Spatio-Temporal Co-occurrence Analyses

for Integrating Solar Active Region Data

from Multiple Reporting Modules

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Solar active regions are frequently associated with other solar activities such as Solar Flare, Coronal Mass Ejection (CME).
National Oceanic and Atmospheric Administration (NOAA)

- NOAA Active Region Number (NOAA AR#)

Spaceweather HMI Active Region Patch (SHARP)

- HMI Active Region Patch Number (HARPNUM)

Spatial Possibilistic Clustering Algorithm (SPoCA)

- SPoCA AR Identifier (SPoCA AR)
## Various Reporting Modules detect Active Regions using their own techniques

<table>
<thead>
<tr>
<th></th>
<th>NOAA</th>
<th>SHARPs</th>
<th>SPoCA</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
<td>24 hours</td>
<td>Every 12 minutes</td>
<td>Around every 4 hours</td>
</tr>
<tr>
<td>Centroid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHARPs</td>
<td></td>
<td><a href="image">Centroid</a></td>
<td></td>
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<tr>
<td>SPoCA</td>
<td></td>
<td></td>
<td><a href="image">Centroid</a></td>
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</table>
Integration Methodology

Spatio-temporal Co-occurrences
Spatio-temporal Co-occurrences

Temporal Coexistence

Spatial Co-locations
Temporal Coexistence

For two time intervals T1 and T2, they have intersected time interval.
For two time intervals T1 and T2, they have intersected time interval.
### Different Reporting Cadence for Active Region Record

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<tr>
<td>Duration</td>
<td>24 hours</td>
<td>Every 12 minutes</td>
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Extrapolation Process for NOAA AR and SPoCA AR in order to match the cadence of SHARP records
Differential Rotation of the Sun

\[ \omega = A + B \sin^2(\varphi) + C \sin^4(\varphi) \]

\( \omega \) represent angular velocity of the sun

\( \varphi \) represent latitude

\( A, B, C \) are approximated constants
Extrapolate the approximate locations of NOAA AR 12 hours backwards and forwards with 12-minute cadence

\[ \Delta T \]  \text{Time difference between Original NOAA AR time and HARP segment time point}

\( \omega \)  \text{Velocity of the sun}

\( \lambda \)  \text{Longitude}

\( \varphi \)  \text{Latitude}

\( \Delta \lambda \)  \text{Extrapolated NOAA AR at} \ t_{\text{EX}}
Extrapolate the approximate locations of SPoCA Bounding Box between start time and end time with 12-minute cadence.
Spatial Co-locations

Spatial co-location is an abstract relationship
Spatial co-location is an abstract relationship

Classroom

We are co-located

Classroom

We are co-located
Spatial Co-locations

For two spatial objects $O_1$ and $O_2$, they have spatial intersection relationship.
Topological spatial relationship is invariant to the space transformation
Some Topological relationship example between different type of spatial objects
Different Spatial Object types represent Active Regions

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<th>NOAA</th>
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<tr>
<td>Centroid</td>
<td>Bitmap in non-minimum Bounding Box</td>
<td>Chaincode and Bounding Box</td>
</tr>
</tbody>
</table>
Spatial intersection between NOAA AR and SHARP, SPoCA AR and SHARP

Point within Bounding Box

Bounding Box overlaps Bounding Box
Spatio-temporal Co-occurrence

Temporal Coexisting Pairs Candidates

Colocation Pairs

Spatio-temporal Co-occurrence Pairs

NOAA AR1

AR1

SPoCA AR1

SHARP1

SHARP2

SHARP3

SHARP1

SHARP1

SHARP2

SHARP3

SPoCA
Spatio-temporal co-occurrence

SHARP-to-NOAA AR, SHARP-to-SPoCA AR

SHARP Bounding Box

NOAA AR Centroid

Time

t_{i-1} \quad t_{i} \quad t_{i+1}

SPoCA AR Bounding Box

SHARP Bounding Box

Time

t_{i} \quad t_{i+1}
Data Source
● **NOAA AR**
   Obtained from NOAA Solar Region Summary (SRS)

● **SHARP series**
   Obtained from Joint Science Operations Center (JSOC)

● **SPoCA ARs**
   Obtained from the Heliophysics Event Knowledge Base (HEK)

For all three data resources, the time range is between **May 2010** and **September 2018**
Between **May 2010** and **September 2018**

