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Space Weather Monitoring and Modeling Requirements for Beyond-LEO Missions
Space Radiation Analysis Group (SRAG), SD2

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Change Record

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Baseline	1.0	Initial Release	12/31/2020

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Purpose

This document defines the requirements and capabilities of the Space Radiation Analysis Group (SRAG) team for the support of real-time nominal and contingency radiation console operations as missions extend beyond Low-Earth Orbit (LEO). Requirement definitions are based on experience with the Shuttle and International Space Station (ISS) missions, using satellite measurements and knowledge of the free space environment to assess likely impacts to human health of radiation exposure that may be experienced during a Beyond-LEO mission due to enhanced environment conditions.

Please be aware that this is a living document. Changes are expected as the concept of operations evolves. SRAG will readdress this document annually and redistribute new versions to the community. For any questions, please contact us at jsc-space-radiation-analysis-group-SpaceWeather@nasa.onmicrosoft.com.

1.2 Scope

This document considers the impact of an enhanced space environment on human spaceflight operations in free space. The impact of the space environment on instrumentation is not covered in this document; the responsibility is left to the hardware designers to assess and mitigate impact to equipment as required. As such, particle types and energies that are of interest when determining hardware damage susceptibility are not considered in this work, if said particles are of negligible impact to the human form when mitigated by light (e.g, Extravehicular Mobility Unit (EMU)) or moderate (e.g, vehicle) shielding.

The space environment is comprised of three different particle sources: Galactic Cosmic Radiation (GCR), Trapped Radiation, and Solar Particle Event (SPE)s. GCR particles tend to be high energy and mass, and effective shielding is consequently difficult with currently available technology. Unlike the transient SPE, GCR is always present as a background source of radiation exposure, changing very slowly with time during the 11-year solar cycle. For these reasons, GCR is considered to be beyond the scope of this document, and mitigation of GCR exposure is left to be worked in a different forum. Trapped Radiation, once the vehicle has left LEO, is no longer a consideration for crew exposure and is therefore out-of-scope in an assessment of mitigation of risks in the free space environment. Further, detailed trapped environment models are already available and in use for vehicle design and mission planning tasks to account for the period when the vehicle is passing through the radiation belts. This requirements document will focus solely on prediction and mitigation of SPE impacts.

As has been noted in the SRAG Artemis Concept of Operations for Mitigation of an Enhanced Space Radiation Environment, it is not possible to characterize all the variants and impacts associated with space weather and its transients; an initial attempt is made here based on collective experience with the Shuttle and ISS programs.

1.3 Change Authority/Responsibility

This document will be used by SRAG to communicate modeling and monitoring requirements to the community. It will be updated as deemed necessary to clarify existing or add new requirements or when available technology allows a marked improvement to current support tasks.

1.4 Convention and Notation

The convention used in this document for requirements is as follows:

Shall – indicates a requirement which must be implemented and verified.
Should – indicates a goal which must be addressed by the design but is not formally verified.
Will – indicates a statement of fact and is not verified.

In some cases, the values of quantities are not always known or have not yet been determined for all requirements. Such values should be designated as follows:

To Be Resolved (TBR) – Approximate values are known.
To Be Determined (TBD) – No known value exists.
To Be Supplied (TBS) – A value is known, but has not yet been supplied.

2 Documents

2.1 Applicable Documents

The documents listed in this paragraph are applicable to the extent specified herein. They contain provisions or other pertinent requirements directly related to and necessary for the performance of the activities specified by this document. A list of scientific papers influencing requirement parameters is included in the References section at the end of the document.

Note: The documents in this section reference the Gateway mission requirements, which are representative of hazards anticipated for all exo-LEO missions. The exact mission definition (e.g., Gateway, Artemis) is beyond this scope of this document and will not be tracked, with the understanding that all exo-LEO missions are obligated to consider impacts of an enhanced space environment while in free space.

Document No.	Title
SD-XXXX	Gateway Human-System Requirements (HSR) for Subsystem Specs
SD-XXXX	Artemis Concept of Operations for Mitigation of an Enhanced Space Radiation Environment

2.2 Reference Documents

The following documents contain supplemental information to guide the user in the application of this document. These reference documents may or may not be specifically cited within the text of this document.

Document No.	Title	Location
NASA-STD-3001 VOL 1	NASA Space Flight Human-System Standard, Volume 1 Crew Health	https://standards.nasa.gov/standard/nasa/nasa-std-3001-vol-1
NASA-STD-3001 VOL 2	NASA Space Flight Human-System	https://standards.nasa.gov/standard/nasa/nasa-std-3001-vol-2

	Standard, Volume 2: Human Factors, Habitability, and Environmental Health	
NCRP Report No. 132	Radiation Protection Guidance for Activities in Low-Earth Orbit	
JSC 28330	Human Health and Performance Configuration Management Plan	https://qmsmasterlist.jsc.nasa.gov/home.aspx/organization/54
JPD 1280.1	JSC Quality Policy	https://cdms.nasa.gov/assets/docs/centers/JSC/Dirs/JPR/JPR1280.2E.pdf
JPR 1280.2	JSC Quality Manual	https://cdms.nasa.gov/assets/docs/centers/JSC/Dirs/JPR/JPR1280.2E.pdf

2.3 Order of Precedence

In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3 Data Requirements for Flight Operations

This section summaries the current monitoring needs of the SRAG team for LEO mission support and details how these needs are expected to change in the exo-LEO era. This list of monitoring requirements serves as a minimum set of standards going forward.

3.1 Design Approach

All requirements presented in the current document are derived from the NASA Standard 3001 Volume 2 [V2 6099], which initially flow into mission-specific documentation such as the Gateway HSR for Subsystem Specs [HSR 6089]. No attempt will be made in the current document to track individual missions, as the crew concerns and requirements listed herein are common to all Beyond-LEO missions. Requirements have been defined based on the experience of SRAG operators throughout the Shuttle and ISS eras, and this knowledge will be applied to the Artemis generation and beyond (Table 1).

Table 1: Synopsis of space weather phenomenon of concern and monitoring capabilities for human spaceflight operations. Several monitors are able to provide the data streams of interest; monitors listed represent those most commonly used for SRAG mission support.

Event Type	Monitor	Data Cadence	LEO Concern	Beyond-LEO Concern
X-Ray Flare	GOES SXR	1 min	None	None
SPE (>10MeV)	GOES Proton Flux	5 min	EVA	EVA
ESPE (>100MeV)	GOES Proton Flux	5 min	EVA/IVA	EVA/IVA

Geomagnetic Storm	K_p Index	3 hr	EVA/IVA	None
CME	LASCO C2/C3	6 min (varies)	EVA/IVA	EVA/IVA

3.2 Current Space Weather Operational Support Functionality

[SW 1001] Systems shall support the continuous monitoring of X-ray flux with a range of wavelengths spanning 1.0-8.0 Å at a cadence of no less than 1 measurement per minute with a latency not to exceed 10 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors X-ray flux activity. Although these phenomena have no impact to the crew, they are an indicator of possible Solar Particle Event (SPE) and/or Energetic Solar Particle Event (ESPE) activity.

