Cancellation analysis of current density in solar active region NOAA10019

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ABSTRACT

Solar flares are often associated with changes in the fine magnetic structure of the emitting active region. Such topological modification results in variations of both the scaling properties of the fields’ fluctuations, and the fractal dimension of the associated gradients. The use of cancellation analysis of the current density has been attempted for the identification and quantitative estimation of such changes. The characteristics of the magnetic vector as measured by THEMIS telescope for the active region NOAA10019 have been studied in this paper, suggesting the presence of disrupted current filaments. The variation of the fractal dimension of the current structures, and in particular their smoothing, is discussed in relationship with occurrence of one flare in the active region.

Key words. Active Regions – Solar flares – Photosphere

1. Introduction

Solar magnetism is characterized by the complex dynamo processes occurring in the Sun. Consequently, emergence of dynamic magnetic field from the solar interior within a convectively driven plasma flow originates a number of transient phenomena. At the photospheric level, one of the most evident aspects of magnetic activity is the generation of active regions (ARs), which are regions of more or less extended and concentrated emerging magnetic field. Active regions appear at the photospheric level as bi- or multipolar magnetic structures, which may include the presence of pores and sunspots, one of the most striking phenomena of solar magnetism. Active regions are often associated with eruptive phenomena, such as flares, which in turn may have consequences on the Earth-space environment, therefore being of great strategic importance for space weather. One of the main goals in solar physics is the identification of magnetic signature of the occurrence of flares within ARs. In recent years, cancellation analysis has been used to correlate the topology of solar magnetic fields in active regions to the occurrence of flares (Abramenko et al. 1998; Yurchyshyn et al. 2000, 2012; Sorriso-Valvo et al. 2004, 2015). Such analysis is complicated by the scarce availability of photospheric magnetic vector measurements synchronized with flares, which are still unpredictable events. This paper is a case study of one instance of such synchronization, where cancellation analysis has been performed on AR NOAA10019, confirming the occurrence of topological changes of magnetic structures related to flaring activity.

2. Signed measure and cancellation analysis

Solar active regions are often characterized by scale dependent formation of energetic and localized structures (Abramenko et al. 1998). Structures can be seen as smooth regions of the magnetic field, embedded in a highly fluctuating background. For zero-mean fields, they can be associated to scale dependent, signed fluctuations of the fields. By introducing a signed measure (as opposed to the usual positive defined probability measure), it is possible to characterize the scaling properties of sign oscillations (or sign persistence) of the fields (Ott et al. 1992). Therefore, it is possible to study the presence and the topological characteristics of structures defined in sign. Signed measure has been successfully used to describe photospheric velocity structures (Consolini et al. 1999), and more extensively for the study of current structures in MHD (Sorriso-Valvo et al. 2002; Graham et al. 2005), Hall-MHD (Martin et al. 2013), and Vlasov-Maxwell (De Vita et al. 2014) numerical simulations. Applications to measurements of magnetic vectors in solar active regions have confirmed cancellation analysis as an interesting tool to detect changes in the scaling properties of the fields’ fluctuations, and of the fractal

The signed measure of a zero-mean scalar field \( f(r) \) can be defined on a \( d \)-dimensional set \( Q(L) \) of size \( L \) as follows (Ott et al. 1992). Let \( \{ Q(I) \subset Q(L) \} \) be a partition of \( Q(L) \) in disjoint subsets of size \( I \). Then, for each scale \( I \) and for each disjoint set of boxes \( Q(I) \), the signed measure is

\[
\mu_s(I) = \frac{\int_{Q(l)} df(r)}{\int_{Q(l)} |df(r)|}. \tag{1}
\]

