

# Methods for correcting higher order ionospheric effects

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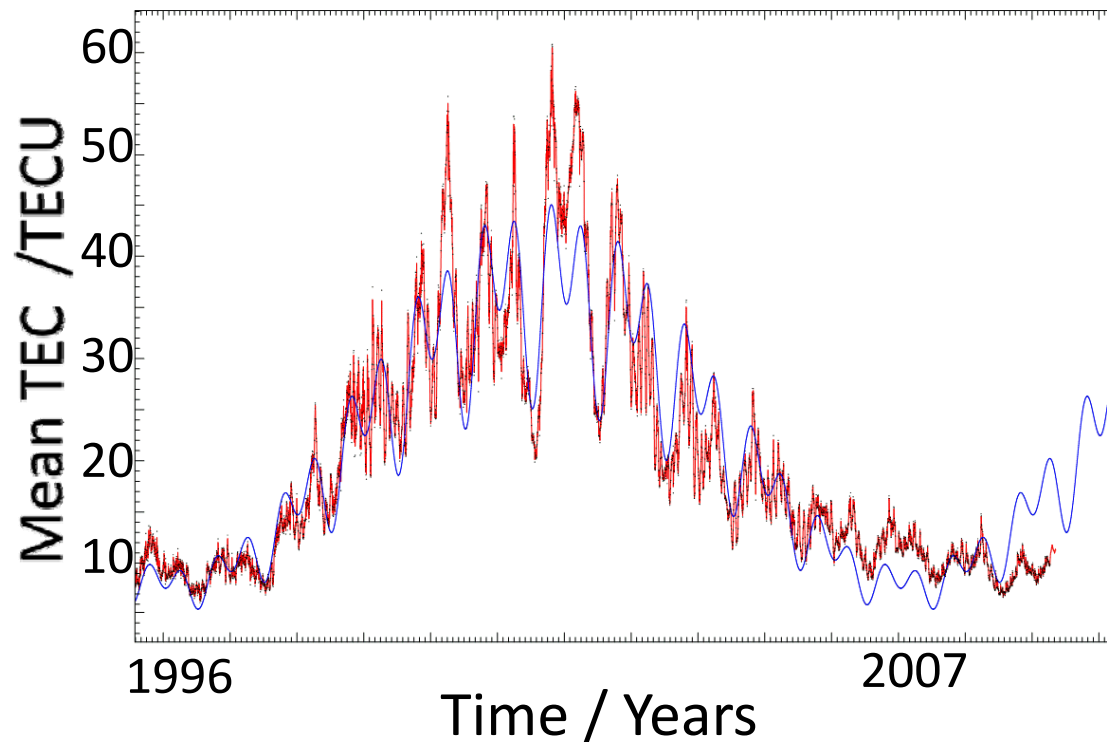
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- 2) gAGE/UPC, Barcelona, Spain
- 3) Delft Institute of Earth Observation and Space Systems, Delft University of Technology, The Netherlands

Liz Petrie was funded by NERC



# Why?

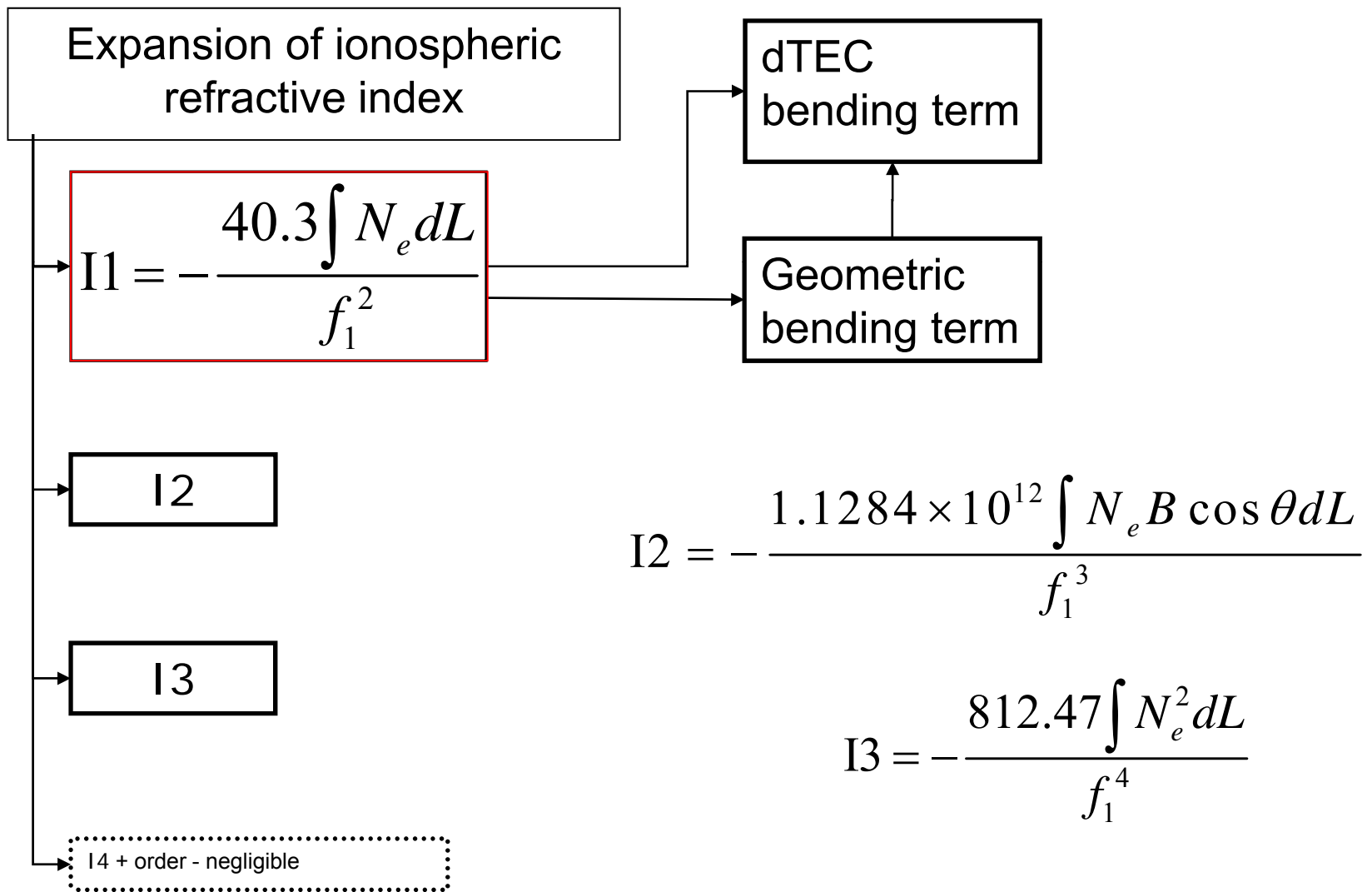
- Higher order effects not removed when using ‘ionosphere-free’ linear combination
- Long term cycles in ionospheric activity



