SOLAR2000 v2.30 and SOLARFLARE v1.01: New Capabilities for Space System Operations

W. Kent Tobiska[*]
Space Environment Technologies, Pacific Palisades, CA, 90272

Space system operational and mission planning users have indicated a strong interest in a) high time- and spatially-resolved irradiances, b) historical 3-hour data, c) improved proxies, indices, and formats, as well as d) new models and datasets. The applications for solar irradiance products that have been identified as most important include characterizations of neutral atmosphere and ionosphere densities along with spacecraft materials' properties under energetic photon bombardment and photon-induced surface charging. We report on major improvements to the SOLAR2000 (S2K) model series that addresses these user interests. First, for the neutral density users, the $S_{10.7}$ index (26-34 nm EUV) of chromospheric plage and active region extreme ultraviolet solar irradiance and the $M_{10.7}$ proxy (145-165 nm FUV) of aeronomically important photospheric background and network Schumann-Runge Continuum far ultraviolet irradiances are now provided. These complement the traditional $F_{10.7}$ proxy for transition region/cool corona active region XUV–EUV (0.1-121.0 nm) energy. These three daily and 81-day smoothed indices/proxies, with 1-, 5-, and 1-day lags, respectively, are the drivers for the new Jacchia-Bowman empirical thermospheric density model (JB2006) that has reduced by half mass density uncertainties compared to previous Jacchia- and MSIS-type models. Second, for ionosphere and spacecraft surface users, nowcast data is assimilated real-time in S2K from the GOES XRS instrument with 2-minute cadence, 1-minute granularity, 7-minute latency, and 6-hour predicts relative to the current epoch. These are used to produce data-driven high time and spectral resolution, physics-based real-time flare evolution assessment through SOLARFLARE. SOLAR2000 continues to produce 1-hour cadence, 1-day granularity, and 4.5-month predicts of high spectral resolution irradiances or broadband indices. The combination of these changes is that S2K has been transformed into a hybrid model that includes physics-based, observation-based, and data-driven modeling.

Nomenclature

EUV	=	*extreme ultraviolet solar irradiances ($10 \leq \lambda < 121$ nm)*
$F_{10.7}$	=	*10.7-cm radio flux proxy for solar EUV in solar flux units (sfu) of $\times 10^{-22}$ W m^{-2} Hz^{-1}*
FUV	=	*far ultraviolet solar emissions ($122 \leq \lambda < 200$ nm)*
ISO 21348	=	*International Standards Organization standard 21348 for determining solar irradiances*
JB2006	=	*Jacchia-Bowman empirical thermospheric density model (2006)*
$M_{10.7}$	=	*proxy for far ultraviolet solar irradiances between $145 - 165$ nm reported in sfu*
NOAA SEC	=	*National Oceanic and Atmospheric Administration Space Environment Center*
$S_{10.7}$	=	*index for extreme ultraviolet solar irradiances between $26 - 34$ nm reported in sfu*

---

[*] Chief Scientist, Space Environment Technologies, 1676 Palisades Dr., Pacific Palisades, CA 90272; Senior AIAA Member.

S2K   = *SOLAR2000 hybrid solar irradiance model*
SFLR   = *SOLARFLARE high time and high spectral resolution model for predicted flare evolution*
SRC   = *Schumann-Runge Continuum solar emissions ($125 \leq \lambda < 175$ nm)*
TRL   = *Technology Readiness Level*
XUV   = *soft X-ray solar irradiances ($0.1 \leq \lambda < 10$ nm)*

Motivation for improved irradiances

The motivation for improving solar spectral irradiances and solar indices or proxies comes from space system operational and mission planning users who have a strong interest in a) high time- and spectrally-resolved irradiances, b) historical 3-hour data, c) improved proxies, indices, and formats, as well as d) new models and datasets. These interests were identified through a Space Environment Technologies (SET) survey conducted in the Fall of 2005 among 488 worldwide users of the SOLAR2000 (S2K) model[1,2,3]. Among the solar irradiance users who received the survey (http://sol.spacenvironment.net:9006/sol/registerUser.html), 12% responded to two multiple choice questions that helped identify which solar products were most important to them and in what applications solar irradiances are most used. The most important identified applications for solar irradiance products were characterizations of neutral upper atmosphere and ionosphere densities along with spacecraft materials' properties under energetic photon bombardment and photon-induced surface charging.

