NorthWest Research Associates
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The Discriminant Analysis Flare Forecasting System

Introduction, Performance, Capabilities, and Options

presented by

NorthWest Research Associates

Boulder, Colorado, USA

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Executive Summary

NorthWest Research Associates presents DAFFS, a system developed under SBIR funding through the United States (US) National Oceanic and Atmospheric Administration (NOAA) /Space Weather Prediction Center (SWPC) for forecasting the likelihood of solar flares. DAFFS constructs probabilistic forecasts based on near-real-time data of the state of the Sun, using multi-dimensional NonParametric Discriminant Analysis. DAFFS is a fast, fully autonomous prototype which has been shown to out-perform the forecasts issued by NOAA, especially for long-range forecasts. DAFFS incorporates graphical context for the probabilistic forecasts, flexibility and options for user-defined forecast specifics, and routinely reports performance metrics.

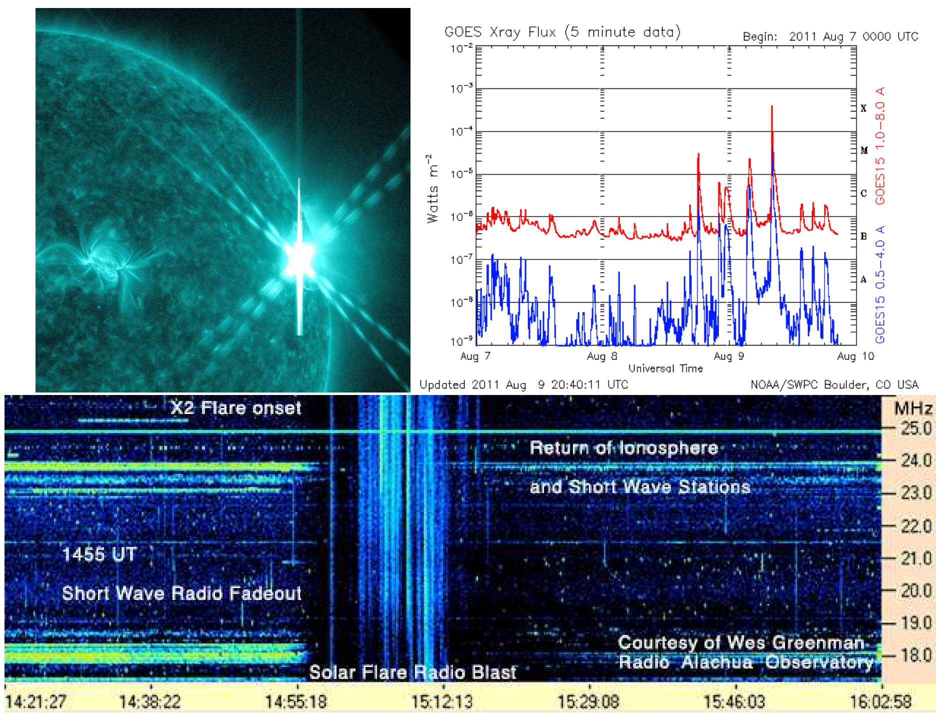

Figure 1: The sudden increase in ionizing radiation from solar flares routinely disrupts the stability of the Earth's upper atmosphere, causing radio blackouts and GPS communication disruption. Flares are often associated with CMEs and SEP events which can produce geomagnetic storms and high-energy particle events; fluctuations in the geomagnetic field can induce localized charging and currents, including on the ground. We introduce DAFFS as a new system for forecasting these events. **Top Left:** A large flare occurred on 09 August 2011, seen saturating the 131Å channel of AIA [1] on Solar Dynamics Observatory. **Top Right:**, the sun-as-a-star GOES Soft-X-ray traces, indicating that this flare (the largest shown) had a peak output of 7×10^{-4} W/m^2 ("X7") prompting an R3 Communications Warning. It also caused a minor radiation storm. To note: NOAA/SWPC forecast a 10% chance of a flare, NWRA forecast would have been closer to 20%. **Bottom:** temporal plot of high-frequency (18-25MHz) radio signals showing the effects of a strong solar flare (an X2 - a different event), including blackout effects lasting many hours at lower frequencies, and a radio blast from the solar event itself.

