Advances in the SMOS-derived Vertical Total Electron Content

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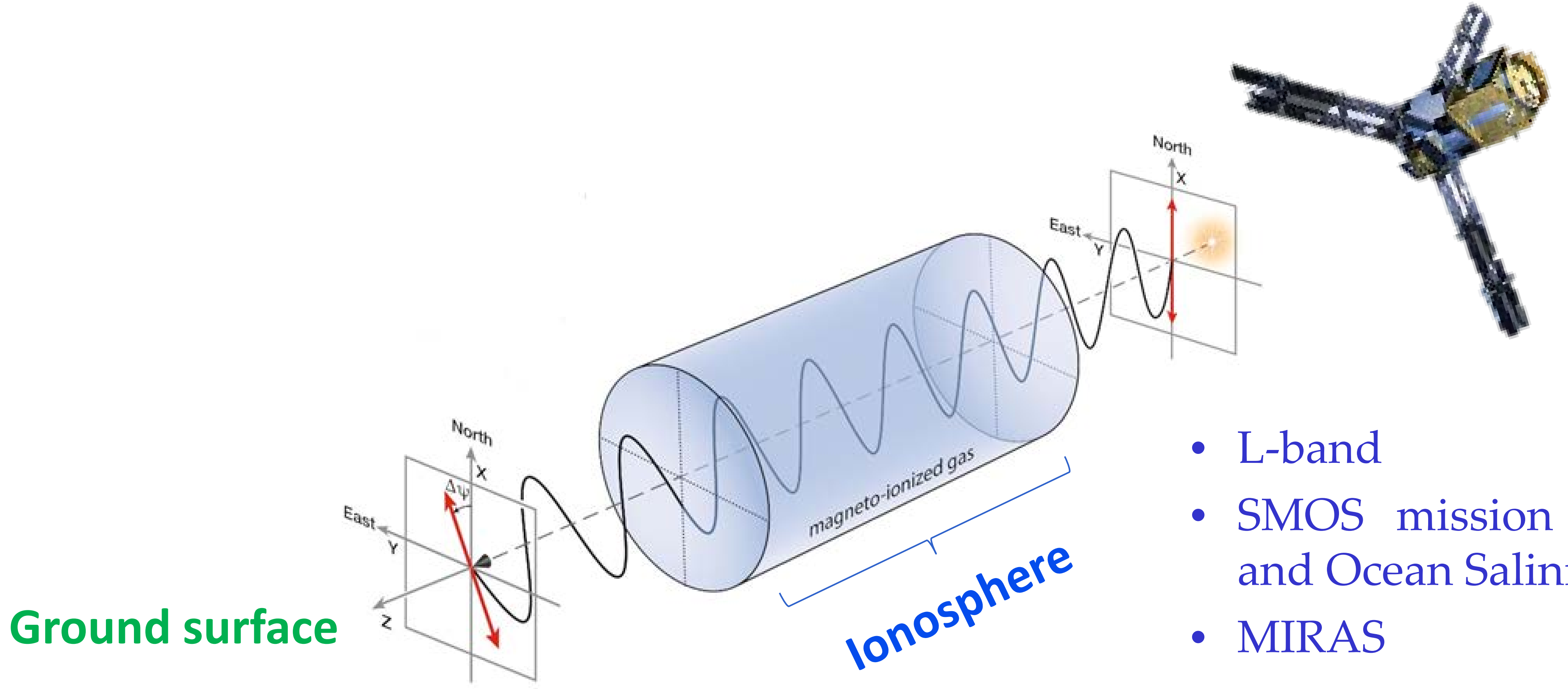
Outline

- Faraday Rotation Angle (FRA) and Vertical Total Electron Content (VTEC)
- FRA and Brightness Temperature
- VTEC retrieval from SMOS radiometric data
- New improvement: the uncertainty is taken account
- Results: VTEC global maps

Faraday Rotation



- 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

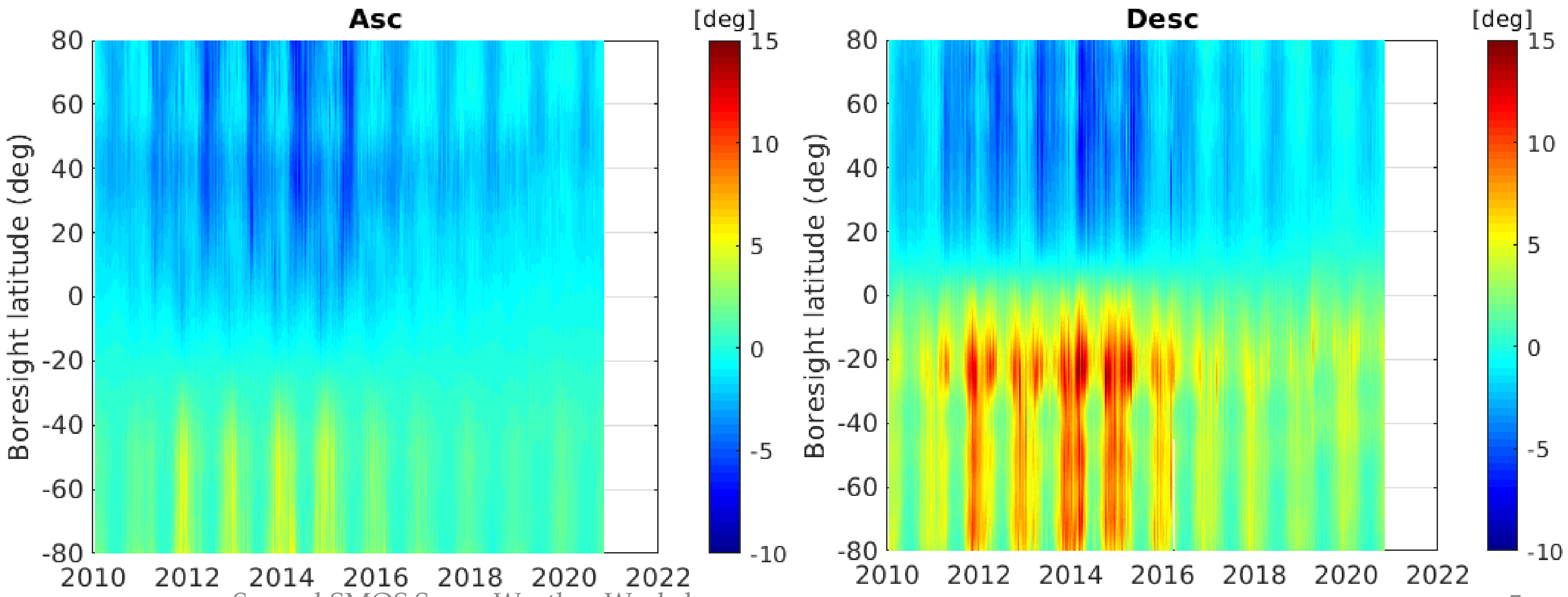
- Ionosphere
  - Earth's atmosphere (~50 to ~600 km)
  - Ionized particles and electrons
  - Sun → source of energy (solar activity)

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



Brightness Temperature frame rotation

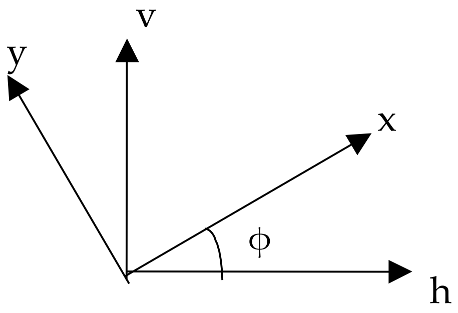
Antenna frame and ground frame

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

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VTEC from SMOS data

(see next two pages)

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

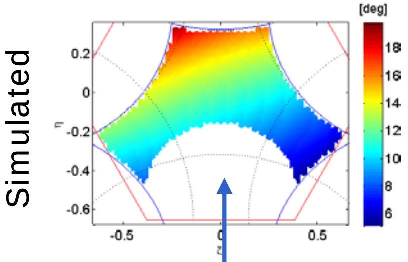
1. Brightness temperature time averaging

