Mitigating orbit planning, satellite operations, and communication surprises from adverse space weather

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Precision satellite orbit determination, constellation station-keeping, debris avoidance, reentry timing, satellite subsystem performance and safety, and communication link enhancement are among the major technological activities that are affected by space weather. We report on progress towards providing applications and services that mitigate adverse effects caused by space weather. In particular, Space Environment Technologies (SET) has developed a new *automated forecast update capability*. This is for new solar indices that reduce 1-sigma uncertainty by 50% in atmosphere density calculations and new solar irradiances that capture solar flare effects on transionospheric communications. The solar products have been developed and tested for: 1) daily time resolution in historical, nowcast, and intermediate-term forecast periods with 1-day granularity, 1-hour cadence, and 1-hour latency extending 4.5 months; 2) high time resolution for recent, nowcast, and short-term forecast periods with 3-hour granularity, 1-hour cadence, and 1-hour latency extending 96 hours; and 3) precision time resolution for recent, current epoch, and near-term forecast periods with 1-minute granularity, 2-minute cadence, and 5-minute latency extending 6 hours. With this automated update capability, these indices and solar irradiances can be used to improve atmosphere density and ionosphere models' outputs for space systems users in satellite operational orbit planning and communication activities.

Nomenclature

ap	=	*planetary geomagnetic index in units of 2 nT*
APEX	=	*SOHO SEM operational data processing system*
$F_{10.7}$	=	*10.7-cm radio flux proxy for solar EUV in solar flux units (sfu) of* $\times 10^{-22}$ $W\,m^{-2}\,Hz^{-1}$
IS 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 SWPC	=	*National Oceanic and Atmospheric Administration Space Weather Prediction Center*
$S_{10.7}$	=	*index for extreme ultraviolet solar irradiances between 26 – 34 nm reported in sfu*
S2K	=	*SOLAR2000 hybrid solar irradiance model*
SFLR	=	*SOLARFLARE high time and high spectral resolution model for predicted flare evolution*
TRL	=	*Technology Readiness Level*

Challenges faced in satellite and communication operations

Adverse space weather affects operational activities in satellite and communication systems. For example, large solar flares create highly variable enhanced neutral atmosphere and ionosphere electron density regions. These regions impact precision orbit determination as well as communication frequencies. Large coronal mass ejections can inundate near-Earth space with

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large quantities of energetic, charged particles that amplify high latitude neutral and electron densities as well as high altitude, geosynchronous orbit particles during geomagnetic storm and substorm periods, i.e., conditions that are conducive to spacecraft charging.

The natural space environment, with its dynamic space weather variability, is additionally changed by human activity. The increase in orbital debris in low Earth orbit (LEO), combined with lower atmosphere CO_2 that rises into the lower thermosphere and causes increased cooling that results in increased debris lifetime, adds to the environmental hazards of navigating in near-Earth space. This is at a time when commercial space endeavors are posed to begin more missions to low Earth orbit during the rise of solar activity cycle toward the next maximum (2012).

For satellite and communications operators, adverse space weather conditions result in greater expenses for orbit management, more communication outages for aviation and ground-based HF radio users, and an inability to effectively plan missions or service customers with space-based communications, imagery, and data transferal during time-critical activities. For example, satellite constellation users will find it more difficult to maintain orbit precision in their LEO constellations or will find more propellant usage and time-management of solar array pointing to mitigate the effects of drag. Orbit precision is required for maintaining the most efficient data transmission between satellites and less precision translates into less bandwidth available for data links. For LEO satellite imagery missions, space weather creates variable satellite drag and makes it more difficult to schedule customer-defined images at the required time and lighting conditions. For commercial aviation users on transoceanic or polar routes, sudden loss of HF capability due to a perturbed ionosphere (figure 1) means diverting routes along other air corridors at the cost of fewer passengers, more air crew time, and more jet fuel. These examples typify some of the revenue-impacting conditions of space weather.

