Investigation of Dynamical Complexity in Swarm-Derived Geomagnetic Activity Indices Using Information Theory

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Swarm 10 Year Anniversary & Science Conference 2024

Outline

1. Swarm-derived Indices
   - Swarm Dst
   - Swarm AE
   - Swarm AE-North/AE-South
   - Interhemispheric Asymmetry (I.A.)

2. Information Theory (I.T.)
   - Shannon Entropy
   - Block Entropy
   - Tsallis Block Entropy

3. Information-theoretic Perspective of I.A.

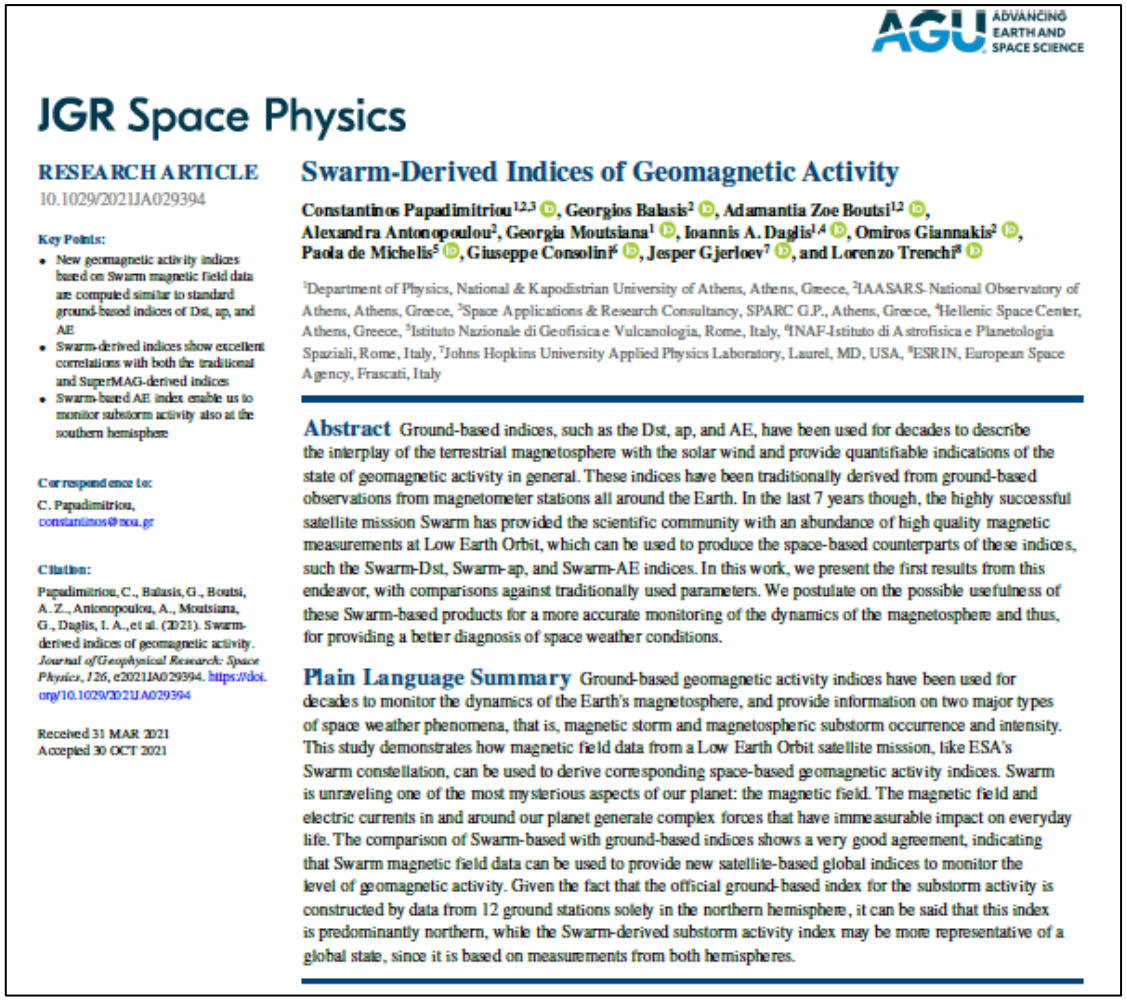
4. … and one more thing

Swarm-derived Indices of Geomagnetic Activity

- Convert B_{NEC} -> B_{MFA}: B_{par} (or B_{total})
- Subtract CHAOS Internal Field Model
- Clean & Interpolate
- Keep only values between certain magnetic latitudes

Index	Magn. Latitude Limits
Dst/SYM-H	[-30°, +30°]
ap	[-60°, -55°] & [+55°, +60°]
AE	[-75°,- 65°] & [+65°, +75°]

- Average to 1-min resolution
- Merge Swarm-A & Swarm-B measurements
- Low-pass filter (diff. cutoff frequency for each index)
- Linear Transform



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JGR Space Physics

RESEARCH ARTICLE

10.1029/2021JA029394

Swarm-Derived Indices of Geomagnetic Activity

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Key Points:

- New geomagnetic activity indices based on Swarm magnetic field data are computed similar to standard ground-based indices of Dst, ap, and AE
- Swarm-derived indices show excellent correlations with both the traditional and SuperMAG-derived indices
- Swarm-based AE index enable us to monitor substorm activity also at the southern hemisphere

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Abstract Ground-based indices, such as the Dst, ap, and AE, have been used for decades to describe the interplay of the terrestrial magnetosphere with the solar wind and provide quantifiable indications of the state of geomagnetic activity in general. These indices have been traditionally derived from ground-based observations from magnetometer stations all around the Earth. In the last 7 years though, the highly successful satellite mission Swarm has provided the scientific community with an abundance of high quality magnetic measurements at Low Earth Orbit, which can be used to produce the space-based counterparts of these indices, such the Swarm-Dst, Swarm-ap, and Swarm-AE indices. In this work, we present the first results from this endeavor, with comparisons against traditionally used parameters. We postulate on the possible usefulness of these Swarm-based products for a more accurate monitoring of the dynamics of the magnetosphere and thus, for providing a better diagnosis of space weather conditions.

Plain Language Summary Ground-based geomagnetic activity indices have been used for decades to monitor the dynamics of the Earth's magnetosphere, and provide information on two major types of space weather phenomena, that is, magnetic storm and magnetospheric substorm occurrence and intensity. This study demonstrates how magnetic field data from a Low Earth Orbit satellite mission, like ESA's Swarm constellation, can be used to derive corresponding space-based geomagnetic activity indices. Swarm is unraveling one of the most mysterious aspects of our planet: the magnetic field. The magnetic field and electric currents in and around our planet generate complex forces that have immeasurable impact on everyday life. The comparison of Swarm-based with ground-based indices shows a very good agreement, indicating that Swarm magnetic field data can be used to provide new satellite-based global indices to monitor the level of geomagnetic activity. Given the fact that the official ground-based index for the substorm activity is constructed by data from 12 ground stations solely in the northern hemisphere, it can be said that this index is predominantly northern, while the Swarm-derived substorm activity index may be more representative of a global state, since it is based on measurements from both hemispheres.

