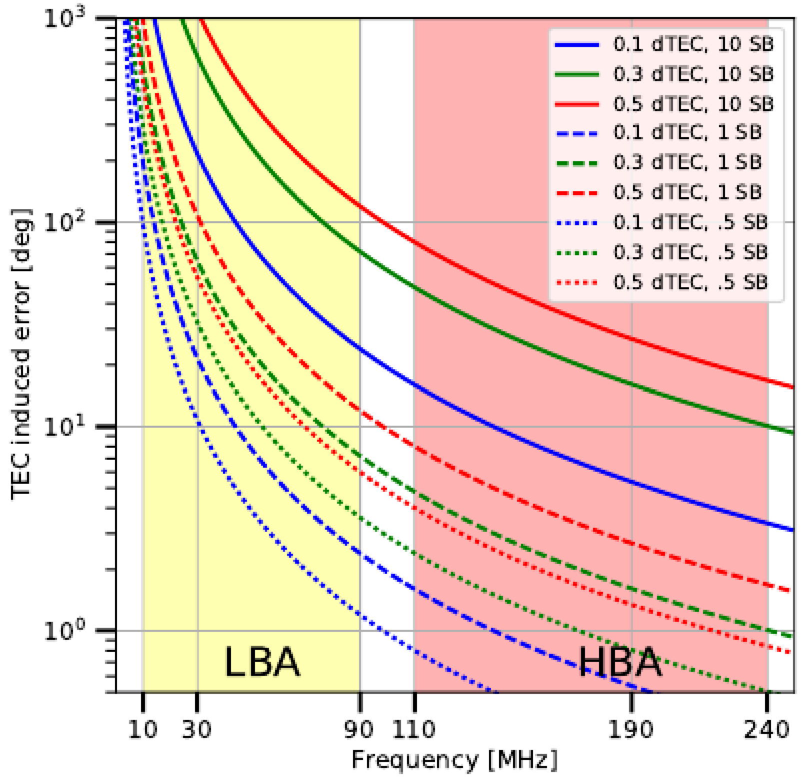
Dispersive phase delay

$\Delta\phi = 8.45e9\ dTEC/\nu$



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

Clock/Tec Separation

direction independent 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

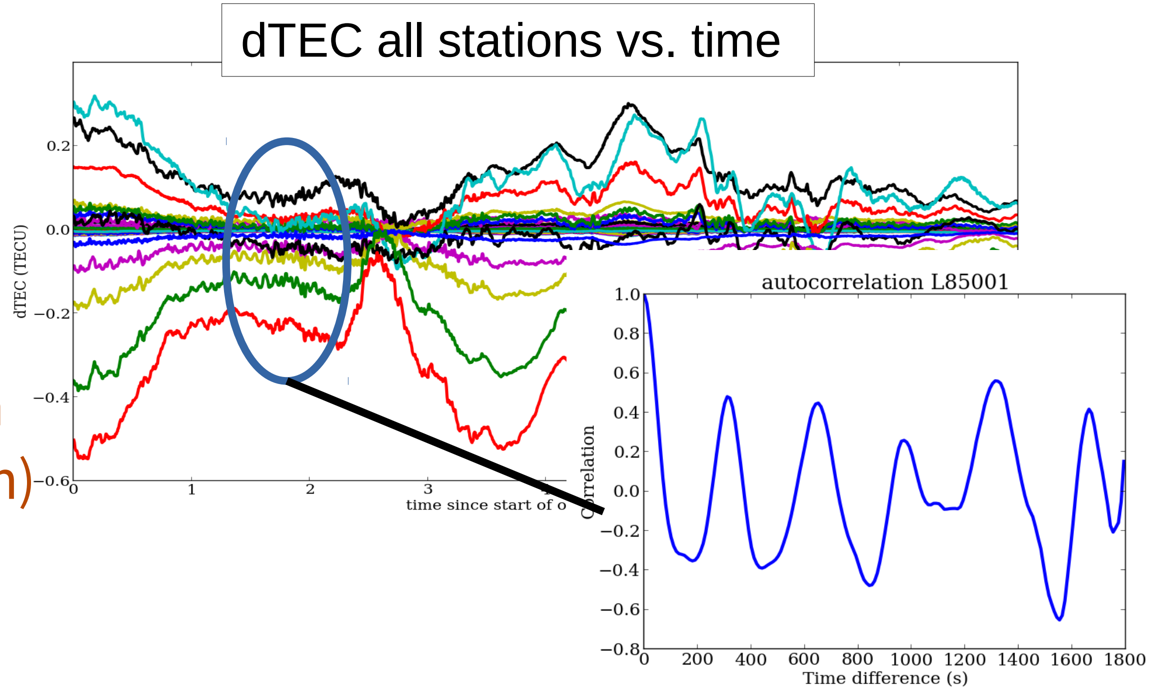
- Using different frequency behaviour and wide bandwidth, fit on calibration phases for clock(A) and TEC(B) in:

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

For LBA <50MHz third order term is also important!

