Solar flare evolution model for operational users

W. Kent Tobiska[a] and S. Dave Bouwer[b]
Space Environment Technologies

A solar flare evolution prediction model has been developed and placed into operations to mitigate flare-related risks to operational systems. The GOES 0.1-0.8 nm X-ray background flux is first determined and the residual flux is used to create a flare index value. The flare index is useful for determining the relative characteristics of a flare separate from its background, for comparison with other flares, and for determining flare initiation. Within the first five minutes of flare initiation, the flare evolution model predicts the flare rise, timing and magnitude of the peak fluxes, decay to half maximum, and termination at background levels. Based on the rise time, a flare is quantitatively categorized as small, medium, or large based on the absolute value of the flare index value and this enables the selection of a flare model shape. Using the convolution of Gaussian and quadratic functions for the modeled flare, the integral of the flare area (magnitude and duration) quantifies its integrated energy content which can be related to the flare's geoeffectiveness. A description of the flare evolution prediction model and its development for operations is presented. The solar flare evolution model and the operational system behind it is compliant with ISO 21348 "Process for Determining Solar Irradiances."

I. Introduction

The near-Earth space environment contains energy and energy transfer processes that affect 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 comprise the domain of the space environment.

The shorter-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 the effects from solar flares and irradiances, solar coronal mass ejections, and solar wind energetic particles (including modulated galactic cosmic rays). All these effects interact with 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.

The activity to understand and mitigate space weather risks is programmatically guided by the interagency National Space Weather Program (NSWP) and summarized in its NSWP *Implementation Plan* (2000). A major NSWP goal is to understand the physics underlying space weather and its effects upon terrestrial systems. A step towards achieving that goal is the development of operational space weather systems which link models and data to provide seamless energy-effect characterizations from the Sun-to-Earth. These systems are built on the evolutionary definition, development, integration, validation, and implementation of empirical and physics-based models for the solar-terrestrial system in order to provide self-consistent, accurate specifications and reliable forecasts of space weather. Space Environment Technologies (SET) develops and operates space weather systems, focusing especially on photon effects and their relation to technological systems.

The accurate and precise specification of solar irradiances, ranging from gamma-ray (γ-ray: $10^{-5} \leq \lambda < 10^{-3}$ nm), hard X-ray (X-ray: $10^{-3} \leq \lambda < 10^{-1}$ nm) and soft X-ray (XUV: $10^{-1} \leq \lambda < 10^{1}$ nm) to extreme ultraviolet (EUV: $10^{1} \leq \lambda < 1.21\times10^{2}$ nm) wavelengths (Tobiska and Nusinov, 2005), is particularly important for ionosphere-related space or ground system operations and engineering activities that are affected by space weather. These wavelengths not only deposit their energy in the Earth's thermosphere, mesosphere, and stratosphere as well as create the ionosphere

[a] Chief Scientist, Space Environment Technologies, 1676 Palisades Dr., Pacific Palisades, CA 90272
[b] Chief Engineer, Space Environment Technologies, 325 Broadway, Boulder, CO 80303

but also provide energy affecting spacecraft components and surfaces through radiation, surface charging, surface degradation, and thermal balance effects (Figure 1). In these short wavelength regions, solar flares can produce, in a matter of minutes, wavelength dependent irradiance increases from a factor of two to several orders of magnitude.

Flare effects upon the terrestrial ionosphere are especially important since the ionosphere's total electron content (TEC) can increase 10 to 20 TEC units (TECU) (1 TECU = 10^6 electrons m^{-2}) at low latitudes within a few minutes during severe solar flare events. Figure 2 shows an event during October 28, 2003 with vertical TEC increasing by 20 TECU in less than 10 minutes as measured at a low-latitude GPS ground station (labeled as NKLG) from 7 GPS satellite links. Rapid TEC changes such as this can create significant errors to navigation users (increased GPS signal uncertainty) and to radio systems (F2 region critical frequency, f_0F2, and HF propagation increased uncertainty).