Swarm-derived Dst/SYM-H Index

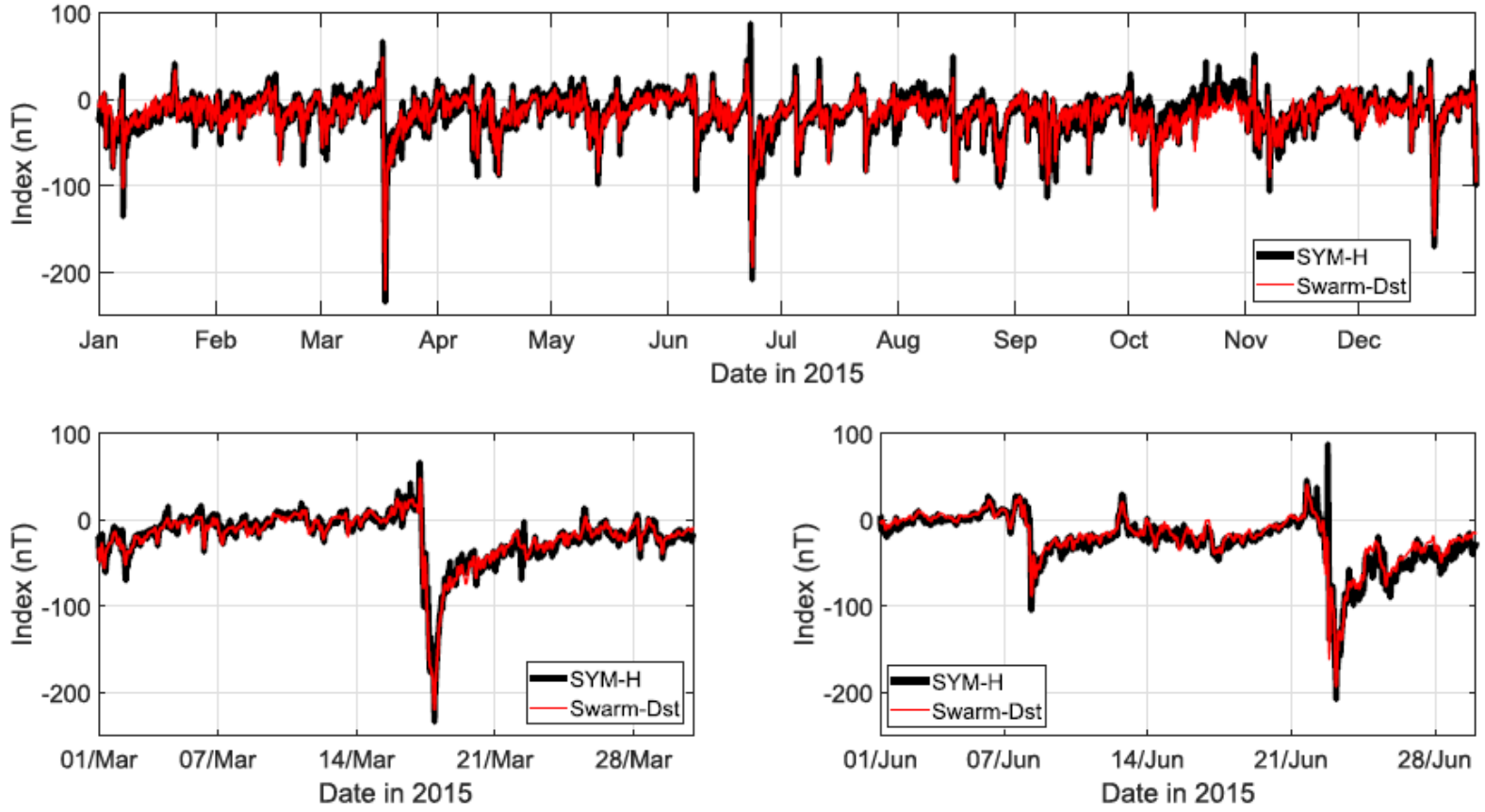


Figure 4. Swarm-derived Dst index (red) compared to the ground-based SYM-H index (black). Top panel shows the entire 12 month period from January 1 to December 31, 2015, while the bottom panels show zoomed pictures for March (bottom left) and June 2015 (bottom right).