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

2. FRA recovery

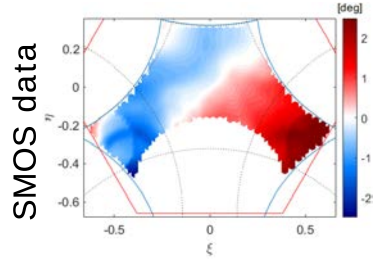
FRA recovery of every snap-shot (ia>25°) with

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



Discard low incident angles

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



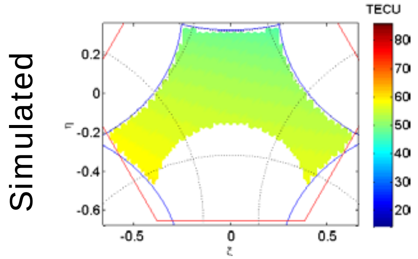
Subtract error pattern to the measured FRA

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

4. VTEC from FRA

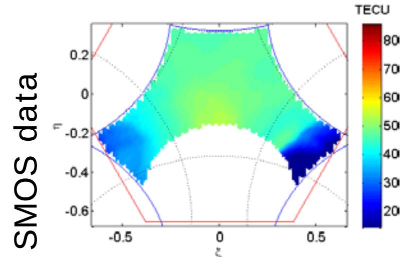
Retrieval of the VTEC from the FRA with

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



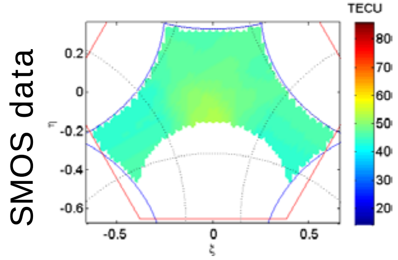
5. Spatial filter

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

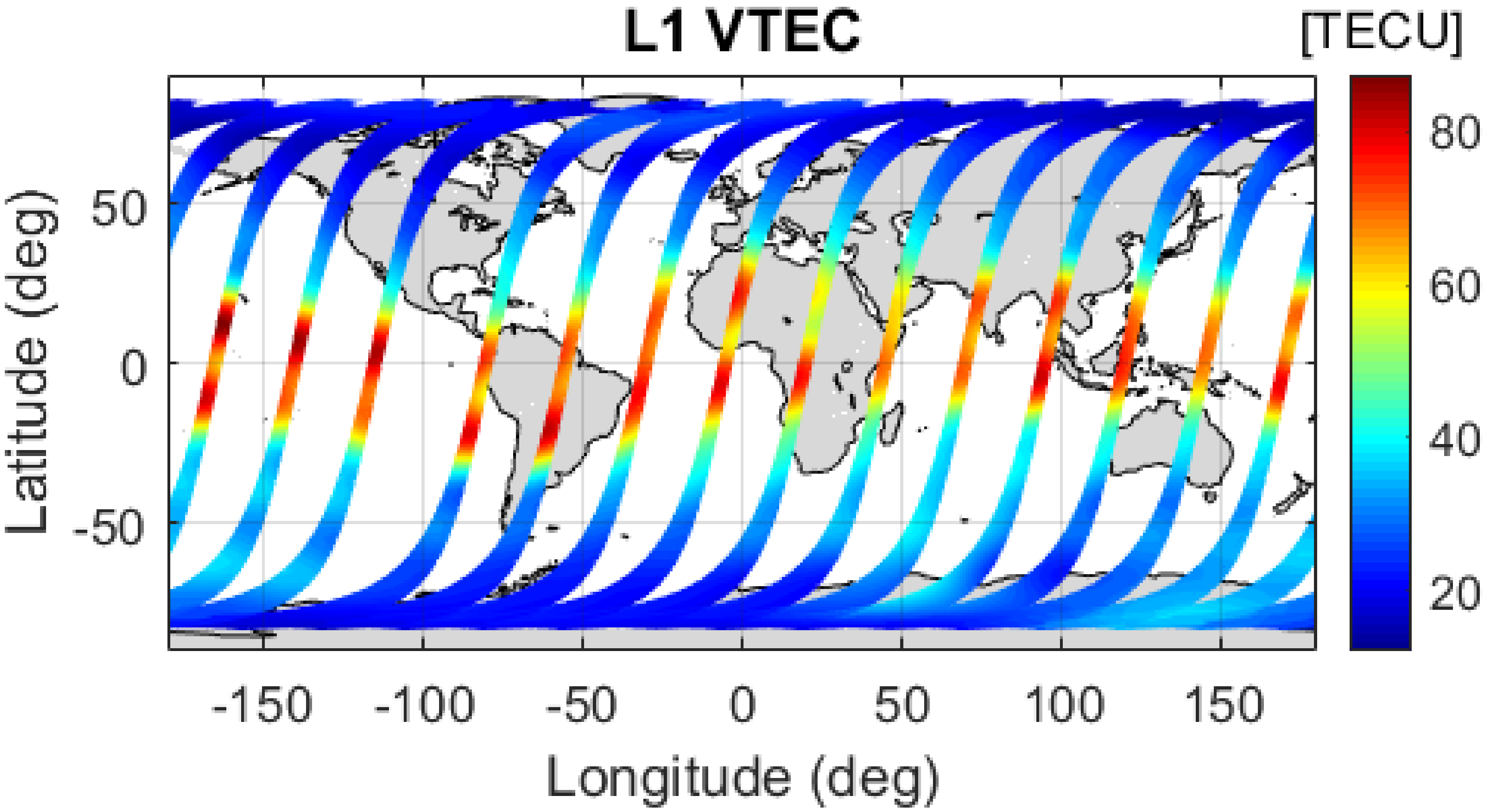
Repeat the border VTEC value of the AF-FoV to the EAF-FoV to mitigate the error in the laterals of the snapshot



7. VTEC maps projected over Earth

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

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



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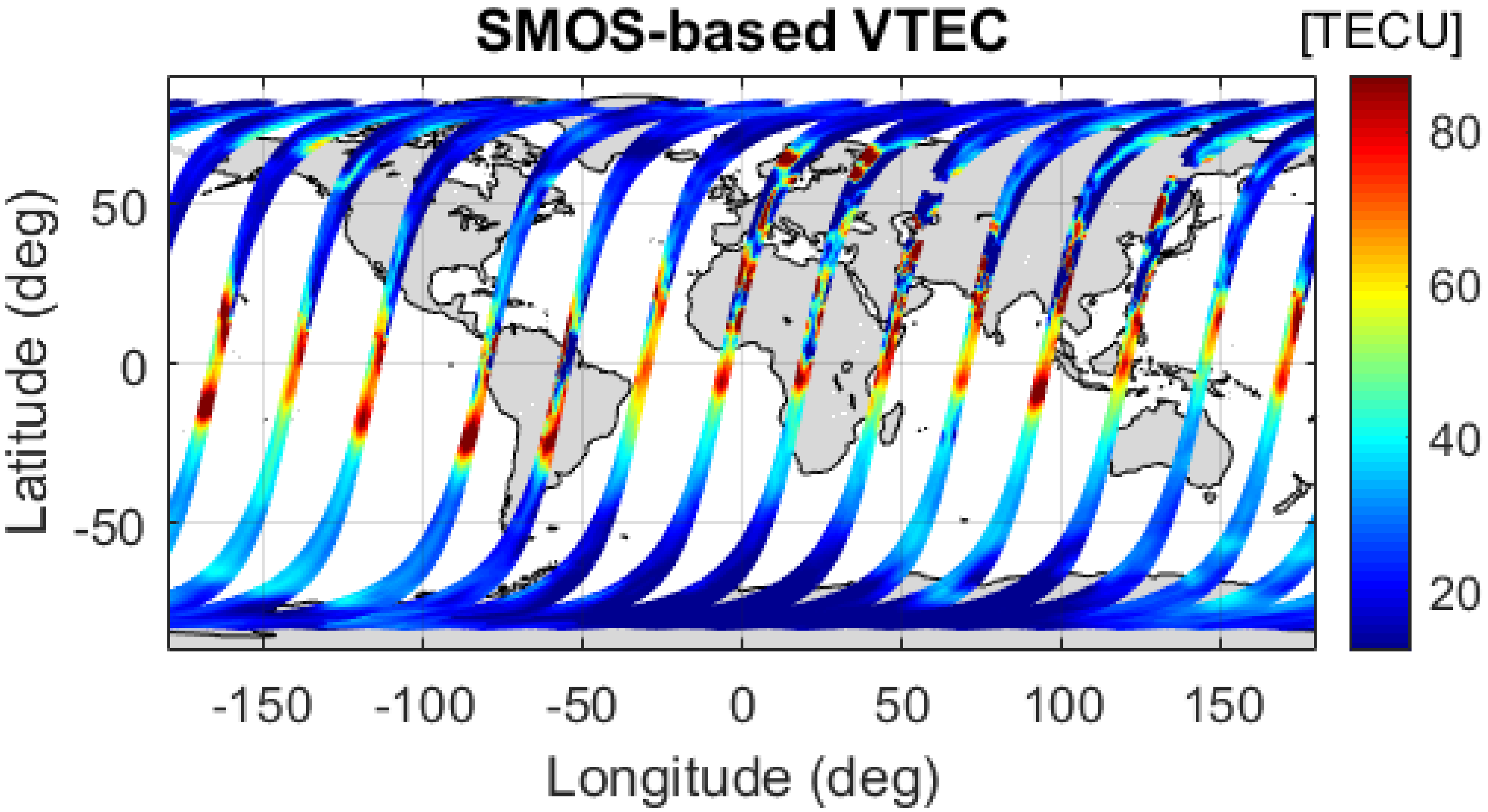

