Quasi real-time monitoring of the ionosphere plasma irregularities by the records of the Swarm mission

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Outline

- The EPHEMERIS project
- Development of the intermittency index
- Geographic distribution of intermittent magnetic fluctuations
- Correlation between intermittent events and on-board losses of GPS signal lock
- Correlation between ionosphere scintillations and intermittent magnetic field observations
- Summary

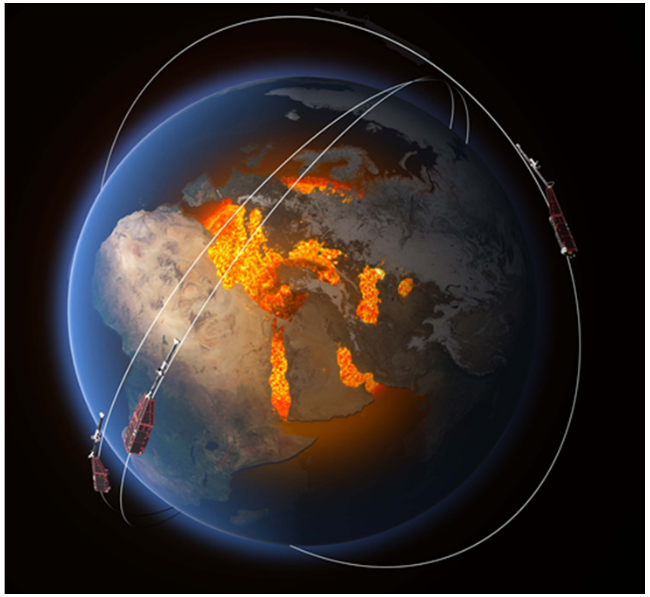
The EPHEMERIS project (Supported by ESA)

<u>Main objectives:</u>

Development of a methodology for the autonomous (and quasi real-time) detection

- ➢ of the **midlatitude ionospheric trough** (MIT) phenomenon (For more details on MIT see: Heilig et al., Monitoring the plasmapause dynamics at LEO (EGU21-15733)
- ➢ of the occurrences of intermittent plasma fluctuations via the newly developed **intermittency index** (IMI)

in the upper ionosphere, along the orbits of the Swarm spacecraft triplet.



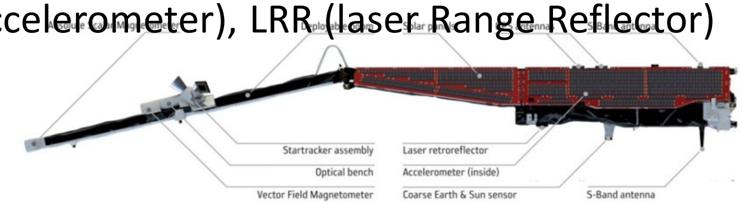
<u>Input data:</u> Plasma and magnetic field records of Swarm mission (Spacecraft triplet)

<u>Date of launch:</u> 22 November, 2013.

<u>Altitudes:</u> <~475 km (Swarm A & C), <~518 km (Swarm B)

<u>Inclination:</u> 87.4° (Swarm A & C), 88.0°(Swarm B)

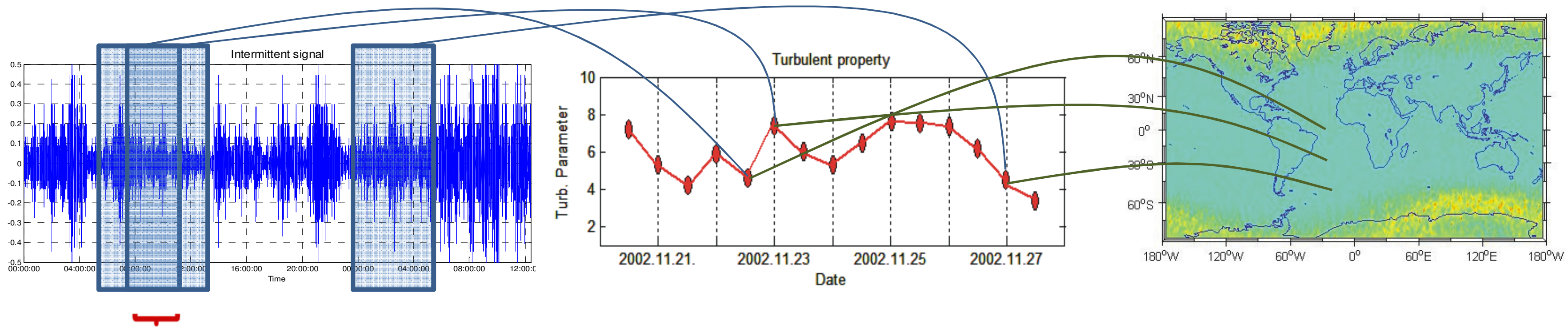
<u>Main instruments:</u> VFM (Vector Field Magnetometer), ASM(Absolute Scalar Magnetometer), EFI (Electric Field Instrument), ACC (Accelerometer), LRR (laser Range Reflector)



Development of the intermittency index

<u>Scheme of the sliding-window PDF analysis</u> (Kovács et al., P&SS, 2014)

(*Input data: MAGx_HR (50Hz magnetic field record of Swarm*)



Computing increment time-series

$$\delta B_{\tau_i}(t) = B(t+\tau_i) - B(t)$$

with increment scales of

$$\tau_i = 1{:}\,1{:}\,25\ s$$

Computing flatness

$$F(\delta B_\tau) = E\left[\left(\frac{\delta B_\tau(t) - \langle \delta B_\tau \rangle}{\langle \delta B_\tau^2 \rangle^{\frac{1}{2}}}\right)^4\right]$$

of increment time-series in terms of τ_i

$$F(\tau)$$

Define intermittency index (IMI) as:

$$IMI_{compr/transv} = \max\big(F(\tau_i)\big)$$

Where $\tau_i = [1-10]\ s$

IMI_{compr} and IMI_{transv}: IMIs of compressional and transverse fluctuations, respectively

Development of the intermittency index

Input data: MAGx_HR high-resolution (50 Hz) vector magnetic field record of Swarm in NEC frame
Period: 2014-2020

Transformations:

