SECOND GENERATION SPACE ENVIRONMENT FORECASTING FOR SATELLITE AND GROUND SYSTEM OPERATIONS

W. Kent Tobiska*
Space Environment Technologies, 1676 Palisades Dr., Pacific Palisades, CA 90272-2111
ktobiska@spacenvironment.net; http://SpaceWx.com

Abstract. Integrated solar irradiance proxies have been developed for use in satellite and ground system operations. As operational solar irradiance forecasting has developed over the past few years in its first generation, the prediction techniques have largely relied on linear predictive algorithms. These marked an advance over previous statistical representations of solar irradiances and their proxies. The second generation forecasting capability that is now being tested continues to produce hourly to solar cycle forecasts of the full solar spectrum as well as the E10.7 index for satellite operations and satellite drag estimation. Major improvements in the near-term and long-term solar forecasts are being integrated into operational software. The 7-21 day improved forecast will eventually use the SOHO SWAN Lyman-alpha data which is the reflected solar farside irradiance from the interplanetary hydrogen at about 3 AU on the other side of the Sun relative to the current Earth position. Using these "mirrored" solar irradiances makes an improvement over linear predictive techniques when compared to the actual irradiances values. In addition, Schatten's dynamo theory solar cycle forecasts are now used to improve the timing of long-term forecasts compared to the statistical solar cycle mean used in the first generation forecasts. In general, second generation forecasting is marked by the use of measurements or physics rather than linear prediction algorithms to specify future solar irradiance values. The new forecast algorithms are part of the SOLAR2000 operational and professional grade models whose solar irradiance specification is compliant with the developing ISO draft standard CD 21348 for Determining Solar Irradiances.

1 BACKGROUND

Operational space and ground systems often use a combination of in-house, proprietary software as well as legacy models obtained from the science and engineering communities in order to perform their missions. While models of the aerospace environment continue to evolve and improve as the physics becomes better-known, there is a trend of developing *systems of models* that is continuing to grow. These are systems of linked space physics models, often of legacy code, into an operational configuration to specify the real-time and/or forecast environmental and operational parameters required by an organization.

Part of this trend has been the development of integrated solar irradiance proxies that come from a common irradiance source but provide the solar variability information in formats usable by different models. The advantages of these integrated solar irradiance proxies are that i) the same energy can be used by differing models regardless of format, ii) the proxy delivery cadence can match operational system requirements, and iii) the solar energy drivers are independent of system-level platforms so that physics advances or newly created models can be easily included.

The SOLAR2000 operational and professional grade models produce the variable, full solar spectrum in three spectral and three energy formats. In addition, they produce a total of seven integrated solar irradiance proxies for the benefit of specific user communities. The seven proxies are the E10.7 which is produced for empirical thermospheric and ionospheric models, the Q_{EUV} thermospheric heating rate created for knowledge of solar-derived upper atmosphere heating, the P_{EUV} which is the EUV hemispheric power provided as a complement to the auroral hemispheric power index, the T_∞ which is the exospheric temperature and is useful for long-term climate change studies, the R_{SN} derived sunspot number for use by operational HF radio ray-trace algorithms, the S integrated solar spectrum used for solar radiation pressure calculations related to spacecraft attitude control, and the E_{1_40} which is the integrated EUV energy flux from 1-40 nm for use in studying the energy required for creating the O/N_2 airglow ratio. Examples of the use of these proxies are shown in figures 1, 2, and 3 for solar flare-induced extreme ultraviolet (EUV) heating, exospheric temperature from solar minimum to maximum, and thermospheric density from solar minimum to maximum, respectively. Figure 1 shows the detail behind the Q_{EUV} proxy, figure 2 shows the T_∞ (dayside subsolar) proxy compared to J70 model (nighttime minimum) values, and figure 3 shows

*AIAA member; SET Chief Scientist

the relative variation in the subsolar point thermospheric densities from solar minimum to maximum created by coupled SOLAR2000 irradiances with a 1-dimensional, time-dependent (1DTD) physics-based thermospheric model.

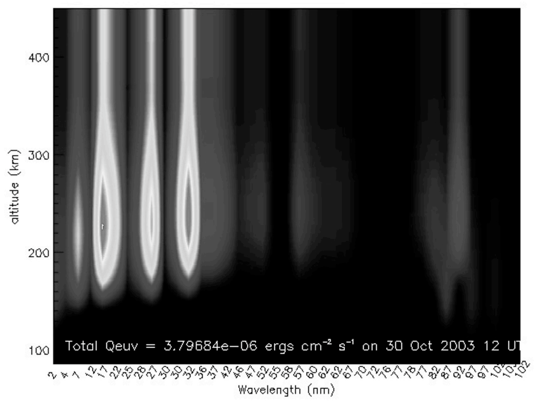

Fig. 1. Detail behind the Q_{EUV} proxy for Oct 30, 3003.