- Calibrator to target transfer: apply clocks only (since ionosphere is different in target field)
- use ionospheric phases to generate phasescreen for interpolation (direction dependent correction)
- inspect ionospheric conditions of observation

Clock/TEC separation script available in Losoto/prefactor



timescale ~5 min

Structure function

Spatial fluctuations:

$$D_\varphi(||r_1 - r_2||) = \langle(\varphi_1 - \varphi_2)^2\rangle$$

Kolmogorov turbulence, thin layer approximation:

$D_\varphi(\mathbf{r}) = (\mathbf{r} / s_0)^\beta$ $\beta = 5/3$,

s_0: diffractive scale,

$D_\varphi(s_0) = 1\ \text{rad}^2$

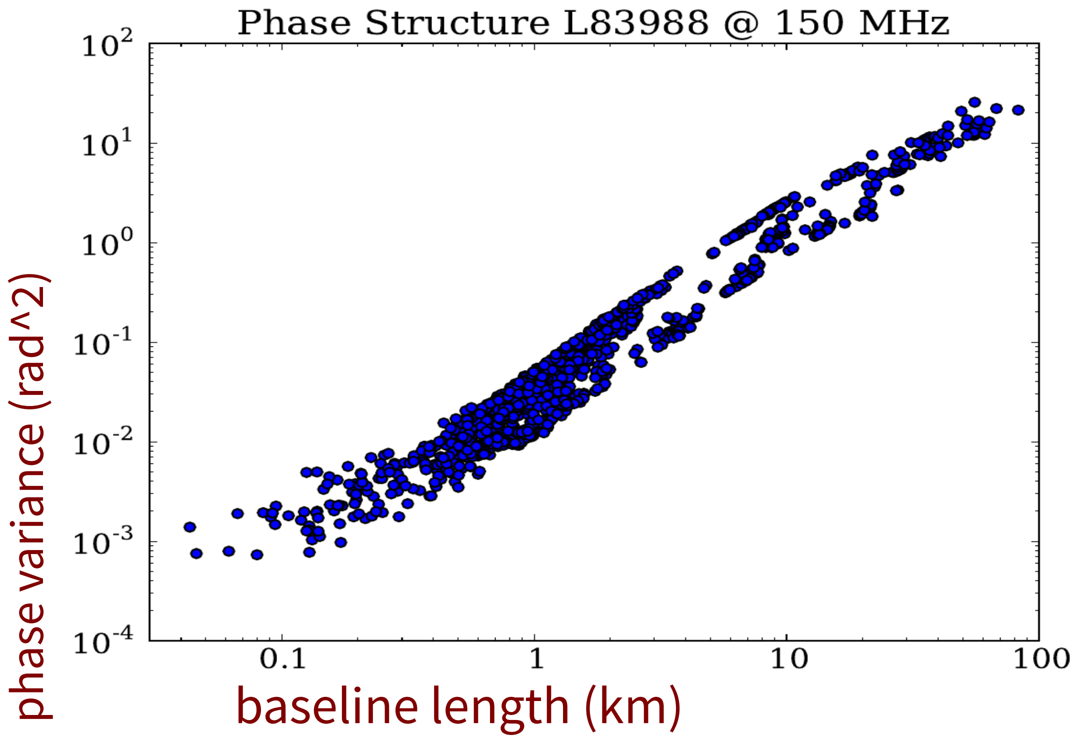
Measure structure function by calculating variance of dTEC vs. time for all baselines