1. Transformation to mean-field aligned frame – Compilation of compressional and transverse time-series

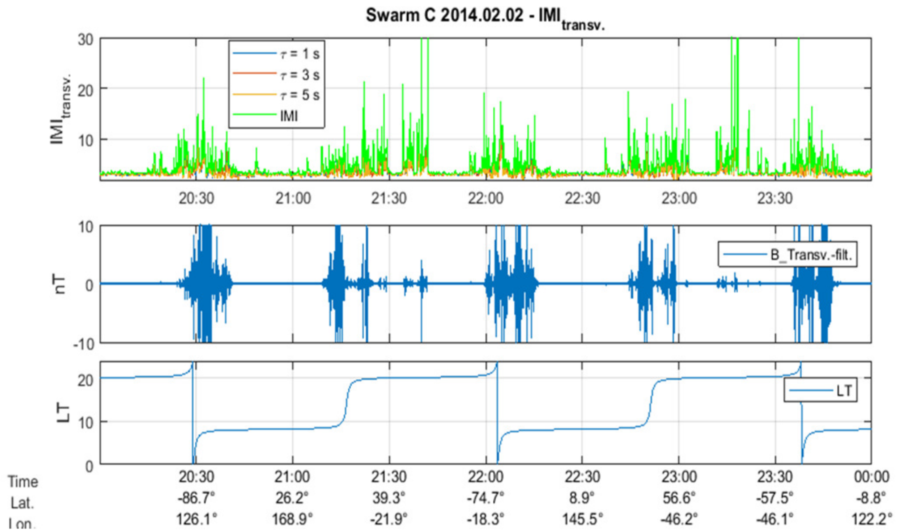
   (MFA frame is dynamically computed from NEC frame data)

2. Butterworth high-pass filtering

Sliding-Window PDF analysis

1. Segmentation of the time-series (transverse/compressional)
2. Generation of increment series
3. Computation of flatness and IMIs for each increment series

Case study



Sample time-series of IMI_{transv} values (top), filtered transverse magnetic field record of Swarm (middle), and the local times (LT) (bottom) of the observations

Main findings:

- The increasing IMI trends coincide with the irregular magnetic field fluctuations.
- Main orbit segments that exhibit strong magnetic field intermittency:

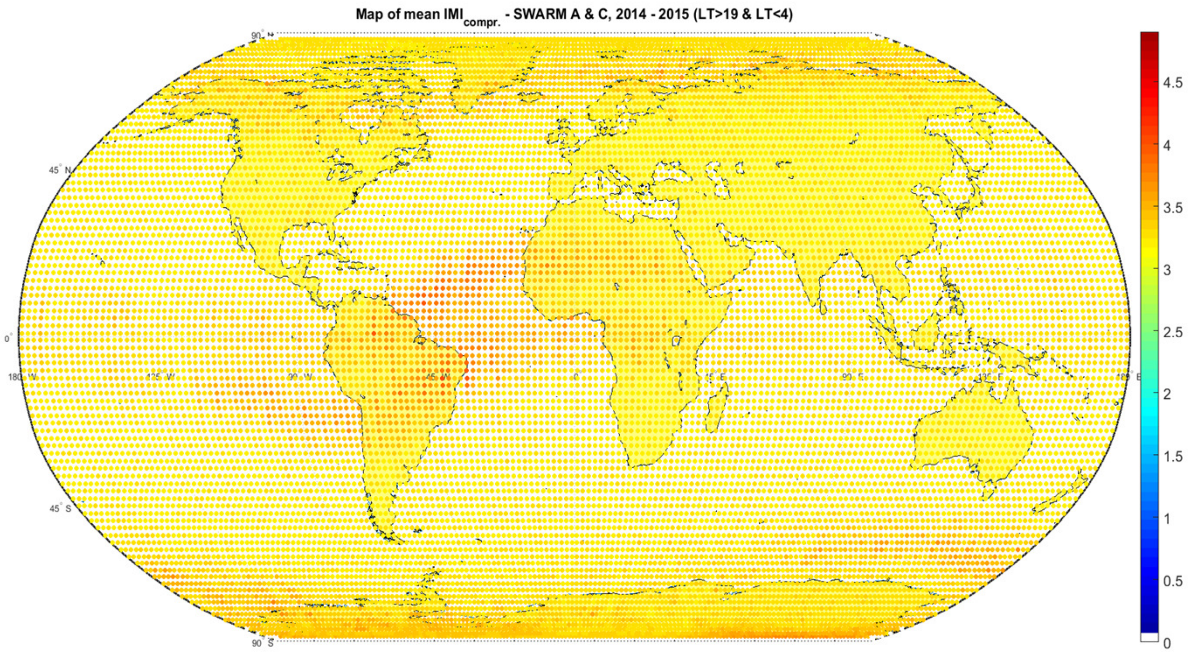
  –High-latitude orbit (only IMI_{transv})

  –Equatorial part of the descending Swarm orbit, (LT~20)

Geographic distribution of intermittent magnetic field fluctuations

Intermittency map of the compressional magnetic field record

(Colors refer to the mean values of compressional IMIs obtained in 2°×2° degree Lat./Lon. bins)



Spacecraft:	Swarm A & Swarm C
Considered period:	2014-2015
Considered local time range:	LT>19 & LT<4

Main findings:

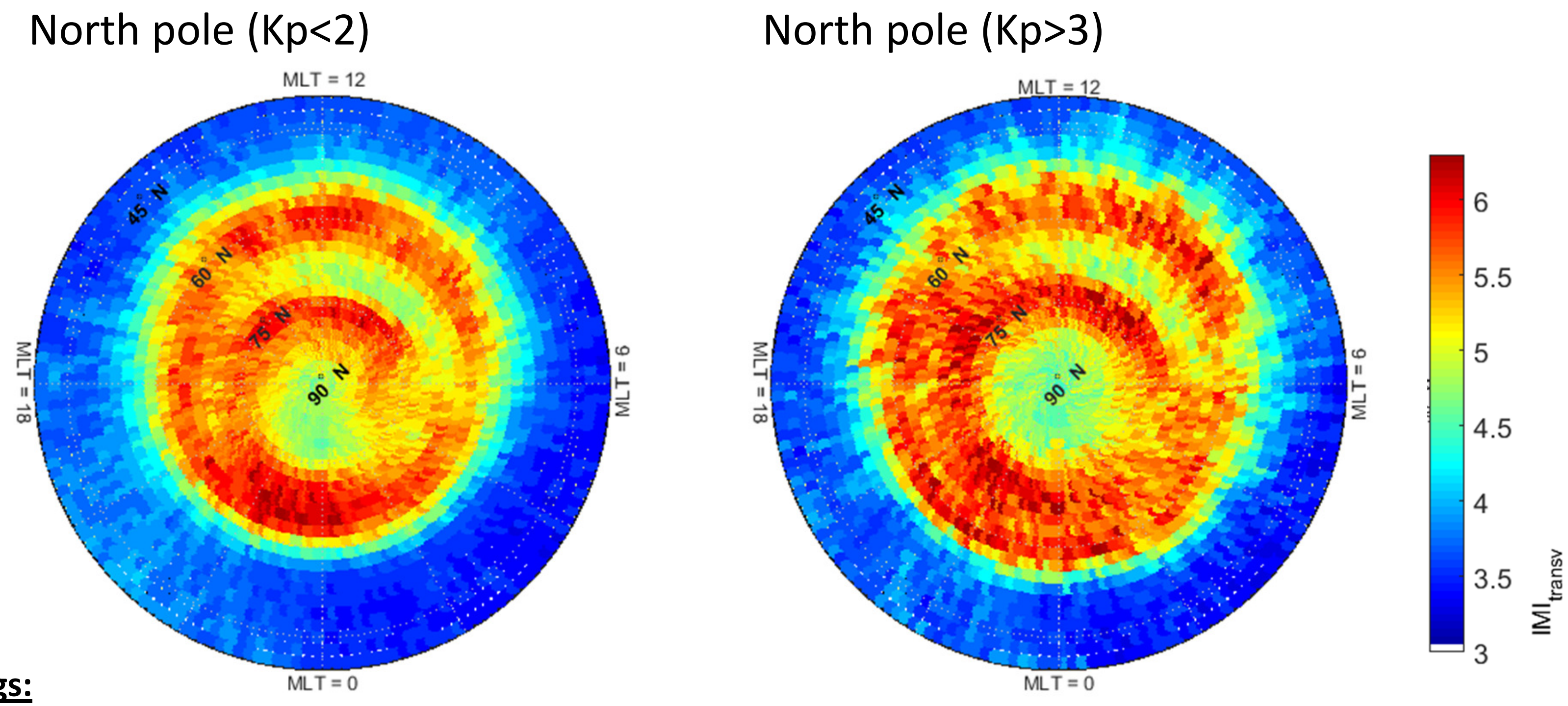
- The strongest intermittency of the compressional magnetic field appear in the equatorial region. The polar region is not accompanied with anomalous compressional magnetic fluctuations.
- The intermittent areas of the compressional fluctuations appear symmetrically about the dip equator, nearly at ±10° geomagnetic latitudes
- The biggest values of IMIs appear in the Atlantic sector and near South-America

