Investigating dynamical complexity at Swarm altitudes using information-theoretic measures

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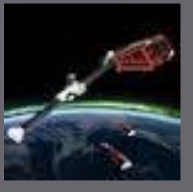
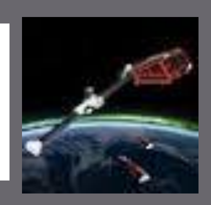


Outline

- Motivation
- Spaceborne magnetometry
  - ESA Swarm mission
- Swarm derived Dst-like and AE-like indices
- Information theory methods
- Results



Motivation

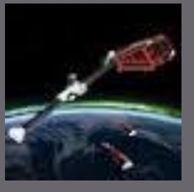
An extreme coronal mass ejection and consequences for the magnetosphere and Earth

(Tsurutani & Lakhina, *GRL* 2014)

- A "perfect" interplanetary coronal mass ejection could create a magnetic storm with intensity up to the saturation limit (Dst ~2500 nT), a value greater than the Carrington storm.

- The interplanetary shock would arrive at Earth within ~12 h with a magnetosonic Mach number ~45, comparable to astrophysical shocks.

- The associated magnetospheric electric field will form a new relativistic electron radiation belt.



ESA Swarm mission

Each satellite is measuring:

- ✓ Strength and direction of the magnetic field
- ✓ Plasma conditions and characteristics
- ✓ Location

The Constellation:

- ✓ 3 identical satellites:
  - 2 side-by-side in low orbit (<460km)
  - 1 in higher orbit
  - (< 530km)
- ✓ three orbital planes for optimal coverage in space and time
- ✓ **Launch 22 November 2013: initially 4 years of operations, currently extended through 2021**

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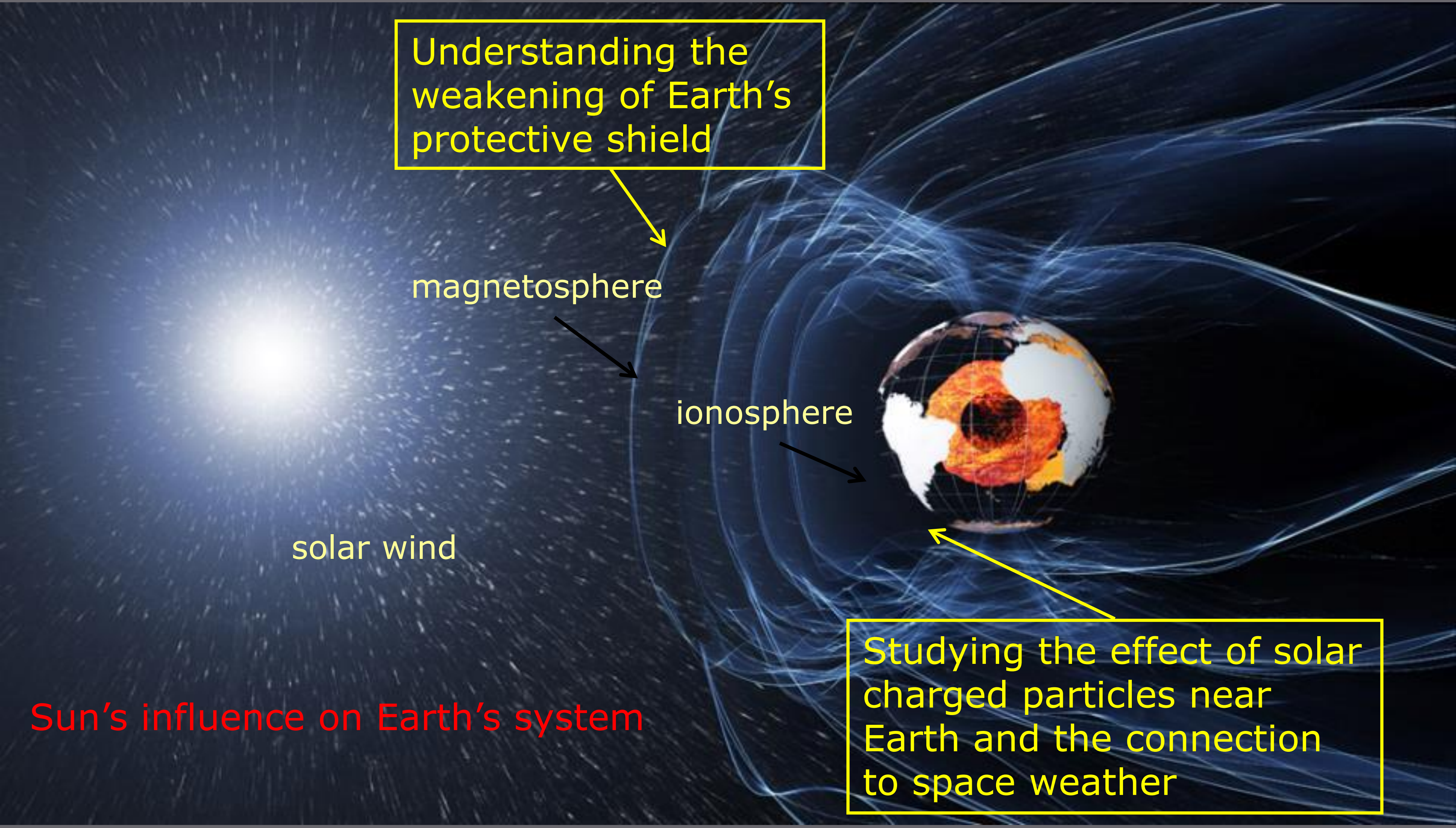
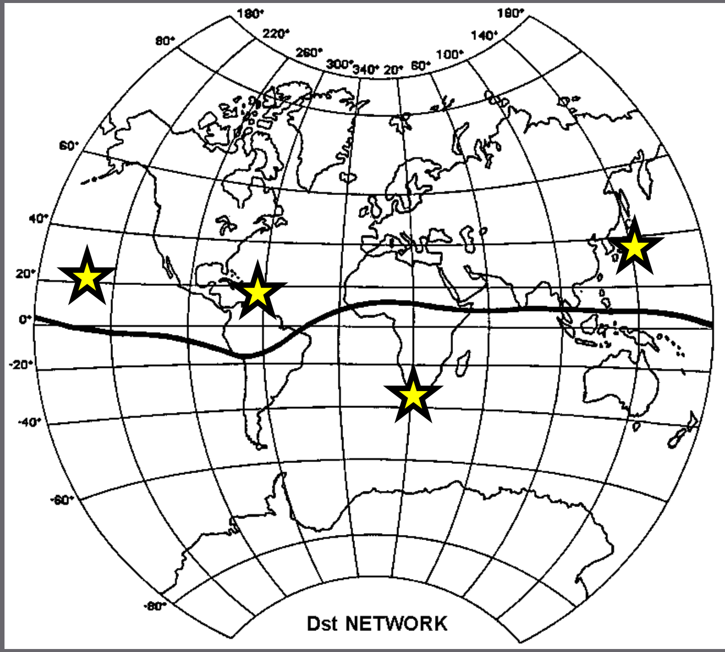
The primary aim of the mission is to provide the best survey ever of the geomagnetic field and the first global representation of its variations on time scales from less than a second to several years.