Typical nighttime S_0 @150 MHz: 2-40 km

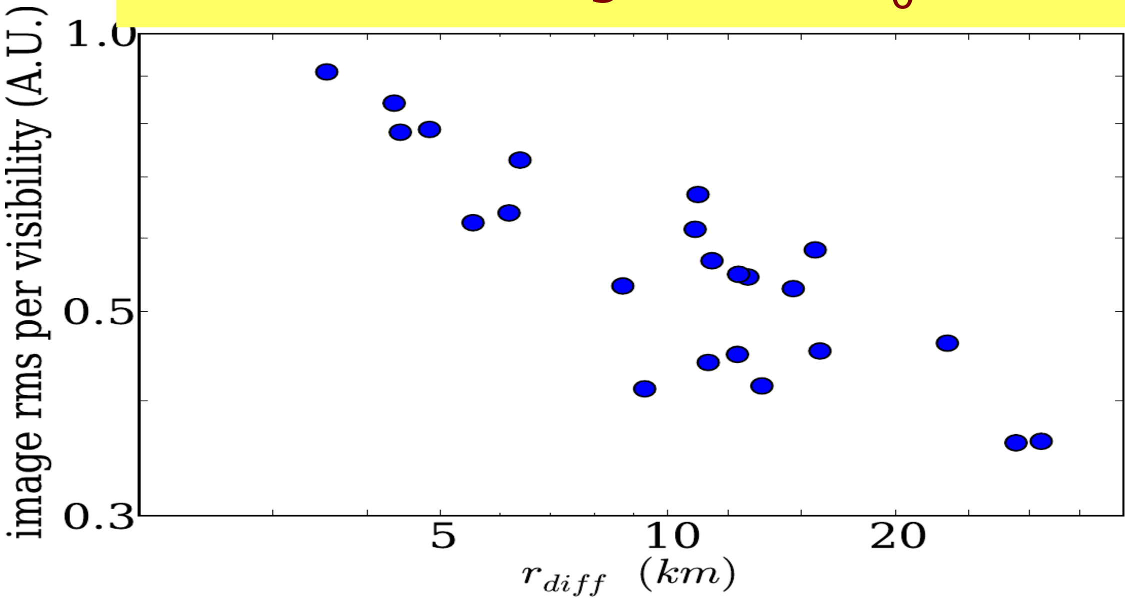
scintillation conditions S_0<2km

Characterize ionospheric quality

Diffractive scale calculation from calibration phases available in Losoto/prefactor



Correlation image noise S_0



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F. de Gasperin et al. 2018

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

2nd order: Faraday Rotation
RM ≈ 2.62 e-6 $B_{\parallel}$TEC

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

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

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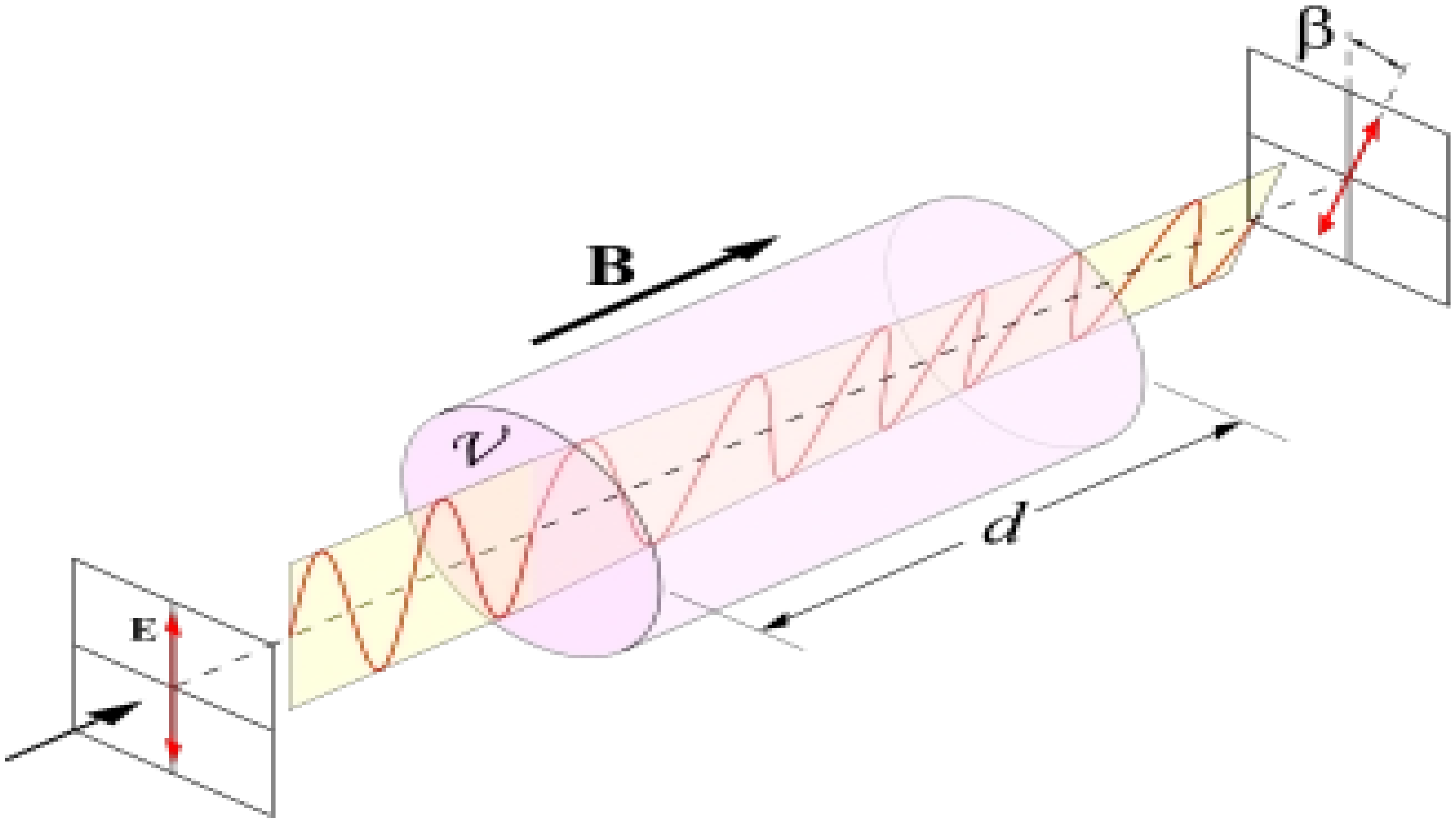
Faraday Rotation

