Systems-Level Space Environment Specification for Satellite and Ground System Operations

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The shorter-term variable impact of the Sun's photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment that can adversely affect technological systems is colloquially known as space weather. It includes, for example, the effects of solar coronal mass ejections, solar flares and irradiances, solar and galactic energetic particles, as well as the solar wind, all of which affect Earth's magnetospheric particles and fields, geomagnetic and electrodynamical conditions, radiation belts, aurorae, ionosphere, and the neutral thermosphere and mesosphere during perturbed and quiet levels of solar activity. We present a summary of two ongoing activities to understand, then mitigate, space weather risks and their impacts to operational systems. The first activity we report on is the development of a flare evolution model for predicting flare rise, timing and magnitude of peak fluxes, and decay to background levels. Secondly, we report on the ongoing development of the ISO 21348 "Process for Determining Solar Irradiances" standard. These two activities will help mitigate risks to operational technological systems from solar irradiances which can adversely affect operational space weather systems.

Nomenclature

EUV = extreme ultraviolet solar irradiances (10 – 121 nm)
λ = spectral irradiance wavelength designator
nm = nanometer (derived SI unit of length)
NSWP = National Space Weather Program
TRL = Technology Readiness Level
XUV = soft X-ray ultraviolet irradiances (0.1 – 10 nm)
$XUV_{0.1\text{–}0.8}$ = the GOES soft X-ray irradiances (0.1 – 0.8 nm)
X_{b10} = the $\log_{10}$ (unitless) number representing the lowest daily decile of the reported GOES $XUV_{0.1\text{–}0.8}$ minutely data
X_{hf} = the $\log_{10}$ (unitless) number representing the difference between the daily (previous running 24-hours) X_{b10} background value that is created hourly and the median of the $XUV_{0.1\text{–}0.8}$ measurements each hour

I. Introduction

The near-Earth space environment contains abundant energy that affects natural and technological systems. The primary energy sources in the space environment come from the conservation, transfer, or exchange of energy related to *photons, particles, and fields*. Galactic, solar, planetary, or other sources such as comets, gas, and dust produce photons, neutral and charged particles, as well as magnetic, electric, and gravitational fields. Together, these comprise the domain of the *space environment*.

The short-term variable impacts of these photons, particles, and fields upon the Earth's environment, especially from sources such as solar irradiances, the solar wind, and the solar interplanetary magnetic field, can adversely affect technological systems and, together, are colloquially known as *space weather*. The impacts include, for example, the effects from solar coronal mass ejections, solar flares and irradiances, and solar wind (including modulated galactic) energetic particles, all of which affect Earth's magnetospheric particles and fields, geomagnetic and electrodynamical conditions, radiation belts, aurorae, ionosphere, and the neutral thermosphere and mesosphere during perturbed as well as quiet levels of solar activity.

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The U.S. activity to understand, then mitigate, space weather risks is programmatically directed by the interagency National Space Weather Program (NSWP) and summarized in its NSWP *Implementation Plan*[1]. That document describes a goal to improve our understanding of the physics underlying space weather and its effects upon terrestrial systems. A major step toward achievement of that goal is being demonstrated with the development of operational space weather systems which link models and data to provide a seamless energy-effect characterization from the Sun to the Earth. As guidance to operational space weather projects, the NSWP envisions the evolutionary definition, development, integration, validation, and transition-to-operations of empirical and physics-based models of the solar-terrestrial system. An end result of this process is the self-consistent, accurate specification and reliable forecast of space weather.

The accurate and precise specification of solar irradiances, ranging from gamma-ray ($10^{-5} \leq \lambda < 10^{-3}$ nm) to radio ($10^{5} \leq \lambda < 10^{11}$ nm) wavelengths[2], is particularly important for space or ground system operations and engineering activities that are affected by space weather. Wavelengths, especially those shortward of 200 nm, not only deposit their energy in the Earth's thermosphere, mesosphere, and stratosphere as well as create the ionosphere but also provide energy affecting spacecraft components and surfaces through radiation, surface charging, surface degradation, and thermal balance effects (Fig. 1).