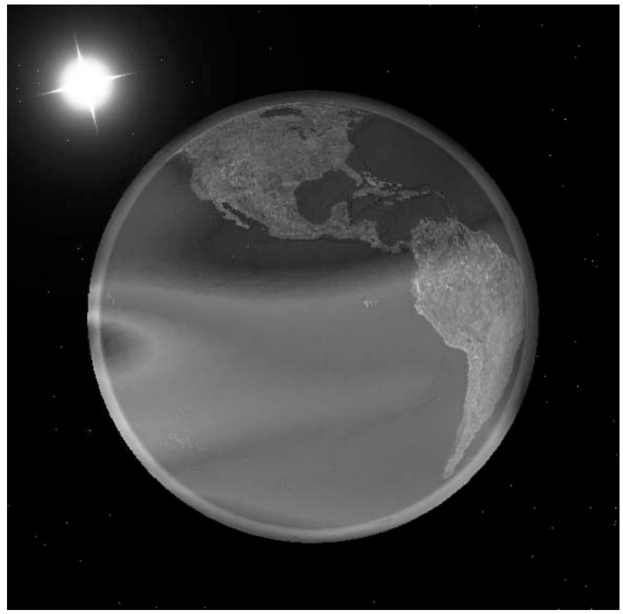

Fig. 1. Artist's view of the total electron content as a 300-km layer shell modulated by solar irradiances.

Solutions for mitigating adverse space weather

Space Environment Technologies (SET) has developed new applications and services that mitigate adverse effects caused by space weather. In particular, SET now operationally provides the JB2006[1] $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar proxies and indices[2,3] that reduce the 1-sigma uncertainty by up to 50% in atmosphere density calculations for satellite orbit determination. SET operationally provides improved solar irradiances that capture solar flare effects on transionospheric communications. These solar irradiance products have been developed and tested for 1) daily time resolution for historical, nowcast, and intermediate-term forecast periods with 1-day granularity, 1-hour cadence, and 1-hour latency extending 4.5 months; 2) high time resolution for recent, nowcast, and short-term forecast periods with 3-hour granularity, 1-hour cadence, and 1-hour latency extending 96 hours; and 3) precision time resolution for recent, current epoch, and near-term forecast periods with 1-minute granularity, 2-minute cadence, and 5-minute latency extending to 6 hours.