Change in the Earth's mean Total Electron Content (TEC) since 1995

Centre for Orbit Determination in Europe (CODE)  
<http://aiuws.unibe.ch/ionosphere/meantec.gif>

# Higher order ionospheric terms



# Ionospheric effects

1<sup>st</sup> order phase delay

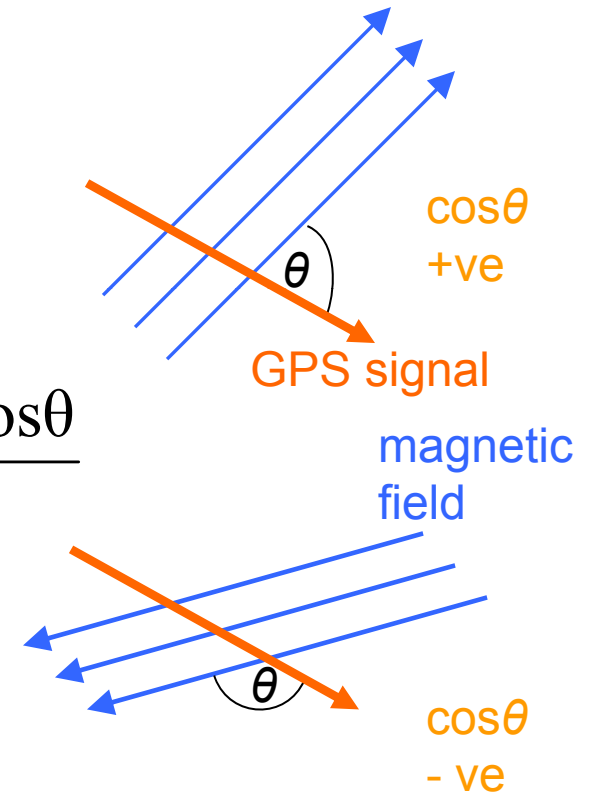
$$= - \frac{\text{constant} * \text{TEC}}{\text{signal frequency}^2}$$

2<sup>nd</sup> order phase delay

$$= - \frac{\text{constant} * \text{TEC} * \text{magnetic field} * \cos\theta}{\text{signal frequency}^3}$$

3<sup>rd</sup> order phase delay

$$= - \frac{\text{constant} * \text{TEC}^2 * N_m * \eta}{\text{signal frequency}^4}$$



# Processing

- GPS reprocessing: 5 comparison runs

Without higher  
order effects

‘Base’

I2 and I3  
modelled

‘IGRF’

‘Dipole’

I2 only  
modelled

‘IGRF2’

I2,I3 and bending  
modelled

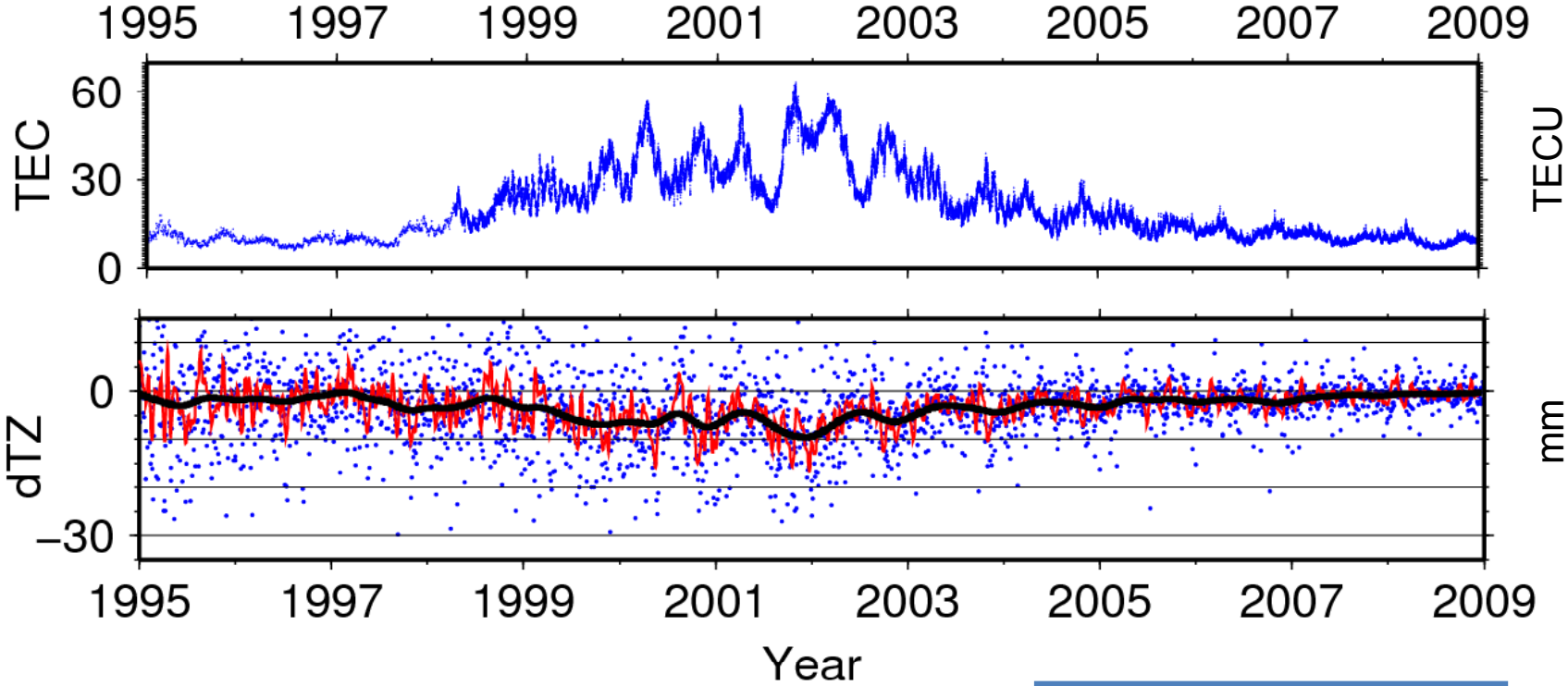
‘Bending’

Hoque & Jakowski  
(2008) empirical  
formulae used

## Strategy

- 60 sites in a global fiducial-free network
- GAMIT v10.35 (adapted)
- odd days during 1995-2008
- VMF1 troposphere mapping functions
- absolute antenna phase center offsets
- met files/VMF1 for a priori zenith hydrostatic delay
- sub-daily atmospheric loading