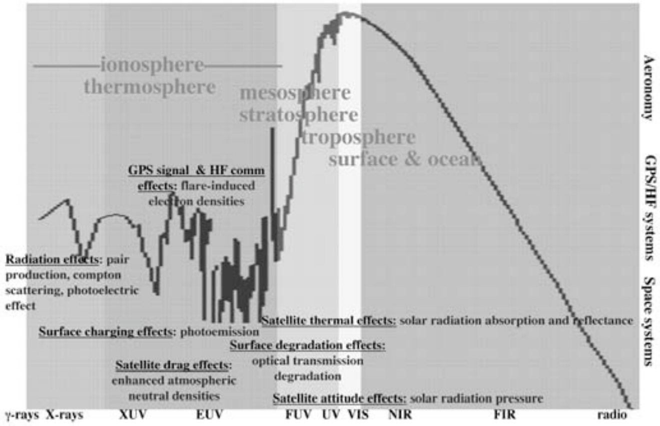

Figure 1. Photon effects in the space environment. *The solar spectrum and associated wavelength regions that affect aeronomy, GPS/HF systems, and space systems users.*

Operational solar irradiance products with sufficient accuracy and precision for contemporary applications have already been transferred to space weather operational users and have been previously reported[3,4,5]. In 2004, additional irradiance specification improvements have been developed including the *capability to predict the evolution of solar flares* immediately after their initiation as well as the *standardization* of irradiance products. Both improvements help mitigate solar irradiance risks to technological systems and these developments are reported in this paper. The main operational users motivating activities include those who require improved command and control capabilities and need updated ionospheric parameters including total electron content (TEC) for GPS signal reduced uncertainty and F2 region critical frequency, f_0f2, for HF propagation knowledge.

II. Mitigation of Space Weather Effects

A. Solar Flare Evolution Prediction

In this report, we demonstrate solar flare evolution prediction at the TRL 3 level (modeled proof-of-concept demonstration) and in 2005 we will move the algorithm to TRL 9 (system operations at Space Environment Technologies (SET)) within the SOLAR2000 model[6,7]. Flare evolution prediction does not estimate when a flare will occur but is, instead, the prediction of a flare's morphology once it has begun. Flare prediction, based on a physics understanding of helicity and magnetic flux tube energy transfer, as well as flare spectral energy distribution are both broad science topics of great contemporary interest. Our work complements the former activity and is the precursor step required to accurately define the latter.

Solar flare evolution prediction characterizes the initiation, timing of peak flux, magnitude of peak flux, and decay from peak flux to background levels for medium and large flares, i.e., those that are geoeffective. There is a two step process for characterizing flare evolution. First, a flare must be distinguished from the background irradiance component; a flare is short-lived (minutes to hours) and is determined by the energy content (helicity) and magnetic flux tube characteristics of localized solar magnetic fields. The transport of charged particles along flux tubes and their energy transfer processes produce irradiances across the spectrum. The background irradiances are long-lived and derive from different physical phenomena, especially a geometrical view relative to the central solar meridian as well as the long-term growth and decay of active regions that are surface manifestations of solar magnetic field evolution. Separating these two components is crucial for understanding how flares evolve beyond the background and we have created an X-ray background index, X_{b10}, and an X-ray flare index, X_{hf}, to define these two components.

The first, X_{b10}, is the $\log_{10}$ (unitless) number representing the lowest daily decile of the reported GOES $XUV_{0.1–0.8}$ minutely data (eq. 1). One-hour of minutely $XUV_{0.1–0.8}$ data is collected and the value of the lowest decile is saved. Over the course of a previous 24-hour period, the lowest of the twenty-four decile values is selected as the X_{b10} background value. The resulting X_{b10} index provides the best removal of flare effects we have found. Physically, it represents the $T \approx 10^6$ K coronal emission that gradually evolves on active region time scales. It is different from the solar 10.7-cm radio flux ($F_{10.7}$ index) which is created in the cooler $T \approx 10^4$ K transition region.

