Leveraging the ESA's Swarm overfly conditions to step into an Equatorial Plasma Bubble

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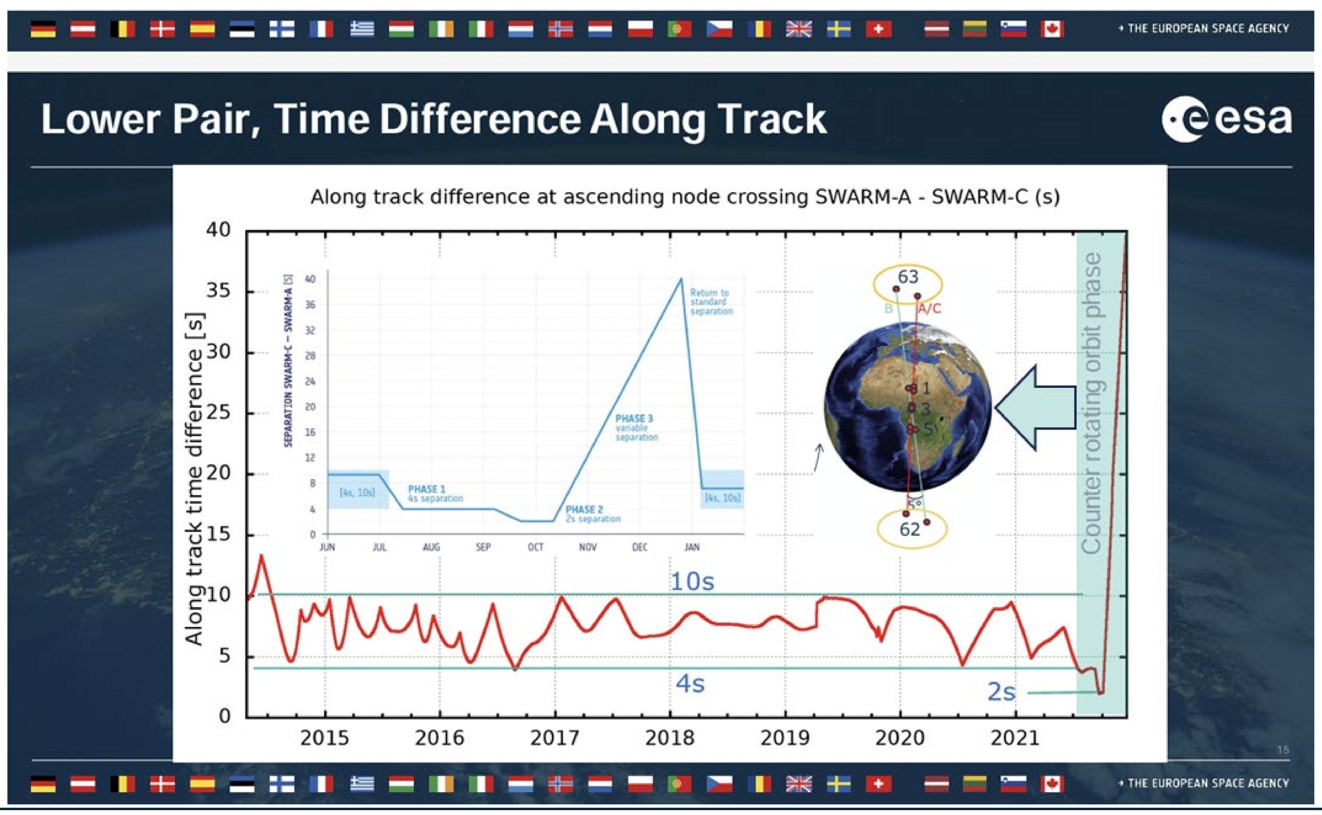
Abstract