Swarm-derived AE Index

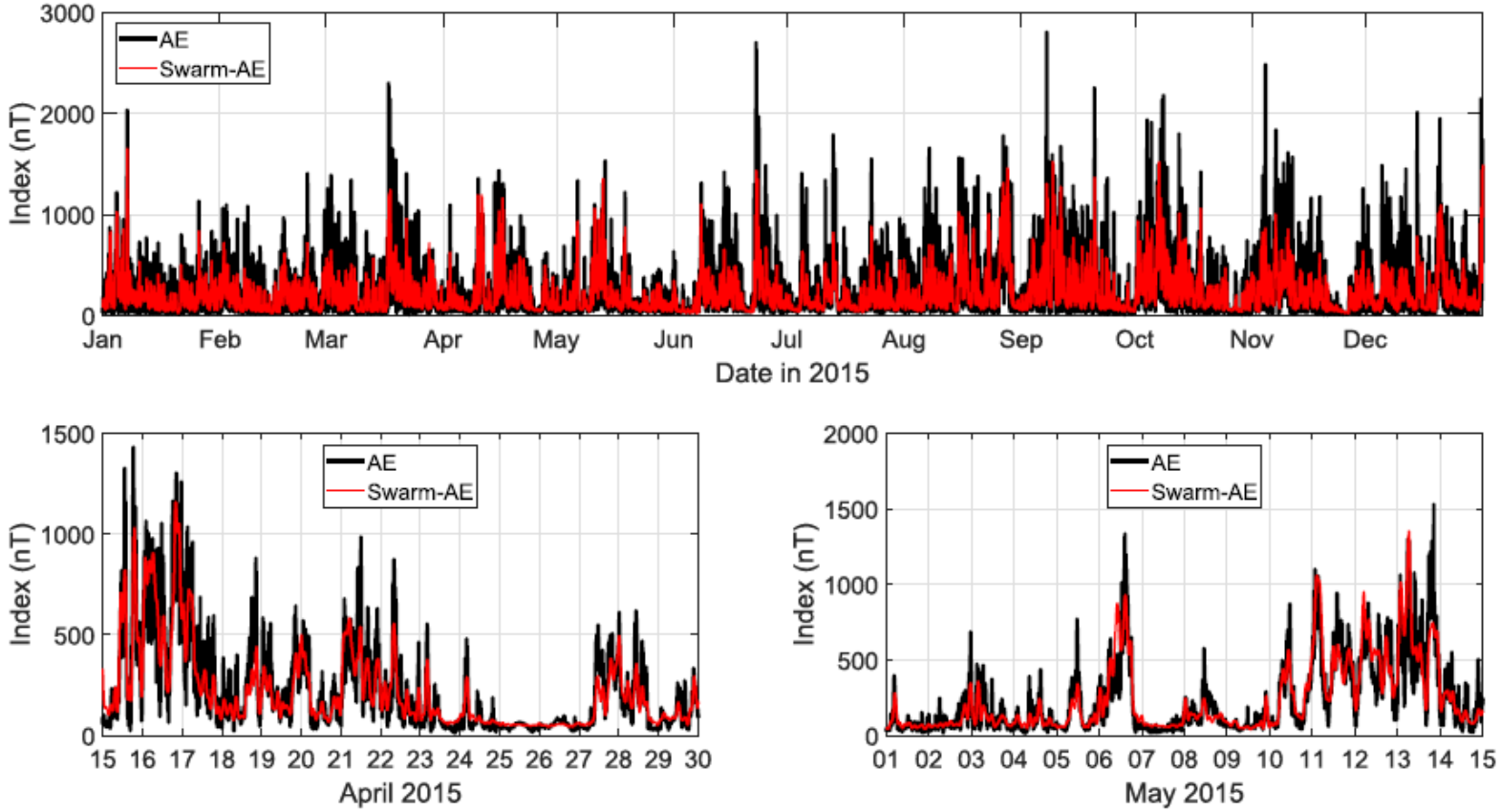
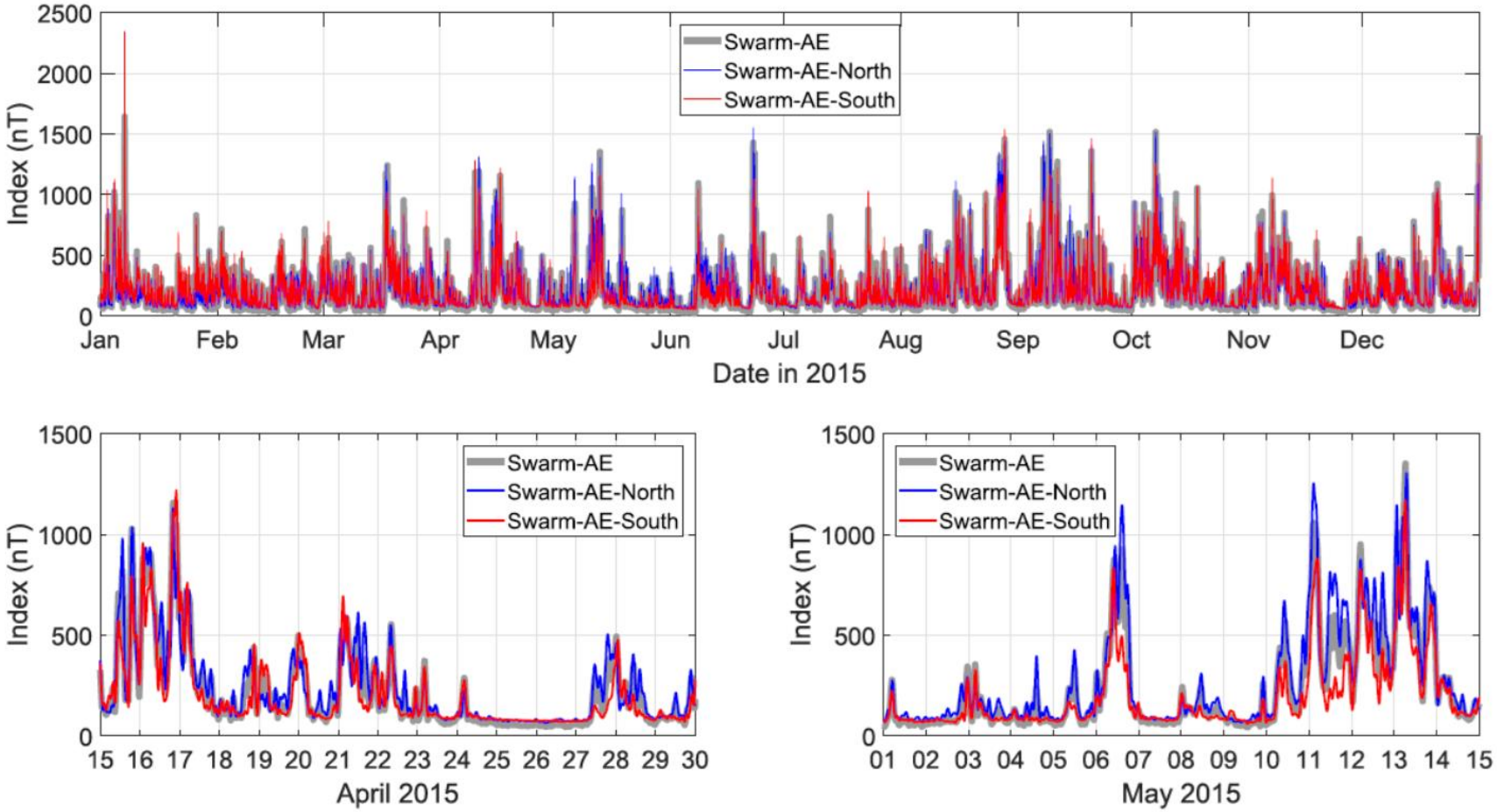


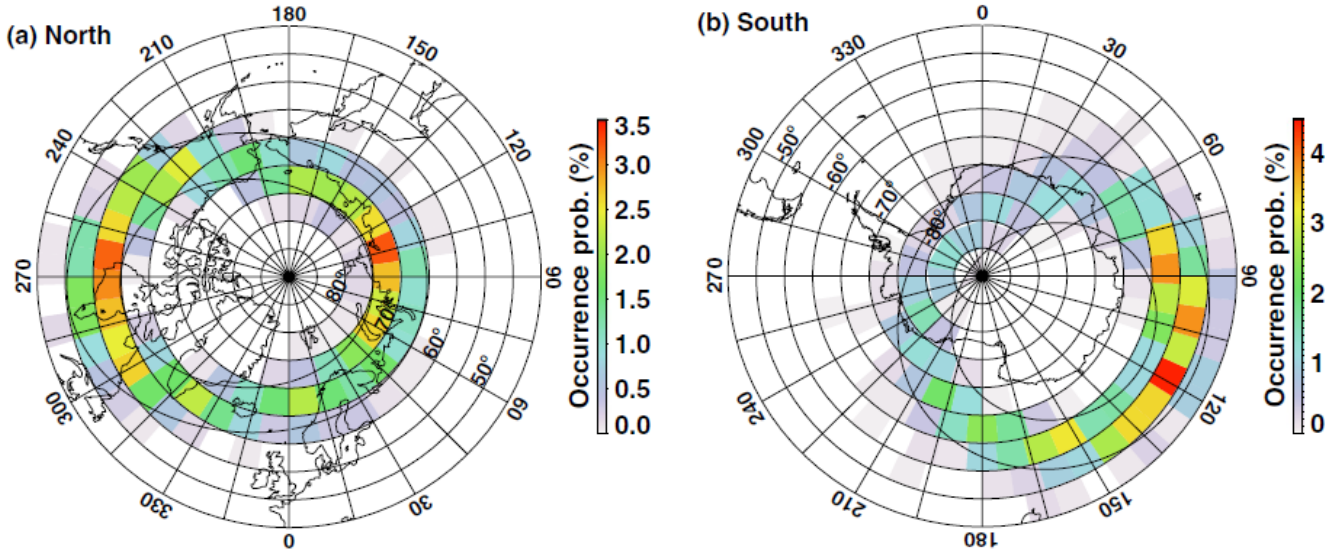
Figure 6. Swarm-derived AE index (red) compared to the standard AE index (black). Top panel shows the entire 12 month period from January 1 to December 31, 2015, while the bottom panels show zoomed pictures from the second half of April (bottom left) and first half of May (bottom right).