The findings reveal that the intermittent fluctuations coincide with the occurrences of equatorial plasma bubble events

Geographic distribution of intermittent magnetic field fluctuations

Intermittency map of the <u>transverse</u> magnetic field record, above the north geomagnetic pole, in quiet (left) and disturbed (right) geomagnetic conditions

(Colors refer to the mean values of transverse IMIs obtained in 2°×0.12 hour QD Lat./MLT bins)



<u>Main findings:</u>

In the night-side sector, the parcels characterised by the most intermittent transverse magnetic field fluctuations coincide with the morphology of the auroral oval. Towards noon, the homogeneous intermittent region of the night sector separates into two intermittent zones corresponding to the locations of the dayside auroral oval and probably the cusp region. Note that the intermittent ovals progress towards the equator during disturbed geomagnetic conditions.

Correlation between intermittent events and losses of on-board GPS signal lock

Selection of events of losses of GPS signal lock

Input data: Swarm GPSx_RO daily row Rinex files

Selection criterion of gap periods (C. Xiong et al. 2016, 2018)

- Interruption of the received GPS signal that is shorter than 30 min. in time (longer interruption means the loss of visibility of GPS s/c)

	Nb. of Rinex records exhibiting losses of GNSS signal lock (**Xiong et al.'s criterion**)	Nb. of Rinex records exhibiting total loss of GNSS signals	Nb. of GNSS signal loss events lasting longer than 10 s (**Additional criteria no. 1a and 1b**)	Nb. of GNSS signal loss events • lasting longer than 10 s, and • exhibiting the loss of at least two signals (**Additional criterion no. 2**)
Swarm A (2014-2020)	1 860 142	125 272 (7%)	28921	2178
Swarm B (2014-2020)	562 379	7 738 (1%)	13912	1002
Swarm C (2014-2020)	3 794 392	22 647 (0.6%)	81663	2558

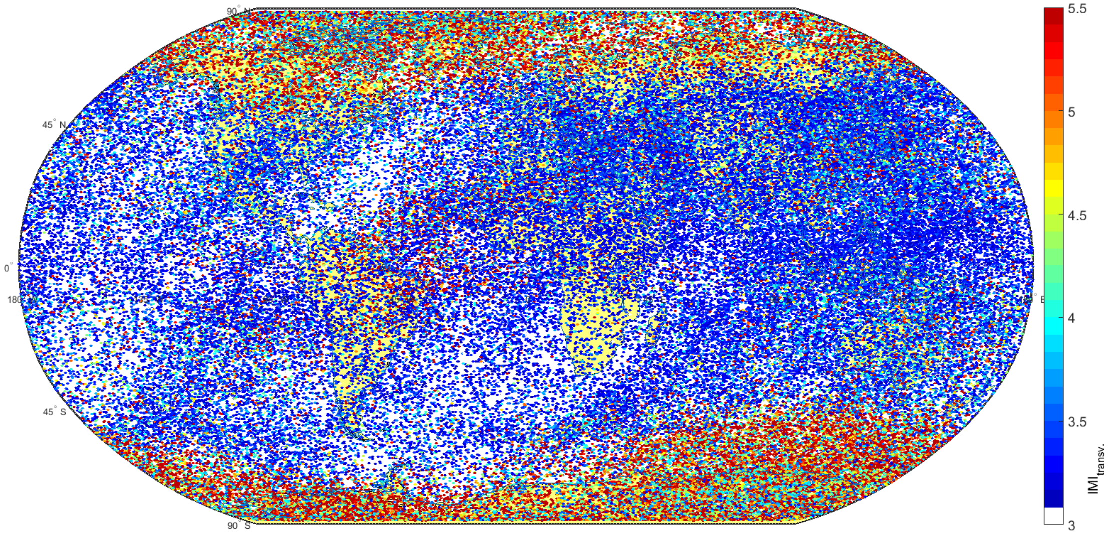
Additional criteria

1a. Periods of total lack of GNSS signal acquisition are neglected in the analysis (probable failure of Swarm's GPS receiver)