[SW 1001V] The ability of the system to support continuous monitoring of X-ray flux shall be verified by inspection that the X-ray data stream is available with a range of wavelengths spanning 1.0-8.0 Å at a cadence of no fewer than 1 measurement per minute with a latency not to exceed 10 minutes.

Rationale: X-ray flux monitoring is currently performed using the Geosynchronous Orbit Earth observing Satellite (GOES) instruments. X-ray flux measurements are available continuously at a cadence of 1 minute and a latency of approximately 10 minutes.

[SW 1002] Systems shall support the continuous monitoring of >10MeV integral proton flux at a cadence of no fewer than 1 measurement per 5 minutes with a latency not to exceed 10 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors SPEs, defined as an increase in >10MeV integral proton flux over the 10 Particle Flux Units (1/cm2-s-ster) (pfu) threshold. Although these lower-energy particles generally do not penetrate into the vehicle, they are still of interest for general situational awareness as well as during Extra Vehicular Activity (EVA). During the Artemis missions, these events will be particularly important to monitor when astronauts are on the surface of the Moon and not being shielded by their vehicle.

[SW 1002V] The ability of the system to support continuous monitoring of >10MeV integral proton flux shall be verified by inspection that data representing >10MeV integral proton flux at the satellite location is available at a cadence of no fewer than 1 measurement per 5 minutes with a latency not to exceed 10 minutes.

Rationale: >10MeV integral proton flux monitoring is currently performed using the GOES instruments. Proton flux measurements are available continuously at a cadence of 5 minutes and a latency of approximately 10 minutes.

[SW 1003] Systems shall support the continuous monitoring of >100MeV integral proton flux at a cadence of no fewer than 1 measurement every 5 minutes with a latency not to exceed 10 minutes.

Rationale: For current and future missions, SRAG monitors ESPEs, defined as an increase in >100MeV integral proton flux over the 1pfu threshold. These higher-energy particles are able to penetrate into the vehicle, and SRAG performs continuous console support throughout the duration of these events to mitigate any impacts to crew health. ESPEs could lead to postponement or cancellation of EVAs on the lunar surface and/or force astronauts to build a shelter in place.

[SW 1003V] The ability of the system to support continuous monitoring of >100MeV integral proton flux shall be verified by inspection that data representing >100MeV integral proton flux at the satellite location is available at a cadence of no fewer than 1 measurement every 5 minutes with a latency not to exceed 10 minutes.

Rationale: >100MeV integral proton flux monitoring is currently performed using the GOES instruments. Proton flux measurements are available continuously at a cadence of 5 minutes and a latency of approximately 10 minutes.

[SW 1004] Systems should monitor solar wind speed, density, temperature and magnetic field strength (B_z and B_t components) at a cadence of no less than 1 measurement per 5 minutes and a latency not to exceed 10 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors solar wind parameters to gain insight into the progression of Coronal Mass Ejection (CME)s and Coronal Hole High Speed Stream (CH HSS) as they become geo-effective. During LEO missions, the planetary K-index (K_p) is tracked as the official indication of the impact of enhanced solar wind on the compression of the Earth's geomagnetic field during an ESPE.

[SW 1004V] The ability of the system to support continuous monitoring of solar wind parameters should be verified by inspection that data representing solar wind speed, density, direction, temperature and magnetic field strength at the satellite location is available at a cadence of no less than 1 measurement per 5 minutes and a latency not to exceed 10 minutes. K_p will not be monitored for Beyond-LEO missions.

Rationale: Solar wind data has been monitored during the ISS era first using the Advanced Composition Explorer (ACE), and later the Deep Space Climate Observatory (DSCOVR), instruments. Data is available continuously at a cadence of 1 minute; latency varies based on the downlink ground station availability.

[SW 1005] Systems shall provide imagery of the entire visible solar disk in the visible light spectrum with wavelengths inclusive of 400-700nm with a cadence not less than one measurement per 15 minutes and a latency not to exceed 15 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors imagery in the visible light spectrum to assess active region location and characteristics as an indicator of possible activity. When a flare has occurred, real-time imagery provides information to the console operator regarding the likelihood of an impact of any associated solar energetic particles based on flare origin.

[SW 1005V] The ability of the system to provide imagery shall be verified by inspection, confirming that visible light imagery is available at a cadence of one measurement per 15 minutes and a latency of 15 minutes.

Rationale: During LEO and Beyond-LEO missions, SRAG console operators used imagery from multiple sources, including (but not limited to) Solar Dynamics Observatory (SDO), which is available at a cadence of one measurement per 15 minutes and a latency of 15 minutes.

[SW 1006] Systems shall provide imagery of the entire visible solar disk in the ultraviolet light spectrum with wavelengths to include 94Å, 131Å, 171Å, 193Å, 211Å, 304Å, 335Å, 1600Å and 1700Å with a cadence not less than one measurement per 15 minutes and a latency not to exceed 15 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors imagery in the ultraviolet light spectrum to assess flare location and association as an indicator of possible activity. When a flare has occurred, real-time imagery provides information to the console operator regarding the likelihood of an impact of any associated solar energetic particles based on flare origin.

[SW 1006V] The ability of the system to provide imagery shall be verified by inspection, confirming that ultraviolet light imagery is available at a cadence of one measurement per 15 minutes and a latency of 15 minutes.

Rationale: During LEO and Beyond-LEO missions, SRAG console operators used imagery from multiple sources, including (but not limited to) SDO / Atmospheric Imaging Assembly (AIA) data. SDO imagery is available at a cadence of one measurement per 15 minutes and a latency of 15 minutes.

[SW 1007] Systems shall provide magnetogram imagery with a resolution equal to or greater than 0.5 arc-seconds with a cadence of not less than one measurement per 60 minutes and a latency not to exceed 15 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors magnetogram imagery to assess active region characteristics as an indicator of possible activity. When a flare has occurred, real-time imagery provides information to the console operator regarding the likelihood of an impact of any associated solar energetic particles based on flare origin.

[SW 1007V] The ability of the system to provide magnetogram imagery shall be verified by inspection, confirming that imagery is available at a cadence of not less than one measurement per 60 minutes and a latency not to exceed 15 minutes.

Rationale: During LEO and Beyond-LEO missions, SRAG console operators use imagery from multiple sources, including (but not limited to) SDO / Helioseismic and Magnetic Imager (HMI) magnetogram data. SDO imagery is available at a cadence of one measurement per 60 minutes and a latency of 15 minutes.

