4.2

MITIGATING AVIATION COMMUNICATION AND SATELLITE ORBIT OPERATIONS SURPRISES FROM ADVERSE SPACE WEATHER

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

1. Introduction

Adverse space weather affects operational activities in aviation and satellite systems. For example, large solar flares create highly variable enhanced neutral atmosphere and ionosphere electron density regions (figure 1). These regions impact aviation communication frequencies as well as precision orbit determination. Large coronal mass ejections can inundate near-Earth space with 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, which 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 the solar activity cycle toward the next maximum (2012).

For satellite and aviation operators, adverse space weather results 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 LEO orbit constellation precision or will encounter more propellant usage and time-management of solar array pointing to mitigate the effects of drag. Orbit precision is required to maintain the most efficient data transmission between satellites; less precision translates into less available bandwidth for data links. For LEO satellite imagery missions, space weather creates variable satellite drag and makes it more difficult to schedule customer-defined image-taking at required time and lighting conditions. For transoceanic or polar route commercial aviation users, sudden HF loss due to a perturbed ionosphere means a diversion to 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.

Corresponding author address: W. Kent Tobiska, Space Environment Technologies, 1676 Palisades Dr., Pacific Palisades, CA 90272; email: ktobiska@spacenvironment.net

2. Solutions for mitigating space weather

Two paths exist for mitigating adverse space weather. The first path is standards development and the second path is the introduction of new or upgraded applications and tools.

Standards provide a common language for exchanging scientific and engineering information as well as for commerce. The International Standards Organization (ISO) Technical Committee 20 (TC20), SubCommittee 14 SC14) Working Group 4 (WG4) has the mandate to develop international standards related to the space environment (natural and artificial). WG4 has identified, as part of its business plan, stakeholder industries in various user domains that are affected by space weather (Figure 2). As a refinement to that stakeholder identification, WG4 is developing standards related to those activities (Figure 3) and these standards are providing common space environment definitions, data, products, practices, and transaction methodologies between diverse communities of users and producers.

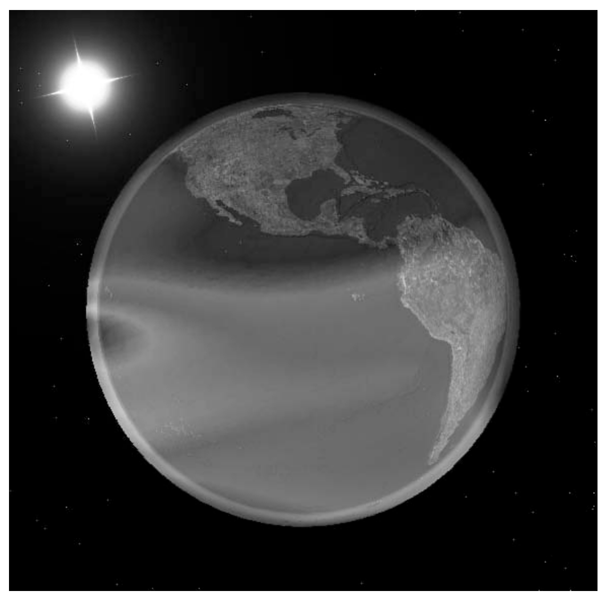

Fig. 1. Artist's view of the total electron content as a 300-km layer shell modulated by solar irradiances.

Beyond standards, unique tools for specific users are important for mitigating adverse space weather effects. Space Environment Technologies (SET) and its partners are developing several new applications and

User domain / Space Env domain	Communication	Navigation	Spacecraft orbital operations	Space exploration	Aviation	Ground Power systems
Solar Photons	✔	✔	✔	✔	✔	
Solar Particles	✔	✔	✔	✔	✔	✔
Solar Fields	✔	✔	✔	✔	✔	✔
Cosmic Rays			✔	✔	✔	
Lunar and Mars environments			✔	✔		
micrometeoroids and orbit debris			✔	✔		
magnetosphere and main field	✔	✔	✔	✔	✔	✔
radiation belts and currents	✔	✔	✔	✔		✔
plasmasphere	✔	✔	✔	✔		
ionosphere	✔	✔	✔	✔	✔	✔
atmosphere			✔	✔	✔	

Fig. 2. ISO TC20/SC14/WG4 stakeholders are shown as user versus space environment domains. The check indicates that the user industry is affected by a particular part of the space environment.

