Deriving Vertical Total Electron Content Maps from SMOS Full-Polarimetric Data

Ignasi Corbella, Roselena Rubino, Nuria Duffo,
Verónica González Gambau

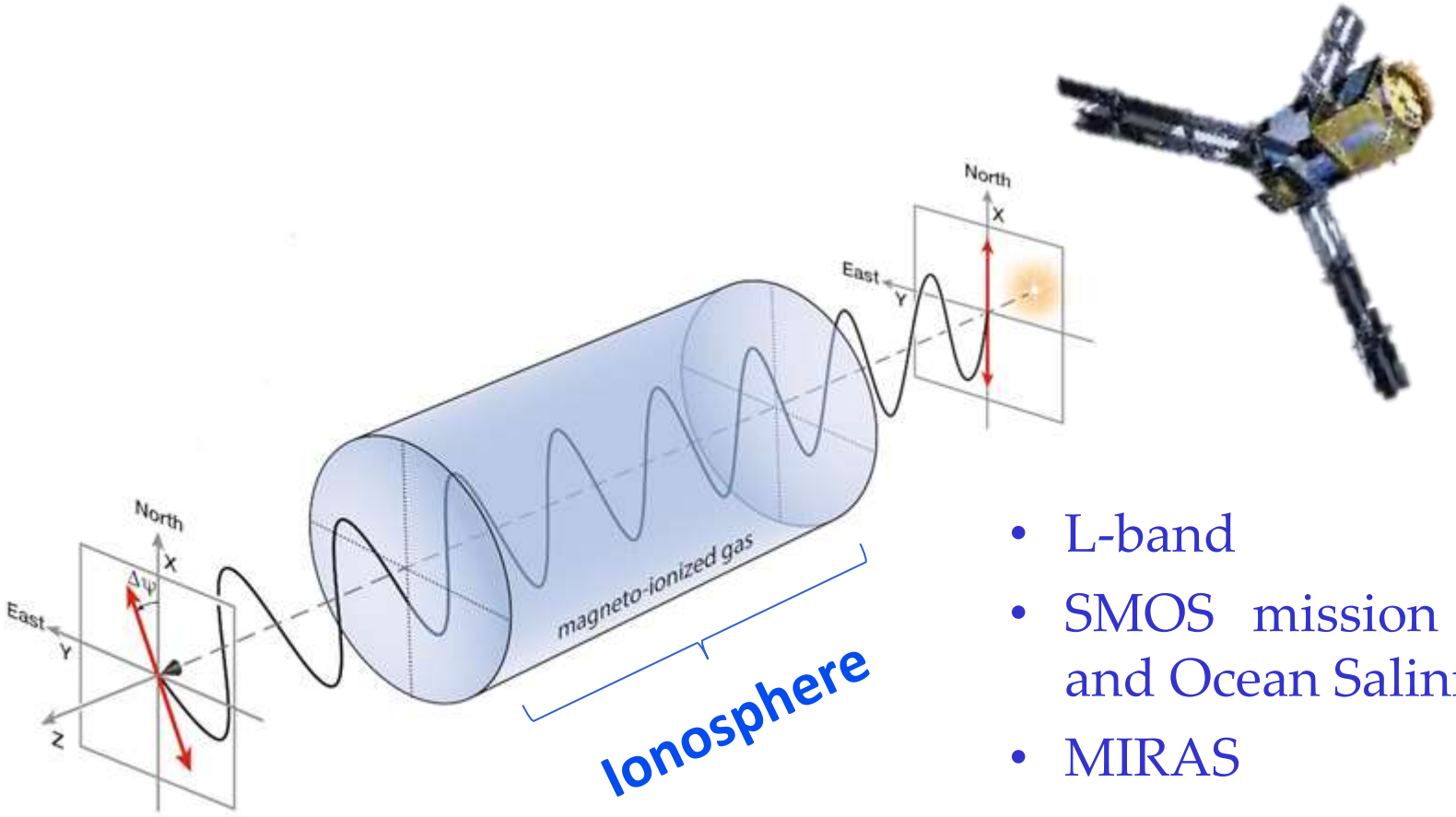
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

November 2022

Outline

- Faraday rotation angle and VTEC (Vertical Total Electron Content)
- Faraday rotation angle and brightness temperature
- VTEC retrieval from SMOS radiometric data
- Results: VTEC global maps

Faraday Rotation



Ground surface

- L-band
- SMOS mission (Soil Moisture and Ocean Salinity)
- MIRAS

K Ferrière, J L West, T R Jaffe, The correct sense of Faraday rotation, *Monthly Notices of the Royal Astronomical Society*, Volume 507, Issue 4, November 2021, Pages 4968–4982, https://doi.org/10.1093/mnras/stab1641

Faraday Rotation Angle

$$\Omega_f = 1.355 * 10^4 * f^{-2} * B_0 * \cos\Theta_B * \sec\theta * VTEC$$

[Yueh, S.H., TGRS 2000]

f: Frequency in GHz (1.4135 in SMOS)

B_0: Geomagnetic field at 450 km of altitude[1] [Tesla]

Θ_B: Angle between the magnetic field and the wave propagation direction[1]

θ: Incidence angle

$VTEC$: Vertical Total Electron Content ➡

Consolidated TEC (SMOS DPGS)

- 20,000 km → 800 km
- Spatial resolution: 2.5° x 5°
- Temporal resolution: 2 h

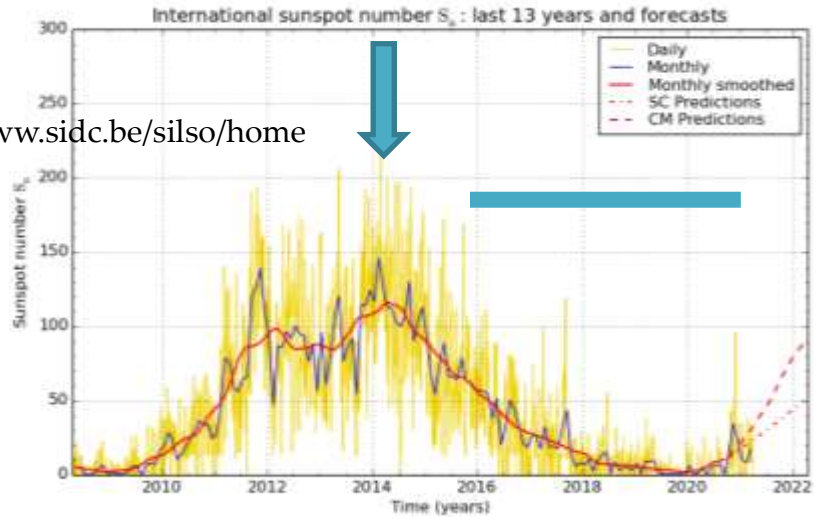
DPGS: Data Processing Ground Segment

[1] 13th Generation International Geomagnetic Field from the IAGA (International Association of Geomagnetism and Aeronomy)

Temporal Variability

- Ionosphere
  - Earth's atmosphere (~50 to ~600 km)
  - Ionized particles and electrons
  - Sun → source of energy (solar activity)