When the size of the subset \( Q(l) \) is large, cancellations between small structures of opposite sign occur within each box, resulting in small contribution to the signed measure. However, as the boxes become smaller and reach the typical size of the structures, each box is more likely to contain a single, sign defined structure, reducing the level of cancellations. The way this happens can be statistically characterized through the “partition function”:

\[
\chi(l) = \sum_{Q(I)} |\mu_s(I)|, \tag{2}
\]

where the sum is extended to all disjoint subsets \( Q(I) \). If the partition function has power-law scaling \( \chi(l) \sim l^{-\kappa} \), the measure is sign singular, and \( \kappa \) is referred to as cancellation exponent. The latter represents a quantitative measure of the cancellation processes. For example, a smooth field will have scale independent, little, or no cancellations, resulting in constant partition function (\( \kappa = 0 \)). On the other hand, for statistical reasons, a completely stochastic process with randomly distributed fluctuations over the whole domain will have cancellations proportional to the square root of the volume, so that the partition function will have a cancellation exponent given by \( \kappa = d/2 \) (Vainshtein et al. 2007). This indicates that cancellations exponents can be used to characterize the scaling properties of the field fluctuations. Furthermore, a simple geometrical argument, based on the separation of the field in correlated (the structures) and uncorrelated (the background field) subsets, establishes a phenomenological relationship between the cancellation exponent and the fractal dimension \( D \) of the typical dissipative structures of the flow, so that (Sorriso-Valvo et al. 2002)

\[
\kappa = (d - D)/2. \tag{3}
\]

It should be pointed out that the use of one single fractal dimension cannot fully capture all the fine details of the typical plasma turbulence processes, which are more likely characterized by multifractal scaling (Muller & Biskamp 2000). Nonetheless, \( D \) still represents a useful indicator of the topological characteristics of the “mean” intermittent structures of the flow.

3. THEMIS data: active region NOAA10019

In this paper we provide an example of application and validity of the cancellation analysis for identifying correlations between topological changes of photospheric magnetic field and occurrence of flares. Toward this goal, the technique was applied to a time series of magnetograms in active region NOAA10019. Observations of this active region were performed between July 3 and July 6, 2002 by exploiting the spectro-polarimetric mode of the ground-based THEMIS telescope,\(^1\) using the photospheric Fe I 630.2 nm spectral line (Briand & Vecchio 2003). The observed active region was located around E39°–S17 on the first day of observation, and reached W08°–S17 on the last day. The active region was therefore located close to the solar center, where perspective effects are reduced. The spatial sampling along the slit was 0.5′′/pixel (the size of the spectrograph entrance slit’s width) and the spectral sampling 22 mA/pixel. The size of field covered by the magnetogram varied from 111×143 to 241×143 pixels. The four Stokes parameters \( I, V, Q, U \) were measured using an exposure time of 300 ms for all wavelengths. The field of view covered by the entrance slits of the spectrograph was 1′. The so-called \( 2 \times 1 \) THEMIS spectro-polarimetric configuration was used: the two beams with orthogonal polarization exiting the analyzer were directed into one single camera. Beam inversion was performed for the linear polarization \( Q \): the top part of the camera received sequentially \( I + Q, I - Q, I + U, \) and \( I - V \), while the bottom part recorded \( I - Q, I + Q, I - U, I + V \). This observing strategy allowed to reduce the impact of the seeing-induced cross-talk between Stokes parameters, due to the time delay between two successive polarimetric measurements (1 s) (Skumanich et al. 1997). The final error of the measurements is \( S/I_c = 10^{-3} \), where \( S \) stands for one of the \( O, U, \) or \( V \) Stokes parameters and \( I_c \) stands for the intensity of the continuum in quiet Sun regions. To derive the magnetic field strength, inclination, and azimuth, the SIR (Stokes Inversion based on Response function), implemented by choosing a one component atmosphere, was used (Ruiz Cobo & del Toro Iniesta 1992). The 180°-ambiguity of the azimuth \( \phi \) was solved by exploiting the property that the penumbral magnetic field is planar and its azimuth changes with continuity. Therefore, following likelihood arguments, the azimuth was fixed by continuity, starting from areas where it is well defined. Magnetic fields were then expressed in the local reference frame coordinates in which the \( z \) component is perpendicular to the solar surface at the point of observation.