Swarm-derived AE Index

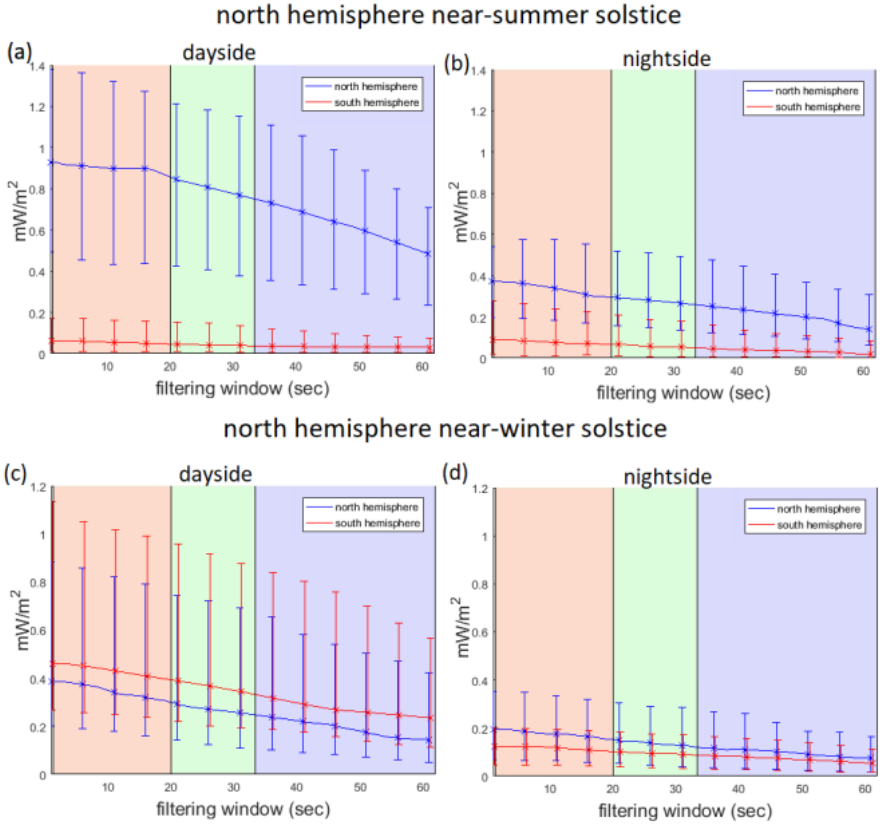


North-South Asymmetry

"Substorm onset is far from north-south symmetric; it is more likely to be initiated in a dark than a sunlit oval; preferred locations of substorm onsets coincide with the local peak of the Earth's magnetic field (or a minimum in the ionospheric conductivity)"



Liou K, Sotirelis T, Mitchell EJ. **North-South Asymmetry in the Geographic Location of Auroral Substorms correlated with Ionospheric Effects**. Sci Rep. 2018 Nov 22;8(1):17230. doi: 10.1038/s41598-018-35091-2



I Pakhotin, IR Mann, K Xie, J Burchill, D Knudsen. **Northern Preference for Terrestrial Electromagnetic Energy Input from Space Weather-** Authorea Preprints, 2022

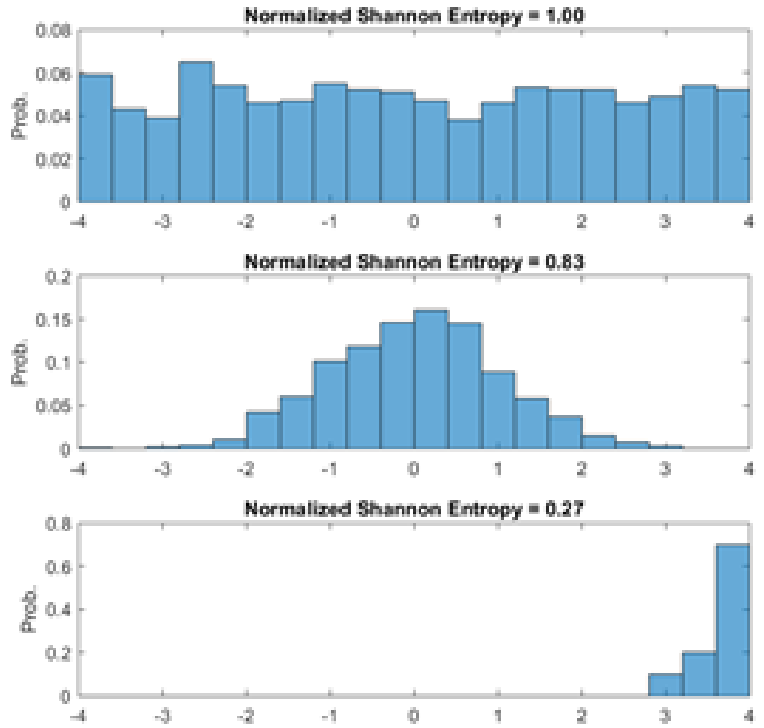
Information-Theory

Given p_i the probability of a telecom. system being in a cell 'i' of its phase space, Shannon defined the information produced by it by means of the Boltzmann H theorem, as the entropy

$$H = -\sum_i p_i \cdot \log_b p_i$$

Continuous variables can be "digitized" in order to define these "cells" of the phase space.

This in essence becomes a "histogram entropy" and loses all sense of temporal information.



(Shannon, 1948)

Information-Theory

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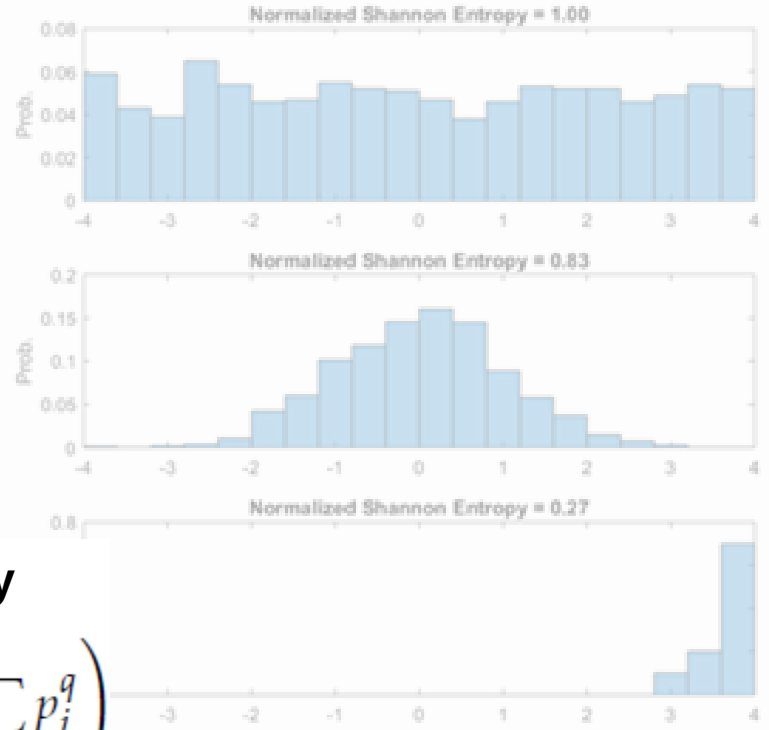

Rényi entropy

$$\mathrm{H}_\alpha(X) = \frac{1}{1-\alpha} \log \left(\sum_{i=1}^{n} p_i^\alpha \right)$$

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ses all sens

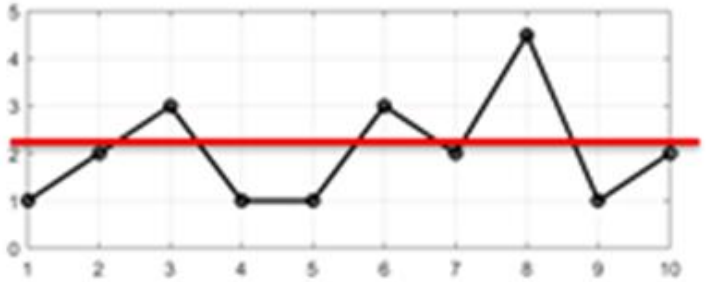
Tsallis Entropy

$$S_q = k \frac{1}{q-1} \left(1 - \sum p_i^q \right)$$

(Shannon, 1948)