Examples of the multiple uses for solar indices that drive neutral thermospheric density models are shown graphically in figure 1. Represented are activities that span a range of timescales (historical, nowcast, and forecast) for a variety of operational scenarios (anomaly analysis, collision avoidance, reentry, and planning). In all cases, a solar index must be energetically self-consistent across all dimensions of space systems and space weather operations.
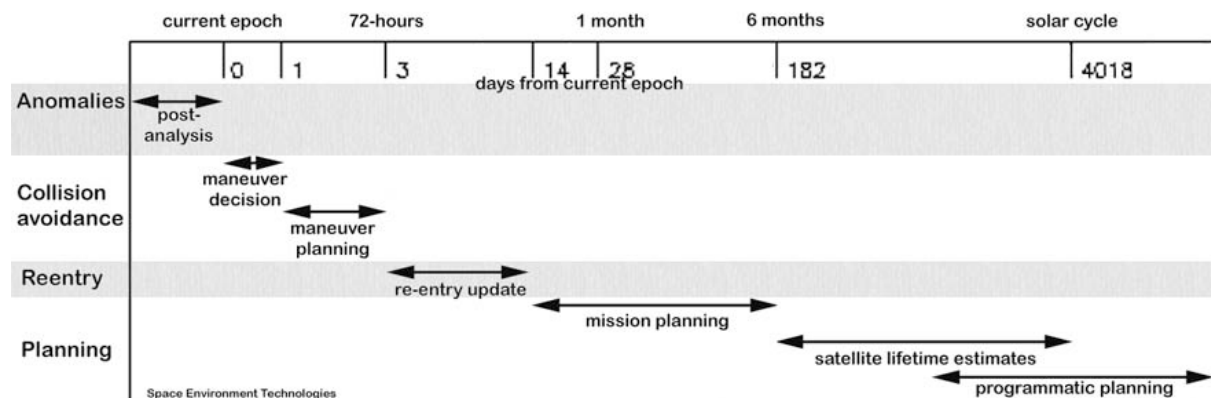

Fig. 1. Solar indices are used for neutral thermospheric density specification across a range of timescales from historical, nowcast (current epoch), and forecast (minutes to solar cycles). Space systems activities requiring solar indices are for anomaly post-analysis, collision avoidance (maneuver decision and planning), reentry update, and planning (mission, vehicle lifetime, programmatic) purposes.

We describe in this paper specific improvements to S2K that address the strong interests of space systems users. New solar indices, the $S_{10.7}$ index (26-34 nm EUV) of chromospheric plage and active region extreme ultraviolet irradiance, the $M_{10.7}$ proxy (145-165 nm FUV) for the aeronomically important photospheric background and network Schumann-Runge Continuum far ultraviolet irradiance, and the traditional $F_{10.7}$ are described. They are used in the new Jacchia-Bowman empirical thermospheric density model (JB2006)[4,5,6] that has reduced by half mass density uncertainties compared to previous Jacchia- and MSIS-type models. The $S_{10.7}$ index in all

American Institute of Aeronautics and Astronautics

time scales is produced by the APEX v3b data processing system described below. SET uses external data suppliers to produce forecasts of $F_{10.7}$ and $M_{10.7}$ solar proxies. Also described in this paper are the high time and high spectral resolution irradiances provided through SOLARFLARE (SFLR) v1.01, which incorporates the Mewe model.

Improvements to SOLAR2000 indices and proxies

The development and selection of $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar proxies and indices, shown in figure 2 with respect to the unit optical depth of photoabsorption by terrestrial atmosphere species, are described in previous work[6,7] for use in the JB2006 model. We use the definitions from ISO 21348[8] for solar irradiance indices and proxies: a solar irradiance *proxy* is a measured or modeled data type that is used as a *substitute* for solar spectral irradiances while a solar irradiance *index* is a measured or modeled data type that is an *indicator* of solar spectral irradiance activity level. The important details of these proxies and indices are summarized here.