In this work, a time series of 15 maps of the vector magnetic field in NOAA10019 was used. The time series starts on July 3 at 08:06 (in Universal Time, UT) and ends on July 6 at 11:39 UT. Dataset for each of the four days includes six, three, two, and four snapshots of the active region, respectively. Due to the absence of an image stabilization system, the THEMIS magnetograms of the target region of the slit were subject to image distortion, caused by the seeing variations. This typically produces artificial image shifting along the slit that results in a stripped pattern on the images. The typical size of such pattern is the slit width, i.e. one pixel in the magnetograms. This could affect the calculation of the current density. In order to correct for this distortion, we used a 1D non-linear filter on each row of the magnetograms (i.e. transverse with respect to the slit direction). The filter is conceived to locally identify and eliminate (through interpolation) the field fluctuations of a given width (Naudy & Dreyer 1968). We have checked that the filter width of one pixel was enough to remove from the magnetograms the stripped pattern due to seeing. Figure 1 shows an example of comparison between the original (a) and filtered, (b) data. As can be seen, the vertical stripes observed in the original data are removed in the filtered magnetograms. Figure 2 shows four examples of the active region field of view, namely the intensity image at Fe I 630.2 nm line center, on four different days of observation.

\(^1\) http://www.themis.iac.es
The sunspot umbral and penumbral boundaries are marked by the contour lines of the Fe I, set at about 90% and at 70% of the quiet sun intensity, respectively. In the legend of Figure 2, the day, hour (in Universal Time) are indicated, along with a letter identifying the snapshot. The boxes \( Q \), \( L_x \), \( L_y \) dimensions \( L_x \approx 80 \) and \( L_y \approx 50 \) pixels (corresponding approximately to \( 30 \times 20 \) Mm) used for the estimation of the cancellation exponents (see Sect. 4 for the description) are shown for each snapshot (black lines). In Figures 3–5, we display four snapshots of the maps of each of the three filtered magnetic field components \( B_x \), \( B_y \), and \( B_z \), for the AR NOAA10019. Again, each snapshot refers to a different day of the observation, as indicated in the legend of Figure 2. Finally, using the two-dimensional measurements of the photospheric vector magnetic field \( \mathbf{B}(x, y) \) on the solar surface, it was possible to estimate the vertical component \( z \) of the current density \( J_z(x, y) = (c/4\pi)(\mathbf{\nabla} \times \mathbf{B})_z \), where \( (x, y) \) are the Cartesian coordinates on the surface of the Sun. This was done by computing, for each pixel of area \( s \), the line integral of the vertical component of the magnetic field \( B_z(x, y) \) over a closed contour \( G \) (Yurchyshyn et al. 2000). \( 4\pi J_z/c = (\mathbf{\nabla} \times \mathbf{B})_z = \int_G \mathbf{B}_z \cdot d\mathbf{r} \). Integration along each side of \( G \) was performed using Simpson’s rule. Figure 6 shows the vertical current density \( J_z \) for the same snapshots as in Figure 2.
4. Cancellation analysis of the current density

Once the vertical current density has been calculated, cancellation analysis was performed for each filtered snapshot of the time series. In order to mitigate noise, portions of the images with low current were eliminated by using reduced boxes $Q(L_x, L_y)$ of minor size varying from $L_x = 50$ to $L_y = 70$ pixels, which track the central part of the active region. Examples of these boxes are depicted in Figures 2–6. Additionally, in order to get a statistically more robust estimate of the cancellation

Fig. 3. Maps of filtered horizontal magnetic field component $B_x$ for the AR NOAA10019 as measured on July 3 (a), 4 (b), 5 (c), and 6 (d), 2002. Time of each snapshot is indicated in the legend of Figure 2. For each snapshot, boxes indicate the portion of image used for the analysis.

Fig. 4. Maps of filtered horizontal magnetic field $B_y$ for the AR NOAA10019 as measured on July 3 (a), 4 (b), 5 (c), and 6 (d), 2002. Time of each snapshot is indicated in the legend of Figure 2. For each snapshot, boxes indicate the portion of image used for the analysis.
of three pixels in one or both directions in the $(x-y)$ plane. This provided, for each snapshot, $N$ subsamples ($N$ varying from 18 to 24, depending on each snapshot’s size). The signed
measure was then estimated for each of the \( N \) sub-sample \( Q(L) \) as

\[
\mu_x(l) = \frac{\int_{Q(l)} j_z(x,y) \, dx \, dy}{\int_{Q(l)} j_z(x,y) \, dx \, dy}.
\]

For each snapshot and for each scale, the average and standard deviation of the \( N \) “running” partition functions were then evaluated. The averaged partition functions were finally used for the analysis, and the standard deviation was used as the corresponding uncertainty (Yurchyshyn et al. 2000). Since the power-law fitting range is limited, the robustness of the cancellation exponent was further tested by allowing the fitting range to shift, expand, or reduce by one or two points in the partition function. The range spanned by the resulting fitting parameter also provides a possible uncertainty on the estimate of the cancellation exponent.