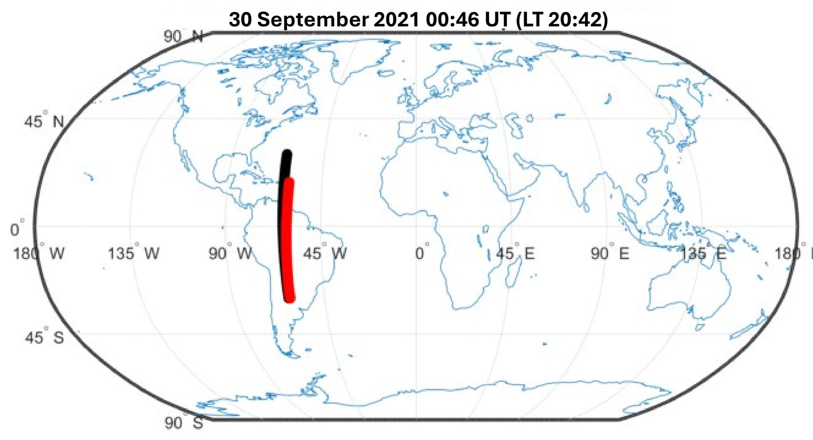
The Swarm constellation by ESA adopted an "overfly" setup during September and October 2021, where the gap between the lower and upper satellites was the smallest since their launch. During nighttime tracks, the positioning favored to observe post-sunset equatorial plasma bubbles (EPBs). This study, recently published, focuses on the specific Swarm overfly from 00:41 UT to 00:59 UT on September 30, 2021, covering a highly instrumented area in South America for studying ionospheric irregularities within EPBs. Leveraging ground-based Global Navigation Satellite System (GNSS) receivers alongside Swarm plasma density measurements, we analyze the irregularities within the EPB formed around ~60°W. The investigation delves into the various scales of these irregularities and the sequential processes along the magnetic flux tubes. We also emphasize the simultaneous occurrence of diffusion along magnetic field lines and plasma uplift, aiding in accurately interpreting the EPB's evolution and decay. The exceptional overfly conditions enable the introduction of ionosphere-related metrics, evaluated across satellite altitudes along the tracks, expanding the analysis beyond the available data along these paths. This opportunity opens avenues to estimate the impact of EPBs on GNSS signals using Low-Earth Orbit satellite data from future missions dedicated to studying the near-Earth environment and ionospheric phenomena. The overfly setup specifically allowed observations of an EPB at different altitudes, demonstrating the potential for quasi-tomographic reconstructions with larger constellations of LEO satellites orbiting at various heights. Within this context, we highlight potentially valuable metrics and their correlation with ionospheric data from ground-based GNSS measurements.



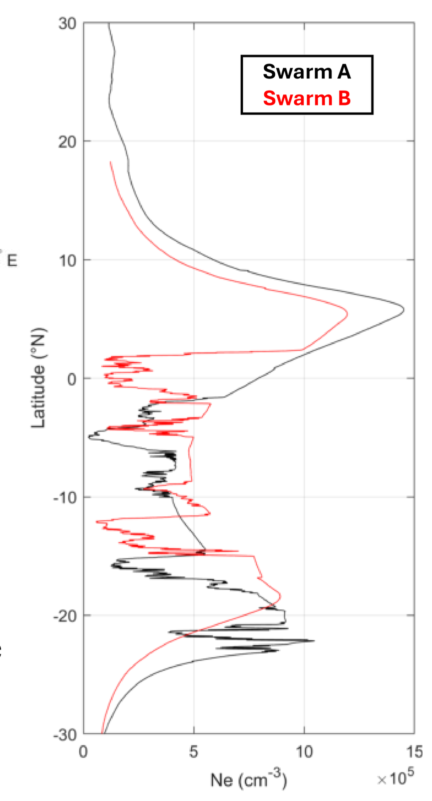
1. Swarm overfly conditions

Between September and October 2021, the longitudinal distance between the lower pair and the upper satellite was at its minimum since the launch of the spacecrafts and the crossing point was very close to the magnetic equator ("overfly" configuration). In this period, the time separation between Swarm A and Swarm C was reduced down to about 2 s, corresponding to 15 km. Specifically, the overfly conditions with minimum time separation between the satellites constituting the lower pair has kept from 22 September to 5 October. Under these conditions, the minimum longitudinal separation was reached at about 03:00 UT on 26 September 2021 and was equal to 0.01°. In addition, the LT of the considered nighttime tracks was favorable to detect and study the post-sunset equatorial plasma bubbles (EPBs).

Read more on Swarm overfly conditions and separation phases



We concentrate on 00:41 UT and 00:59 UT on 30 September 2021, which covered one of the most well instrumented regions. This event has been selected because it is the only one that guarantees that the overfly condition occurs in correspondence with the availability of a significant amount of ground-based instrumentation and in the region in which EPBs form.



