Ionospheric effects

Ilse van Bemmel
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Outline

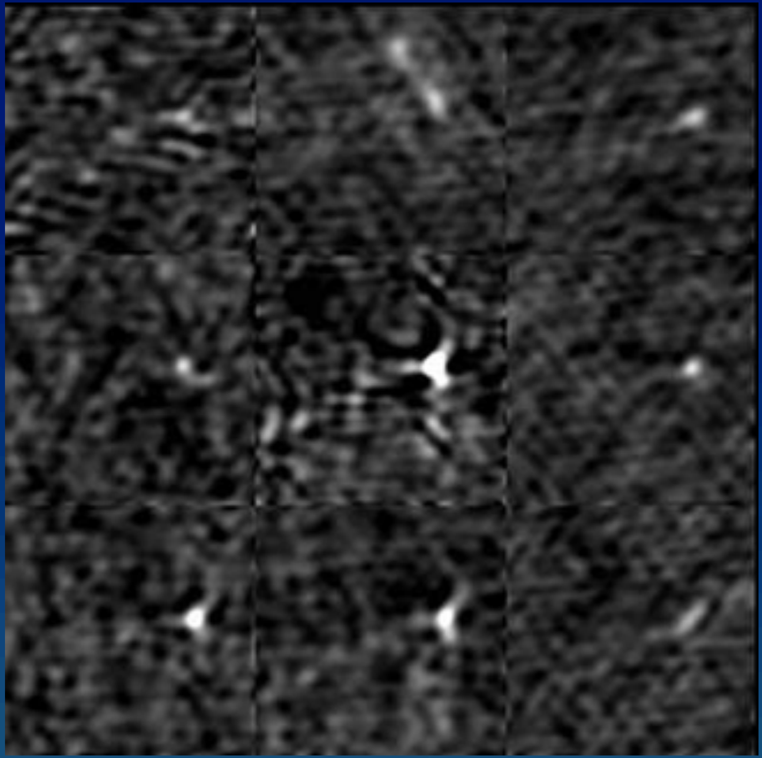
- Introduction to ionosphere
- Effects on radio waves
- Calibration and simulations

Introduction

What is the ionosphere?

Why do we care?

Why do we care?



VLSS sources in single field

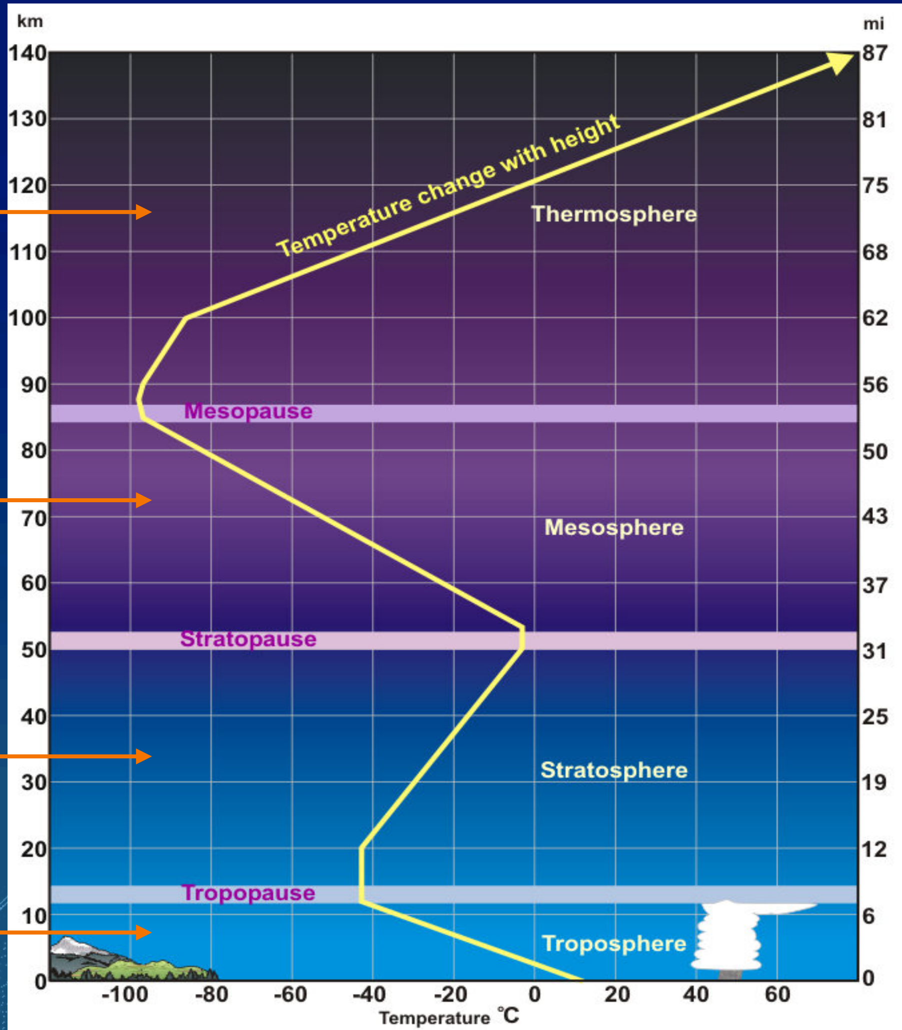
Atmosphere

X-ray & UV absorption

Meteors

Ozone generation

Water vapor



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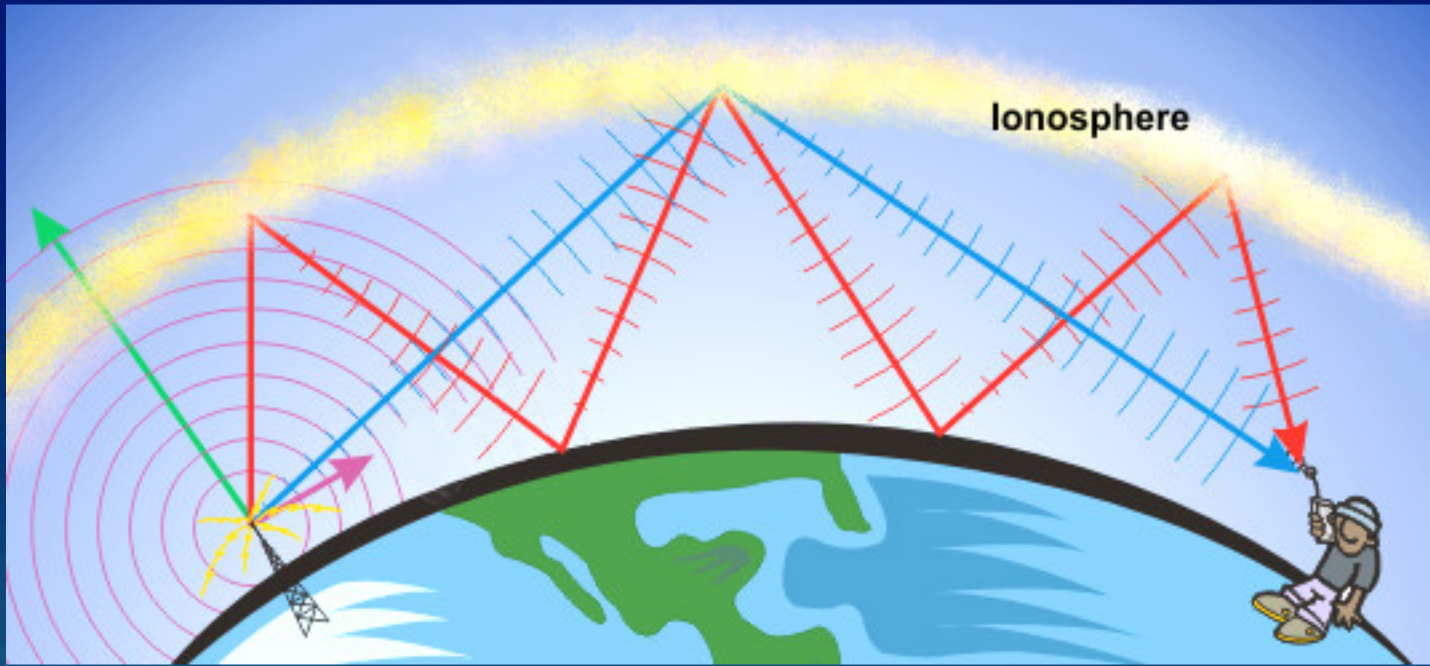
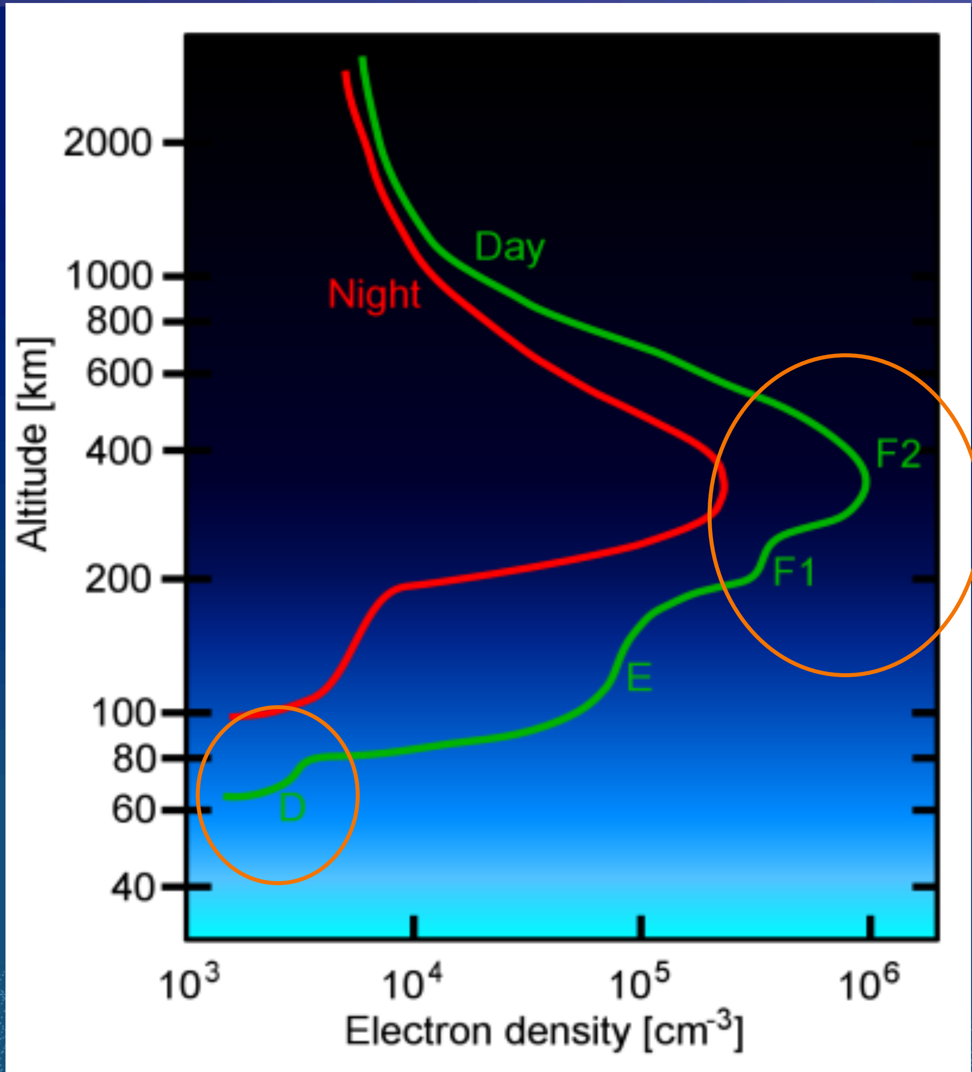
Ionosphere



Ionosphere



2000
1000
800
600
400
200
100
80
60
40
Altitude [km]
Day
Night
F2
F1
E
D
10^3
10^4
10^5
10^6
Electron density [cm^{-3}]

Ionosphere

- D-layer: 50-90 km
  - disappears at night
- E-layer: 90-120 km
  - reflects radio waves with ν < 10MHz
  - E_s: reflection up to 200MHz
- F-layer: 120-400 km
  - highest electron density
  - splits during day-time