Examples of the partition functions, as obtained from the four photospheric current density snapshots shown in Figure 6, are plotted in Figure 7, together with a power-law fit \( \chi(l) = A(l/L)^{-\kappa} \) is superimposed on each partition function. In the bottom section of each panel, the partition function is compensated by multiplying for the fitted power law, so that the actual power-law range is visible as horizontal line.

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\[
\chi(l) = \frac{\int_{Q(l)} j_z(x,y) \, dx \, dy}{\int_{Q(l)} j_z(x,y) \, dx \, dy}.
\]

\[
\kappa = 0.48 \pm 0.03
\]

\[
\kappa = 0.46 \pm 0.03
\]

\[
\kappa = 0.45 \pm 0.02
\]

\[
\kappa = 0.47 \pm 0.01
\]

Fig. 7. The averaged partition functions for the four snapshots shown in Figure 6. A power-law fit \( \chi(l) = A(l/L)^{-\kappa} \) is superimposed on each partition function. In the bottom section of each panel, the partition function is compensated by multiplying for the fitted power law, so that the actual power-law range is visible as horizontal line.

5. Time evolution and flaring activity

X-ray observation of the active region NOAA10019 showed periods of low and enhanced flaring activity. During the observations, the active region produced eight C-class flares whose list, as extracted from GOES X-ray flux database, is given in Table 1. Figure 8 shows the peak X-ray flux for the flares listed in the table (vertical bars, right y-axis), measured in active region NOAA10019 during the time of observation. The time axis is set so that \( t = 0 \) at 00:00 UT on July 3, 2002, the first day of observation. In the same plot, we display the time evolution of the fractal dimension of current structures \( D \) (symbols
tation functions, reproduced in bottom panel of Figure 9 for the
the jump is also significant with respect to the possible error
observation, similar to previous results ( Abramenko et al.
fractal dimension remained roughly steady, with
iciation of the cancellation exponent due to any reasonable shift
y parameter $j$
(3). The error bars are the
vertical axis). The vertical lines show the X-ray class of flares (right
vertical axis). The gray area indicates the range of variability due to
modification of the fitting range.

and dashed line, left y-axis), as calculated from the fitting
parameter $x$ through the relation (3). The error bars are the
standard deviation of the exponents over the different sub-sets
of each snapshot, while the gray shaded area is the error associ-
atied with the choice of the fitting range, i.e. the range of var-
iation of the cancellation exponent due to any reasonable shift
of fitting range. During the first part of the observation, the
fractal dimension remained roughly steady, with $D \approx 1$, which
is the value expected in the presence of one-dimensional cur-
etnal filaments. However, a sudden increase from $D(t_1) = 1.10$
to about $D(t_2) = 1.38$ is clearly present near the end of the
observation, between $t_1 = 79.33$ h, or 07:20 UT, and
$t_2 = 80.33$ h, or 08:20 UT, both on July 6. This increase occurs
corresponding to a C-class flare (with flux above $10^{-6}$ W/m$^2$)
recorded at $t_F = 81.45$ h or 09:27 UT on the same day. This
observation, similar to previous results (Abramenko et al.
Yurchyshyn et al. 1998; Yurchyshyn et al. 2000; Sorriso-Valvo et al.
suggests that the magnetic field structures could be smoothed out
by dissipative effects which anticipate the flare explosion.
The sharp jump observed in the fractal dimension was
$\Delta D_{12} = |D(t_2) - D(t_1)| = 0.28$. This value represents a sig-
nificant 25% variation relative to the mean dimension
$D = 1.13$, and a nontrivial factor 10 in units of standard devi-
ation $\sigma_D = 0.03$. Both the average and the standard deviation
were computed over the whole observation time. Furthermore,
the jump is also significant with respect to the possible error
deriving from the shift of the fitting range, evidenced in gray.
This is also clear from the direct observation of the two parti-
tion functions, reproduced in bottom panel of Figure 9 for the
two snapshots at $t_1$ and $t_2$. The corresponding current maps
are reported in the top panels of the same figure.