Looking into the force that protects Earth



Disturbance storm time (Dst) Index



- Represents the axially symmetric disturbance (of the horizontal component) of the magnetic field at the dipole equator on the Earth's surface.

- Derived using data from 4 stations
  - Hermanus (South Africa)
  - Kakioka (Japan)
  - Honolulu (US-HI)
  - San Juan (Puerto Rico)

IAGA Bulletin N°40: http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html

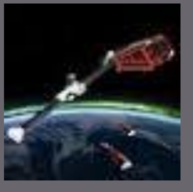
Dst-like Index From Swarm Data

1. Extract Total Magnetic Field Series from MAG_LR (1 Hz) product (Swarm-A)
   - Both VFM and ASM measurements can be used

2. Subtract CHAOS-6 (Finlay et al., *EPS* 2016) Internal Field Model
   - The External component models the Ring Current which is what drives the Dst Index so it must remain in the data

3. Remove values that lie above ±40° in Magnetic Latitude

4. Remove spikes and interpolate small data gaps



Dst-like Index From Swarm Data

5. Apply a low-pass Chebysev Type I filter with a cutoff period of 13 hours
   - A 12-hour averaging provides **complete global coverage!**

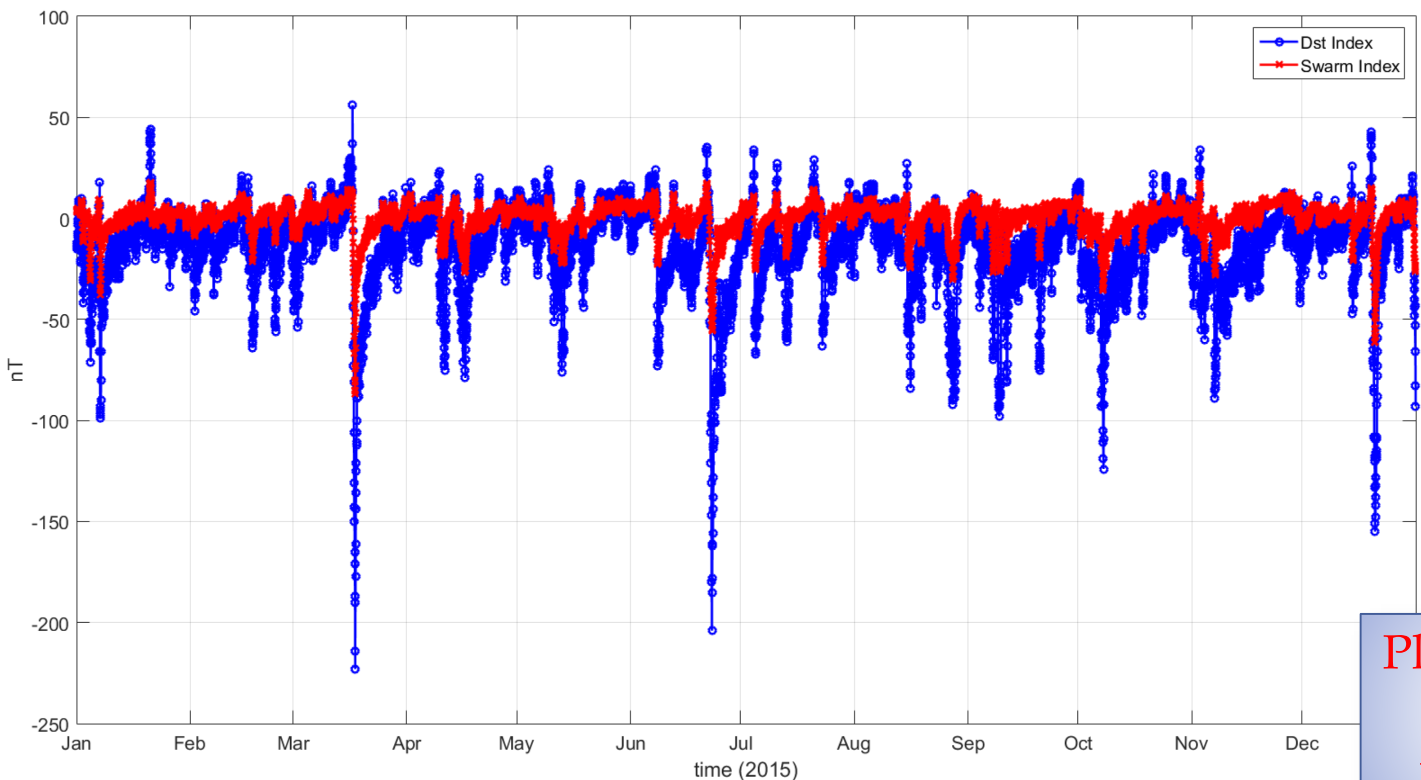
     (better than the 4 stations used for Dst Index derivation!)
6. Remove seasonal effects and the Local Time drift of the satellites' orbit
   - Use a Chebysev Type I filter with a cutoff period of approx. 4 months to model this slowly varying component
   - Subtract it from the filtered series of step 5.

- Apply a linear transform to get the Swarm Index

$$S_{index} = 2.5\, B_{(6)} - 15$$

Dst-like Index From Swarm Data

Before Linear Transform



Plot markers at 1-hour intervals!