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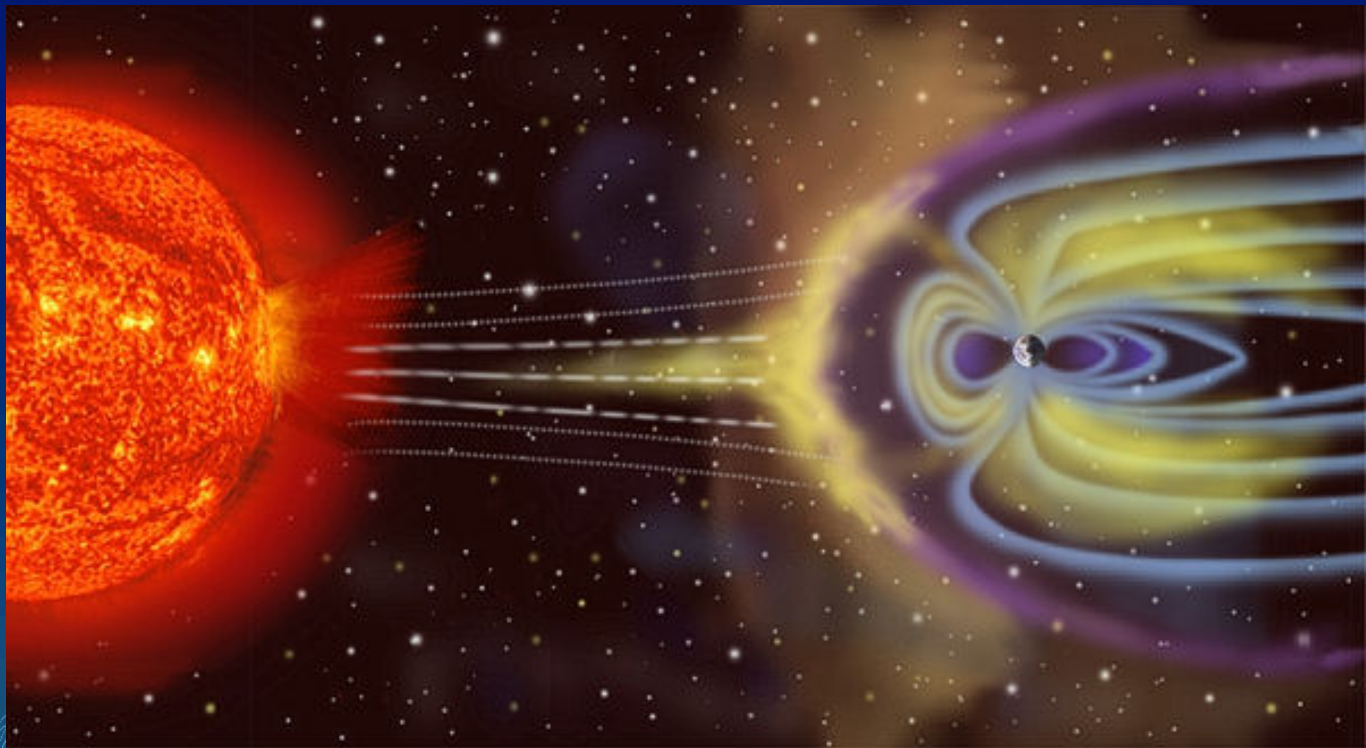
Ionospheric structure

- Global scale
- Solar illumination: daily cycle
- Large and small scale waves
- Turbulence

The magnetosphere



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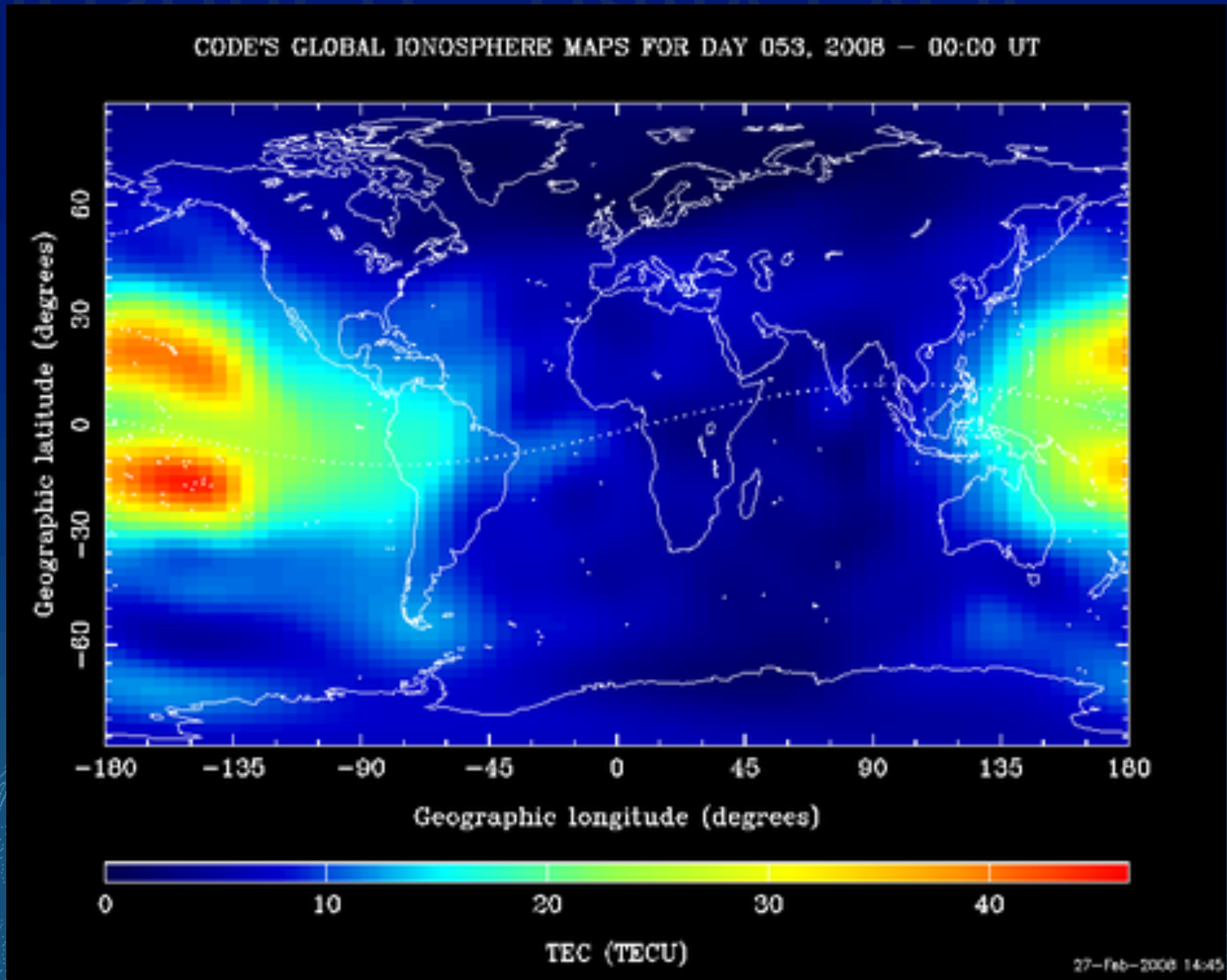
Ionosphere: daily cycle



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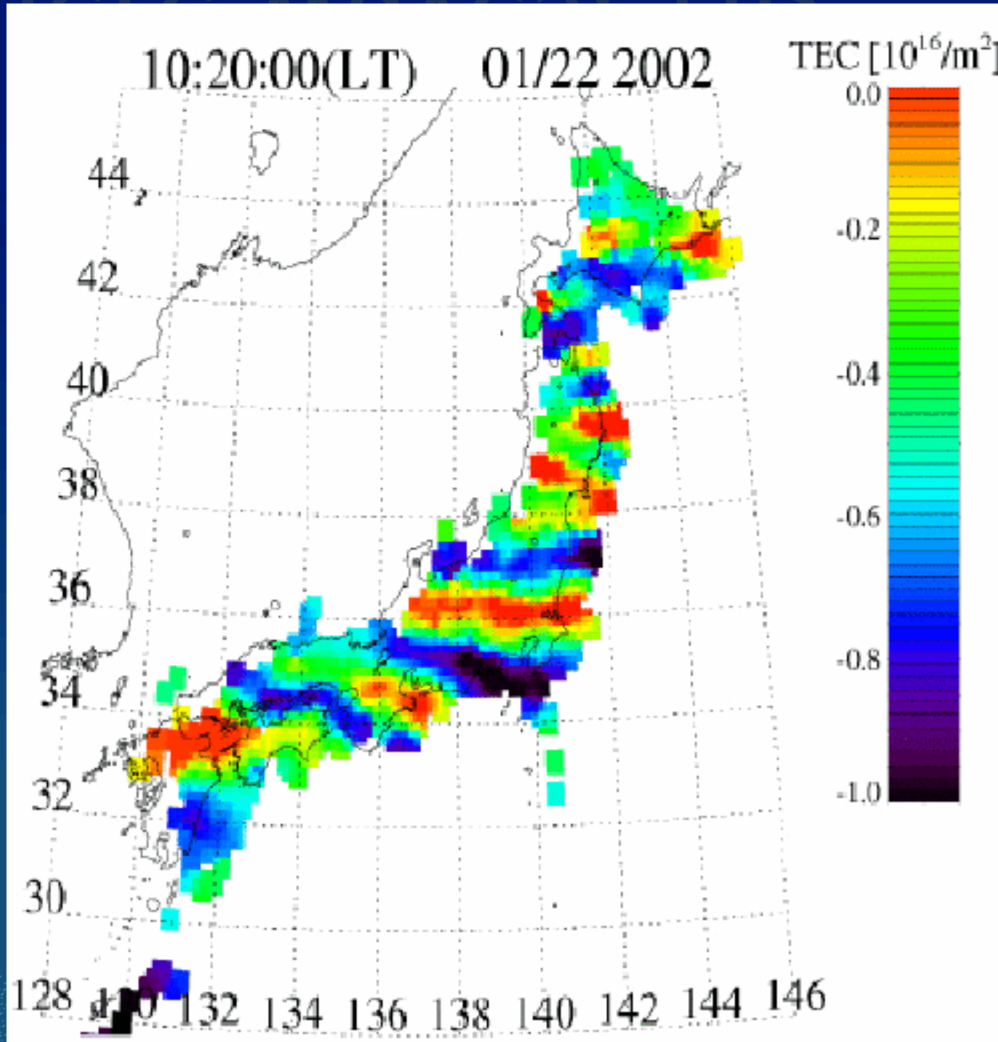
Ionosphere waves: TID



Ionosphere waves: TID

From ionospheric research:

- Wavelength: 250-1000 km
- Velocity: 300-700 km/h
- Amplitude: 1-5%
- Direction: any
- Altitude: 200-400 km