In order to test for reliability of the observed change of
fractal dimension and for the validity of the non-linear filter,
we compared the filtered data with the original data. Furtber-
more, we tested the robustness of the results with respect to
stronger seeing image degradation by artificially reducing the
data resolution. To evaluate the effect of image distortion on
the slope of the sign-singularity spectrum, all components of
each magnetic field vector, within each original magnetogram,
have been smoothed over $3 \times 3$ or $5 \times 5$ pixels, before recalcu-
ating the current density and performing the cancellation anal-
ysis (Yurchyshyn et al. 2000). In Figure 10 we show one
example of the scaling behavior of the partition function $\chi(l)$
for the four cases, namely: the original data (circles), the fil-
tered data (squares), the $3 \times 3$ pixels smoothed data (dia-
monds), and the $5 \times 5$ pixels smoothed data (triangles). The
example shown here refers to the snapshot taken at 17:20
UT on July 3, 2002. For the smoothed fields, the small scale
saturation of the partition functions was observed to cover an
increasingly large range of scales, as the smoothing area
increases. This is a trivial consequence of the field becoming
smoother, so that sign singularities are no longer present
(Yurchyshyn et al. 2000). Note that the partition function of
the unsmoothed field does not saturate to unity, probably
because elementary flux tube is smaller than the instrumental
resolution (Sorriso-Valvo et al. 2002). Compared to the origi-
nal data case, in the intermediate region of scales the cancella-
tion exponent is found to slightly decrease with the size of the
smoothing area, as indicated in the legend. The non-linear fil-
tered data also show a decrease in the dimension. However,
the relative variation of the scaling exponent in these cases is
always less than 10%. Figure 11 shows the time dependence of
dimensions $D$ for the four series. While the general effect
of the filtering and smoothing was the evident increase in frac-
tal dimension, the main features of the time dependence, and in
particular the sharp jump observed on the last day, were not
lost, resulting in a robust 25% increase of $D$ in all cases. More
quantitatively, the mean increase of the dimension $\Delta D_n$
due to the filtering (subscript $n$ = filter) and to the $n \times n$
smoothing (subscript $n$ = smooth) over the whole
time window, obtaining
$\Delta D_{\text{filter}} = 0.04$, $\Delta D_{\text{smooth}} = 0.04$, and
$\Delta D_{\text{smooth}} = 0.09$. Therefore, the observed jump is always signifi-
cantly larger than the filtering and smoothing effect,
$\Delta D_{12} > \Delta D_n$, confirming the goodness of the observation.

Therefore, since the cancellation exponent is robust with
respect to the filter or degree of smoothing, we can conclude
that the variation of fractal dimension observed for the flare
on July 6, 2002 is nontrivial, and does not significantly depend
on the measurement resolution.

Incidentally, it is worth noticing that a few similar flares
have occurred during the time span of our observation.
However, no clear changes in the cancellation exponent were

<table>
<thead>
<tr>
<th>t (days)</th>
<th>0</th>
<th>12</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (W/m²)</td>
<td>10⁴</td>
<td>10³</td>
<td>10²</td>
<td>10¹</td>
<td>10⁰</td>
<td>10⁻¹</td>
<td>10⁻²</td>
<td>10⁻³</td>
<td>10⁻⁴</td>
</tr>
<tr>
<td>NOAA10019</td>
<td>M</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

Fig. 8. Fractal dimension of the photospheric current density structures $D$ versus time (symbols connected by solid line, left
vertical axis). The vertical lines show the X-ray class of flares (right
y-axis). The gray area indicates the range of variability due to
modification of the fitting range.

Table 1. Row 1: the start time of flares occurring since 00:00 UT on 3 July 2002 and for the whole observation period. Row 2: the class of flares
(full disk emission from GOES X-ray database).