To mitigate space weather effects resulting in reduced communication and navigation capabilities, SET has developed and implemented an operational system near Technology Readiness Level 9 (TRL 9). TRL 9 is defined as a successful operational capability that is a) fully integrated with operational hardware/software systems, b) thoroughly demonstrated and tested in its operational environment, c) documented, and d) supported by in-place sustaining engineering. The SET flare evolution prediction system provides the solar flare qualities that affect the TEC and operational users. These qualities include detection of flare initiation, timing of peak flux, magnitude of peak flux, decay from peak to full-width half-maximum (FWHM) flux values, timing of FWHM flux levels, and decay to pre-flare background levels. The SET flare prediction capability reported in this paper complements other operational solar irradiance products and applications such as those produced by SET with the SOLAR2000 model which have been previously reported (Tobiska, *et al.,* 2000; Tobiska, 2002; Tobiska, 2003a; Tobiska, 2003b).

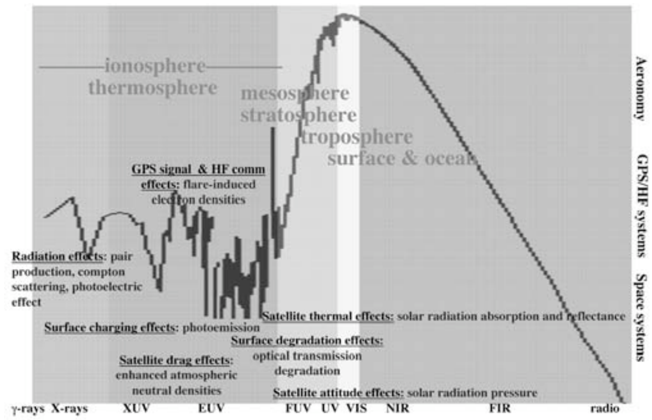

Figure 1**.** Solar irradiances affect aeronomy, communication, navigation, geolocation, and space systems users.

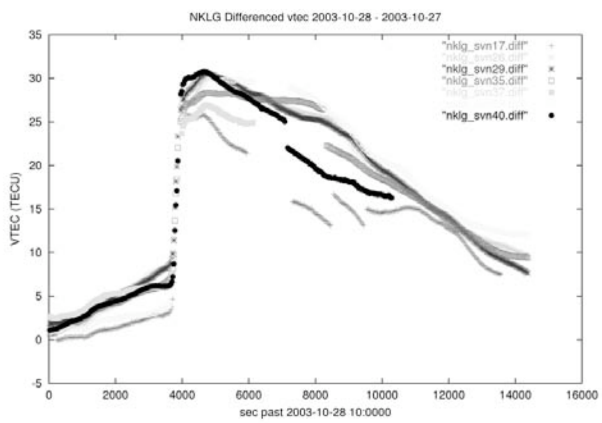

Figure 2. Example of TECU comparisons using GPS TEC data for flare conditions (figure courtesy of X. Pi).

II. Discussion

A. Solar Flare Evolution Prediction

In this paper, we demonstrate solar flare evolution prediction at the TRL 8 (operational prototype demonstration) – TRL 9 level. We have previously reported on the development of this capability starting at TRL 3 (model development and proof-of-concept demonstration) (Tobiska, 2004; Tobiska and Bouwer, 2005; Tobiska, 2005). Flare evolution prediction does not forecast when a flare will occur but is the prediction of flare morphology and flare qualities once it has begun. Flare forecasting (predicting when a flare will occur) relies upon a physical understanding of helicity and magnetic flux tube energy transfer. Specifying flare spectral energy distribution/partitioning is based upon a physical understanding of solar photon radiative transfer. Both of these topics enjoy contemporary scientific interest and the work presented in this paper supplements flare forecasting while providing comparative information that is useful for understanding flare spectral energy partitioning.