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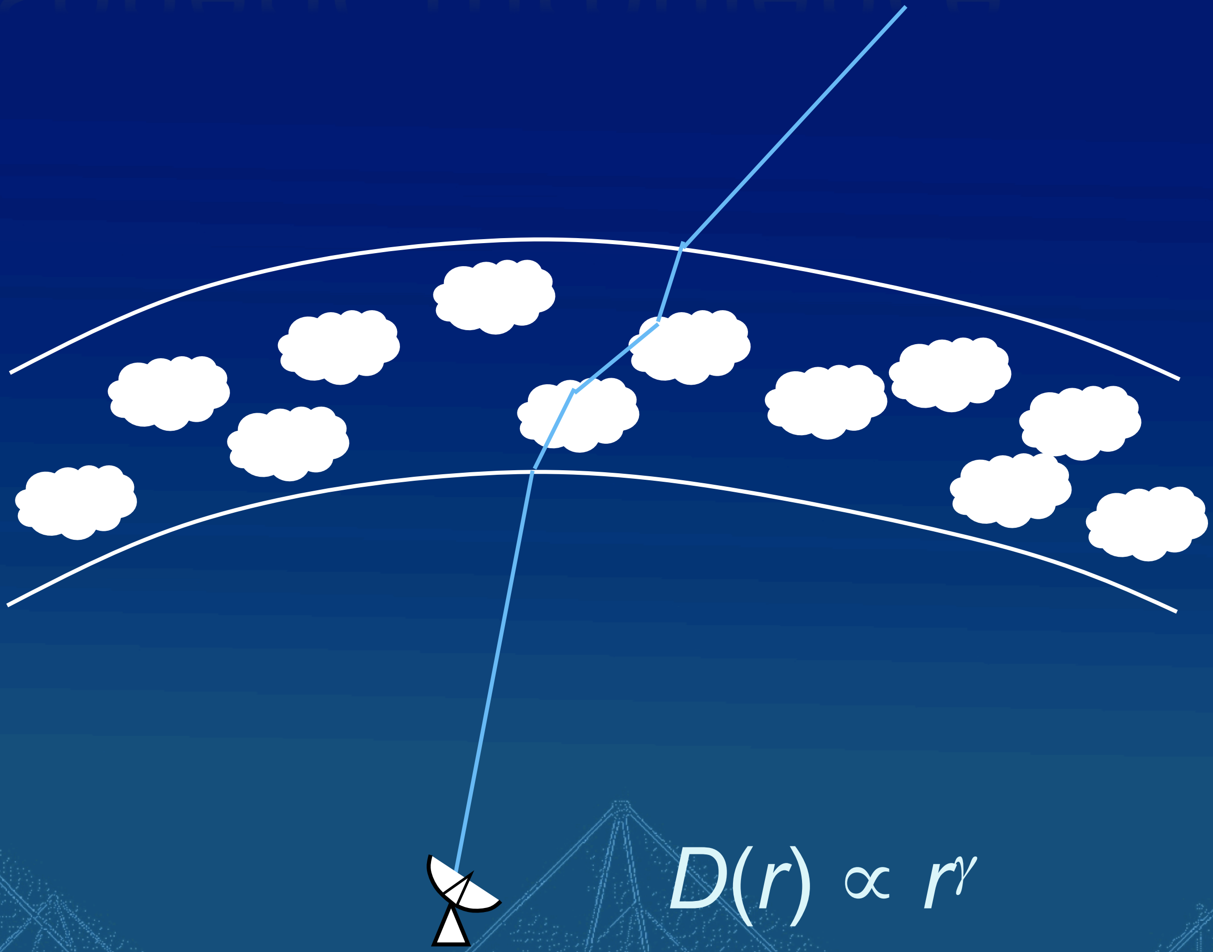
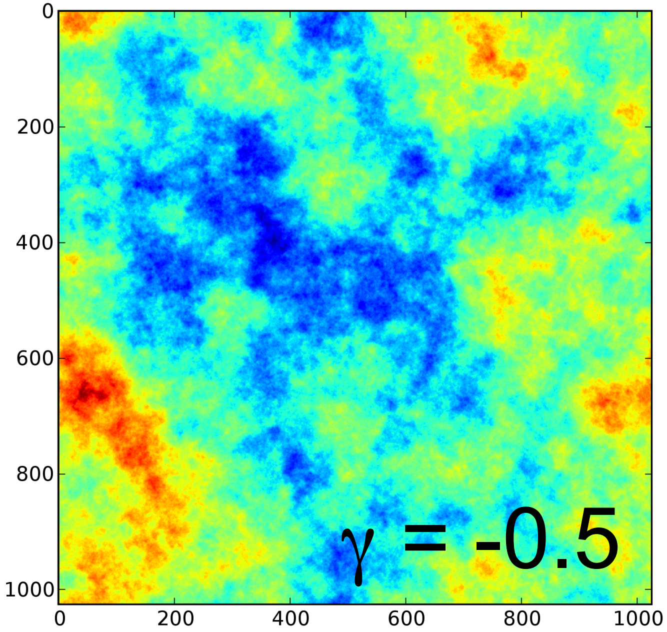
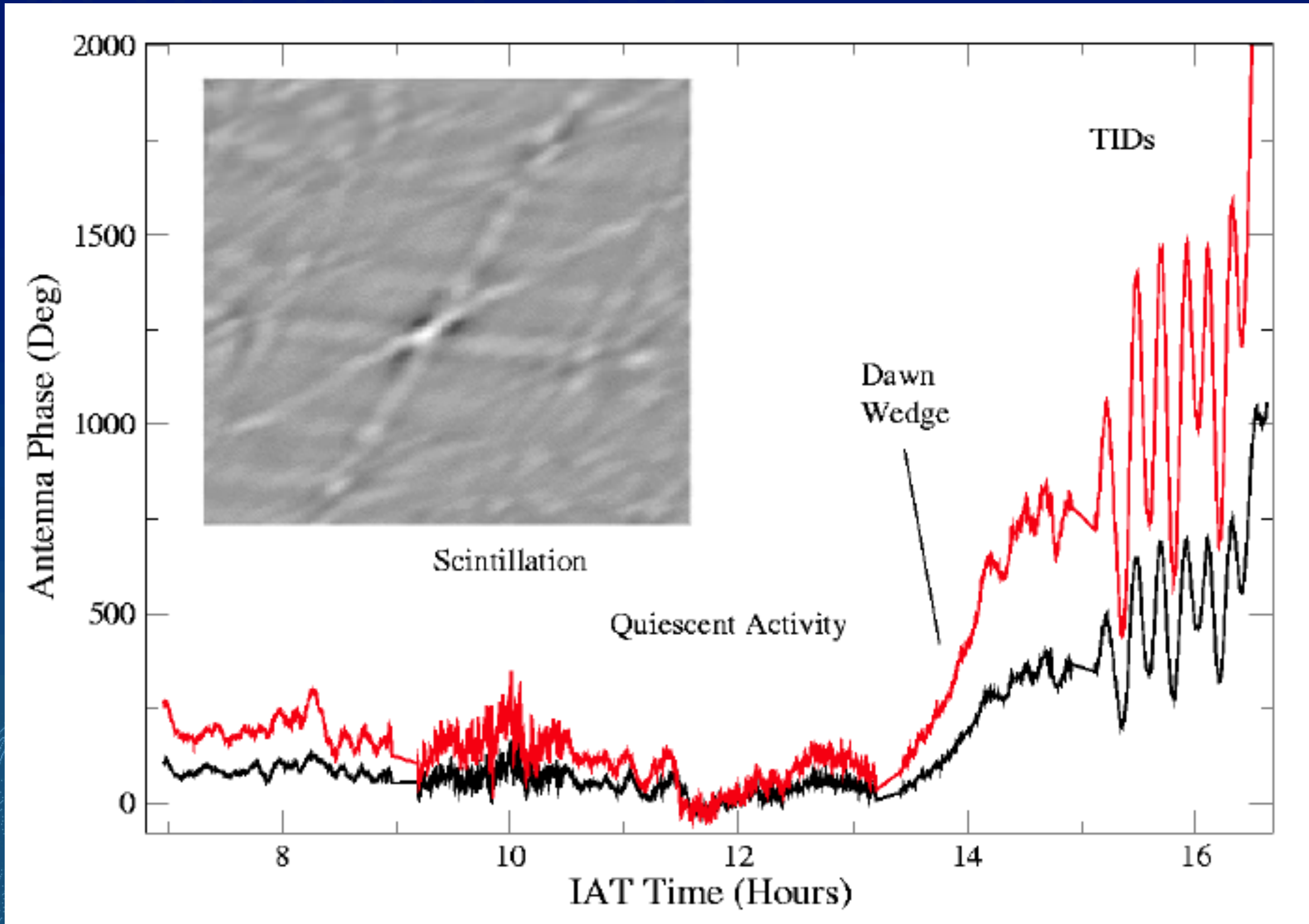
Ionospheric turbulence



Ionospheric turbulence



Why do we care?



Physical principles

How does the ionosphere affect radio waves?

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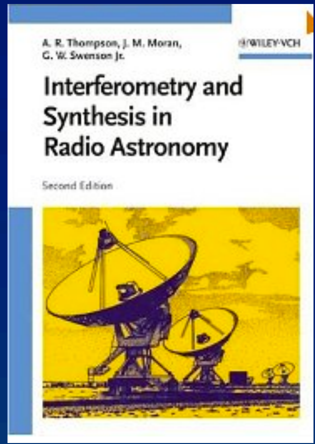
Physical effects

- Faraday rotation
- Refraction
- Absorption
- Reflection



For details see Chapter 13 of
Thompson, Moran & Swenson

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Some plasma physics

- Ionized plasma: electron density n_e
- No collisions, no magnetic field

Plasma frequency: $\nu_p \approx 9 \sqrt{n_e}$

- Linearly polarized wave: frequency ν

Refractive index: $n^2 \approx 1 - (\nu_p / \nu)^2$

Faraday rotation

- With magnetic field
- Parallel to propagation direction

Gyrofrequency: $\nu_c = eB / 2\pi m$

Refractive index:

$$n^2 = 1 - \frac{\nu_p^{\,2}}{\nu(\nu \mp \nu_c)}$$

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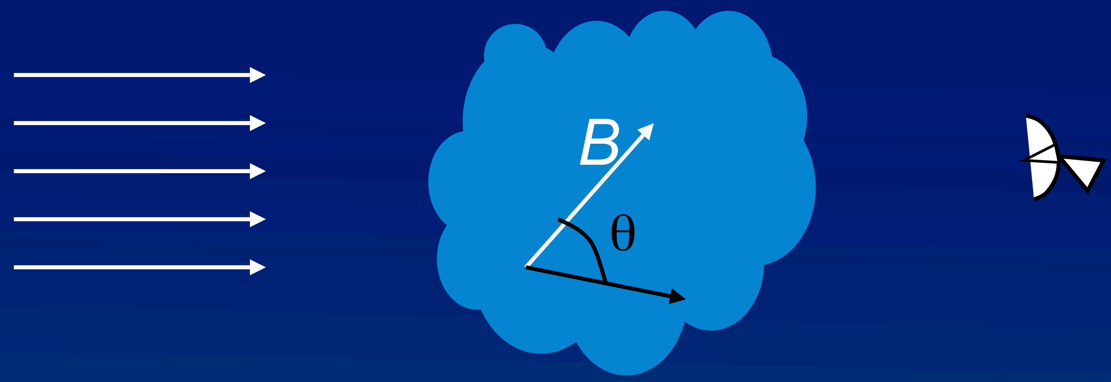
Faraday rotation