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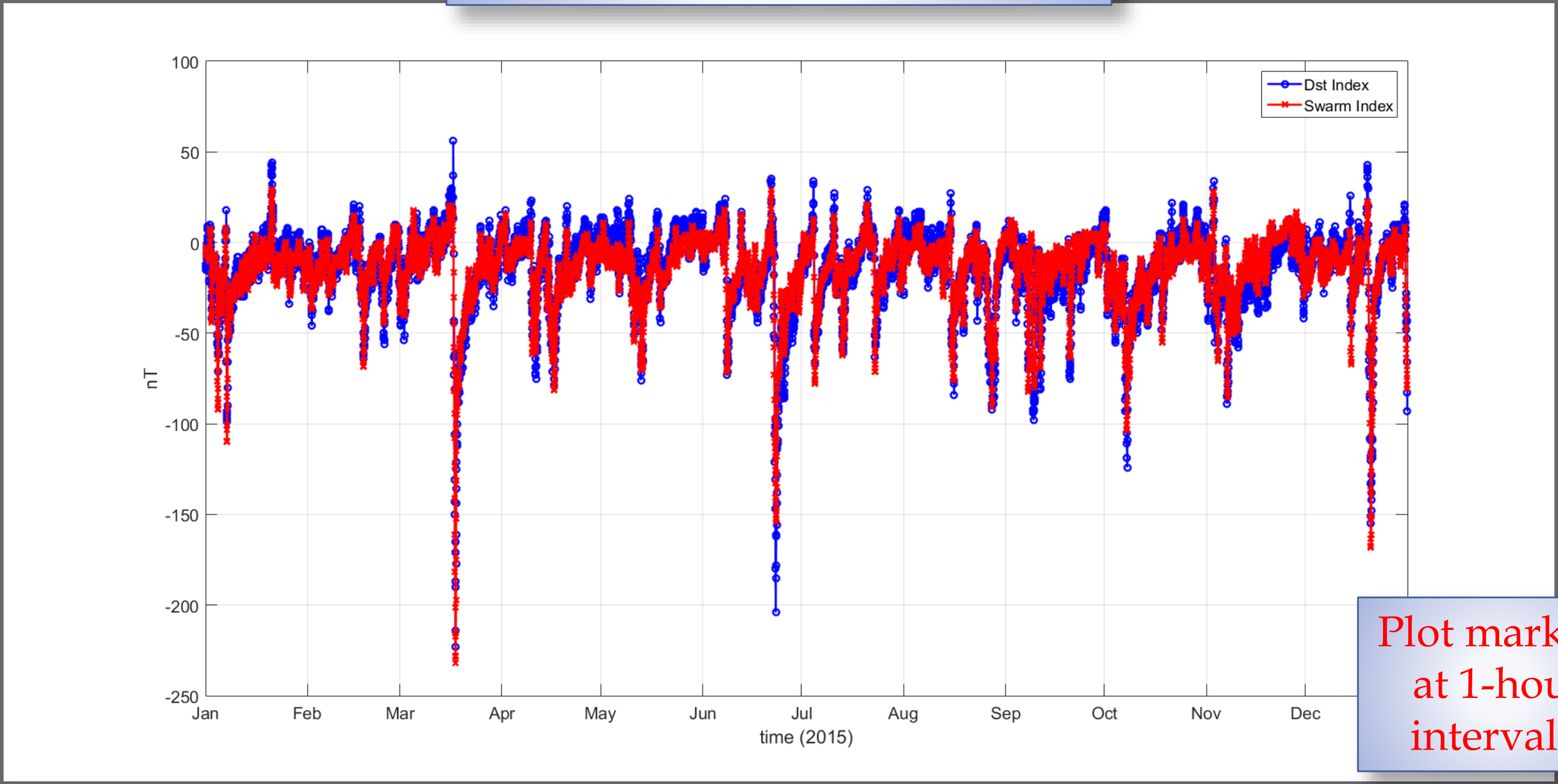
Dst-like Index From Swarm Data

After Linear Transform



Plot markers at 1-hour intervals!

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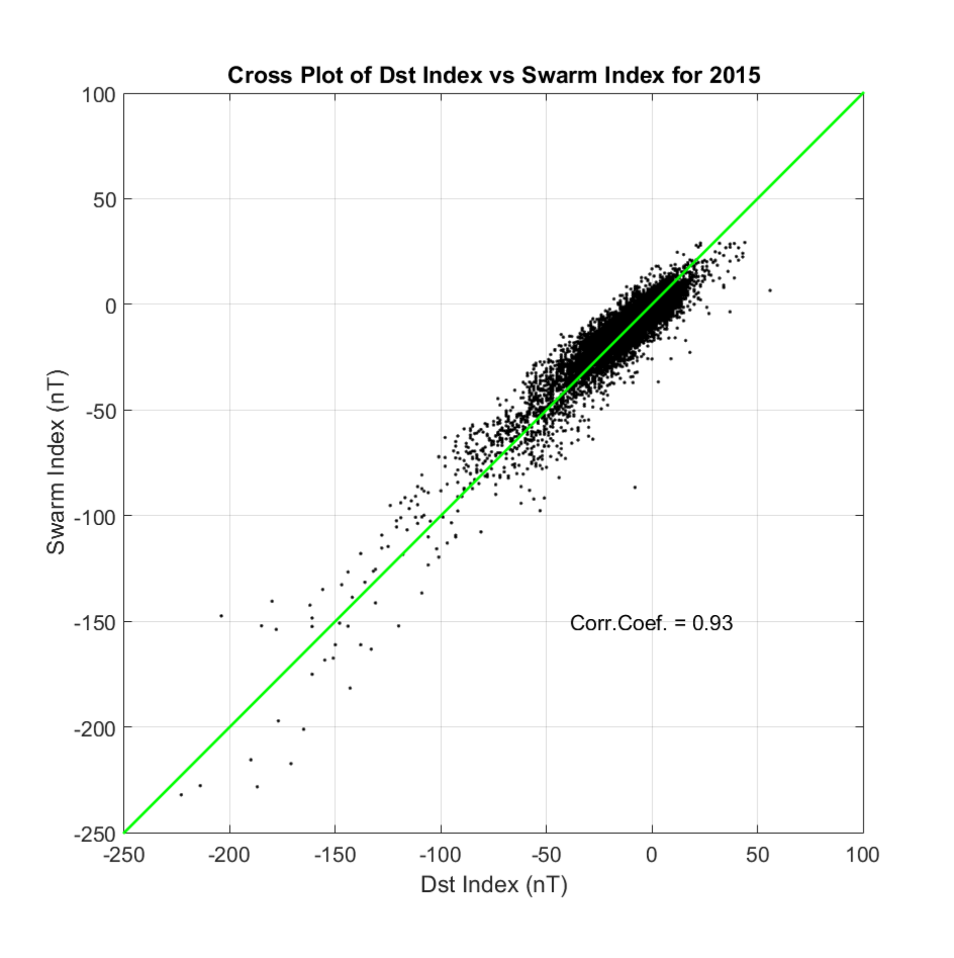
Swarm Index vs Dst Index for 2015



Correlation Study

- Up-sample Dst Index series to 1-sec sampling rate by linear interpolation
- Estimate Pearson's Correlation Coefficient for the entire 2015 time series
- Values >0.90 for a wide range of values for the free parameters

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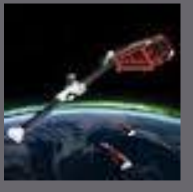

Key Reference

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Research

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One contribution of 9 to a theme issue 'Solar eruptions and their space weather impact'.