The solar flare evolution prediction model used in this work has been previously described (Tobiska, 2005) and characterizes the detection of flare initiation, timing of peak flux, magnitude of peak flux, decay from peak to FWHM flux values, timing of FWHM flux levels, and decay to pre-flare background levels for small, medium, and large flares. Small, medium, and large flares are defined by the magnitude of the flare index that is described below (small indicates index values of ≤50, medium equals 50–100, and large equals ≥100). Medium or large flares tend to be geoeffective.

As described by Tobiska (2005), a multiple-step process is used to characterize flare evolution. First, a flare must be distinguished from the active region background irradiance from which it emerges. Active regions are long-lived (months) manifestations of bundled solar magnetic field lines configured in a semi-balanced relationship at a regional heliocentric longitude and latitude. On the other hand, when the magnetic field line interactions become energetically imbalanced, the energy content (helicity) changes and local energy releases can occur over a very short time (minutes to hours) thus producing a flare. The acceleration of charged particles along magnetic field line flux tubes and their subsequent energy state changes produce elevated irradiance levels across the spectrum.

Separating these two components (background and flare) is crucial for understanding how flare irradiances are spectrally and temporally very different from the background irradiances. Therefore, as a first step in the flare evolution prediction process, we create an X-ray background index, X_{b10}, and an X-ray flare index, X_{hf}, to specify these two components. X_{b10} is the $\log_{10}$ (unitless) number representing the lowest daily (running 24-hour) decile of the reported GOES 0.1–0.8 nm ($XUV_{0.1–0.8}$) minute-cadence data. X_{hf} is the $\log_{10}$ (unitless) number representing the difference between the daily (previous running 24-hours) X_{b10} background value, created every two minutes operationally but calculated for the previous hour interval, and the $XUV_{0.1–0.8}$ measurements over the previous hour. The X_{b10} index provides the most effective removal of flare effects we have found and it physically represents the 10^6 K coronal emission that gradually evolves on active region time scales. It behaves differently from the solar 10.7-cm radio flux ($F_{10.7}$ index) which is created in the cooler 10^4 K transition region. The X_{hf} index provides a good estimate

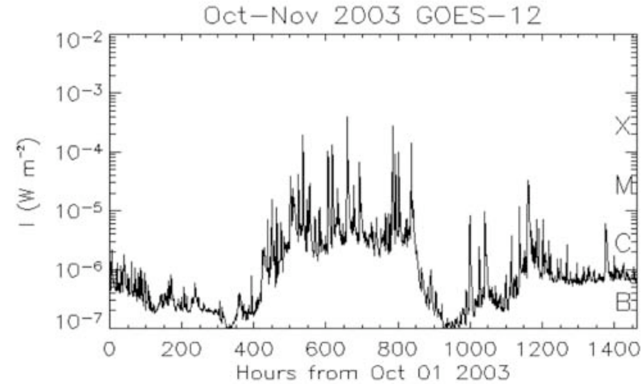

Figure 3. The GOES 0.1–0.8 nm X-ray data as reported by NOAA/SEC during the October-November 2003 solar storm period.

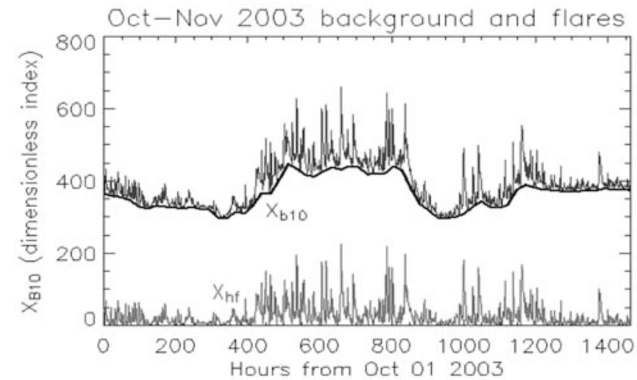

Figure 4. The X_{b10} and X_{hf} separated from one another during the October-November 2003 solar storm period.