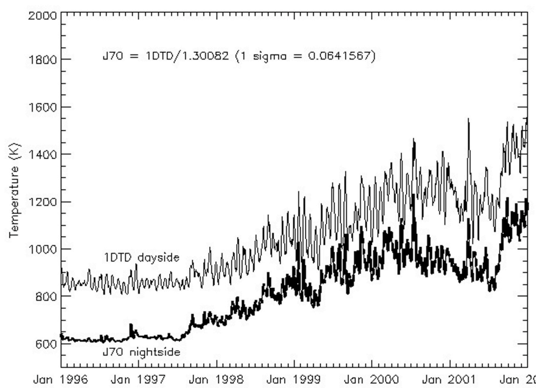

Fig. 2. T_∞ (dayside subsolar) proxy compared to J70 model (nighttime minimum).

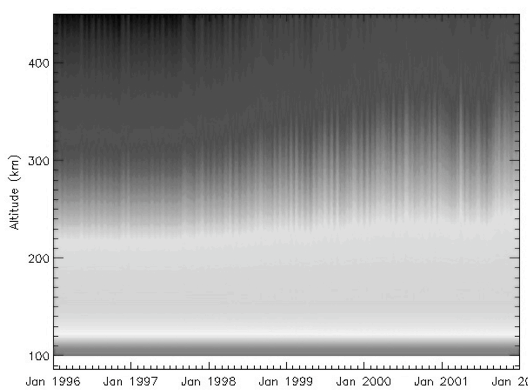

Fig. 3. Variation in solar minimum to maximum thermospheric densities created from coupled models.

2 IRRADIANCE ACCURACY

In support of improving the accuracy of solar input into operational space and ground systems, a key activity by the solar irradiance community at the present time is to reduce the differences between measurements and models. There are several solar models now in use and these are shown in figure 4. SOLAR2000 provides proxies and spectral irradiances across the spectrum while other models provide spectral irradiances in the EUV and far ultraviolet spectral regions. Figure 5 demonstrates one example of the version 2.22 regression fit of SOLAR2000 to the prominent He II 30.4 nm line. The black dots are the model while measurement sets are shown in shades of gray.

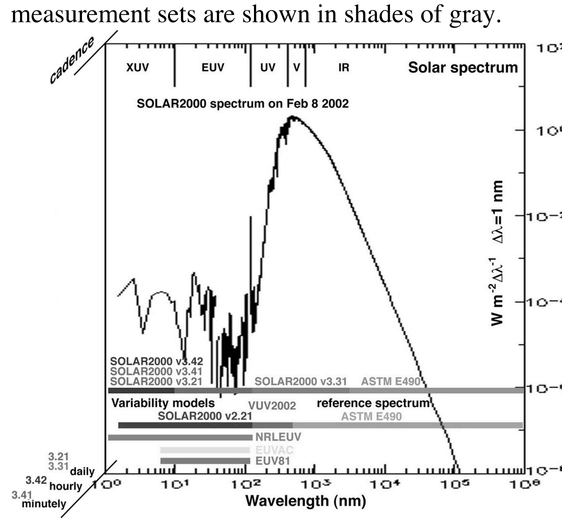

Fig. 4. Solar models with their spectral coverage shown as bars.

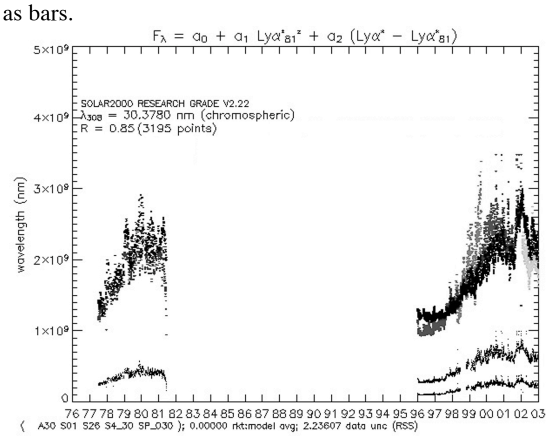

Fig. 5. SOLAR2000 v2.22 regression fit of the He II 30.4 nm line. Model values are the solid black dots while satellite measurements are differing shades of gray.