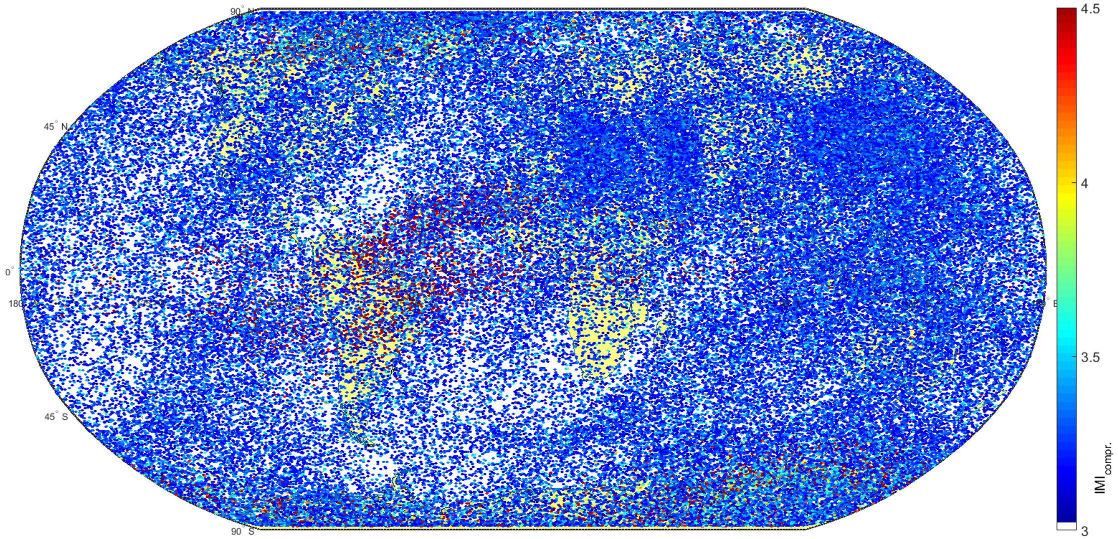
1b. The signal loss events must be longer than 10 s (~70 km in spatial scale)

2. At least two GNSS signals must be lost

Correlation between intermittent events and losses of on-board GPS signal lock



Intermittency level (IMI) of transverse magnetic field fluctuations

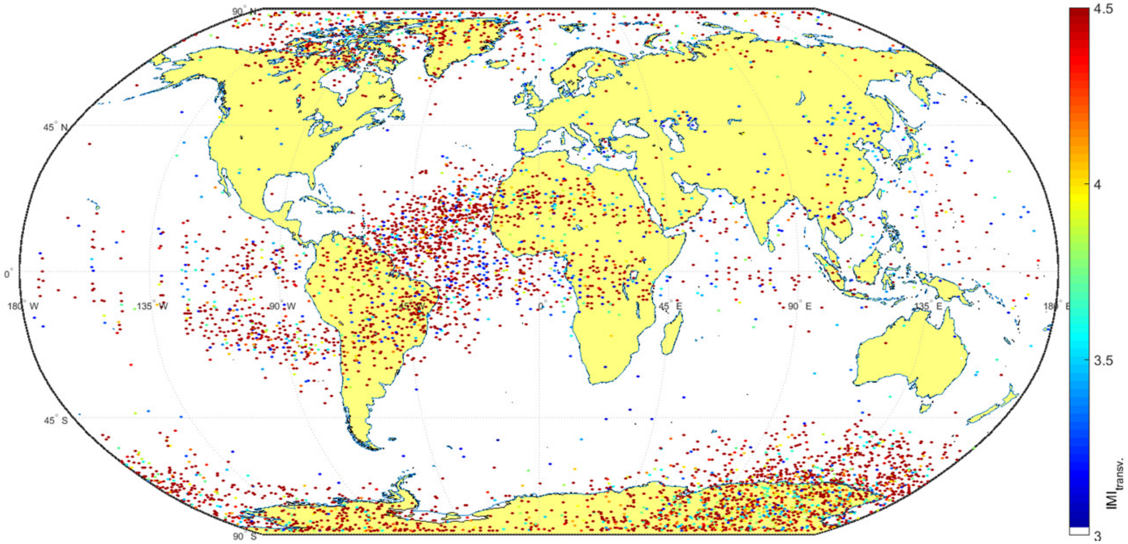


- Dots represent the places of losses of GPS signal lock (according to Xiong et al.'s criterion plus additional criteria no. 1a and 1b, see prev. slide)
- Colors represent the values of IMIs obtained in conjunction with signal loss events

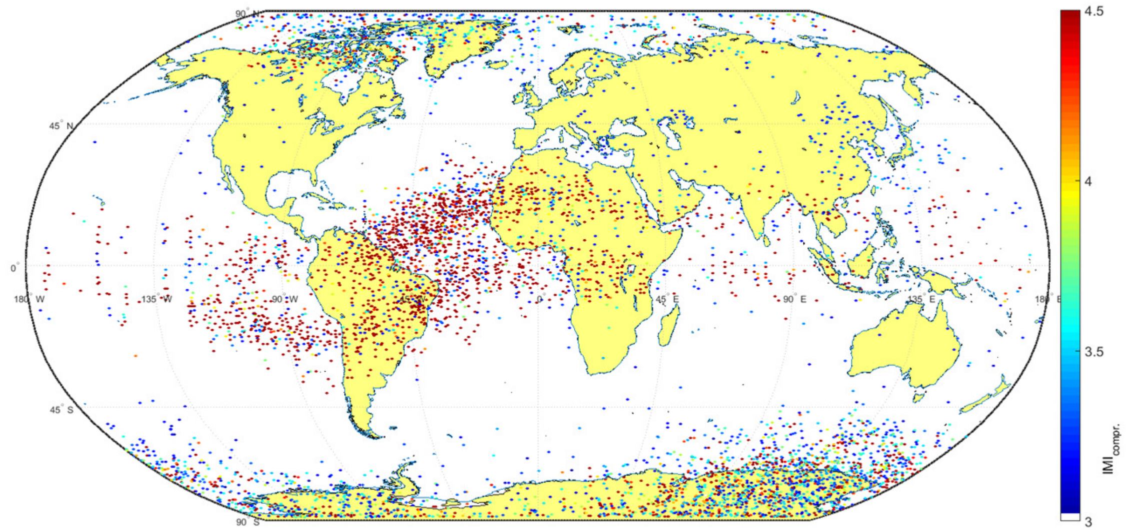
Most of the GPS signal losses are associated with low level of intermittent fluctuations (low IMI value, i.e. blue color). Intermittency occurs only in known areas of intermittent fluctuations (aurorae and equatorial regions). Therefore, this picture doesn't provide strong evidence for the correlation between GPS signal losses and intermittent magnetic field fluctuations.

Intermittency level (IMI) of compressional magnetic field fluctuations

Correlation between intermittent events and losses of on-board GPS signal lock (at least two signals are missing)



Intermittency level of (IMI) of transverse magnetic field fluctuations



- Events when only one GPS signal is lost on-board Swarm are neglected
- As before, dots represent the remaining places of loss of GPS signal lock (according to Xiong et al.'s criterion plus additional criteria no. 1a and 1b, and 2 see prev. slide), and colors represent the values of IMIs obtained in conjunction with the remaining signal loss events

Near the equator, the IMIs (both transverse and compressional) exhibit anomalous values. It implies that the signal loss events and the magnetic field irregularities have common origin.