# Effect of I2 and I3

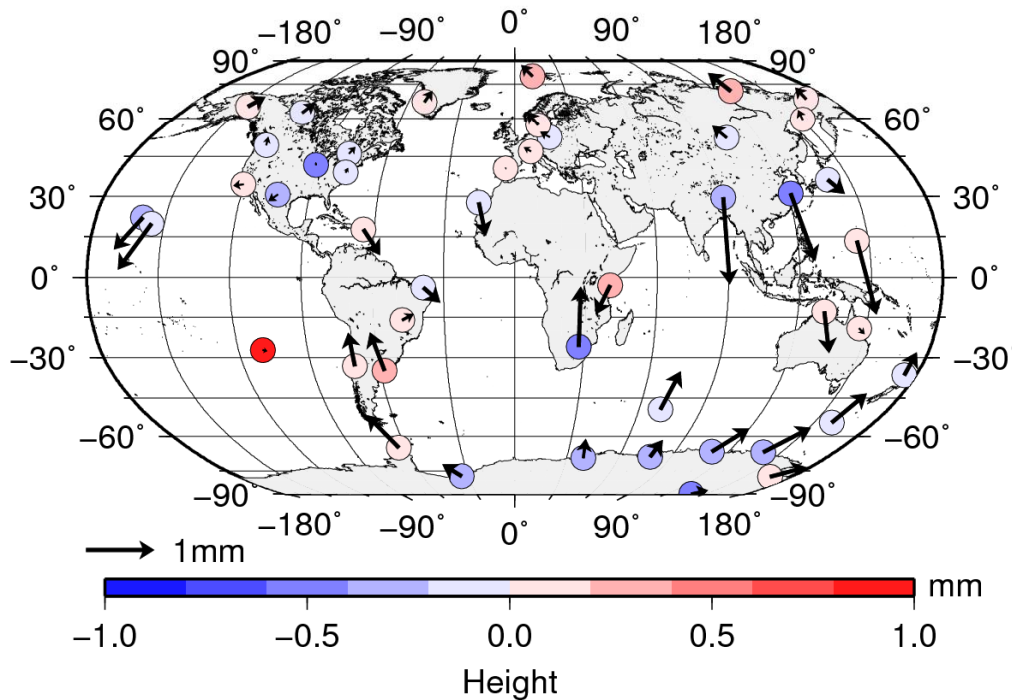


'Base'-IGRF

- 7 day Gaussian smoothing
- 90 day Gaussian smoothing

Data in Petrie et al. (2010)  
J Geophys Res 115(B3): B03417