Information-Theory

Digitization of continuous time series (as an easy example consider the binary case, performed by a simple mean-value thresholding)



0, 0, 1, 0, 0, 1, 0, 1, 0, 0

Parsing the symbolic series in blocks of length 'm', e.g. for m=3

Gliding/Sliding Method (overlapping)										Lumping Method (non - overlapping)									
0,	0,	1,	0,	0,	1,	0,	1,	0,		0,	0,	1,	0,	0,	1,	0,	1,	0,	0
0,	0,	1,	0,	0,	1,	0,	1,	0,		0,	0,	1,	0,	0,	1,	0,	1,	0,	0
0,	0,	1,	0,	0,	1,	0,	1,	0,		0,	0,	1,	0,	0,	1,	0,	1,	0,	0

In both cases, count the probability of appearance of each "block of length m" and compute the block entropy H(m).

The entropy of the source is given by H(m+1) – H(m), for m > 1

[Karamanos & Nicolis, 1999]

Information-Theory

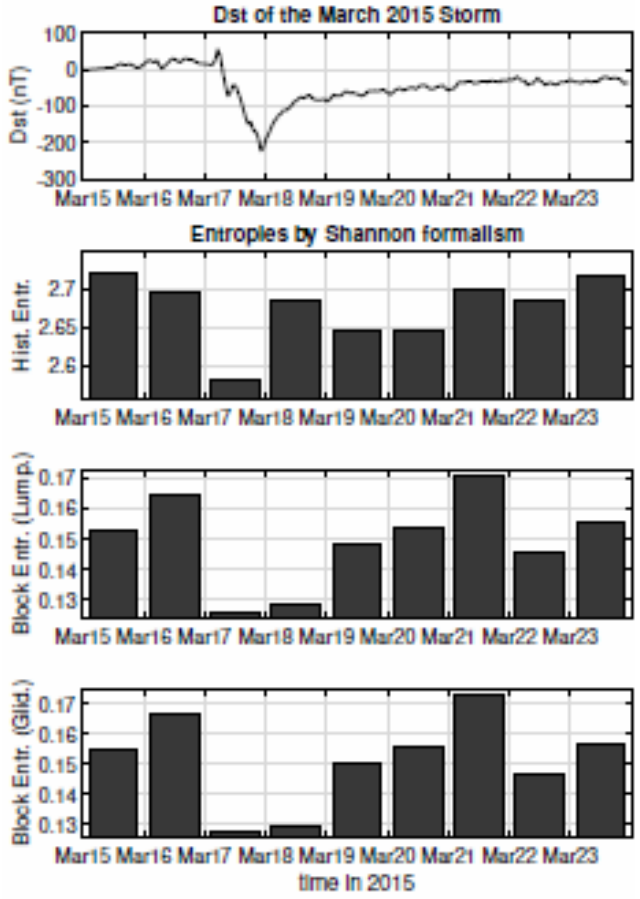
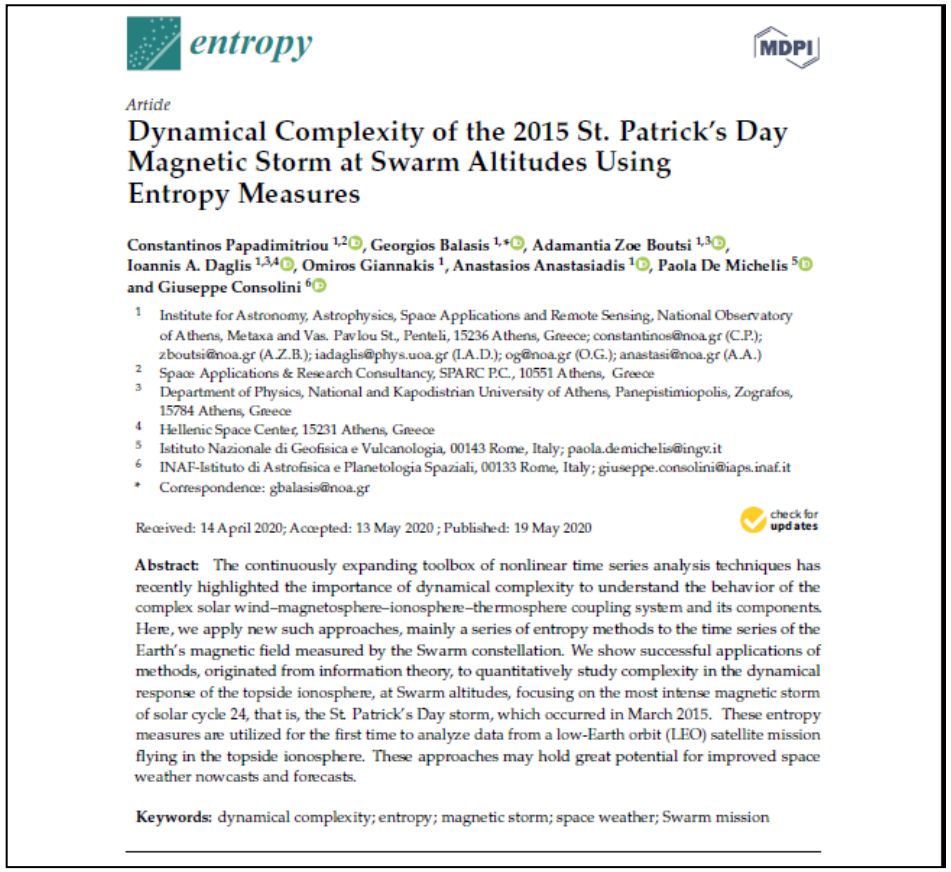


Figure 3. Entropy analysis according to Shannon formalism of the Swarm B total (external) field for the March 2015 magnetic storm.



entropy

MDPI

Article

Dynamical Complexity of the 2015 St. Patrick's Day Magnetic Storm at Swarm Altitudes Using Entropy Measures