<table>
<thead>
<tr>
<th>(h)</th>
<th>7.95</th>
<th>8.80</th>
<th>11.72</th>
<th>28.58</th>
<th>40.35</th>
<th>41.68</th>
<th>63.83</th>
<th>81.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>C3.4</td>
<td>C1.1</td>
<td>C7.3</td>
<td>C4.5</td>
<td>C3.4</td>
<td>C2.4</td>
<td>C6.3</td>
<td>C6.0</td>
</tr>
</tbody>
</table>
present in these cases. While this can probably be attributed to the poor temporal sampling of the magnetograms, there is at least one case (the C-class flare around $t = 64 \text{ h}$) for which the cancellation exponent was estimated only a few hours after the flare, and for which no particular deviation from the mean value is observed. However, with the data at hand it is not possible to assess whether this was due to sampling time.

Fig. 9. Top panels: the vertical current $J_z$ before ($t = t_1$) and after ($t = t_2$) the sudden fractal dimension increase. Bottom panel: the partition functions of the above maps, with the power-law fits and the corresponding cancellation exponents.

Fig. 10. The partition functions $\chi(l)$ versus the scale ($l/L$) for the current density $J_z$ calculated for the original data (circles), for the filtered data (squares), and for the smoothed ($3 \times 3$, diamonds, and $5 \times 5$, triangles) data. This example refers to the snapshot taken on July 3, 2002 at 17:20 UT. Note that the first point at the smallest scale is identically 1 because of the normalization. Cancellation exponents $\kappa$ obtained through the power-law fit for the four cases are indicated in the legend. The error bar is $\pm 0.03$ for all cases.

Fig. 11. Fractal dimension versus time for the four datasets, obtained using the original, filtered, and smoothed data (see legend). The vertical lines show the X-ray class of flares (right y-axis).
6. Conclusions

In this paper we used the cancellation analysis technique to investigate the topological properties of the typical current structures in the solar active region NOAA10019. To this purpose, we calculated the vertical component of the current density from magnetic field data acquired by the spectro-polarimetric mode of the ground-based THEMIS telescope, using the photospheric Fe I 630.2 nm spectral line. In particular, we focused on the temporal evolution of the current structures in response to photospheric magnetic field dynamics by studying the variation of the scaling index describing the cancellations of positive and negative current density, which can be related to the typical fractal dimension of the current patterns. In the considered active region, and far from large flares, the values of the cancellation exponent are consistent with the presence of sign-persistent current structures. Moreover, we found that the dynamics of the magnetic field fluctuations and mean vertical current describes quite well the transition of the AR into the flare activity stage. Indeed, during the first days, the fractal dimension showed almost constant values around $D = 1$, compatible with presence of one-dimensional current filaments. On the other hand, with the occurrence of a C-class flare a sudden significant increase, of about 25% relative to the mean fractal dimension, is observed indicating that the current structures are affected by the dissipative effects at work before the flare. The abrupt variation of the fractal dimension is plausibly the signature of dissipation due to reconnection events, which are believed to originate flares. We verified that our results are stable with respect to the application of a nonlinear filter, used to remove the seeing effects from the images. Moreover, robustness of the results was tested by adding an artificial reduction of the spatial resolution, which mimics a stronger seeing-induced image degradation of the magnetic field components. The stability of our results is related to the fact that the spatial scales affected by the seeing, of the order of 1 Mm, are far from the typical size of the current structures, as identified by the bottom of the fitting range (around 3.5 Mm). For both tests, a general increase in fractal dimension is observed, with relative variation below 10%. This value is well below the sharp 25% jump observed at the C-class flare, indicating that the variation of fractal dimension is nontrivial, and does not significantly depend on the measurement resolution and data quality.

The high-quality, space-based data available today (thanks to e.g. Solar Dynamics Observatory [SDO] or Hinode instrumentation) allow the study of extremely fine details of the magnetic complexity, which can help understand better the physical processes occurring in flaring active regions. Nevertheless, the results presented in this paper, corroborated by the robustness tests, are particularly interesting precisely because the analyzed data are not of high quality, in this case due to seeing conditions and to the lack of compensating technique at the time of the measurements. Indeed, the robustness of the cancellation analysis, even when low quality data are used, suggests that this kind of approach can be used for the analysis of older dataset. This will allow to enrich the statistics of the flare-related topological changes, fundamental for the application of this technique for the purpose of space weather monitoring.

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