# Effect of I2 and I3



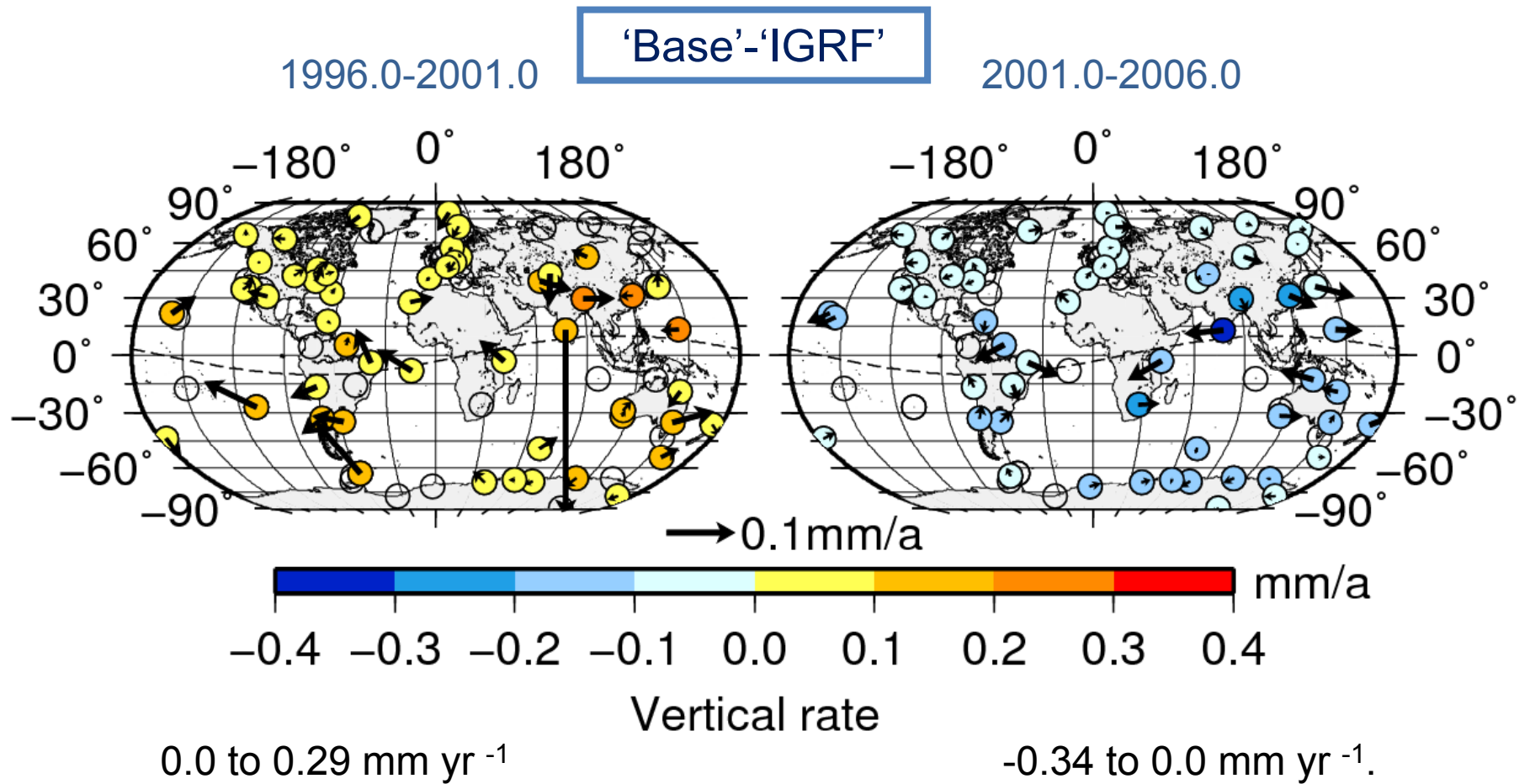
Mean coordinate differences

2000.0-2003.0

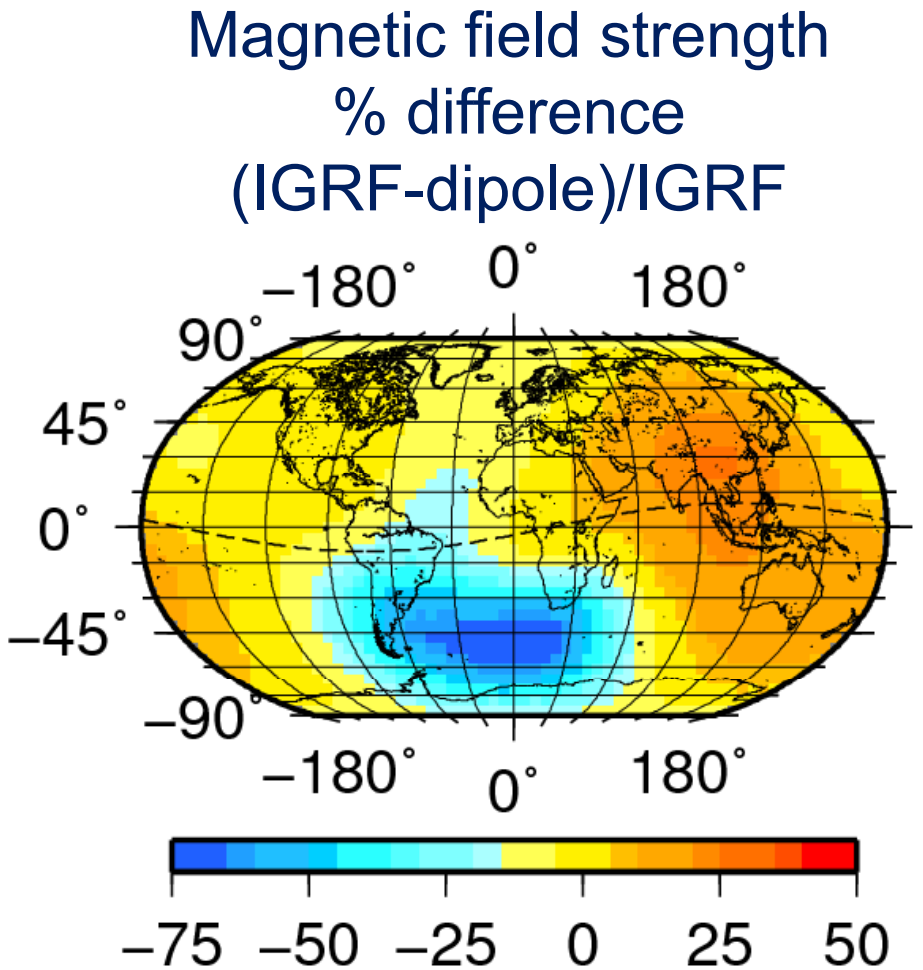
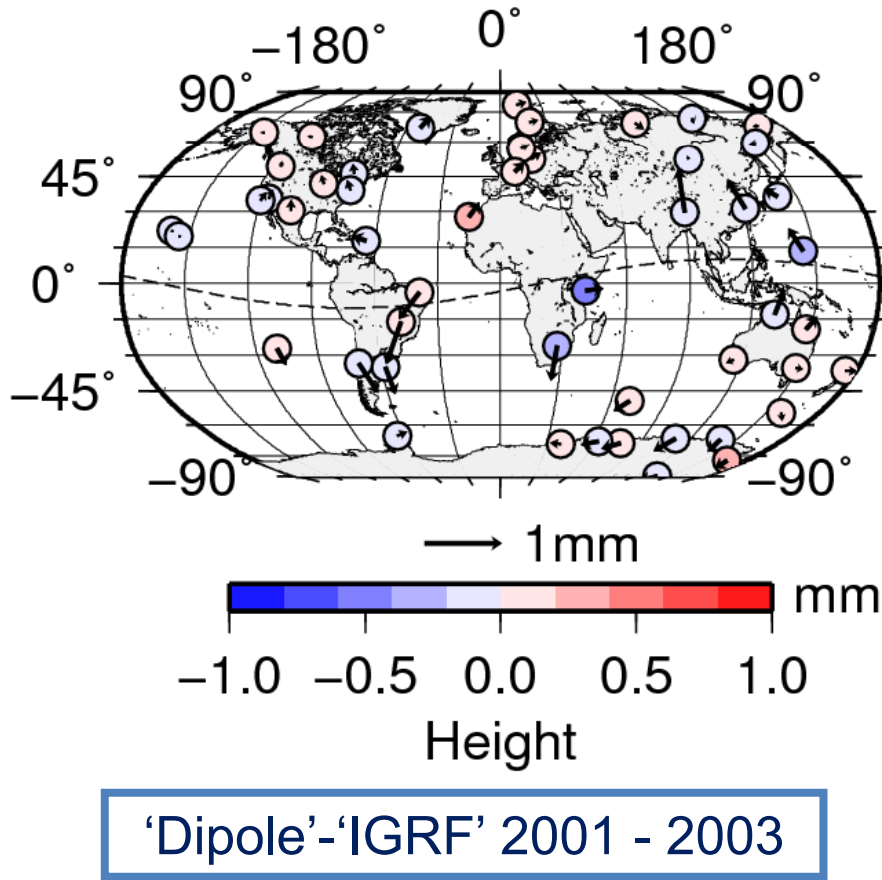
Sites shown have at least 2.5 years of data.

'IGRF'-'Base'