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 angle:

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

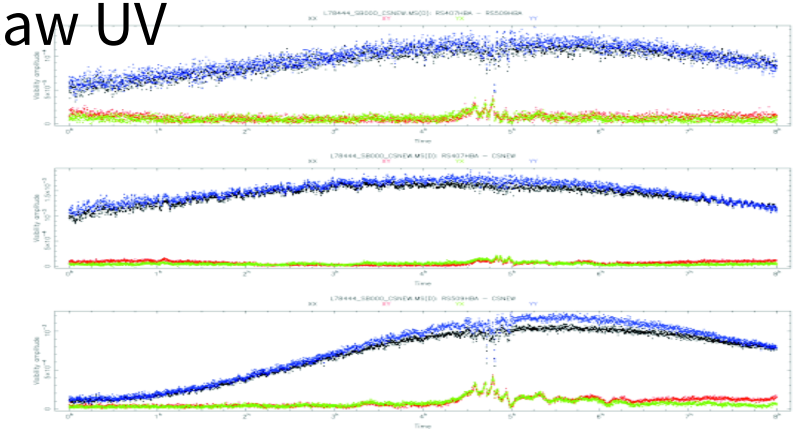
Differential Faraday rotation

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

$$\beta = \mathrm{RM}\nu^{-2}$$

- HBA: small rotation most of the time
  - sometimes (“wild' ionosphere) visible in RAW uv data
- LBA: significant effect

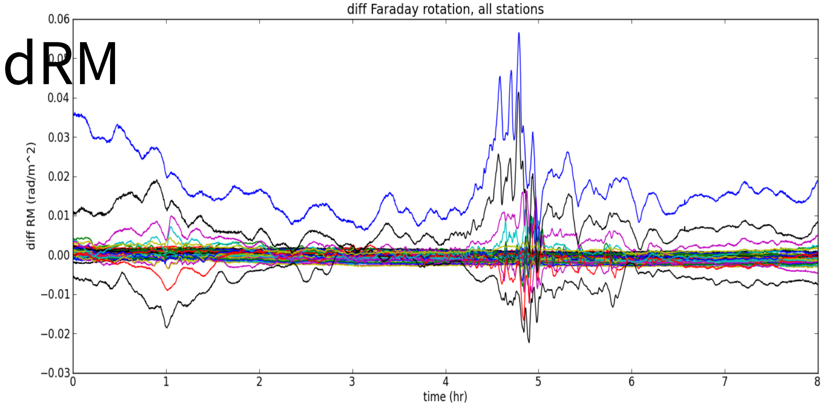
Raw UV



Selfcal: either

- solve full polarization matrix or
- diagonal gains + 1 rotation matrix or
- convert to circular polarization:
  - difference in R and L phases gives Faraday rotation angle

dRM



Differential Faraday rotation provides clean independent measure of ionospheric fluctuations (ignoring differential B)