F$_{10.7}$: The 10.7-cm solar radio flux, $F_{10.7}$, is produced daily at the ground-based Dominion Radio Astrophysical Observatory located in Penticton, British Columbia. The physical units of $F_{10.7} = \times 10^{-22}$ W m^{-2} Hz^{-1} and we use the numerical value without the multiplier expressed as solar flux units (sfu) as is customarily done. In other words, a 10.7-cm radio emission of 150×10^{-22} W m^{-2} Hz^{-1} is simply referred to as $F_{10.7} = 150$ sfu. The running 81-day centered smoothed values, using the moving boxcar method, is created and these data are referred to as F_{81}. For the convenience of comparisons, we use linear regression with daily $F_{10.7}$ to scale and report all other solar indices in units of sfu, including their 81-day averages. Missing data values are not included in the regressions.
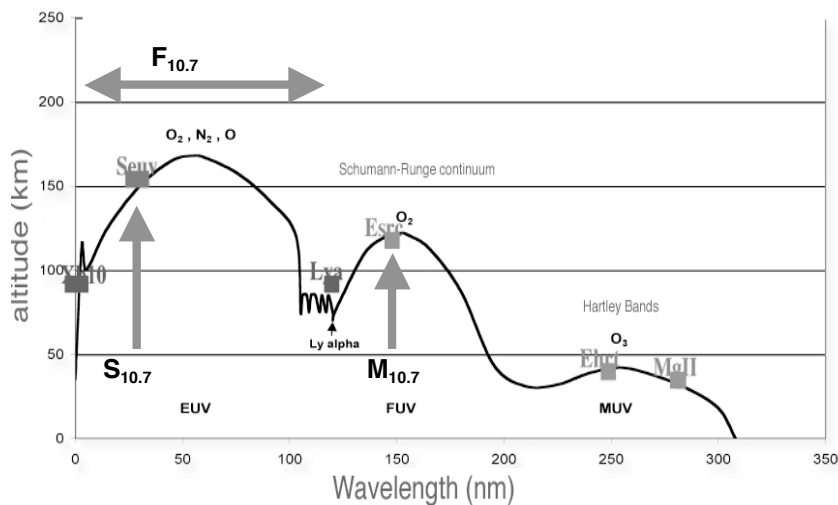
Fig. 2. Unit optical depth (altitude of maximum heating) for solar irradiances ranging from X-ray to MUV wavelengths. Neutral species that participate in heating are labeled in black and index designator for selected bandpasses are shown in gray.

$F_{10.7}$ is the traditional solar energy proxy that has been used since Jacchia developed empirical exospheric temperature equations for atmospheric density models. It's formation is physically dominated by non-thermal processes in the solar transition region and cool corona and, while it is a non-effective solar emission relative to the Earth's atmosphere, it is a useful proxy for the broad combination of chromospheric, transition region, and coronal solar EUV emissions modulated by bright solar active regions whose energy, at Earth, is deposited in the thermosphere. It is used with a 1-day lag in the JB2006 model.

S$_{10.7}$: The NASA/ESA Solar and Heliospheric Observatory (SOHO) research satellite operates in a halo orbit at the Lagrange Point 1 (L1) on the Earth-Sun line, approximately 1.5 million km from the Earth, and has an uninterrupted view of the Sun. One of the instruments on SOHO

American Institute of Aeronautics and Astronautics

is the Solar Extreme-ultraviolet Monitor (SEM)[9] that was built and is operated by University of Southern California's (USC) Space Science Center (SSC). As part of its continuous solar observations, the SEM instrument measures the 26–34 nm solar EUV emission with 15-second time resolution in its first order broadband wavelength range as shown in figure 3 (December 7, 2006). These data are produced by the APEX v3b data processing system developed by SET for USC SSC. The orbit and solar data are both retrieved daily by APEX for automated processing in order to create 15-second and daily solar irradiances with a latency of at least 24 hours.
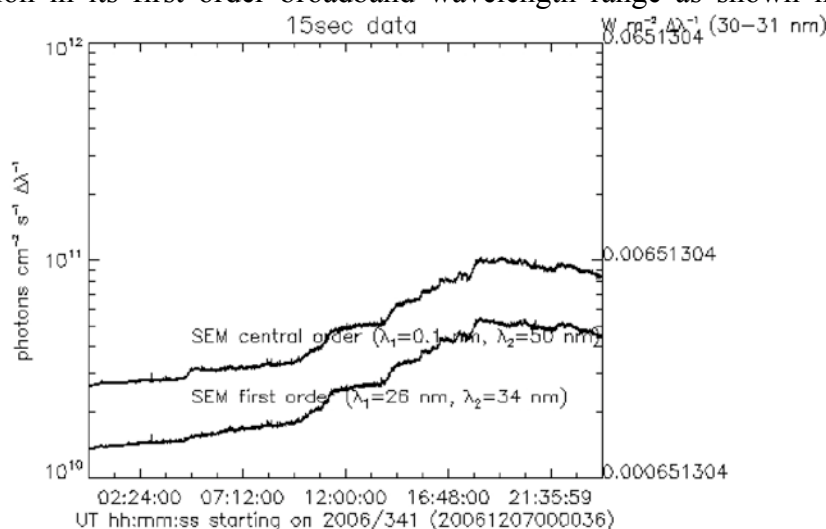

Fig. 3. SOHO SEM 15-second data in 2 channels (first order 26-34 nm, central order 0.1-50 nm) produced by the APEX v3b system and used to create $S_{10.7}$.