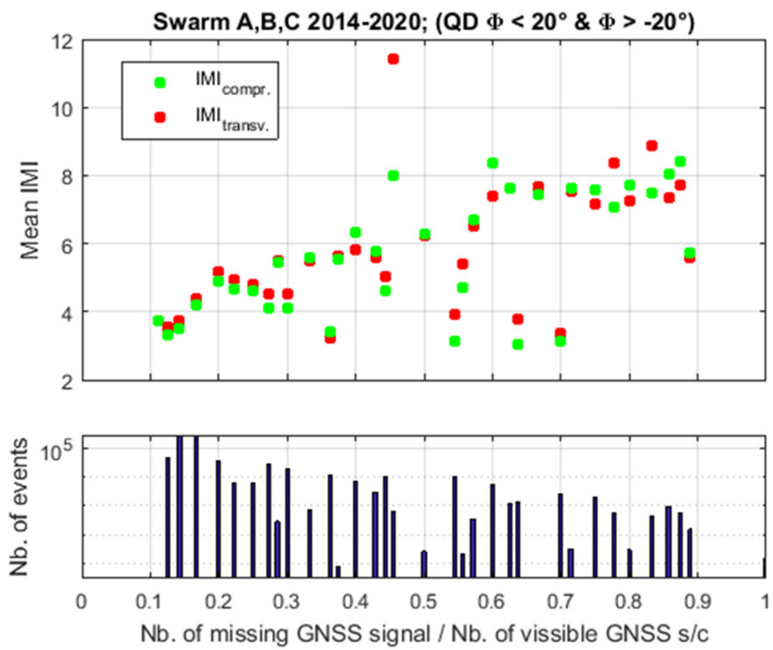
In the polar region the transverse IMIs are not uniformly anomalous in places of GPS signal loss. Therefore, the correlation between the two phenomena cannot be unambiguously stated.

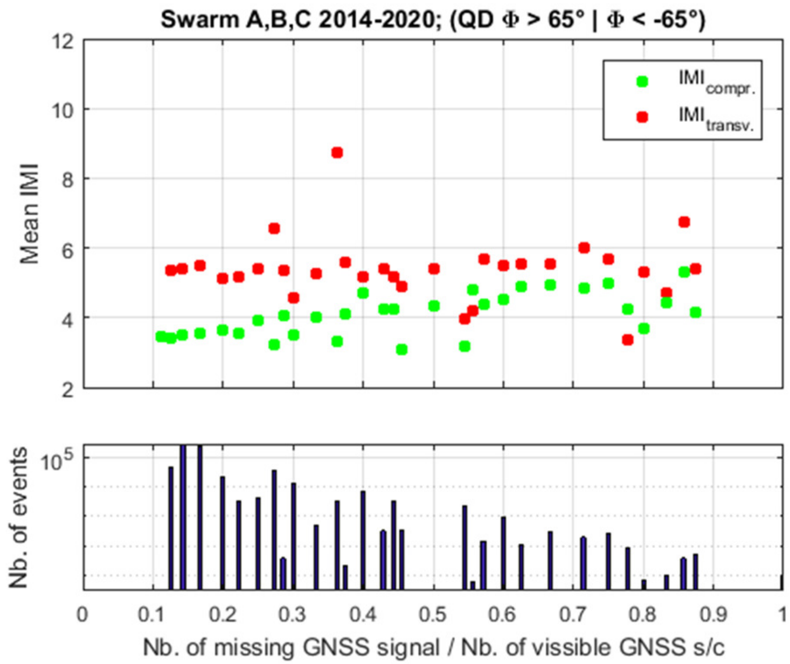
Intermittency level of (IMI) of compressional magnetic field fluctuations

Correlation between intermittent events and losses of on-board GPS signal lock

Mean IMIs vs. severity of GNSS signal loss events (only Xiong et al.'s criterion is used)

Equatorial region





High-latitude region

The severity of GNSS signal loss events is measured by the ratio of the numbers of lost and visible GNSS signals.

Main conjectures:

- *Left panel*: In the equatorial region a clear increasing tendency of the mean IMI_{transv} and IMI_{compr} values are exhibited with the severity level of GNSS signal losses.
- *Right panel*: On the other hand, this trend is not observable for the polar region, i.e. the irregularity level of the magnetic field fluctuations is seemingly independent from the severity of GNSS signal failures.

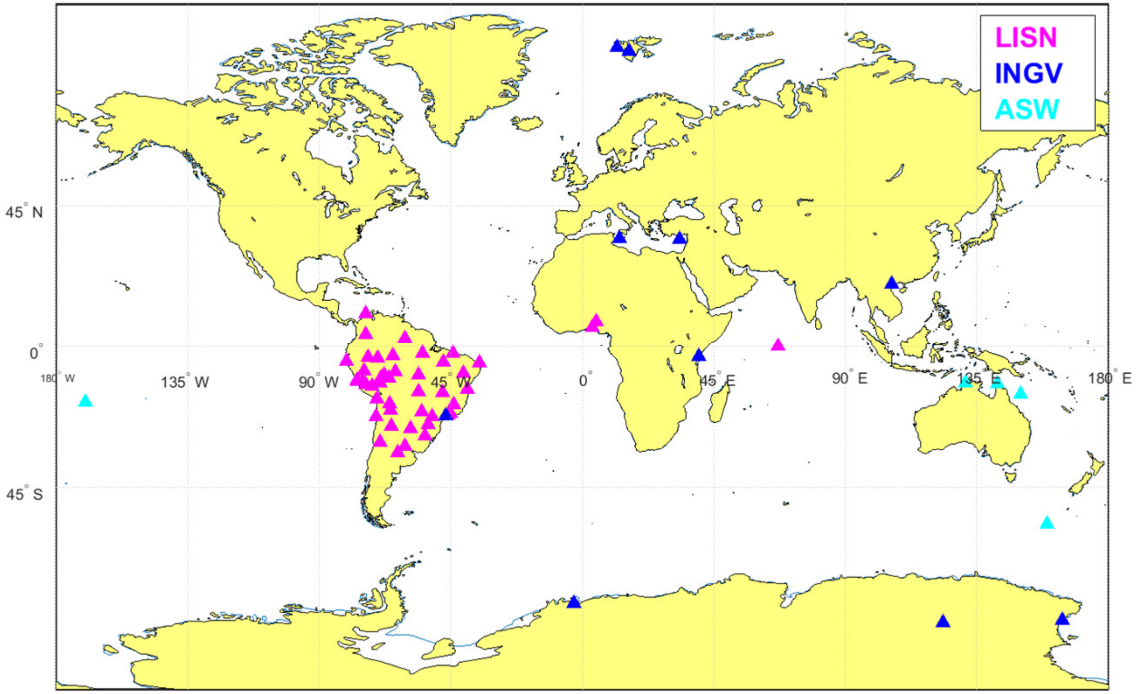
Correlation between ionosphere scintillations and intermittent magnetic field observations

Small-scale plasma irregularities may severely distort the GNSS signal transmission. This effect is called signal scintillations. Scintillation effects are measured in ground GNSS stations by scintillation indices.