2. Network and data

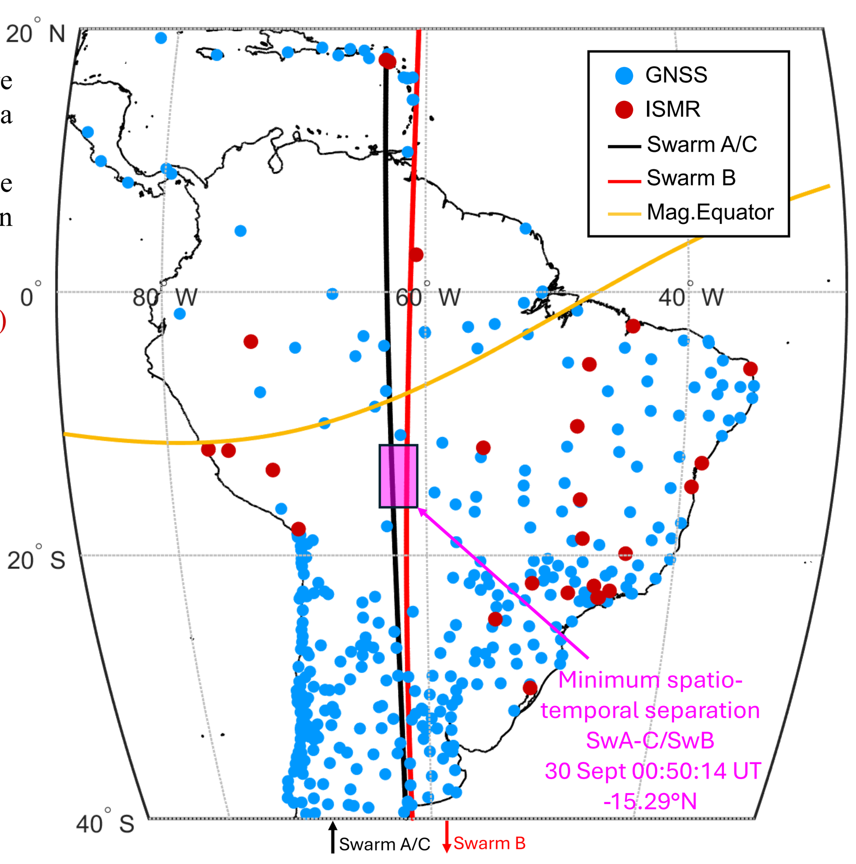
GNSS data from ground instruments are sorted into two species: (a) GNSS data from geodetic receivers dedicated to TEC and ROTI determination (blue dots) and (b) ISMRs data for scintillation (red dots).

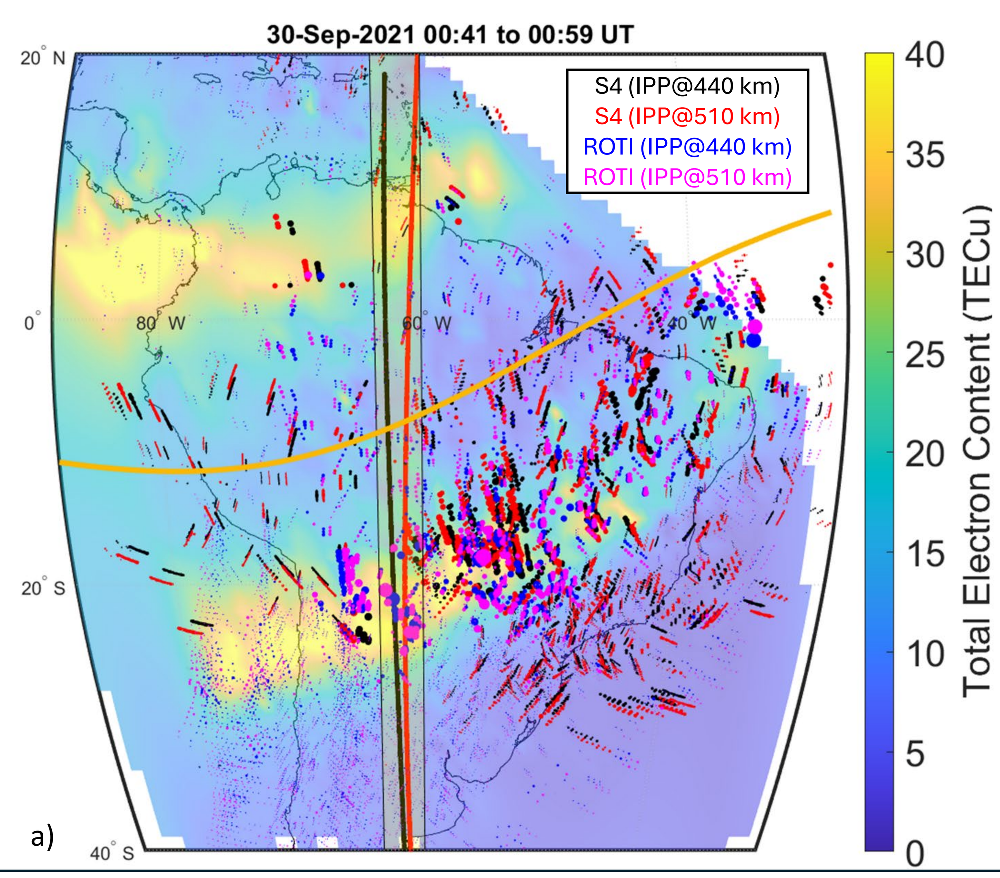
ISMR – S4 (Fresnel's scale irregularities)