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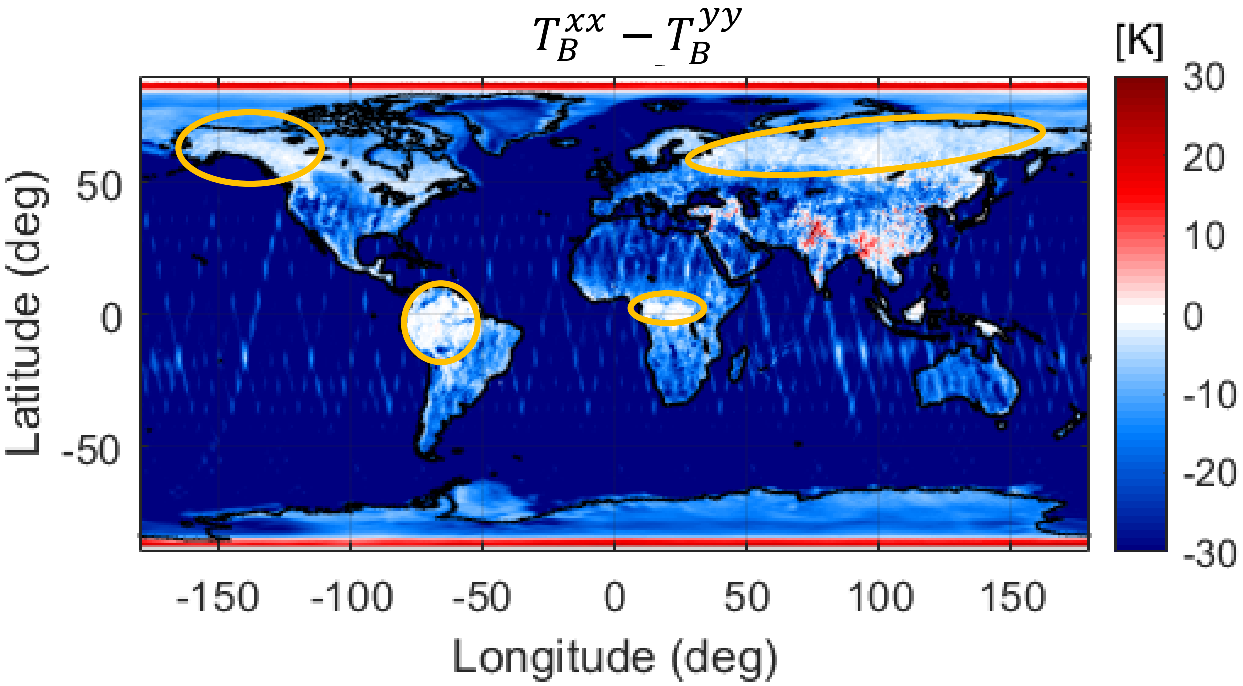
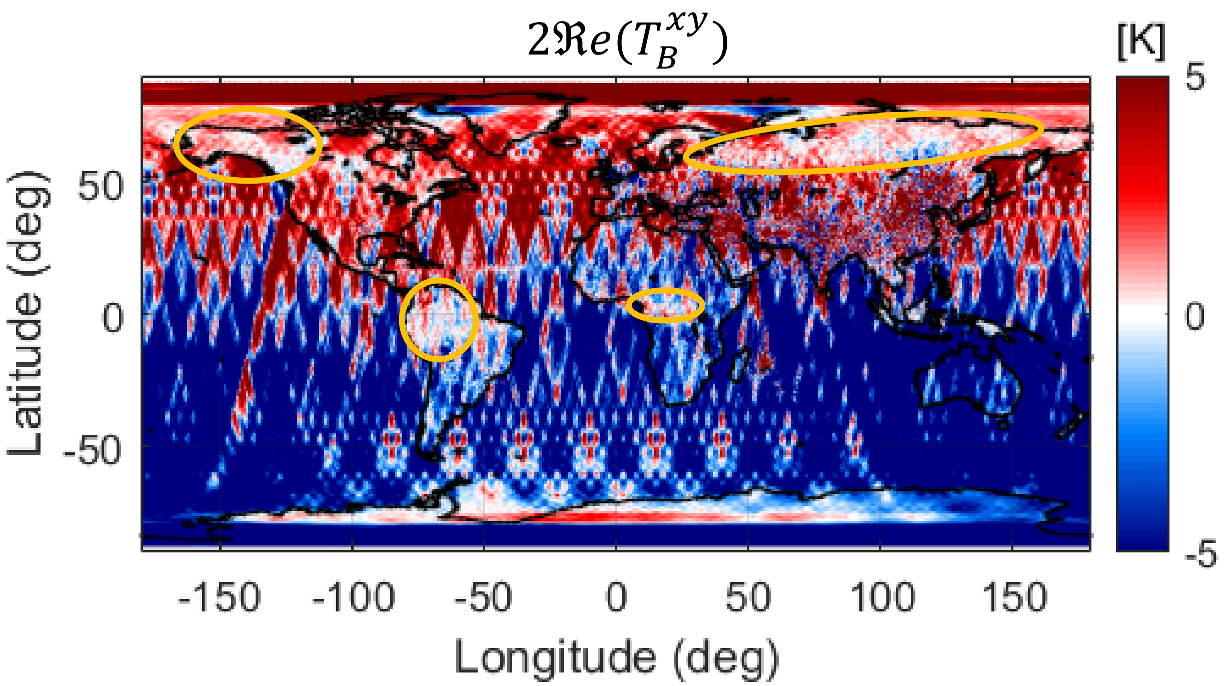
SMOS Brightness temperatures (March 2014)

