Interpretable Machine Learning to Forecast SEP Events for Solar Cycle 23

SOLSTICE Solar Storms & Terrestrial Impacts Center

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Overview

VISION:

Create a machine learning capability which will forecast Solar Energetic Particle events with improved accuracy and reliability.

SUMMARY:

SOLSTICE uses machine learning methods to predict whether an active region (AR) which produces flares will lead to a solar energetic particle (SEP) event.

- We use a new data product called Space-Weather Michelson Doppler Imager (MDI) Active Region Patches (SMARPs).
- SMARPs are derived from maps of the solar surface magnetic field taken by the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory (SOHO).
- We use ARs associated with flares that appear on the solar disk between June 5, 1996 and August 14, 2010.
- We label those that produced SEPs as positive and the rest as negative.
- This data is used to train two different types of machine learning methods, the support vector machines (SVMs) and the regression models.

SOLSTICE will bring major advances in space weather science and Solar Energetic Particle prediction capability.

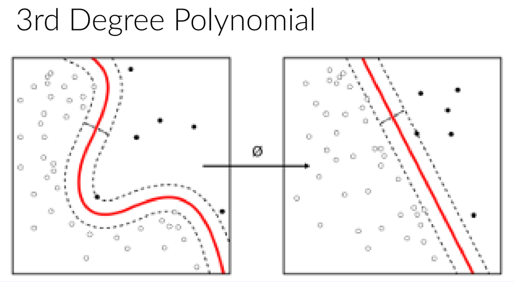
KEY POINTS:

- SMARP data can correctly predict whether a solar flare will lead to a solar energetic particle (SEP) event 72% of the times.
- Flare peak intensity is the strongest SEP predictor and can be coupled with SMARP data to achieve accuracy $\leq 0.92 \pm 0.07$.
- The SMARP dataset provides a leading time of 55.3 ± 28.6 minutes for forecasting the SEP events.