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Keywords:
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Ionospheric response to solar and interplanetary disturbances: a Swarm perspective

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The ionospheric response to solar and interplanetary disturbances has been the subject of intense study for several decades. For 5 years now, the European Space Agency's Swarm fleet of satellites surveys the Earth's topside ionosphere, measuring magnetic and electric fields at low-Earth orbit with unprecedented detail. Herein, we study *in situ* the ionospheric response in terms of the occurrence of plasma instabilities based on 2 years of Swarm observations. Plasma instabilities are an important element of space weather because they include irregularities like the equatorial spread F events, which are responsible for the disruption of radio communications. Moreover, we focus on three out of the four most intense geospace magnetic storms of solar cycle 24 that occurred in 2015, including the St Patrick's Day event, which is the strongest magnetic storm of the present solar cycle. We examine the associated ionospheric response at Swarm altitudes through the estimation of a Swarm Dst-like index. The newly proposed Swarm derived Dst index may be suitable for space weather applications.

This article is part of the theme issue 'Solar eruptions and their space weather impact'.

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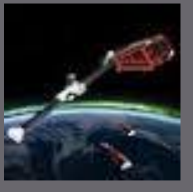
Information theory methods

- **Linear time series analysis techniques**
  - **Wavelet transforms (Hurst exponent)**
  - **Rescaled range analysis (Hurst exponent)**

  [Balasis et al.*, ANGEO* 2006]

- **Nonlinear time series analysis techniques**
  - **Entropies (Shannon entropy, Block entropy, T-complexity, Approximate entropy, Sample entropy and Fuzzy entropy)**
  - **Nonextensive statistical mechanics (Tsallis entropy)**

  [Balasis et al.*, GRL* 2008*, JGR* 2009*, Entropy* 2013*, Frontiers* 2016*, JGR* 2018]



Power-law

- If a time series is a temporal fractal then a power law of the form:

$$S(f) \sim f^{-\beta}$$

is obeyed with

- $S(f)$ - power spectral density
- f - frequency
- β - spectral scaling exponent,

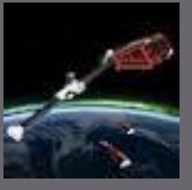
a measure of the strength of time correlations

- r - linear correlation coefficient,

the fit of the time series to a power-law

In general, $-1<\beta<3$, but it describes 2 classes of signal: fractional Gaussian noise (fGn) or fractional Brownian motion (fBm)

The Hurst exponent - H is calculated using different formulas for fGn ($-1<\beta<1$) or fBm ($1<\beta<3$)

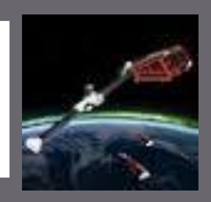


β exponent and its relation to Hurst

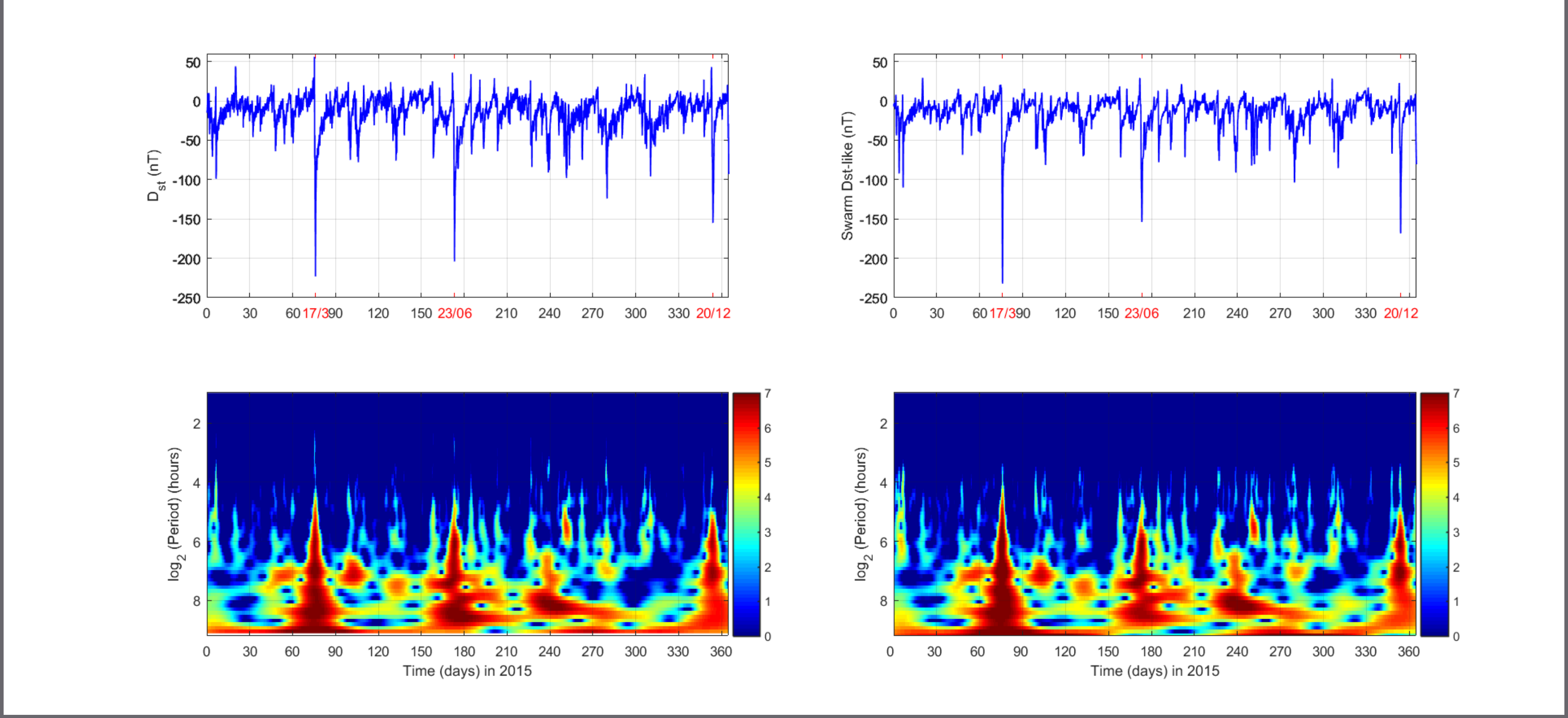
β *= 2**H**+1*, where ***H*** is the Hurst exponent for the fBm case (1 < ***β*** < 3)