During the coming two years, there will be additional major upgrades to SOLAR2000. The first has been the release of the Professional Grade model series on November 22, 2003. This model provides observed *daily historical, nowcast, and forecast* solar irradiance products, the latter available for 3-days, 14-days, 28-days, 4-months, 1-solar cycle, and 5-solar cycle time frames. The proxy files driving the model are downloaded on-demand (24/7) from a server by program modules when needed by the user. The model can generate a continuous data time series for up to 4018 days (1 solar cycle) and provide continuous wavelet transform (CWT) analyses of time series data. User communities of this model are typically space- or ground-systems engineers and researchers who perform operational analyses, design, and risk assessment; they may require special analyses of daily historical trend data up through the current date or as daily forecast for a defined time frame.

In late 2004, the SOLAR2000 v3.00 model for operational, professional, and research purposes will be released. This version series will contain full spectral variability and will integrate into the variable "solar constant." In late 2005, the v4.00 model series will be released and will include unprecedented accuracy by incorporating the physics-based, full resolution variable solar spectrum as defined by the NCAR/HAO SunRISE radiative transfer mean disk model.

3 FORECAST GENERATION 1

The SOLAR2000 model has evolved its forecasting ability during the past two years. We started with Forecast Generation 1 (FGen 1) and this capability was used in the USAF High Accuracy Satellite Drag Model (HASDM) project. That project was able to achieve uncertainty of 4-5% at the current epoch which was a factor of 4 improvement from previous uncertainties that had reached a plateau from 1960-2000.

The HASDM version of the forecast algorithms, FGen 1x, used a linear prediction technique for the 0 to 72 hour forecast and was extracted from a 4.5 month forecast linear prediction algorithm. The 6 month forecast simply substituted the past 6 months with a 30-day convolution smooth, the 1/2 to 11 year forecast substituted the past 11 years with a 365-day convolution smooth, and the 1 to 5 solar cycle forecast was simply the mean of the five previous solar cycles. Even with this scheme, using overlay/interpolation of one forecast time frame over another, there was improvement. For the 72 hour forecast, figure 6 shows that the 8% 1-sigma uncertainty using E10.7 was an improvement over using F10.7 which had an 11% uncertainty. This resulted in about a 5% reduction of near-term uncertainty for satellite orbits in the HASDM validation tests.

The primary reason for the substantial improvement in the E10.7 forecast compared to F10.7 is that E10.7 uses the lower-variability Mg II core-to-wing ratio for 90% of its signal (not energy) as denoted by wavelength bin.

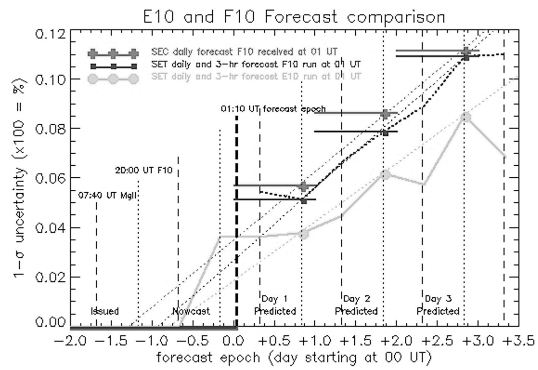

Fig. 6. E10.7 1-sigma uncertainty at the 72-hour forecast is 8% while F10.7 is 11% during the first 180 days of 2001, i.e. a period of high solar activity.

4 FORECAST GENERATION 2

Our expectation is that the second generation of forecasting development can improve the accuracy in irradiance specification for all time scales. The distinguishing feature between FGen 1 and FGen 2 is that the latter moves away from linear predictive techniques and provides a methodology for uniting physical measurements and physics-based models to forecasts.

For the underlying trends of the forecast scheme in FGen 2, SOLAR2000 uses the Schatten solar dynamo algorithm to produce a prediction for the next five solar cycles. Figure 7 demonstrates the coronal, chromospheric, and photospheric proxies that Schatten's algorithm produces for the next five cycles.

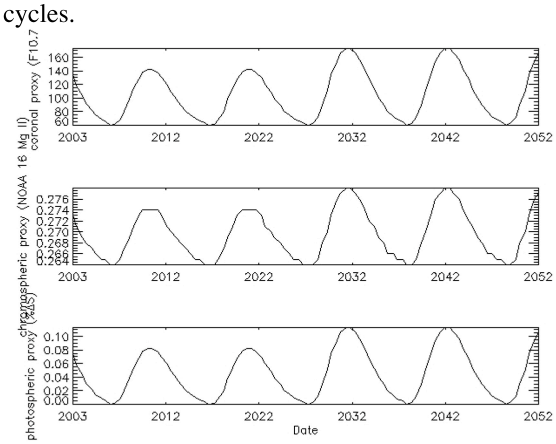

Fig. 7. Schatten solar dynamo algorithm for providing forecasts out to 5 solar cycles for coronal (top), chromospheric (middle), and photospheric (bottom) proxies.