Introduction

Modern communications and positioning relies on satellite systems such as the GPS which are susceptible to transmission errors and blackouts when the Earth's ionosphere reacts to the sudden influx of X-rays from a Solar Flare (Figure 1). This scenario puts many systems at risk. The oft-accompanying Coronal Mass Ejections (CMEs) and Solar Energetic Particle (SEP) events can produce radiation surges; fluctuations in the geomagnetic field can induce localized charging and currents, including on the ground. Any and all communication and locating technology, military and civilian, that relies on satellite positioning and communication with ground-based hardware, is susceptible. Humans in the space environment are particularly vulnerable to the radiation environment [2] from sudden energetic solar events; this includes high-altitude military aircraft.

In response to a call from NOAA/SWPC through the SBIR program, NorthWest Research Associates (NWRA) demonstrated that the research version of DAFFS improved on the NOAA/SWPC solar flare forecasts by the target 25% as measured with standard skill scores. With this success, NWRA secured a Phase-II contract, and DAFFS is now a near-real-time fully autonomous forecasting system which runs as a prototype at NWRA.

Method

DAFFS evaluates the state of the magnetic field on the Sun – believed to be the power source of solar flares – for evidence of energy being stored and for the magnetic complexity known to be associated with flare productivity [3, 4, 5]. DAFFS also evaluates the recent flare history, since persistence does provide a fairly good window on future activity. By default, DAFFS uses the near-real-time vector magnetic field data from the Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager (HMI) instrument [6, 7, 8, 9, 10, 11], along with near-real-time flare reports from the NOAA Geostationary Operational Environmental Satellite (GOES) 1–8Å detections; when vector

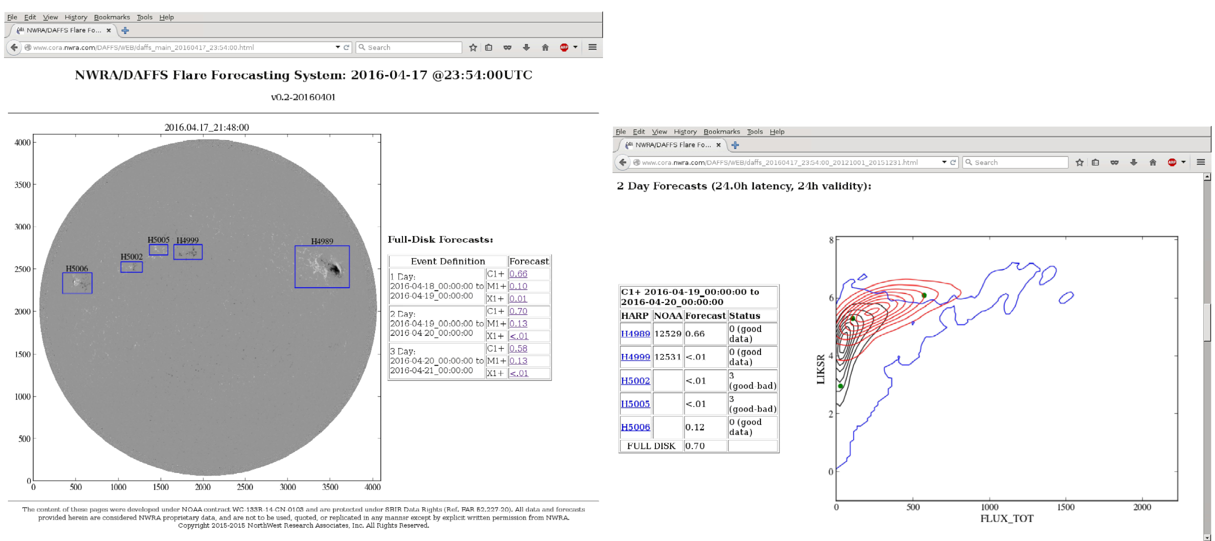

Figure 2: Screenshots of the DAFFS forecast website. **Left:** Landing site showing full-disk images of the solar magnetic field, and a summary of full-disk forecasts. **Right:** Region-by-region forecasts and parameter context. Highlighted here are the forecasts (region and full-disk), showing the flare probabilities for `C1.0+`, 24 hr latency (lag-time) forecasts, data quality flags, and the NPDA results with each region's parameters plotted for context. Red/Blue contours are the distributions of yes/no populations for this event definition, the 50% probability contour (blue) is included for context, and the multiple parameters used here are the combination of the total magnetic flux and the flux within strong-gradient magnetic neutral lines within the target region.