- The exponent ***H*** characterizes the ***persistent/anti-persistent*** properties of the signal. The range *0<**H**<0.5 (1<**β**<2)* during the normal period indicates ***anti-persistency***, reflecting that if the fluctuations increase in a period, it is likely to decreasing in the interval immediately following and vice versa.
- We pay attention to the fact that the time series appears ***persistent*** properties, *0.5<**H**<1 (2<**β**<3)*. This means that if the amplitude of fluctuations increases in a time interval it is likely to continue increasing in the interval immediately following.
- ***H****=0.5 (**β**=2)* suggests no correlation between the repeated increments. Consequently, this particular value takes on a special physical meaning:

  It marks the transition between persistent and anti-persistent behavior in the time series.



Wavelet spectral analysis



[Balasis et al., *under preparation*]

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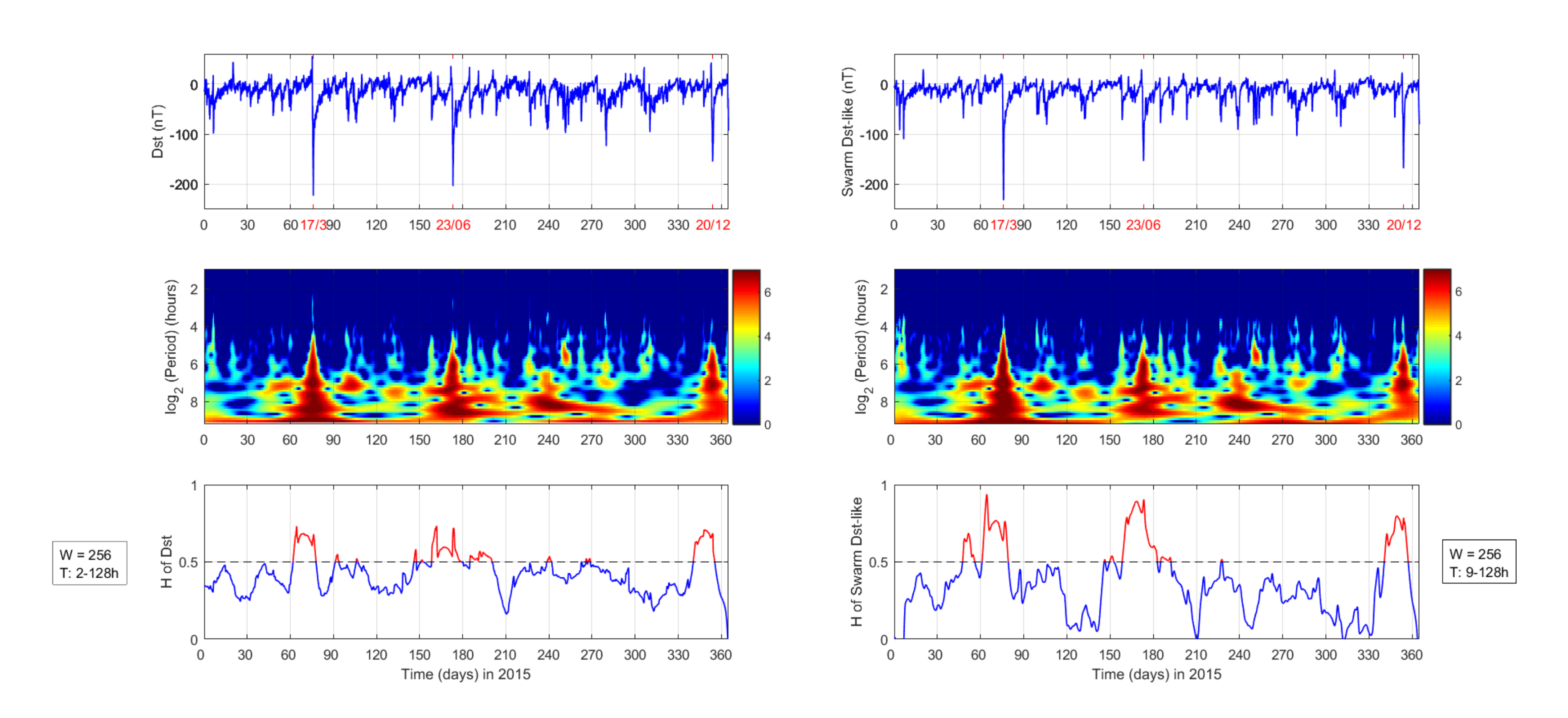
Temporal Variation of the *H* index



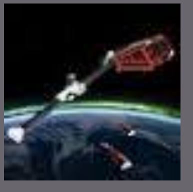
[Balasis et al., *under preparation*]

Entropies I

- Approximate entropy (ApEn) has been introduced by Pincus as a measure for characterizing the regularity in relatively short and potentially noisy data. More specifically, <u>ApEn examines time series for detecting the presence of similar epochs; more similar and more frequent epochs lead to lower values of ApEn.</u>

- Sample entropy (SampEn) was proposed by Richman and Moorman as an alternative that would provide an improvement of the intrinsic bias of ApEn.

- Fuzzy entropy (FuzzyEn), like its ancestors, ApEn and SampleEn, is a "regularity statistic" that quantifies the (un)predictability of fluctuations in a time series. For the calculation of FuzzyEn, the similarity between vectors is defined based on fuzzy membership functions and the vectors' shapes. FuzzyEn can be considered as an upgraded alternative of SampEn (and ApEn) for the evaluation of complexity, especially for short time series contaminated by noise.