Credit: https://www.sidc.be/silso/home

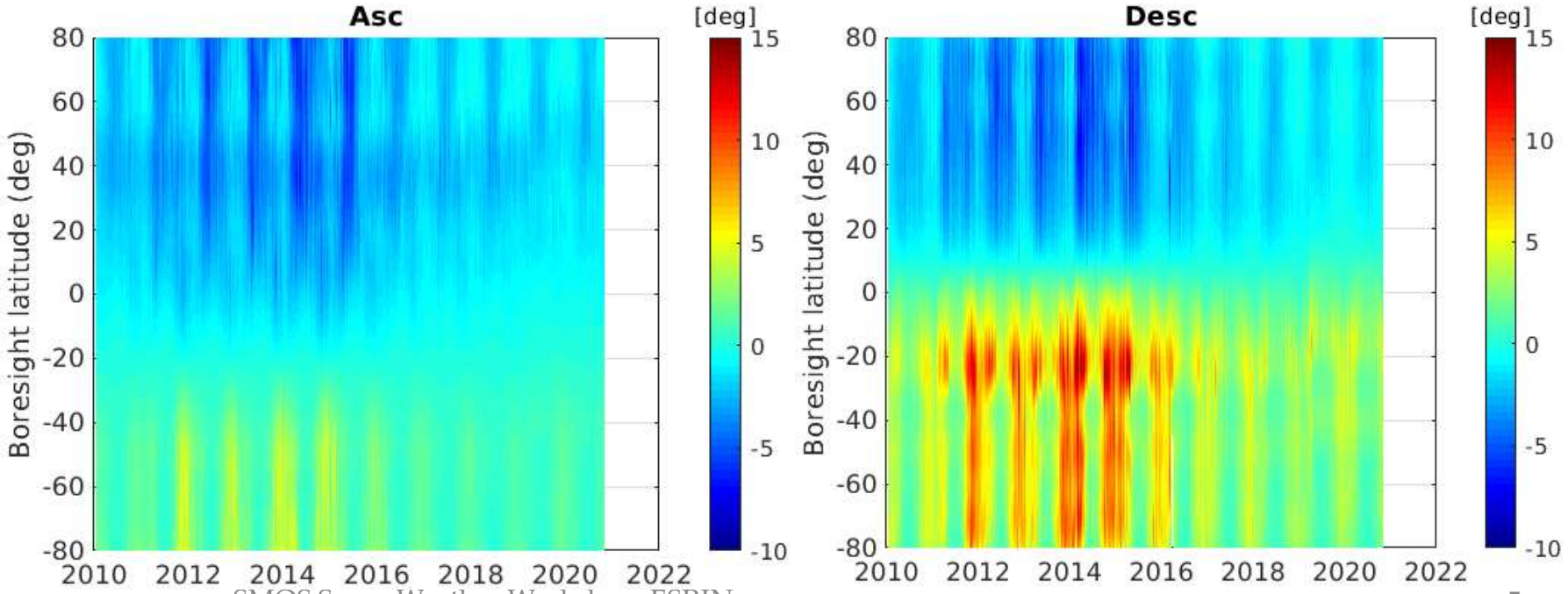


Hovmöller

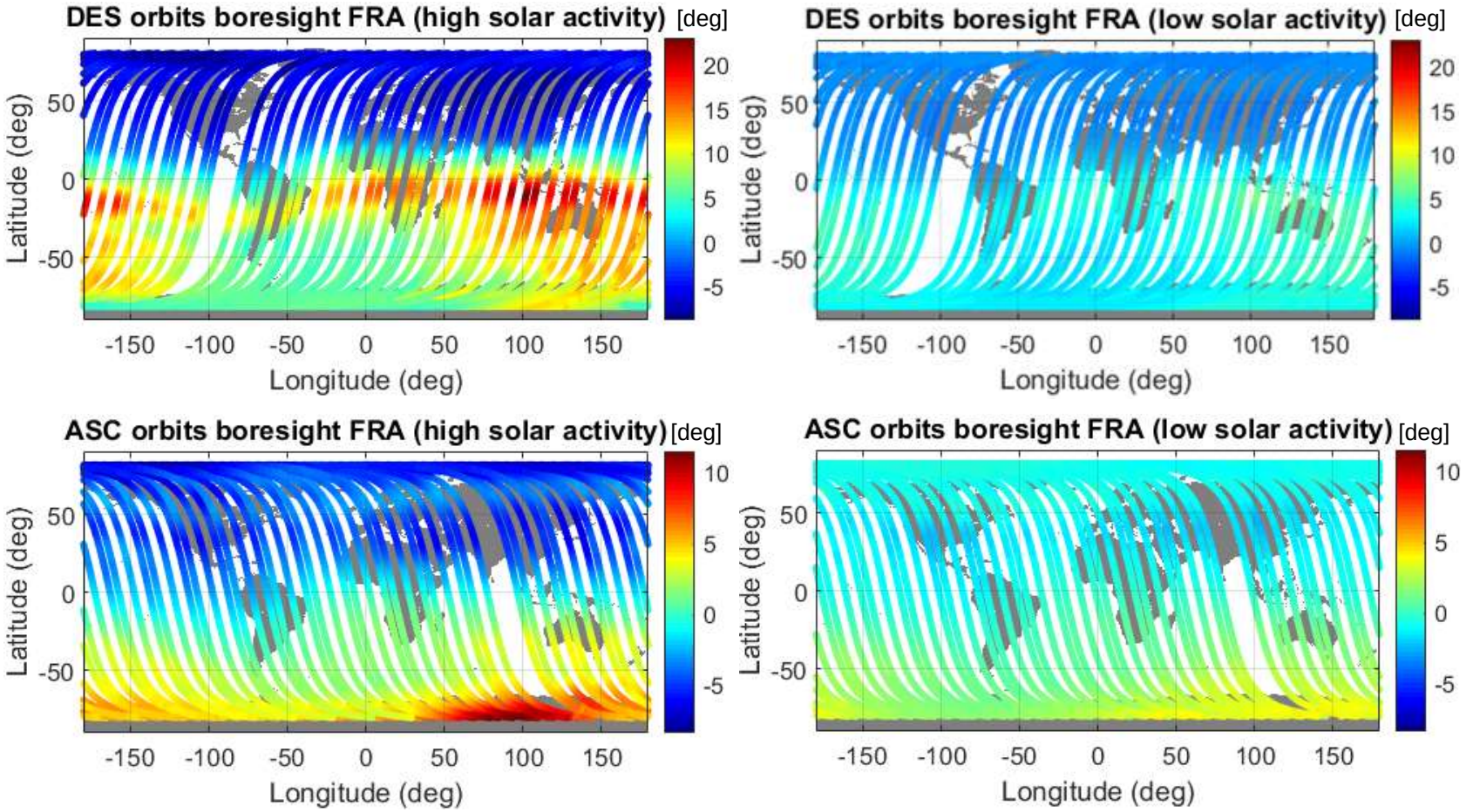
- Time (x-axis)
- Latitude (y-axis)
- 1 orbit per day
- Boresight coordinates
- L1 VTEC

- ASC ↓ (6 a.m. equator LT)
- DES ↑ (6 p.m. equator LT)

Faraday rotation angle



Spatial Variability



Brightness Temperature frame rotation

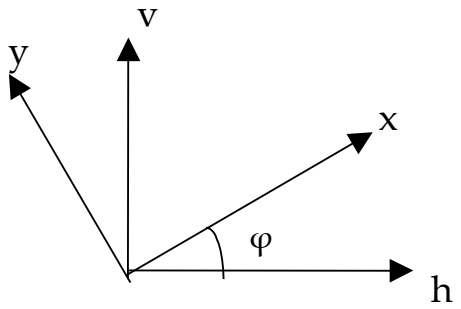
Antenna frame and ground frame

Considering $T_B^{hv} = T_B^{vh} = 0$

$$\begin{bmatrix} T_B^{xx} \\ 2T_B^{xy} \\ T_B^{yy} \end{bmatrix} = \begin{bmatrix} \cos^2\varphi & \sin^2\varphi \\ -\sin 2\varphi & \sin 2\varphi \\ \sin^2\varphi & \cos^2\varphi \end{bmatrix} \begin{bmatrix} T_B^{hh} \\ T_B^{vv} \end{bmatrix}$$