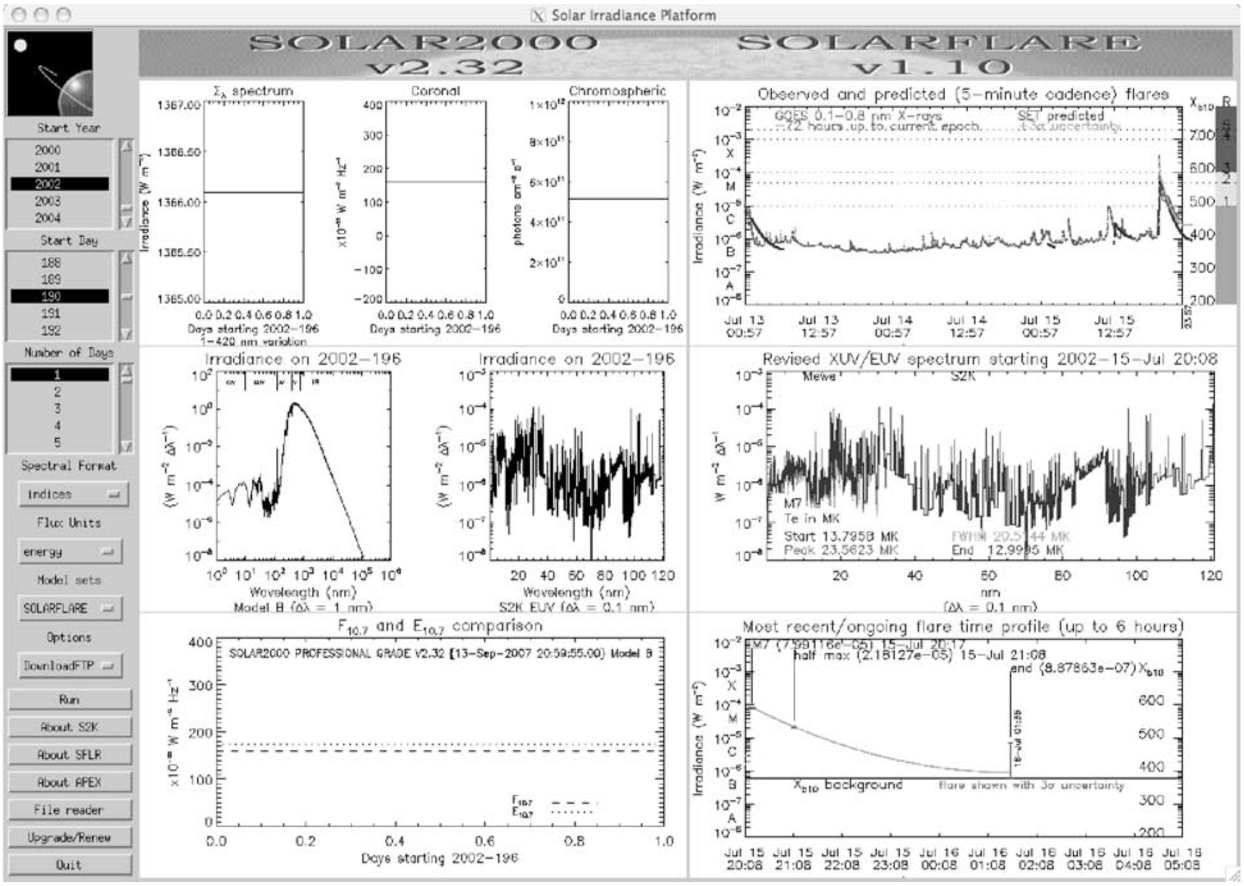

Fig. 2. SIP v2.32 solar irradiances from the SOLAR2000 v2.32 and SOLARFLARE v1.10 models.

The solar irradiance products that can be used operationally, and particularly the daily $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar proxies and indices and 1-minute flare irradiances, are reported through the Solar Irradiance Platform (SIP) v2.32 (figure 2), which was released December 1, 2007. SIP incorporates empirical and physics-based solar irradiance models such as SOLAR2000[4,5,6] v2.32 and SOLARFLARE[7] v1.10 along with reference rocket measurements and real-time satellite data stream systems such as APEX v1.00. Special features of SIP v2.32 are:

- **Automatic Forecast Updates**: The “Auto update” option provides a new, unique capability to update plots, reports, and files of the daily solar forecast, the most recent data, and historical data. These automatic updates are provided for operational users in satellite (“Sat ops”), and communications (“Com ops”) industries. For satellite users, this option retrieves updated JB2006 *SD_delivery81_v3_9.txt* solar index and *SD_deliveryAp_v3_9.txt* geomagnetic index files. These have data to near the current epoch (24-hour latency) reported at a user-specified cadence (usually 1 hour). A bar plot (figure 3) shows the ±3-sigma daily flux ($F_{10.7}$), the % change of neutral density at 450 km from the selected time frame’s mean value, the timing of significant events, and the risks associated with significant events. For communications users, HF outage conditions in the form of the global maximum usable frequencies (average worst case MHz availability) are reported along with solar flare conditions that may be affecting communications. A bar plot (figure 4) shows the global communications conditions,