We use the integrated 26–34 nm emission and normalize it by dividing the daily value by the solar cycle 23 mean value, 1.9955×10^{10} photons cm^{-2} s^{-1}, for the 26-34 nm bandpass. The normalized value is converted to sfu through linear regression with $F_{10.7}$ over solar cycle 23 and the resulting index is called $S_{10.7}$. Figure 4 shows the $S_{10.7}$ index and the S_{81} (81-day centered smoothed) values for 1996–2005 compared with the TIMED SEE[10] data (2002–2005); the latter is integrated over the
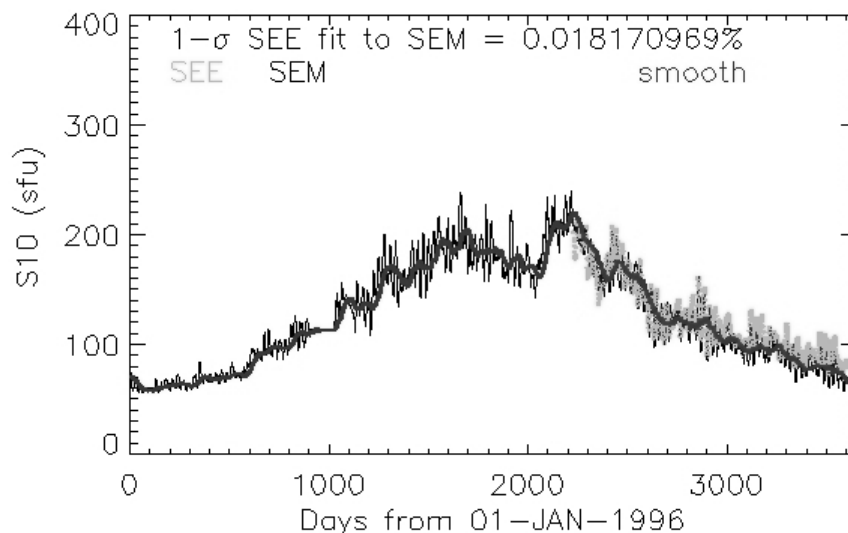

Fig. 4. $S_{10.7}$, as created from the SOHO SEM data, shown in dark gray from 1996 into 2005 in sfu and 81-day centered smooth shown in black. The light gray data beginning near the peak of solar cycle 23 and continuing to solar minimum is the TIMED SEE data integrated over the 27-34 nm bandpass and reported in sfu.

27-34 bandpass and reported in sfu.

The broadband SEM 26-34 nm irradiances, represented by the $S_{10.7}$ index, are EUV line emissions dominated by the chromospheric He II line at 30.4 nm with contributions from nearby chromospheric and coronal lines. This energy principally comes from solar active regions, plage,

4

and network. Once the photons reach the Earth, they are absorbed in the terrestrial thermosphere mostly by atomic oxygen above 200 km. We use the daily index with a 1-day lag in JB2006 as previously described[6,7].

$M_{10.7}$: The NOAA 16 and NOAA 17 operational satellites host the Solar Backscatter Ultraviolet (SBUV) spectrometer that has the objective of monitoring ozone in the Earth's lower atmosphere. In its discrete operating mode, a diffuser screen is placed in front of the instrument's aperture in order to scatter solar MUV radiation near 280 nm into the instrument's optical path.

This solar spectral region is operationally observed by the SBUV spectrometer and contains weakly varying photospheric continuum longward and shortward of the core chromospheric line emissions (Mg II *h* and *k* lines at 279.56 and 280.27 nm, respectively). On the ground, a Mg II core-to-wing ratio is calculated between the highly variable lines and weakly varying continuum wings. The result is a measure of full-disk chromospheric solar active region variation that is independent of instrument sensitivity changes and is referred to as the Mg II core-to-wing ratio (cwr). It is provided daily by NOAA Space Environment Center (SEC) as described by Viereck *et al.*[11]

The ratio is an especially good proxy for some solar FUV and EUV emissions and it represents very well the photospheric and lower chromospheric solar FUV Schumann-Runge Continuum (SRC) emission when used with a 3- to 6-day lag. We have taken the Mg II cwr and performed a linear regression with $F_{10.7}$ for solar cycle 23 to derive the $M_{10.7}$ index, i.e., the Mg II cwr reported in $F_{10.7}$ units. Since SRC emission is not operationally available we use the daily index as a proxy in JB2006 with a 5-day lag previously described[6,7].