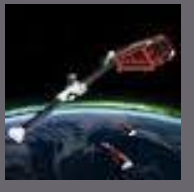


Entropies II

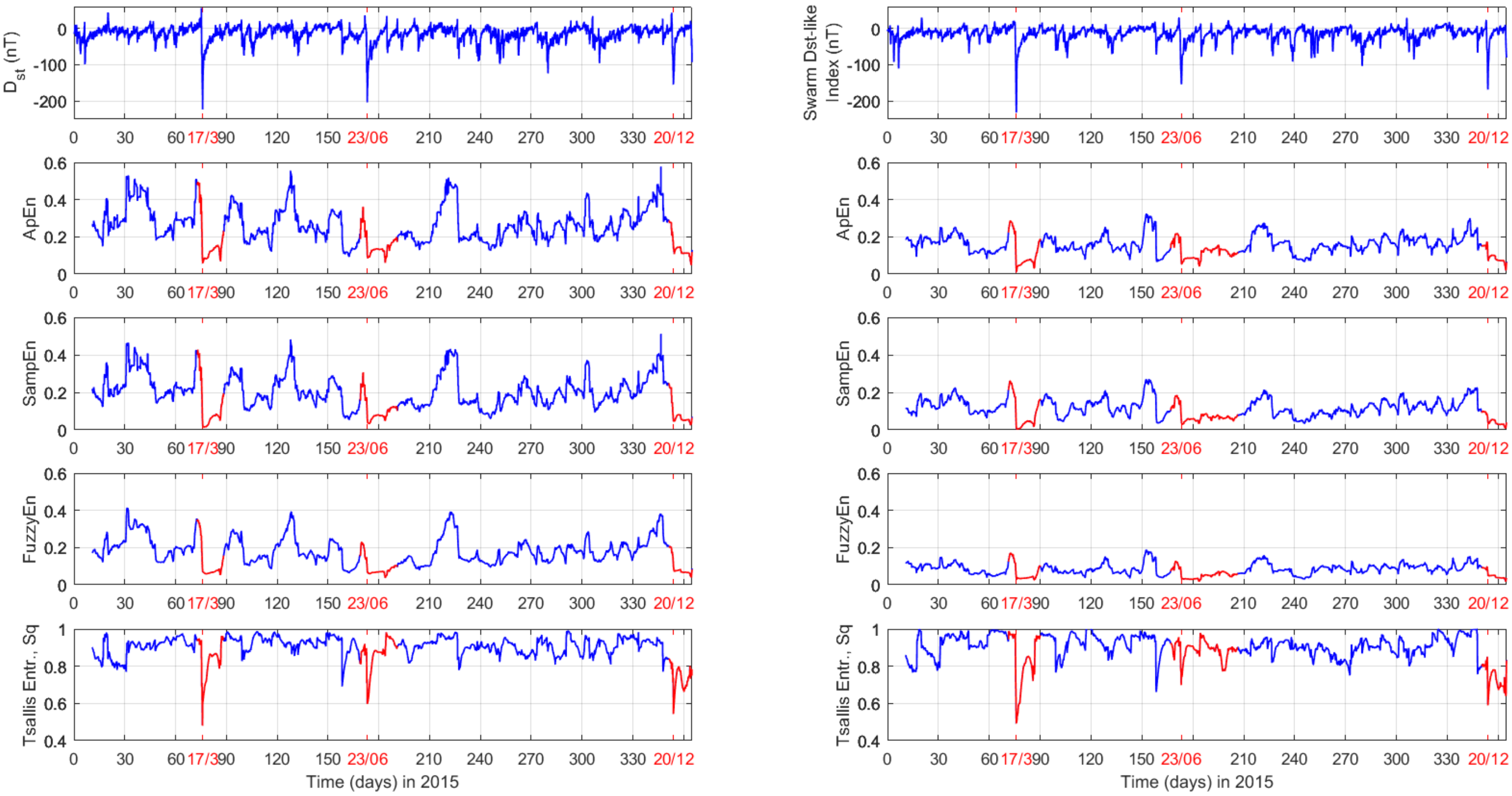
- The uncertainty of an open system state can be quantified by the Boltzmann-Gibbs (B-G) entropy, which is the widest known uncertainty measure in statistical mechanics.

- B-G entropy ($S_{B\text{-}G}$) cannot, however, describe nonequilibrium physical systems characterized by long-range interactions or long-term memory or being of a multi-fractal nature.

- Inspired by multi-fractal concepts, Tsallis [1988, 1998] has proposed a generalization of the B-G statistics.



Entropies



[Balasis et al., *under preparation*]

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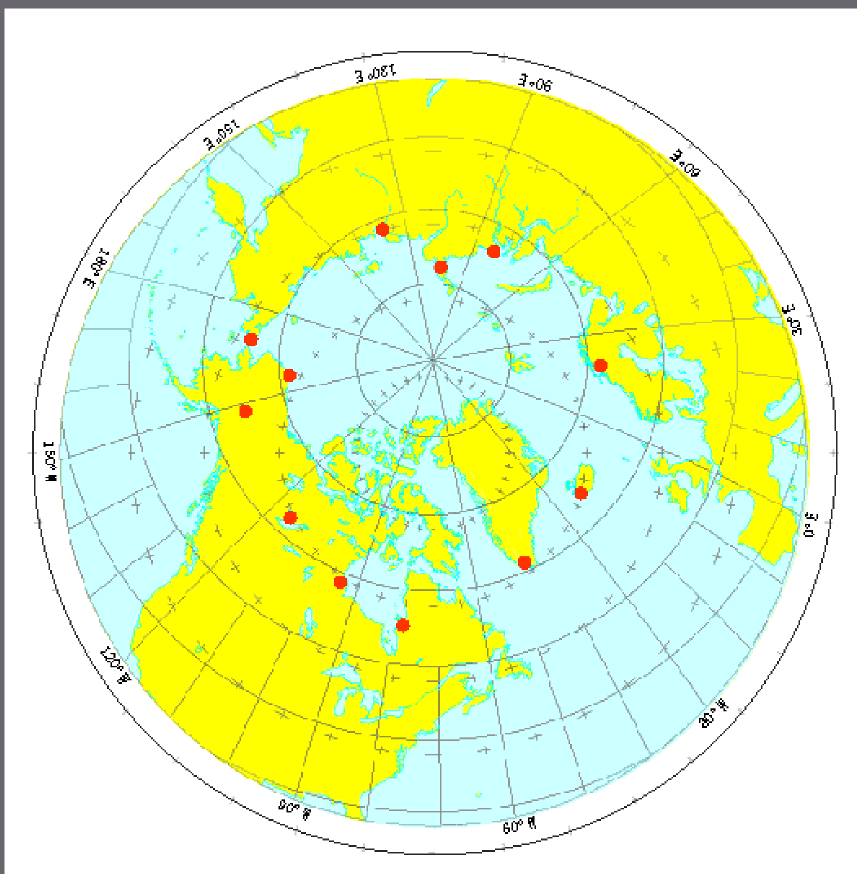
Auroral Electrojet (AE) Index

The AE index is derived from geomagnetic variations in the horizontal component observed at selected observatories along the auroral zone in the northern hemisphere.