Machine Learning Models

Support Vector Machines

- Linear
- RBF
- 2nd Degree Polynomial
- 3rd Degree Polynomial



Linear Models

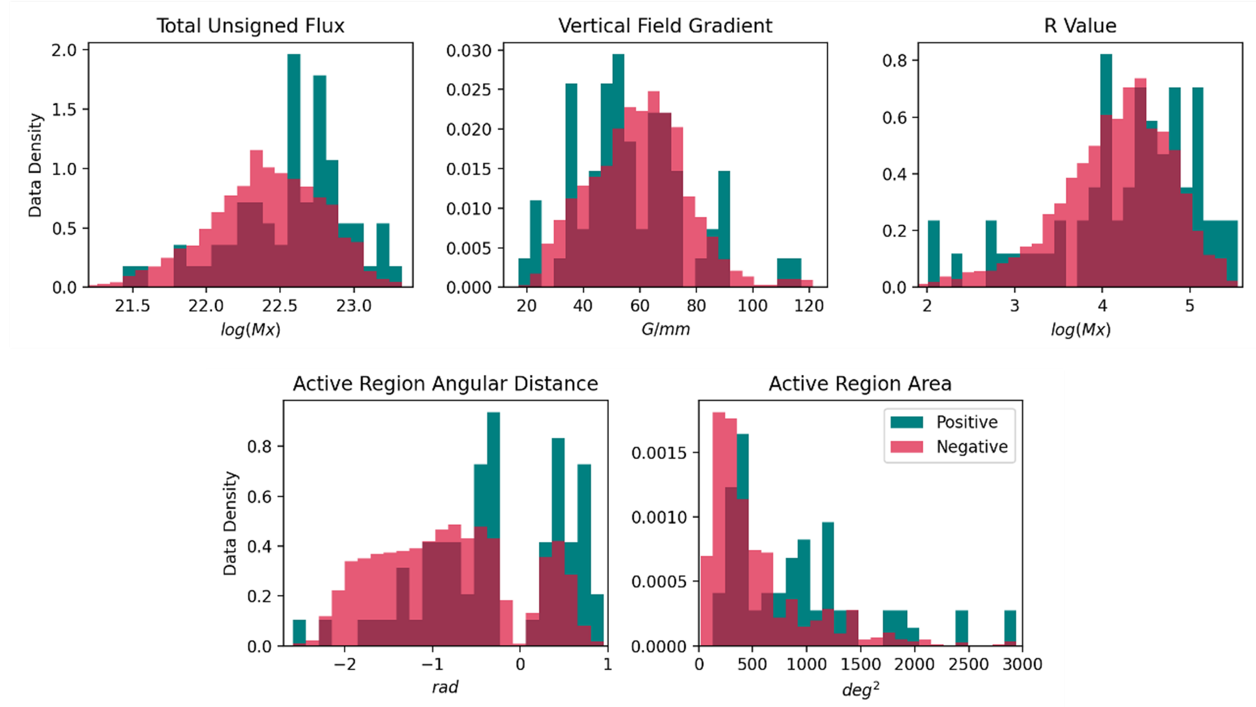
- Ridge

$$J_{Ridge} = \|w^\top x - y\|_2^2 + \alpha \|w\|_2^2$$

- Logistic Regression

$$J_{LR} = \frac{1}{2} w^\top w + C \sum_{i=1}^{n} \log(e^{-y_i(x_i^\top w + c)} + 1)$$

SMARP Data



The magnetogram is measured by the Michelson Doppler Imager onboard SOHO between June 5, 1996 and August 14, 2010. Based on the magnetogram, a new database is derived called Space-Weather MDI Active Region Patches (SMARPs), which contains characteristics of the active regions on the solar surface.

Three physical keywords are calculated using the pixels in the active region:

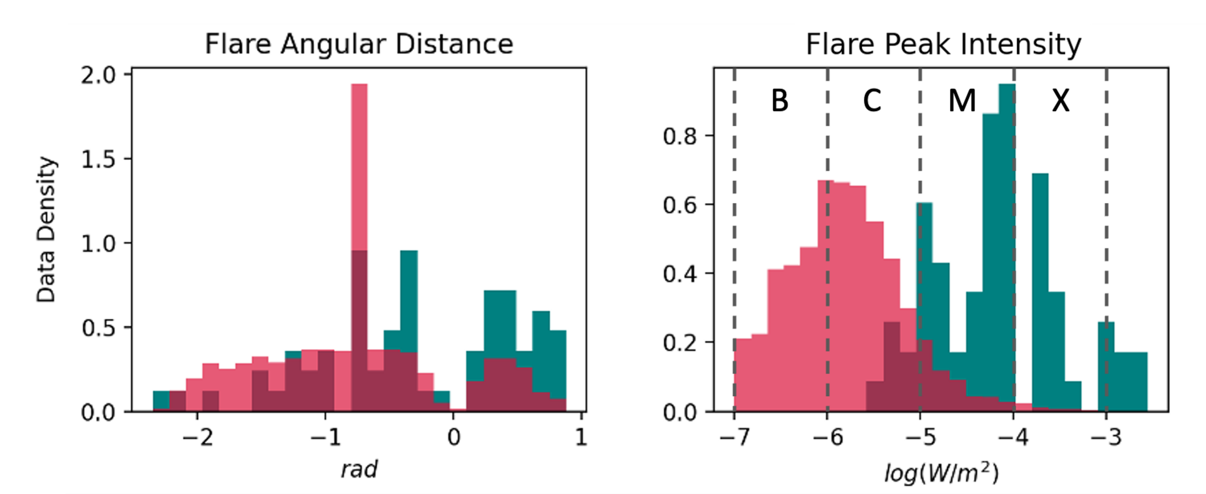
- Total unsigned flux (**USFLUXL**)
- Mean gradient of the vertical field (**MEANGBL**)
- Logarithm of the total unsigned flux near polarity inversion line (**RVALUE**)

SMARP also contains four spacial features specifying the location of the corresponding AR on the solar surface: the minimum and maximum latitude (**LATDMIN**, **LATDMAX**) and the minimum and maximum longitude (**LONDTMIN**, **LONDTMAX**).