[SW 1008] Systems shall provide coronagraph imagery displaying the area surrounding the sun at distances of (1) 2-6 R_{sun} and (2) 6-32 R_{sun} with a cadence of not less than one measurement per 60 minutes and a latency not to exceed 60 minutes.

Rationale: For LEO and Beyond-LEO missions, SRAG monitors coronagraph imagery to assess CME identification and characteristics.

[SW 1008V] The ability of the system to provide coronagraph imagery shall be verified by inspection, confirming that imagery is available at a cadence of not less than one measurement per 60 minutes and a latency not to exceed 60 minutes.

Rationale: During LEO and Beyond-LEO missions, SRAG console operators use imagery from multiple sources, including Large Angle and Spectrometric Coronagraph Experiment (LASCO) C2 and C3 instruments, available at a cadence of one measurement per 60 minutes and a latency of 60 minutes.

[SW 1009] Systems shall provide solar radio frequency emission data in the range of 10-3000MHz at a cadence of not less than one measurement per 15 minutes and a latency not to exceed 15 minutes.

Rationale: For LEO and Beyond-LEO missions, Type II and Type IV bursts alert the SRAG console operator of possible enhancements in solar activity, including ESPEs. A 10.7cm (2800MHz) radio burst, which presents as a significant increase over the daily measurement, can also indicate an enhancement. Type III bursts can indicate an increase in electrons. This data would be critical into providing advanced lead time for ESPEs that could impact astronauts on the Lunar surface.

[SW 1009V] The ability of the system to provide solar radio frequency emission data shall be verified by inspection, confirming that data is available at a cadence of not less than one measurement per 15 minutes and a latency not to exceed 15 minutes.

Rationale: During LEO and Beyond-LEO missions, SRAG console operators use solar radio frequency emission data to augment GOES X-ray and proton integral flux measurements. A cadence of not less than one measurement per 15 minutes and a latency not to exceed 15 minutes are required for this data stream to adequately complement the particle flux measurements.

4 Forecasting Requirements for Flight Operations

This section defines the current model functionality of SRAG for ISS support, representing the minimum state to be carried forward through exo-LEO operational support. A pictorial representation is shown in Figure 1, including data and/or model calculations required and the desired forecast lead time.

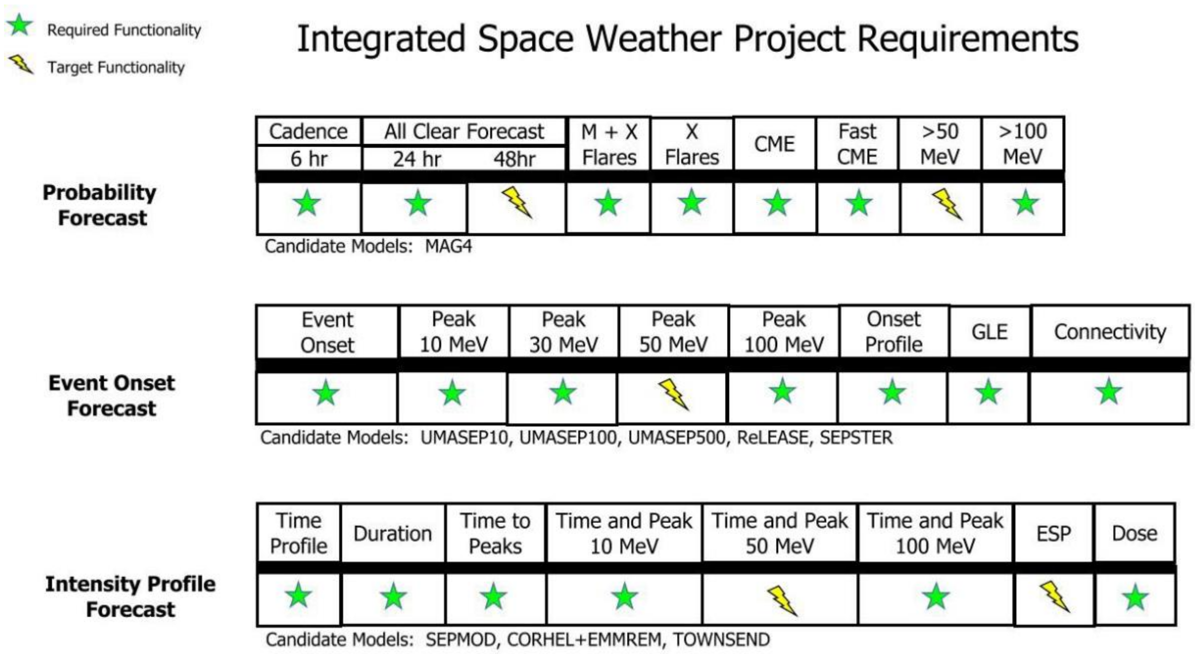

Figure 1: Current SRAG operational requirements. All energy references pertain to integral proton flux.

4.1 Event Parameter Definitions

4.1.1 General Terms

- Advanced Warning Time: The time between the forecast issue time and observed quantity (i.e., time of event onset, time of peak intensity, etc.) (Figure 2)
- All-Clear (post-eruption): A "no" forecast of event occurrence from a categorical forecast such that the forecasted Solar Energetic Particle (SEP) flux (for deterministic models) together with model uncertainty falls below the SPE or ESPE threshold.
- All-Clear Forecast (pre-eruption): A "no" forecast of event occurrence from a categorical forecast, and a forecasted probability (for probabilistic models) together with model uncertainty that falls into the Low Concern category. An All-clear forecast cannot be made within two days of an active region rotating around the west limb without behind-the-limb observations.
- Cadence: Frequency of availability of data measurements and/or model output.
- Categorical Forecast: Forecast of a "yes" or "no" of event occurrence (i.e., M- or X-class flare, SPE, or ESPE occurrence).
- Connectivity: The path of particles from the sun (‘footpoint’) to the end location of interest, frequently Earth.
- Dose: Energy deposition in tissue due to radiation exposure. Space weather prediction models are not expected to calculate dose; however, models of energy deposition may use particle fluence as an input.

- Event Onset Forecast: Forecast of an event onset time (Section 4.1.2).
- Fast CME: CME with a speed greater than 1000-1500 km/s. Some flexibility is given to this definition to accommodate the needs of the individual model inputs.
- Forecast Issue Time: The time the forecast is made (Figure 2).
- Forecast Lag Time: The time between the availability of input data and the forecast issue time (Figure 2).
- Forecast Lead Time: Period of time between the forecast issue time and the beginning of the forecast period (Figure 2).
- Forecast Period: Period of time over which a forecast is valid (Figure 2).
- Ground-Level Event (GLE): A type of SPE defined by high-energy (>500MeV) protons that are detectable at the Earth's surface by ground neutron monitoring stations due to the generation of secondary particles. Many SPEs are not GLEs; therefore, this parameter is usually tracked operationally as an indicator of harder-than-usual event spectra rather than its own event classification.
- High Concern: Historic event frequency between 20-100%.
- Low Concern: Historic event frequency between 0-7%.
- Medium Concern: Historic event frequency between 7-20%.
- Post-eruption: The time after the occurrence of a flare or CME.
- Pre-eruption: The time before the occurrence of a flare or CME.
- (Intensity) Profile Forecast: Forecast of the changes to the proton flux for specified particle energies with time throughout the forecast period.
- Qualifying Event: For the purposes of bounding the SRAG model suite, a Qualifying Event has been defined as M/X flare event onset and/or a sustained increase of >10MeV or >100MeV integral proton flux over background levels.
- Time to Peak: Length of time between event onset (Section 4.1.2) and the time the maximum value of the event parameter of interest (e.g., X-ray flux or proton flux) is measured. The dose measured at time to peak is indicative of the total event dose behind a specified amount of shielding material.