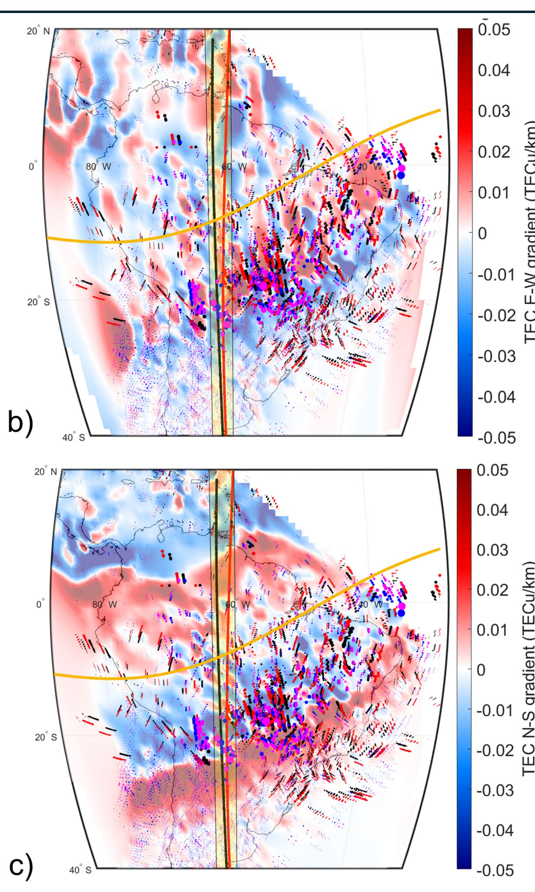
- CIGALA/CALIBRA
- LISN
- EMBRACE
- KNMI

GNSS – ROTI (km scale irregularities)

- RBMC (Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS).
- CNS (Centro Sismológico Nacional, Chile)
- UNAVCO
- RAMSAC (Red Argentina de Monitoreo Satelital Continuo)



