How MAG4 Improves Space Weather Forecasting

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Dangerous space weather is driven by solar flares and Coronal Mass Ejection (CMEs). Forecasting flares and CMEs is the first step to forecasting either dangerous space weather or All Clear.

### Flare

<table>
<thead>
<tr>
<th>Electromagnetic Radiation (Immediate: <strong>Time 8 Min</strong>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-EUV, Ultra-Violet, Visible Light, Radio Waves</td>
</tr>
</tbody>
</table>

### Solar Energetic Particle Event (SPE or SEP Event)

<table>
<thead>
<tr>
<th>High Energy Particles (Delayed &lt; Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic Nuclei</td>
</tr>
</tbody>
</table>

### CME

<table>
<thead>
<tr>
<th>Enhanced Solar Wind (Delayed ~3 Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions and Electrons</td>
</tr>
</tbody>
</table>

### Space Weather

#### Immediate Effects

- **Increased D-Layer Ionization**
- **Geomagnetic Disturbance**
- **Anomalous Radio Propagation**
- **Outburst of Radio Noise**
- **Radio Interference**

#### Delayed Effects

- **Enhanced Energetic Particles**
  - Manned Flight Radiation Hazard (I)
  - Spacecraft Radiation Hazard (C3)
- **Ionization**
  - Anomalous Radio Propagation
  - Radar Clutter
- **Geomagnetic Storm**
  - Ionospheric Storm and Induced Currents
  - Radio Effects
  - Satellite Drag
  - Aurora
What is MAG4?

- MAG4 (Magnetogram Forecast), developed originally for NASA/SRAG (Space Radiation Analysis Group), is an automated program that analyzes magnetograms from the HMI (Helioseismic and Magnetic Imager) instrument on NASA SDO (Solar Dynamics Observatory), and automatically converts the rate (or probability) of major flares (M- and X-class), Coronal Mass Ejections (CMEs), and Solar Energetic Particle Events.

- MAG4 does not forecast a flare will occur at 12:02 tomorrow, but the probability of one occurring tomorrow.

- GONG (Global Oscillations Network Group) magnetograms, can be used instead as a backup but at a lower forecast accuracy.

- Present cadence of new forecasts: **96 minutes**. Vector magnetogram actual cadence: **12 minutes**.
MAG4 Background

- Flares and CMEs are known to be drivers of the most severe space weather
- Flares and CMEs typically originate in active regions (aka sunspots)
- Flares and CMEs are examples of exceptionally large explosive releases of magnetic energy stored in the corona
- While the amount of free energy cannot be measured directly, free-energy proxies can be measured
- Event rates have been shown to be correlated with values of free-energy proxies
Magnetic Free Energy

Is it Magnetic Free (title) or Free Magnetic as below?

Contours Vertical Magnetic Field
Arrows Transverse Magnetic Field

Currents $\sim 10^{12}$ Amps

Less

More

Twist

Size

Free Magnetic Energy
R2O Timeline of MAG4

• **1973** The MSFC (Marshall Space Flight Center) Vector Magnetograph was made to support Skylab.

• **2000-present** MSFC analyzed vector magnetograms to study CME correlation with free-energy proxy.

• **2007-12** Co-I in a Multidisciplinary University Research Initiative/Neutral Atmosphere Density Interdisciplinary Research

• **2008** Partnered with SRAG (Space Radiation Analysis Group) and won an R20 NASA/Technical Excellence Initiative grant: Began building a database that grew to ~40,000 magnetograms of ~1,300 active region, covering years 1996-2004 with event catalog from SOHO/MDI (Solar and Heliospheric Observatory/Michelson Doppler Imager) observations.

• **2010-present** NASA’s HEOMD (Human Exploration and Operations Mission Directorate) support.

• **2010** SDO is launched began transitioning from MDI to HMI line-of-sight magnetograms.

• **2011** MAG4 installed at SRAG a NRT (Near-Real-Time) forecasting tool, and SRAG began pre-operations testing.

• **2012** Provided NOAA web access to MAG4 NRT forecasts.