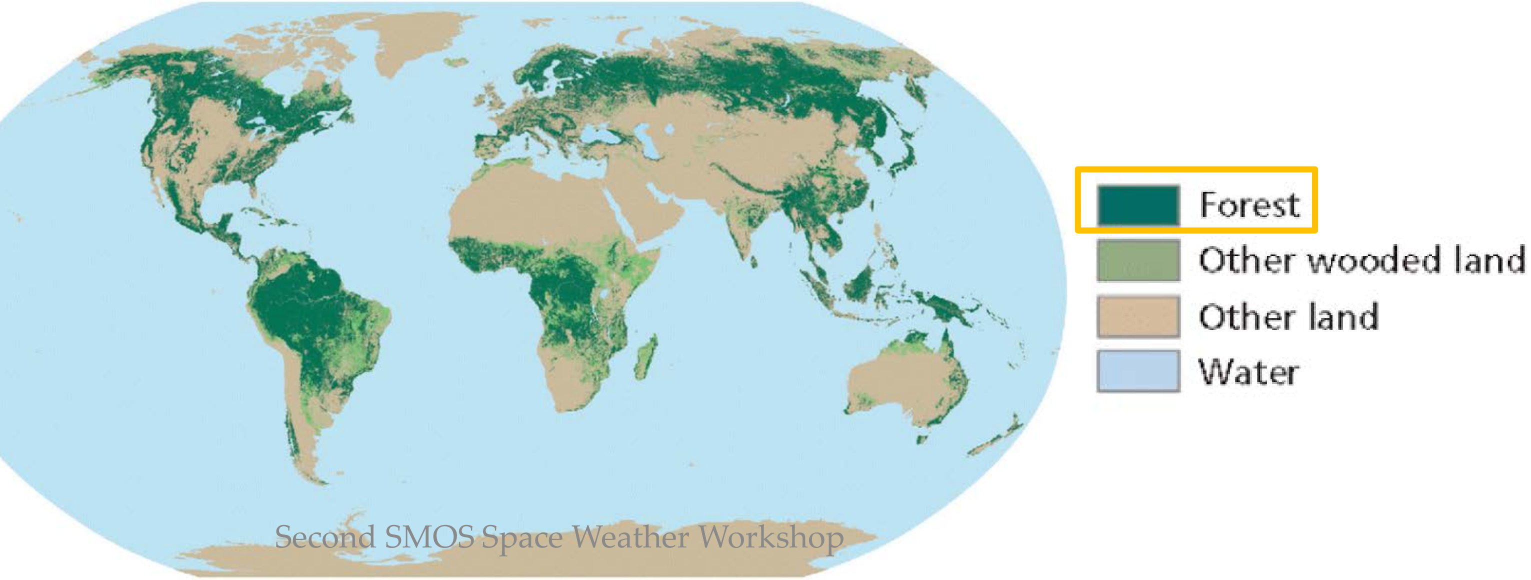




In dense forests

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

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



Collaborations from First Space Weather Workshop

- Marjolijn Adolfs, from DLR, has developed a neural network-based (NN) TEC model for global Vertical TEC (VTEC) predictions that could reproduce the Nighttime Winter Anomaly (NWA). She is using our SMOS-derived VTEC products.

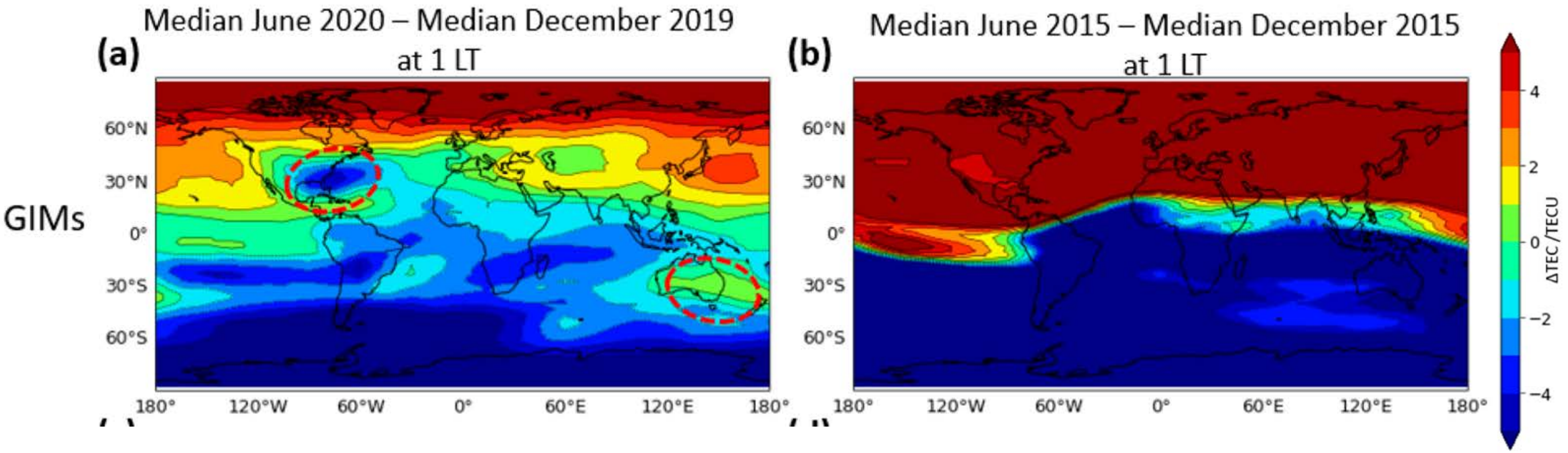
    Adolfs, M.; Hoque, M.M. A Neural Network-Based TEC Model Capable of Reproducing Nighttime Winter Anomaly. Remote Sens. 2021, 13, 4559. https://doi.org/10.3390/rs13224559

- The SWARM team expressed interest to compare VTEC derived from SWARM and SMOS missions:

    - The two measurements look complementary (SMOS: below 700 Km, SWARM: above 500 Km).