The AE index represents the overall activity of the electrojets

TABLE 1 - List of AE(12) Stations.

Observatory	IAGA Code	Geographic Coord. Lat.(°N)	Geographic Coord. Long.(°E)	Geomagnetic Coord. Lat.(°N)	Geomagnetic Coord. Long.(°E)
Abisko	ABK	68.36	18.82	66.04	115.08
Dixon Island	DIK	73.55	80.57	63.02	161.57
Cape Chelyuskin	CCS	77.72	104.28	66.26	176.46
Tixie Bay	TIK	71.58	129.00	60.44	191.41
Cape Wellen	CWE	66.17	190.17	61.79	237.10
Barrow	BRW	71.30	203.25	68.54	241.15
College	CMO	64.87	212.17	64.63	256.52
Yellowknife	YKC	62.40	245.60	69.00	292.80
Fort Churchill	FCC	58.80	265.90	68.70	322.77
Poste-de-la-Baleine	PBQ	55.27	282.22	66.58	347.36
Narsarsuaq (Narssarssuaq)	NAQ	61.20	314.16	71.21	36.79
Leirvogur	LRV	64.18	338.30	70.22	71.04

> 55˚ lat.

Davis and Sugiura, 1966

AE-like Index from Swarm Data

- Get Magnetic Field data in FAC (Bpar, Bper1, Bper2) after pre-processing and removal of the CHAOS-6 Model.
- Build the "horizontal" component, assuming that at high latitudes, this is mostly given by the perpendicular FAC components

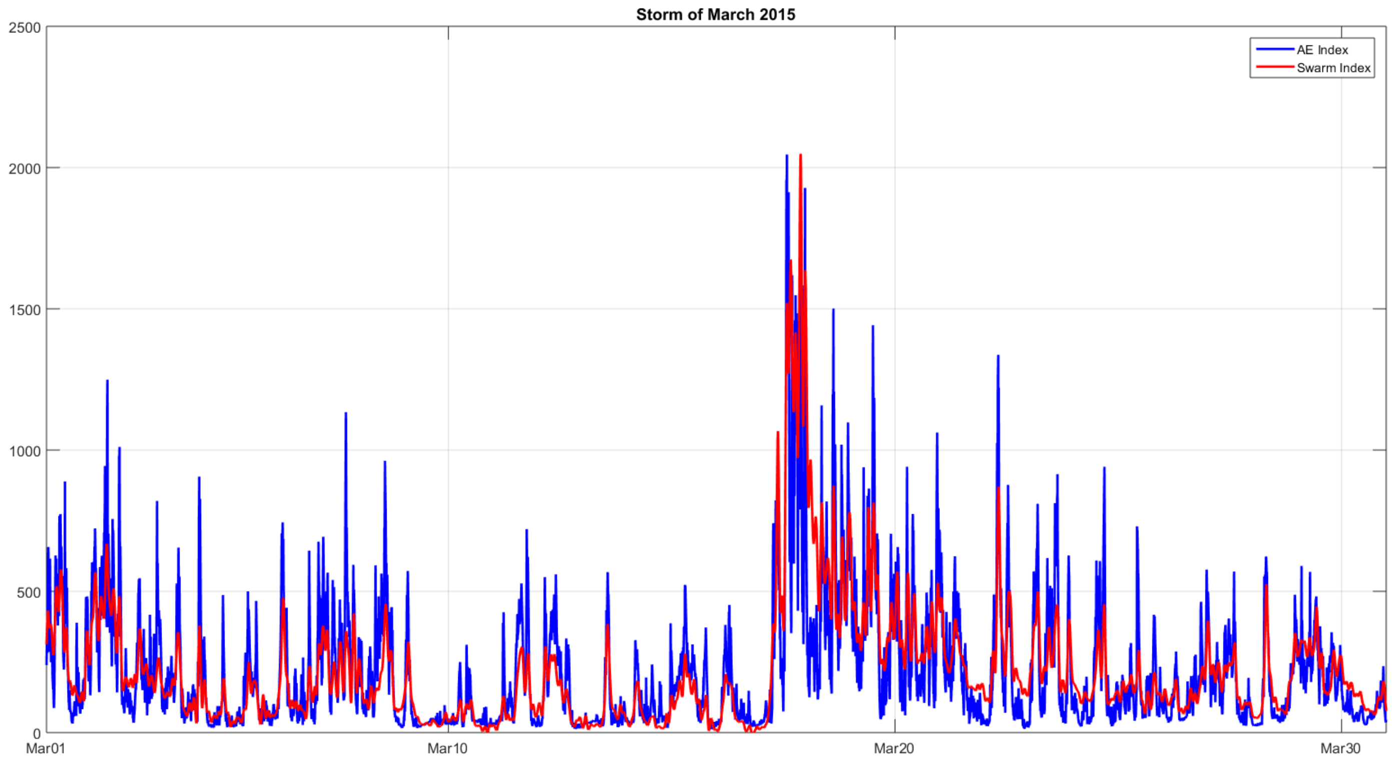
$$B_{horz} = \sqrt{B_{per1}^2 + B_{per2}^2}$$

- Keep only values above 50˚ or below 50˚ in MLat
- Low-pass filter with a a cutoff period of 2.4 hours to get B_f
- Apply a linear transform to get the Swarm Index

$$S_{index} = 5.3\, B_f - 75$$

B_{horz} formula, Latitude & freq. cutoffs designed to maximize correlation coef.	*Model Training*
Multiplicative factor designed to achieve similar variance with AE Index	*with March 2015*
Offset designed to minimize RMSE	*data*