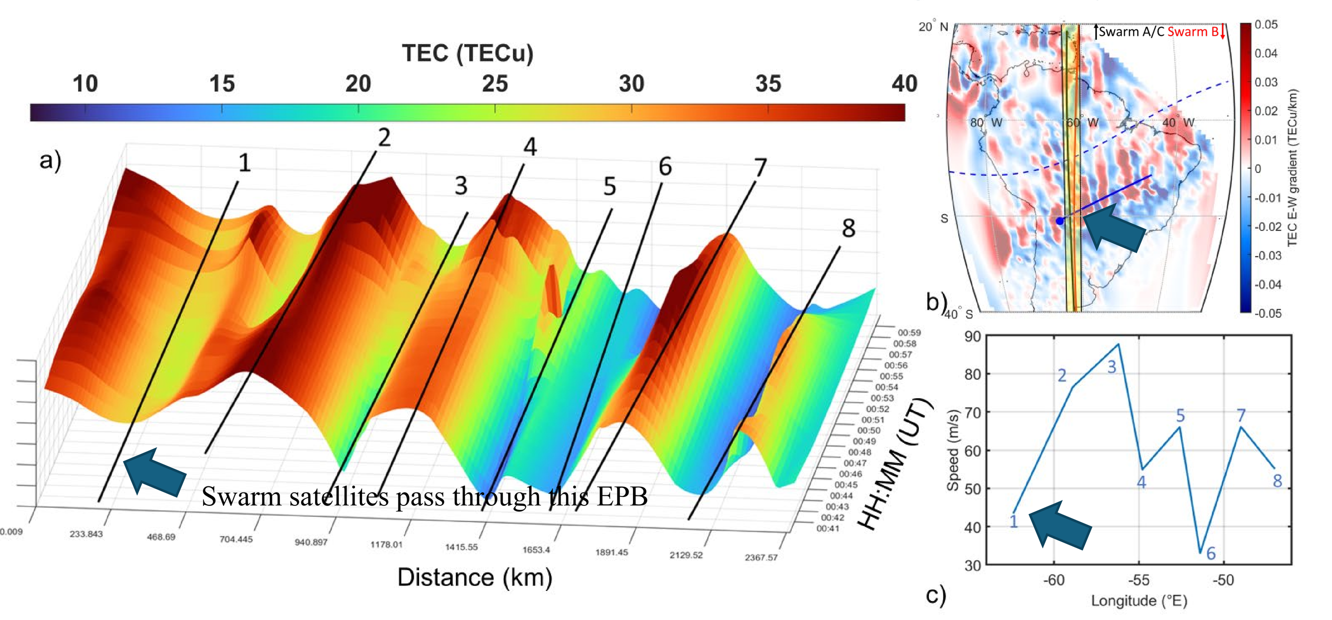




3. Geographical distribution of the irregularities

Maps of TEC (a), and of its E-W (b) and N-S gradients (c) obtained by integrating GNSS measurement between 00:41 UT and 00:59 UT on 30 September 2021. Values of *S4* and ROTI (IPPs @440 and @510 km). The size of the dots is proportional to the *S4* and ROTI magnitude. The ground-projected tracks of Swarm A and Swarm B are reported with black and red lines, respectively. The yellow shaded area indicates the geographical selection for the overfly analysis. The purpose of this Figure is to show the overall ionospheric scenario given by the TEC and TEC gradients maps and to highlight the corresponding occurrence of the irregularities in the area probed by the overfly. The alternance of positive and negative TEC E-W gradients along the magnetic parallels is the signature of the presence of regularly spaced EPBs in the southern hemisphere.

4. Can the EPB be considered as frozen during the overfly?



TEC (a) along the blue line in (b) as a function of the distance from the blue dot in (b) and UT. The numbered black lines connect maxima and minima considered for the EPBs speed estimate reported in (c) as a function of longitude. EPB drifts at 43.4 m/s eastward. The eastward displacement is ~ 50 km between 00:41 UT and 00:59 UT, which is below the minimum distance during the overfly, i.e., the minimum spatial resolution. **The EPB can be considered as frozen during the overfly.**

5. Defining new cross-track parameter to understand plasma structuring and irregularities

Panel a)

Latitudinal profile of Ne for Swarm A (black line), Swarm B (red line) and TEC along the track (a) for the whole period (00:41 UT–00:59 UT, cyan line) and for the minute in which the closest overfly occurs (00:51 UT, cyan dashed line).

Panel b) and c)

Latitudinal variation of $\Delta Ne_{\perp}$ (b), defined as the difference between density measured by two spacecrafts at the same latitude is evaluated.

