Space Weather Monitoring Capabilities of ESA's Swarm & SMOS Missions

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ESA Swarm mission

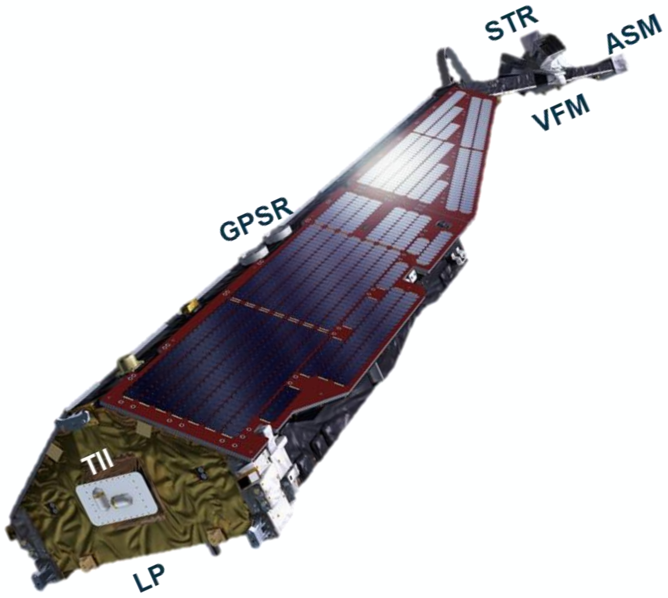
Swarm mission: 3 identical s/c launched in Nov. 2013. Swarm Alpha and Charlie flying side by side at ~470 km, Swarm Bravo flying at ~510 km

Objectives: measure the Earth's magnetic field and it's time evolution and monitor the Ionospheric environment.

Thanks to Swarm instruments accuracy, it is also able to provide valuable observations for Ionosphere Magnetosphere coupling, Ocean motion, Vulcanoes eruption, etc.

Each s/c with 7 instruments:

- Vector Field Magnetometer (**VFM**)
- Absolute Scalar Magnetometer (**ASM**)
- Electric Field Instrument (**EFI**): Ion Imagers + Langmuir Probes
- Accelerometer (**ACC**)
- GPS receiver (**GPSR**)
- 3 Star trackers (**STR**)
- Laser Retroreflector (**LRR**)



Standard OPERATIONAL CHAIN

- 4 processors providing data with a latency of 4/5 days for L1B & L2 Cat-2 products (19 data products for each spacecraft).
- Latest L1B dataset released in November 2023 includes new Nelec, Nion, new Te artificial spike flags

A new **"FAST" chain** is now also available providing data with ~12 h latency

- **Same algorithms** (with some alternative input files)
- **Same product types**
- **Same time resolution**

- **L2 FAC** since June 2024
- **L2 TEC** since Feb 2025
- **AOBxFAC_2F - Auroral Boundaries product -** since Mar 2026
- **AEJxLPL_2F – Auroral electrojet product -** since Mar 2026

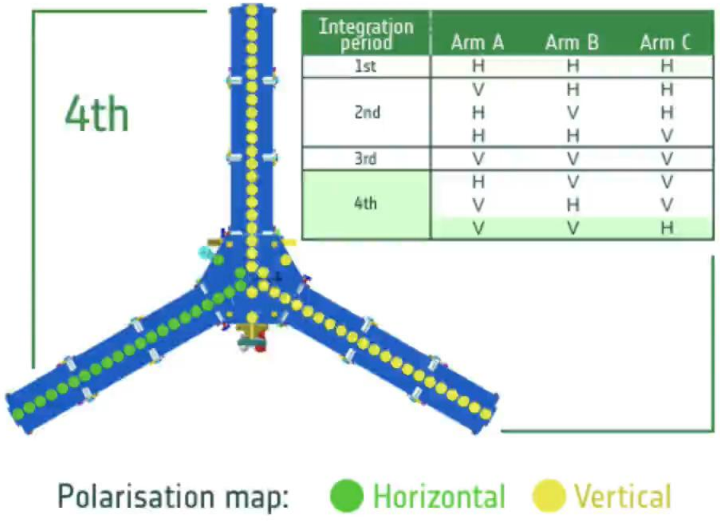
ESA SMOS Mission

SMOS mission: launched in Nov. 2009, **Sun-synchronous** orbit (dusk-dawn **6am/6pm**) with a mean altitude of 758km.

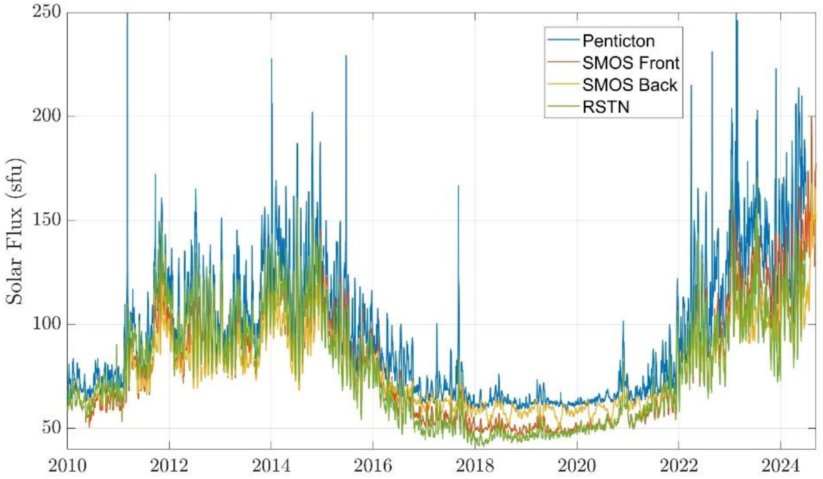
Objectives: global observations of soil moisture over land and salinity over oceans, to advance our understanding of exchange processes between Earth's surface and atmosphere improving weather and climate models.

