Advances in research of equatorial plasma depletions enabled by the Swarm missions

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Equatorial plasma irregularities

- Major event ("convective storm") in space physics
  - Magnetic field/ionosphere/atmosphere interaction
  - During geomagnetic quiet and disturbed times
  - Initiation and growth processes under research

Hysell, JASTP, 2000
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• Affecting radio wave propagation
  o Disturbance / Loss of GNSS signals
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- Affecting radio wave propagation
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- Systematic signatures in the magnetic field

Number of detections of irregularities in the magnetic field (IBI)
Swarm observations of plasma irregularities

- In situ data – at about 450 km
- Multi parameter, high-precision
Swarm observations of plasma irregularities

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- Complements remote sensing methods

Rodríguez–Zuluaga et al., ESS, 2021
Swarm observations of plasma irregularities

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- Multi parameter, high-precision
- Complements remote sensing methods
- stable and long-term (> 10 years)

Rodríguez–Zuluaga et al., ESS, 2021
Determining the location of the dynamo source

Field-aligned Poynting flux ($S_\parallel$)

- F-region winds act as the dynamo source
- E-region conductivity acts as the load
- Well centred within a symmetric ionosphere
Determining the location of the dynamo source

Field-aligned Poynting flux ($S_\parallel$)

- **Observations**: Swarm mainly observes uni-directional Poynting flux
Determining the location of the dynamo source

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Determining the location of the dynamo source

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- **Cornell physical model**: meridional winds determine the “separatrix”
Co-located observations of plasma depletion and GPS observables


Occurrence rate of loss of GPS signal

Plasma irregularities (total count of positive IBI index)

Xiong et al., Space Weather, 2016; AnGeo, 2018.
Co-located observations of plasma depletion and GPS observables

GPS loss occurrence for depletions > $10 \times 10^{11}$ m$^{-3}$
(For steep plasma density gradients)

GPS loss occurrence for depletions < $10 \times 10^{11}$ m$^{-3}$
(For shallow plasma density gradients)

Xiong et al., Space Weather, 2016; AnGeo, 2018.
Statistical model of occurrence of irregularities

- Based on 9 years of CHAMP and 9 years of Swarm magnetic data (IBI)
- Estimate of probability (0-1) for a given local time, longitude, day of year and F10.7 solar flux
- https://igit.iap-kborn.de/ibp/ibp-mode
A forecast for a binary event by a probabilistic model is better the larger the area, $A$, under the $ROC$ curve is:

$$ GC = 2A - 1 $$

**Good:** $GC = 1$

**Bad:** $GC = 0$

- $GC$ (all $\Delta Ne$) = 0.43
- $GC$ ($\Delta Ne < 2 \times 10^5 \text{cm}^{-3}$) = 0.10
- $GC$ ($\Delta Ne > 2 \times 10^5 \text{cm}^{-3}$) = 0.76
Post-midnight irregularities

Zakharenkova et al., *Space Weather*, 2023; COSMIC-2, year 2021, F10.7 = 75 sfu, $\Delta$Ne > 0.6$\cdot$10$^5$cm$^{-3}$

Wan et al., *JGR*, 2018; Swarm A, 2013-2017, Kp < 3, $\Delta$Ne > 0.5$\cdot$10$^5$cm$^{-3}$

- The statistical model is sensitive to depletions of $\Delta$Ne > 2$\cdot$10$^5$cm$^{-3}$
  - Relates to magnetic signatures and GNSS scintillations!

Pre-midnight

Swarm/CHAMP statistical model (IBI)

F10.7 = 80 sfu

Post-midnight

0.2 nT
Post-midnight irregularities

Zakharenkova et al., *Space Weather*, 2023; COSMIC-2, year 2021, F10.7 = 75 sfu, $\Delta N_e > 0.6 \times 10^5 \text{cm}^{-3}$

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Colours: Ground-based scintillation S4 at Caribbeans
Contours: 25% probability predicted by model
2018 – 2024

KNMI (Courtesy: Eelco Doornbos)
Summary

- The Swarm mission **convinces** with its multi-parameter suite of high-precision instruments, its constellation and long time operation!

- The mission has lead to **characterising** equatorial plasma depletions and their effects in **multiple** disciplines.
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Remaining targets:

- Explore seeding mechanisms of plasma irregularities in combination with low-inclination orbit satellites and remote sensing data, such as, the role of upward propagating atmospheric gravity waves
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Remaining targets:

- Explore seeding mechanisms of plasma irregularities in combination with low-inclination orbit satellites and remote sensing data, such as, the role of upward propagating atmospheric gravity waves

- Forecasting ionospheric scintillation related to these depletions on GNSS or radar applications at ground and space.