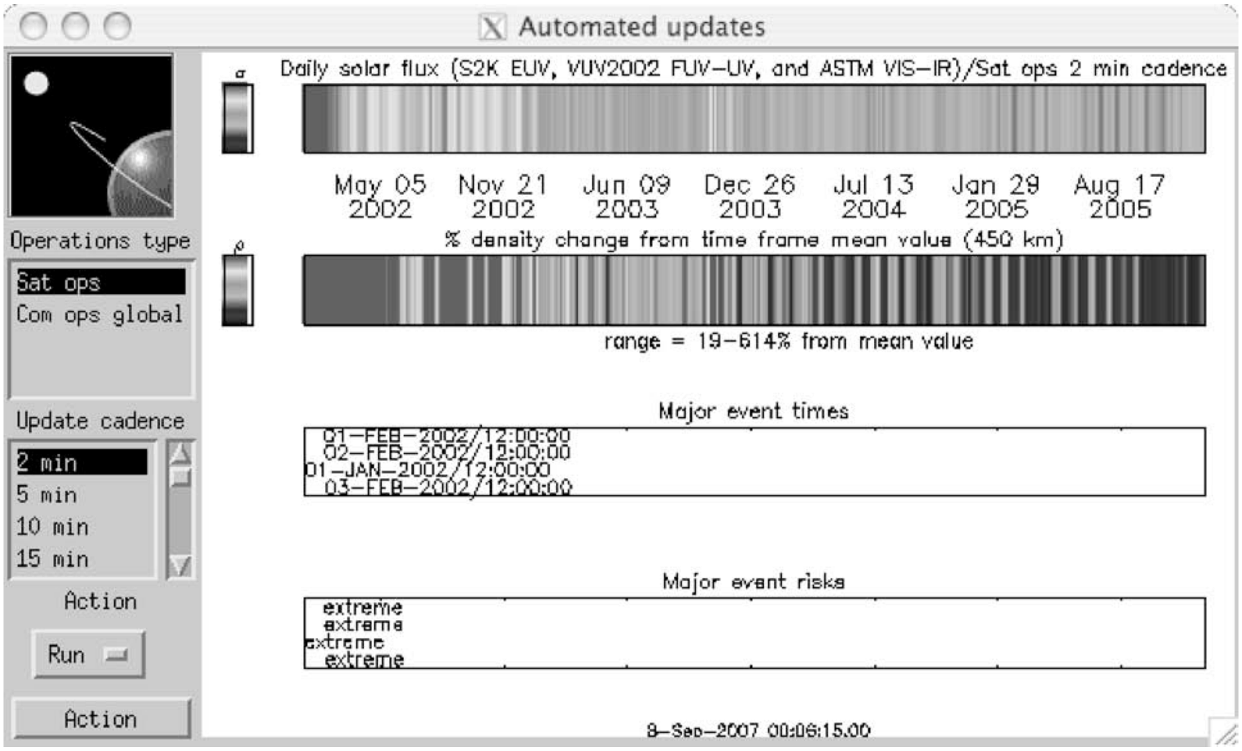

Fig. 3. SIP v2.32 satellite operations automated update with 1st bar daily solar flux ($F_{10.7}$) and 2nd bar % density change at 450 km. The major event times (3rd bar) and major event risks (4th bar) are also shown.

the ±3-sigma forecast and historical daily solar flux ($F_{10.7}$), the ±3-sigma forecast and historical 1-minute solar flare data, and the ±3-sigma forecast and historical 3-hour geomagnetic activity (ap) (inactive in this release). The user-specified cadence for communications is usually 2-minutes during solar active conditions and 10-minutes to one-half hour for quiet solar conditions.

- **New data download capabilities**: This release includes improved capabilities for downloading recent satellite instrument data from SOHO SEM with less than 1-week latency. Real-time data can be downloaded from TIMED SEE with less than 1-day latency and GOES XRS with less than 5-minutes latency. In addition the JB2006 solar indices' latency has been reduced to ~24 hours with the automated retrieval of the *SD_delivery81_v3_9.txt* file. The v3_9 update for JB2006 includes improvements to the $S_{10.7}$ and $M_{10.7}$ solar cycle 23 minimum values. In $M_{10.7}$, there has been long-term instrument change in the NOAA 16 SBUV Mg II data. We believe this may be due to shadowing of the diffuser screen by other spacecraft components but NOAA SWPC is still looking at the causes. The trend in 2004-2005 was not evident when the first $M_{10.7}$ index was first created. By mid-2007, the change was very apparent and this has been now been corrected. The $S_{10.7}$ index also changed for different reasons, including changes in the data processing algorithm by the SOHO SEM instrument team since the index was first derived in 2004 as well as SET's fitting algorithms for the newer data compared to the older data as we reached solar minimum. These corrections are now reflected in $S_{10.7}$ v3_9. $F_{10.7}$ has not changed. $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ have different observation and report times. To standardize reporting, all values are reported in sfu units at 12 UT. Observations are 3-times daily for $F_{10.7}$ (20 UT used), every 5 minutes for $S_{10.7}$ (daily average used), and twice daily for $M_{10.7}$ (7 and 16 UT). For modeling, the values should be used as a daily value between 0-24 UT for a given calendar date (see figure 5). $F_{10.7}$ and $S_{10.7}$