Table 1: DAFFS Default Event Definitions for Forecasts Issued at 00:00UT and 12:00UT

	(Level)	Minimum threshold (Watt m^{-2})	latency (hr)	validity period (hr)	Region/ Full Disk
C+1	C1.0	$\geq 10^{-6}$	0	24	FD, R
M+1	M1.0	$\geq 10^{-5}$	0	24	FD, R
X+1	X1.0	$\geq 10^{-4}$	0	24	FD, R
C+2†	C1.0	$\geq 10^{-6}$	24	24	FD, R†
M+2	M1.0	$\geq 10^{-5}$	24	24	FD, R†
X+2	X1.0	$\geq 10^{-4}$	24	24	FD, R†
C+3†	C1.0	$\geq 10^{-6}$	48	24	FD, R†
M+3	M1.0	$\geq 10^{-5}$	48	24	FD, R†
X+3	X1.0	$\geq 10^{-4}$	48	24	FD, R†

†: Not included in NOAA's forecasts but produced by DAFFS by default.

magnetic field data are not available for analysis, DAFFS employs line-of-sight magnetic field data from the Global Oscillations Network Group (GONG) network [12], a ground-based international network of observing stations. In this way, DAFFS has redundant data sources included.

The results from the near-real-time observational data are compared using Multi-Variate NPDA to the results from an extensive training set. Bayes' theorem is employed to produce a probabilistic forecast. After data acquisition, all subsequent analysis for near-real-time forecasts is performed in < 15 minutes.

Forecasts

DAFFS presently matches the event definitions of the forecasts issued by NOAA/SWPC, with a few additional forecasts made available (Table 1). The latency (forecast lead time) is measured from the forecast issuance time; both full-disk and region-centered forecasts are issued.

DAFFS displays the forecasts in two graphical contexts, a region-context image and a parameter-context image for each of the event definitions (Figure 2). This allows forecasters to both intuitively understand the reason behind a region's published probabilities, and also alerts for questionable data which may not have been trapped by the numerous failure modes built into DAFFS.

Forecasts are presently issued twice daily, at 00:00 UT and 12:00 UT. A single validity time period (24 hr) is used, although this is a customizable feature, as are the specific event definitions.

Performance

Forecast validation is crucial for confidence. DAFFS incorporates regular self-evaluation and reporting the performance results to the user. Standard skill scores and metrics are used to measure the performance of DAFFS. NWRA staff bring to DAFFS experience in statistical forecast validation, strengthened by NWRA's collaboration with NOAA forecast validation and verification experts.

The prototype of DAFFS was developed specifically because DAFFS was shown to perform better than the NOAA/SWPC forecasts (Figure 3). This is especially true for larger event thresholds and longer forecast lead times. Note that the examples in Figure 3 are drawn from different training sets than the scores reported in Table 2, and thus are not expected to agree (this is a true