Using this information we calculate the:

- Angular distance between the AR and the magnetic foot-point of the earth (**ARDIST**)
- Active region area (**ARAREA**)

Flare Data

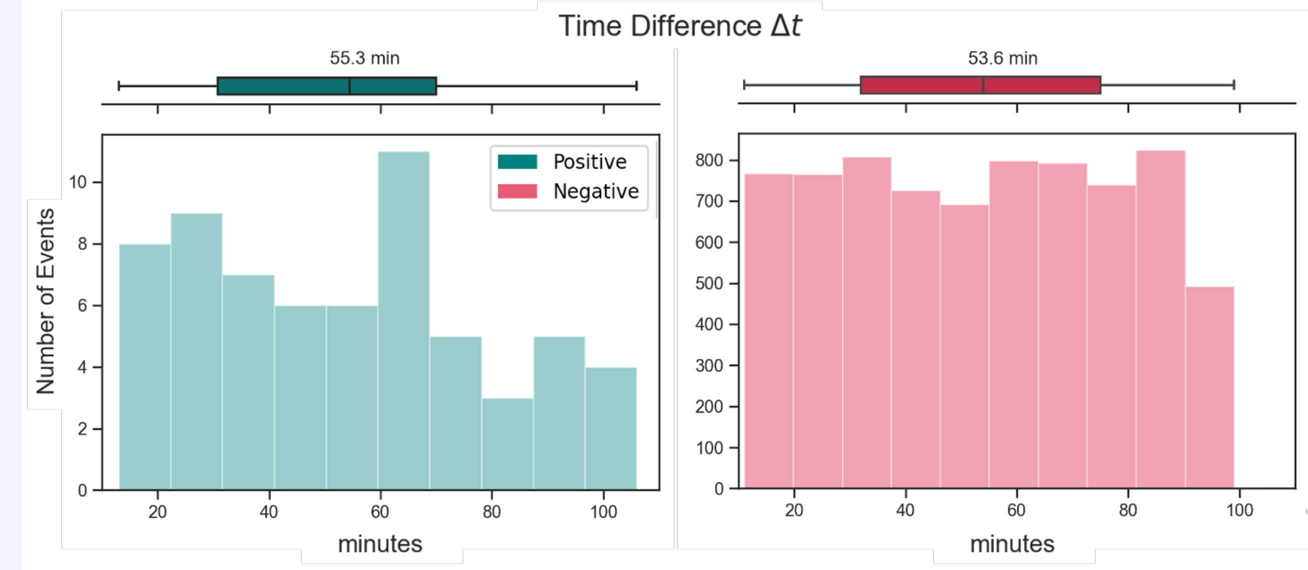


We evaluate the prediction power of SMARP dataset on SEP events by comparing the prediction results with those obtained by only using the flare information, i.e. flare peak intensity and flare location. We use the solar long wavelength X-ray flare data that NOAA's Geostationary Operational Environmental Satellites (GOES) continuously provides since 1975.

Similarly to the SMARP Predictors, we calculate the:

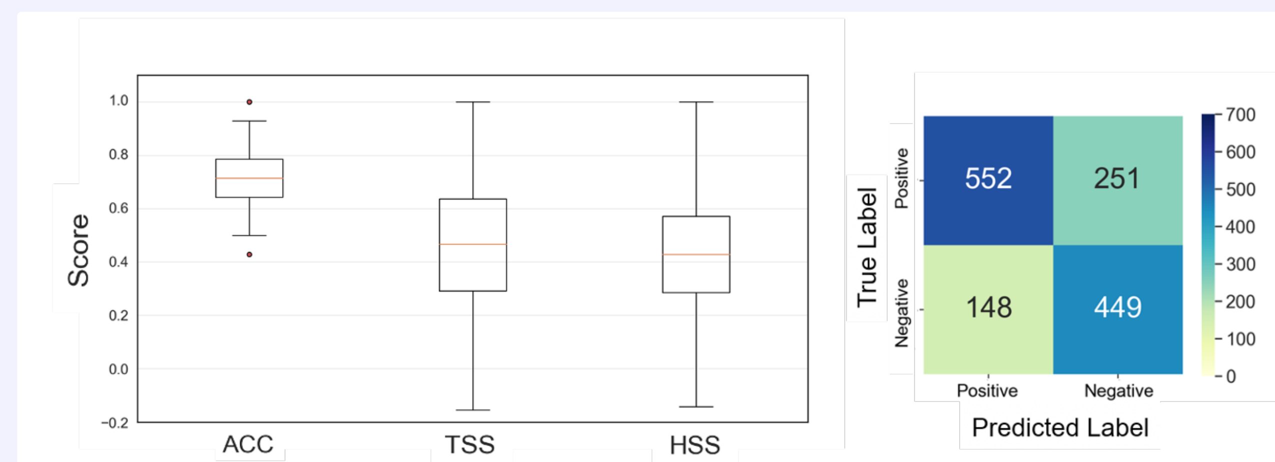
- Logarithm of flare intensity
- Flare angular distance from the earth's magnetic foot-point location, W45°, on the sun

Prediction Window

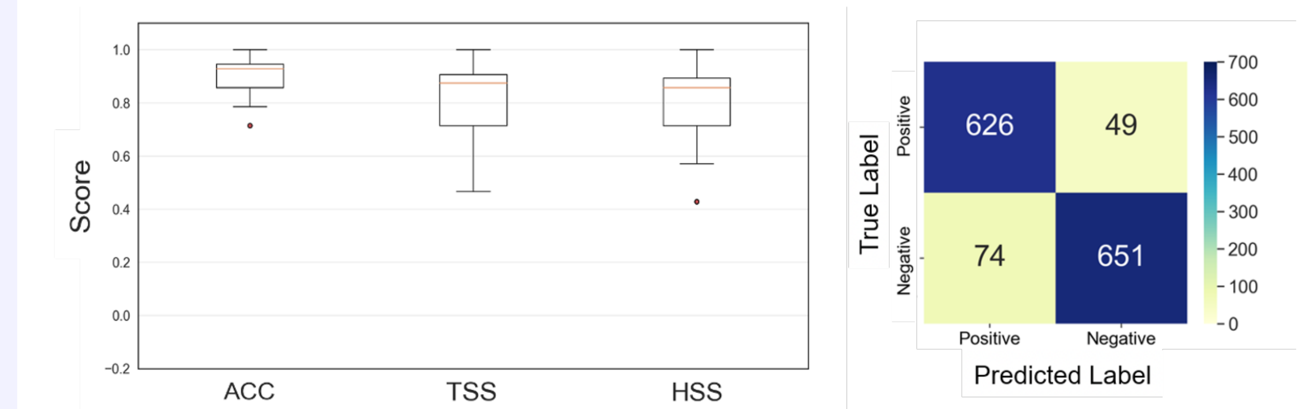


Histograms for the time difference between the flare peak time and the selected SMARP data. The distributions range between 10 and 100 minutes. The mean time differences shown in the error bars above the graphs are 55.3 and 53.6 minutes with a standard deviation of 28.6 and 24.8 minutes for the Positive (green) and Negative (red) datasets respectively.