• **2013** Improve MAG4 so that it can use a combination of free-energy proxy and previous flare activity.

• **2013** Transition to HMI line-of-sight to vector magnetograms.
Flowchart MAG4 Automated Processes

Download HMI Magnetogram

Identify Active Regions

Calculates Free-Energy Proxy

Predicted Event Rate

Make Forecasts

MAG4 is completely automated, from downloading magnetograms to outputting forecast products.
Process 1: Identifying Active Regions

- Magnetograms are spatial maps of the magnetic field strengths.
- They come in two basic types:
  - line-of-sight (right)
  - vector magnetograms
- Free-energy proxies can be measured for Active Regions (areas with sunspots) from either type of magnetogram.
- Line-of-sight magnetograms suffer reduced accuracy further from disk center.

Introduce Magnetogram, indentify ARs.
Process 2: Calculating the Free-Energy Proxy

- Where the transverse gradient of the vertical (or line-of-sight) magnetic field is large, there is more free-energy stored in the magnetic field.
- For each Active Region: The integral of the gradient along the neutral line is the free-energy proxy.
Process 3: Converting Free-Energy Proxy to Predicted Event Rates

These empirical forecast curves are used to convert our free-energy proxy into predicted event rates. Curves are derived from a sample of 40,000 magnetograms, from 1300 active regions observed between 1996-2004.
### Multiplicative uncertainty example

<table>
<thead>
<tr>
<th>Rate (Events/day)</th>
<th>1 sigma</th>
<th>Probability (66% Confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.01-0.05</td>
<td>0.7-5%</td>
</tr>
<tr>
<td>0.7</td>
<td>0.3-1.9</td>
<td>20-80%</td>
</tr>
</tbody>
</table>

For a Multiplicative Uncertainty of 2.7x

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**MAG4 Forecast**

<table>
<thead>
<tr>
<th># AR#</th>
<th>WLDSGN Lng Lat (deg)</th>
<th>24 Hour Event Rate</th>
<th>Disk Forecast Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 11428</td>
<td>9  -21 -17</td>
<td>0.020 0.020 0.009 0.002 0.003</td>
<td>2.7x 2.1x 2.2x 3.0x 2.4x</td>
</tr>
<tr>
<td>5 11429</td>
<td>65 -41 17</td>
<td>0.700 0.400 0.200 0.100 0.080</td>
<td>44!</td>
</tr>
<tr>
<td>6 11430</td>
<td>11 -25 20</td>
<td>0.020 0.030 0.010 0.004 0.005</td>
<td>32!</td>
</tr>
<tr>
<td>1 11431</td>
<td>1  36 -27</td>
<td>0.000 0.001 0.001 0.000 0.000</td>
<td>45!</td>
</tr>
</tbody>
</table>

**Multiplicative Uncertainties**
- 2.7x
- 2.1x
- 2.2x
- 3.0x
- 2.4x

**Disk All-Clear Forecast Probabilities**
- 50.00% 70.00% 80.00% 90.00% 92.00%

**Uncertainties**
- 40.00% 20.00% 10.00% 10.00% 7.00%
Comparison of Safe and Not Safe Days

June 26, 2013
C1, C1.5 flares

March 7, 2012
X5.4, X1.3, C1.6
CME 2684, 1825 km/sec,
Solar Energetic Proton Event reaches
6530 particle flux unit >10MeV
The Free-Energy Proxy evolves on time periods of days, and the forecast is on those time scales.
Operation of MAG4
1. Recent Flare History (In Progress)

Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future.
Improving the Forecasts:

2. Vector Magnetograms (In Progress)

- MAG4 presently uses SDO/HMI line-of-sight magnetograms
- Near-real-time Ambiguity-Resolved SDO/HMI vector-magnetograms have recently become available
- We are transitioning to using these new data from SDO
- Implementation just started
MAG4 Improvements: Vector Magnetograms

- Both vectors shown in red have positive $B_z$ (magnetic field out of the sun), but have opposite sign $B_{\text{LOS}}$ and thus a false (unphysical) neutral line in the line-of-sight (LOS) field.