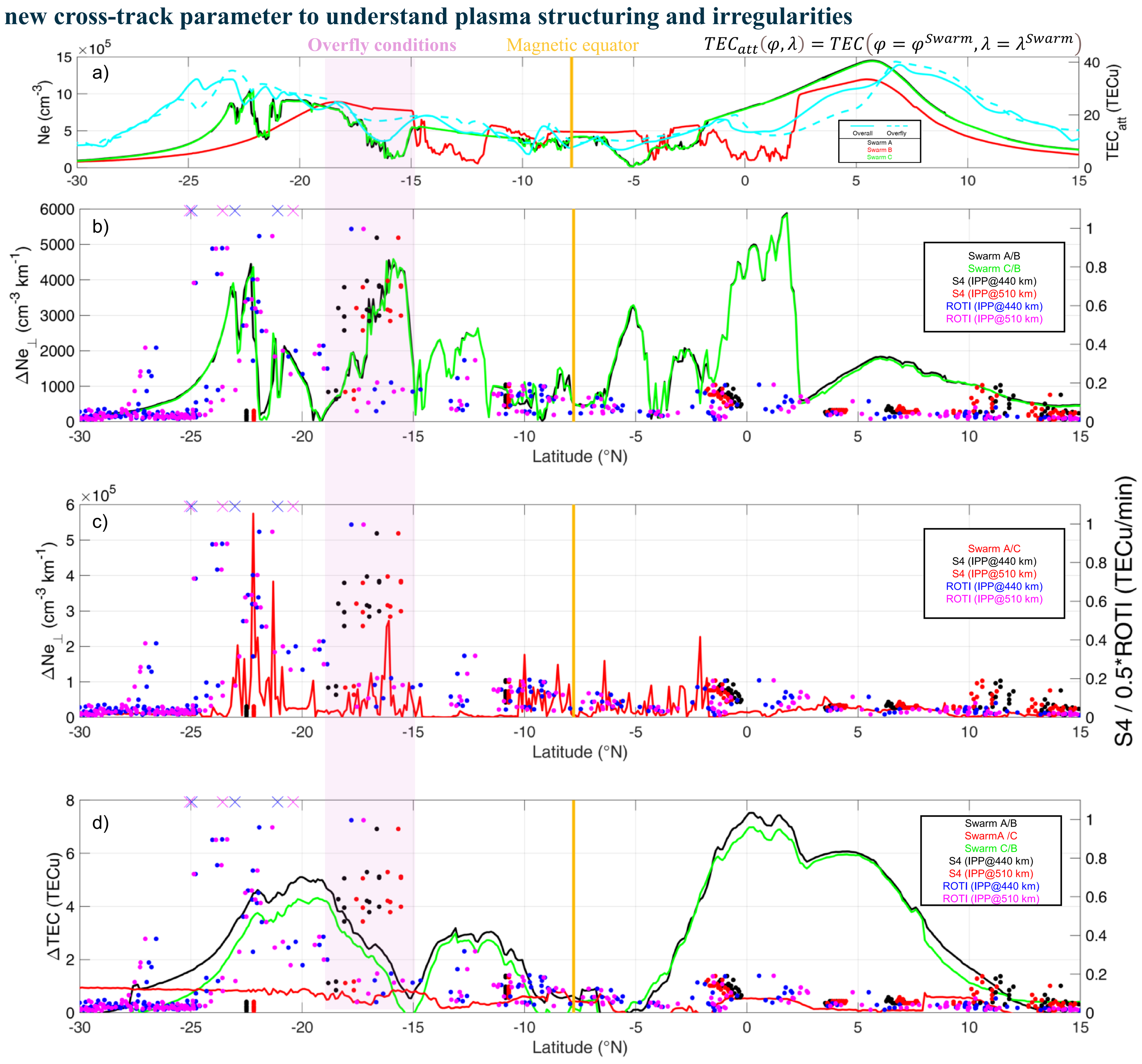
Panel d)

Latitudinal variation of ΔTEC between spacecrafts (red line, panel c), and between Swarm C and Swarm B (green line, panel c).