The payload of **SMOS** is **MIRAS** instrument, a passive microwave 2-D interferometric full polarization radiometer at 1.413 GHz (wavelength of 21 cm).

Due to antenna size, it captures full Earth-disk and part of the surrounding sky, including the Sun (noise for Earth observation, but interesting signal for Space Weather application).



Integration period	Arm A	Arm B	Arm C
1st	H	H	H
2nd	V	H	H
	H	V	H
	H	H	V
3rd	V	V	V
4th	H	V	V
	V	H	V
	V	V	H



Land products:

- soil moisture,
- soil state (freeze/thaw),
- vegetation optical depth

Sea products:

- sea surface salinity,
- sea ice thickness,
- sea surface wind speed
- cyclone wind radii

+ Space weather products:

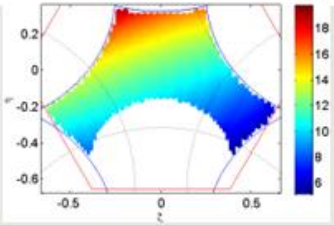
- **L-band Solar flux**
- **Ionospheric Total Electron Content**

Retrieval of SMOS-based VTEC from Faraday Rotation Angle

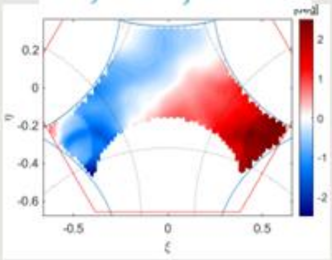
SMOS fullpol TBs → Temporal filtering → Computation of FRA → Computation of systematic FRA errors → Computation of VTEC and its uncertainty → Spatial filtering of VTEC → Geolocation and averaging of VTEC and uncertainty on-ground → VTEC retrievals in the SMOS swath

Processing per full polarization block and in antenna frame

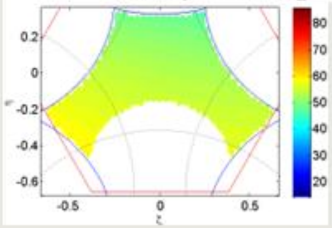
$$\Omega_f^m = -\varphi_g - \frac{1}{2}\tan^{-1}\left(\frac{2\Re\left(T_B^{xy}\right)}{T_B^{xx} - T_B^{yy}}\right)$$