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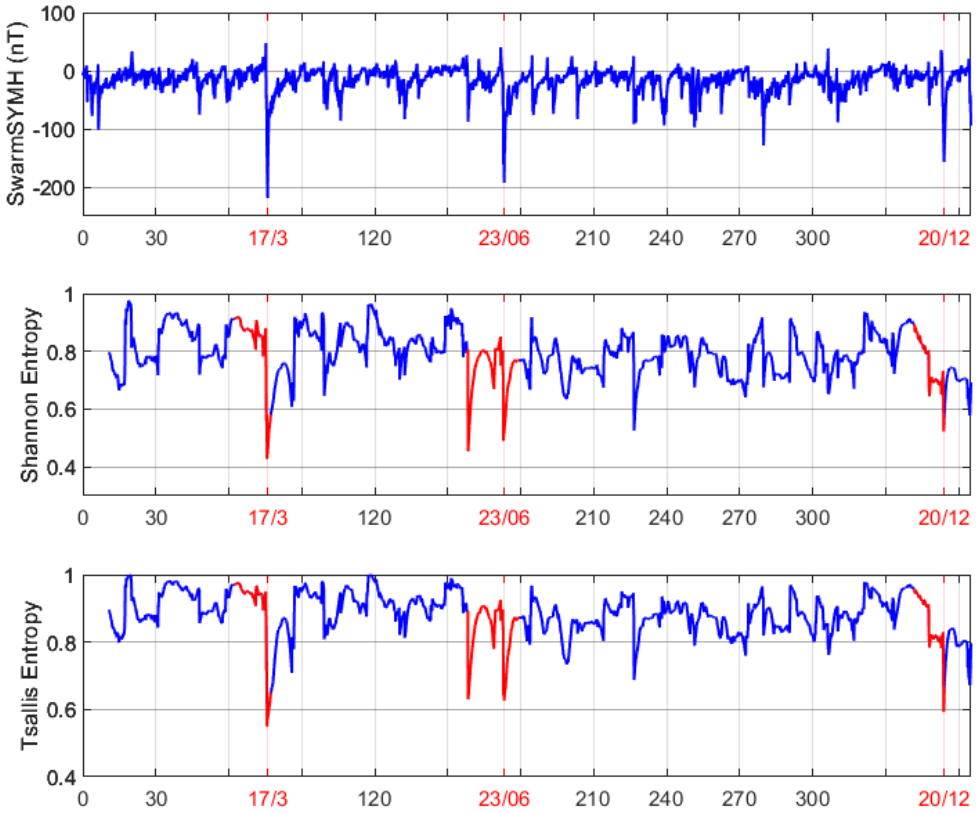
Abstract: The continuously expanding toolbox of nonlinear time series analysis techniques has recently highlighted the importance of dynamical complexity to understand the behavior of the complex solar wind–magnetosphere–ionosphere–thermosphere coupling system and its components. Here, we apply new such approaches, mainly a series of entropy methods to the time series of the Earth's magnetic field measured by the Swarm constellation. We show successful applications of methods, originated from information theory, to quantitatively study complexity in the dynamical response of the topside ionosphere, at Swarm altitudes, focusing on the most intense magnetic storm of solar cycle 24, that is, the St. Patrick's Day storm, which occurred in March 2015. These entropy measures are utilized for the first time to analyze data from a low-Earth orbit (LEO) satellite mission flying in the topside ionosphere. These approaches may hold great potential for improved space weather nowcasts and forecasts.

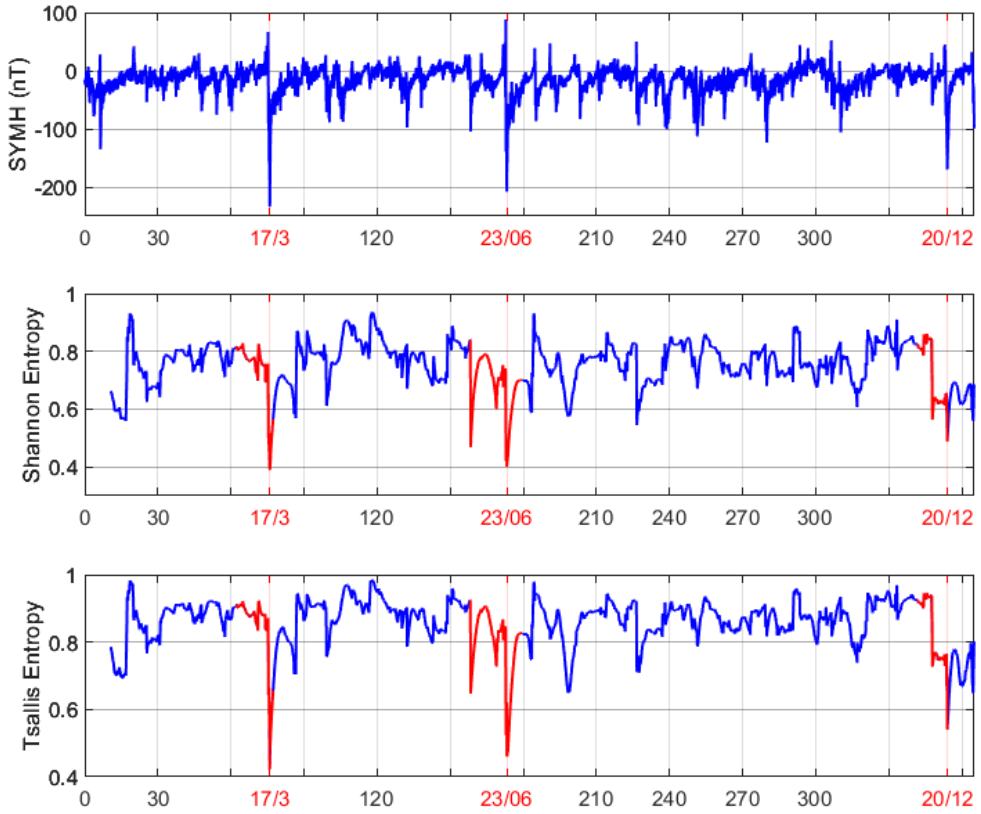
Keywords: dynamical complexity; entropy; magnetic storm; space weather; Swarm mission