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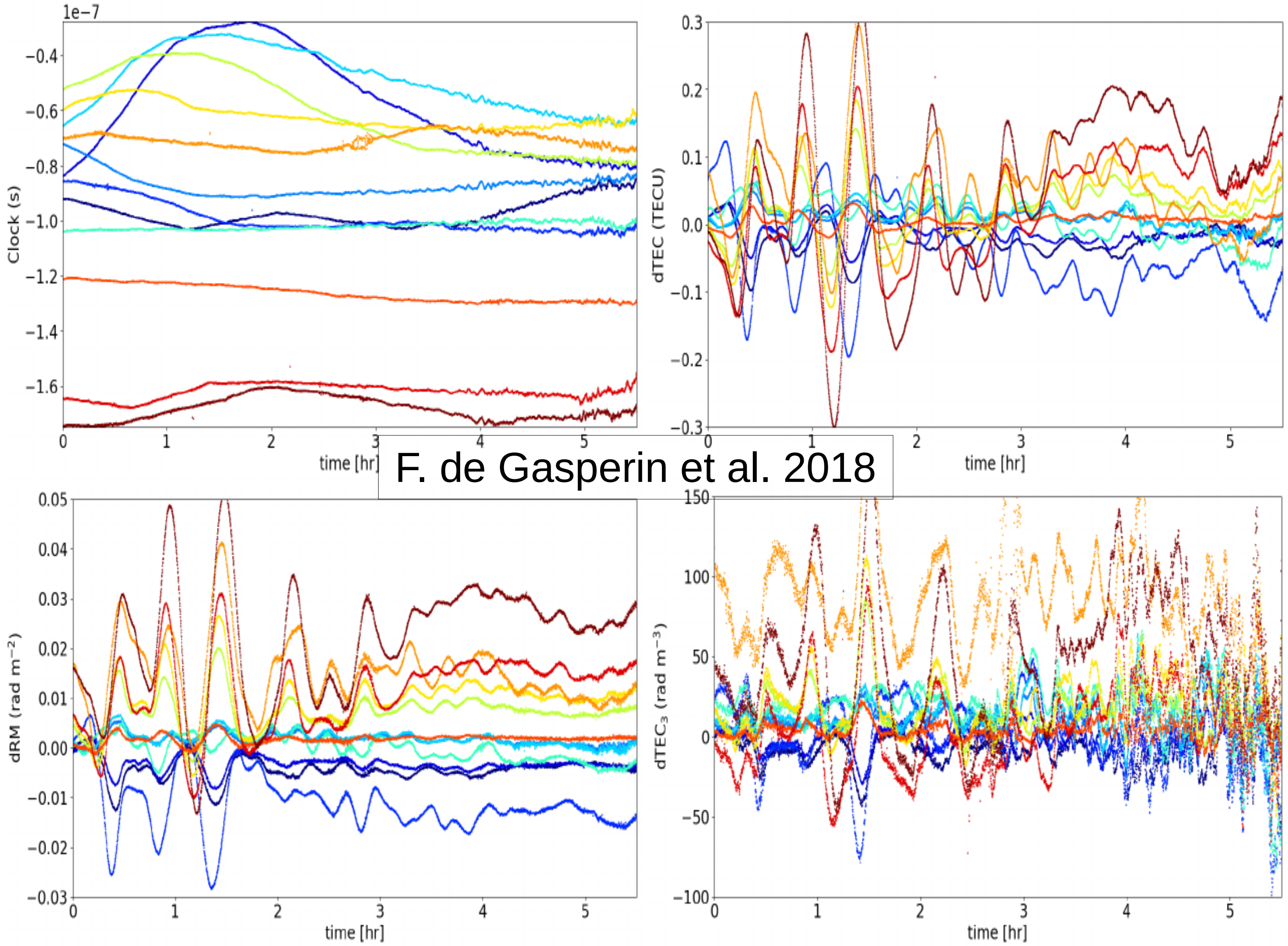
dClock