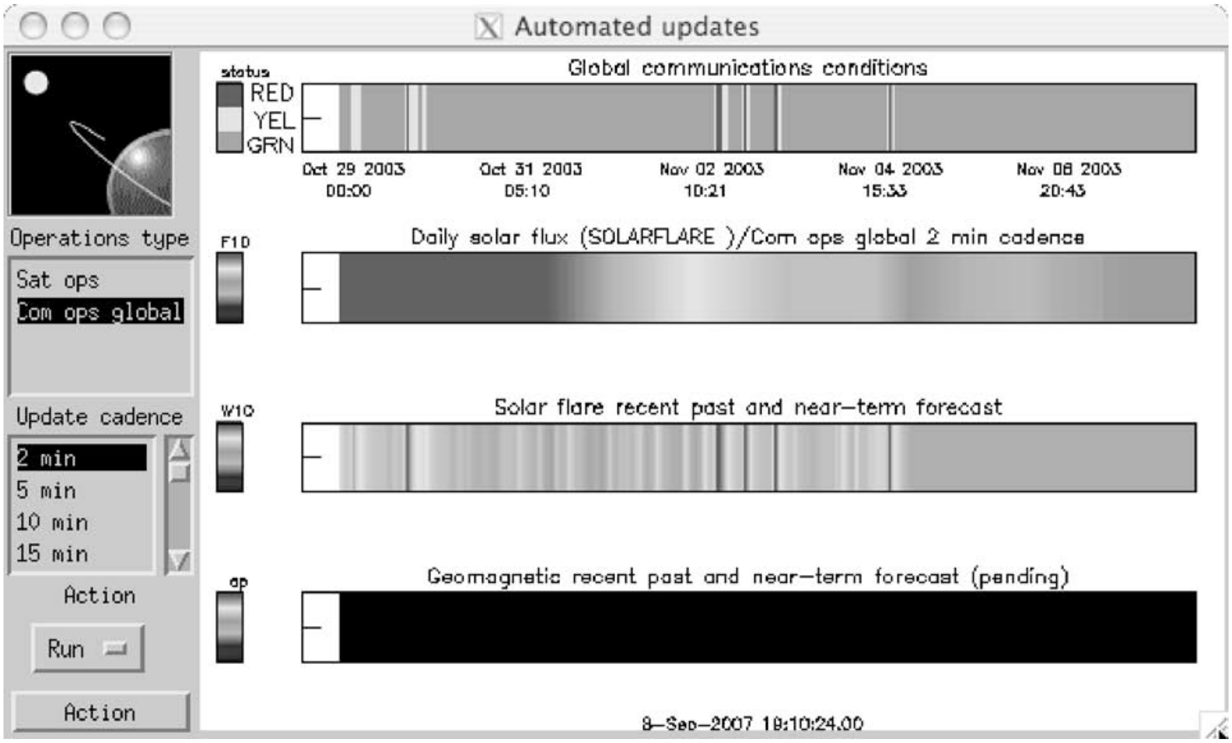

Fig. 4. SIP v2.32 communications operations automated update shown with 1st bar global HF worst case usable frequencies, 2nd bar daily solar flux ($F_{10.7}$), solar flare data (3rd bar), and geomagnetic data (4th bar).

are 1-day lagged and $M_{10.7}$ is 5-day lagged in JB2006. The 81-day centered values are used with the same respective lag times.

- **Automatic Notification:** Auto notification is incorporated to notify users of new releases that can be downloaded at the http://SpaceWx.com web link.
- **TIMED SEE v9**: TIMED SEE v9 data is used in the derivation of SOLAR2000 (S2K) as part of this release. The absolute S2K flux levels are calibrated to the absolute solar cycle values of SEE v9. There are differences between S2K daily and 27-day variations and the SEE v9 data due to long-term degradation removal differences, beta angle anomalies, and model fitting uncertainties. SEE data are continuing to be calibrated.
- **Flexible User Options**: The “Plot index” option provides a capability to plot most of the solar indices that are listed in the *s2k_output.txt* file. The Esrc index and the photoionization variables are not yet included in this release.
- **System Grade Model**: This is the first time the new System Grade (SY) model is provided for atmosphere and ionosphere physics-based models and systems. The SY application is a callable IDL routine using IDL *.sav* files. A user-modified input file holds the beginning date, number of days to be modeled, spectral format required, and flux units specified. The model “B” (S2K+VUV2002) is the default model type used. A sample *s2k_ops_input_v2_32.txt* input file is shown in Table 1 for the case of daily data starting on 19-AUG-2007/18:40:54, for 5 subsequent days, and in 39 wavelength bins/groups each day in units of photon flux using the SOLARFLARE model.