AE-like Index From Swarm Data
March 2015 Storm



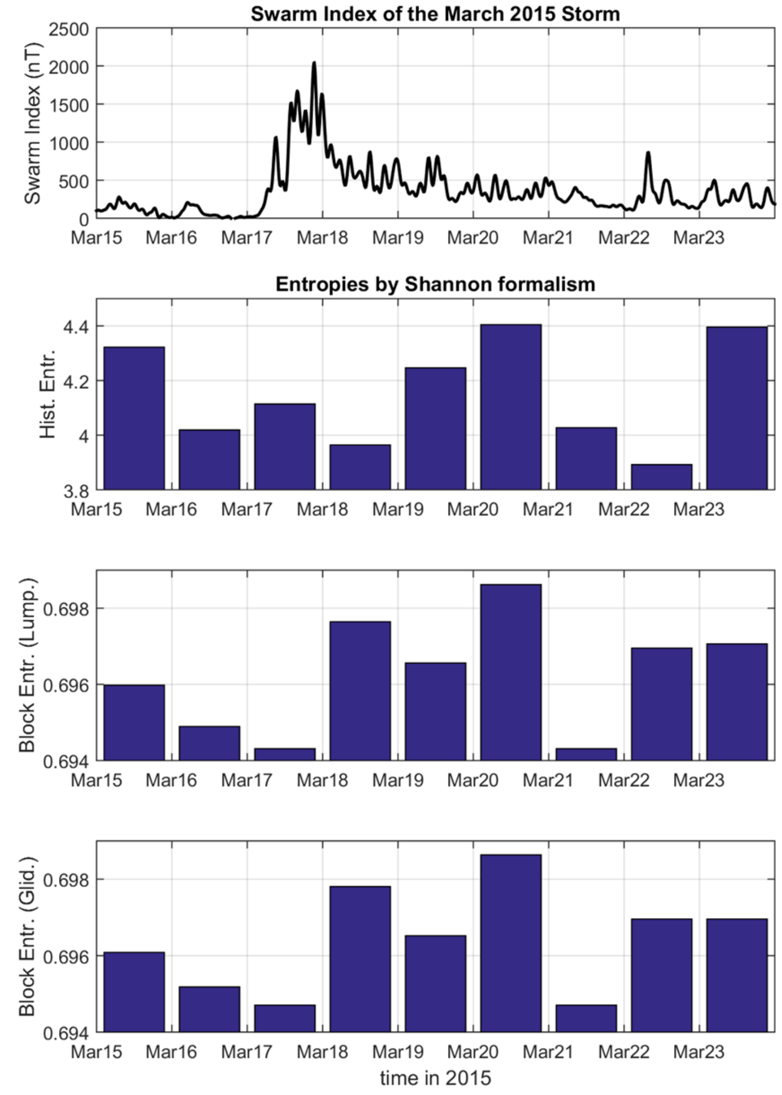
Case Study: March 2015 Storm

Swarm-A, AE-like Index, 1 Hz sampling rate.

Keeping only high latitudinal measurements, segmented into daily, non-overlapping windows.

Histogram Entropy computed in 100 bins.

Block entropies computed on binary symbolic series (median threshold), up to m=5.



Summary

- The newly proposed Swarm-inspired Dst index [Balasis et al., *RSTA* 2019] monitors magnetic storm activity at least as good as the standard Dst / SYM-H indices.

- It yet remains to be investigated whether the standard Dst or the Swarm Dst index is a better representation of the currents contributing to the coupled ionosphere-magnetosphere system (e.g. ring current), especially during stormy periods.

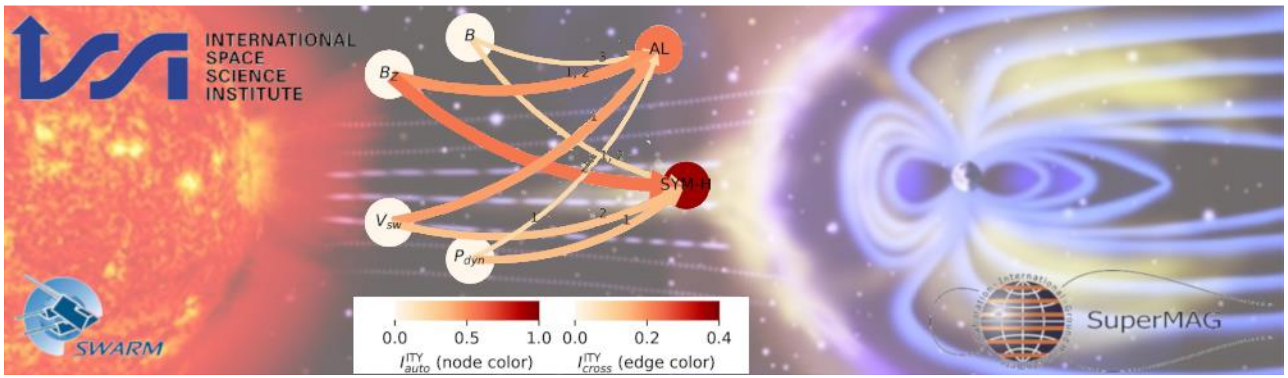
  - The Hurst exponent and various entropy measures show the complexity dissimilarity among different "physiological" (normal) and "pathological" states (intense magnetic storms) of the magnetosphere.
  - They imply the emergence of two distinct patterns: (i) a pattern associated with normal periods, which is characterized by a lower degree of organization / higher complexity, and (ii) a pattern associated with the intense magnetic storms, which is characterized by a higher degree of organization / lower complexity.

- The newly proposed Swarm-inspired AE index monitors magnetospheric substorm activity similarly to the standard AE index.

New ISSI International Team 2019

Complex Systems Perspectives Pertaining to the Research of the Near-Earth Electromagnetic Environment

ISSI Team led by G. Balasis (GR)



The Team attempts to combine advanced mathematical tools and identify key directions for future methodological progress relevant to space weather forecasting using Swarm, SuperMAG, and other space/ground datasets. By utilizing a variety of complementary modern complex systems based approaches, an entirely novel view on nonlinear magnetospheric variability is obtained. Taken together, the multiplicity of recently developed approaches in the field of nonlinear time series analysis offers great potentials for uncovering relevant yet complex processes interlinking different geospace subsystems, variables and spatio-temporal scales. The Team will provide a first-time systematic assessment of these techniques and their applicability in the context of geomagnetic variability.

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