Brightness Temperatures at antenna frame (x,y)

Brightness temperatures at ground frame horizontal, vertical (h-v)



x-y: Antenna frame
h-v: Ground frame
φ: Geometrical plus Faraday rotation angle

$$\Omega_f = -\varphi_g - \frac{1}{2}\tan^{-1}\left(\frac{2\Re e\left(T_B^{xy}\right)}{T_B^{xx} - T_B^{yy}}\right)$$

φ_g : geometrical rotation angle

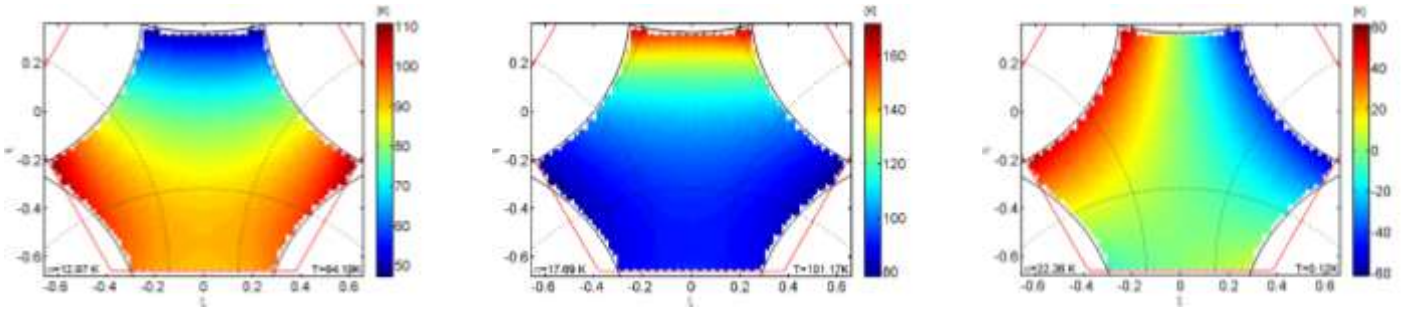
T_B^{pq}: Polarimetric Brightness Temperatures

SMOS Snapshot

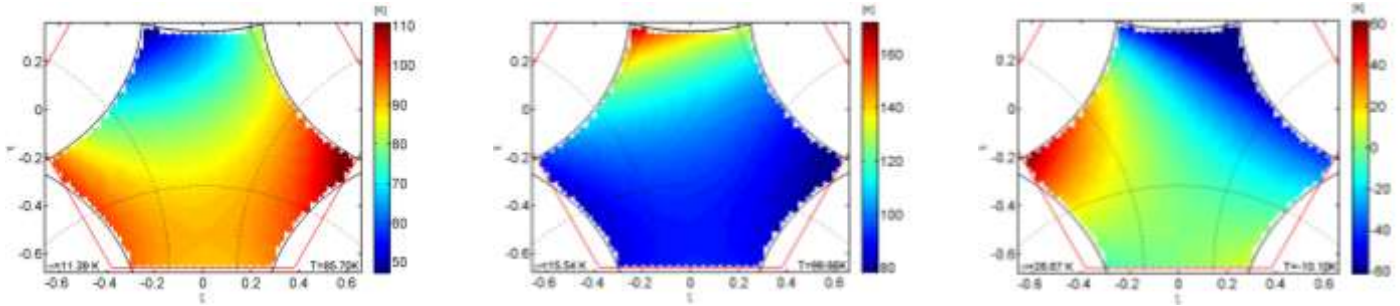
Modeled TB for Ocean (Specular): Salinity: 35 psu. SST: 294 K