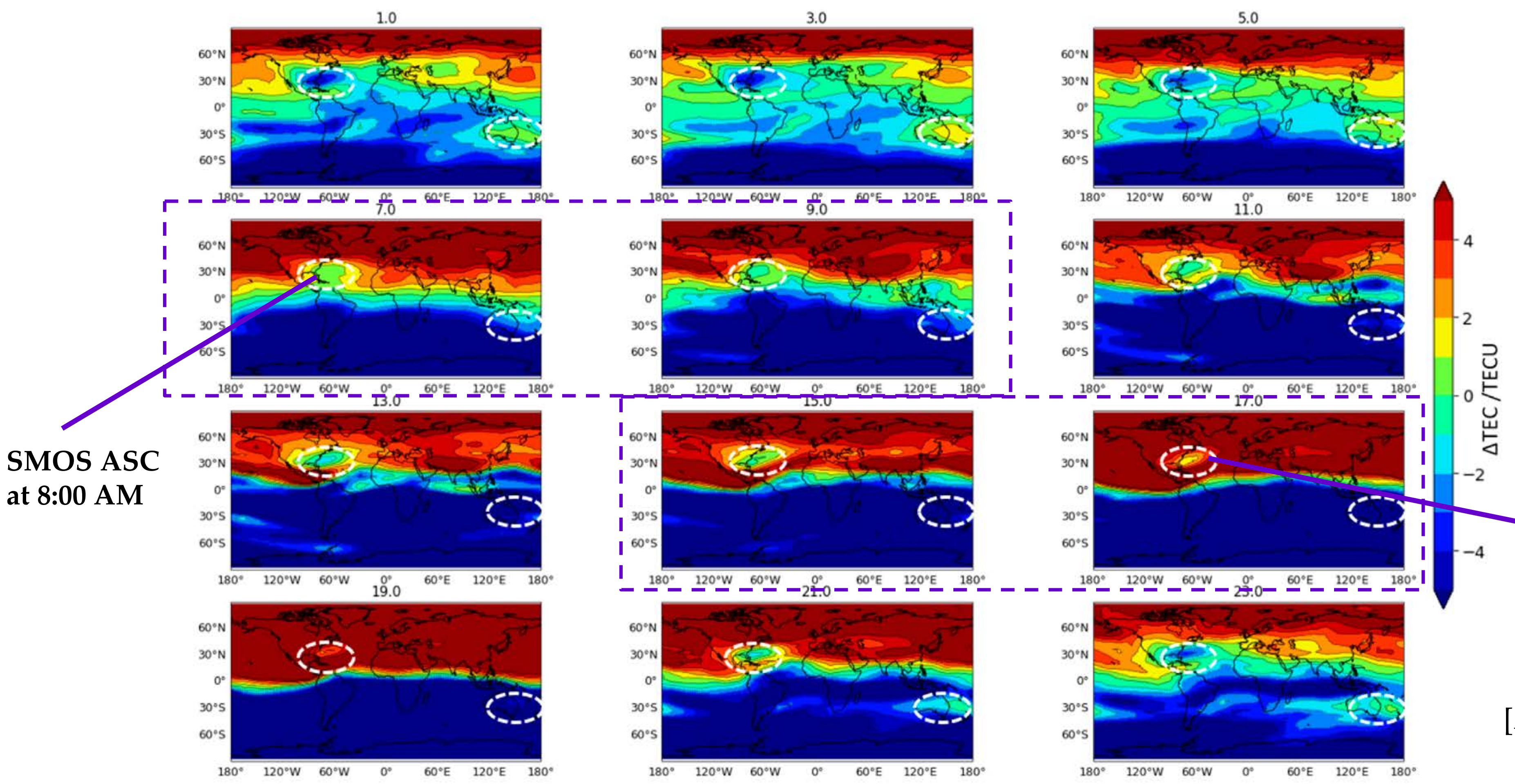
Nighttime Winter Anomaly

- NWA occurs during nighttime in low solar activity period at mid latitudes in the northern hemisphere in the American sector and southern hemisphere in the Asian sector.
    - Caused by higher ionization level in winter nights than in summer nights.
    - Visible in the difference between monthly median TEC maps in December and June.



Nighttime Winter Anomaly

GIMs Median June 2020 – Median December 2019

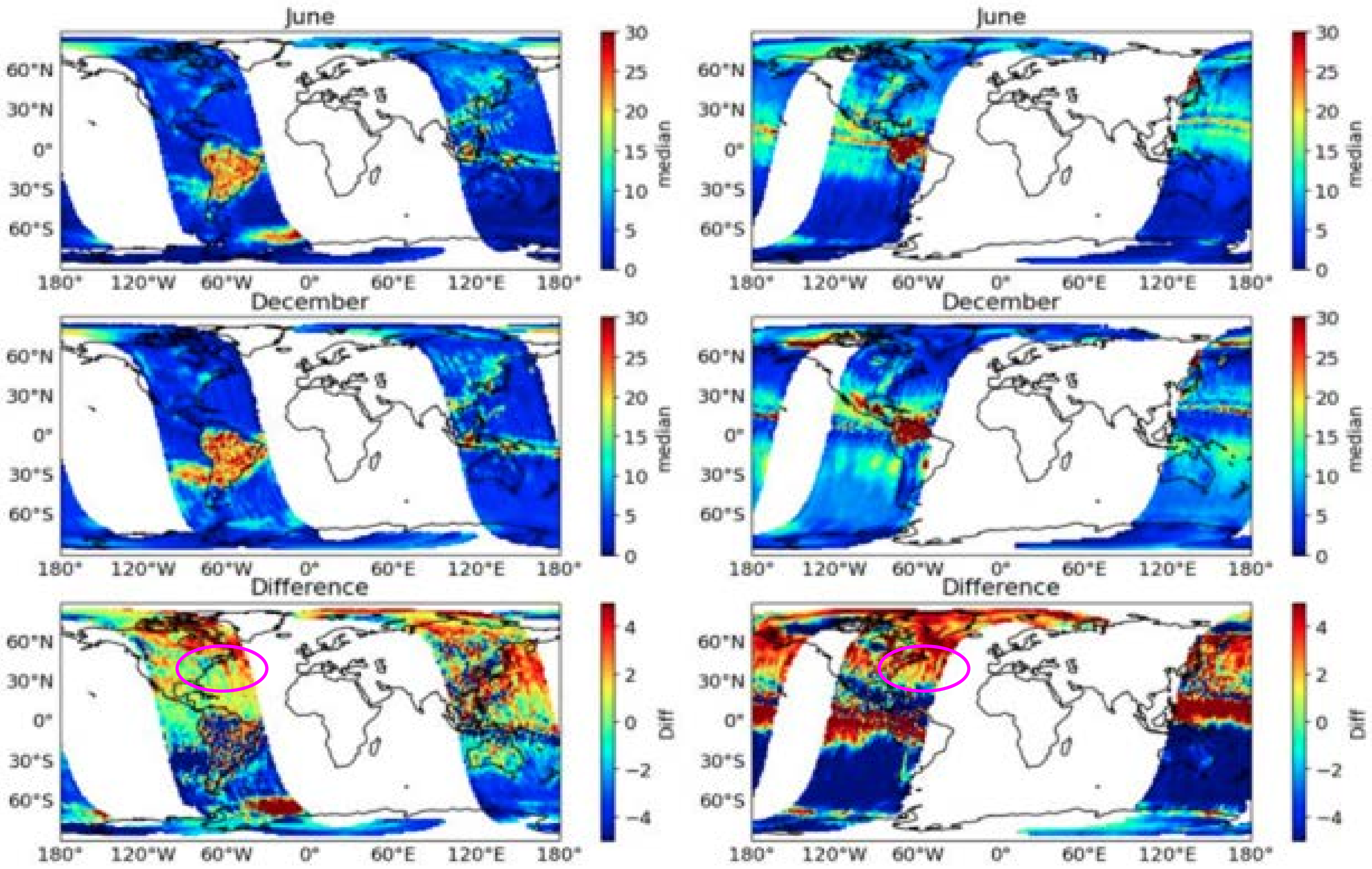


We need to capture changes of 1-2 TECU!

[Alfons & Mainul, 2021]

Nighttime Winter Anomaly

- All the retrieved VTEC measurements have been used in the generation of the monthly VTEC maps (no filtering at all).
- An uncertainty field is required to filter out those outliers in the generation of VTEC maps.



Uncertainty of each measurement

- The uncertainty of each individual VTEC measurement through the propagation of the estimated errors for the brightness temperatures has been derived:

- $VTEC = \frac{\Omega_f * cos\theta}{C_n * f * cos\Theta_B} = C * \left[-\varphi_g - \frac{1}{2}\tan^{-1}\frac{2\Re e\left(T_B^{xy}\right)}{T_B^{xx} - T_B^{yy}}\right]$

- $\sigma_{VTEC}^2 = \left(\frac{\partial VTEC}{\partial T_B^{xx}}\right)^2 * \sigma_{T_B^{xx}}^2 + \left(\frac{\partial VTEC}{\partial T_B^{yy}}\right)^2 * \sigma_{T_B^{yy}}^2 + \left(\frac{\partial VTEC}{\partial T_B^{xy}}\right)^2 * \sigma_{T_B^{xy}}^2$

Theoretical radiometric accuracy
in each polarization

Uncertainty of each measurement

- Where the partial derivatives of VTEC with respect to TBs can be computed as follows:

$$\frac{\partial VTEC}{\partial TB^{xx}} = C * \frac{2Re(TB^{xy})}{(TB^{xx} - TB^{yy})^2 + (2Re(TB^{xy}))^2}$$

$$\frac{\partial VTEC}{\partial TB^{yy}} = -C * \frac{2Re(TB^{xy})}{(TB^{xx} - TB^{yy})^2 + (2Re(TB^{xy}))^2}$$

$$\frac{\partial VTEC}{\partial Re(TB^{yy})} = -C * \frac{2\,(TB^{xx} - TB^{yy})}{(TB^{xx} - TB^{yy})^2 + (2Re(TB^{xy}))^2}$$

Uncertainty of each measurement

- Then, once we have computed the uncertainty for each individual VTEC retrieval, we make a weighted average of all the VTEC individual measurements that fall in each grid cell of the ETOPO5 grid, with the weights:

$$W_{ij} = \frac{1}{\sigma^2_{VTECij}}$$

$$VTEC_{\mathrm{j}} = \frac{\sum_i VTEC_{ij} * W_{ij}}{\sum_i W_{ij}}$$

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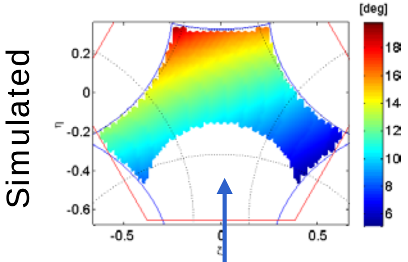