Amplitude and phase scintillation indices

Normalized and un-normalized standard deviations of GNSS signal intensity and phase data segments

- Amplitude scintillation index: $S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$
- Phase scintillation index: $\sigma_\Phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}$



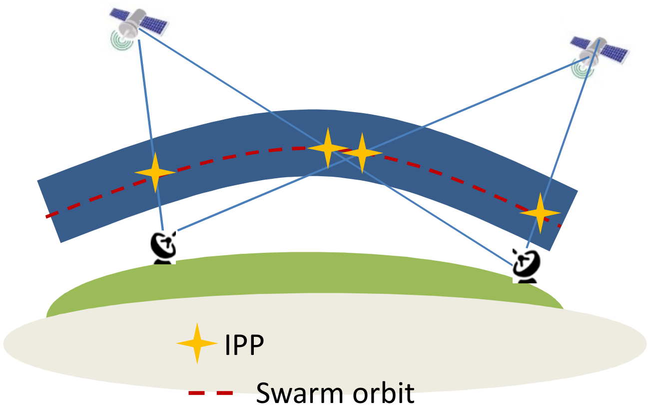
GNSS networks whose scintilation data are used in the analysis (see map also)

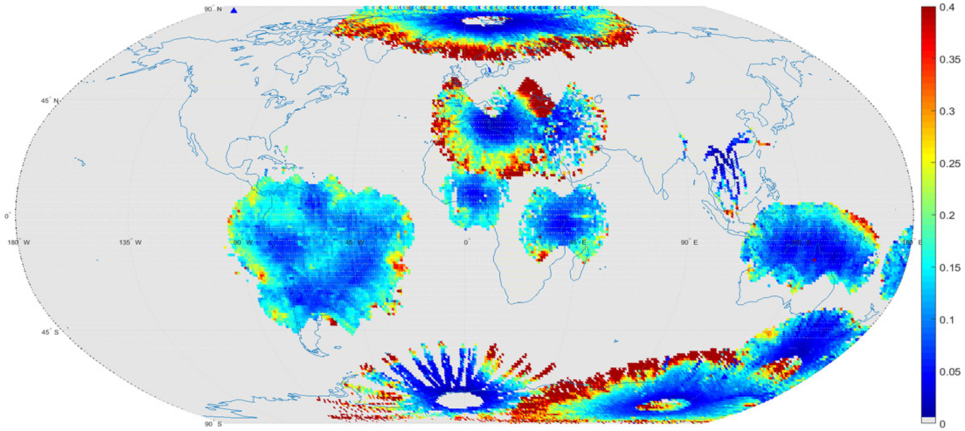
- **ASW – 5 stations (S4 and σ_Φ)**
(Australian Space Weather Service of Bureau of Meteorology, Australian Government)
- **LISN – 40 stations (S4 only)**
(Low-Latitude Ionospheric Sensor Network, maintained by Istituto Geofisico del Peru)
- **eSWua – 10 stations (S4 and σ_Φ)**
(electronic Space Weather upper atmosphere, maintained by INGV, Italy)

Total number of st.: 55
Temporal resolution: 1 min.

Correlation between ionosphere scintillations and intermittent magnetic field observations

- Each ground station receives GNSS signals from several satellites
- We determine the ionosphere piercing points (IPP) of signal paths at Swarm altitudes
- Criteria of the selection of the GNSS signals:
  - ❖ Signal path should intersect the Swarm orbits within 5° and 1° of latitude and longitude tolerance range, respectively
  - ❖ Signal's elevation should be bigger than 30°





Colour map of average S4 scintillation indices referenced to the IPPs of the GNSS signal paths at Swarm's altitude. The averages are computed for 1°×1° Lat./Lon. bins. No elevation limit criterion was applied. Note the seemingly unrealistic S4 means at the edges of regions covered by IPPs of a certain station. The table contains the numbers of IPPs gathered from the three networks since the launch of the Swarm mission, with the application of different sets of criteria.

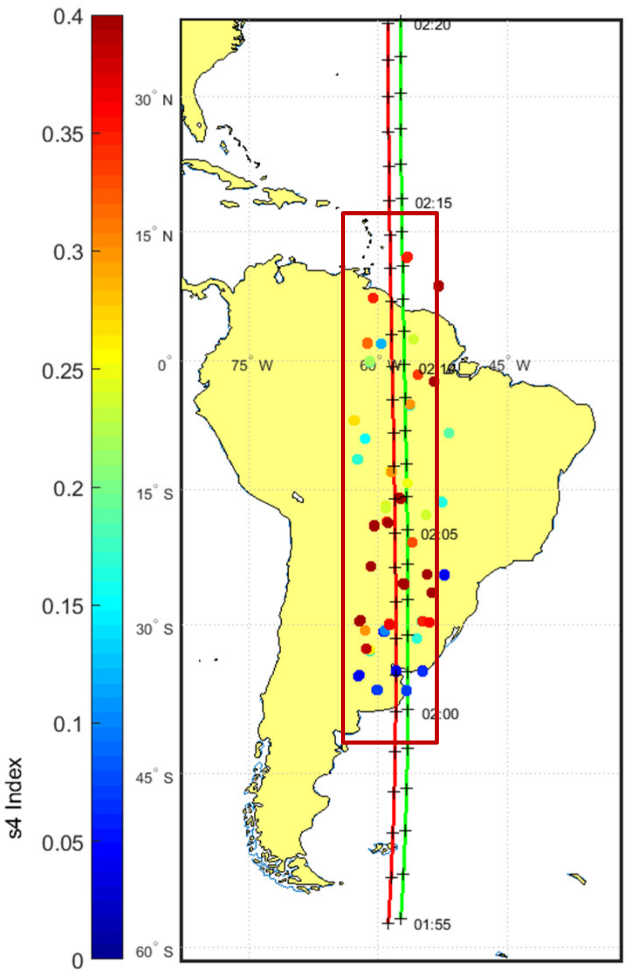
Network	**Nb. of IPPs** (Swarm A, B, C) no elevation limit Distance from Swarm orbit in Lat. and Lon. < 5°	**Nb. of IPPs** (Swarm A, B, C) elevation > 30° Distance from Swarm orbit in Lat. < 1° in Lon. < 5°
ASW	**557 902** (187614, 184080, 186208)	**55 227** (18676, 18242, 18309)
LISN	**3 325 125** (1116989, 1102698, 1105438)	**347 636** (116883, 115245, 115508)
eSWua	**1 245 519** (416399, 411450, 417670)	**125 144** (42096, 41148, 41900)