# Effect of I2 and I3

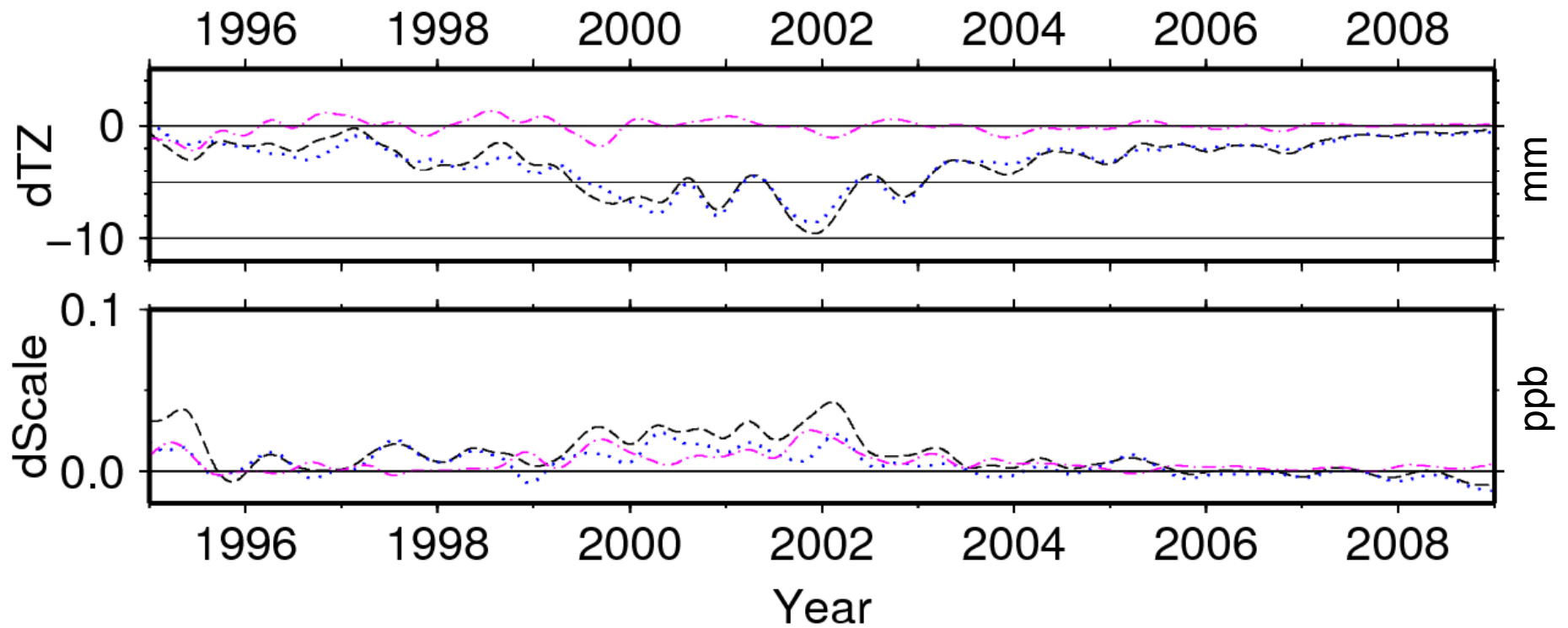


# 12 – effect of magnetic field model



# Effect of I3

## Reference frame

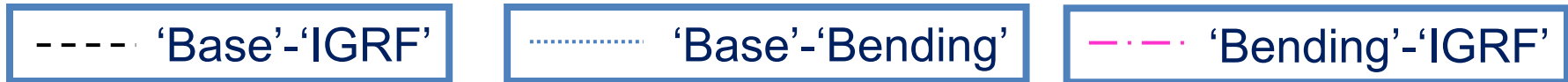
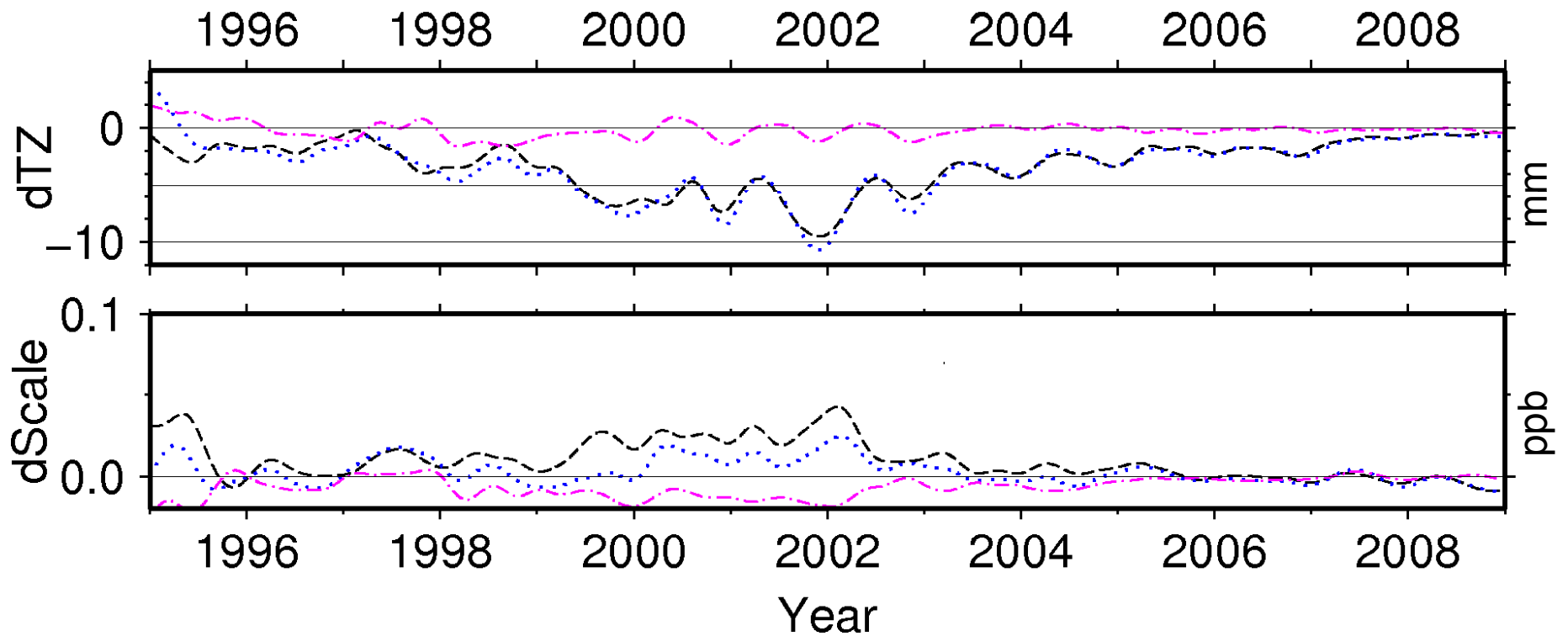


--- 'Base'-'IGRF'

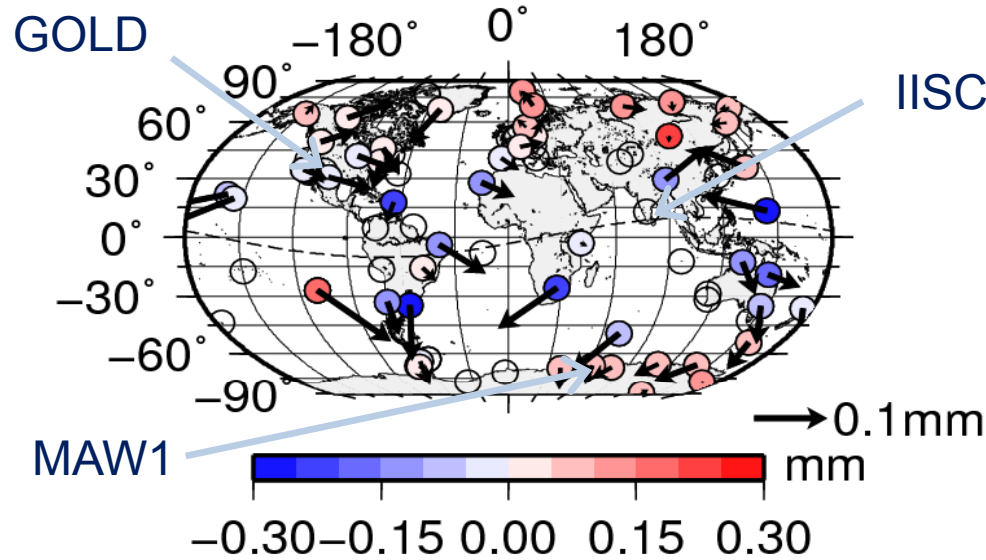
..... 'Base'-'IGRF2'

-.-.- 'IGRF2'-'IGRF'