Table 1. SIP v2.32 System Grade input file format

```
                         SOLAR2000 input data
OPERATIONAL GRADE V2.32
19-Aug-2007 18:40:54.00
Metadata:
5  (number of input variables lines to read)

Line 1 = starting date (DD-MMM-YYYY/12:00:00 UT convention);
                         for flares, start 6 days earlier than 0 UT of desired date
Line 2 = number of time steps (1 = 1 day, 1.125 = 3 hourly for 1 day)
Line 3 = spectral format (0 = indices, 1 = 1nm, 39 = 39 wlg, 809 = 809 wl, 1210 = 1210 wl)
Line 4 = flux units format (e = energy, p = photon, s = SI, n = none)
Line 5 = model sets (b = S2K+VUV2002, x = SOLARFLARE)
                    Model sets (A-Z) (use lowercase)
                    A=S2K+ASTM490,B=S2K+VUV2002,C=VUV2002,D=SC21REFW,
                    E=REF74113,F=REF76200,G=REF79050,H=REF79226,I=REF79314,
                    J=REF82222,K=REF83228,L=REF88298,M=REF88315,N=REF92301,
                    O=REF93277,P=REF94307,Q=REF96318,R=REF97135,S=GOES XRS,
                    T=GOES EUV,U=SOHO SEM,V=TIMED SEE,W=SDO EVE,X=SOLARFLARE,
                    Y=IDAR,Z=JB2006

DATA *******************************************************
19-AUG-2007/18:40:54
5
39
p
x
```

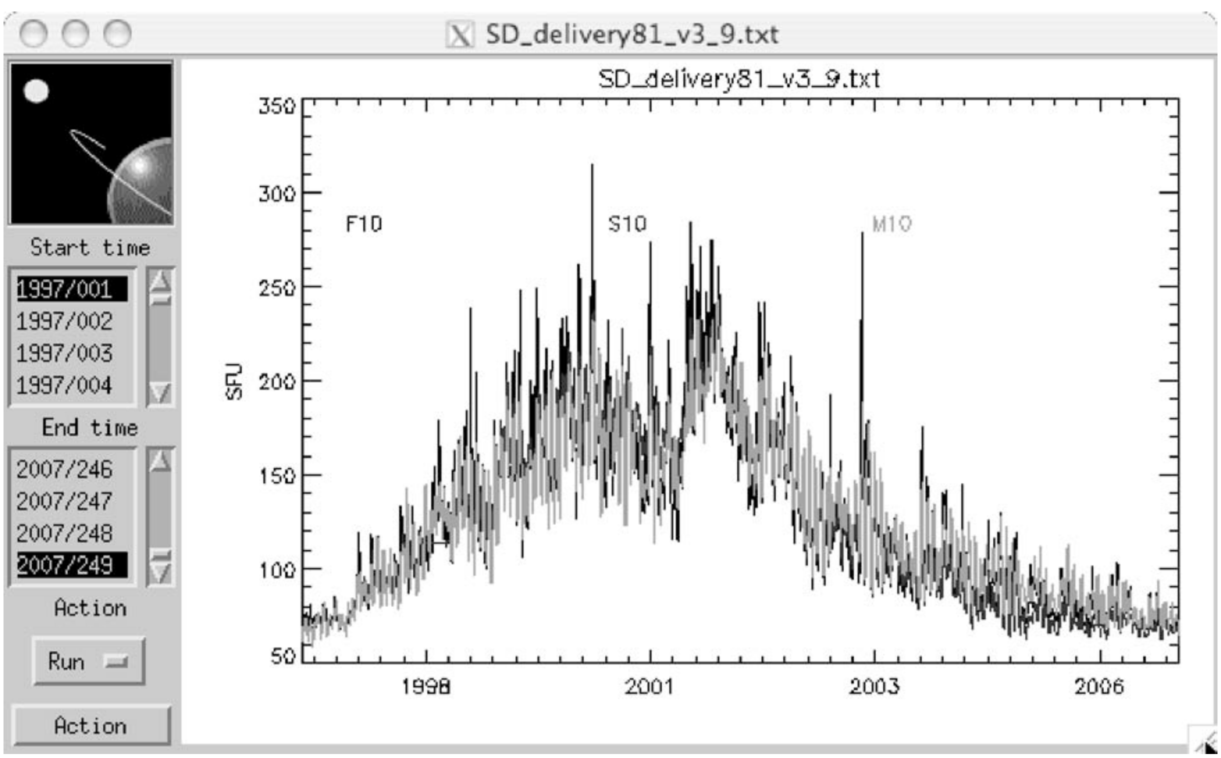

Fig. 5. SIP v2.32 $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar indices for the JB2006 empirical thermospheric density model.