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<tr>
<td><strong>NOAA AR Trajectories</strong></td>
<td><strong>1,661</strong></td>
<td><strong>4,075</strong></td>
</tr>
<tr>
<td><strong>Individual Daily Reports</strong></td>
<td><strong>15,742</strong></td>
<td><strong>2,613,321</strong></td>
</tr>
<tr>
<td><strong>SHARPs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Individual Reports</strong></td>
<td><strong>14,375</strong></td>
<td><strong>100,030</strong></td>
</tr>
<tr>
<td><strong>SPoCA ARs</strong></td>
<td></td>
<td></td>
</tr>
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</table>

For **4075 SHARPs**, we annotate corresponding **NOAA AR number** and **SPoCA AR id** to each **SHARP Individual Reports**.
Evaluation and Analysis
Explore the daily movement pattern of NOAA ARs

Updates NOAA AR events and SHARP-to-NOAA AR association
Divide the average latitude of NOAA ARs into four groups

0 to +/- 10 degree

 +/- 10 degree to +/- 20 degree

 +/- 20 degree to +/- 30 degree

 +/- 30 degree to +/- 90 degree
Daily Longitudinal displacement of NOAA ARs

- Longitude move between +13 to +14 degree towards west-limb
- Some outlier moved towards east, not change location, or moved over 22 degree
Daily Latitudinal displacement of NOAA ARs

- Latitude usually stay the same
- Some outlier changed over 8 degrees within a day
For these outliers, we examine their trajectories on full disk AIA and HMI images and manually update their location.
Location **Outliers for**

**NOAA AR 11490**

**NOAA AR 11489**

**NOAA AR 11492**
We use updated NOAA AR location, update the SHARPs-to-NOAA ARs association
Discrepancy Analysis with JSOC Data
We compare SHARP-to-NOAA AR pair provided by JSOC to our co-occurrence association pairs.

For **4075** SHARP-to-NOAA AR associations:

**3934** of 4075 are in accordance with our results.

**141** of 4075 do not fully matched.
For these **141** SHARP-to-NOAA AR Association Discrepancies

<table>
<thead>
<tr>
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<th>JSOC Association</th>
<th>Co-Occurrence Association</th>
</tr>
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<tbody>
<tr>
<td><strong>NOAA AR in JSOC association</strong></td>
<td><img src="image1" alt="SHARP1" /></td>
<td><img src="image2" alt="NOAA AR1" /></td>
</tr>
<tr>
<td><strong>NOAA AR in Co-occurrence association</strong></td>
<td><img src="image4" alt="SHARP2" /></td>
<td><img src="image3" alt="Cross" /></td>
</tr>
<tr>
<td><strong>Combination Above</strong></td>
<td><img src="image6" alt="SHARP3" /></td>
<td><img src="image7" alt="NOAA AR3" /> <img src="image8" alt="NOAA AR4" /></td>
</tr>
</tbody>
</table>
SHARP and NOAA AR do not temporally coexist

Lifespan
SHARP 1844
2012-07-06 17:36
2012-07-08 20:00

Lifespan
NOAA AR 11522
2012-07-13 2012-07-18

Time Interval Disjoint

SHARP 1844 and NOAA AR 11522

2012-07-06 2012-07-08
17:36 20:00
SHARP 1844 and NOAA AR 11522
NOAA AR in JSOC association, but not in Co-occurrence association

SHARP and NOAA AR coexist, but not colocated

SHARP 1998 and NOAA AR 11557
SHARP 1998 and NOAA AR 11557
NOAA AR not in JSOC association, but in our co-occurrence association

SHARP 2511 and NOAA AR 11688
SHARP 2511 and NOAA AR 11688
To quantify the strength of the co-occurrence between SHARP-NOAA AR

\[
\text{cof}(\text{NAR, SHARP}) = \frac{\text{Length of co-occurrence time interval between NOAA-AR and SHARP}}{\text{Length of co-existence time interval between NOAA-AR and SHARP}}
\]

\[
\text{Cof(NOAA,SHARP)} = \frac{\text{Co-Occurrence: 2 hours}}{\text{Coexistence: 4 hours}} = 0.5
\]
To quantify the strength of the co-occurrence between SHARP-NOAA AR

\[ \mu_{min\text{-}dist}(NOAA-AR, SHARP) = \frac{1}{N} \sum_{t_i} \text{mindist}(NOAA-AR.g_i, SHARP.g_i) \]

\[ \mu_{min\text{-}distance}(NOAA-AR,SHARP) = \frac{d_1 = 0 + d_2 = 0 + d_3 = 5 + d_4 = 7}{4} = 3 \]
Conclusion
We provide a detailed spatiotemporal integration of solar active regions from three reporting modules.

We discovered and updated the erroneous locations of NOAA ARs.

Using updated NOAA ARs, we updated SHARP-to-NOAA AR associations.
Thank you