$$\Delta\Psi = 2.6 \times 10^{-13}\, n_e\, \lambda^2\, L\, B\cos\theta$$

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Refraction

- Refraction → excess pathlength

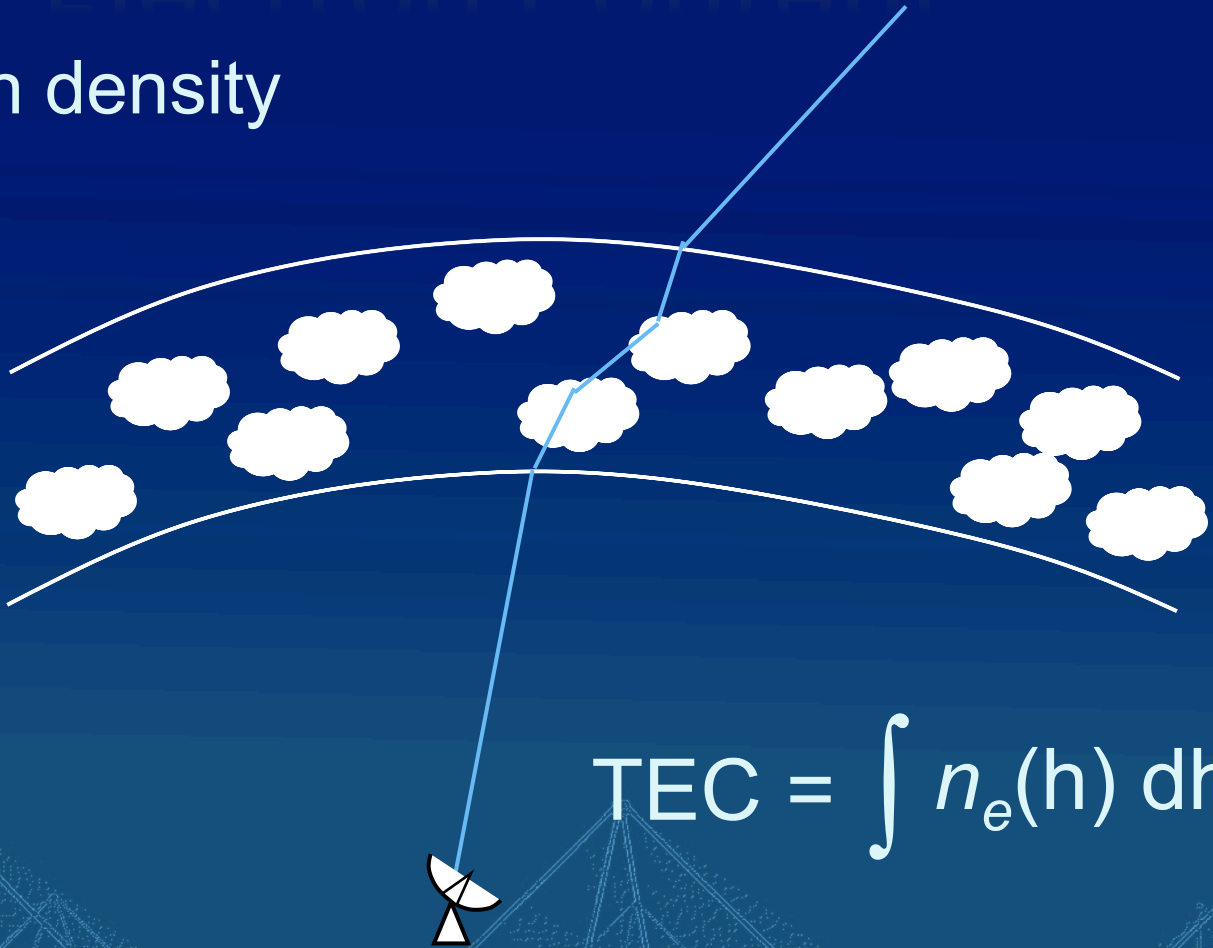
$$L_0 = \int [n(h) - 1]\, dh$$

- Pathlength → additional delay
- Delay → phase shift

$$\phi \approx -25\, \lambda\, \mathrm{TEC}$$

Total Electron Content

Column density



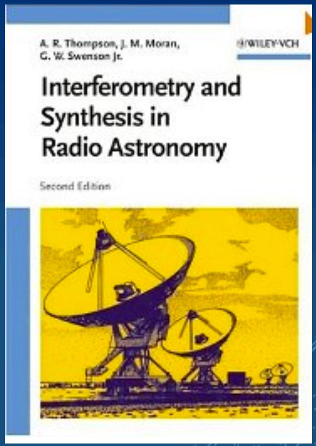
$$\mathrm{TEC} = \int n_e(h)\,dh$$

Other effects

- Decorrelation: amplitude drops
- De-focussing
- Absorption

↳ relatively small

For details see Chapter 13 of
Thompson, Moran & Swenson



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The essence

Ionosphere introduces phase variability

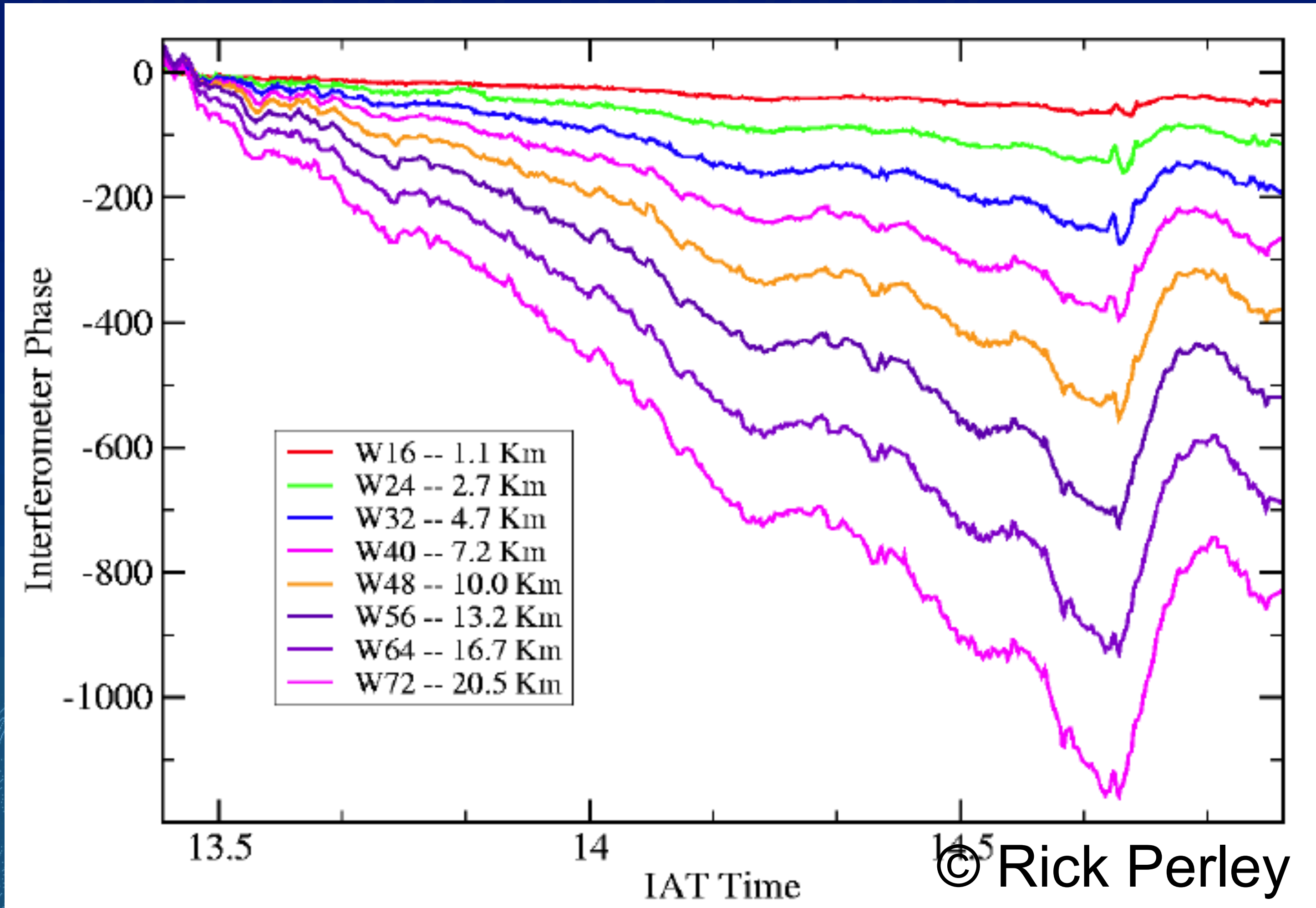
- in time
- in direction

$$\Delta\phi \approx -25\,\lambda\,\Delta\mathrm{TEC}$$

Imaging needs relative TEC

Polarization needs absolute TEC

Long vs short baselines



Calibration and simulation

Measurement equation

Calibration difficulties

Simulations in MeqTree

New calibration methods

Remember ME?

And That's The Measurement Equation!

$$\boldsymbol{V}_{pq} = \boldsymbol{J}_p \boldsymbol{B} \boldsymbol{J}_q^{\dagger}$$

- Or in more pragmatic terms:

$$\overbrace{\begin{pmatrix} XX & XY \\ YX & YY \end{pmatrix}}^{\text{measured}} = \overbrace{\begin{pmatrix} j_{xx(p)} & j_{xy(p)} \\ j_{yx(p)} & j_{yy(p)} \end{pmatrix}}^{\boldsymbol{J}_p} \overbrace{\frac{1}{2}\begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix}}^{\text{source}} \overbrace{\begin{pmatrix} j^*_{xx(q)} & j^*_{yx(q)} \\ j^*_{xy(q)} & j^*_{yy(q)} \end{pmatrix}}^{\boldsymbol{J}_q^{\dagger}}$$

- NB: it is also possible to write the ME with a circular polarization basis (RR, LL, etc.) We'll use linear polarization throughout.

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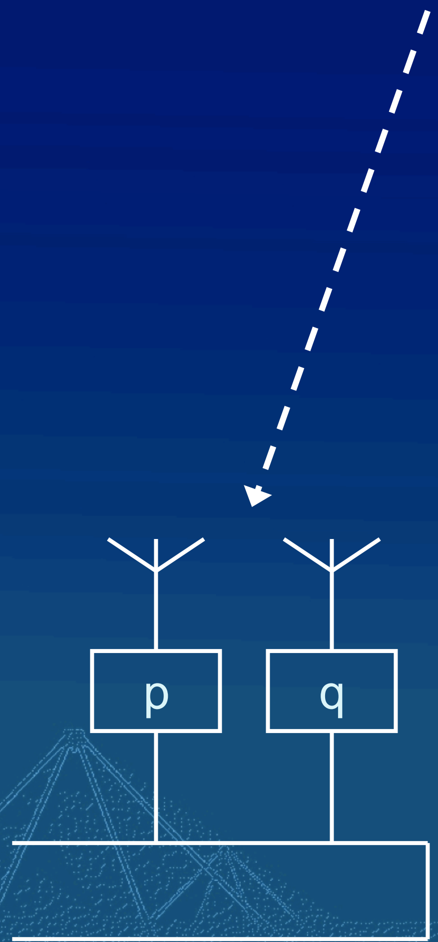
Ionosphere in ME



F: Faraday rotation

P: Parallactic rotation

C: Ideal feed response

D: Feed errors

G: Electronic gain

R

$$J = RCPF$$

$$V_{pq} = J\ B\ J^{\dagger}$$

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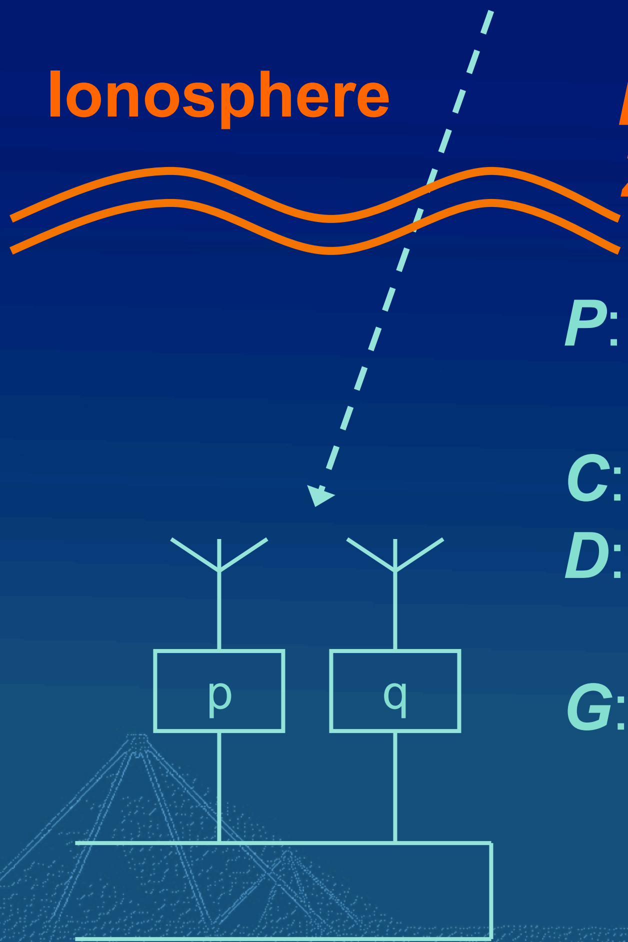
Ionosphere in ME



F: Faraday rotation
Z: phase change

P: Parallactic rotation

C: Ideal feed response
D: Feed errors
G: Electronic gain

$\left.\begin{array}{l} D \\ G \end{array}\right\} R$

$$J = RCPZF$$

$$V_{pq} = J\ B\ J^{\dagger}$$

ζ-jones

Also frivolous
and useless…

Z-jones

2 x 2 scalar Jones matrix

$$Z_J = \begin{bmatrix} e^{-i\phi} & 0 \\ 0 & e^{-i\phi} \end{bmatrix}$$

$$\phi_{ion} \approx -25\,\lambda\,\mathrm{TEC}$$

Z-jones

image plane effect: varies with *l,m*

Let's rewrite the $\boldsymbol{J}_p$ product as:

$$\boldsymbol{J}_p = \underbrace{\overbrace{\boldsymbol{J}_{pn} \cdots \boldsymbol{J}_{pk+1}}^{\text{uv-plane only}}}_{\boldsymbol{G}_p} \boldsymbol{K}_p \underbrace{\overbrace{\boldsymbol{J}_{pk-1} \cdots \boldsymbol{J}_{p1}}^{\text{uv- \& image-plane}}}_{\boldsymbol{E}_p(l,m)}$$

⇧

Z lives here

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Question to ponder

Can we ever perfectly correct for ionospheric effects?

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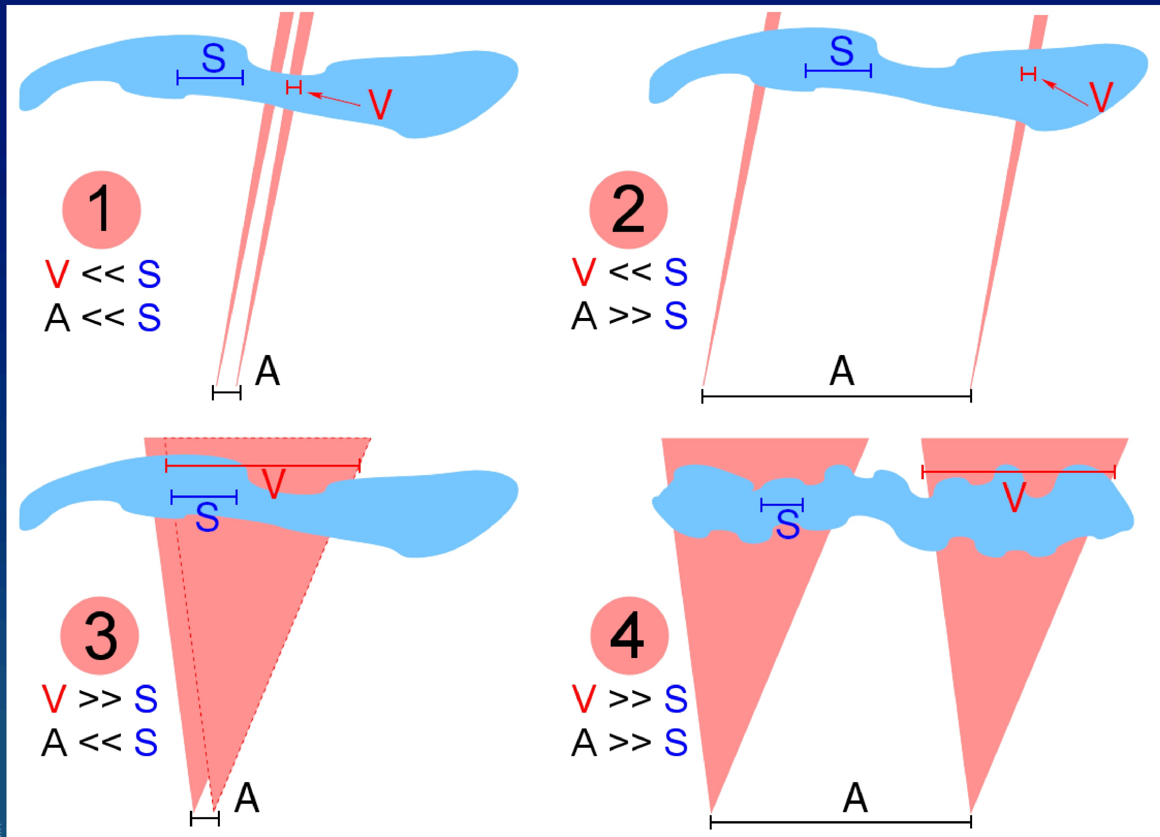
Calibration regimes



(Colin Lonsdale, 2005)