The daily $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar proxies and indices are reported through S2K v2.30. We note that the $S_{10.7}$ index that is operationally produced by the APEX system has not yet been fully integrated into S2K with the v2.30 release; instead, there is a placeholder index provided from the S2K model's integrated 26-34 nm bandpass (reported in sfu). We expect that the APEX version of $S_{10.7}$ will be incorporated into S2K in 2007.
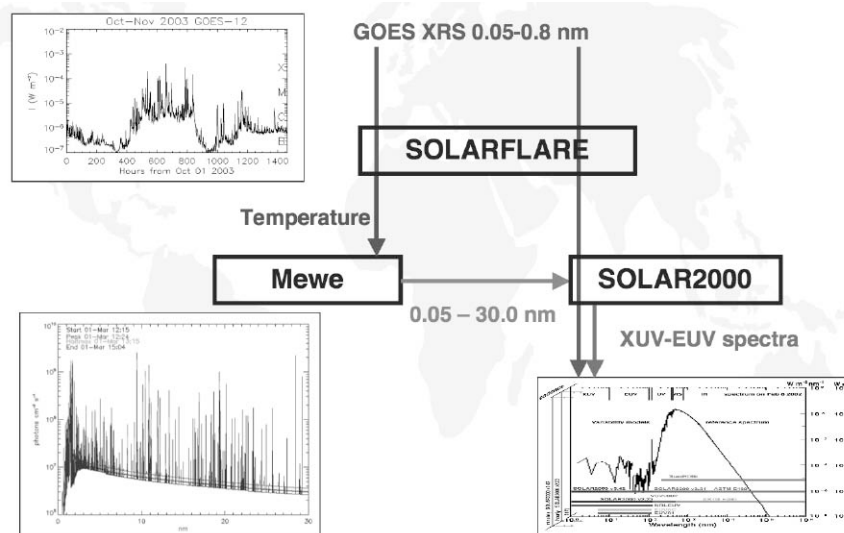
Incorporation of SOLARFLARE with SOLAR2000

Fig. 5. Notional process of GOES XRS real-time data ingested into SFLR, transformed into temperatures, used in Mewe spectral calculations, and output to the S2K high time and high spectral resolution application.

The SOLARFLARE[12] (SFLR) v1.01 model has been coupled with SOLAR2000 in order to produce high time and high spectral resolution irradiances. SFLR is a mature model at the Technology Readiness Level (TRL) 8 that incorporates the Mewe[13,14,15] model to produce 0.1 nm spectral lines based on solar coronal abundances. The Mewe model subroutine requires an input electron temperature (in MK) in order to produce a spectrum. A time-series temperature vector is created from the relationship between

GOES XRS 0.1–0.8 nm flux and electron temperatures as described previously[3,16]. The activity sequence is as follows. We collect the GOES XRS real-time data from NOAA SEC, insert it into a SET database, provide data on demand via a desktop PC GUI application that runs both S2K v2.30 and SFLR v1.01, create a predicted flare evolution on a 1-minute time grid starting at the current epoch, form an electron temperature vector, pass it to the Mewe subroutine, produce high resolution spectral irradiances, apply a preliminary calibration to the spectrum based on SORCE XPS measurements (a final calibration will be incorporated in SFLR v1.02), concatenate the 0.05 – 30.0 nm spectrum with the daily S2K high resolution spectrum, and report the results through the SFLR GUI. Figure 5 demonstrates this notional process, starting with the GOES XRS observations converted to temperatures, fed into Mewe, and placed into S2K. Figure 6 shows the GUI interface to both the S2K and SFLR models and figure 7 shows a screen shot capture of output from SFLR on 1-minute time steps and 0.1 nm spectral resolution from 0.05 to 121.0 nm.
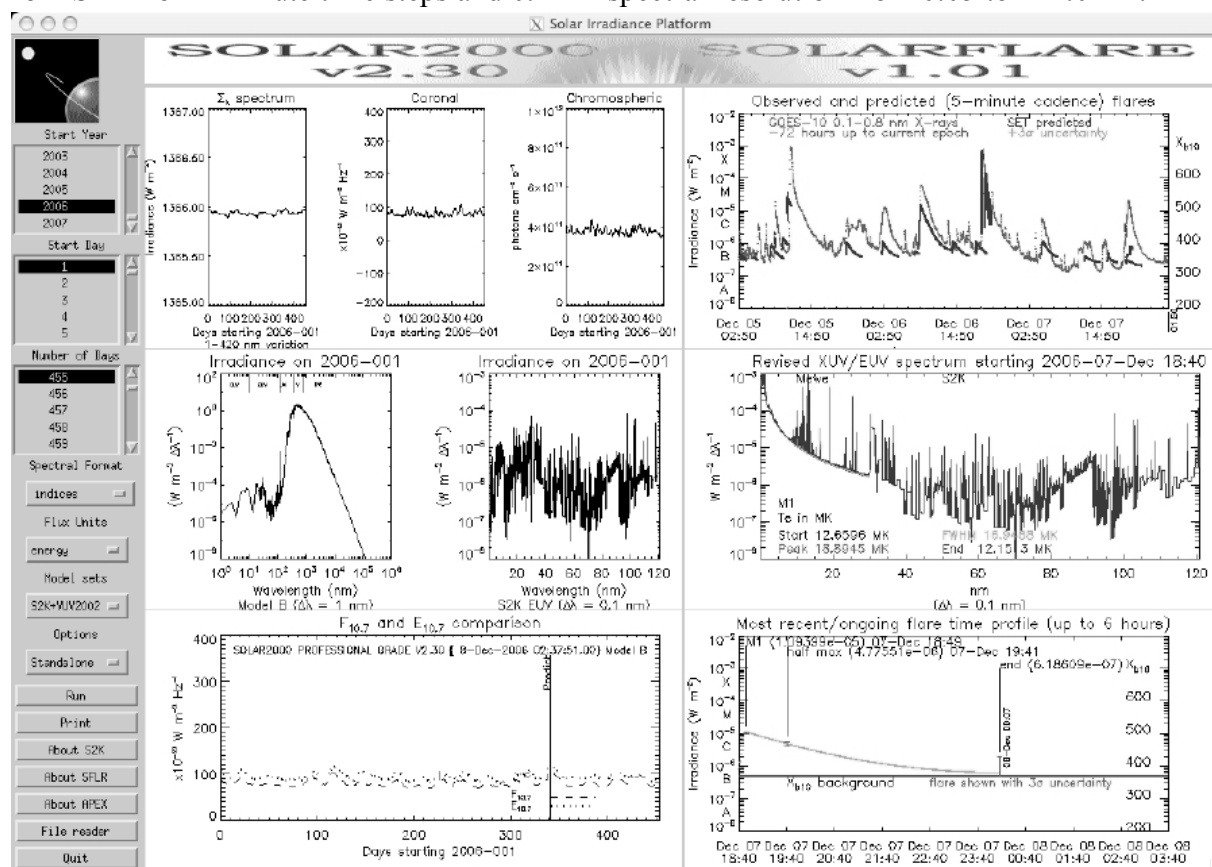