$$X_{b10} = 100 \log_{10} (XUV_{0.1–0.8} \times 10^{10}) \tag{1}$$

The second index, X_{hf}, is the $\log_{10}$ (unitless) number representing the difference between the daily (previous running 24-hours) X_{b10} background value that is created hourly and the median of the $XUV_{0.1–0.8}$ measurements each hour. This index provides a good estimate of $T \approx 10^6$ K or $T \approx 10^7$ K hot coronal flare activity. Figure 2, top panel, shows the $XUV_{0.1–0.8}$ measurements each hour for the two-month period of October 1 – November 30, 2003 during major flares. NOAA Space Environment Center (SEC) flare classes are listed on the right-hand side of the panel. The figure 2 bottom panel shows X_{b10} and X_{hf} separated from each other.

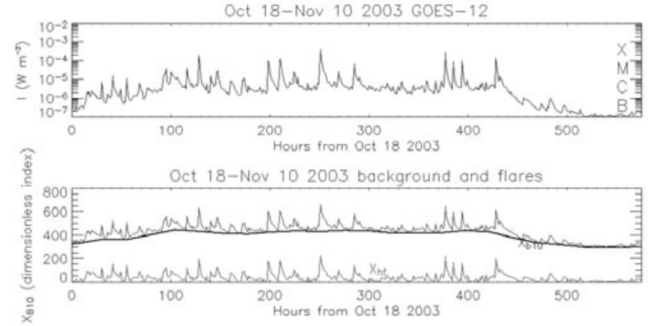

Figure 2. X-ray background and X-ray flares. *The GOES 0.1–0.8 nm X-ray data is shown in the top panel as reported by NOAA/SEC while the bottom panel demonstrates the* X_{b10} *and* X_{hf} *separated from one another during the Oct-Nov 2003 solar storm period.*

The flare initiation, timing of peak flux, magnitude of peak flux, and decay from peak flux to background levels for medium and large flares has been modeled using a correlation between the time rate of change of the flare, dX_{hf}/dt, and its magnitude. The variable, dX_{hf}/dt, is obtained after separating the X_{b10} background so that the actual flare start time, rise phase, and decay shape can be determined. Figure 3 shows the correlation of dX_{hf}/dt versus flare magnitude, figure 4 demonstrates the empirical flare model which uses a Gaussian combined with a quadratic function, figure 5 compares the flare model with two of the largest flares during the November 2003 storm period, and equations 2, 3, and 4 describe the flare model using only the dX_{hf}/dt and time, *t,* variables as input.

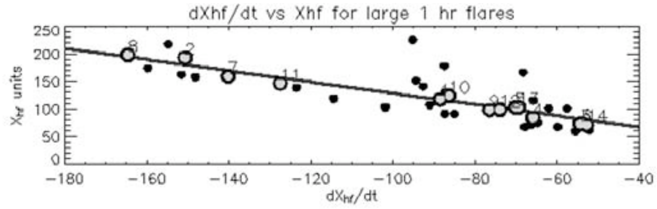

Figure 3. dX_{hf}/dt vs flare magnitude. *The (inverse) correlation between flare rate of change,* dX_{hf}/dt*, and flare magnitude is shown as the straight line with a correlation coefficient of –0.78; large flares that are compared with the model are shown as large circles and numbered.*

In 2005, at the TRL 9 level, SET will produce previous-hour X_{b10} and X_{hf} indices from the GOES $XUV_{0.1–0.8}$ measurements every 5 minutes in order to generate dX_{hf}/dt and the running 6-hour prediction of X_{hf} at that cadence. The resulting flare peak magnitude, timing, and duration will be combined with the running background level to then generate other irradiances and proxies for use in operational applications[6,7].