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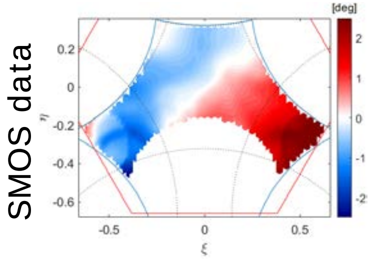

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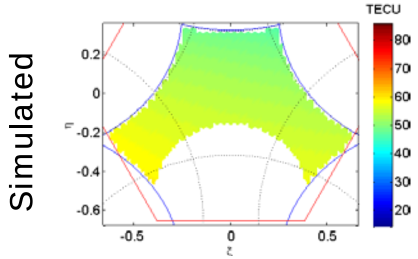

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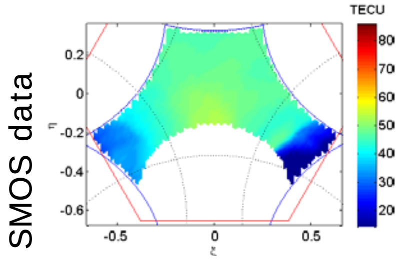

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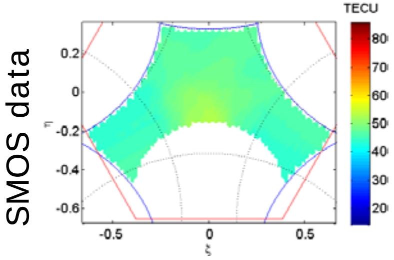

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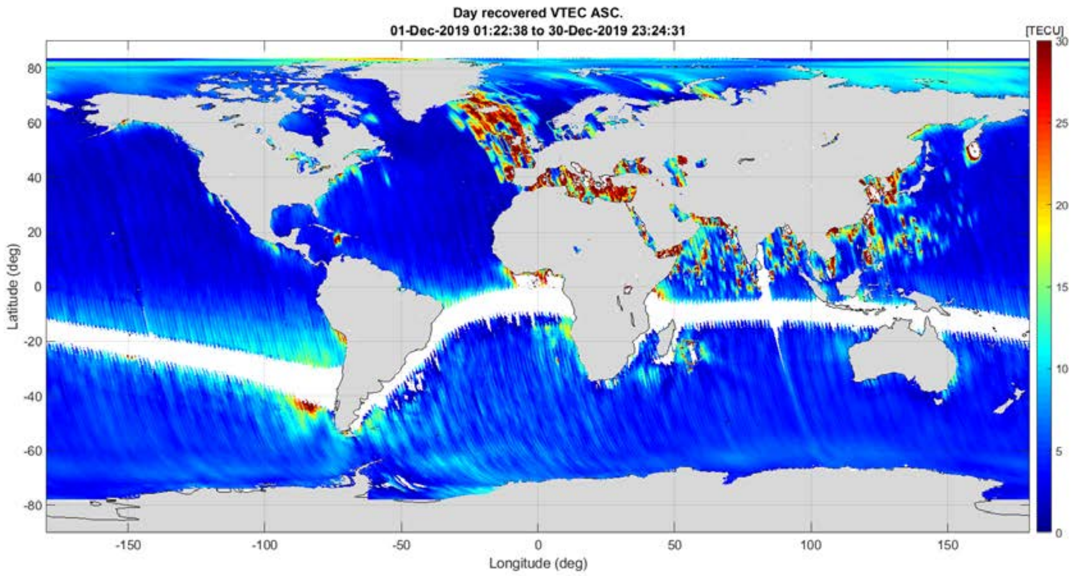
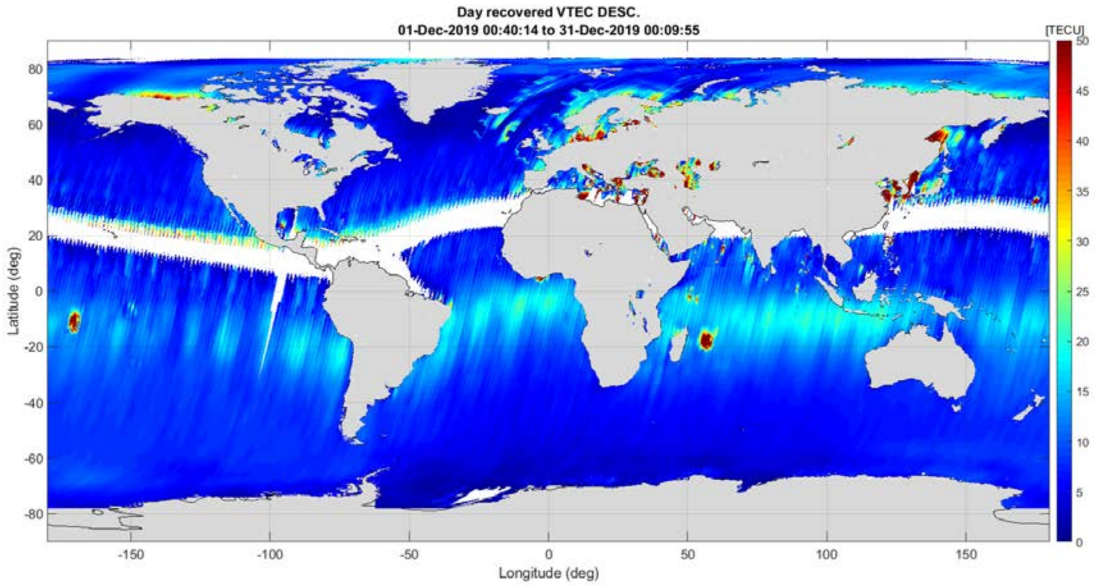
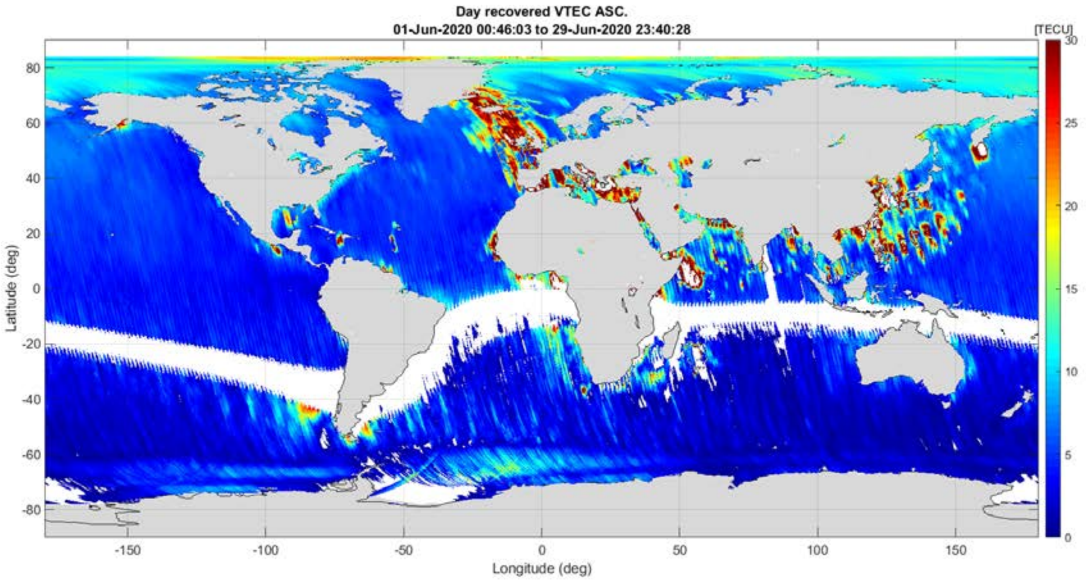
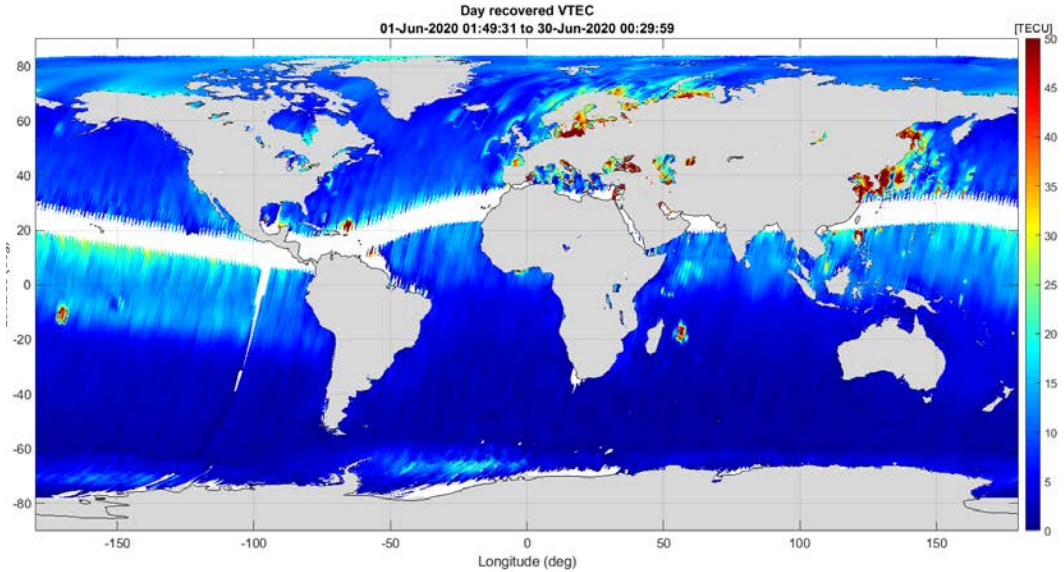
VTEC of December 2019