Fig. 6. SOLAR2000 v2.30 and SOLARFLARE v1.01 GUI application that provides historical, nowcast, and forecast solar irradiance and indices with 1-minute time resolution and 0.1 nm spectral resolution.

Users have indicated that it is important to have warnings, forecasts, and analysis capabilities for space weather-related phenomena such as surface charging, radio high frequency (HF) signal loss, ionosphere total electron content (TEC) change, and satellite drag that result from solar photons. The S2K and SFLR coupled models, with real-time data capabilities via server access, now provide these capabilities in a desktop PC environment. In particular, SFLR provides output of: a) two unitless X-ray indices, i.e., the X_{b10} background index and the X_{hf} flare index; b) electron temperature, T_e, in MK; c) flare geoeffective energy at Earth across an areal disk out to 500 km altitude, E_{geo}, in $\log_{10}J$; d) irradiances, $I(\lambda,t)$, in W m^{-2} (figure 7); e) various parameters (tim-

ing, irradiance, temperature, 3-sigma uncertainty, flare class, geoeffective energy ($\log_{10}$J)) for flare initiation, peak, full width half maximum FWHM on the flare decline, as well as flare end (figure 7); f) flare effects for 4 engineering disciplines; and g) flare status notifications (Table 1).

Table 1. Flare status notifications

NOTIFICATION	INTERPRETATION	SOURCE
Warning	Warnings are issued when a hazardous weather event is occurring, is imminent, or has a very high probability of occurring. A warning is used for very active conditions posing a threat to life or property.	NOAA NWS
Advisory	Advisories highlight special weather conditions that are less serious than a warning. They are for events in active to very active conditions that may cause significant inconvenience, and if caution is not exercised, it could lead to situations that may threaten life and/or property.	NOAA NWS
Watch	Watches are issued when the risk of a hazardous weather event has increased significantly, but its occurrence, location, and/or timing is still uncertain. It is intended to provide enough lead-time in active conditions so that those who need to set their plans in motion can do so.	NOAA NWS
Monitor	Monitoring is performed when the risk of a hazardous weather event minimal and its occurrence, location, and/or timing is uncertain. It is intended to update a current epoch status of quiet to active conditions so that those who need to set their plans in motion can do so.	SET
Quiet	Quiet is announced when the risk of a hazardous weather event is minimal and the occurrence, location, and/or timing are uncertain. It is intended to provide a current epoch status of quiet conditions so that those who need to set their plans in motion can do so.	SET
Alert	Alerts are issued when an event threshold is crossed and contain information that is available at the time of issue. Alerts are provided directly to users who demonstrate an urgent need for such information.	NOAA SEC
Summary Message	Summary messages are issued after the event ends, and contain additional and corroborating information available at the time of issue.	NOAA SEC