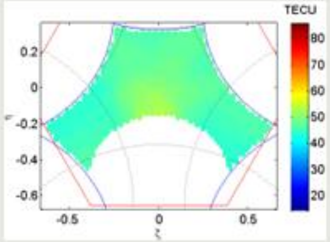


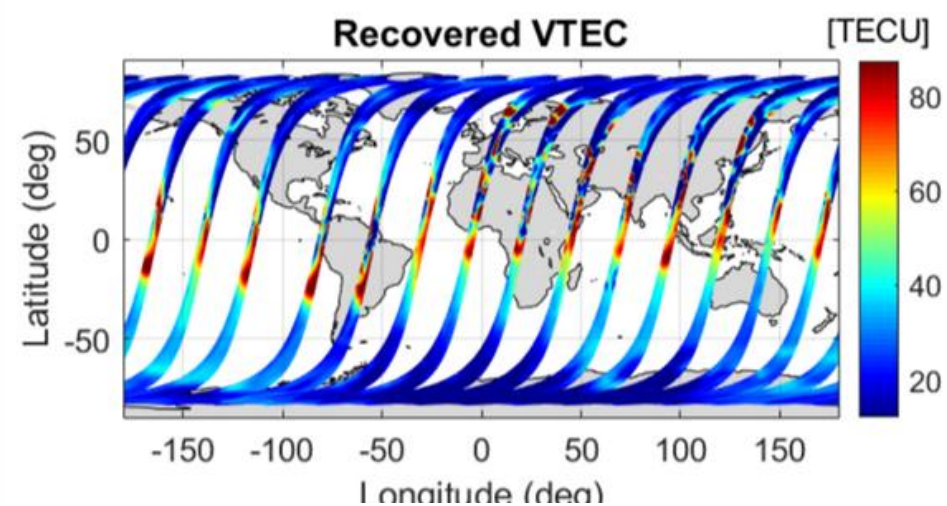
$$\Omega_f = \Omega_f^m - \Delta$$



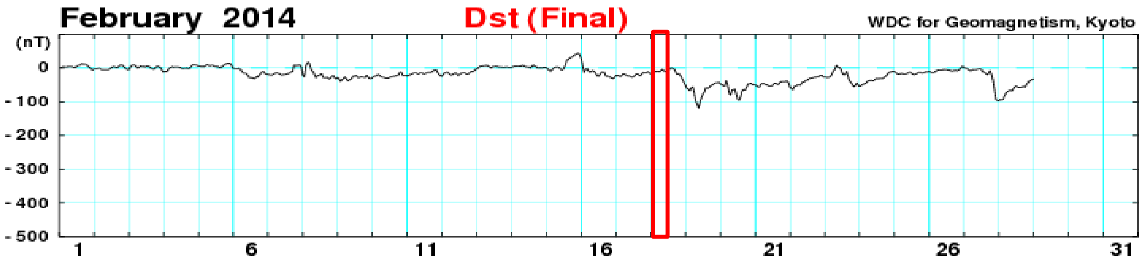
$$VTEC = \frac{\Omega_f * \cos\theta}{Cn * f * \cos\Theta_B}$$







SWARM/SMOS VTEC comparison during quiet conditions

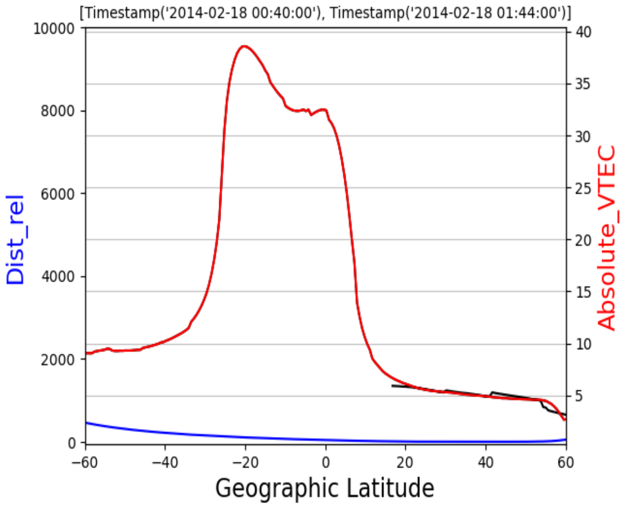


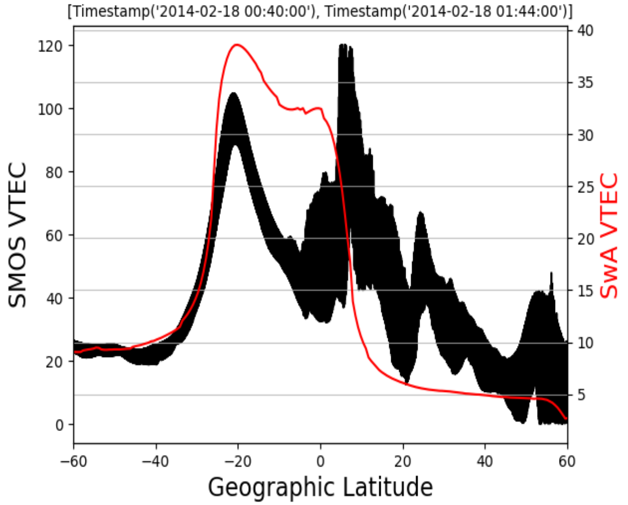
VTEC comparison is possible when Swarm and SMOS orbits were approximately coplanar.

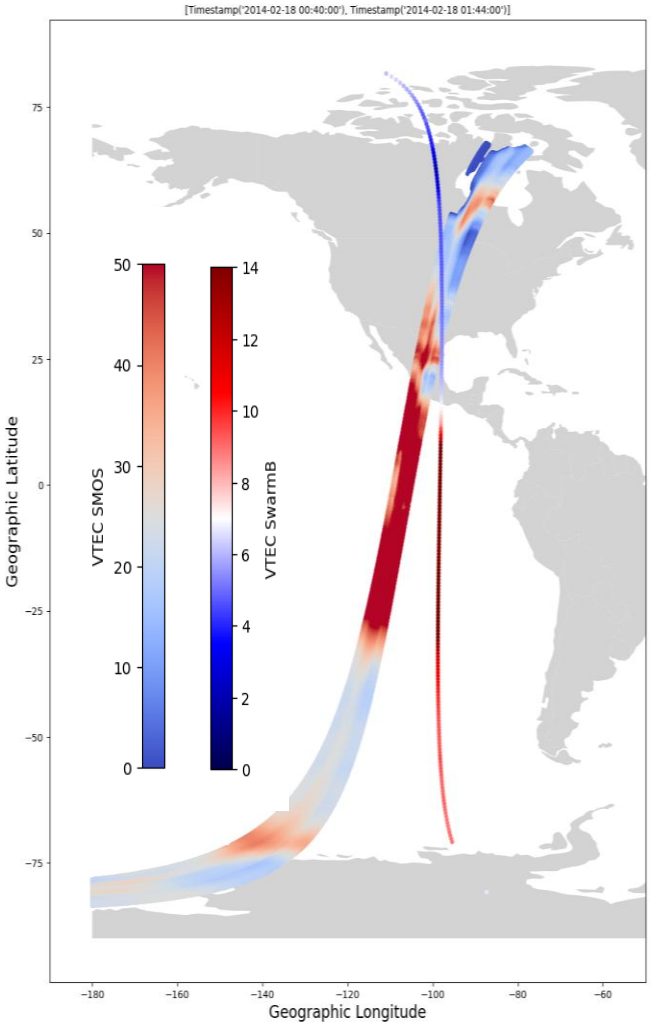
This conjunction occurs every 4 months, due to the precession of Swarm orbits.