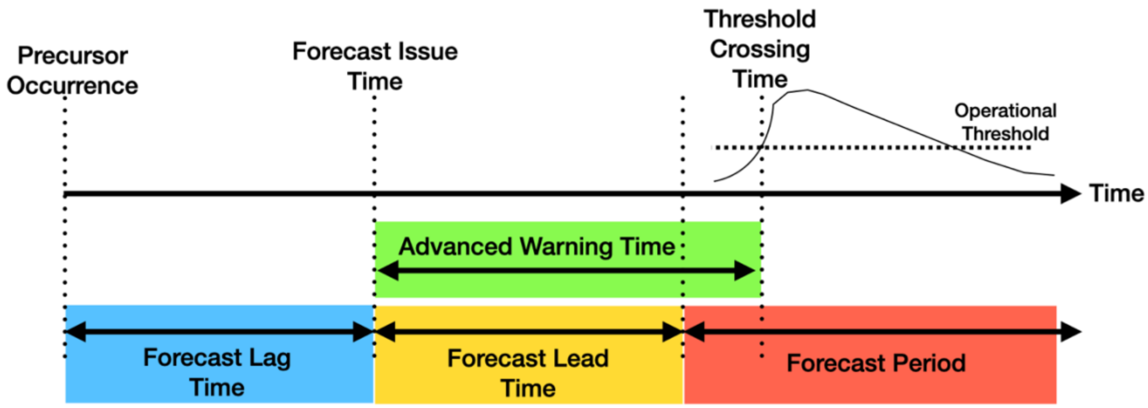

Figure 2: Diagram of forecast definitions. Note: Advanced Warning Time can pertain to any observed time quantity such as event onset time, time of peak intensity, etc.

4.1.2 Event Onset

Event onset is defined as the time at which the space weather phenomenon of interest surpasses a defined threshold per the reference instrument. It is understood that the scientific community frequently defines event onset differently (e.g., an increase above an instrument's background level measurements); however, the threshold crossings defined below are used herein due to their relevance to missions operations.

- Flare: For the purpose of this document, onset is defined as the time that the X-ray flux measured by the primary GOES satellite surpasses the stated threshold. An X-ray flare is classified by the maximum threshold crossed; M1- (1 x 10-5 W/m2), M5- (5 x 10-5 W/m2), and X1- (1 x 10-4 W/m2) class flares are of interest to human spaceflight operations. The secondary GOES satellite shall be used if the primary satellite is unavailable.

- SPE: For the purpose of this document, onset is defined as the time that the integral flux of the >10MeV protons has surpassed the threshold of 10pfu, as measured by the primary GOES satellite, for three successive readings. The primary GOES satellite for proton flux measurements may not be the same as that for X-ray flux measurements. The secondary GOES satellite shall be used if the primary satellite is unavailable.

- ESPE: For the purpose of this document, onset is defined as the time that the integral flux of the >100MeV protons has surpassed the threshold of 1 pfu, as measured by the primary GOES satellite, for three successive readings. The primary GOES satellite for proton flux measurements may not be the same as that for X-ray flux measurements. The secondary GOES satellite shall be used if the primary satellite is unavailable.

- CME: CME onset shall be defined as the date/time of first observation in the appropriate coronagraph: LASCO C2 and/or Solar Terrestrial Relations Observatory (STEREO) A/B. Note: No signal has been received from STEREO B since September 23, 2016.

Although the >30MeV and >50MeV proton flux data are of interest to human spaceflight operations,
no standardized threshold is defined corresponding to event onset and cessation. SRAG will therefore refrain from specifying a threshold for these proton flux values in the current

document, choosing instead to consider them as additional information for situational awareness when studying SPEs and ESPEs.

4.1.3 Event Termination and Duration

Event termination is defined operationally as the time at which the parameter defining an event in progress has decreased under a defined threshold. Duration is then defined as the length of time corresponding to event persistence (e.g., termination - onset). Note that event durations for different space weather phenomenon are not necessarily directly correlated.

- Flare: Event termination shall be defined in this document as the time at which the X-ray flux has decayed to a value halfway between the maximum flux and the pre-event background. This definition is designed to maintain consistency with that of the Space Weather Prediction Center (SWPC).

- SPE: Event termination shall be defined in this document as the time at which >10MeV proton flux returns below the 10pfu threshold. It is not unusual for proton flux to fluctuate when returning to background levels after an event; for the purpose of operational support, the event shall be deemed terminated once the monitoring instrument (e.g., GOES) registers 3 sequential readings below the 10pfu threshold.

- ESPE: Event termination shall be defined in this document as the time from which >100MeV proton flux returns below the 1pfu threshold. It is not unusual for proton flux to fluctuate when returning to background levels after an event; in this case, the event shall be deemed terminated once the monitoring instrument (e.g., GOES) registers 3 sequential readings below the 1pfu threshold.

- CME: Event termination shall be defined as CME shock passage at Earth as indicated by sudden decrease of >10MeV and/or >100MeV integral proton flux. Dynamic effects will persist for a period post CME passage.

Although the >50MeV proton flux data are of interest to human spaceflight operations, there is no standardized threshold corresponding to an event. SRAG will therefore refrain from specifying a threshold for these proton flux values, choosing instead to consider them as additional information for situational awareness when studying SPEs and ESPEs.

4.2 Metric Definitions

The following desired metrics shall be used when assessing model accuracy, basing calculations on training and validation sets approved by SRAG/ Coordinated Community Modeling Center (CCMC).

4.2.1 Categorical Forecasts

Metric calculation for categorical forecasts begins with the construction of a contingency table (Table 2) to indicate a true hit (‘A’), a correct null (‘D’), a missed event (‘B’) and a false alarm (‘C’). It is important to note that, depending on the research investigator, the definitions of ‘B’ and ‘C’ may be switched. It is crucial to understand the definitions used when comparing statistical analyses between research groups.

Table 2: Contingency table defining correct and incorrect forecasts.