TB^{xx} TB^{yy} $2\Re e(TB^{xy})$

VTEC=0

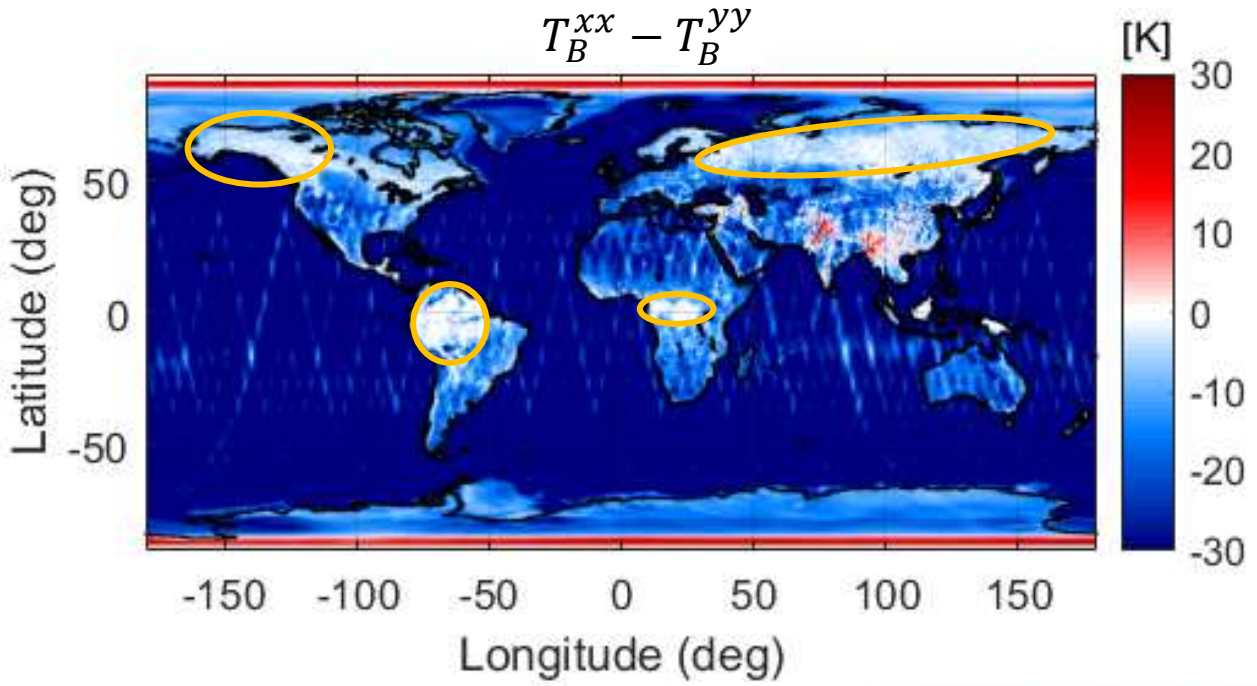


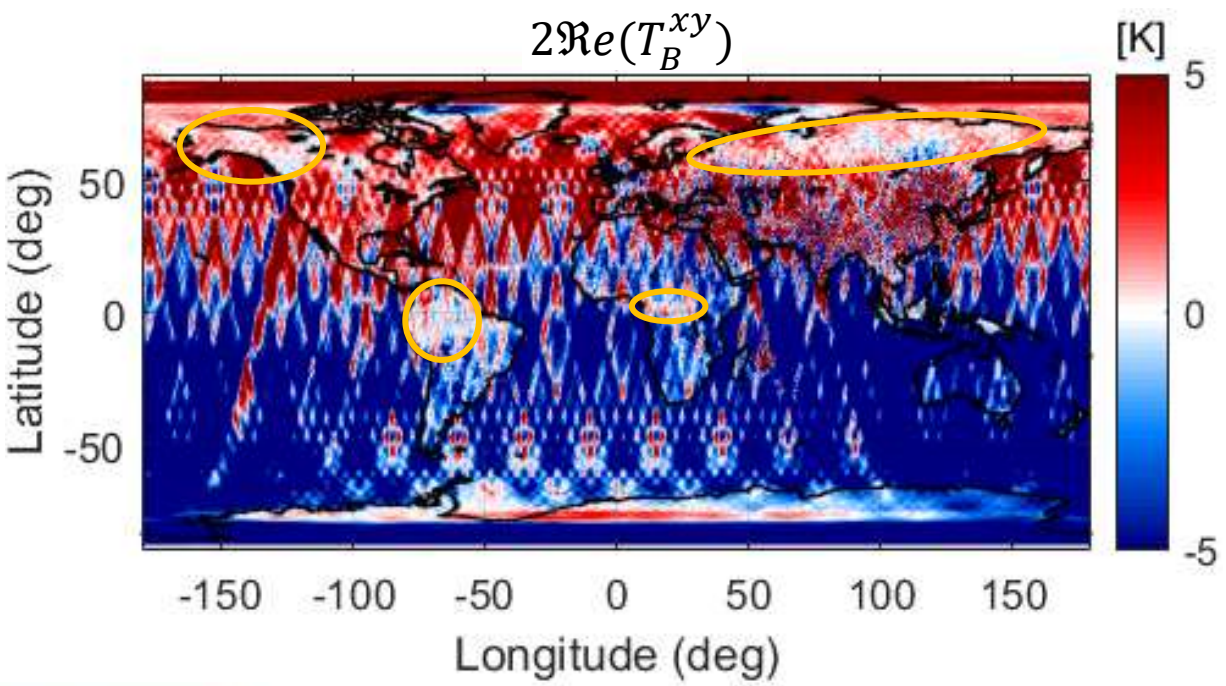
Consolidated VTEC (SMOS DPGS)



- Nadir is at about [0, -0.5]
- At nadir $T_B^{xx} = T_B^{yy}$ and $T_B^{xy} = 0$
- Geometric rotation is different at each grid point (spatial direction)

SMOS Brightness temperatures (March 2014)

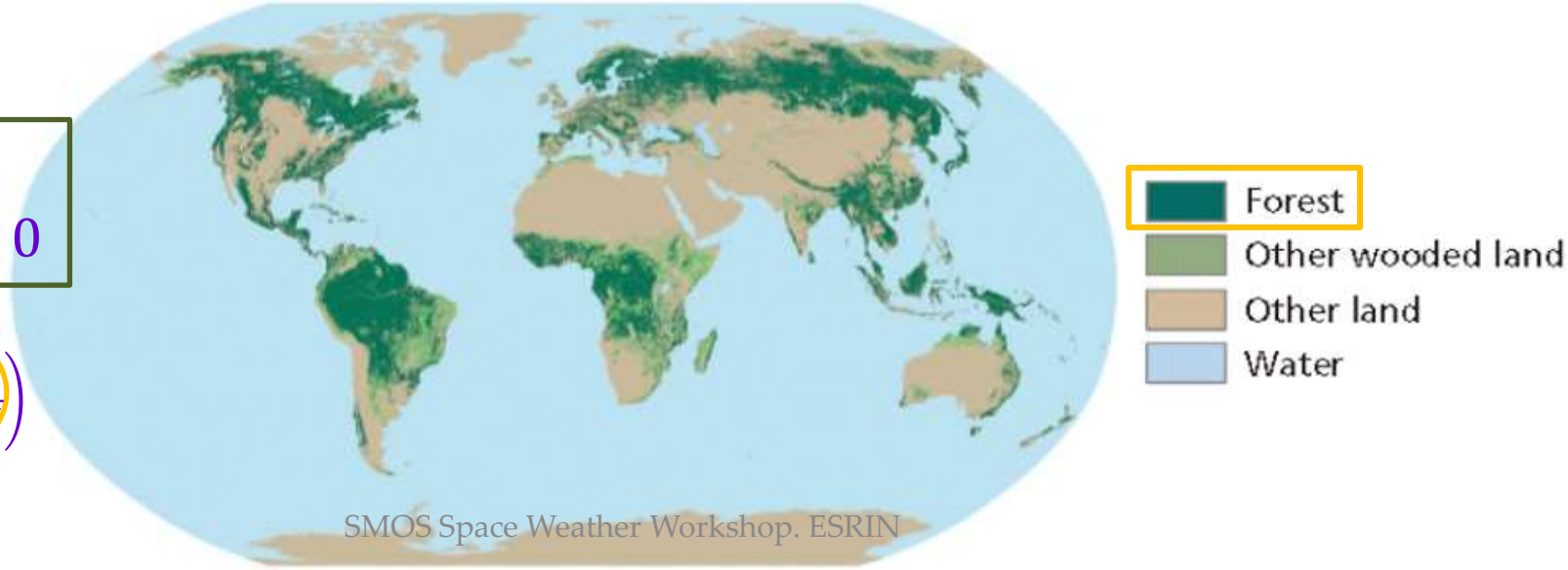




In dense forests

- $T_B^{xx} \approx T_B^{yy}$ and $T_B^{xy} \approx 0$

$$\Omega_f = -\varphi_g - \frac{1}{2}\tan^{-1}\left(\frac{2\Re e(T_B^{xy})}{T_B^{xx} - T_B^{yy}}\right)$$



VTEC from SMOS data

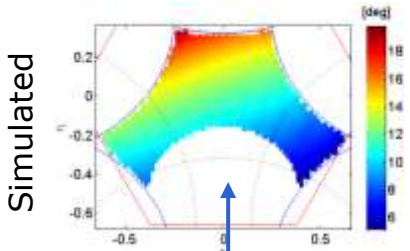
1. Brightness temperature time averaging

Done with a triangular filter with a window size of 43 snapshots

2. FRA recovery

FRA recovery of every snap-shot (ia>25°) with

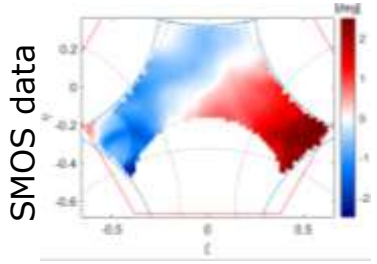
$$\Omega_f^m = -ra - \frac{1}{2}\tan^{-1}\left(\frac{2\Re e\left(T_B^{xy}\right)}{T_B^{xx} - T_B^{yy}}\right)$$



Discard low incident angles

(see next two pages)

3. Correction of the FRA systematic error contribution (Δ)



Subtract error pattern to the measured FRA

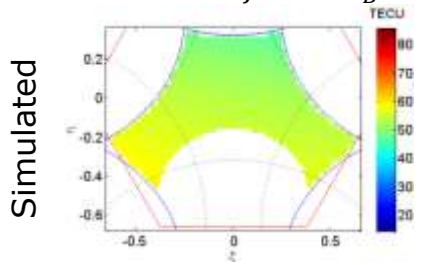
$$\Omega_f = \Omega_f^m - \Delta$$

$\text{abs}(\cos\Theta_B) > 0.05$

4. VTEC from FRA

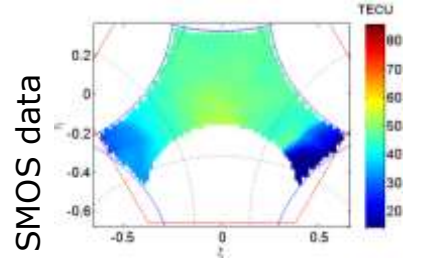
Retrieval of the VTEC from the FRA with

$$VTEC = \frac{\Omega_f * \cos\theta}{Cn * f * \cos\Theta_B}$$



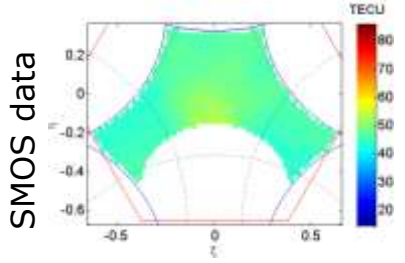
5. Spatial filter

Apply filter with radius 0.189 at snapshot level (ξ-η plane) to mitigate noise



6. Extending the AF-FoV VTEC border to the EAF-FoV

Repeat the border VTEC value of the AF-FoV to the EAF-FoV to mitigate the error in the laterals of the snapshot