This comparison in morning of 18 Feb, during quiet geomagnetic conditions.

A Python code to plot VTEC only when Swarm - SMOS relative distance (Δlat2+ Δlon2)<800 km



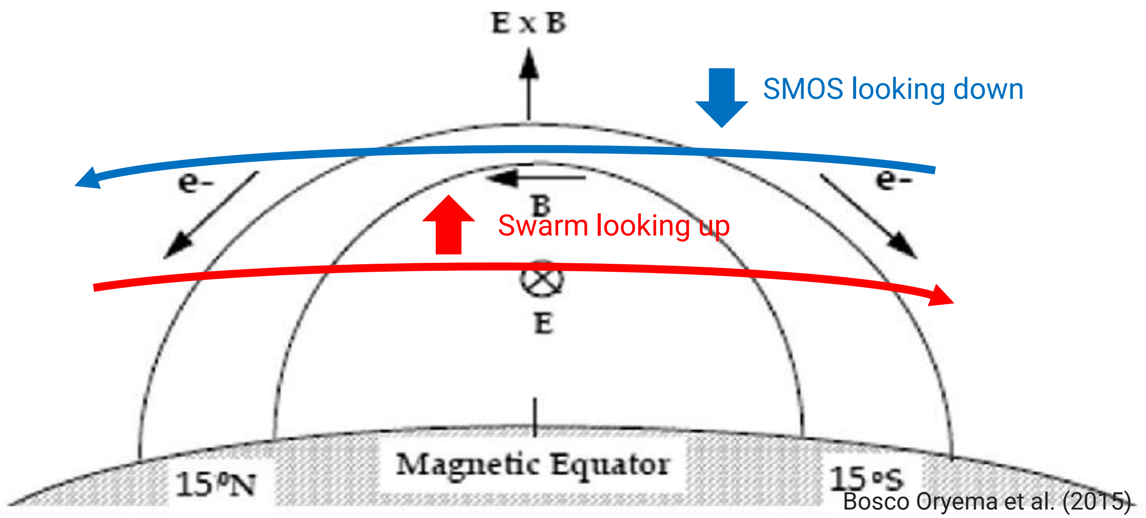


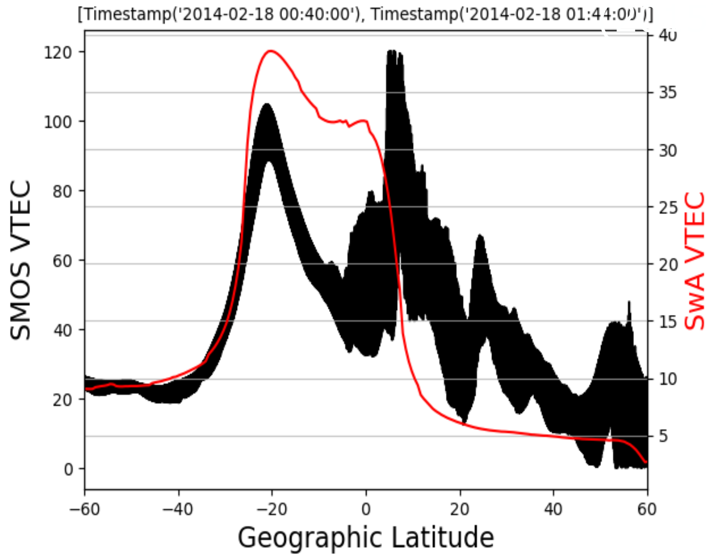


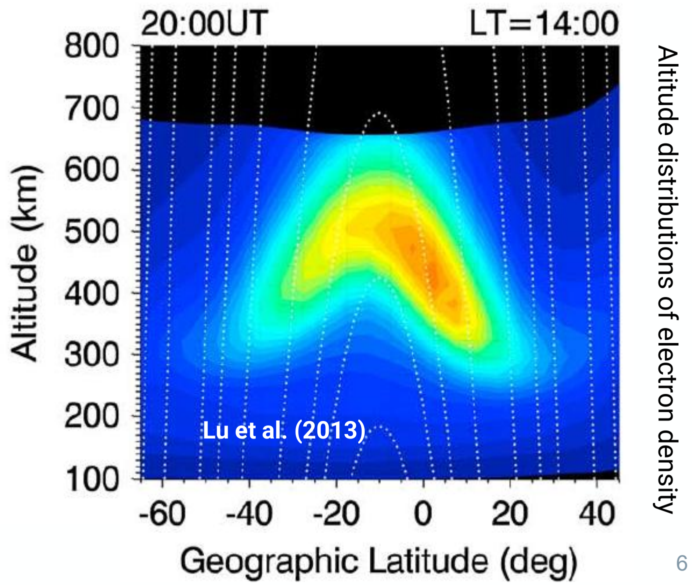
SWARM/SMOS VTEC comparison during quiet conditions

Comparison during **quiet geomagnetic conditions**:

- Good agreement among the trend of SMOS & SWARM, when SMOS data is not contaminated (LSC, RFIs,...).
- Larger SMOS VTEC values, as expected, since it samples the lower and denser ionosphere.
- Both clearly measure the Fountain effect , the intensification of density around the magnetic equator (single peak for SWARM and a double peak for SMOS).