dTEC



F. de Gasperin et al. 2018

dRM

3^{rd} order

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OTHER EFFECTS

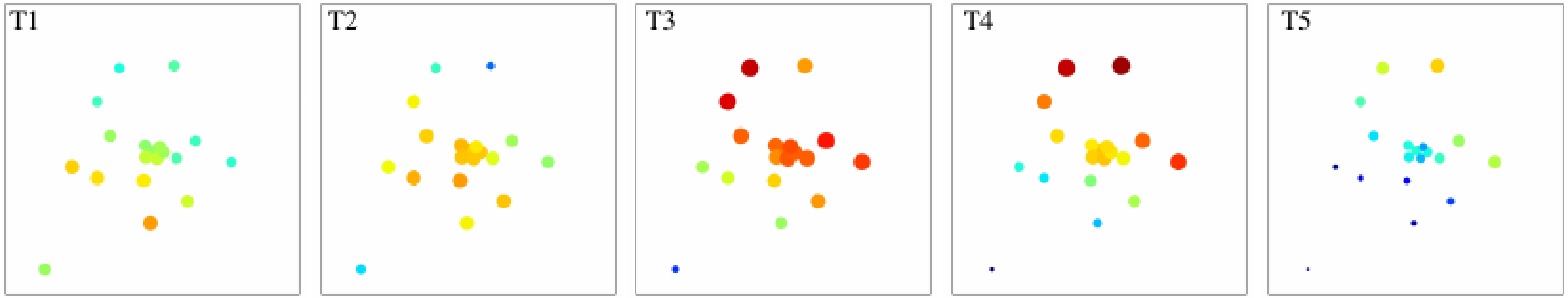
Amplitude scintillation:

Amplitude de-correlation due to very turbulent conditions

Typical size of ionospheric irregularities < Fresnel scale $\sqrt{2\lambda d}$

Occasional in HBA observations

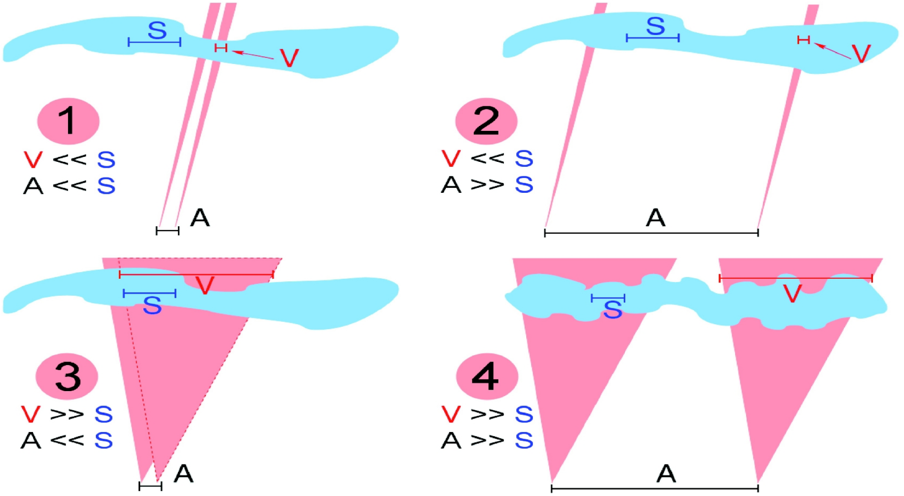
Very frequent in LBA



LBA: Amplitude correction per station, time between panels 10s

Calibration Strategies

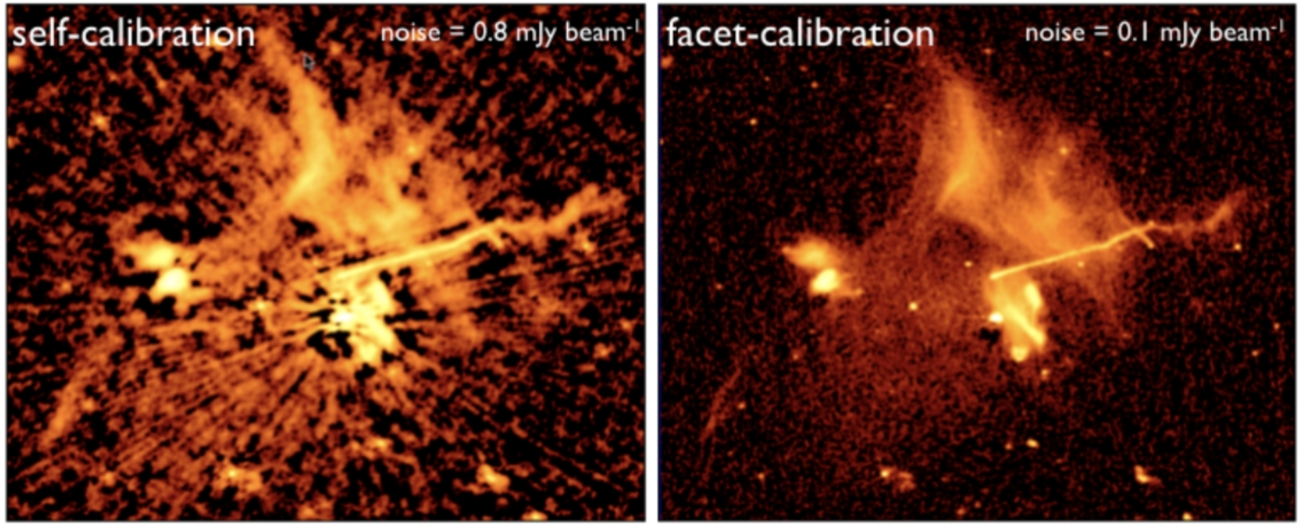
- Calibration strategies of the ionospheric distortions depends on your science goal
- In general:
  - dispersive delay requires high frequency resolution
  - time variability requires high time resolution
    - TID timescales ~ 15 min
    - moving turbulence: smaller amplitude but faster variations
  - spatial variability requires direction dependent calibration

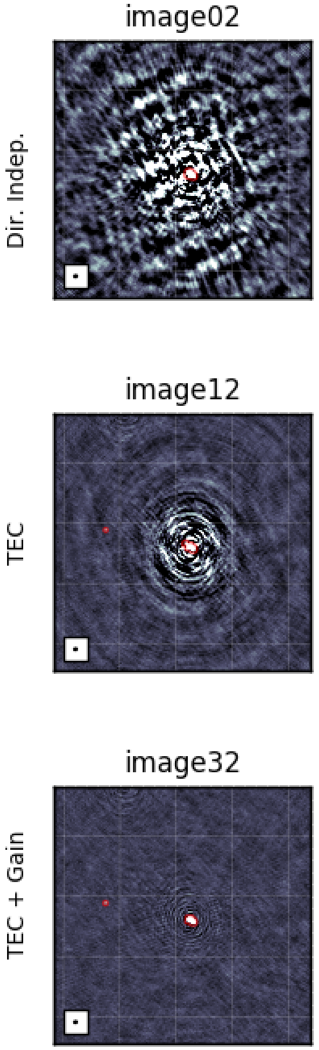


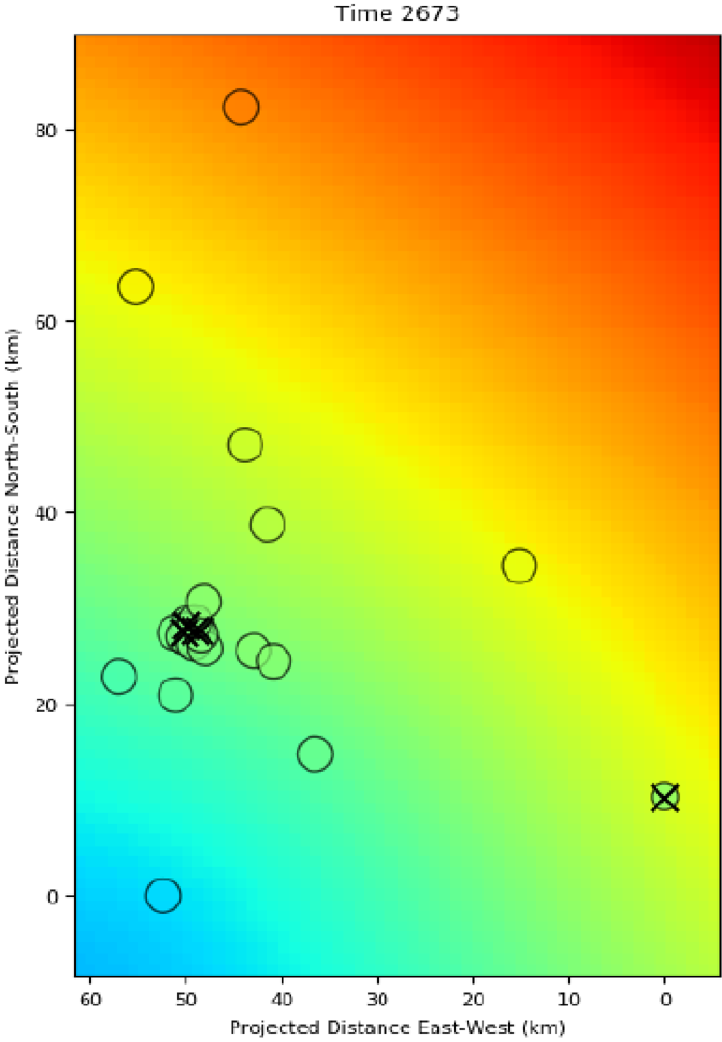
Lonsdale (2005)