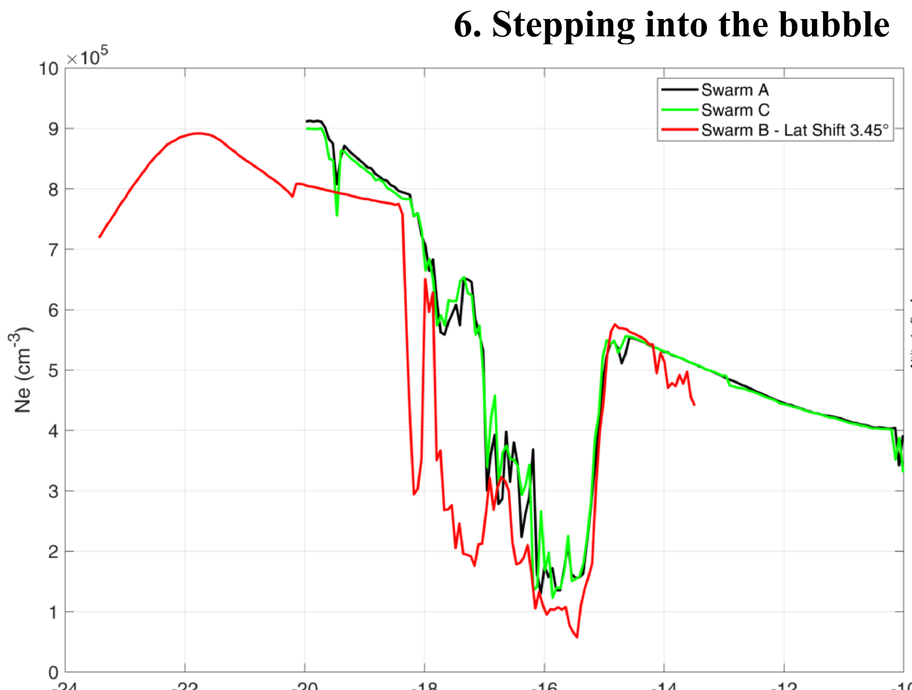
Panel b), c) and d) – right axis

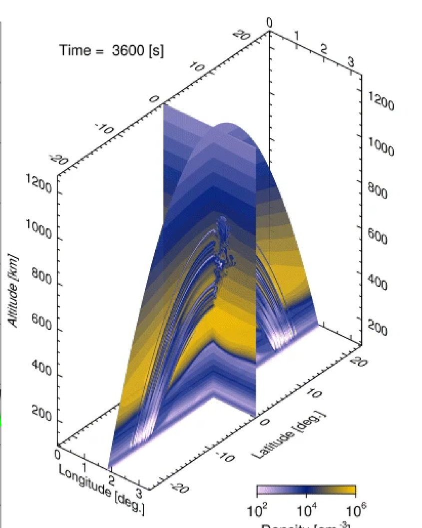
Latitudinal profile of S4 and ROTI/2 at the IPP at 440 and 510 km, according to the color code reported in legend, is also reported in each panel. Crosses show ROTI/2 values above the maximum value in the right y-axis. Orange lines mark the latitude of the magnetic equator.

Shaded area is featured by the time of the overfly and by presence of both small- and medium-scale irregularities: S4/ROTI enhancements. The considered overfly is exactly a **stepping into an EPB**.



6. Stepping into the bubble





Simulation of plasma density distribution in a three-dimensional domain from *Yokoyama et al (JGR, 2014).*

Zoom of the Ne latitudinal profile in the range (−20°N, −10°N), but considering a latitudinal shift of 3.45° southward for Swarm B. This provides stunning evidence of the same plasma depletion along the magnetic field in the N-S direction (Yokoyama, 2014) and that Swarm A, C, and B are passing exactly in the same EPB. The identified depletions are on the same interval [−16° to −14°] of Apex Latitude further confirming that they are elongated along the same field line.

Conclusions

Swarm overfly conditions occurred between 00:41 UT and 00:59 UT on 30 September 2021 over South America. The simultaneous use of ROTI and S4 from the various receivers allow identifying the areas covered by the Swarm overfly featured by irregularities of medium to large scales (enhancing the sole ROTI) and those in which irregularities reach the Fresnel's scale and below (enhancing both S4 and ROTI). Overfly allows investigating new Swarm-based cross-track quantities. The times characterized by the minimum distance between the lower pair and the upper satellite (00:50:14 UT, latitude 15.29°S) are found to be characterized by the more structured ionosphere. This is a clear signature that Swarm during the overfly is passing through a plasma depletion elongated along the N-S direction. Hence, the overfly is a stepping into an EPB decay along the magnetic field lines. This is highlighted by enhanced cross-track parameters, by the simultaneous presence of both high S4 and ROTI values. Diffusion along the magnetic field lines occurs simultaneously with the uplift and not only after when the plasma falls back to lower altitudes.

Spogli, L., Alfonsi, L., & Cesaroni, C. (2023). Stepping into an equatorial plasma bubble with a Swarm overfly. *Space Weather, 21.*

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