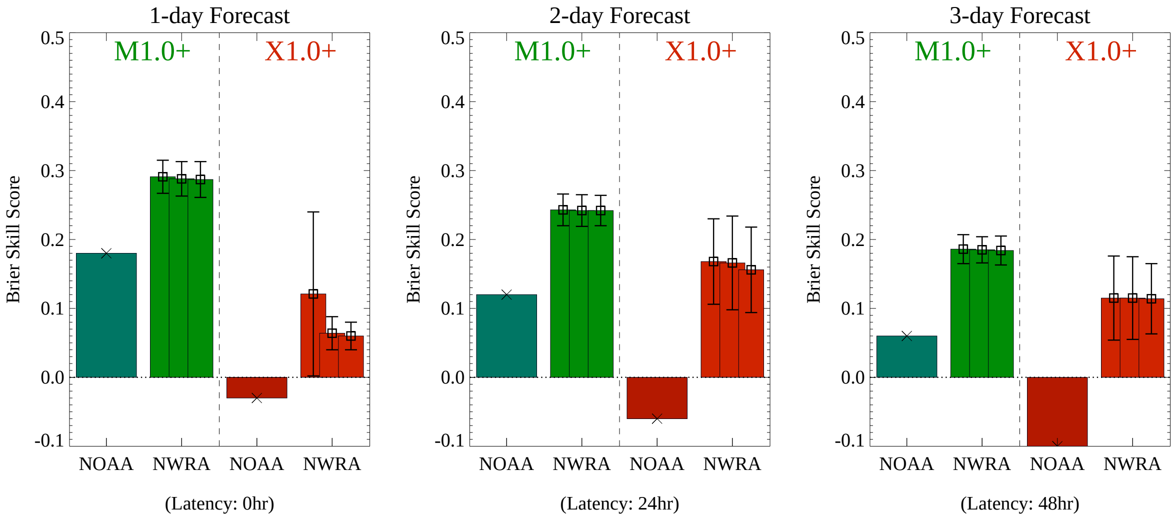

Figure 3: A comparison of Brier Skill Scores for full-disk forecasts, NOAA published (left of pairs) and NWRA/DAFFS (right of pairs, with error bars), for the interval 2010.05.10 – 2013.12.31. For the DAFFS forecasts, the three top-performing variable combinations are shown, with error bars from a 100-draw bootstrap. The DAFFS forecasts match NOAA published forecasts in event definition, validity (0 hr) and varying latencies: 0, 24, and 48 hr (left:right); hence, there are no `C1.0+` full-disk forecasts as they are not part of the published NOAA forecasts. NOAA `X1.0+` forecasts unfortunately show a negative Brier skill score; their annual reports indicate a wide variability in scores for this event definition [14]. The NWRA DAFFS forecasts show improvement.

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cautionary statement regarding any direct comparisons of forecasts and Skill Scores [see 13]).

The full DAFFS reporting includes numerous metrics, as each provides different information about performance. For example, the Brier Skill Score (BSS) compares the Mean Square Error of the target forecast's event probabilities and those of a Climatological Forecast. The BSS is complemented by Reliability Plots (Figure 4, top) that indicate systematic over- or under-prediction, as well as indicate uncertainties primarily due to sample sizes. The Peirce Skill Score (PSS) (also known as the True Skill Statistic (TSS)) reports the probability of detection (hit rate) minus the probability of false detection (false alarm rate), and is most applicable to categorical forecasts (Table 2, bottom). The behavior of these two components of forecasts relative to each other with varying probability thresholds indicate a forecast's ability to discriminate between events and non-events in Relative Operating Characteristic (ROC) plots (Figure 4, bottom), a perfect forecast lying completely above and away from the $x = y$ line (that indicates "no skill").

Regarding DAFFS' present performance, the key points are:

- ⇒ The reported skill scores are solidly in positive territory, especially as the cross-validation used in DAFFS provides an unbiased estimate of the scores, and the 100-draw bootstrap provides error bars to further the confidence in these results.
- ⇒ The `X+1` reliability plot in fact shows very favorable characteristics: most points near low observed frequencies are forecast with low probabilities, and the points at very high forecast probability have high observed frequency.
- ⇒ The ROC curves for all event definitions are well above and well away from the $x = y$ line, indicating a high potential for excellent "All Clear" forecasts. for example.
- ⇒ The DAFFS skill scores decrease with latency (lag), but stay definitively positive.
- ⇒ The fairly small degree of under-prediction for the `C+1 M+1` event definitions is understood, and NWRA is working to correct it.

Table 2: `DAFFS` Skill Scores (2012.11.01 – 2016.03.31)

Latency	`C1.0+`	`M1.0+`	`X1.0+`
	Brier Skill Scores		
0hr	0.31 ± 0.03	0.27 ± 0.03	0.26 ± 0.09
24hr	0.25 ± 0.03	0.22 ± 0.04	0.18 ± 0.11
48hr	0.16 ± 0.04	0.16 ± 0.03	0.15 ± 0.09
	Peirce Skill Scores (True Skill Statistic)		
0hr	0.57 ± 0.03	0.47 ± 0.04	0.63 ± 0.12
24hr	0.48 ± 0.03	0.40 ± 0.05	0.56 ± 0.12
48hr	0.46 ± 0.03	0.35 ± 0.04	0.50 ± 0.12