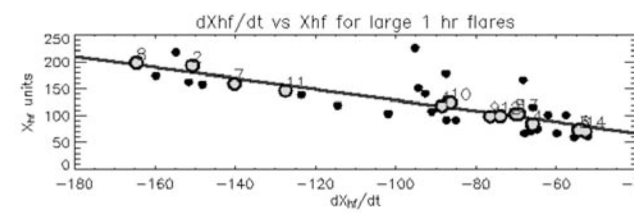

Figure 5. The (inverse) correlation between flare rate of change, dX_{hf}/dt, and flare magnitude (straight line) with a correlation coefficient of –0.78; large flares (numbered circles) are shown in figure 6.

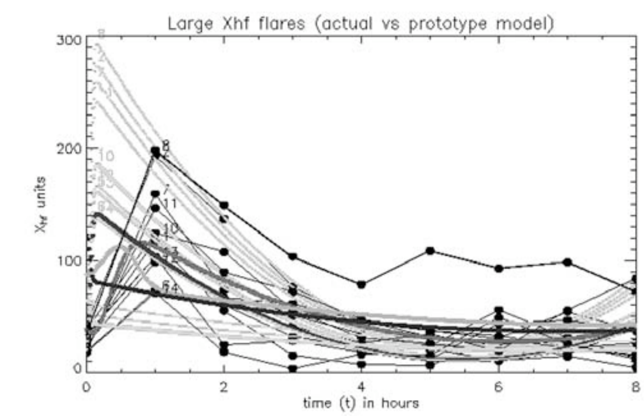

Figure 6. The 1-hour flare data (connected black dots) are compared with several modeled flares (light gray lines).

of 10^6 K or 10^7 K hot coronal flare activity. The summation of X_{b10} and X_{hf} and their rescaling is the reconversion back to irradiance units.

As an example of this step, Figure 3 shows the monitored $XUV_{0.1–0.8}$ measurements each hour for the two-month period of October 1 – November 30, 2003 during major flares. The NOAA Space Environment Center (SEC) flare classes are listed on the right-hand side of the figure. Figure 4 shows the second step of separated X_{b10} and X_{hf} for the same time period.

At this point, it is possible to detect flare initiation. Once this has occurred, the timing of peak flux, magnitude of peak flux, decay from peak to FWHM flux values, timing of FWHM flux levels, and decay to pre-flare background levels for all sizes of flares is modeled using the correlation between the time rate of change of the flare, dX_{hf}/dt, and its magnitude as described by Tobiska (2005). Figure 5 shows the correlation of dX_{hf}/dt versus flare magnitude. Figure 6 demonstrates the final step of flare modeling with several cases using the convolution of Gaussian and quadratic functions. The quadratic function creates a minimum at some time, *t,* after the flare peak (approximately 6 hours after flare start in the large flare cases) and this minimum is used as the flare cut-off value which defines the flare duration and stop time. For medium and small flares, the cut-off time is less than 6 hours, typically varying from 3 to 5 hours. The only input to the flare model is the dX_{hf}/dt derived variable and, depending upon the magnitude of X_{hf}, a small, medium, or large flare model case is selected. There is one set of flare equations for each of the three sizes of models and only fast-rising flares (larger absolute magnitude dX_{hf}/dt) are now modeled.

B. Operational implementation of flare evolution prediction

SET's operational system on its proprietary server uses a combination of IDL® and Java routines to monitor the GOES-10 $XUV_{0.1–0.8}$ every 2 minutes as reported by the NOAA Space Environment Center (SEC). The algorithms automatically detect a flare's initiation as determined by the dX_{hf}/dt derived variable and, using the X_{hf} flare index, the model size is determined so that the flare qualities can be generated using the convolution of Gaussian and quadratic functions. Validation of the flare qualities is performed at several levels including pre-operations verification of flare predictions versus actual data for solar quiet to solar active conditions (figures 7 and 8). Other operational checks include those for missing X-ray input data, out-of-bounds input and output values, and interrupted server processes. There is a data value reported every 1 minute from GOES while SET monitors the SEC data stream with a cadence of 2 minutes. Including processing and data transfer times, there is a total data latency consisting of the following components: the SEC site is updated every 4-6 minutes (varying with SEC server traffic), data extraction from SEC is counted in seconds and flare model processing takes 1-2 minutes (varying with the number of flares during the previous 72-hours that must be modeled); JPEG and ASCII file transfer from the SET server to the SET website is counted in seconds and this results in a total latency of 5-8 minutes. The latency can be cut to 2-3 minutes when SET extracts the $XUV_{0.1–0.8}$ data directly from SEC's internal database rather than its web site.