- **Flexible User Analysis**: For interactive data inspection, plotting, and analysis this release creates an IDL *.sav* file shown in Table 2 containing the following arrays [note: the variables are the same as those in the *s2k_output.txt* file (days = number of days selected by user)]:

Table 2. User analysis data in IDL *.sav* file

```
E107            FLOAT Array[days]
E162            FLOAT Array[days]
E1_40           FLOAT Array[days]
E30_70          FLOAT Array[days]
E81             FLOAT Array[days]
ESRC            DOUBLE xxx.xxxxx
F54             FLOAT Array[days]
FLUX809E        FLOAT Array[1210, days]
FLUX809P        FLOAT Array[1210, days]
FLUX809S        FLOAT Array[1210, days]
INDEX           LONG  Array[1]
MG10            FLOAT Array[days]
MG54            DOUBLE Array[days]
MG81            DOUBLE Array[days]
PEUV            FLOAT Array[days]
PHOTON_FLUX     FLOAT Array[2121, days] (2121 wavelengths)
PIRT            FLOAT Array[185]
QEUV            FLOAT Array[days]
REFERENCE_SPECTRA
         STRUCT    = -> REFS Array[1]
  REFERENCE_DATA  STRUCT  -> REF_DATASETS Array[1]
REF74113        STRUCT    -> REF_74113 Array[1]
REF76200        STRUCT    -> REF_76200 Array[1]
REF79050        STRUCT    -> REF_79050 Array[1]
REF79226        STRUCT    -> REF_79226 Array[1]
REF79314        STRUCT    -> REF_79314 Array[1]
REF82222        STRUCT    -> REF_82222 Array[1]
REF83228        STRUCT    -> REF_83228 Array[1]
REF88298        STRUCT    -> REF_88298 Array[1]
REF88315        STRUCT    -> REF_88315 Array[1]
REF92301        STRUCT    -> REF_92301 Array[1]
REF93277        STRUCT    -> REF_93277 Array[1]
REF94307        STRUCT    -> REF_94307 Array[1]
REF96318        STRUCT    -> REF_96318 Array[1]
REF97135        STRUCT    -> REF_97135 Array[1]
RSN             FLOAT Array[days]
S               STRING Array[total # days in historical proxy file]
S0F10           FLOAT Array[days]
S0F81           FLOAT Array[days]
S1F10           FLOAT Array[days]
S1F54           FLOAT Array[days]
S1F81           FLOAT Array[days]
SOLAR_CONSTANT  DOUBLE Array[days]
TINF            FLOAT Array[days]
XE10            FLOAT Array[days]
```

Operational characteristics

The SIP v2.32 application represents a capability that is at Technology Readiness Level (TRL) 7 where models and data are linked in an operationally-viable environment. It uses TRL 9 (fully operational) data created by SET's servers to provide hybrid (empirical, physics-based, data assimilative) irradiances with the following characteristics:

- **applicable to operational technologies affected by space weather** such as satellite, communication, and navigation systems;
- **systems' compatibility** with SET's S2KOPS, SDOPS, IONOPS, CHGOPS, and APEX systems that use irradiances identical to and interchangeable with those produced in SIP v2.32;
- **proven TRL strategy** where SOLAR2000, SOLARFLARE, IDAR, and JB2006 were developed as TRL 6 models; the SIP platform provides community tools at TRL 7; upgrades are incorporated in S2KOPS, SDOPS, IONOPS, CHGOPS, and APEX TRL 8 prototypes; systems level applications are implemented in TRL 9 operational centers at SET and NOAA SWPC;
- **standards-based** compliance with IS 21348[8] by SIP v2.32 using common time, spectral, proxy, index definitions from IS 21348; and
- **internationally accessible** application where SIP v2.32 provides Research, Professional, System, and Operational Grade products to global users in 5 multi-disciplinary communities (operations, planning, research, standards, and education).