Results

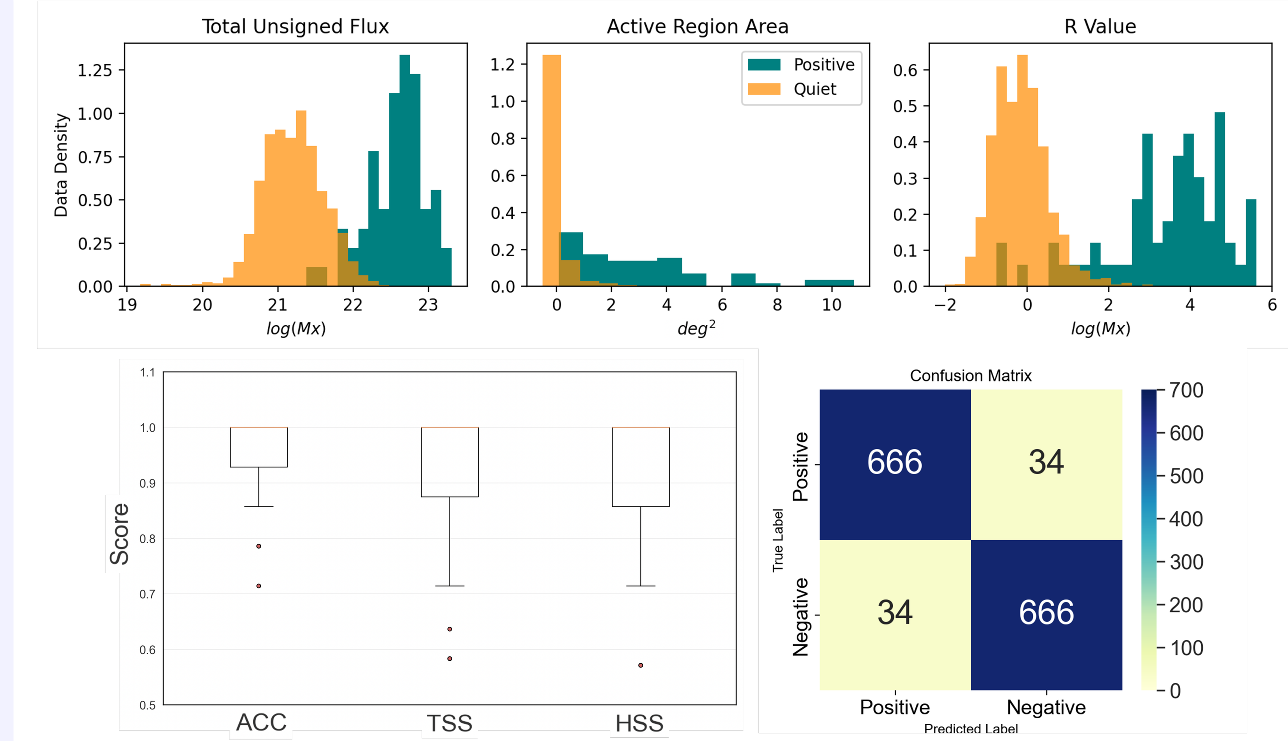


The distribution of k = 100 different ACC, TSS and HSS values are shown in the box plots (left). The values were obtained using the USFLUX & AR Distance on a Third Degree Polynomial SVM and constitute the best SEP prediction the SMARP data can achieve. Adding all the individual TP, TN, FP and FN values respectively we produce a cumulative confusion matrix for the 100 different runs (right). The results show that the Linear Models can predict whether a flare will be accompanied by SEPs with ACC values $\geq 0.70 \pm 0.12$ for a number of SMARP Predictor combinations.