User domain / Space Env domain	Communication	Navigation	Spacecraft orbital operations	Space exploration	Aviation	Ground Power systems
Solar Photons	IS 21348, NWI on solar predictions					
Solar Particles	NWIs on solar energetic particles, cutoffs, geomagnetic activity, solar cells					
Solar Fields	NWI on solar wind and **B**?					
Cosmic Rays			IS 15390			
Lunar and Mars environments			NWIs on lunar dust, Moon & Mars radiation			
micrometeoroids and orbit debris			NWI on MMOD			
magnetosphere and main field	CD 22009, NWI on main field					
radiation belts and currents	NWI on radiation belts					NWI on **E**?
plasmasphere	TS 16457					
ionosphere	TS 16457					
atmosphere			NWI on Earth atmosphere density above 120 km, TR Atm Guide			

Fig. 3. The ISO TC20/SC14/WG4 standards in development that are matched with users and space environment domains. IS = International Standard, NWI = New Work Item, CD = Committee Draft, TS = Technical Specification, TR = Technical Report.

services for operational users that are affected by space weather.

Aviation applications and solution tools that are needed to meet specific challenges include:

- **HF/VHF communication outages:** identification of foF2 for geographic regions provided as a result of 1-12 hour forecasts of evolving flare, geomagnetic, and auroral boundary conditions that can be used to avoid HF communication outages for polar and transoceanic flight paths;
- **degraded geolocation and navigation:** identification and reduction of total electron content (TEC) uncertainty provided as a result of 1-6 hour forecasts of evolving flare and geomagnetic conditions that can be used to specify GPS position uncertainty for aviation and ground-system operations;
- **radiation effects on aircrews:** identification of dose rates as a function of time for aviation altitudes provided as a result of 1-6 hour forecasts of evolving solar energetic particle events that can be used to minimize anomalously high radiation exposure for air crew members and frequent flyers.

Spaceflight applications and solution tools that are needed to meet specific challenges include:

- **precision orbit determination:** identification of high time resolution densities provided as a result of 1-7 day forecasts of evolving solar flux and geomagnetic conditions that can be used to avoid orbit debris conjunctions and improve planning for instrument operations;
- **satellite surface and internal charging:** identification of charging conditions provided as a result of 1-3 hour forecasts of substorm 1-50 keV electron densities that can be used to take preventative actions for charging;
- **degraded geolocation and navigation:** identification and reduction of total electron content (TEC) uncertainty provided as a result of 1-6 hour forecasts of evolving flare and geomagnetic conditions that can be used to specify GPS position uncertainty for satellite operations;
- **radiation effects on materials:** identification of dose rates as a function of time for orbital altitudes provided as a result of 1-6 hour forecasts of evolving solar energetic particle events that can be used to minimize anomalously high radiation exposure for space crew members and sensitive satellite components.

As specific examples of applications now available, SET operationally provides the JB2006 (Bowman, *et al.,* 2006) $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar proxies and indices (Bowman and Tobiska, 2006; Tobiska, *et al.* 2006) 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.

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 4), which was released December 1, 2007. SIP incorporates empirical and physics-based solar irradiance models such as SOLAR2000 v2.32 (Tobiska, et al., 2000; Tobiska, 2004; Tobiska and Bouwer, 2006) and SOLARFLARE v1.10 (Tobiska and Bouwer, 2005) 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