Future tasks

The formal release of S2K v.2.30 on October 7, 2006 is the 28th release since 1999. This is the first formal release of SFLR v1.01. The physics-based, observation-based, and data-driven hybrid model system now provides high time resolution and high spectral data in forecast, nowcast, as well as historical modes. With coming versions, we plan to introduce the following upgrades in our coupled system of models:

- S2K v2.31 + SFLR v1.02 + APEX v3c: incorporate on-demand historical GOES XRS data via server downloads, apply the calibration of 0.05–30.0 nm spectra to SORCE XPS observations, release updated flare lists, and operationally generate the $S_{10.7}$ index (winter 2007).
- S2K v2.32 + SFLR v1.03 + APEX v3c: incorporate GOES XRS data into the 0.05-0.8 nm spectral range in S2K, incorporate APEX SOHO SEM $S_{10.7}$ into the S2K output indices, and improve the windowing representation of predicted flare evolution (summer 2007).
- S2K v2.33 + SFLR v1.03 + APEX v3d: incorporate real-time TIMED SEE and SORCE SOLSTICE data into S2K; decrease the latency of the SOHO SEM data (fall 2007).
- S2K v2.34 + SFLR v1.04 + APEX v3e: link operational $F_{10.7}$ and $M_{10.7}$ proxies' generation with S2K proxy output in a format usable by JB2006, improve slow rising flare predictions, and operationally remove proton contamination in SOHO SEM flare data (winter 2008).
- S2K v2.35 + SFLR v1.05 + APEX v3e: assimilate GOES EUV data (summer 2008).

Conclusion

The S2K v2.30 and SFLR v1.01 coupled models, with real-time data capabilities via server access, now provide capabilities for warnings, forecasts, and analyses of space weather-related solar photon phenomena in a desktop PC environment. Such phenomena include surface charging, HF signal loss, TEC change, and satellite drag. These capabilities continue to expand an overarching SET objective to provide system-level risk mitigation of dynamical space weather phenomena. Our cross-linked systems *create quality data products rapidly*, enable them to be *interpreted quickly*, and foster *appropriate reactions to real-time and predicted information with timely actions*.

The S2K v2.30 and SFLR v1.01 coupled models provide: improved solar irradiances, $I(\lambda,t)$, in the XUV–EUV during flare periods; better proxies and indices (X_{b10}, X_{hf}, Te, E_{geo}, $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$) for atmospheric density models (JB2006); more energy and spectral formats (0.1 nm spectral resolution at 1-minute time resolution); inclusion of other models (SFLR, Mewe) along with archived rocket data sets and GOES XRS data; and standards (ISO 21348 compliance) and definitions (flare status notifications). User priorities have provided the basis for developing this hybrid solar irradiance system: for research and operational applications on standalone, modular, and server-based platforms; for incorporating historical measurements, current observations, and future predictions; for using multiple physics-based and observation-based models as well as historical and real-time data-driven algorithms; for providing identical solar energy across the full solar spectrum in high spectral and time resolution formats as well as through solar indices; for producing irradiances across all heliophysical time scales (flares, solar rotation, solar active region evolution, and solar-cycle); and while maintaining compliancy with ISO 21348.
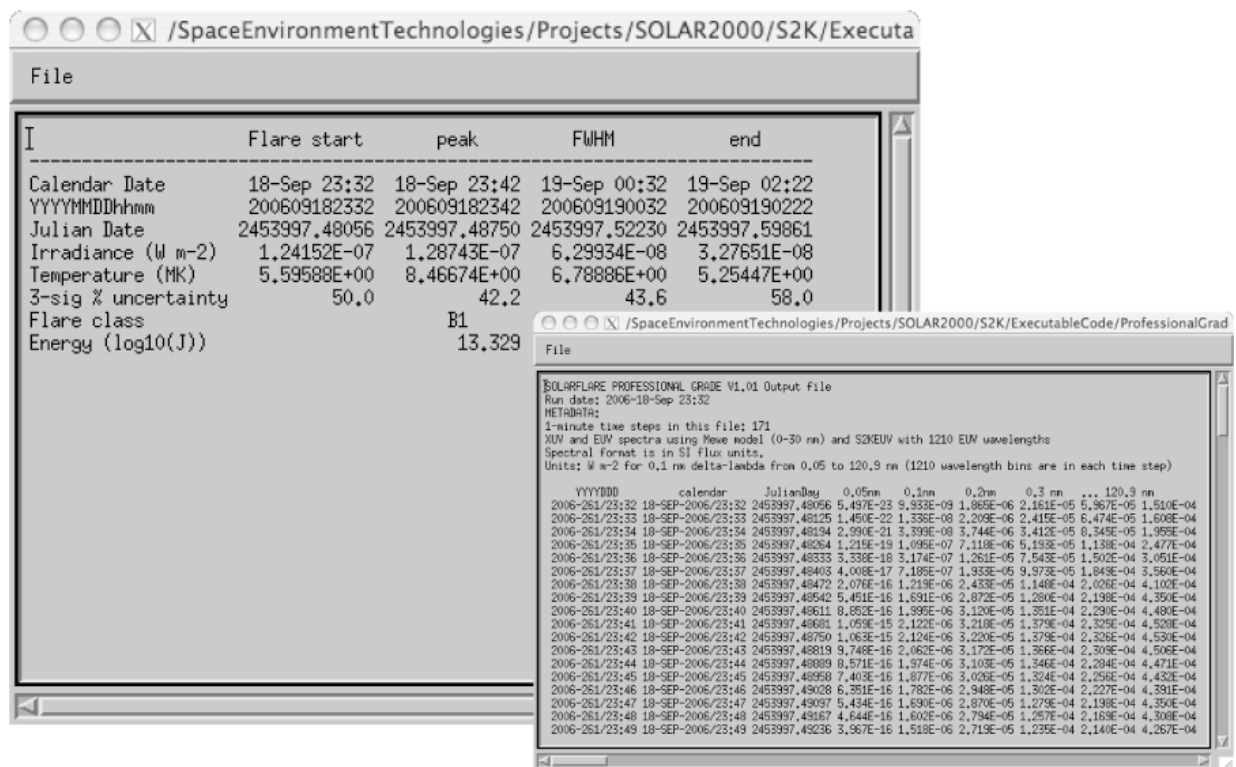