	Event Forecasted	**No Event Forecasted**
Event Occurred	'A' (Hit)	'B' (Miss)
No Event Occurred	'C' (False Alarm)	'D' (Correct Null)

The following definitions represent descriptive metrics for categorical forecasts:

- Probability of Detection (POD) = A/(A+B)
- False Alarm Ratio (FAR) = C/(A+C)
- Probability of False Detection (POFD) = C/(C+D)
- True Skill Score (TSS) = POD-POFD
- Heidke Skill Score (HSS) = 2(A*D-B*C)/[(A+B)(B+D)+(A+C)(C+D)]

4.2.2 Probabilistic Models

The following definitions represent desired metrics for probabilistic models:

- Brier Score (BS) = (1/n)Σ[(f_i-o_i)^2], where f_i is the forecasted probability, o_i is the observation (0 for event not occurring, 1 for event occurring), and n is the total.
- Brier Skill Score (BSS) = 1-(BS/BS_{ref}), where BS is the Brier Score of the model, and BS_{ref} is the Brier Score of a reference forecast (e.g., climatology, persistence).

4.2.3 Deterministic Models of Proton Flux

The following are desired metrics for deterministic models that predict proton flux. Logarithmic scales are assumed.

- Mean Log Error (MLE) = (1/n)Σ[$\log_{10}(f_i)$-$\log_{10}(o_i)$], where f_i is the forecast, o_i is the observation, and n is the total.
- Mean Absolute Log Error (MALE) = (1/n)Σ|$\log_{10}(f_i)$-$\log_{10}(o_i)$|, where f_i is the forecast, o_i is the observation, and n is the total.

4.2.4 Deterministic Models of Event Timing

The following are desired metrics for deterministic models that predict timing quantities. Linear scales are assumed.

- Mean Error (ME) = (1/n)Σ[f_i-o_i], where f_i is the forecast, o_i is the observation, and n is the total.
- Mean Absolute Error (MAE) = (1/n)Σ|f_i-o_i|, where f_i is the forecast, o_i is the observation, and n is the total.
- Advanced Warning Time (AWT): The time between the forecast issue time and event onset.

4.2.5 Alternate Definitions

The following metrics below were used in previous University of Malaga Solar Energetic Particles (UMASEP) and High Energy Solar Particle Event Forecasting and Analysis / Relativistic Electron Alert System for Exploration (HESPERIA/REleASE) validation efforts and are defined here to support this document.

- Average Warning Time (AWT): Time from model projection to first alert. **Note:** this definition also corresponds to Forecast Lead Time (Section 4.1.1).
- Intensity Error (UMASEP-100): Difference between the observed log10 intensity and the predicted log10 intensity at (event start time + 3h) [1].
- Root Mean Squared (RMS) Error (UMASEP-10): Error between the observed log10 intensity and the average of the predicted band of values (minimum and maximum, log10) at (event start time + 7h) [2]

4.3 Forecast Model Requirements

This section will outline requirements for new models to be considered by SRAG in support of Beyond-LEO missions. The goal of the model suite will be to close the gap between current operational capabilities and the new challenges introduced by the space environment during these missions.

SRAG seeks models that show improved metrics compared to the current state-of-the-art. Table 3 lists pre-eruption (Section 4.1) forecast examples, while Table 4 and Table 5 list post-eruption forecast examples. A detailed validation report (Section 5), including both the final metrics and the events used in their determination, is required to evaluate improvement over the existing capability.

Table 3: Example of metrics used to define models currently considered by SRAG to be state-of-the-art. These represent probabilistic, pre-eruption forecast of M- and X-class flares [10], X-class flares [10], and >10 MeV protons (H. Bain, private communication, publication under review). Note: currently no >100 MeV proton (ESPE) state-of-the-art forecast.

Forecast	Categorical Metrics	Probabilistic Metrics
SWPC 1-day M- and X-class flare forecast	POD=0.56, FAR=0.57, TSS=0.53, HSS=0.47	BSS (climatology)=0.031
SWPC 1-day X-class flare forecast	POD=0.49, FAR=0.57, TSS=0.49, HSS=0.45	BSS (climatology)=0.004
SWPC 1-day proton forecast	POD=0.62, FAR=0.16, TSS=0.61, HSS=0.70	BSS (climatology)=0.46, BSS (persistence)=0.25

*Table 4: Example of metrics used to define post-eruption models currently considered by SRAG to be state-of-the art. These models provide projections of onset and peak proton flux for energies of interest to human spaceflight operations (*RMS Error, **Intensity Error)*

Model	Output	POD	FAR	AWT	Error
UMASEP-10	>10MeV	0.81	0.34	05:10	0.41*
UMASEP-100	>100MeV	0.81	0.30	01:06	0.58**
UMASEP-500	>500MeV	0.54	0.30	00:08	N/A
REleASE (SOHO/EPHIN)	15.8-39.8MeV 28.2-50.1MeV	0.63	0.29	01:47	N/A

HESPERIA/REleASE (ACE/EPAM)	15.8-39.8MeV 28.2-50.1MeV	0.63	0.35	02:03	N/A

Table 5: Example of metrics used to define models currently considered by SRAG to be state-of-the-art. These models can be used for forecasting SEP flux time profile quantities, based on assessment performed internally at SRAG. TSS is NAN and HSS is low due to no events in the validation test set falling below operational thresholds.

Quantity	**Metrics**
SPE threshold crossing	POD=0.44, FAR=0, TSS=NAN, HSS=0
ESPE threshold crossing	POD=0.45, FAR=0, TSS=NAN, HSS=0.17
Onset time (>10 MeV)	ME=7.92, MAE= 7.92
Onset time (>100 MeV)	ME=8.17, MAE= 8.17
Peak intensity (>10 MeV)	MLE=-1.05, MALE=1.18
Peak intensity (>100 MeV)	MLE=-1.10, MALE=1.32
Time of peak (>10 MeV)	ME=7.94, MAE=8.02
Time of peak (>100 MeV)	ME=9.96, MAE=9.96
Event duration (>10 MeV)	ME=-32.79, MAE=47.09
Event duration (>100 MeV)	ME=8.63, MAE=31.19

Model requirements based on a detailed validation follow:

[SW 2001] The model suite shall produce a categorical forecast of event occurrence of M- and X-class flares, SPEs, and ESPEs (for pre-eruption models) and SPE/ESPE threshold crossing (for post eruption models). The model shall have an AWT no fewer than 2 hours and cadence not to exceed 6 hours.

Rationale: The knowledge that an event is imminent gives the SRAG operator situational awareness for further monitoring of the space weather environment and any necessary communications with the Flight Control Team (FCT).

[SW 2001V] The model suite shall demonstrate an improved POD, FAR, TSS, and HSS over the current state-of-the-art.

Rationale: Improvement over the current state-of-the-art forecasts such as those presented in Table 3, Table 4 and Table 5 are desired. Note that, in the context of this document, ‘state-of-the-art’ refers to models currently in use by the ISEP project and does not imply a comparison to outside work.