In figures 7 and 8, the previous 72-hours and the current epoch (right side of plots) are shown.

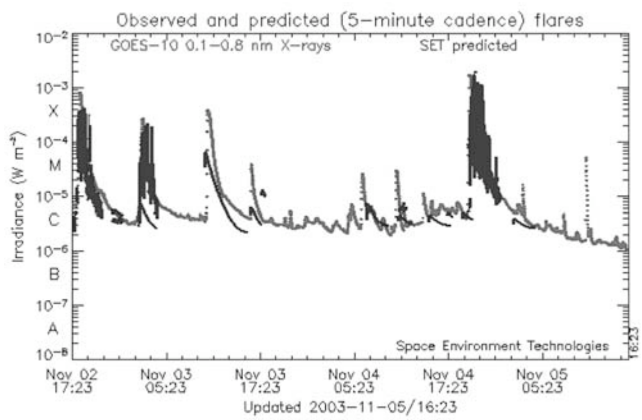

Figure 7. The flare prediction model results (heavy dark lines) compared with actual 1-minute GOES $XUV_{0.1–0.8}$ data for November 2-5, 2003 during a period of active solar activity. There are multiple predictions (every 5 minute window) for the historical 72-hour data. The current epoch is the plot right edge.

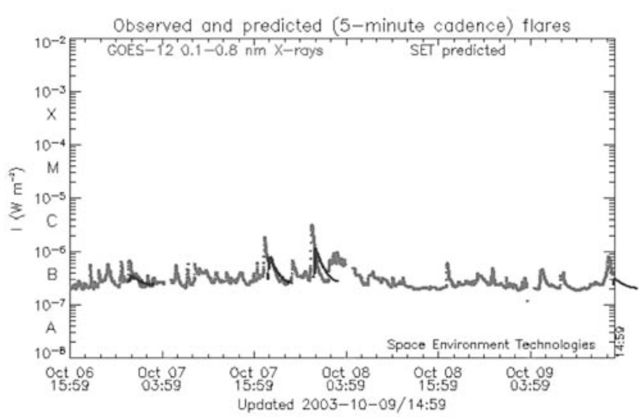

Figure 8. The flare prediction model results (heavy dark lines) compared with actual 1-minute GOES $XUV_{0.1–0.8}$ data for October 6-9, 2003 during a period of quiet solar activity.

The flare and data values for every minute are shown but the flares are calculated over a sliding 5-minute window that reduces processing time during operations. Since the plots are updated every 1 minute on the web browser using 2-minute updated data files from SEC, there will often be slight differences between successive plots from minute to minute as the 72-hour historical flares are calculated with slightly different dX_{hf}/dt derived values each 1-minute run. Forecast flares will overhang the right side of the plot.

Details for each predicted flare are provided every minute via a web browser's automatic update (http://SpaceWx.com and the flare quick-link menu item). The flare start, peak, FWHM, and end UT times in calendar, YYYYMMDDhhmm, and Julian date formats (to the minute level of time resolution) are provided for each flare event. Additionally, the irradiance values (W m^{-2}) and 3-sigma percentage uncertainties are provided for each flare event. The flare class and magnitude are defined for each flare as are the background flux values in X_{b10} units. The integrated flare energy in units of $\log_{10}$(Joules) are calculated for the total energy arriving at the circular area extending to the top of the Earth's atmosphere (the exobase at 500 km). The integrated flare energy is provided so that flares can be compared to determine their geoeffectiveness. This will eventually provide new flare metrics and categories. SET provides text describing flare status, monitors the flare progress, and anticipates predicted flare effects on five user communities: communications, navigation, LEO orbital environment, LEO spacecraft surfaces and systems, and GEO spacecraft surfaces and systems. Metrics for prediction skill score are being developed and will be reported in a separate paper.