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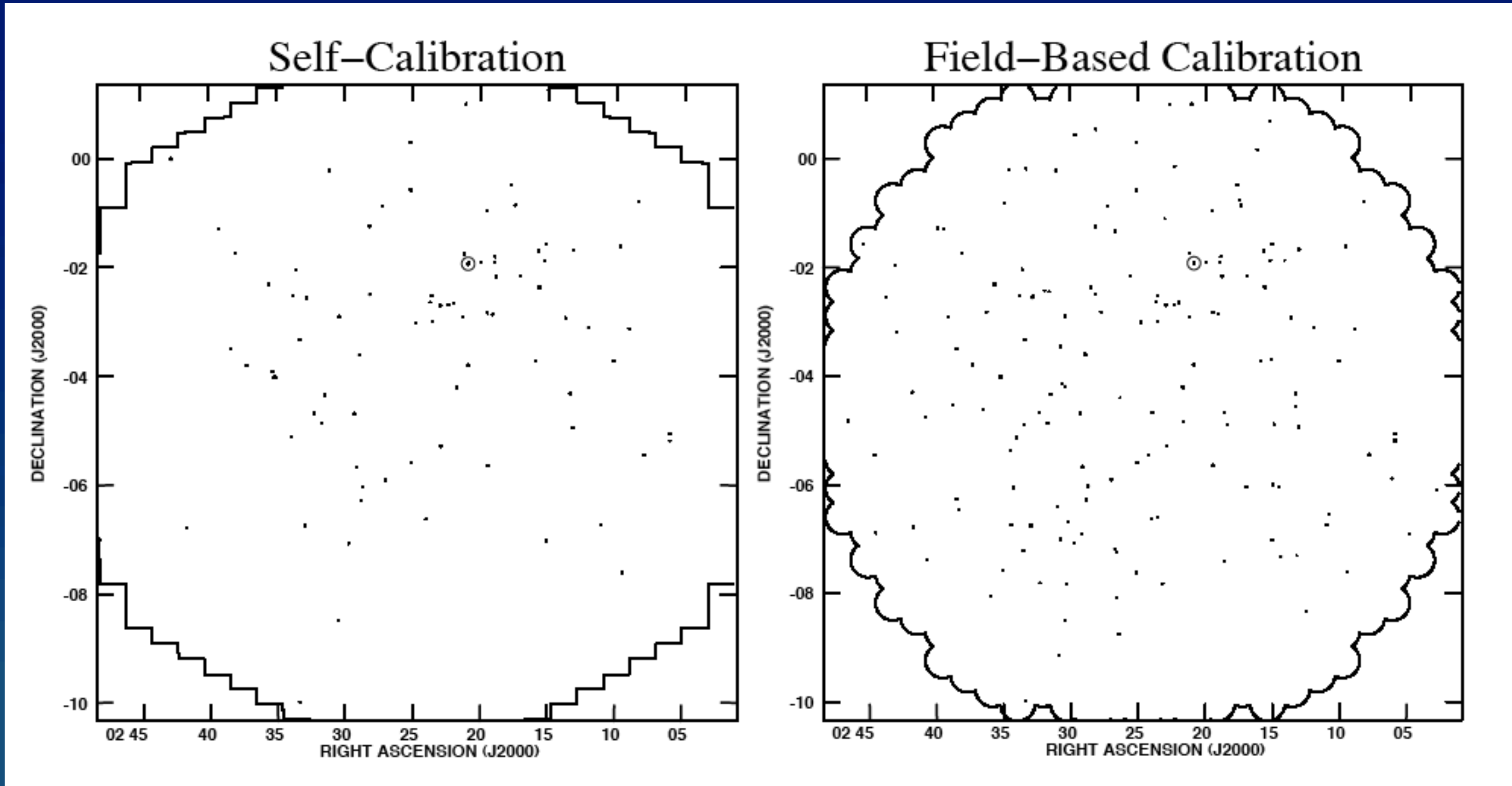
Traditional self-cal fails

Self-cal assumes constant phase error in FOV

Corrects *uv*-plane effects only
(independent of direction)

Traditional self-cal fails



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Now what?

- Simulate
  - Ionosphere model (weather forecast)
  - Instrumental limitations
  - Testbed for new calibration methods

- Next generation calibration techniques
  - Field-based calibration (Cotton et al. 2004)
  - SPAM (Intema et al. 2008, 2009)
  - New methods?

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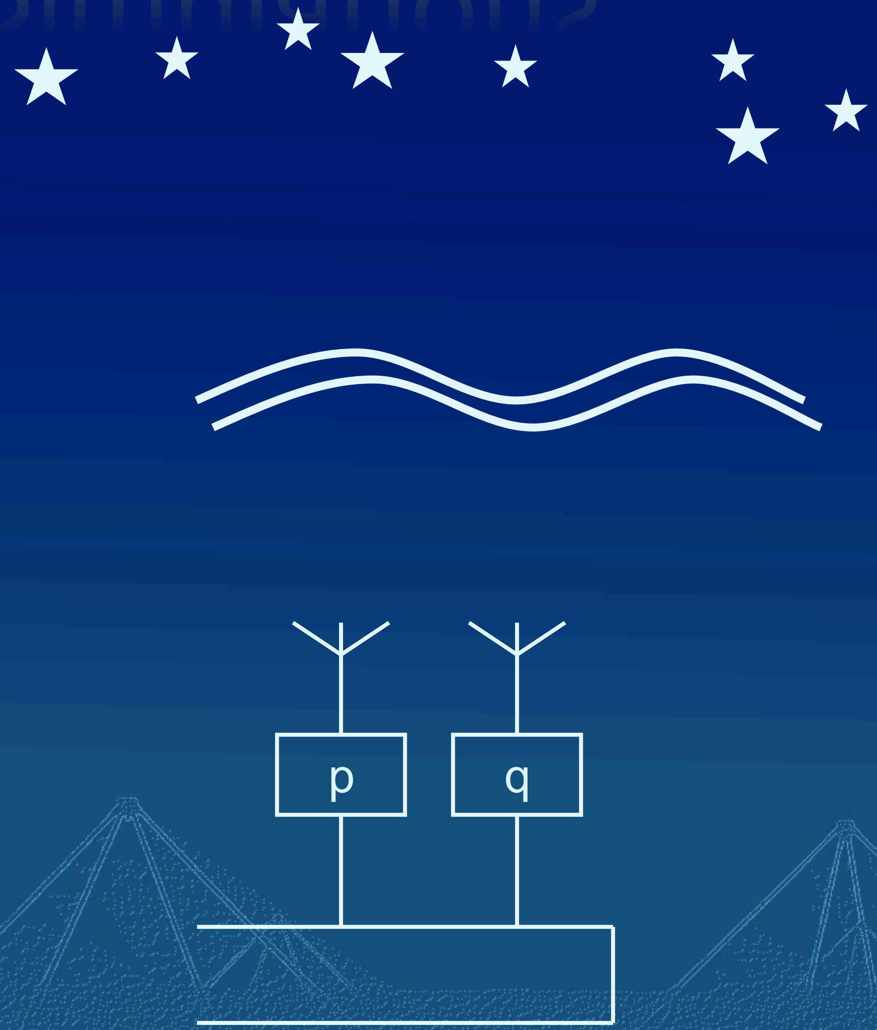
Simulations



Sky model

Ionosphere model

Instrument model

Software: **MeqTree**

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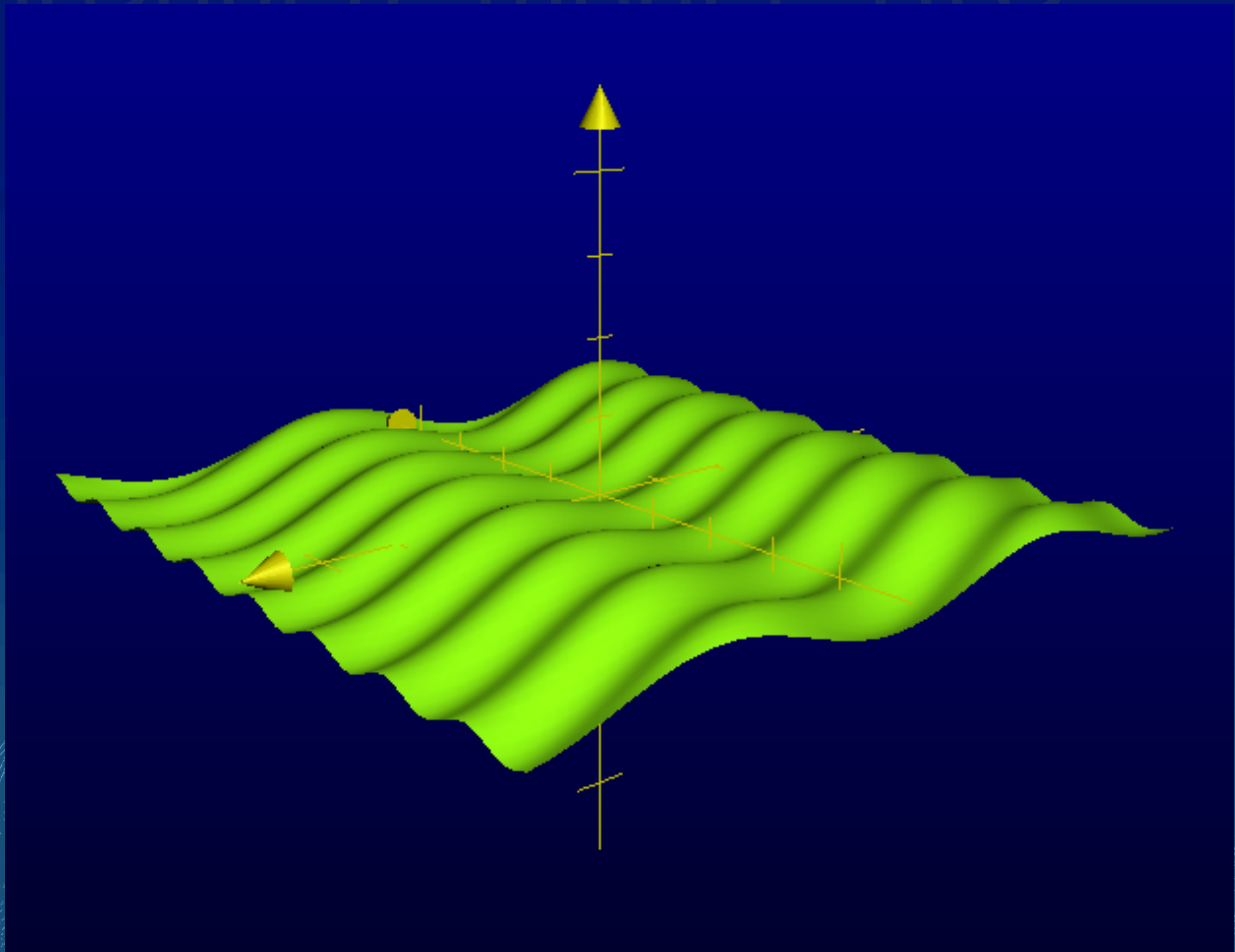
Ionosphere model: TIDs



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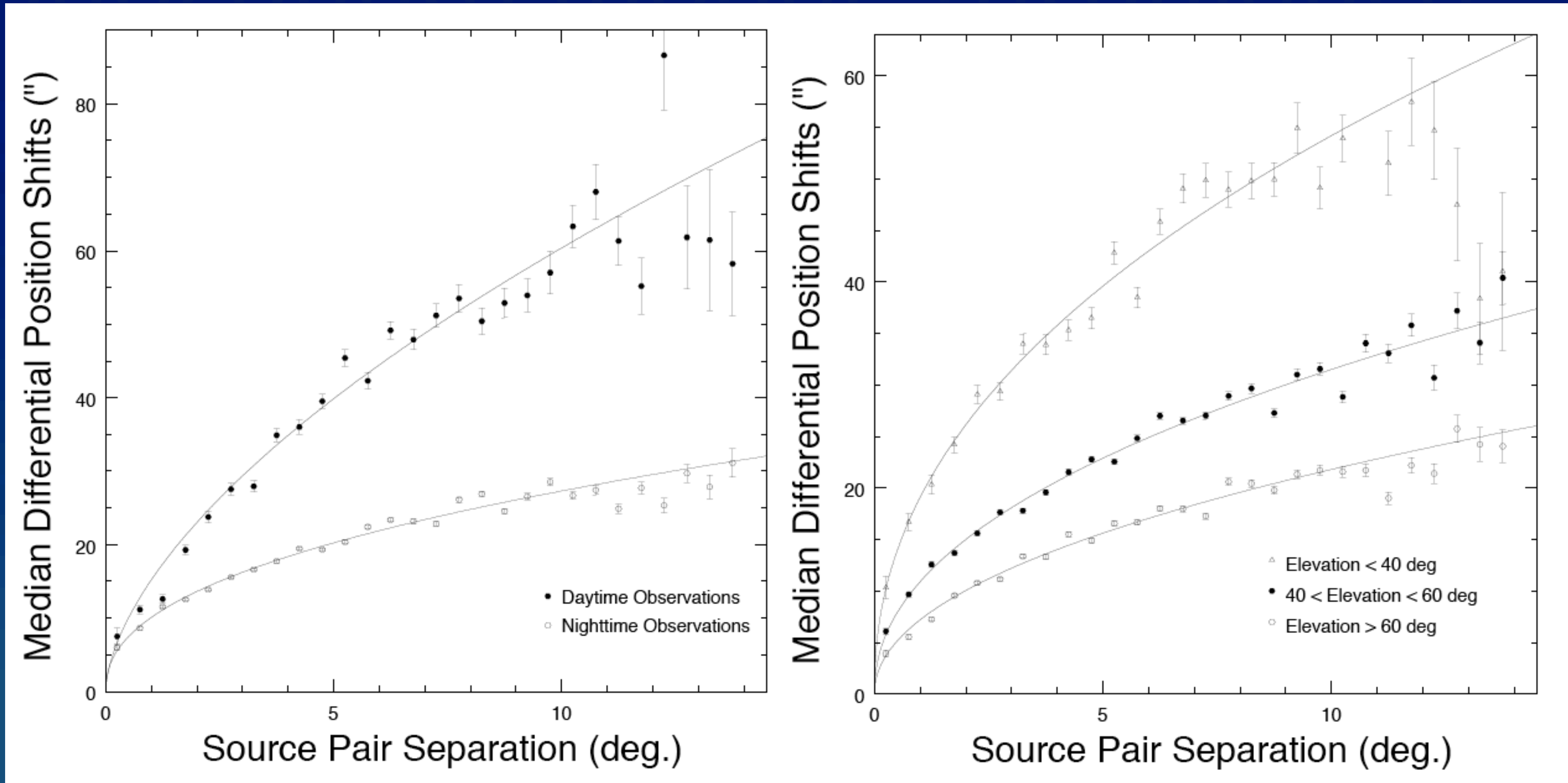
Ionosphere model: turbulence