[SW 2002] A probabilistic model shall also produce a categorical forecast by applying a probability threshold (i.e., where a probability above this threshold is a "yes" forecast and a probability below this threshold is a "no" forecast) such that the POD, TSS, and HSS are maximized while the FAR is minimized.

Rationale: The FCT often asks if an event will occur or not. A categorical forecast is therefore desired. Applying a probability threshold will convert a probabilistic model into a categorical forecast. Maximizing the POD, TSS, and HSS while minimizing the FAR will provide SRAG console operators with confidence in their recommendations to the FCT.

[SW 2002V] The provision of a categorical forecast shall be verified by demonstration.

Rationale: The categorical provides additional information to support console operators when communicating with the FCT.

[SW 2003] A deterministic model that forecasts SEP flux shall also produce a categorical forecast by discretizing the forecast using SRAG's operational thresholds (i.e., where forecasted SEP flux above the operational threshold is a "yes" forecast and below is a "no" forecast).

Rationale: SRAG's operational thresholds are defined such that SEP flux above these thresholds poses a risk to crew health and operations. A categorical forecast of whether SEP flux will be above or below these operational thresholds will provide SRAG console operators with confidence in their recommendations to the Flight Control Team.

[SW 2003V] The provision of a categorical forecast shall be verified by demonstration.

Rationale: The categorical provides additional information to support console operators when communicating with the FCT.

[SW 2004] The model suite shall provide an All-Clear forecast for the occurrence of M- and X-class flares, SPEs, and ESPEs (for pre-eruption models) and SPE/ESPE threshold crossing (for post-eruption models). The cadence shall not exceed 6 hours.

Rationale: Knowledge that an event will not occur over a short duration (e.g., the next 24-72 hours) is useful for mission planning, including contingency EVA tasks.

[SW 2004V] The ability to provide an All-Clear forecast shall be verified by demonstration. The model shall meet the criteria presented in the All-Clear (pre-eruption) and All-Clear (post-eruption) definitions (Section 4.1.1).

Rationale: The criteria for All-Clear include a level of confidence beyond a simple categorical forecast in order to support console operators when communicating with the FCT.

[SW 2005] The SRAG model suite shall provide, upon observation of a Qualifying Event, a projection of time of threshold crossing of the >10MeV and >100MeV proton integral fluxes. The model suite shall demonstrate an AWT no fewer than 0.5 hours for prompt events and no fewer than 2 hours for gradual events.

Rationale: The radiation shelter on the Beyond-LEO vehicle is designed and tested to be set up and ingressed within 30 minutes after notification by the FCT. Additionally, preliminary radiation exposure assessments performed within SRAG indicate that mitigation steps in the first 2 hours of an event can effectively reduce total event dose.

[SW 2005V] The ability of the system to support projections of threshold crossing shall be verified by demonstration that a new model, when validated against historic events, has an improved ME and MAE over the current state-of-the-art (e.g., Table 5), with an AWT greater than 0.5 hours for prompt events and greater than 2 hours for gradual events.

Rationale: Advanced knowledge of time of threshold crossing, to the extent beyond that with currently existing models available to SRAG, will allow the SRAG operator to make a meaningful assessment of expected changes to the space environment during the ESPE. The operator will use this information when communicating any necessary radiation exposure mitigation steps to the FCT. Note that, in the context of this document, 'state-of-the-art' refers to models currently in use by the ISEP project and does not imply a comparison to outside work.

[SW 2006] The SRAG model suite shall provide, upon observation of a Qualifying Event, a projection of time and magnitude of peak flux for the following proton integral fluxes: >10MeV, >30MeV, >50MeV and >100MeV. The model shall demonstrate an AWT of no fewer than 2 hours.

Rationale: Preliminary radiation exposure assessments performed within SRAG indicate that mitigation steps in the first 2 hours of an event can effectively reduce total event dose. Predictions of the peak flux will help estimate the possible event dose and help console operators communicate mitigation steps with the FCT.

[SW 2006V] The ability of the system to support projections of time and magnitude of peak integral proton flux shall be verified by demonstration. A new model for consideration shall have an AWT no fewer than 2 hours, improved ME and MAE for time of peak flux over the current state-of-the-art (i.e., Table 5), and improved MLE and MALE for the magnitude of peak flux over the current state-of-the-art (i.e., Table 5).

Rationale: Advance knowledge of time and magnitude of peak integral proton flux, to the extent beyond that with currently existing models available to SRAG, will allow the SRAG operator to make a meaningful assessment of expected changes to the space environment during the ESPE. The operator will use this information when communicating any necessary radiation exposure mitigation steps to the FCT. Note that, in the context of this document, 'state-of-the-art' refers to models currently in use by the ISEP project and does not imply a comparison to outside work.

[SW 2007] The SRAG model suite should provide, upon observation of a Qualifying Event, a categorical forecast of GLE occurrence. The model shall demonstrate an AWT of no fewer than 2 hours.

Rationale: Predictions of highly energetic GLEs will help SRAG console operators characterize the severity of events.

[SW 2007V] The ability of the system to provide a categorical forecast of GLE occurrence shall be verified by demonstration by including the POD, FAR, TSS, and HSS.

Rationale: Ratios and skill scores from the categorical forecast will provide SRAG console operators with confidence in their assessment of the event.

[SW 2008] Upon SPE and/or ESPE event onset, the SRAG model suite shall provide initial and updated event time profiles, including event duration, until event termination.

Rationale: Advanced knowledge of event duration and profile will allow the SRAG operator to make a more meaningful assessment of expected changes to the space environment during the ESPE. The operator will use this information when communicating any necessary mitigation steps to the FCT.

[SW 2008V] The ability of the system to provide event time profile projections shall be verified by demonstration. Using an approved historic event data set, the model shall demonstrate improved metrics (i.e., ME and MAE for timing quantities, MLE and MALE for SEP flux quantities) over the current state-of-the-art.

Rationale: Cutting-edge magnetohydrodynamic (MHD) models show great promise in extending SRAG's ability to project the behavior of an event with time, improving the group's ability to mitigate event impacts. Work to improve the knowledge of the time profile of SPEs/ESPEs is being pursued as forward work through academic and small business collaborations.

[SW 2009] Probabilistic models shall provide a Reliability Diagram, including uncertainties.

Rationale: Reliability Diagrams (Figure 3) are a comparison between each forecast probability of event occurrence and the observed frequency of historic events. This information will provide a measure confidence to SRAG console operators, as the probability forecasted and its respective reliability can translate into SRAG's definitions of Low, Medium, and High Concern.

[SW 2009V] The reliability diagram, uncertainties, and knowledge of the historic event data set used in its derivation shall be verified by demonstration.