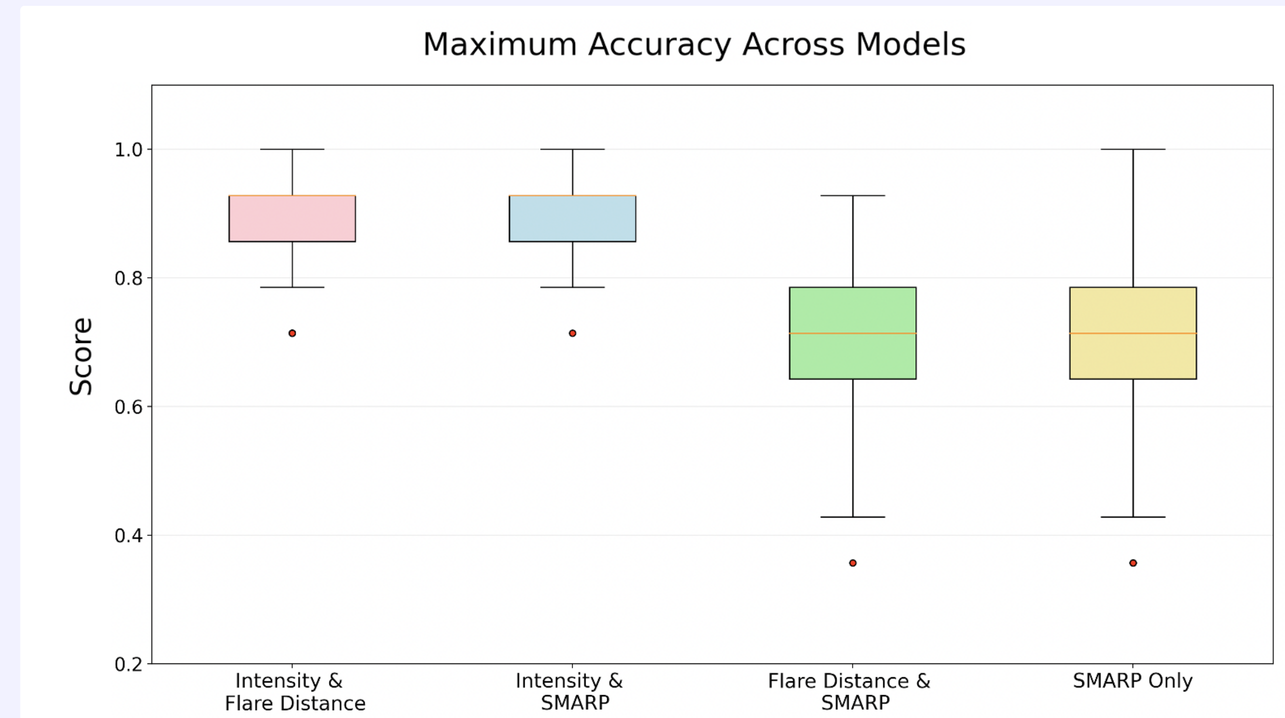
The distribution of k=100 different ACC, TSS and HSS values are shown in the box plots (left). The values were obtained using the Flare Peak Intensity & Flare Distance on a Ridge Regression model and constitute the best SEP prediction the flare data can achieve. Adding all the individual TP, TN, FP and FN values respectively we produce a cumulative confusion matrix for the 100 different runs (right). These results show that all models, when using the Flare Peak Intensity, can successfully predict $\leq 92\%$ of the times if a flare will be accompanied with an SEP. The flare predictors do not provide a time window therefore they are used in this study only for comparison reasons.

Quiet Active Regions



The negative dataset includes SMARP data only from the active regions that produced at least one flare throughout their lifespan. In a real-world application, the forecaster does not have prior knowledge of whether an AR is going to produce flares or not. We chose to disregard quiet active regions because they are very easily distinguishable compared to the ARs that produced SEPs. This claim is demonstrated in the above figure, where the results of the binary classification between Positive SMARP events and SMARPs chosen randomly from quiet active regions are presented.

Summary



A cumulative box plot for the four main categories of predictor combinations. The plot makes evident the superiority of the flare peak intensity over the SMARP data. Although the SMARP data cannot provide SEP forecast of quality similar to the flare peak intensity, it provides us with a larger leading time compared to the Flare Predictors as the flares precede in time the SMARP data points.

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