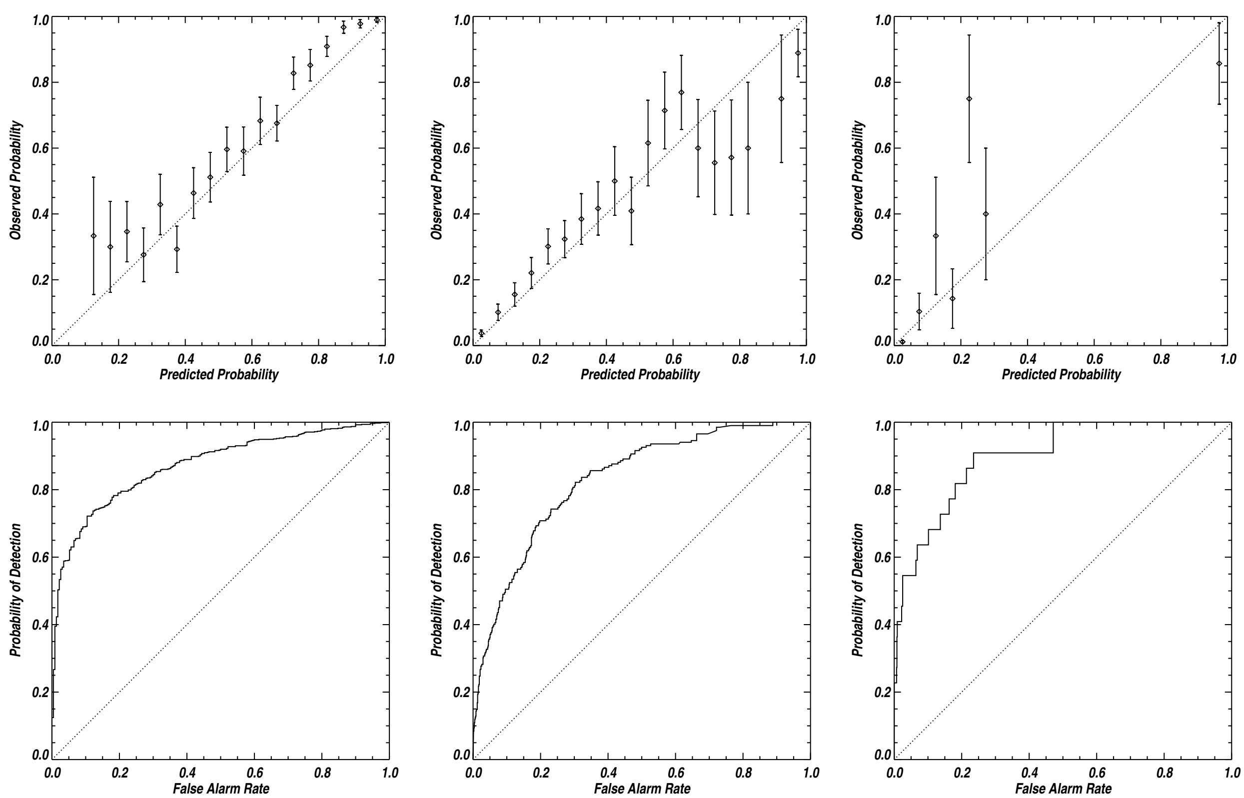

Figure 4: Sample performance plots for (left:right) `C+1`, `M+1`, `X+1` full-disk `DAFFS` for the period 2012.11.01 – 2016.03.31. **Top:** Reliability plots, the $x = y$ line is plotted for reference as an indication of under- or over-prediction; **Bottom:** ROC plots, the $x = y$ indicates no skill, farther above the $x = y$ line indicates better discrimination between the Probability of Detection and False Alarm Rate behavior of the forecasts.

Capability Summary

The present and potential capabilities of DAFFS include:

- ⊙ *Fast:* once data are received (generally 0.25 hr – 2.5 hr, depending on source), processing to a forecast is completed in minutes.
- ⊙ *Physics-based:* `DAFFS` evaluates the solar magnetic field and prior energy release events for evidence of available energy and magnetic "readiness" to flare.
- ⊙ *Redundancy:* multiple data-sources, both space-based and ground-based, plus extensive training datasets, allow forecasts even when one (or all) data are unavailable.
- ⊙ *Coverage:* no restriction on solar observing angle (minimal loss of skill to 80° away from "solar disk center"; some loss of skill beyond 80°, but forecasts are still issued).
- ⊙ *Flexibility and Customizability:* wide range of options for customization in terms of performance and graphical interface.
- ⊙ *Validation:* performance metrics routinely calculated and provided to user.
- ⊙ *Running Prototype:* `DAFFS` is presently at Technology Readiness Level (TRL) 6 and is ready for transition to an operational environment (TRL-7+).