Rationale: Knowing the limitations of the model's reliability provides confidence to the console operators and the resultant recommendations for mitigation responses.

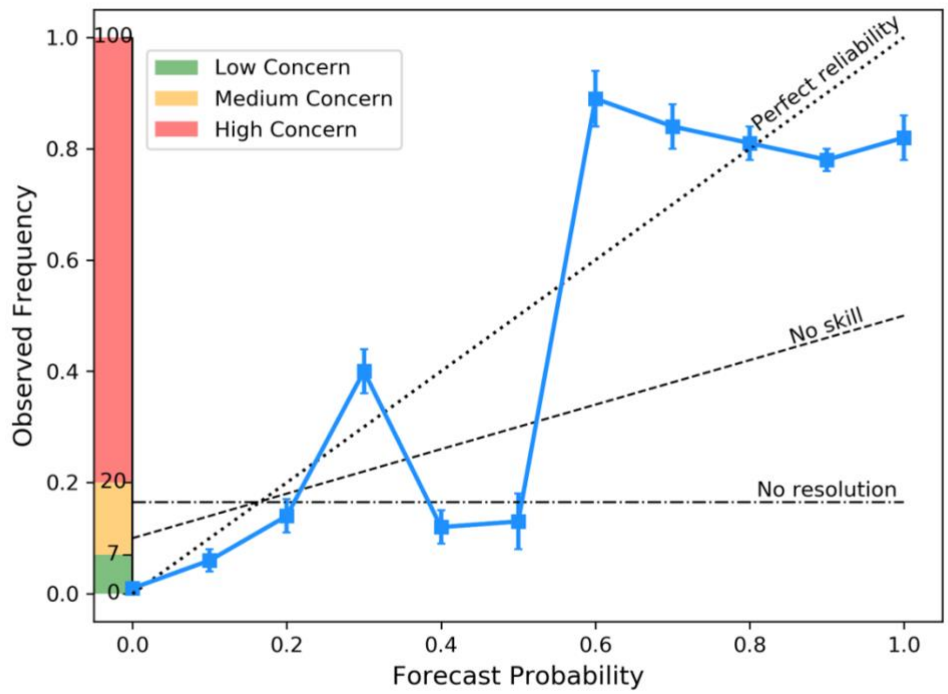

Figure 3: Example of a Reliability Diagram (toy data), comparing observed frequency of historic events with forecast probability of occurrence. Unity represents perfect reliability. The y-axis shows SRAG's definitions of Low, Medium and High Concern.

4.4 Current Space Weather Operational Support Model Capabilities

This section summarizes the current capabilities of space weather projection models that are available for operational use to SRAG in addition to requirements for any models for consideration in mission operations. Any additional models considered for the Beyond-LEO SRAG model suite should be an improvement in (1) existing functionality and/or (2) model accuracy. Table 6 summarizes the input data streams for the current suite of models under consideration by SRAG as those capable of performing the projections described above [1,2,4-9].

The current UMASEP suite of models uses the GOES satellite Soft X-Ray (SXR) and differential proton flux data as inputs. HESPERIA/REleASE uses the Electron Proton and Helium Instrument (EPHIN) sensor on SOHO/Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) and ACE/Electron, Proton, and Alpha Monitor (EPAM) data for input. The MAG4 tool uses a full disk magnetogram from SDO/HMI as an input. The ENLIL+SEPMOD (SEP MODel) coupling uses ENLIL to drive a solar wind solution, which uses a magnetogram from SDO/HMI and CME parameters derived via forecaster for inputs; SEPMOD uses the solution from ENLIL as its sole input. The SPE Threat Assessment Tool (STAT) only uses user inputs and pre-run flux rope CME simulations. The prediction inspired by the SEP STEReo (SEPSTER) model uses inputs of CME speed (typically provided by forecasters), connection angle (determined from spacecraft longitude), and spacecraft footpoint (computed by either a Parker Spiral model or ENLIL).

Table 6: Suite of space weather models under consideration by SRAG. Multiple instruments are indicated if the model has or plans to incorporate the capability to use the alternate data stream. PX = Differential Proton Data Channel.

Model	Output	1°Data Source	2°Data Source
MAG4	Event Probability	SOHO/MDI (prev. SDO/HMI) Magnetogram	Global Oscillation Network Group (GONG) Magnetogram
UMASEP (all)	Integral Proton Flux	GOES SXR (1.0 - 8.0 A)	Microwave Data (4.995, 8.8 and 15.4GHz) - no current real-time source indicated
UMASEP-10	>10MeV Proton Flux	GOES Differential Proton Flux P3(9-15MeV) - P7(165-500MeV)	None indicated
UMASEP-100	>100MeV Proton Flux	GOES Differential Proton Flux P6(80-165MeV) - P11(>700 MeV)	None indicated
UMASEP-500	>500MeV Proton Flux	GOES Differential Proton Flux P9-P11(>420MeV)	SOHO/EPHIN (100MeV - >1GeV)
REleASE	Differential Proton Flux	SOHO/COSTEP/EPHIN Relativistic Electrons (250keV-1MeV)	ACE/EPAM Near-Relativistic Electrons (175-315keV)
ENLIL+SEPMOD	>10 and >100 MeV Proton Flux (User specified)	ENLIL: Magnetogram, CME Parameters SEPMOD: Shock and Field Information from ENLIL	None indicated
SEPSTER	>10, >30, >50, >100 MeV Proton Peak Flux	CME Speed, Connection Angle, and Spacecraft Footpoint	None indicated
STAT	Time Profile of Proton Flux at User Specified Energies and GOES Energy Channels	User Chosen Pre-run Flux Rope CME Simulation, and User Inputs of Grid Resolution, Energy Levels, Mean Free Path, and Perpendicular Diffusion	None indicated

5 Verification and Validation Methods

This section summarizes validation and verification methods to be used in the comparison of models to be considered for use in Beyond-LEO mission support.

5.1 Definitions

The following definitions shall be used for system verification and validation:

- Forecast Mode: Operational use of model incorporating real-time and/or historic data sources.
- Testing Mode: Testing use of model as a phase of model development using optimized runs, where the developer interjects as needed to update parameters.
- Testing Data Set: Flare, SPE and/or CME data set aside for model testing. This data set shall not be used for model training.
- Trainable Model: An empirical model. Trainable models are further classified as re- trainable (by the end user) or not retrainable (trained only by the developer) for the purposes of validation.
- Training Data Set: Flare, SPE and/or CME data used for model development.
- Untrainable Model: A physics-based model.

5.2 Verification Requirements

Verification shall be defined as confirmation that the model meets the specified requirements and intended purpose. All models shall be installed and run functionally on the CCMC systems.

[SW 3001] Delivered model package shall include an executable, source code, and documentation that details model installation procedure, how to use it, how the theory is implemented, and the structure of the code to both JSC/SRAG and Goddard Space Flight Center (GSFC)/CCMC.