The SIP v2.32 application adheres to seven operational principles that have been developed by SET to guarantee TRL 9 redundancy, robustness, validation, and verification:

1. **time domain definitions** of past, present, and future that are demarcated with identifiable granularity, cadences, and latencies starting with identification of the current epoch;
2. **information redundancy** is clearly established using multiple data streams;
3. **data reliability** is ensured when quality output forecast data flows uninterruptedly regardless of subsystem anomalies;
4. **system robustness** is ensured when an operational forecasting system is modular, manageable, and extensible using tiered architecture;
5. **TRL evolution** occurs as models and data achieve system-level maturity by evolution through TRL stages where mature models and data (TRL 6) are linked for operational environments (TRL 7) and tested through prototype demonstrations (TRL 8) before operational implementation (TRL 9);
6. **geophysical validation** is ensured when an output forecast represents the geophysical conditions within specified limits; and
7. **operational verification** is ensured when an output forecast meets the intent of the requirements.

Future tasks

The formal release of S2K v2.32 on December 1, 2007 is the 30th release since 1999. SFLR v1.10 and APEX 1.00 were also released with this version of SIP. The physics-based, observation-based, and data-driven hybrid model system provides high time resolution and high spectral data in forecast, nowcast, as well as historical modes with automatic updates and on-demand satellite data. There are new operational needs we are presently working on, including:

- **reentry accuracy** to improve lower thermosphere density specification, to improve drag coefficients from free molecular to continuum flow, and to improve forecasts out to 7 days;

- **flare prediction** to improve the magnitude and timing of flare probability estimates, to improve the timing of physics-based flare initiation, and to improve the utility of flare irradiances for communications and satellite operations; and
- **spacecraft charging/discharge processes** to improve the operational specification of environment conditions leading to ESD.

With upcoming releases of SIP, we plan to introduce the following upgrades:

- SIP v2.33 – forecast $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ for JB2006; provide the solar μ parameter for Lyman-alpha; expand photoionization rates to aeronomy diatomic molecules;
- SIP v2.34 – assimilate SOHO SEM, TIMED SEE, GOES XRS real-time data into the appropriate S2K and SFLR spectral ranges; extend the SC21REFW format to 200 nm; expand the capability of plotting irradiances; continue calibration of the SOLARFLARE values compared with SORCE XPS; revise the wavelength binning scheme greater than 0.1 nm;
- SIP v2.35 – expand photoionization rates to spacecraft material molecular compounds; link with spacecraft charging applications; incorporate FISM, SRPM, and EUVAC models; improve the windowing representation of predicted flare evolution; improve slow rising flare predictions, and operationally remove proton contamination in SOHO SEM flare data; and
- SIP v3.00 – incorporate IDAR feature analysis of images to generate temperature components of physics-based model; compare with MHD modeled irradiances; assimilate GOES EUV data.

Conclusion

The SIP v2.32 application incorporates automated forecast updates, including warnings and forecasts, of JB2006 and SOLARFLARE parameters useful for satellite and communication operational users. Real-time GOES XRS, SOHO SEM, and TIMED SEE data download capabilities now exist. Flexible user tools for analysis, plotting, and data inspection of space weather-related solar photon phenomena related to satellite drag, HF signal loss, navigation precision loss, and surface charging are provided in a desktop PC environment. With the release of SIP v2.32 we provide for the first time the System Grade model for use by physics-based ionosphere and thermosphere algorithms that require a solar irradiance subroutine.

These capabilities continue to expand an overarching SET objective of providing 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*. We have built this hybrid solar irradiance system by understanding user priorities for:

- research and operational applications on standalone, modular, and server-based platforms;
- incorporating historical measurements, current observations, and future predictions;
- using multiple physics-based and observation-based models as well as historical and real-time data-driven algorithms;
- providing identical solar energy across the full solar spectrum in high spectral and time resolution formats as well as through solar indices;
- producing irradiances across all heliophysical time scales (flares, solar rotation, solar active region evolution, and solar-cycle); and
- maintaining compliancy with the International Standard IS 21348.

Acknowledgments

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