Cohen & Röttgering, 2009

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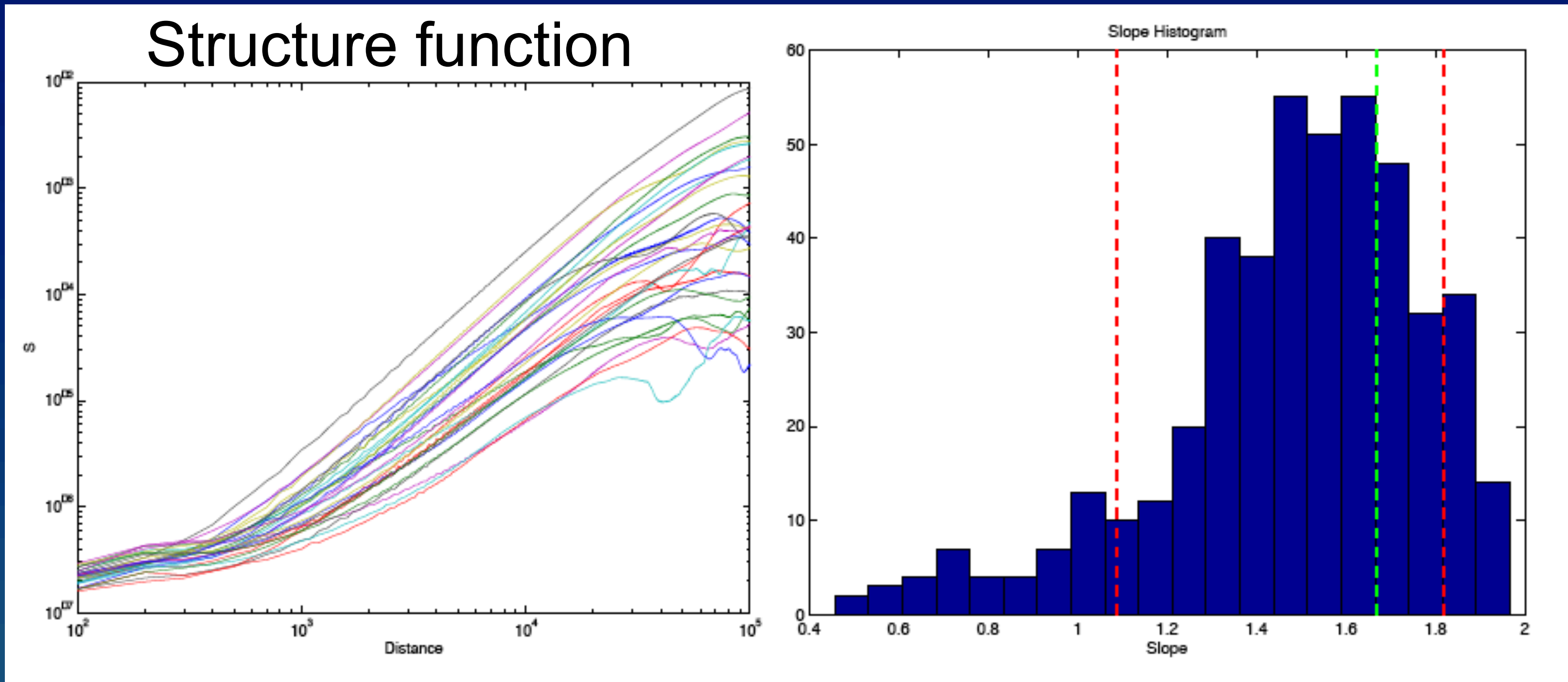
Ionosphere model: turbulence

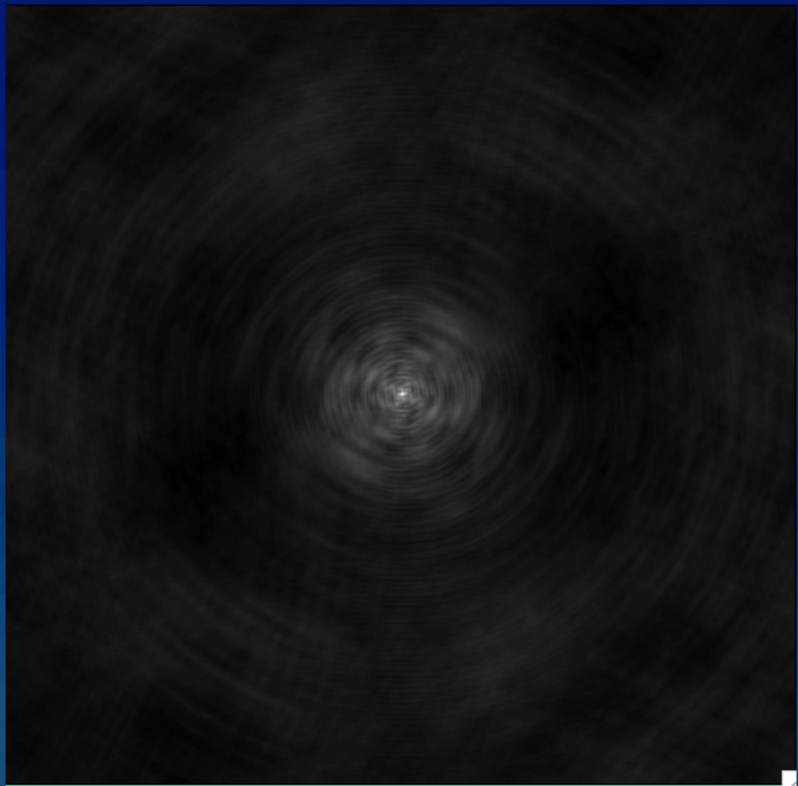


LIONS framework

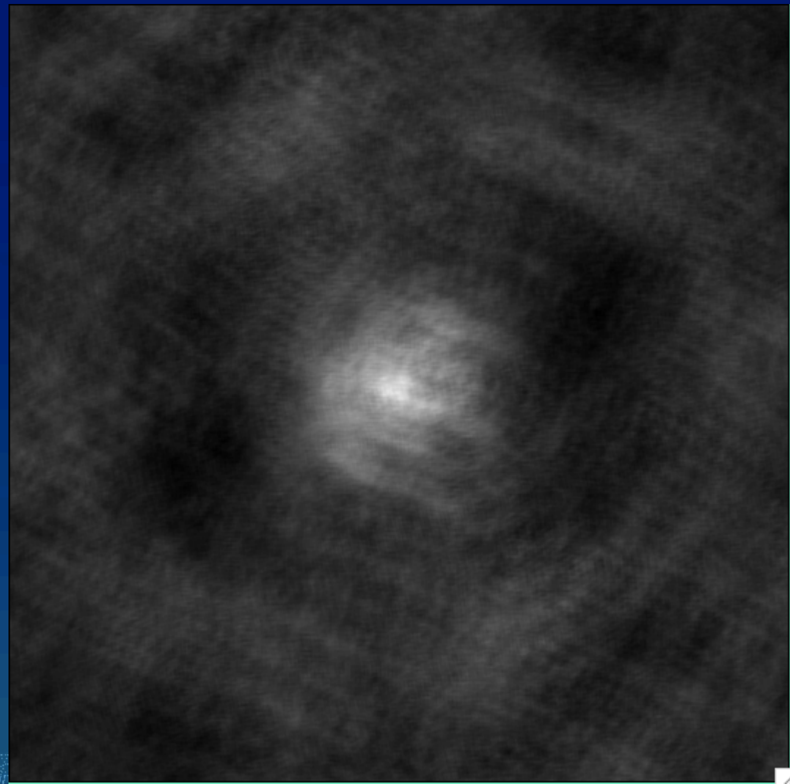
- MeqTree ionosphere module
- TID and Kolmogorov turbulence
- Different sky models
- Any instrument (input MS)