Actual Examples

False Neutral Lines occur on limbward sides of sunspots.

Problem fixed by converting from $B_{\text{LOS}}$ and $B_{\text{Transverse}}$ to $B_z$ and $B_{\text{Horizontal}}$.
How Well Does MAG4 Forecast:

1. Situational Awareness

- During periods when flare-productive active regions cross the disk, the predicted rate and actual rate both increase, providing situational awareness.
- The results are best when flares and predicted rates are limited to inner 45 degree circle (Right).

## M or X-Class Flares

<table>
<thead>
<tr>
<th>Date</th>
<th>Rate of No X or M flare</th>
</tr>
</thead>
<tbody>
<tr>
<td>09-Apr</td>
<td></td>
</tr>
<tr>
<td>02-May</td>
<td></td>
</tr>
<tr>
<td>26-May</td>
<td></td>
</tr>
<tr>
<td>18-Jun</td>
<td></td>
</tr>
</tbody>
</table>

**Full disk Rates**

- 5 Day smoothed X&M flare rate

**Central Disk 45°**

- 5 Day smoothed X&M flare rate

**Predicted Event Rate**

**Predicted Event Rate Inner 45°**
How Well Does MAG4 Forecast:

2. Skill Metrics

<table>
<thead>
<tr>
<th>Forecast Method</th>
<th>YY</th>
<th>YN</th>
<th>NY</th>
<th>NN</th>
<th>PC</th>
<th>POD</th>
<th>FAR</th>
<th>HSS</th>
<th>TSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>McIntosh/NOAA</td>
<td>259</td>
<td>638</td>
<td>631</td>
<td>18476</td>
<td>93.7</td>
<td>0.29</td>
<td>0.71</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Free-Energy Proxy</td>
<td>273</td>
<td>284</td>
<td>618</td>
<td>18830</td>
<td>95.5</td>
<td>0.31</td>
<td>0.50</td>
<td>0.35</td>
<td>0.47</td>
</tr>
<tr>
<td>Present MAG4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free-energy proxy and previous flare activity</td>
<td>340</td>
<td>317</td>
<td>551</td>
<td>18797</td>
<td>95.7</td>
<td>0.38</td>
<td>0.48</td>
<td>0.42</td>
<td>0.49</td>
</tr>
<tr>
<td>Upgraded MAG4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best</td>
<td>890</td>
<td>0</td>
<td>0</td>
<td>19114</td>
<td>100</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Suggested Collaboration Tasks with AFWA

- Customizing MAG4 to AFWA needs

- Further development of MAG4
  - R2O: use time series, Heliosphere propagation of CME, Helioseimology, Improve forecasts as with flare history
  - Operational Tool: Robustness, usability, interface

- Independent Verification Tests
## How Well Does MAG4 Forecast:

### 2. Skill Metrics Equations

<table>
<thead>
<tr>
<th></th>
<th>Actual Yes</th>
<th>Actual No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predict Yes</td>
<td>YY</td>
<td>YN</td>
</tr>
<tr>
<td>Predict No</td>
<td>NY</td>
<td>NN</td>
</tr>
</tbody>
</table>

**Metric Equations**

- **Percent Correct**
  \[
  PC = \frac{YY+NN}{YY+YN+NY+YY}
  \]

- **Probability of Detection**
  \[
  POD = \frac{YY}{YY+NY}
  \]

- **False Alarm Rate**
  \[
  FAR = \frac{YN}{YY+YN}
  \]

- **Heidke Skill Score**
  \[
  HSS = \frac{2(YY*NN-YN*NY)}{(YY+NY)*(YN+NN)+(YY+YN)*(YN+NN)}
  \]

- **True Skill Score**
  \[
  TSS = \frac{YY*NN-NY*YN}{(YY+NY)*(YN+NN)}
  \]
How well it works (All-Clear)

Flares occur when high free-energy proxy active regions crossing disk.

All Clear Probability

Probability of No X or M flare

Times of X or M Flares

09–Apr 02–May 26–May 18–Jun

Date 2012