Customization

Forecast customization is a major feature of DAFFS. Options include:

- ⊙ **Event Size:** while DAFFS matches the lower thresholds set by NOAA/SWPC, both lower and upper thresholds for GOES peak flux are available, or relevant thresholds for event type of the user's choice.
- ⊙ **Event Character:** DAFFS presently forecasts for GOES 1–8Å peak flux, but total Soft X-Ray flux, CME, SEP events are examples of other possible options.
- ⊙ **Validity Period, Latency, Timing:** the preferred timing specifics and frequency of forecasts can be specified by the user.
- ⊙ **Full Disk / Region:** the forecasts are issued for full-disk and/or particular magnetic areas on the Sun, as specified by the user.
- ⊙ **Costs of Errors:** DAFFS can provide customized forecasts according to the costs of Missed Events *vs.* False Alarms provided by the user, *i.e.* minimizing overall cost.

Additionally, customization is available regarding the graphical output (the "look and feel" of the context plots, for example, see Fig. 2).

User Options

NorthWest Research Associates (NWRA) is interested in promoting DAFFS as a research and operational advisory tool to the space-weather user community and forecast centers. Table 3 describes some of the user levels that NWRA envisions may be of interest.

NorthWest Research Associates

NorthWest Research Associates (NWRA; `www.nwra.com`) is a small scientific research organization owned and operated by its Principal Investigators, with expertise in the space and geophysical sciences. Focused areas in basic and applied research include, but are not limited to: fundamental

Table 3: Options for DAFFS Users

"Access Only"	Annual Subscription for access to the DAFFS forecast website at NWRA	Minimal cost; access to website and optional pushed text summaries
"Customization"	Create custom forecasts to user specifications.	Costs according to number, complexity of customization options and additional data requirements
"Make it Better"	Incorporate *known* improvement modes into DAFFS prototype	Variable costs. Examples include: ◦ Optimize data analysis ◦ Incorporate time-series parametrization ◦ Include coronal-model parametrization ◦ Adaptive Kernel NPDA
"Research toward Improved Operations"	Enable *future* improvements to DAFFS	Variable costs. Performance of research-inspired enhancements to DAFFS are tested, near-real-time capabilities of the most promising results are prototyped. Examples include: ◦ New data parametrizations ◦ New data sources
"Make it run *here*"	Install DAFFS locally	Costs according to platform, security

fluid dynamics, atmospheric science, ionospheric, solar, and stellar physics, oceanography, sea-ice mechanics, and electromagnetism. NWRA has 78 employees with offices in four locations.

The NWRA staff responsible for DAFFS are Senior Research Scientists Dr. K. D. Leka and Dr. Graham Barnes, Software Engineer Mr. Eric Wagner, with additional IT help from NWRA Technical Manager Mr. Orion Poplawski. Drs. Leka and Barnes are both internationally-recognized experts in solar magnetic field observation, analysis, and statistical methods. They have led efforts on flare-forecasting comparisons [2, 13, 15], and statistical methods of forecast validation [4, 5, 16, 17, 18], with on-going collaborative ties to experts in validation at NOAA/SWPC. DAFFS was developed under funding from the US SBIR program through NOAA. DAFFS forecasts are presented for research and advisory purposes only.

For additional information on DAFFS please contact:
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Acronyms

AIA Atmospheric Imaging Assembly. 1

BSS Brier Skill Score. 4

CME Coronal Mass Ejection. 1, 2, 6

DAFFS Discriminant Analysis Flare Forecast System. 1–4, 6, 7

GOES Geostationary Operational Environmental Satellite. 2, 6

GONG Global Oscillations Network Group. 3

GPS Global Positioning System. 1, 2

HMI Helioseismic and Magnetic Imager. 2

NOAA National Oceanic and Atmospheric Administration. 1–4, 6, 7

NPDA NonParametric Discriminant Analysis. 2, 3, 7

NWRA NorthWest Research Associates. 2–4, 6, 7

PSS Peirce Skill Score. 4

ROC Relative Operating Characteristic. 4

SBIR Small Business Innovative Research. 1, 2, 7

SDO Solar Dynamics Observatory. 1, 2

SEP Solar Energetic Particle. 1, 2, 6

SWPC Space Weather Prediction Center. 1–3, 6, 7

TSS True Skill Statistic. 4

US United States. 1, 7