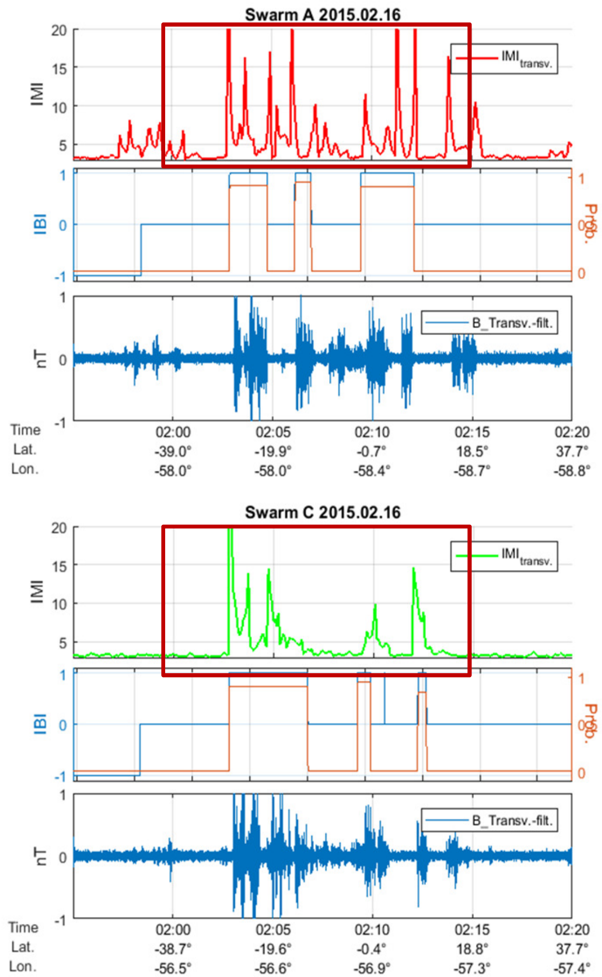
Correlation between ionosphere scintillations and intermittent magnetic field observations

Case study I.

Interval:
16th of Feb., 2015, 01:55-02:20

GNSS Network:
LISN (only S4 index)





The map shows the IPPs of the GNSS signal paths observed by the LISN network near the orbit of the Swarm A and C spacecraft. The colours refer to the intensity of the amplitude scintillations. The spacecraft orbit paths are shown by red (Swarm A) and green (Swarm C) lines.

The middle graphs exemplify for Swarm A (*top panel*) and Swarm C (*bottom panel*) the time-series of transverse IMIs (*top graphs*), bubble indices/probabilities (*middle graphs*), and filtered transverse magnetic field, for the investigated period. Red boxes are the corresponding orbit and time-series segments in the map and graphs.

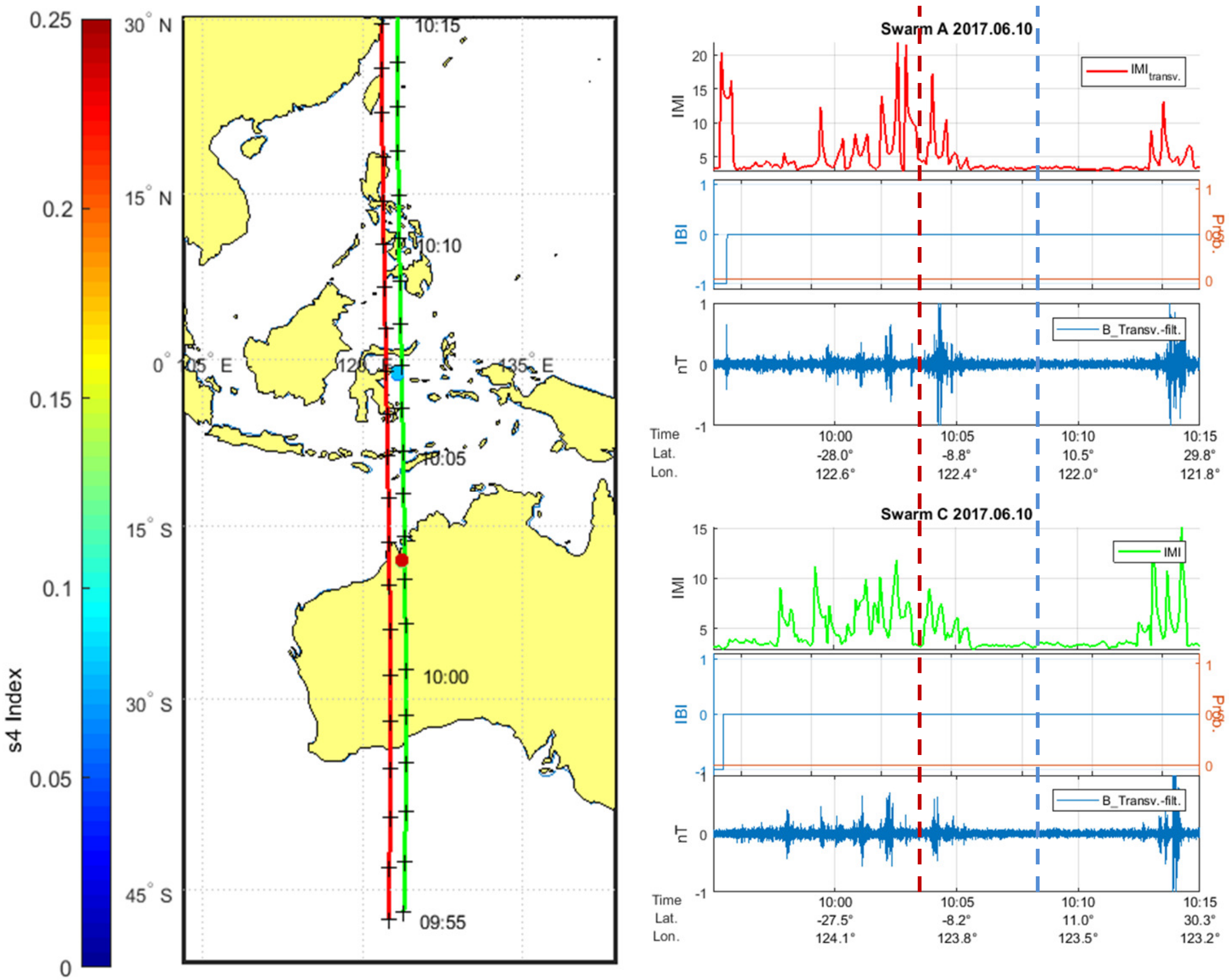
Clearly, medium scintillations are associated with intermittent transverse magnetic field fluctuations. The intermittent behaviour and the scintillations have common plasma bubble origin as exemplified by the bubble indices.

Correlation between ionosphere scintillations and intermittent magnetic field observations

Case study II.