Entropy Analysis of Swarm Dst/SYM-H

Swarm-derived SYM-H

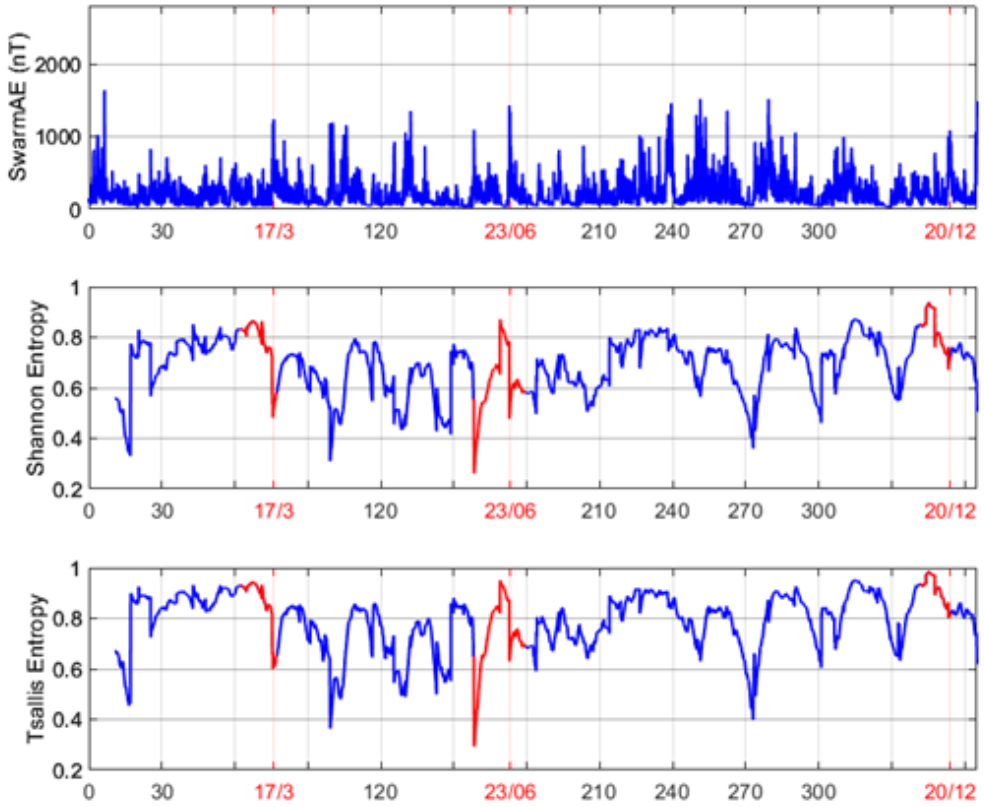


Ground-based SYM-H

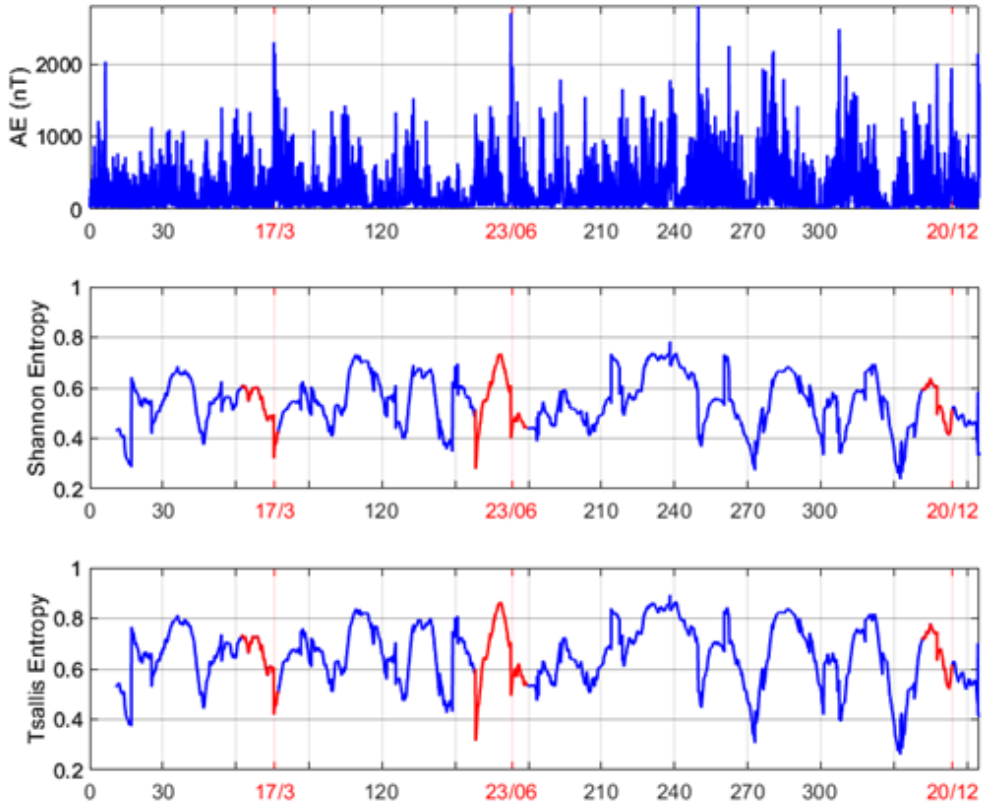


Entropy Analysis of Swarm AE North vs South

Swarm-derived AE

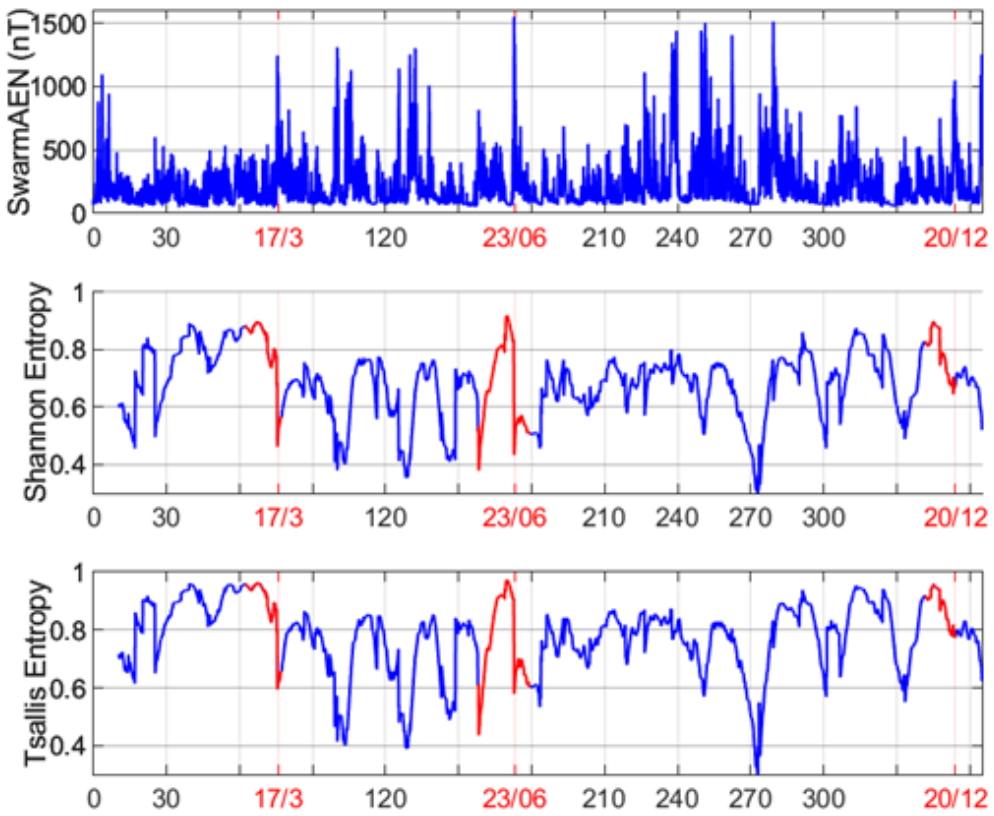


Ground-based AE

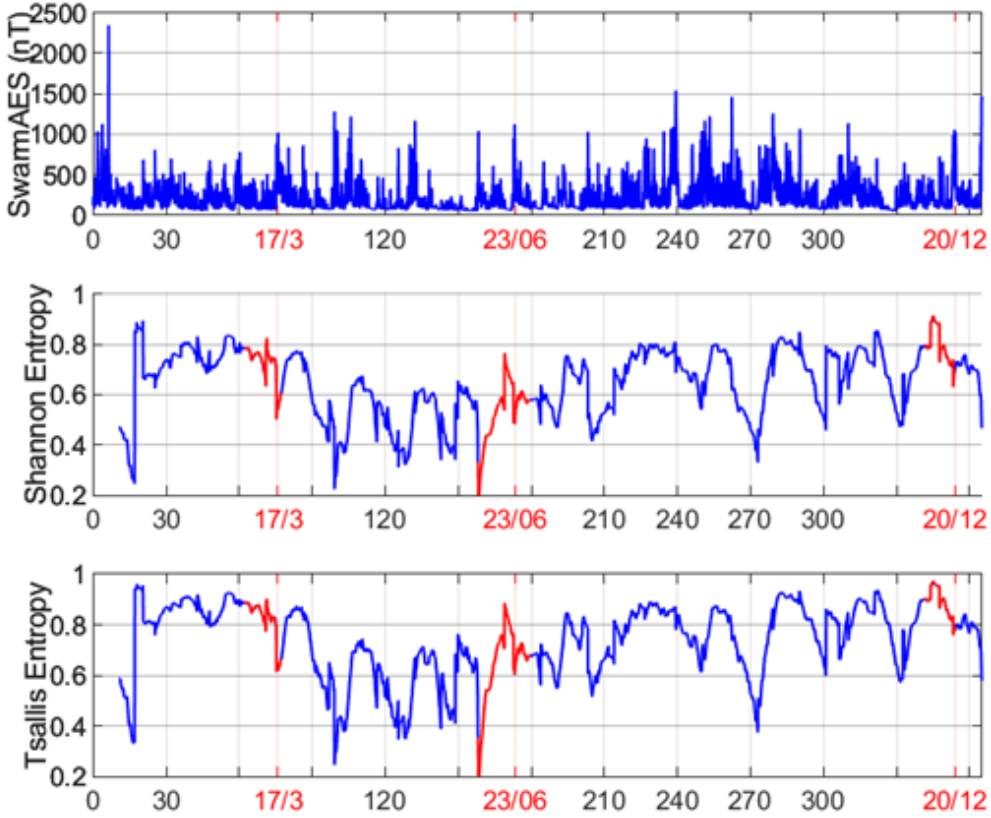


Entropy Analysis of Swarm AE North vs South

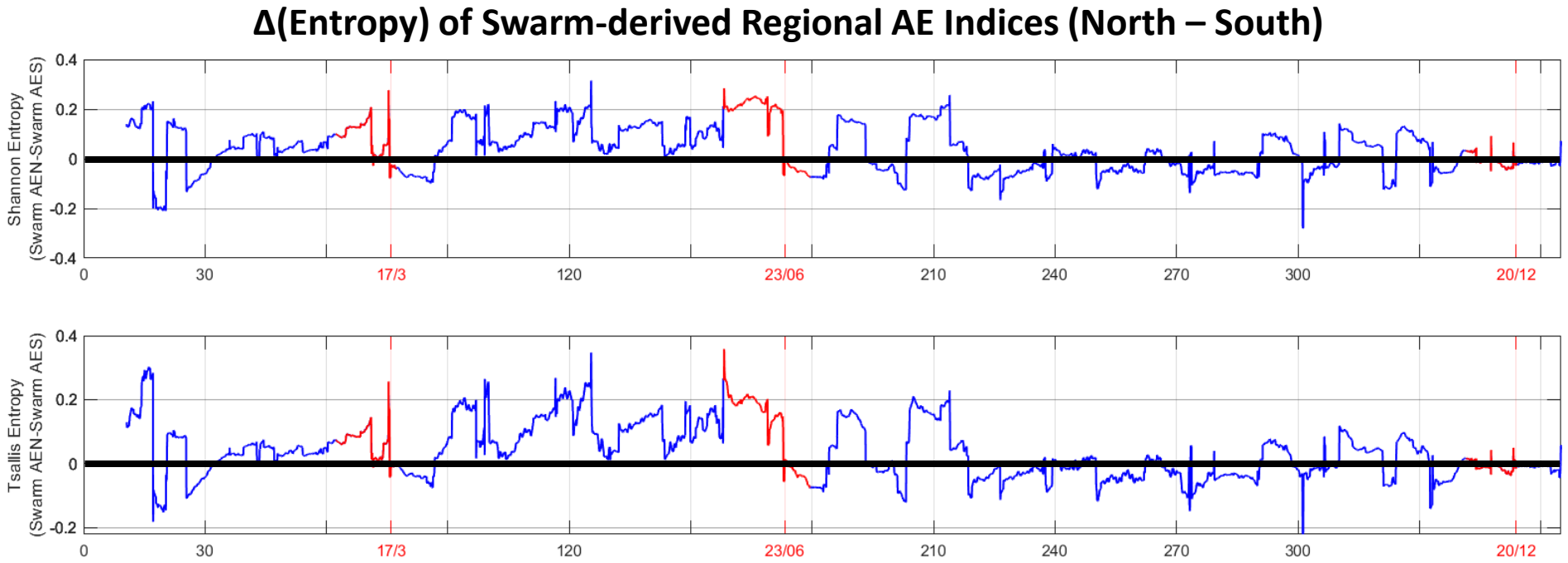
Swarm-derived AE-North



Swarm-derived AE-South



Entropy Analysis of Swarm AE North vs South

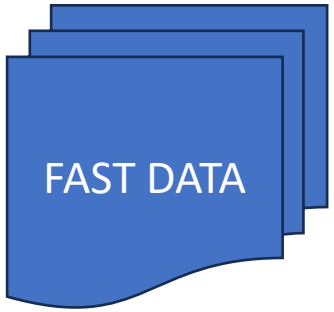