7. VTEC maps projected over Earth

VTEC maps are obtained by geolocating the snapshots over a regular ETOPO5 grid

Systematic pattern error

$$\Omega_f^m = -\varphi_g - \frac{1}{2}\arctan\left(\frac{2\Re e\left(T_B^{xy}\right)}{T_B^{xx} - T_B^{yy}}\right)$$

Measured Faraday rotation angle

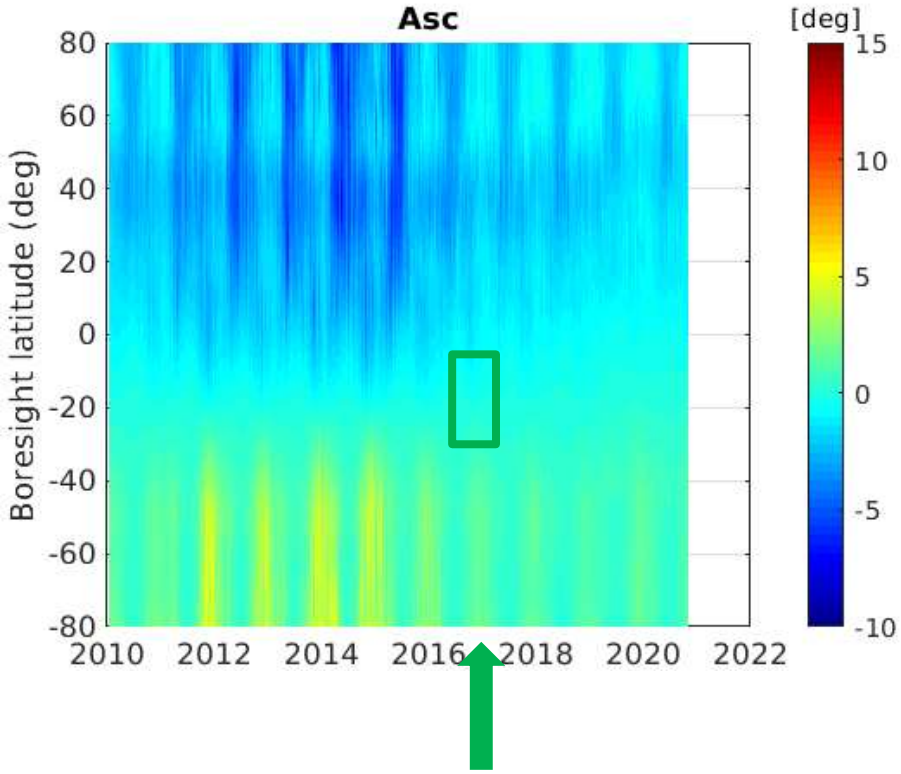
$$\Omega_f^m = \Omega_f + \Delta$$

Δ: Systematic pattern error

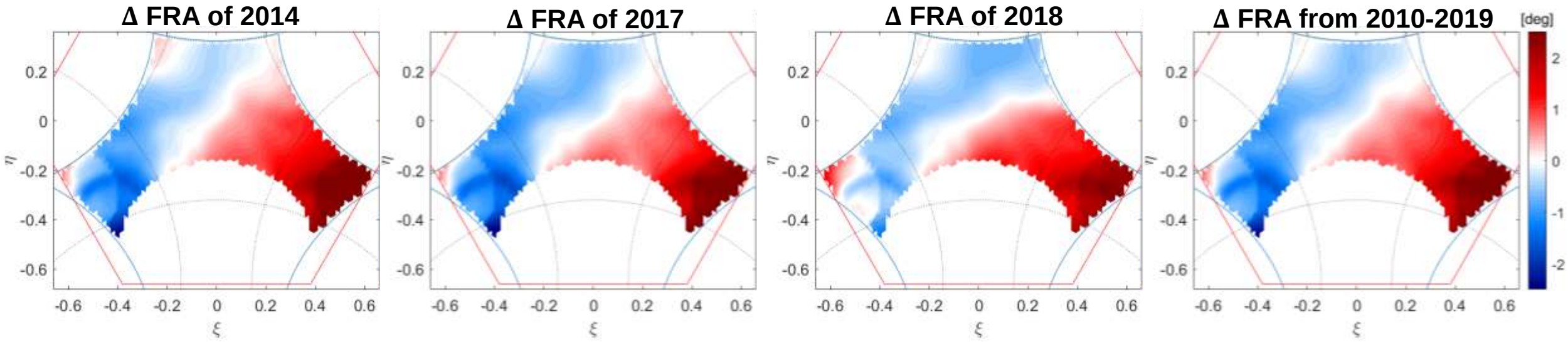
If $\Omega_f = 0$, then $\Omega_f^m = \Delta$

Low Faraday rotation angle:

- Ascending orbits
- 3-consecutive days
- Latitude 30°S to 5°S

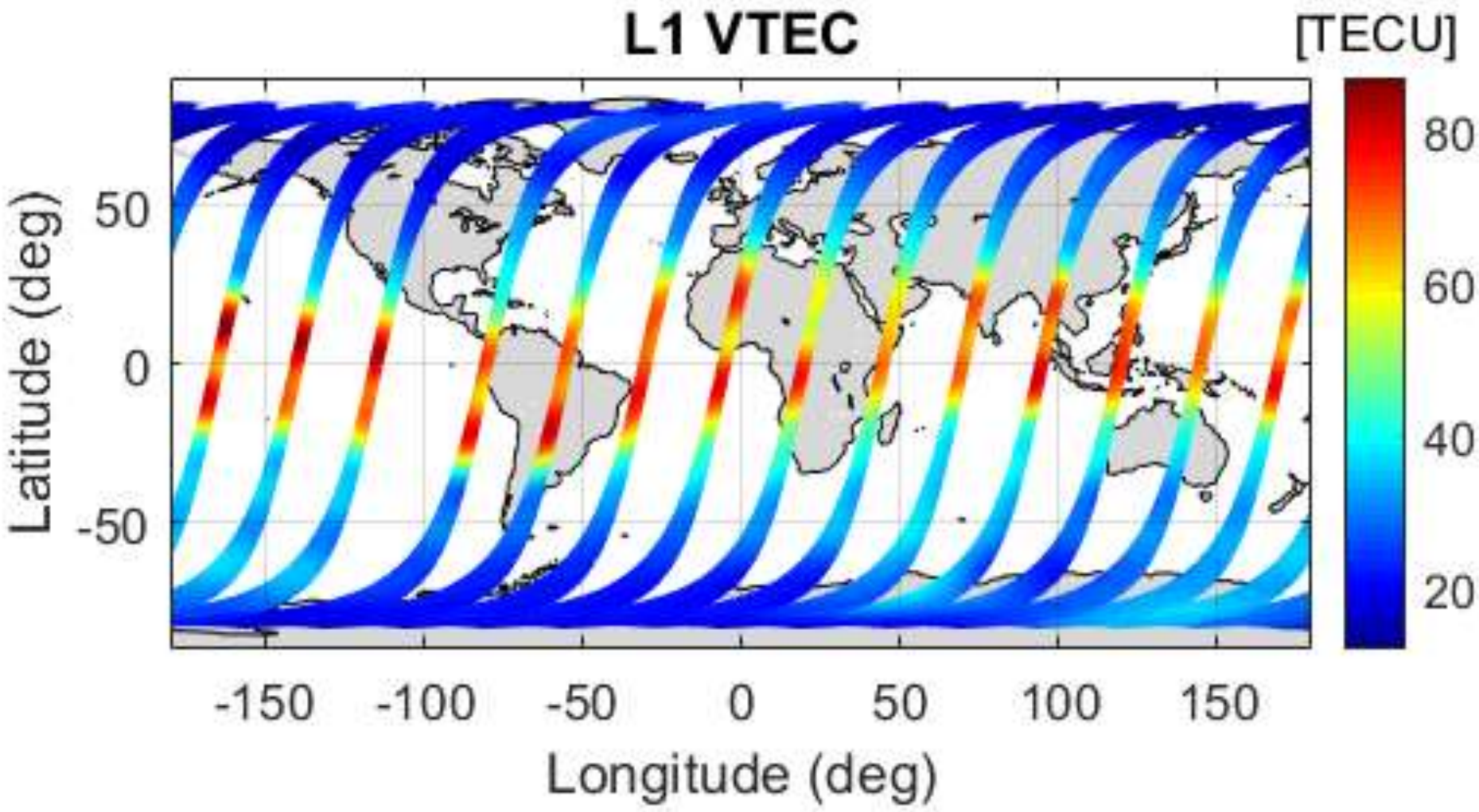


Stability of error pattern

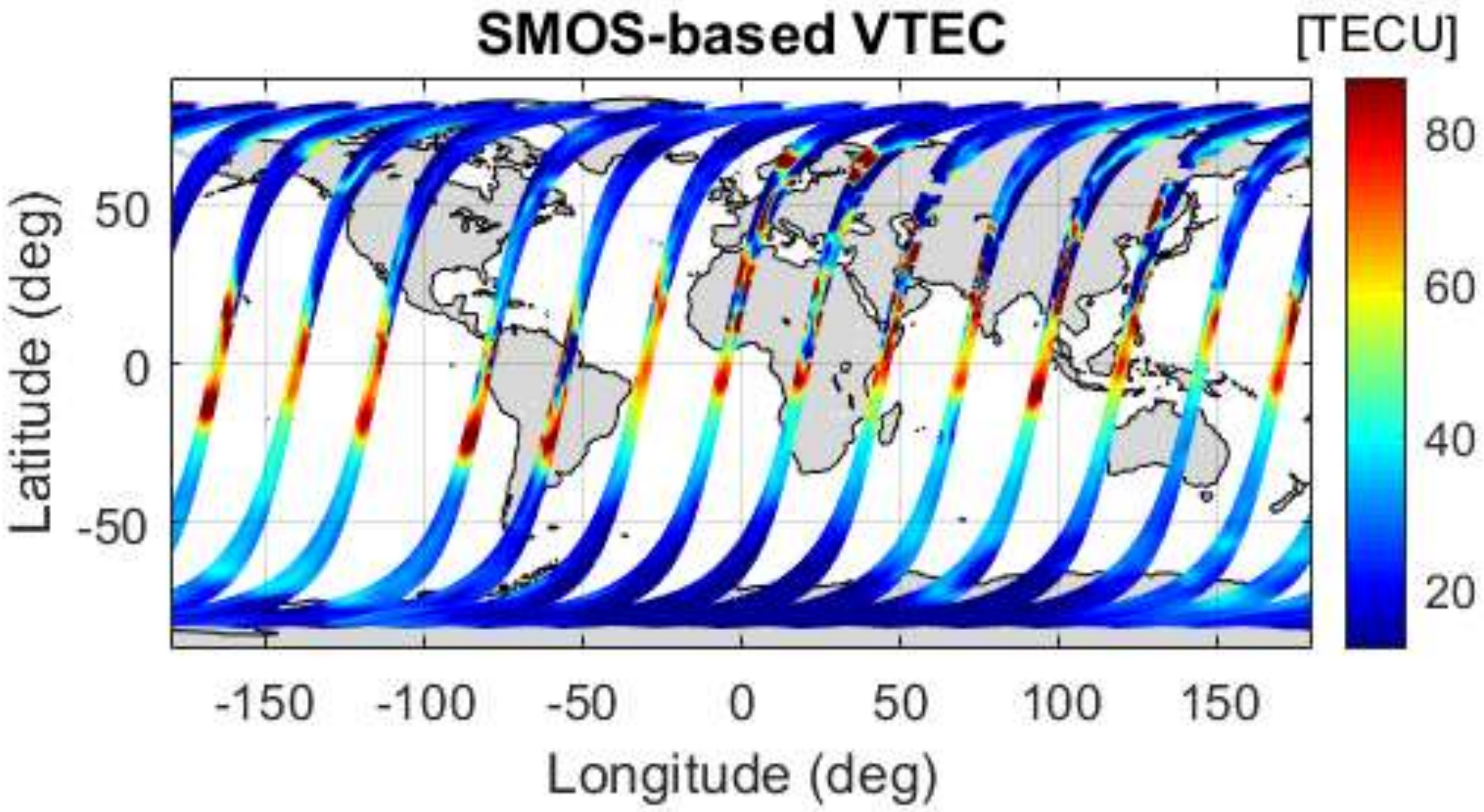


TEMPORALLY ESTABLE

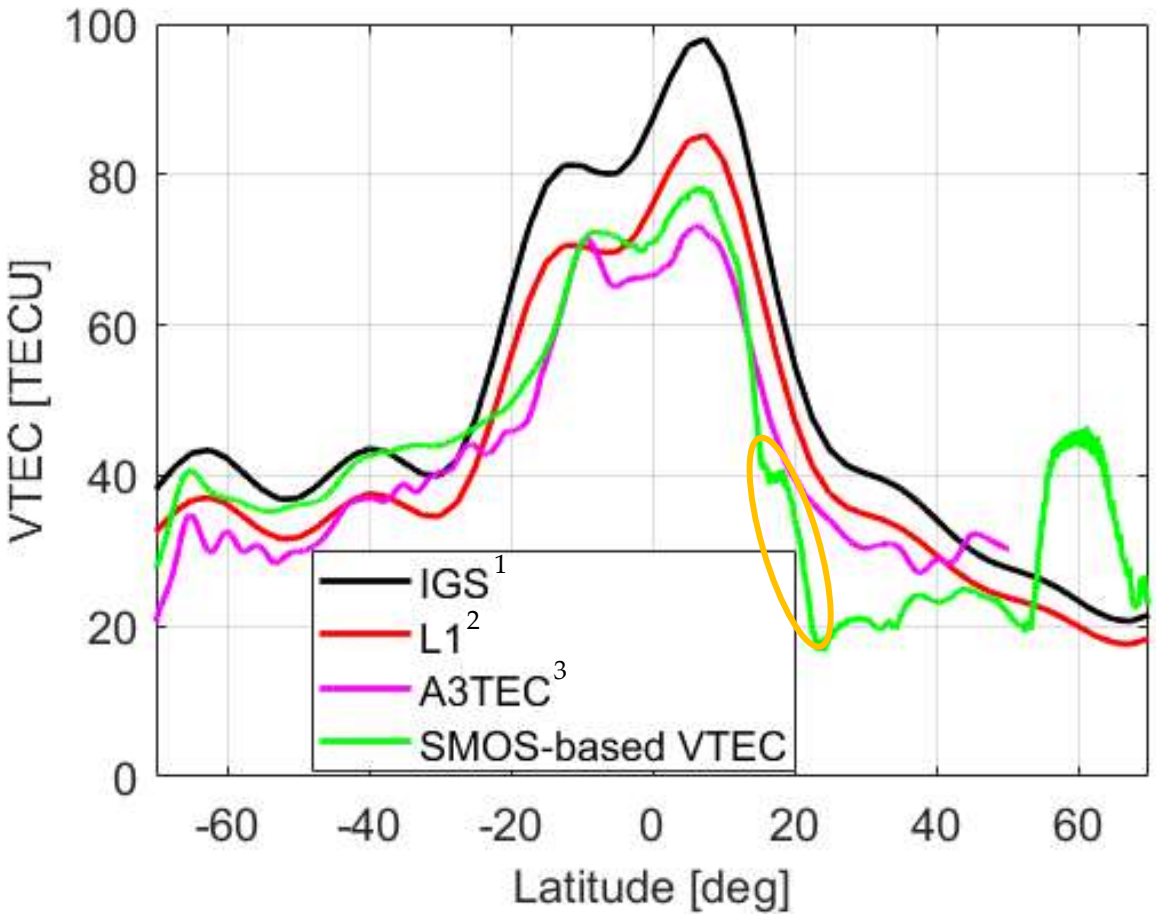
VTEC of a day (March 20th, 2014 DES)