- In practice S/N can complicate above
  - Calibrator phases cannot always directly be applied to target field due to spatial variations

Correcting DD effects







FACET calibration/ imaging (FACTOR/DDFacet/kMS)
Sagecal → subtract corrupted sources

Phase screen methods (DPPP):

- needs several bright enough sources in FOV
- selfcal source models need good ionospheric calibration
- ignores 3D structure of ionosphere
- crossing of piercepoints depends on chosen height of layer(s)

Apply as Aterm during imaging

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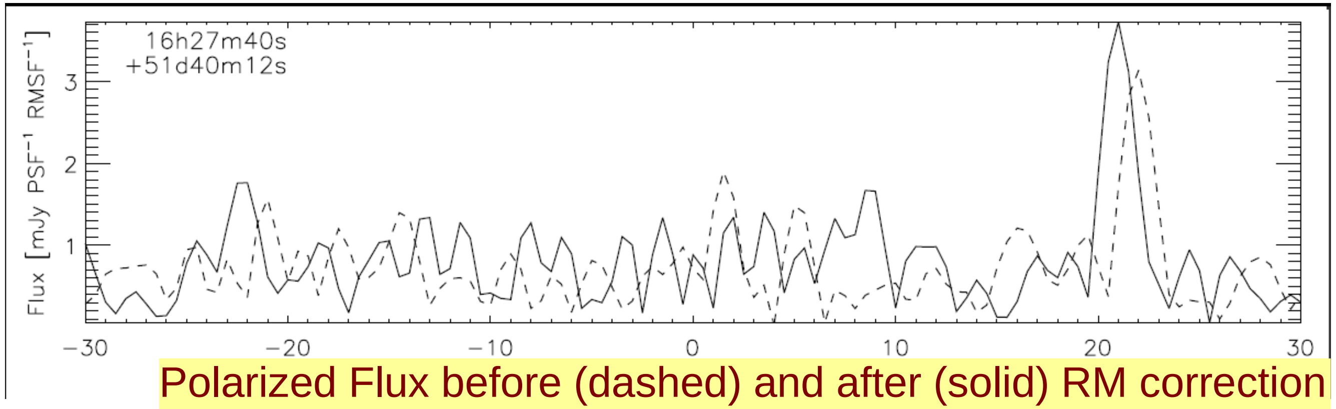
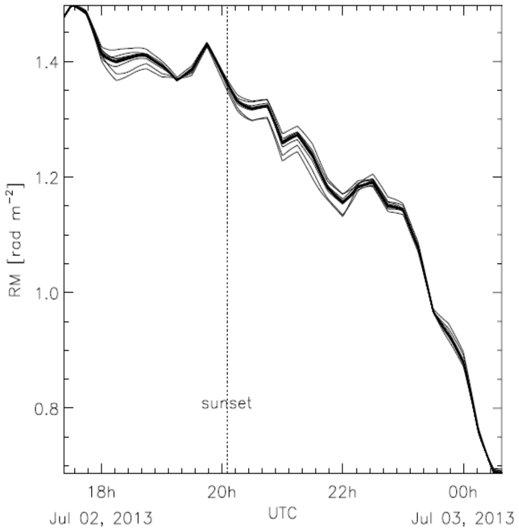
Absolute Faraday Rotation

- For polarization studies:
  - correct time variation of ionospheric Faraday rotation
- Calculate RM variation:
  - GPS data + Earth Magnetic Models
  - RMselfcal (more accurate)
- Correct data using single rotation matrix
  - GPS models do not provide accurate enough resolution to correct spatial variation

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



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



RMextract: Mevius, M. (2018) RMextract, Astrophysics Source Code Library, record [ascl:1806.024]

implementation in prefactor available

Conclusion

- When doing radio astronomy @ low frequencies, you cannot ignore the ionosphere
- 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
- New calibration/imaging strategies are necessary (under development)