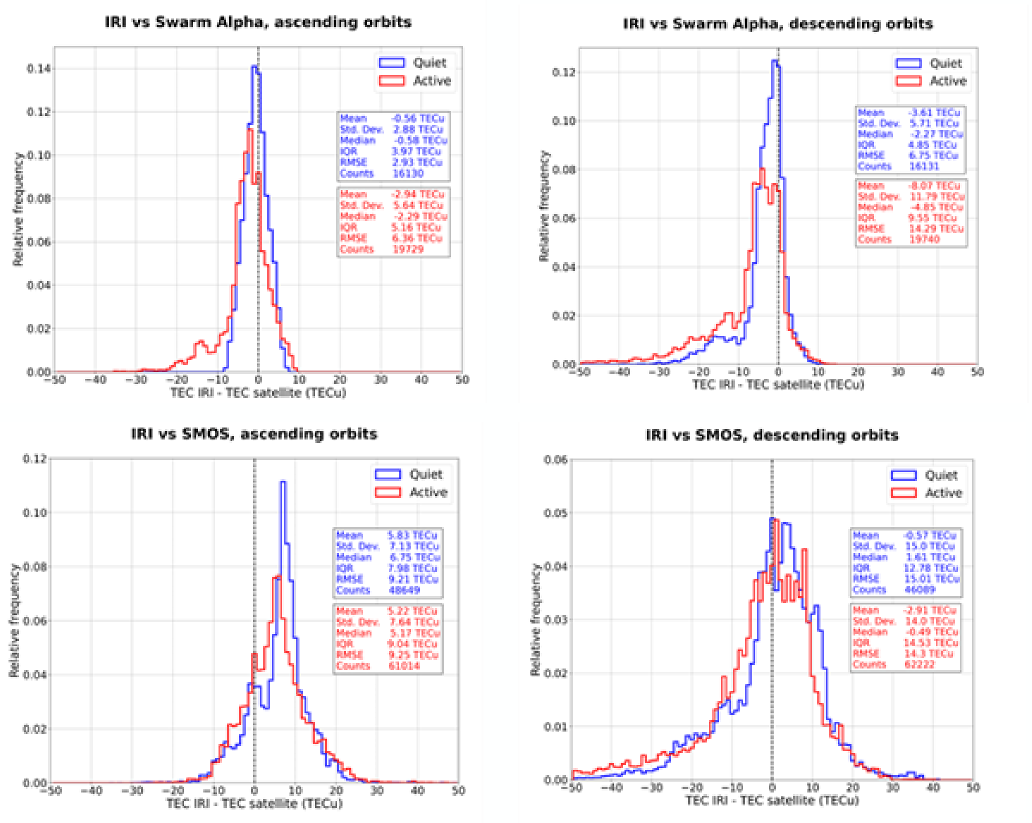


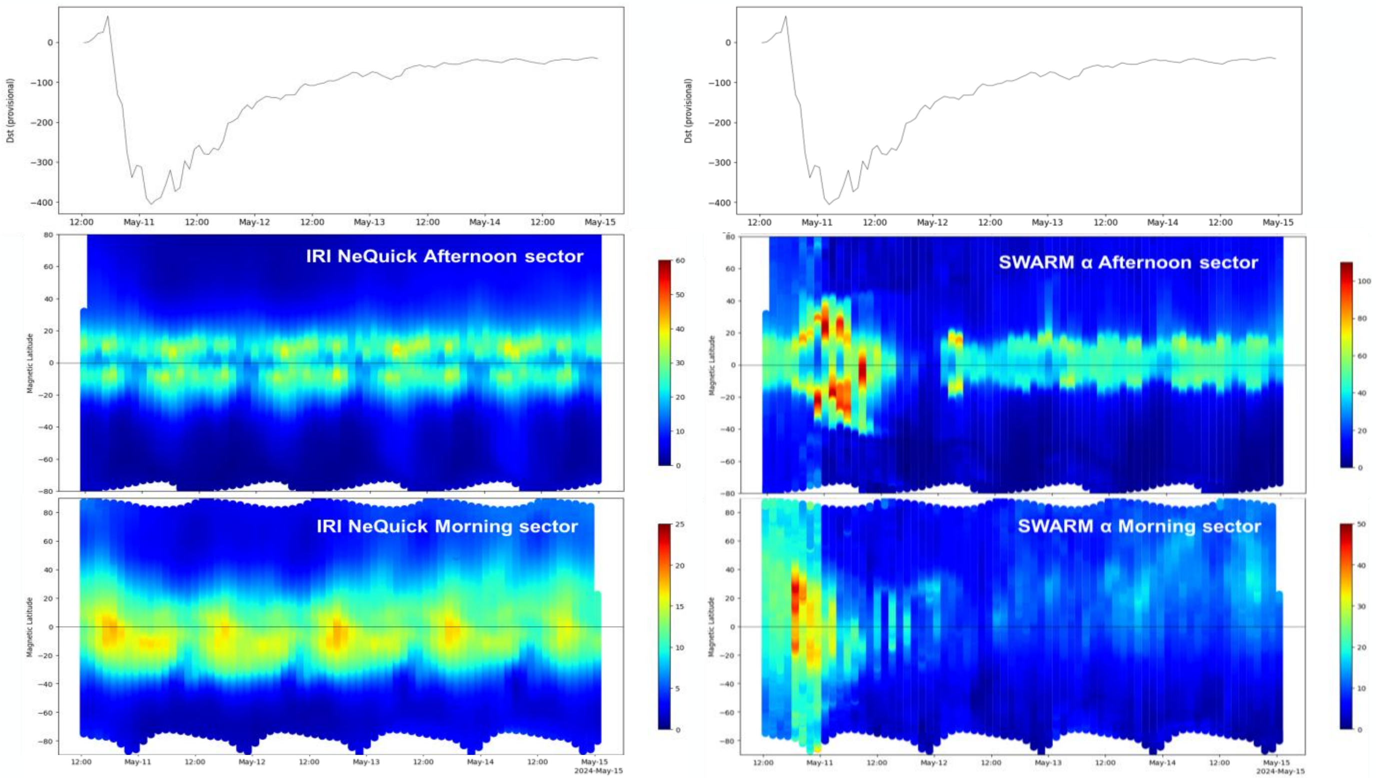




SWARM-SMOS-IRI VTEC comparison during 10 – 15 May 2024 geomagnetic storm

Swarm alpha (&Charlie) on 07 AM 07 PM LT, only one hour apart from SMOS LT (6 AM – 6PM).

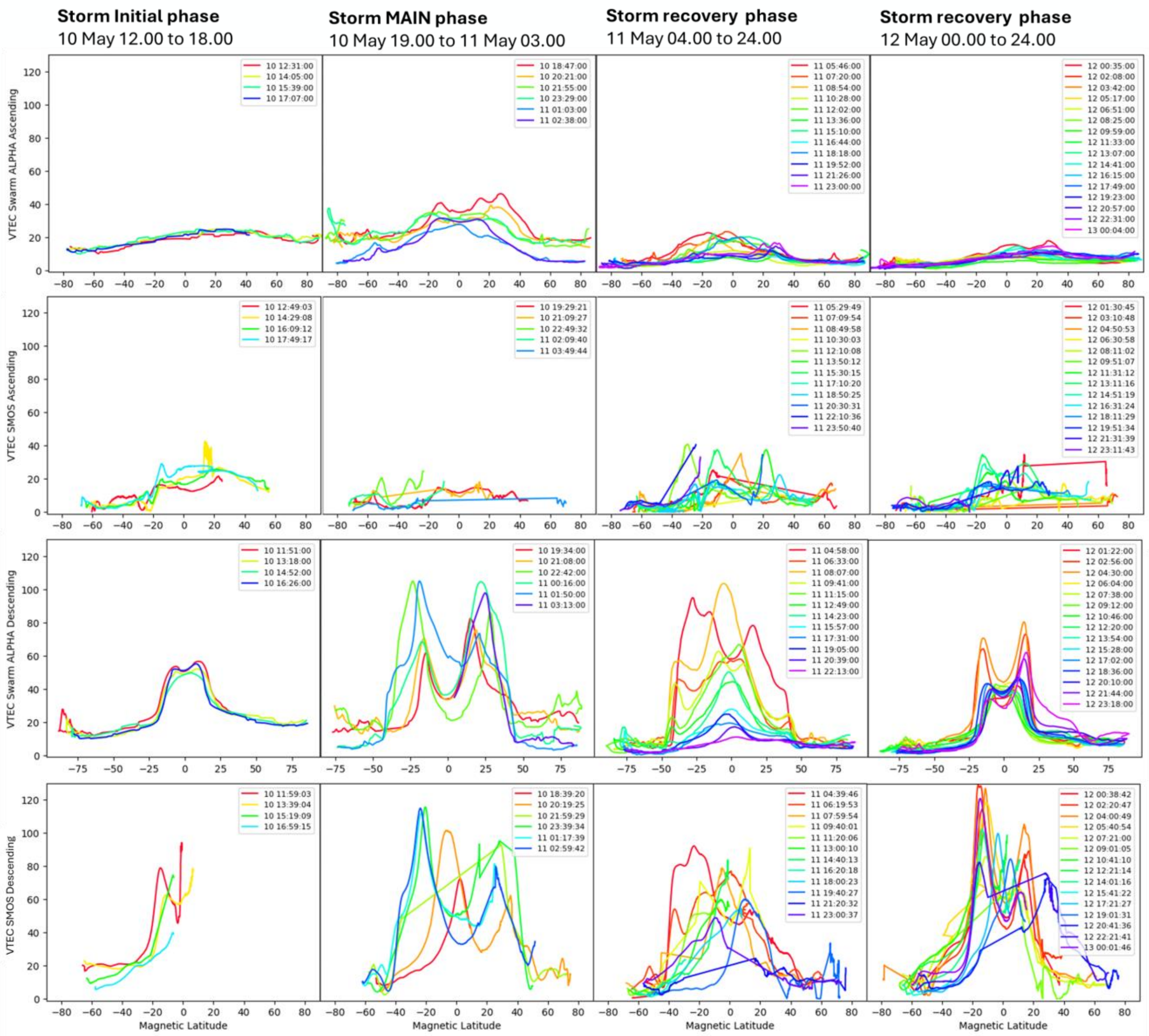




Reasonably good agreement with IRI predictions for both S/C during the quiet interval preceding the Storm (05 - 09 May 2024)

Clear VTEC modulations in Swarm VTEC, both in morning and afternoon sector, including a negative storm effect during the recovery phase.
IRI VTEC is instead constant during the storm => IRI not able to capture ionospheric variability during active conditions.