<u>Interval:</u>
10th of June, 2017, 09:55-10:15

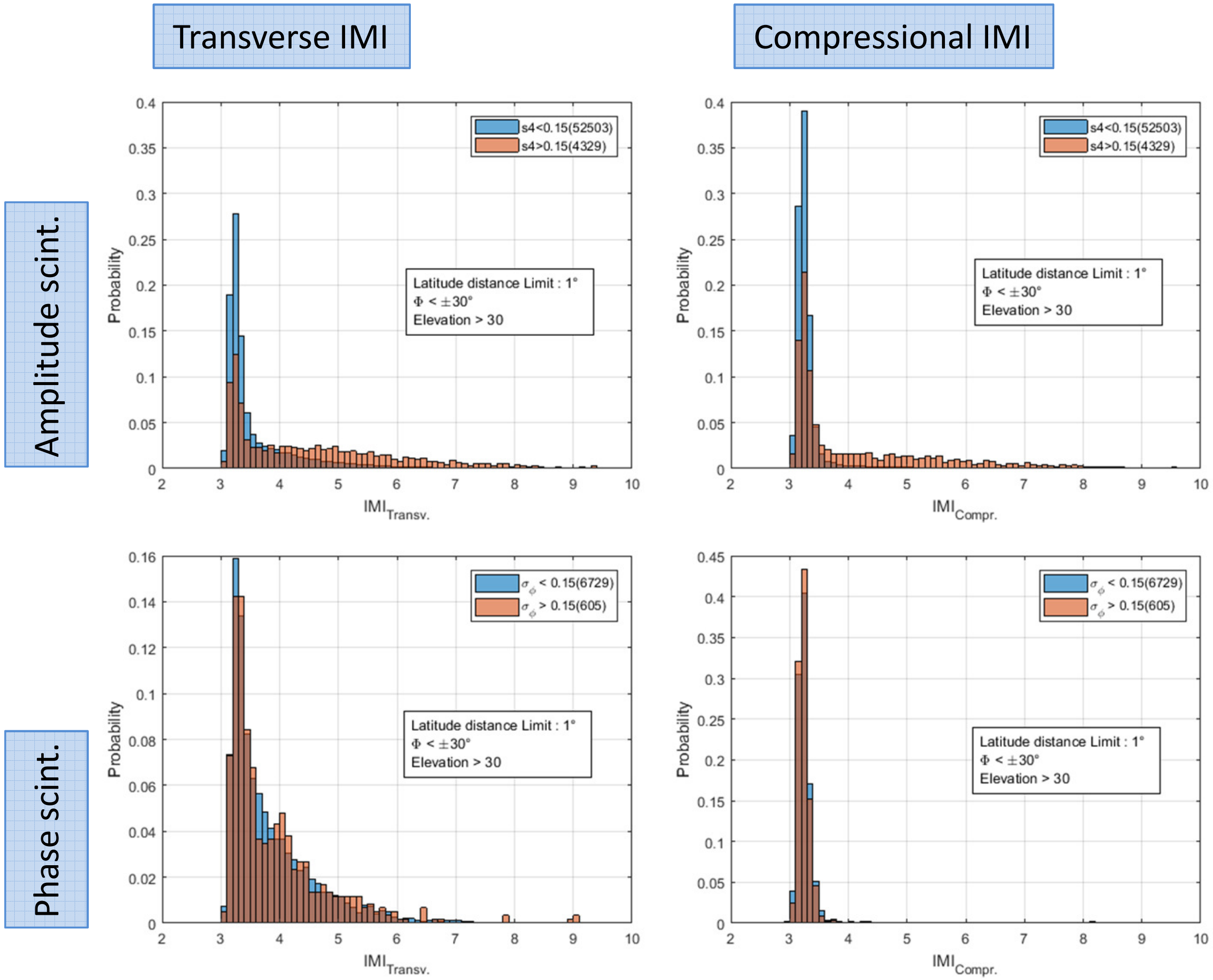
<u>GNSS Network:</u>
ASW



For the information shown by the map and the graphs see the previous slide.
In this period only four scintillation data are collected by the ASW network whose IPPs are closer than 1° in latitude and 5° in longitude to the s/c orbits. The southern/northern (above Australia / above Indonesia) pairs of amplitude scintillations possess big/low values. The big scintillation observation (between 10:02 and 10:03, *red dashed line*) corresponds to strong transverse magnetic field fluctuations and high values of IMI_{transv} , while near the low scintillation point in the ionosphere (at 10:07, *blue dashed line*) the magnetic field is quiet. Though the latitude range of the orbit segment would be favourable for the observation of plasma bubble events (bubble index is not -1), the magnetic and plasma records don't indicate any bubble activity (bubble probability equals to zero).

Correlation between ionosphere scintillations and intermittent magnetic field observations

Satistical analysis in low latitudes



- Correlation is investigated in the equatorial region (<u>Latitude limit:</u> $|\Phi| < 30°$)
- Definition of scintillation event:

  $S4 > 0.15$ or $\sigma_\Phi > 0.15$
- **IMIs are sorted according to the occurrences of contemporary scintillation events**
- Distributions of IMIs belonging and not belonging to scintillation events are shown

<u>Conclusion:</u>
The distributions exhibit apparent differences in regard to amplitude scintillation events (*upper histograms*). That is, transverse (compressional) IMIs bigger than 5 (4) are very likely associated with scintillation events. Such correspondence is not observed with phase scintillations (*lower histograms*).

Summary

- An index has been developed for the characterization of the intermittent behaviour of the compressional and transverse magnetic field fluctuations in the upper ionosphere by the use of the high-resolution magnetic field records of the Swarm mission. The index is called probability density function analysis based intermittency index, in short IMI.
- The strongest intermittency of the compressional magnetic field appear in the equatorial region, symmetrically about the dip equator, nearly at ±10° geomagnetic latitudes, in post sunset local time observations. The finding reveals that the intermittent fluctuations coincide with the occurrences of equatorial plasma bubble events.
- The transverse magnetic field fluctuations exhibit intermittent bahaviour within and near to the auroral oval zone. The polar cap area is less exposed to intermittent transverse magnetic fluctuations.
- We have studied the correlation between intermittent magnetic field fluctuations and losses of GNSS signal lock on-board Swarm. In the equatorial region the anomalous IMI observations and the GNSS signal losses are correlated. Apparently, they common origin are the equatorial plasma bubble occurrences. On the other hand, in the polar region the correlation between GNSS signal failures and the irregular transverse magnetic field fluctuations are not unambiguously proven.
- Ionosphere scintillations measured in ground GNSS stations via scintillation indices are correlated with in-situ intermittent magnetic field fluctuations, in the equatorial region. Quantitatively, it is shown that transverse (compressional) IMIs bigger than 5 (4) are very likely associated with scintillation events.

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