VTEC of a day (March 20th, 2014 DES)



Comparing VTEC with other sources (March 20th, 2014 DES)



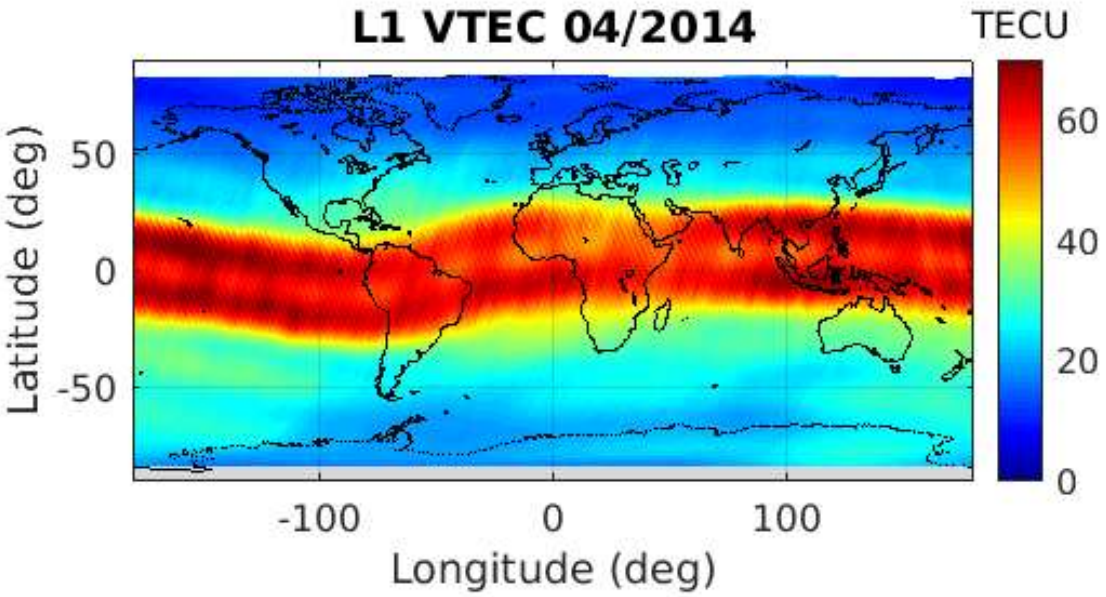
$$VTEC = \frac{\Omega_f * \cos\theta}{Cn * F * \cos\Theta_B}$$

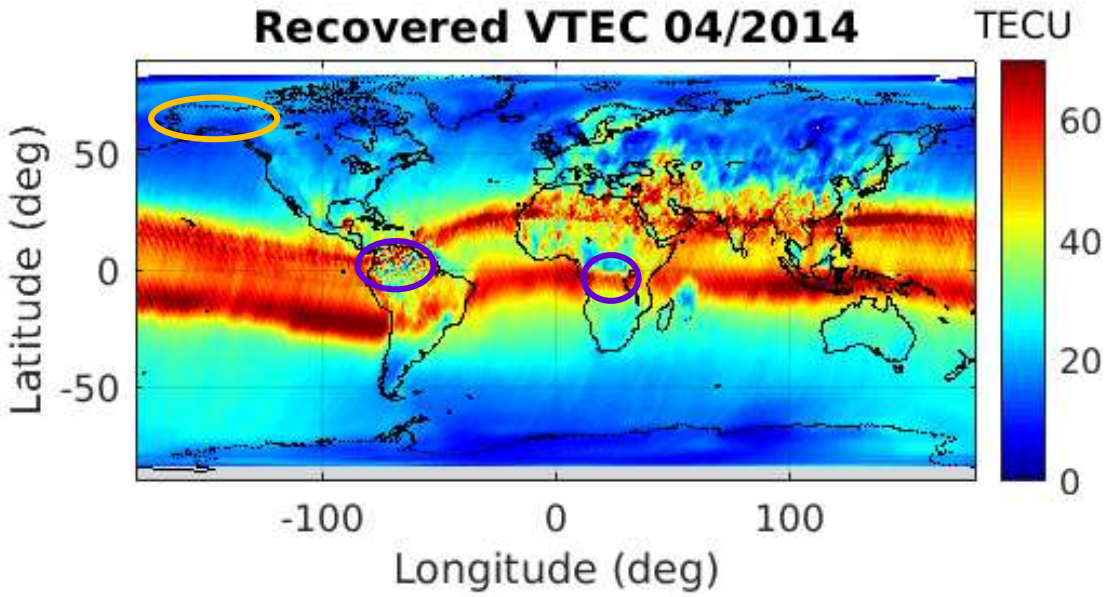
vanishes

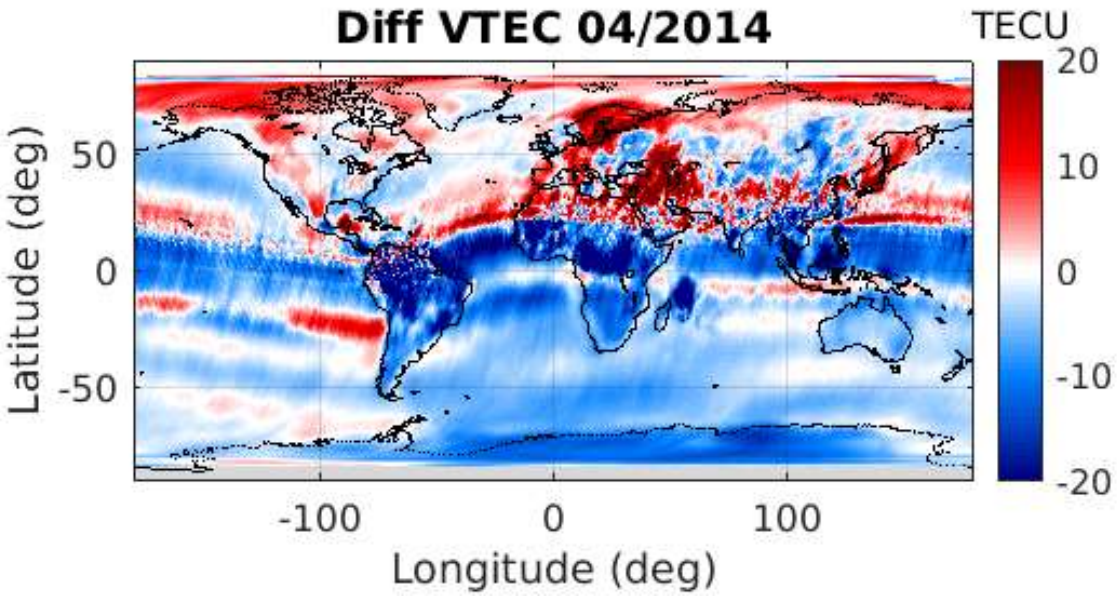
$\Omega_f * \cos\theta \approx 0$

1. Hernández-Pajares, M. IGS Ionosphere WG Status Report: Performance of IGS Ionosphere TEC Maps -Position Paper-. 26
2. Bengoa, B. *SMOS Level 2 and Auxiliary Data Products Specifications*; 2017
3. Vergely, J.-L.; Waldteufel, P.; Boutin, J.; Yin, X.; Spurgeon, P.; Delwart, S. New total electron content retrieval improves SMOS sea surface salinity. *J. Geophys. Res. Oceans* **2014**, *119*, 7295–7307