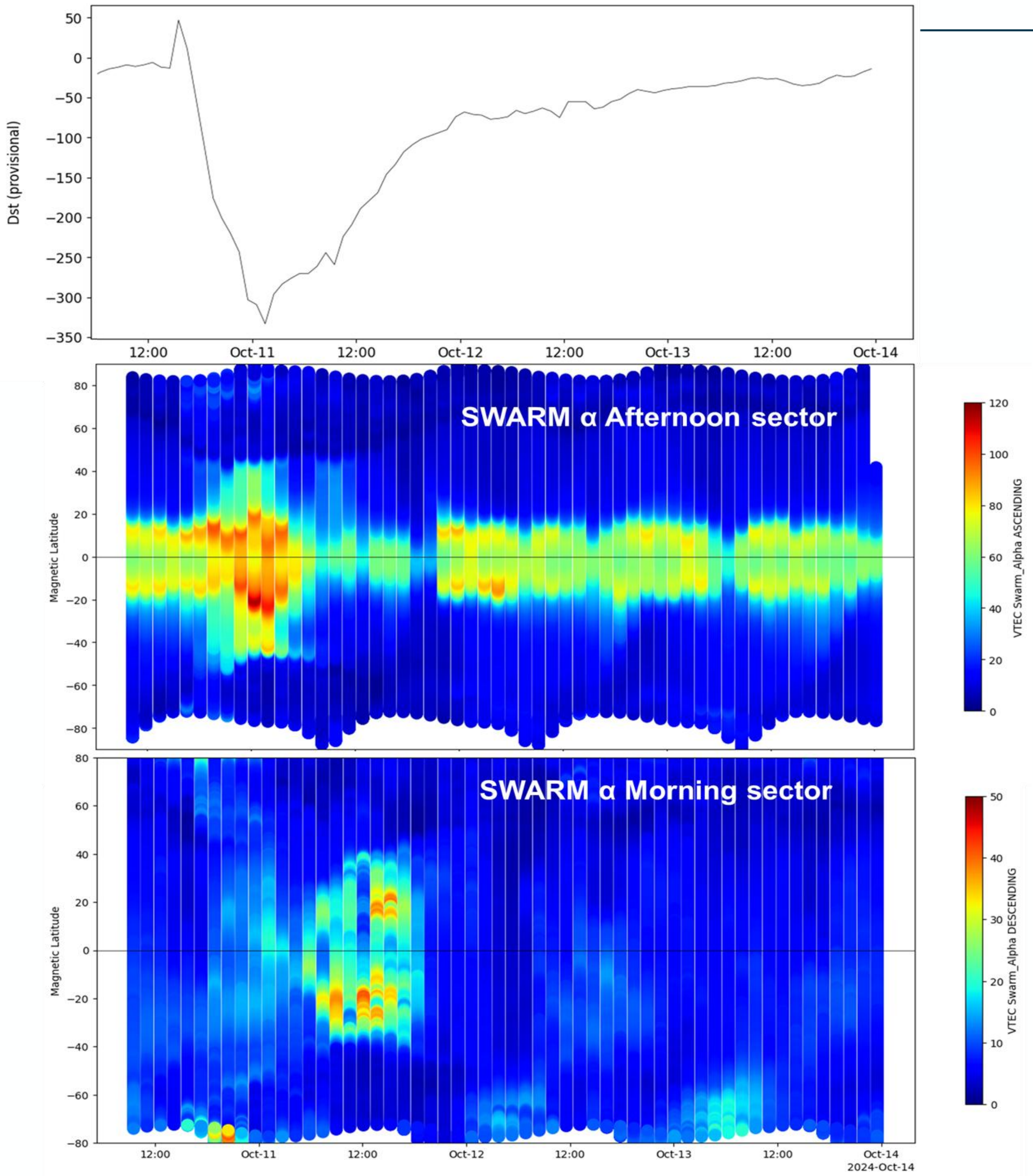
SWARM/SMOS/IRI VTEC comparison during 10 – 15 May 2024 geomagnetic storm



- Swarm and SMOS VTEC data show similar trend during this intense geomagnetic storm, both in terms of VTEC enhancement and regarding the shift of the VTEC peaks to lower geomagnetic latitudes.

- The polar orbit of these S/C allow to recover latitudinal VTEC profiles with high cadence, very useful to understand which physical mechanism is responsible for the positive and negative VTEC variations (penetration electric fields, disturbance dynamo processes, thermospheric composition changes, ionospheric plasma redistribution).