Rationale: The model source code, executable and detailed documentation are required for successful implementation on the JSC and GSFC systems.

[SW 3001V] Verification shall be performed by inspection and model use, to be considered successful when the end user (SRAG and/or CCMC) completes installation of the model on their internal system using the documentation provided by the vendor.

Rationale: The installation of the individual vendor model on the internal SRAG and CCMC network is necessary for completion of the overarching model suite and is therefore considered the endpoint for a successful delivery.

[SW 3002] Delivered models shall result in matching test case outputs upon successful platform-independent installation and execution by the end user (SRAG and/or CCMC).

Rationale: The final model suite is expected to be able to be used in multiple locales; therefore, platform-independence is required to limit potential roadblocks to adoption.

[SW 3002V] Verification shall be performed by inspection, to be considered successful upon installation and execution by the end user (SRAG and/or CCMC) that results in matching test case outputs.

Rationale: The installation of the individual vendor model on the internal SRAG and CCMC network is necessary for completion of the overarching model suite and is therefore considered the endpoint for a successful delivery.

[SW 3003] Delivered models shall provide meaningful error handling upon presentation with anomalous input and/or output values without critical failure, to be defined as follows:

- When satellite data input is unavailable or the associated server is down, the model shall display a meaningful error message indicating the missing data source. The model shall continue to run as originally scheduled without critical failure until input is available; however, any output generated shall either indicate that input is unavailable (caveat) or be presented in such a manner as to indicate to the end user that it is of degraded quality (e.g., a negative value).

- The model shall provide a check on the data input. When data input is available but highly inaccurate (e.g., very large/small value, negative value, NAN), the model shall display a meaningful error message indicating the faulty data source. The model shall continue to run as originally scheduled without critical failure until corrected input is available; however, any output generated shall either indicate that input is unavailable (caveat) or be presented in such a manner as to indicate to the end user that it is of degraded quality (e.g., a negative value).

- The model shall provide a check on the model output. When model output is highly inaccurate (e.g., very large/small value, negative value, NAN), the model shall display a meaningful error message indicating the faulty output. The model shall continue to run without critical failure.

Rationale: When the model is experiencing issues that prevent production of meaningful output, the end user shall be notified that (1) the current output should not be used for decision making and (2) investigation into the root cause may be needed.

[SW 3003V] Verification shall be performed by testing. A model shall be determined to be robust once testing is successfully completed.

***Rationale*:** Model robustness is required for a successful transition from research to operational mode.

5.3 Validation Requirements

Validation shall consider the accuracy of the model. When possible, validation will be performed by the end user as described below.

[SW 4001] Models that are not retrainable shall set aside a testing data set for validation that is not included in the model development.

Rationale: Model functionality cannot be validated using the same data set upon which the model was developed, i.e., the training data set.

[SW 4001V] Verification shall be performed by inspection. Model developers shall provide the training and testing data sets used, based on historical data, to SRAG and CCMC.

Rationale: The solar weather phenomenon of interest is sporadic in nature. The model validation shall be performed using historical events to eliminate the need to wait for future events for testing.

[SW 4002] If a model is retrainable, the model developer shall provide the testing and training data sets used during development.

Rationale: If a model is retrainable, SRAG and/or CCMC can use k-fold cross validation across all historical events to validate the model.

[SW 4002V] Verification shall be performed by inspection. Model developers shall provide the training and testing data sets, based on historical data, used to SRAG and CCMC.

Rationale: Provision of the training and testing data sets will allow SRAG and CCMC to understand results observed when performing k-fold cross validation.

[SW 4003] Trainable models shall be trained in forecast mode.

Rationale: Testing mode represents a condition where the developer is actively updating the model parameters to improve scientific capability. The transition from scientific (research) to operational (real-time) use requires a transition from testing to forecast mode.

[SW 4003V] Verification shall be performed by inspection. Developers shall confirm that models were trained in forecast mode.

Rationale: SRAG and/or CCMC will use all models operationally in forecast mode. No parameters will be updated during operational use.

[SW 4004] If a model is untrainable, the end-user shall have the ability to perform validation through comparison against historical event(s) modeled in forecast mode.

Rationale: The development of a physics-based model differs from that of an empirical model; by definition, no training or data sets are used.

[SW 4004V] Verification shall be performed by demonstration, comparing model results using historical event inputs against the actual historical event progression.

Rationale: Physics-based models use testing mode during development; validation shall be performed in forecast mode as real-time data is available to the end user.

6 Acronyms

ACE Advanced Composition Explorer
AIA Atmospheric Imaging Assembly
AWT Advanced Warning Time
AWT Average Warning Time

BS Brier Score
BSS Brier Skill Score

CCMC Coordinated Community Modeling Center
CH HSS Coronal Hole High Speed Stream
CME Coronal Mass Ejection
COSTEP Comprehensive Suprathermal and Energetic Particle Analyzer

DSCOVR Deep Space Climate Observatory

EMU Extravehicular Mobility Unit
EPAM Electron, Proton, and Alpha Monitor
EPHIN Electron Proton and Helium Instrument
ESPE Energetic Solar Particle Event
EVA Extra Vehicular Activity

FAR False Alarm Ratio
FCT Flight Control Team

GCR Galactic Cosmic Radiation
GLE Ground-Level Event
GOES Geosynchronous Orbit Earth observing Satellite
GONG Global Oscillation Network Group
GSFC Goddard Space Flight Center

HESPERIA High Energy Solar Particle Event Forecasting and Analysis
HMI Helioseismic and Magnetic Imager
HSR Human-System Requirements
HSS Heidke Skill Score

ISS International Space Station
IVA Intravehicular Activity

JSC Johnson Space Center

LASCO Large Angle and Spectrometric Coronagraph Experiment
LEO Low-Earth Orbit

MAE Mean Absolute Error
MALE Mean Absolute Log Error
MDI Michelson Doppler Imager

ME	Mean Error
MHD	MagnetoHydroDynamic
MLE	Mean Log Error
pfu	Particle Flux Unit (1/cm2-s-ster)
POD	Probability of Detection
POFD	Probability of False Detection
REleASE	Relativistic Electron Alert System for Exploration
RMS	Root Mean Squared
SDO	Solar Dynamics Observatory
SEP	Solar Energetic Particle
SEPMOD	Solar Energetic Particle MODel
SEPSTER	Solar Energetic Particle STEReo
SOHO	Solar and Heliospheric Observatory
SPE	Solar Particle Event
SRAG	Space Radiation Analysis Group
STAT	Solar Particle Event Threat Assessment Tool
STEREO	Solar Terrestrial Relations Observatory
SWPC	Space Weather Prediction Center
SXR	Soft X-Ray
TBD	To Be Determined
TBR	To Be Resolved
TBS	To Be Supplied
TSS	True Skill Score
UMASEP	University of Malaga Solar Energetic Particles

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