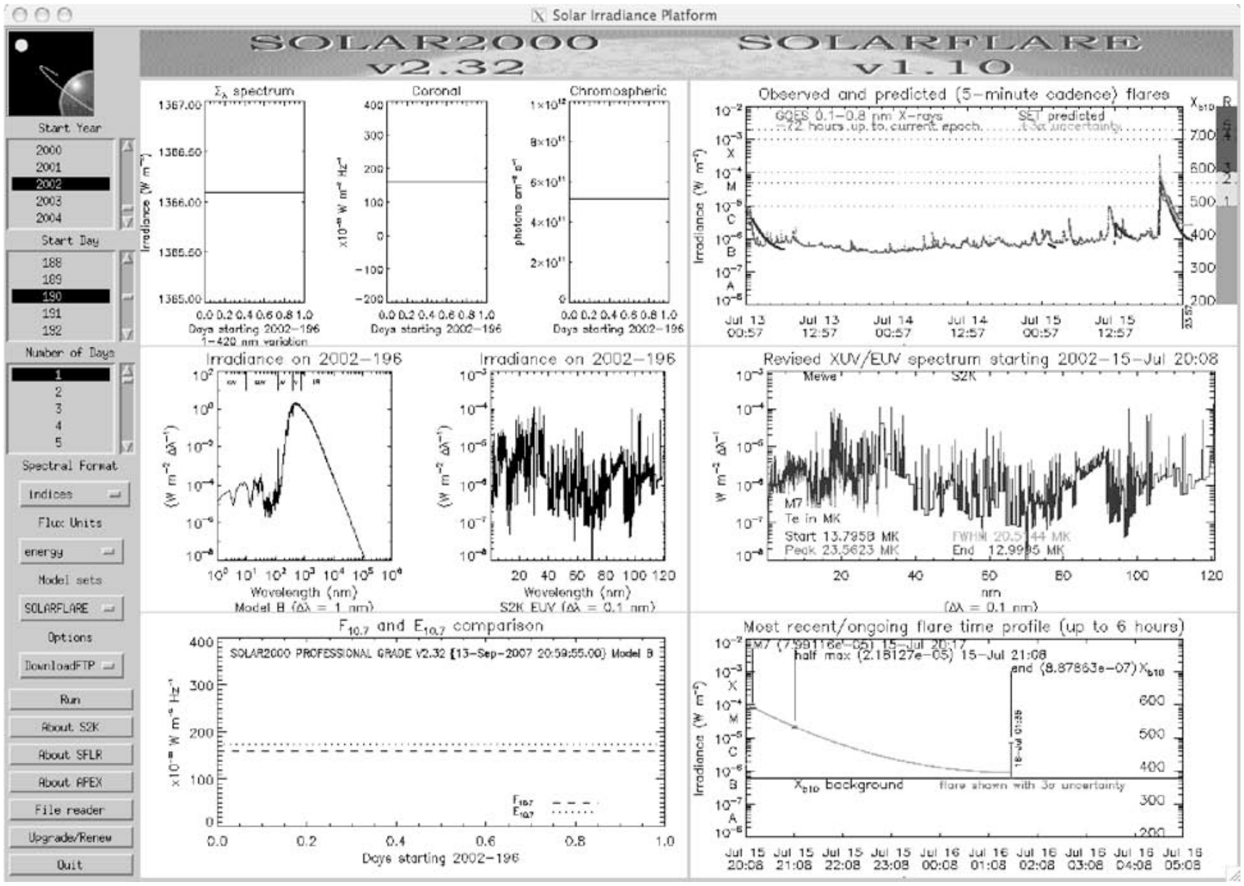

Fig. 4. SIP v2.32 solar irradiances from the SOLAR2000 v2.32 and SOLARFLARE v1.10 models.

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 solar index and 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 5) 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 6) shows the global communications conditions, 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**: SIP v2.32 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 automated data file retrieval. 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-

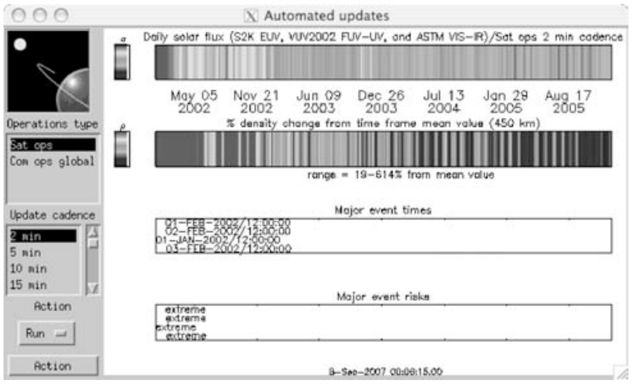

Fig. 5. SIP v2.32 satellite operations automated update with 1st bar daily solar flux ($F_{10.7}$) and 2nd bar % density change at 450 km. The major event times (3rd bar) and major event risks (4th bar) are also shown.