In summary, SET provides, through fully automated operational code, predicted flare evolution information on rise phase, timing and magnitude of the flare peak, timing and magnitude of full-width half maximum during the decay phase, and timing of the flare end as well as the 3-sigma uncertainties associated with each of these events. The capability is currently available via internet access to SET's server. In the second half of 2005, the capability will be expanded as a standalone system and SET will provide text and email messaging services for flare alerts. SET is also making available historical flare and indices values in late 2005.

III. ISO 21348 compliance

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) (Tobiska and Nusinov, 2005). 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.

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 predicting solar flare irradiances reported in this paper is compliant with ISO International Standard 21348: Space Environment (Natural and Artificial) – Process for determining solar irradiances (types 3 and 5, i.e., modeled solar XUV irradiances and proxies).

IV. Conclusion

Space Environment Technologies has developed and operationally implemented a solar flare evolution prediction system to mitigate flare-related risks to operational systems. The GOES 0.1-0.8 nm X-ray background flux, X_{b10}, is first determined and the residual flux is used to create a flare index, X_{hf}. The time rate of change of the X_{hf} flare index is used to detect flare initiation and, once determined, a small, medium, or large flare evolution model predicts the timing of peak flux, magnitude of peak flux, decay from peak to FWHM flux values, timing of FWHM flux levels, and decay to pre-flare background levels for all sizes of flares. Modeling is performed using a correlation between the time rate of change of the flare, dX_{hf}/dt, and its magnitude. Using Gaussian and quadratic equations to functionally model only fast-rising flares presently, the integral of the flare area (magnitude and duration) is calculated to quantify its integrated energy content which can be related to the flare's geoeffectiveness. The solar flare evolution model output is reported on SET's web site and the operational system behind it is compliant with ISO 21348 "Process for Determining Solar Irradiances."

Acknowledgments

Support for this work has been provided by the Space Environment Technologies Solar Flare Initiative research and development effort (2004-2005). The flare evolution prediction can be obtained real-time at the http://SpaceWx.com web site, FLARE QUICK-LINK menu item.

References

National Space Weather Program Implementation Plan, 2nd Edition, FCM-P31-2000, Washington, July 2000.

Tobiska, W.K., E10.7 use for global atmospheric density forecasting in 2001, AIAA 2002-4892, AIAA Aerospace Sciences Meeting, Reno, NV, January, 2002.

Tobiska, W.K., Forecasting of space environment parameters for satellite and ground system operations, AIAA 2003-1224, AIAA Aerospace Sciences Meeting, Reno, NV, January, 2003a.

Tobiska, W.K., Forecast E10.7 for Improved LEO Satellite Operations, J. Spacecraft Rock., 40 (3), 405-410, 2003b.

Tobiska, W.K., SOLAR2000 irradiances for climate change research, aeronomy, and space system engineering, *Adv. Space Res.,* 34, 1736-1746, 2004.

Tobiska, W.K., Systems-Level Space Environment Specification for Satellite and Ground System Operations, AIAA 2005-0069, AIAA Aerospace Sciences Meeting, Reno, NV, January, 2005.

Tobiska, W.K., T. Woods, F. Eparvier, R. Viereck, L. Floyd, D. Bouwer, G. Rottman, and O.R. White, The SOLAR2000 empirical solar irradiance model and forecast tool, *J. Atm. Solar Terr. Phys.,* **62,** 14, 1233-1250, 2000.

Tobiska, W.K. and S.D. Bouwer, New Developments in SOLAR2000 for Space Research and Operations, *J. Adv. Space Res.,* in review, 2005.

Tobiska, W.K. and A.A. Nusinov, Status of ISO draft international standard for determining solar irradiances (DIS 21348), *J. Adv. Space Res.,* in review, 2005.