Come and see me for a demo
if you're interested

Ionosphere effects

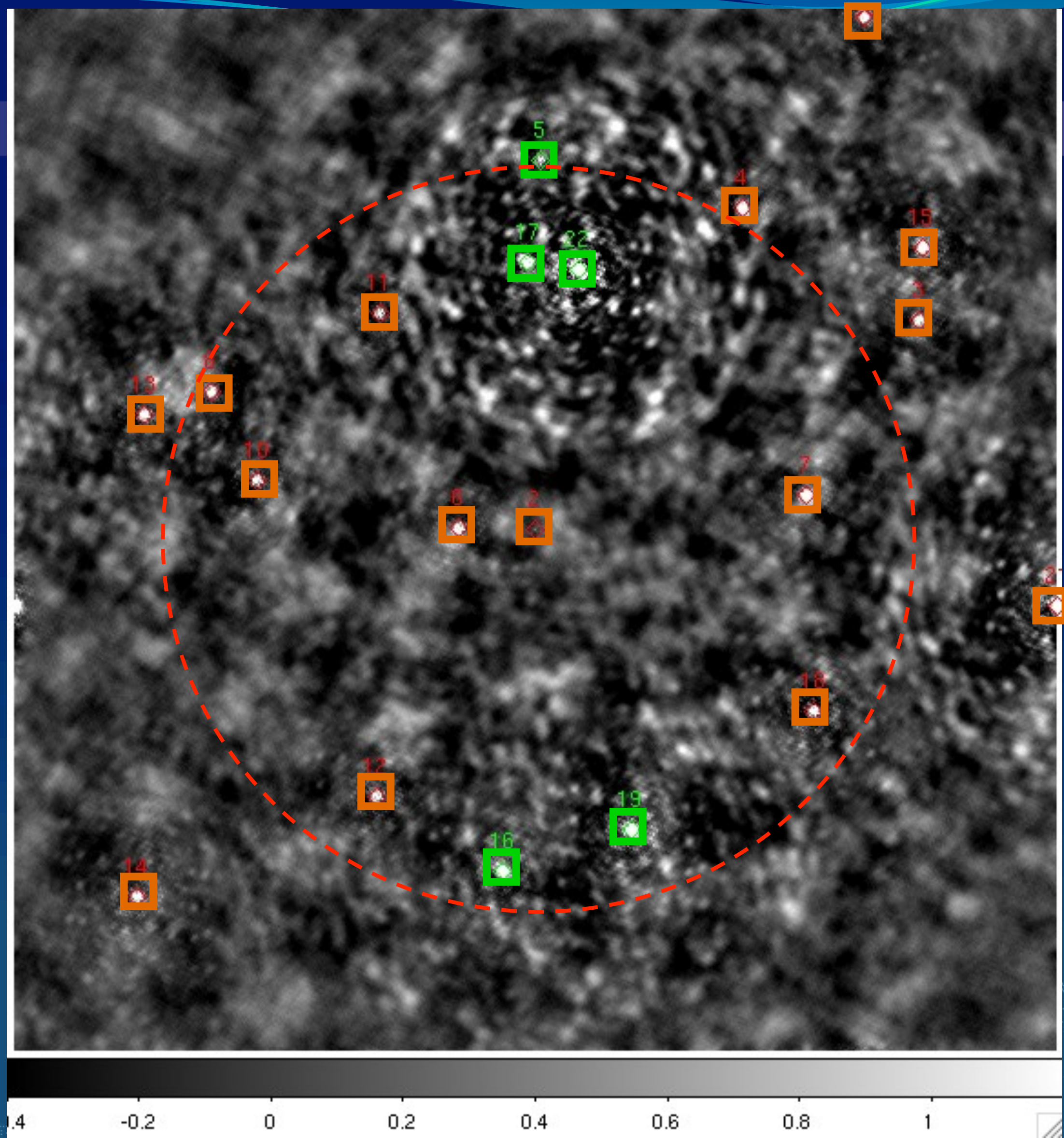


without ionosphere

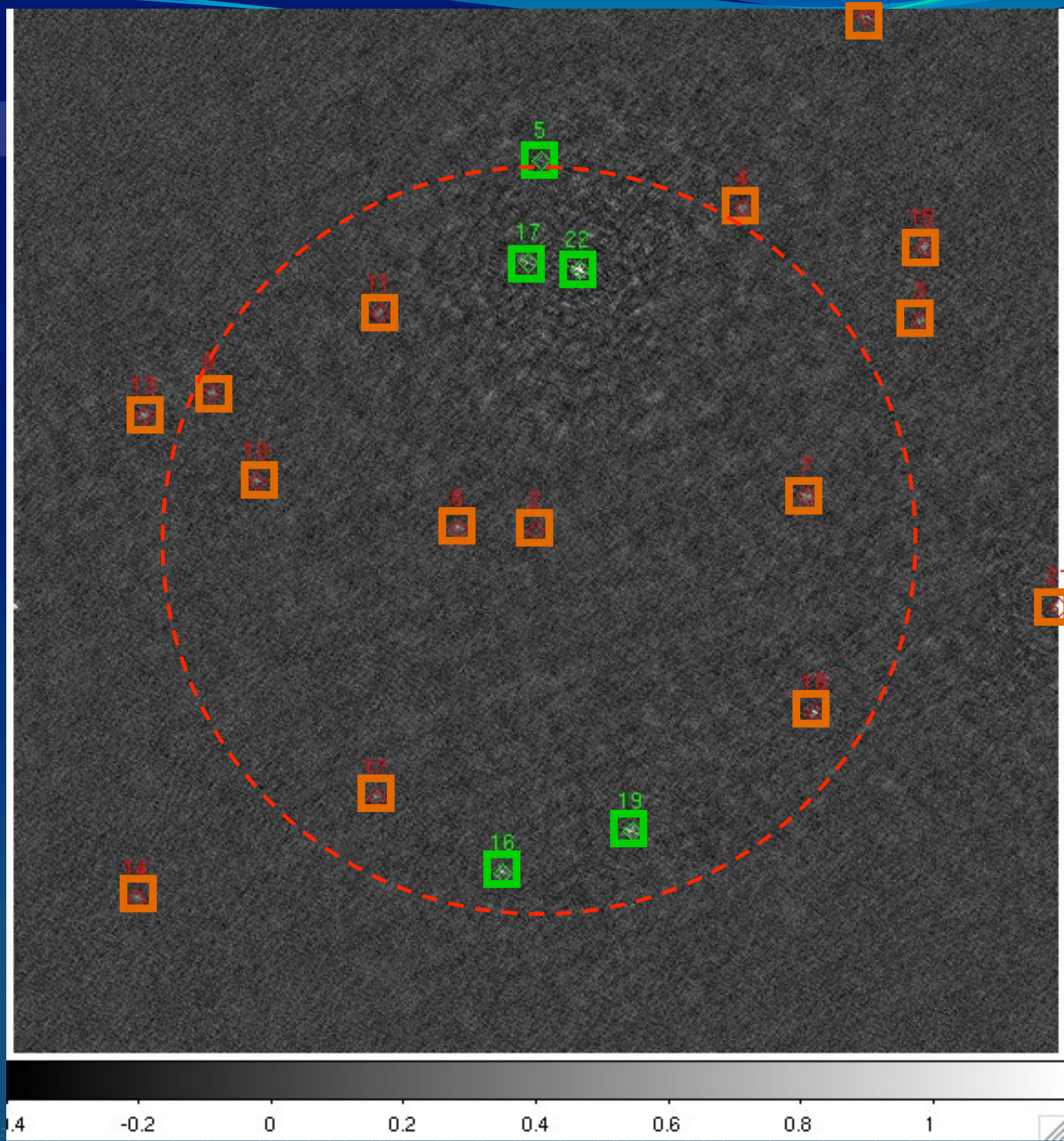


with ionosphere TID

Result



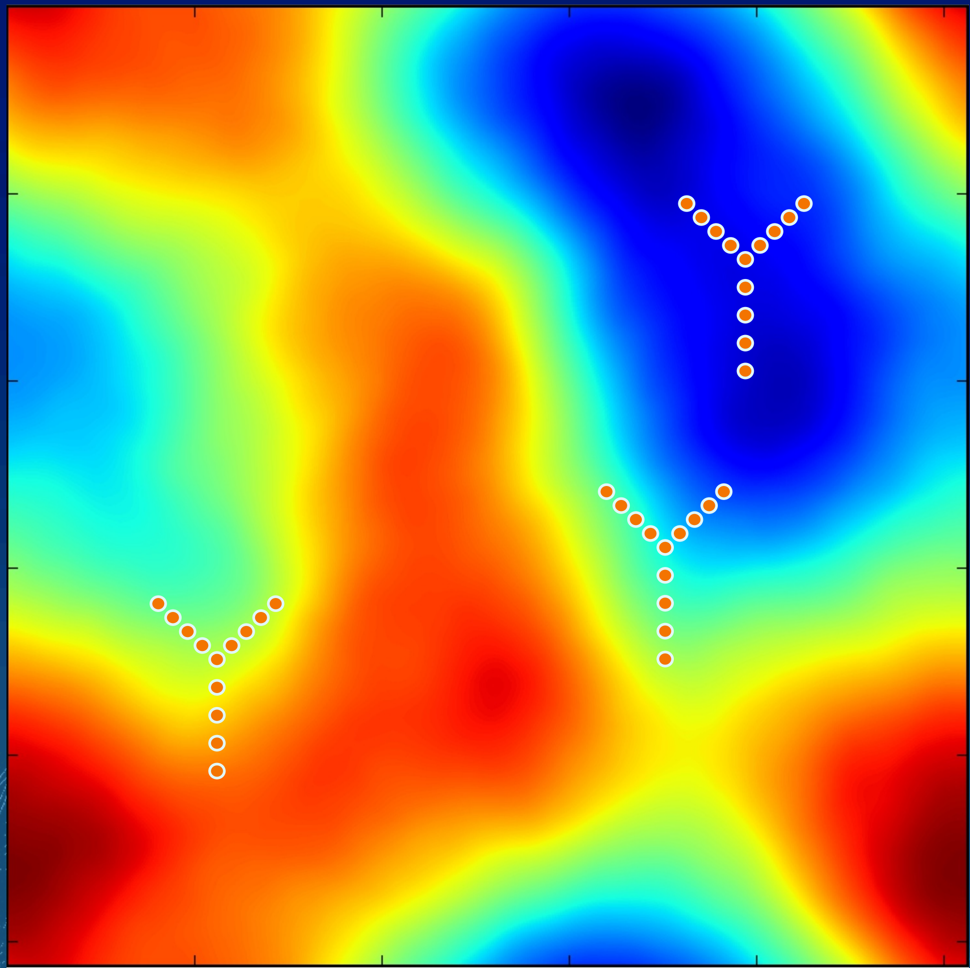
Result



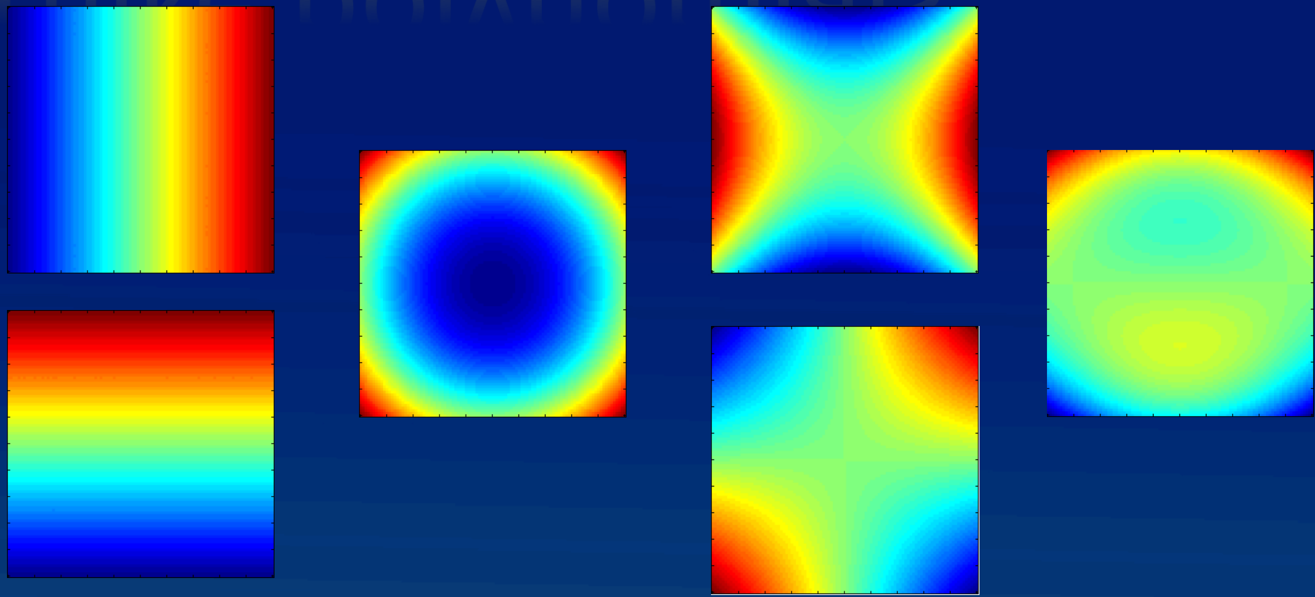
New calibration methods

- Get ionospheric phases
  - Time interval
  - Position / viewing direction
- Fit a model to observed phases per timestep
- Interpolate model to correct each timestep
- Image corrected data

Pierce-points



Zernike polynomials

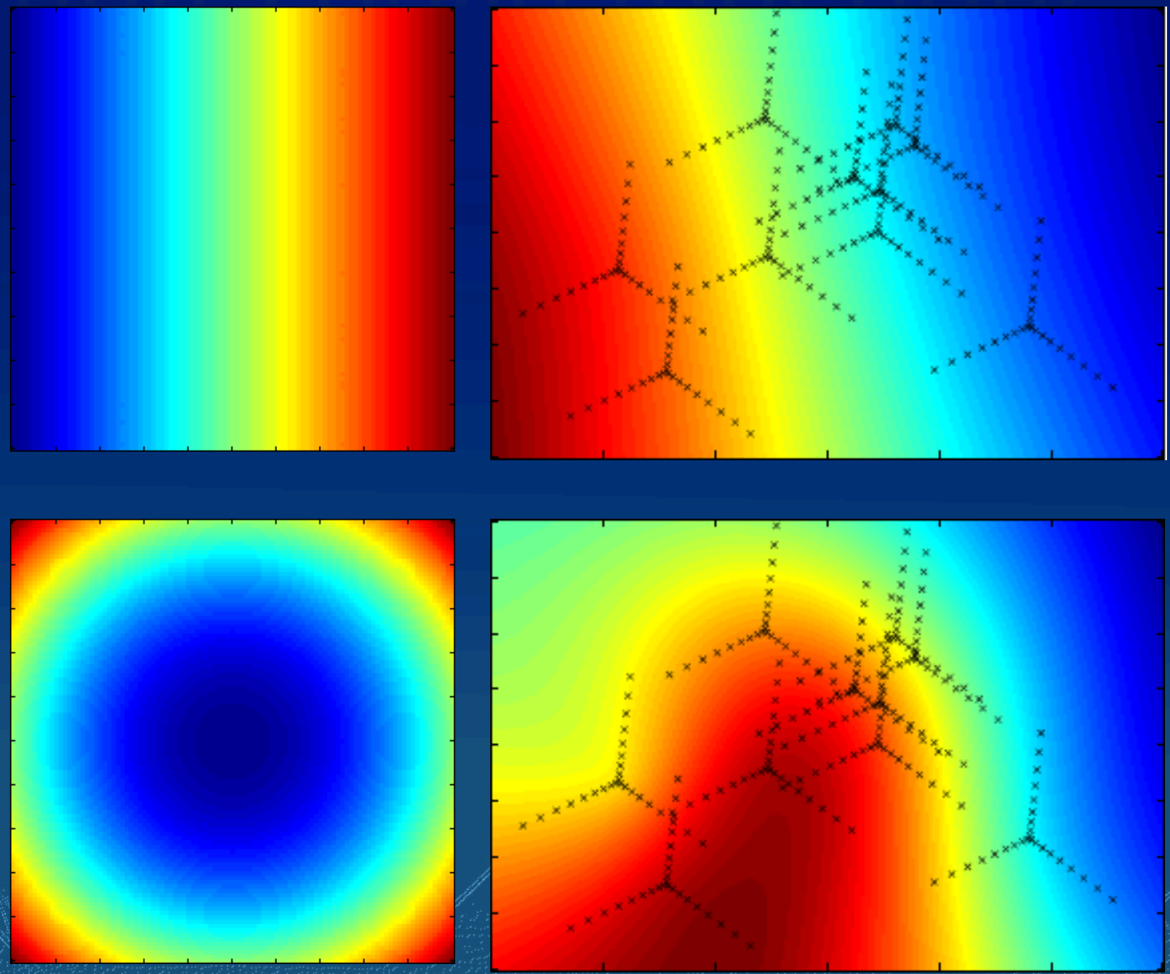


$z2 = \rho\, \mathrm{Cos}[\theta];$	Tilt x
$z3 = \rho\, \mathrm{Sin}[\theta];$	Tilt y
$z4 = -1 + 2\rho^2;$	Power
$z5 = \rho^2\, \mathrm{Cos}[2\theta];$	Astig x
$z6 = \rho^2\, \mathrm{Sin}[2\theta];$	Astig y
$z7 = \rho\,(-2 + 3\rho^2)\, \mathrm{Cos}[\theta];$	Coma x
$z8 = \rho\,(-2 + 3\rho^2)\, \mathrm{Sin}[\theta];$	Coma y

Karhunen-Loève functions

Z2

Z4



Basis functions

- Regular polynomial
  - Taylor series for TIDs
  - Chebyshev
- Zernike polynomials (optics)
- Karhunen-Loève functions

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Karhunen-Loève functions

- Known pierce-point locations
- Assume certain ionospheric statistics

  e.g. turbulence: $D(r) \propto r^{\gamma}$
- Fix height and γ
- Transform Zernike polynomials

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Field-based calibration

- Solve for ϕ_{ion} as function of position within the FOV
- Use 2nd order Zernike polynomials
- Assumptions
  - All baselines << isoplanatic patc
  - Smooth ionosphere