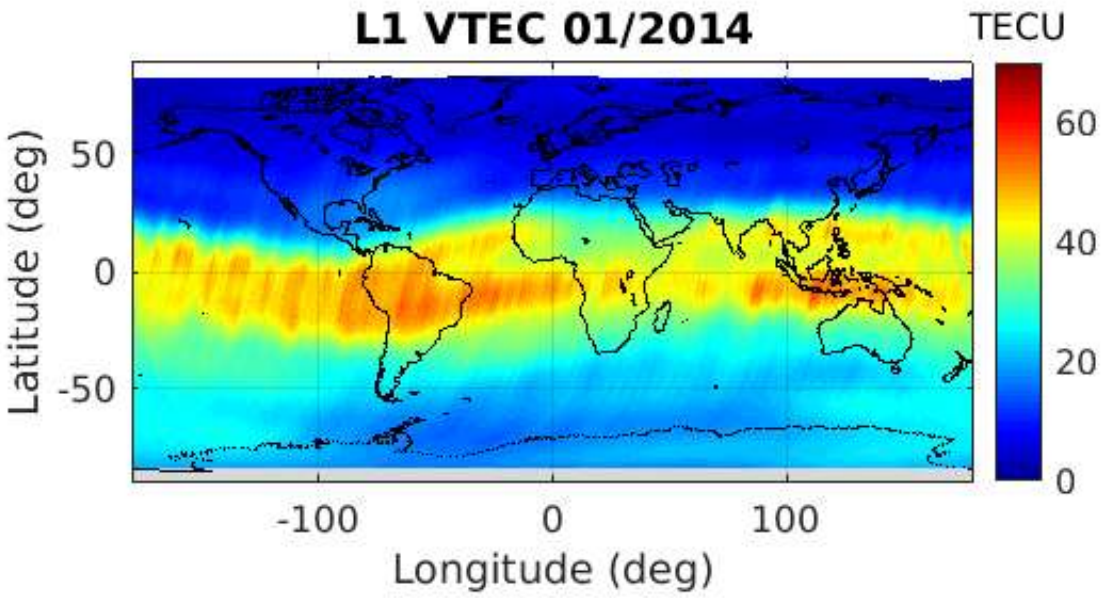
Global VTEC map April 2014 (DES)

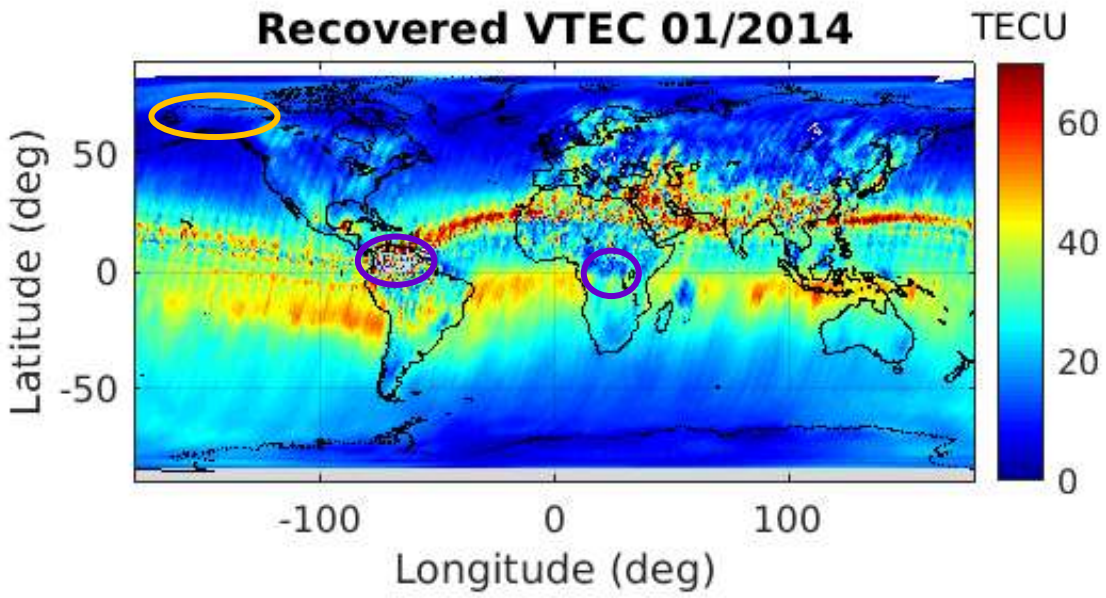


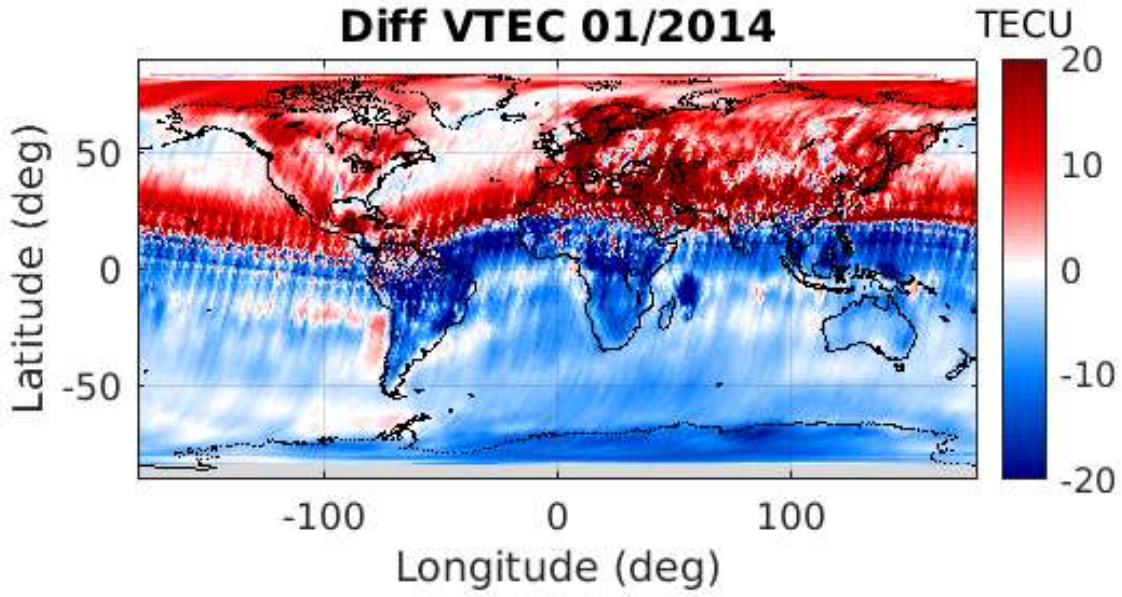




Global VTEC map January 2014 (DES)







Conclusion

- SMOS radiometric data allows retrieving the Vertical Total Electron content of the Ionosphere.
  - Filtering data and correcting systematic biases needed.
- The methodology recovers independently of the target
  - Error in the recovery when $\cos \Theta_B \approx 0$ (FRA vanishes)
  - Over land, limitations when $T_x \approx T_y$ & $T3 \approx 0$ (forest), and in presence of RFIs