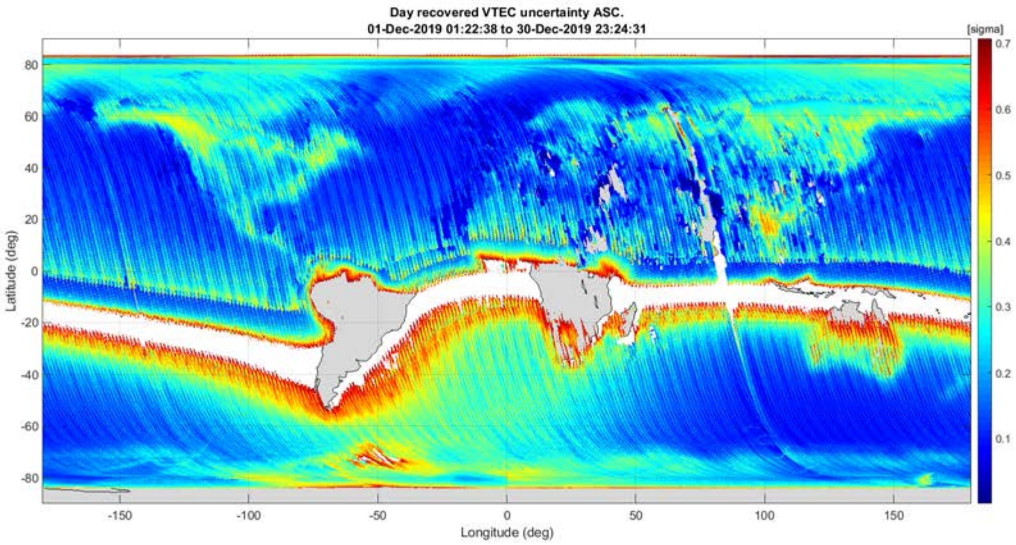


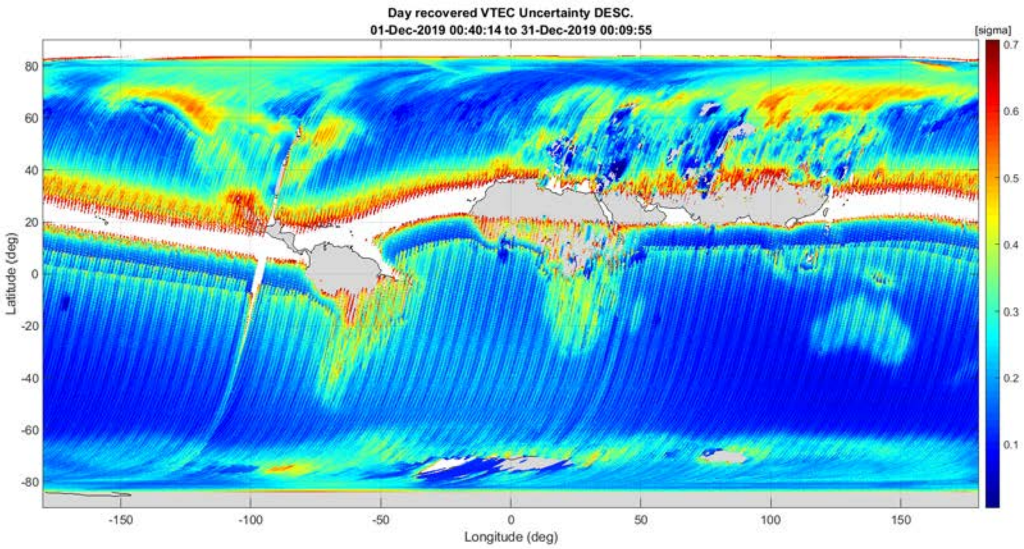
VTEC of June 2020





Uncertainty of VTEC





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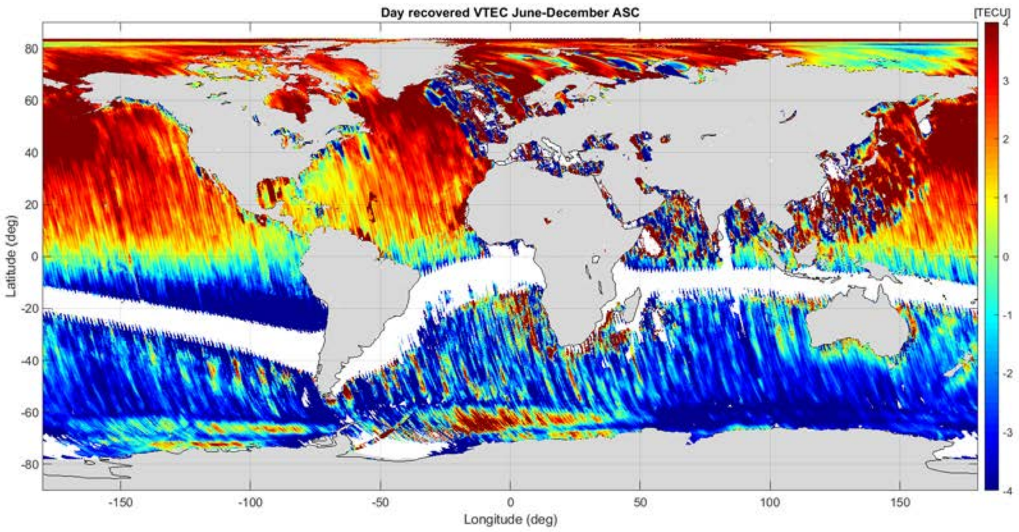
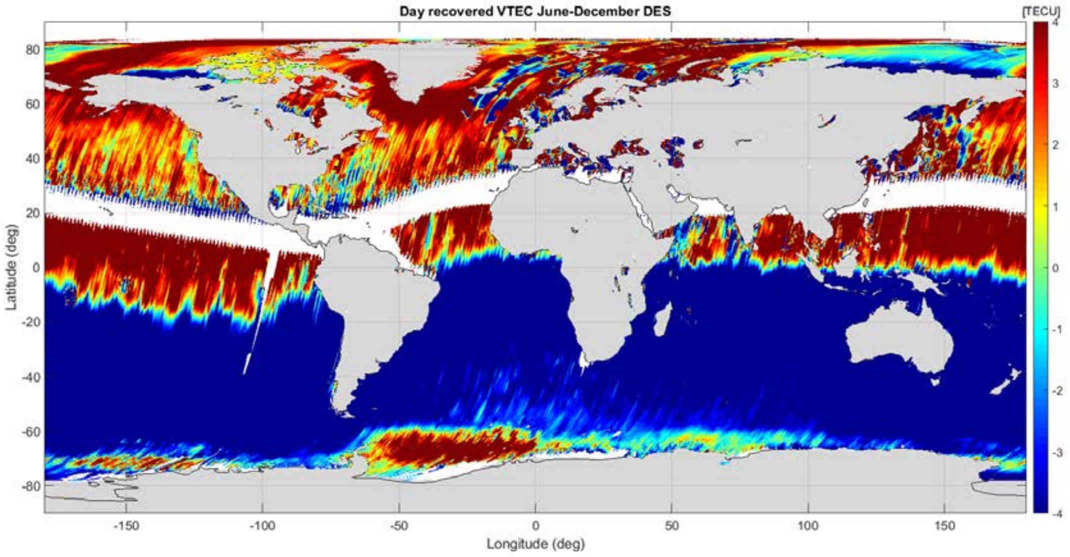
VTEC of June 2020 –December 2019