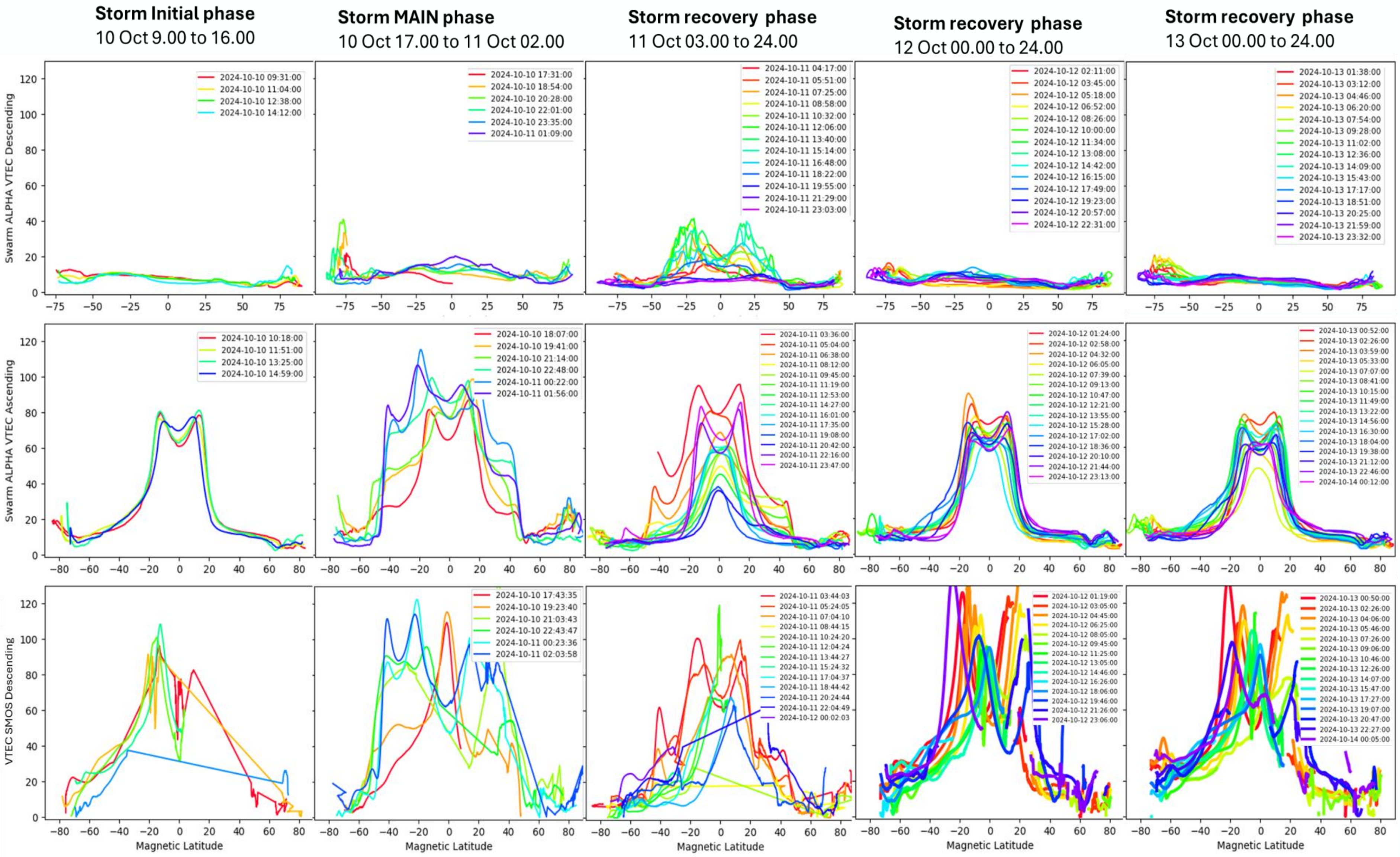
SWARM-SMOS-IRI VTEC comparison during 10 – 15 October 2024 geomagnetic storm



Also during this October 2024 storm Swarm alpha (and Charlie) orbit was very close to dawn-dusk Local Time of SMOS, being at 05.40 AM – 05.40 PM LT.

=> Swarm Alpha VTEC is appropriate to be compared with SMOS VTEC. Swarm Charlie data are not reported here, since they are very similar to Swarm Alpha measurements.

SWARM-SMOS-IRI VTEC comparison during 10 – 15 October 2024 geomagnetic storm



- A clear enhancement and double peaks to lower geomagnetic latitudes occurs in both S/C VTEC in the main phase of the storm, around the minimum peak Dst value.
- The recovery of SMOS VTEC occurs later than Swarm VTEC, probably indicating a slower response of the lower Ionosphere.

Summary

- SMOS VTEC over oceans is accurate, as demonstrated by the good agreement with IRI model during quiet geomagnetic conditions, and with Swarm during storms.
- The intense geomagnetic storms have a strong impact on VTEC, currently not represented by IRI model predictions.
- Different physical mechanisms, such as penetration electric fields (which lift ionospheric plasma to higher altitudes), disturbance dynamo processes, and thermospheric composition changes on ionospheric plasma redistribution are responsible for both positive and negative VTEC variations during the storms.
- high-resolution measurements from Swarm and SMOS can explain how VTEC is enhanced during the various phases of the storm, understanding the origin of inter-hemispheric asymmetries, analysing separately the upper ionosphere and plasmasphere (Swarm) with respect to the E & F ionospheric layers (SMOS), => better understanding of the MIT coupling.