# Effect of bending terms



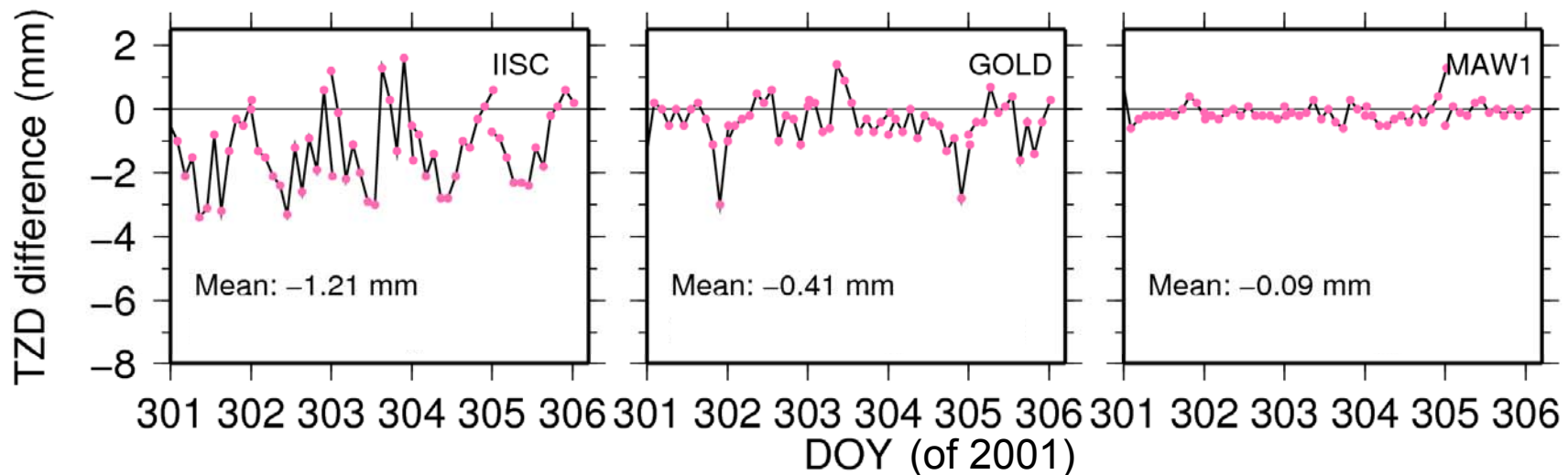
# Effect of bending terms



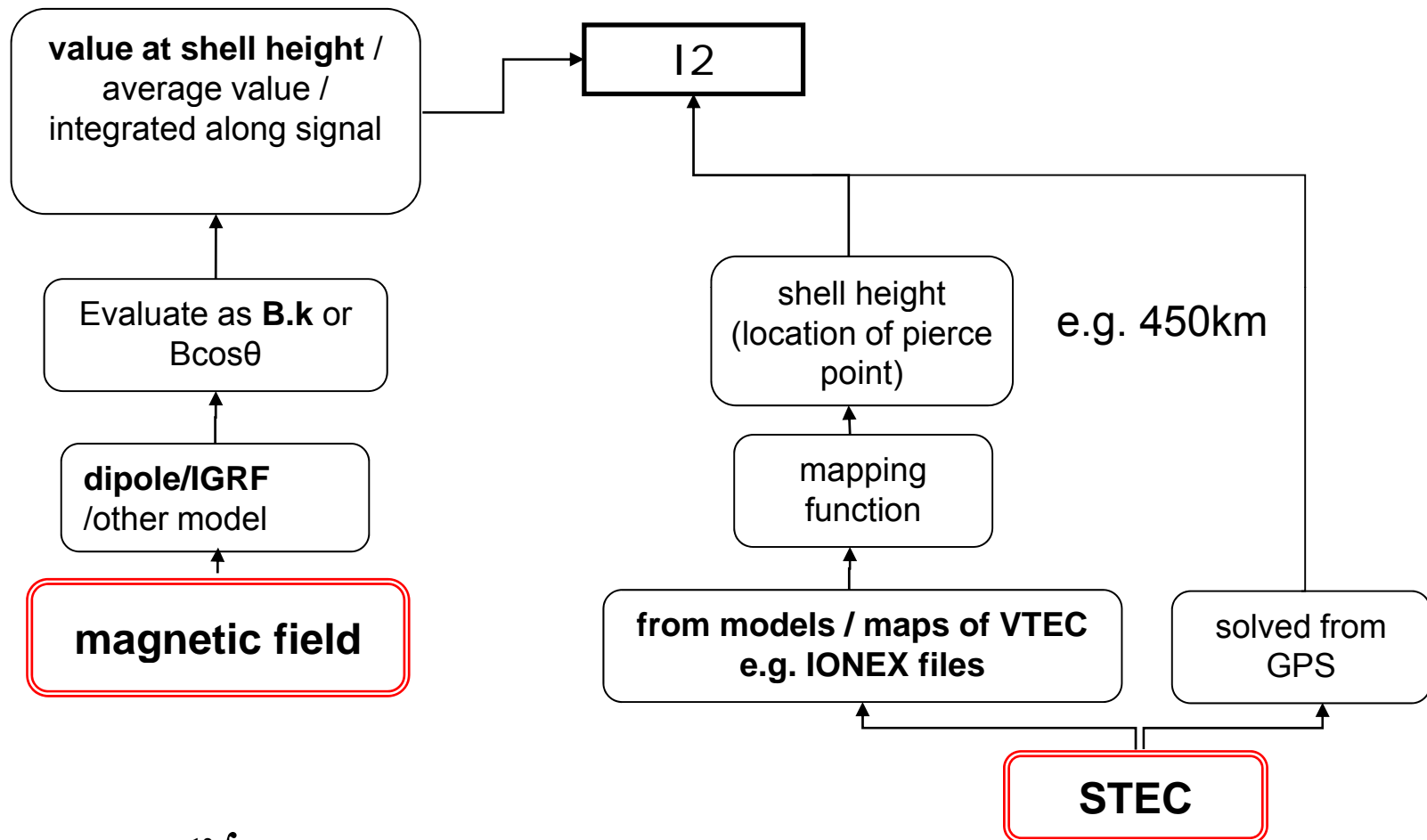
Mean coordinate differences

2001.0-2004.0

Sites shown have at least 2.5 years of data.