Collaboration with the SWARM team

- The SWARM team has derived periods in which the SWARM satellites are on orbit plan similar to SMOS (06.00 a.m. / p.m)

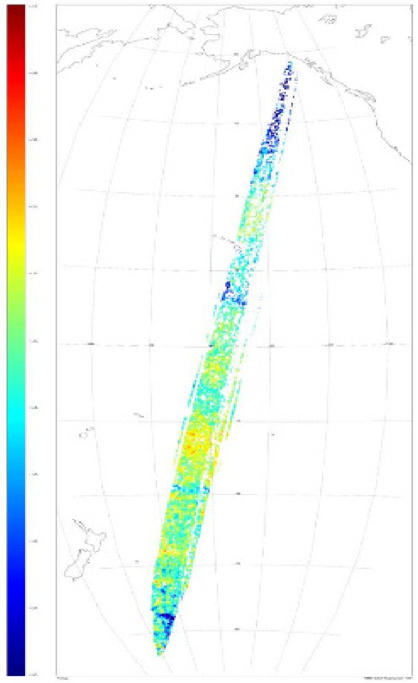
SWARM Alpha - Charlie			SWARM Bravo	
Start	Stop		Start	Stop
18/02/2014	02/03/2014		18/02/2014	03/03/2014
02/07/2014	16/07/2014		07/07/2014	22/07/2014
18/11/2014	30/11/2014		28/11/2014	14/12/2014
29/03/2015	09/04/2015		17/04/2015	01/05/2015
06/08/2015	20/08/2015		04/09/2015	18/09/2015
21/12/2015	01/01/2016		19/01/2016	03/02/2016
03/05/2016	15/05/2016		09/06/2016	24/06/2016
03/09/2016	26/09/2016		30/10/2016	15/11/2016
21/01/2017	03/02/2017		17/03/2017	28/03/2017
06/06/2017	18/06/2017		02/08/2017	17/08/2017
20/10/2017	01/11/2017		21/12/2017	06/01/2018
26/02/2018	09/03/2018		12/05/2018	28/05/2018
10/07/2018	23/07/2018		02/10/2018	15/10/2018
22/11/2018	06/12/2018		12/02/2019	26/02/2019
04/04/2018	16/04/2019		03/07/2019	20/07/2019
13/08/2019	28/08/2019		25/11/2019	10/12/2019
26/12/2019	07/01/2020		11/04/2020	26/04/2020
09/05/2020	21/05/2020		29/08/2020	12/09/2020
20/09/2020	02/10/2020		13/01/2021	28/01/2021
26/01/2021	08/02/2021		07/06/2021	18/06/2021
10/06/2021	25/06/2021		26/10/2021	10/11/2021
27/10/2021	07/11/2021		10/03/2022	24/03/2022
03/03/2022	16/03/2022		28/07/2022	14/08/2022
14/07/2022	29/07/2022			

- We have provided the SWARM team with the following data for a first preliminary analysis:
  - Year 2014, global coverage
  - Swath-based data
  - ETOPO5 grid
  - netCDF format

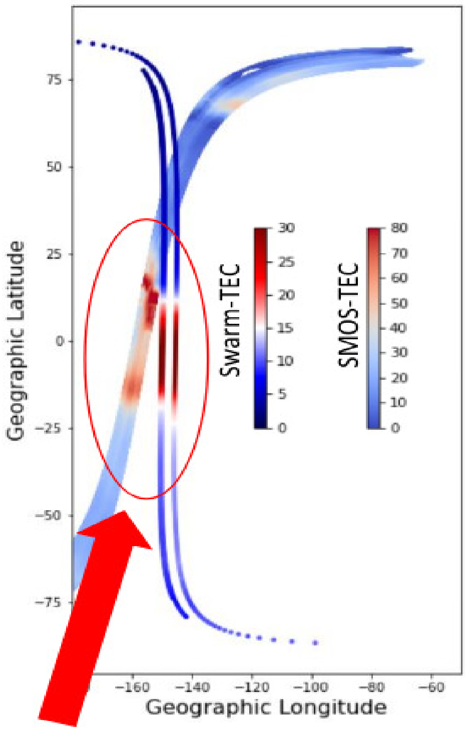
Collaboration with the SWARM team

Feedback from SWARM team (24-03-2023)

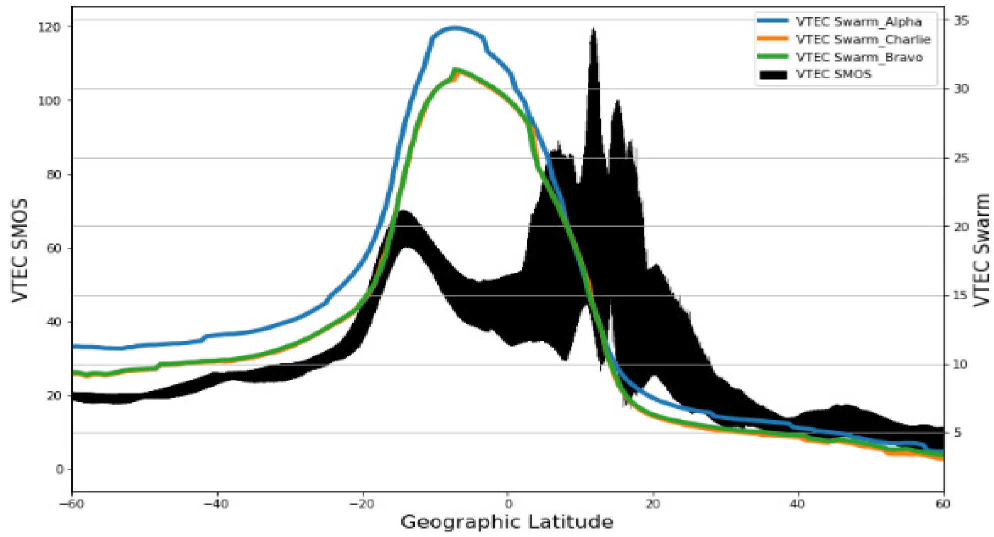
A preliminary comparison of Swarm Vs SMOS Vertical TEC on 2014-02-18



SMOS over pacific ocean: no VTEC contaminations from land signals



On 2014-02-18 a good conjunction around the equator, longitudes ~ -140°



- VTEC enhancement at the equator observed by all s/c with reasonably good agreement.
- Larger VTEC values are expected from SMOS, since it measures from satellite altitude to the ground, including E and F ionospheric layers. Swarm conversely measures from Swarm orbit, upward.
- Double-peak from SMOS Vs single-peak from Swarm: to be investigated.

Conclusions

- 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
- The Uncertainty of the measurements have been used to average them:
  - Cleaner images are obtained.