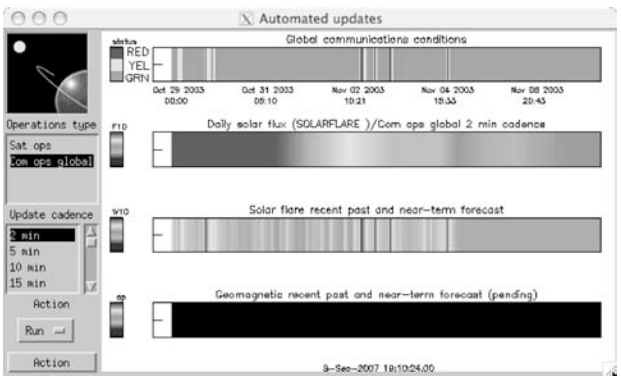

Fig. 6. SIP v2.32 communications operations automated update shown with 1st bar global HF worst case usable frequencies, 2nd bar daily solar flux ($F_{10.7}$), solar flare data (3rd bar), and geomagnetic data (4th bar).

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 atmosphere density modeling, the proxies and indices should be used as a daily value between 0-24 UT for a given calendar date (see figure 7). $F_{10.7}$ and $S_{10.7}$ are 1-day lagged and $M_{10.7}$ is 5-day lagged in JB2006. The 81-day centered values are used with the same 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.
- **Flexible User Analysis**: For interactive data inspection, plotting, and analysis this release creates an IDL *.sav* file containing the same variables as those in the *s2k_output.txt* file.

3. 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 (IS 21348, 2007) 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;

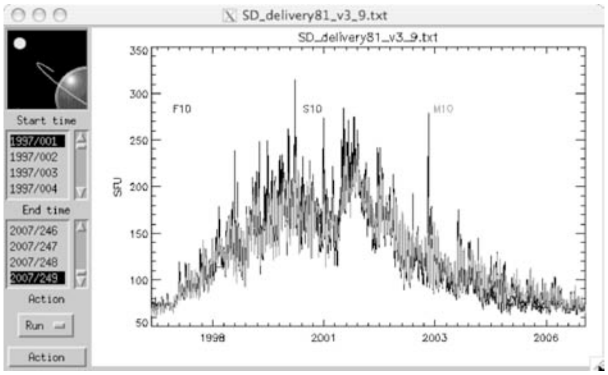

Fig. 7. SIP v2.32 $F_{10.7}$, $S_{10.7}$, and $M_{10.7}$ solar indices for the JB2006 thermospheric density model.

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.

4. Future tasks

The formal release of SIP v2.32 on December 1, 2007 includes the 30th release of the SOLAR2000 model 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 electrostatic discharge.

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.

5. 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.

6. Acknowledgments

Support for this work has been provided by the NASA TIMED contract NAG5-11408 and by the NASA Living With a Star contract NNH05CD15C. We thank the USC/SSC SOHO/SEM team for graciously providing SEM data, which can be downloaded at the APEX server at http://71.33.233.20/~semdata/. The historical indices described here for input to the JB2006 model are provided by SET at http://www.spacewx.com/ *JB2006* quick-link. A web-based version of SFLR can be viewed at http://www.spacewx.com/ *Flare Quick-Link*. SIP v2.32 can be freely downloaded at http://www.spacewx.com/ *SIP Quick-Link.* The solar irradiance products reported in this work are IS 21348 Types 3, 4, and 5 products for the visible, ultraviolet, and X-ray spectral categories. 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*.

7. References

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

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

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

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

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

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

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

IS 21348, Space Environment (natural and artificial) – Process for determining solar irradiances, International Standards Organization (ISO), Geneva, 2007.