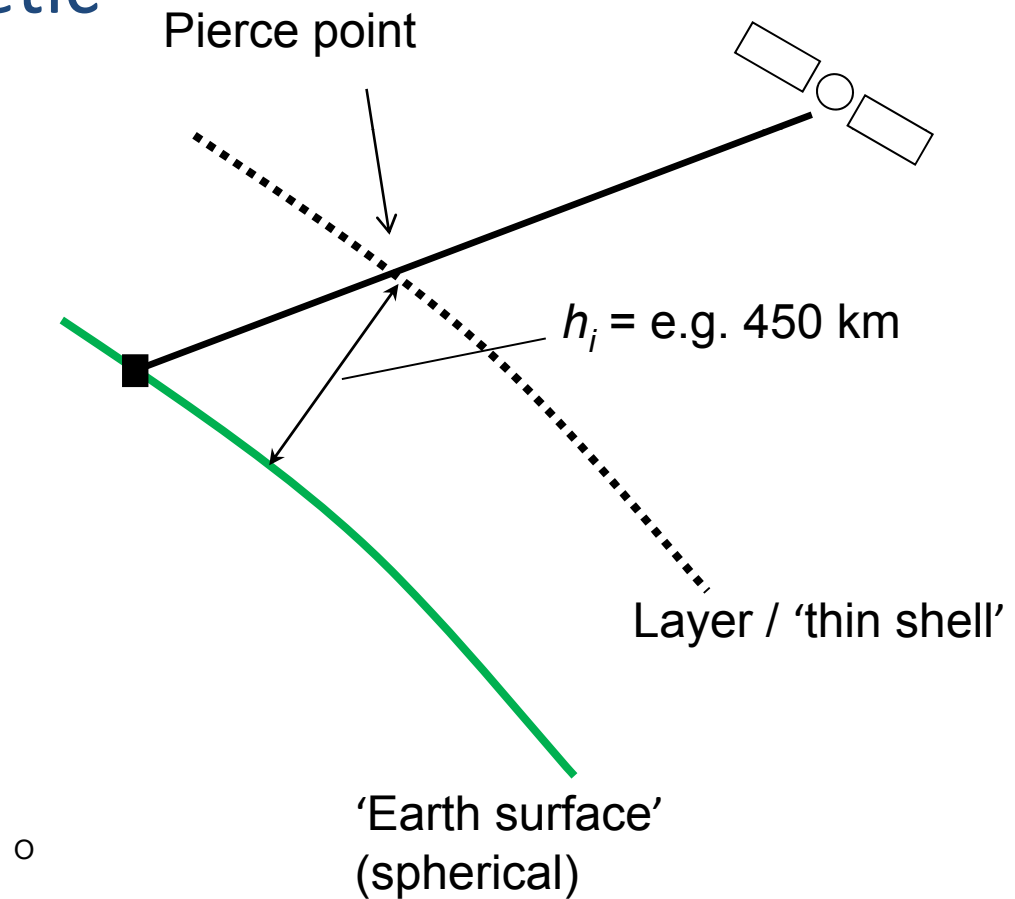
# Factors affecting I2



$$I2 = -\frac{1.1284 \times 10^{12} \int N_e B \cos \theta dL}{f_1^3} \approx -\frac{1.1284 \times 10^{12} B \cos \theta STEC}{f_1^3}$$

# Some remaining issues

- source of STEC
- height of magnetic field evaluation



# STEC from maps

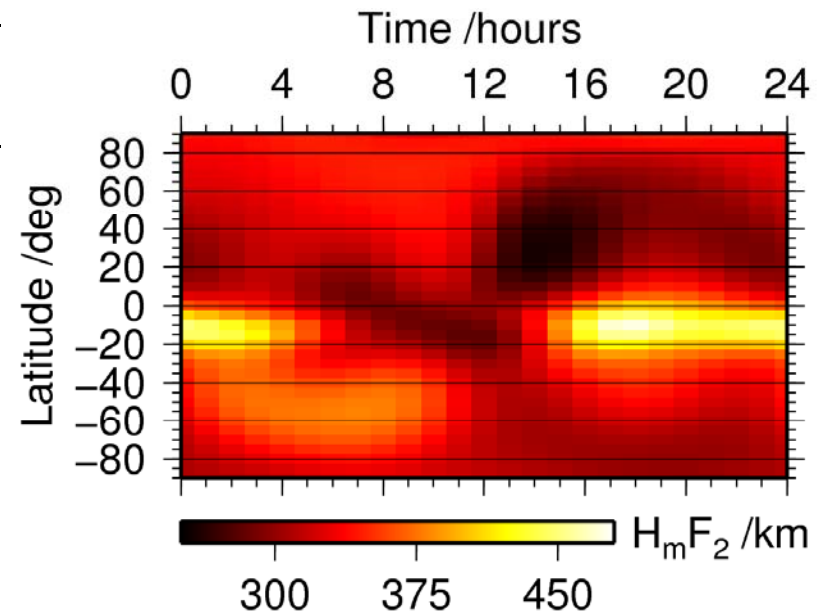
$h_i$ /km	F	VTEC /TECU
300	2.943	118.908
450	2.549	137.305
600	2.295	152.529

Variations in estimated VTEC with varying thin layer height,  $h_i$ , based on:

- STEC of 350TECU
- 10 degrees elevation

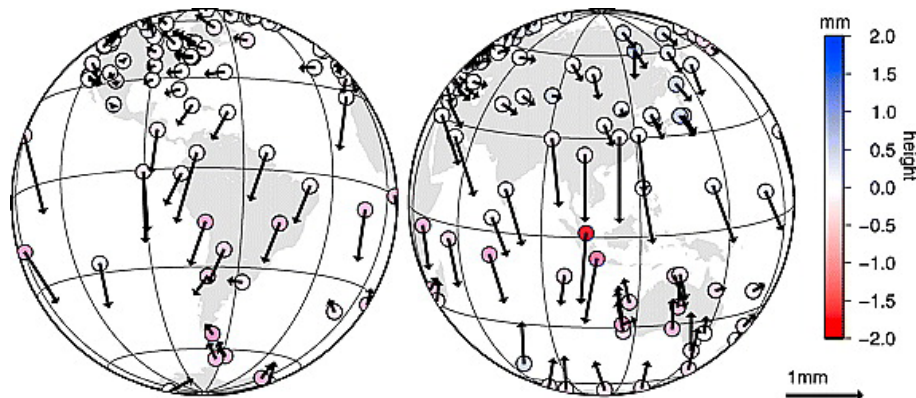
$$F(z) = \frac{1}{\cos z'} \quad \text{with} \quad \sin z' = \frac{R}{R + h_i} \sin(z)$$

Height of peak electron density at 270° longitude, DOY 301, 2001, based on IRI2007



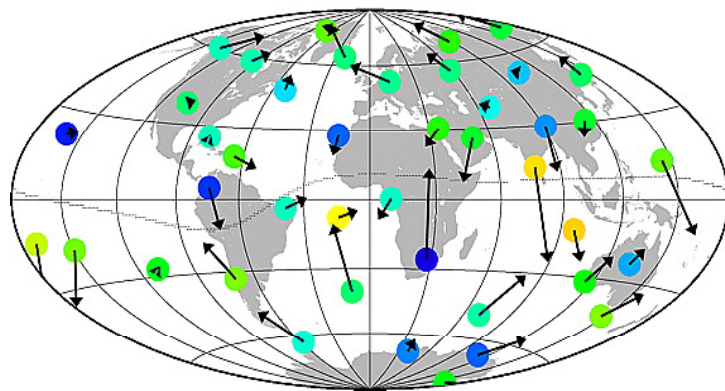
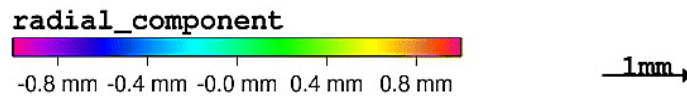
Petrie et al. (2010) J. Geod. (online).