Fig. 7. SOLARFLARE v1.01 GUI application output of flare features (left rear screen) and forecast solar irradiances with 1-minute time resolution and 0.1 nm spectral resolution from 0.05–121.0 nm (right front screen).

Acknowledgments

References

[1] 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*, 1233-1250, 2000.

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

[3] Tobiska, W.K. and S.D. Bouwer, New Developments in SOLAR2000 for Space Research and Operations, *Adv. Space Res., 37*(2), 347-358, doi:10.1016/j.asr.2005.08.015, 2006.

[4] Bowman, B.R., W.K. Tobiska, and F.A. Marcos, A New Empirical Thermospheric Density Model JB2006 Using New Solar Indices, AIAA 2006-6166, 2006.

[5] Marcos, F.A., B.R. Bowman, and R.E. Sheehan, Accuracy of Earth's Thermospheric Neutral Density Models, AIAA 2006-6167, 2006.

[6] Tobiska, W.K., S.D. Bouwer, and B.R. Bowman, The development of new solar indices for use in thermospheric density modeling, AIAA 2006-6165, 2006.

[7] Bowman, B.R. and W.K. Tobiska, Improvements in Modeling Thermospheric Densities Using New EUV and FUV Solar Indices, AAS 06-237, 2006.

[8] ISO 21348, Space Environment (natural and artificial) – Process for determining solar irradiances, International Standards Organization (ISO), Geneva, in press, 2006.

[9] Judge, D.L., H.S. Ogawa, D.R. McMullin, P. Gangopadhyay, and J.M. Pap, The SOHO CELIAS/SEM EUV Database from SC23 Minimum to the Present, *Adv. Space Res., 29* (12), 1963, 2001.

[10] Woods, T.N., G.J. Rottman, R.G. Roble, O.R. White, S.C. Solomon, G.M. Lawrence, J. Lean, and W.K. Tobiska, TIMED Solar EUV Experiment, *SPIE Proc., 2266,* 467, 1994.

[11] Viereck, R., L. Puga, D. McMullin, D. Judge, M. Weber, W.K. Tobiska, The Mg II Index: A Proxy for Solar EUV, *Geophys. Res. Lett., 28* (7), 1342, 2001.

[12] Tobiska, W.K. and S.D. Bouwer, Solar flare evolution model for operational users, *2005 Ionospheric Effects Symposium,* ed. J.M. Goodman, JMG Associates, 76, 2005.

[13] Mewe, R., E.H.B.M. Gronenschild, and G.H.J. van den Oord, Calculated X-radiation from optically thin plasmas. V, *Astron. & Astrophys. Suppl., 62*, 197, 1985.

[14] Mewe, R., J.R. Lemen, and G.H.J. van den Oord, Calculated X-radiation from optically thin plasmas. VI - Improved calculations for continuum emission and approximation formulae for nonrelativistic average Gaunt factors, *Astron. & Astrophys. Suppl., 65*, 511, 1986.

[15] Meyer, J.-P., Solar-stellar outer atmospheres and energetic particles, and galactic cosmic rays, *Ap. J. Suppl., 57*, 173, 1985.

[16] Tobiska, W.K., Systems-Level Space Environment Specification for Satellite and Ground System Operations, AIAA 2005-069, 2005.