$$X_{hf}(t) = F(dX_{hf}/dt)\{-129.289e^{-z^2/0.5} + 150.746 - 50.9065t + 4.6531t^2\} \tag{2}$$

$$z = t/0.0964943 \tag{3}$$

$$F(dX_{hf}/dt) = 0.5\{0.897508 - 0.0195723(dX_{hf}/dt)\} \tag{4}$$

B. Space Environment Standardization

The International Standards Organization Technical Committee 20, *Aircraft and space vehicles*, Subcommittee 14, *Space systems and operations*, Working Group 4, *Space Environment – Natural and Artificial* has developed a Draft International Standard “Space environment (natural and artificial) – Process for determining solar irradiances”

(ISO 21348)[2]. The draft standard specifies the process for determining all representations of solar irradiances including measurements, reference spectra, empirical models, theoretical models, and solar irradiance proxies. The purpose of the standard is to provide common methods and formats for characterizing all solar irradiances for use by space systems and materials users. The space physics scientific community and other engineering disciplines will also be potential users of this standard.

ISO 21348 does not specify one measurement set, one reference spectrum, one solar model, or one solar irradiance proxy as a single standard. Instead, in order to encourage continual improvements in solar irradiance products, ISO 21348 is written as a process-based standard for determining solar irradiances. In other words, in the course of developing a solar irradiance product, a reporting process is followed in order to certify compliance with the standard and this ensures that a robustness of standardization is achieved. The process used for determining solar irradiances reported herein is compliant with ISO International Standard 21348: Space Environment (Natural and Artificial) – Process for determining solar irradiances (type 5 solar proxy for XUV and EUV irradiances).

III. Conclusion

We present a model of flare evolution for use by space and ground system operational users interested in characterizing solar irradiance energy input by time and magnitude for ionospheric and thermospheric applications. The model accurately detects the initiation of flares and predicts the peak flux timing and magnitude within 20%.

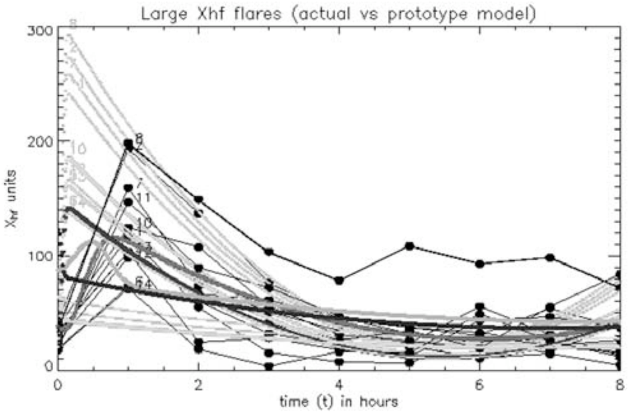

Figure 4. Flare evolution model. *The 1-hour flare data (black dots) are compared with several modeled flares (numbers are referenced to figure 3).*

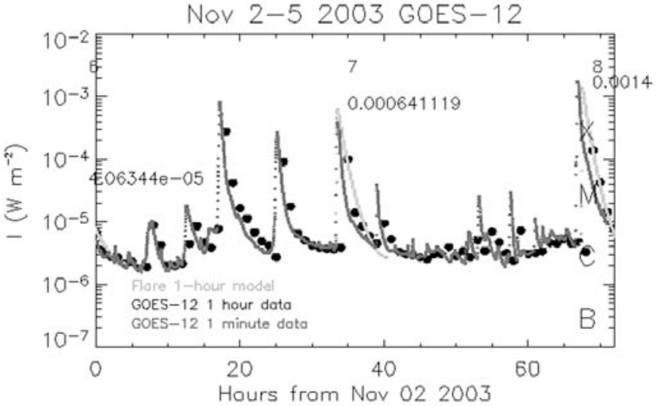

Figure 5. Flare evolution model compared with data. *The 1-hour flare data (black dots) and the 1-minute (gray dots) are compared the flare model for November 2–4, 2003 (integer numbers are referenced to figure 3 and real numbers are flare model irradiance values); magnitude uncertainties are ~20%.*

Acknowledgments

Support for this work has been provided by the NASA TIMED contract NAG5-11408 and by the NASA Living With a Star contracts NASW-02030 (GSFC) and 4200000428 (MSFC).

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