# Effect of STEC source?



2001.0-2004.0

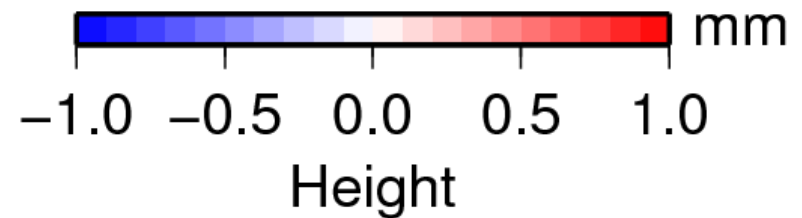
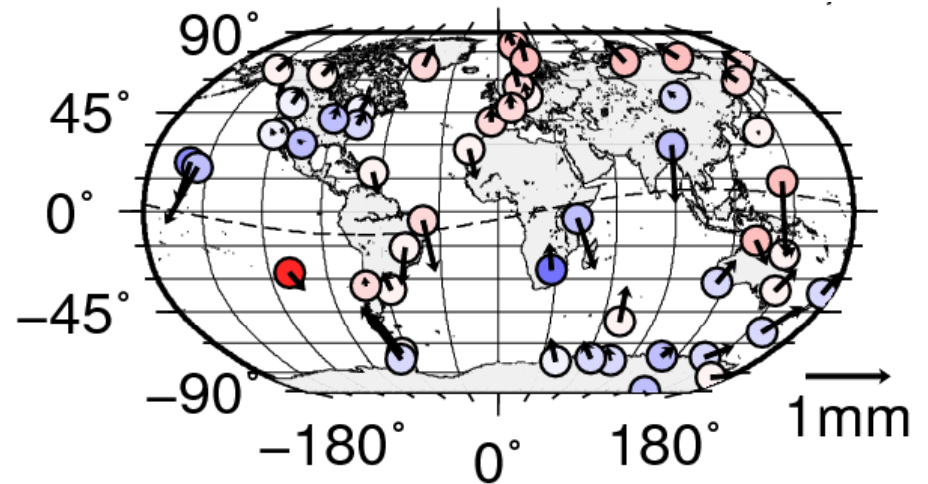
Steigenberger et al. (2006) J. Geophys. Res.



DOY 100, 2002 to DOY 365, 2003

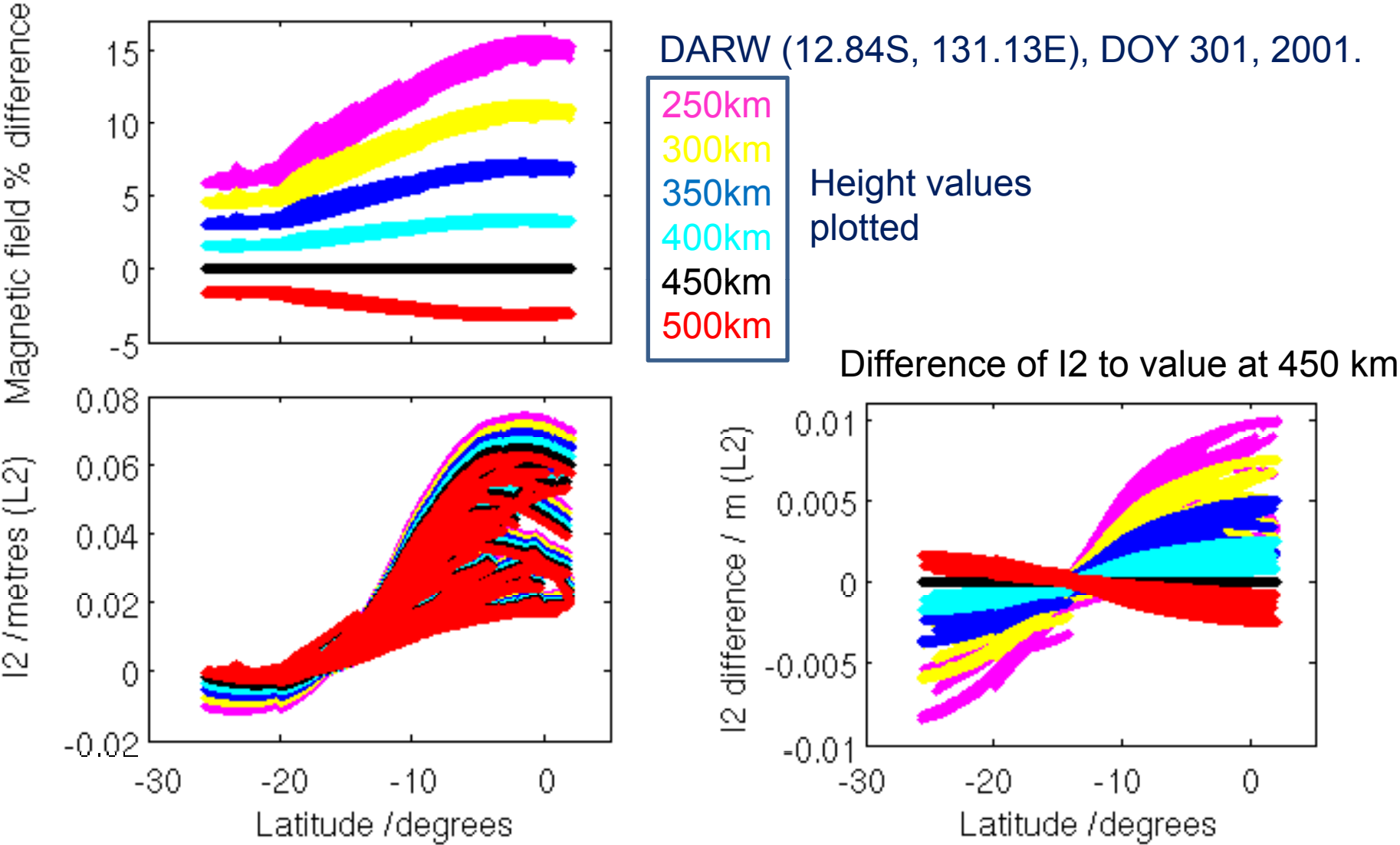
Hernández-Pajares et al. (2007) J. Geophys. Res.

'Dipole'-'Base'  
2001.0-2004.0



Petrie et al. (2010) J. Geophys. Res.

# Magnetic field – changing shell height



# Summary

- Neglecting higher order ionospheric effects
- bias of up to  $\sim 0.34$  mm/yr rates,  $\sim 10$ mm Z-translation
- Effect of IGRF/dipole  $< 1$ mm (mean coordinates)
- I3 term only limited effect
- Bending terms
  - trial implementation: seem to be absorbed by TZDs
- Solar activity is currently increasing towards the next ionospheric maximum