Cotton et al., 2004

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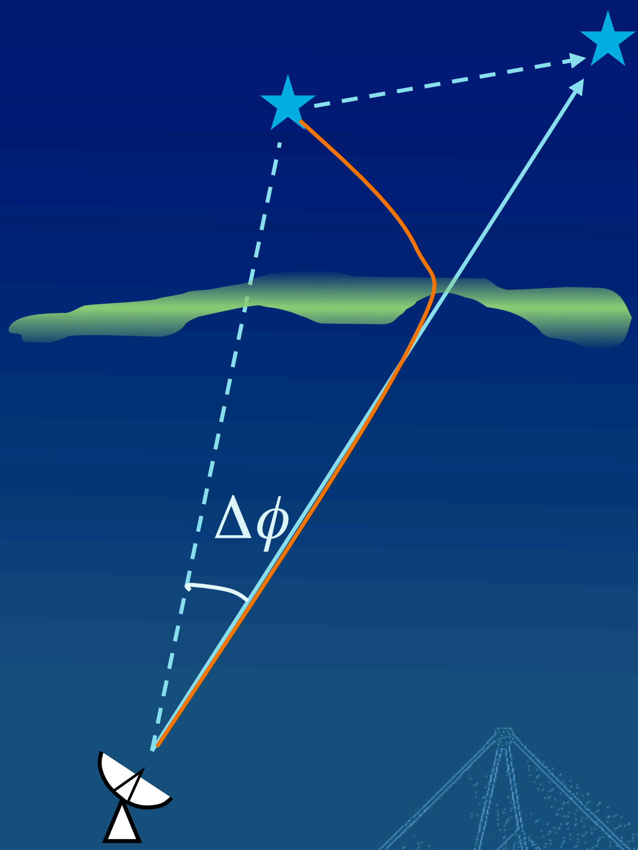
Field-based calibration



Field-based calibration

- Get $\phi_{obs}(t)$ for calibrators
- Fit $\phi_{mod}(t)$ over field (gradient only)
- Apply correction per time step
- Make an image

Works in calibration regime 3, not in 4…

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Featuring SPAM

Source

Peeling &

Atmospheric

Modeling

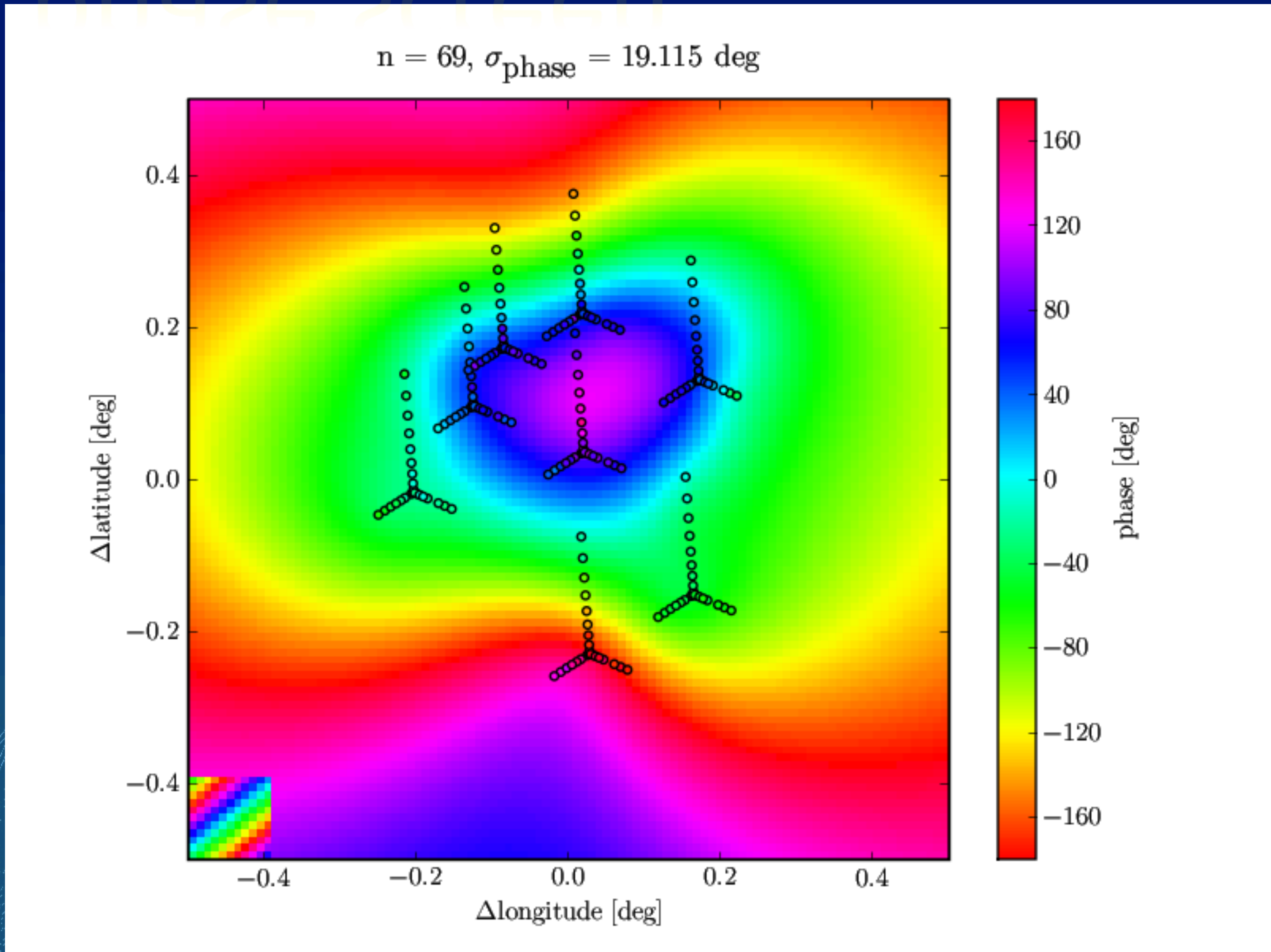
© Monty Python, Huib Intema (NRAO)

SPAM principle

- Get $\phi_{obs}(t)$ from peeling of calibrators
- Fit model on KL basis
- Correct each facet with model phase
- Make image

Not limited to gradients only!

Fit phase screen



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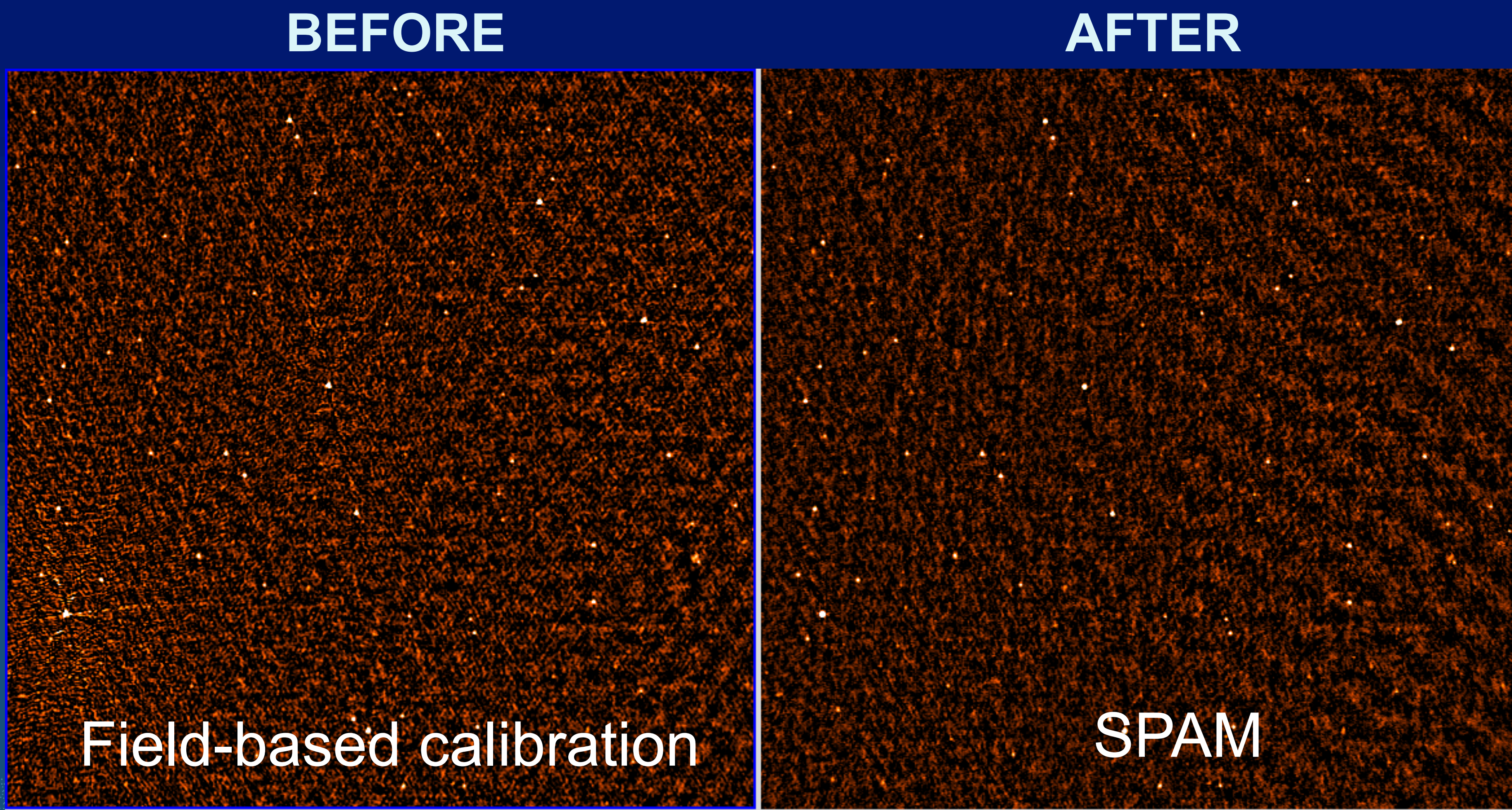
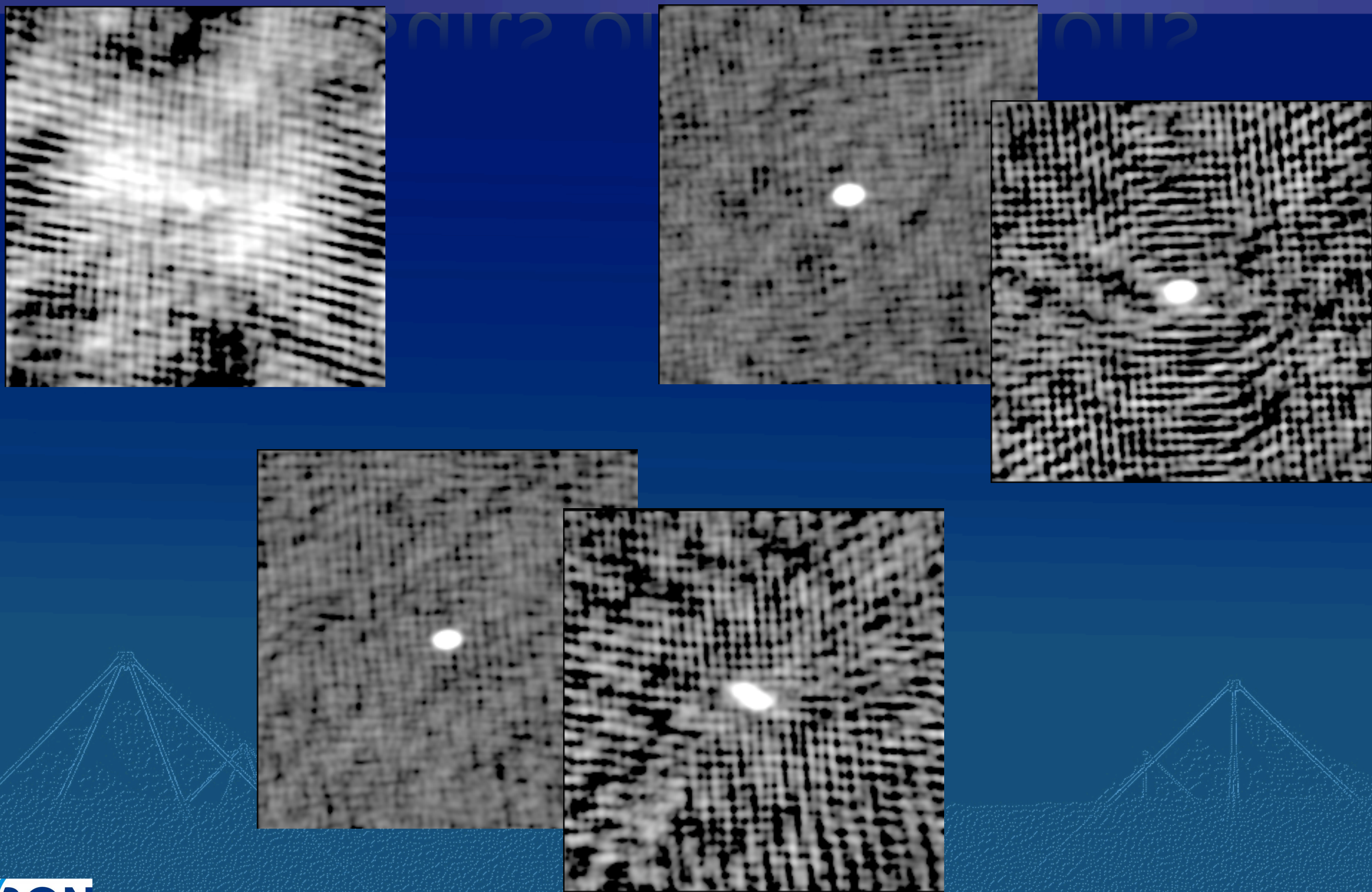
SPAM imaging



SPAM results on simulations



In the making

Clock-TEC analysis (van der Tol)

BBS direction dependent gain solutions:

- Timestep
- Frequency (subband/channel)
- Station
- Source

Fit per timestep for all baselines:

TEC phase $\propto \lambda^{1}$

Clock phase $\propto \lambda^{-1}$

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Question to ponder

Can we ever perfectly correct for ionospheric effects?

Thanks!