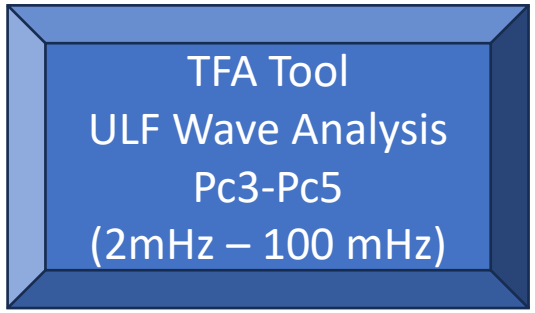
Summary

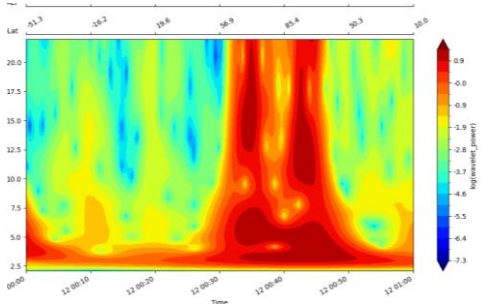
- Regional, Swarm-derived indices can help elucidate the asymmetries of the terrestrial Ionosphere/Magnetosphere and their related phenomena

- Analysis based on Information-Theory tool is another possible avenue of exploration in highlighting these differences.

Swarm-based Radial Diffusion Coefficients D_{LL}







$$D_{LL}^{B} = c \sum_{m} m^2 P_m$$

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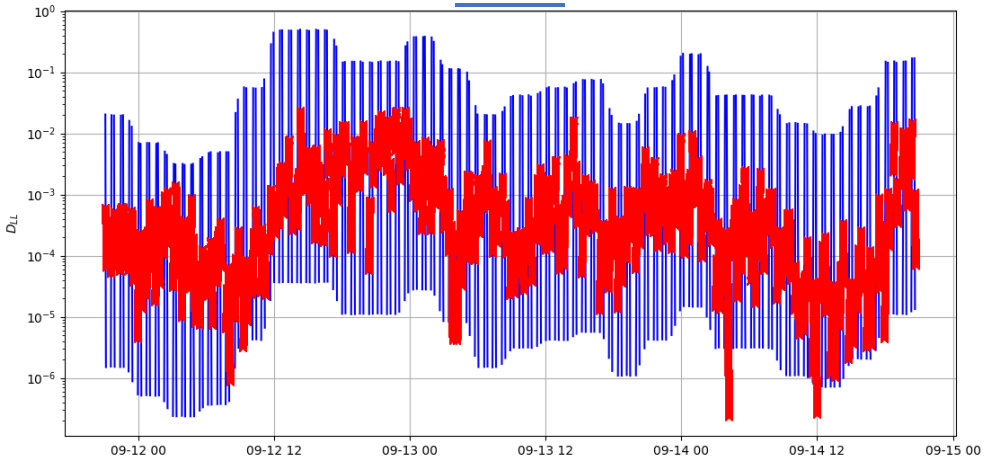

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