For the 7-21 day forecasts, we have collaborated with the SOHO SWAN team and found that there appear to be improvements over the linear predictive techniques. SOHO SWAN looks at the 2-3 AU interplanetary hydrogen (IP H) atoms that are flowing through the solar system.

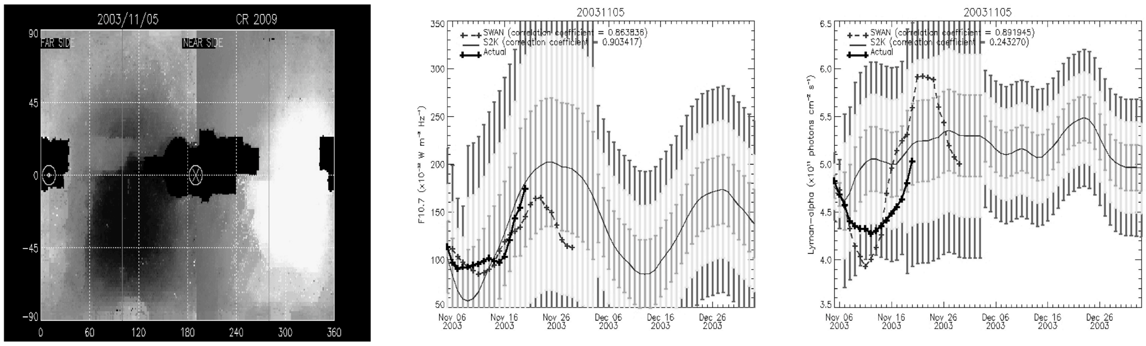

Fig. 8. SOHO SWAN image on Nov. 5, 2003 (left) with comparison (middle) of SWAN (gray dots), linear predictive (solid line with 1-,2-,3-sigma error bars), and F10.7 data (dark black connected dots). The right plot shows the Lyman-alpha comparison. (SOHO SWAN data and image courtesy of Eric Quémerais and the SWAN team.)

The solar Lyman-alpha line is absorbed by hydrogen and is then resonantly-scattered; when measuring this IP H emission generated from the solar farside Lyman-alpha, one is "looking in a mirror" at the backside of the Sun. Figure 8 shows the SOHO SWAN measurement and its predicted F10.7 and Lyman-alpha compared to the linear predictive technique and to actual data. This technique does not predict solar flares.

FGen 2 will be incorporating continuous wavelet transforms to i) propagate statistical information at the appropriate time scale from the past into the future and ii) smooth the blend between weighted values from the differing forecast algorithms. This is a five-step process. One first generates "seed" forecasts based on algorithms or measurements (figure 9). The forecasts are combined into a single time series through an overlay mode convolved with a weighting function to appropriately partition the power through the different time scales. The forecast time series is then concatenated with the historical data to form a single time series extending from the past into the future. The 1-sigma variability is calculated to get a quantitative estimate of the uncertainty in the forecast and is formally combined with any other uncertainties in the historical data. The CWT is then run across the entire time series and filtering (smoothing) applied at appropriate time scales for the future data segment to reduce the "noise." Figure 10 shows part of the final step in this process, i.e., the CWT representation of the entire time series with historical and future E10.7 data. This figure is based on a forecast made January 2, 2004 by the SOLAR2000 Professional Grade model v2.22.

5 CONCLUSIONS

New solar irradiance tools in the form of SOLAR2000 Professional Grade and Operational Grade models are available to mitigate space weather impacts on satellite and ground systems. Both grades of the model provide forecasts and the Forecast Generation 1 provides reduction in 1-sigma error from 11% down to 8% out to 72-hours compared to traditional F10.7 predictions. Forecast Generation 2 provides a methodology for incorporating physics and measurements into forecasting and two elements of the algorithm, Schatten's solar dynamo and CWT processing, are already being used.

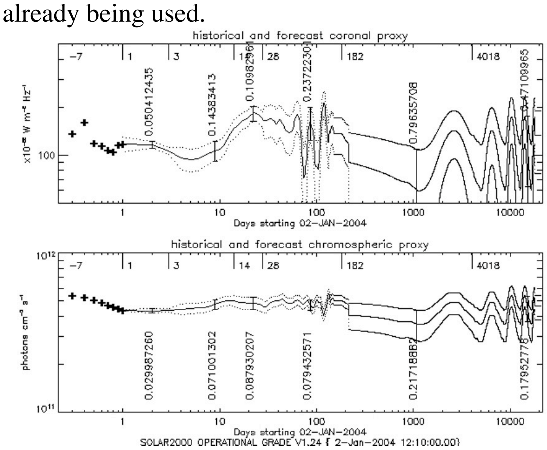

Fig. 9. Forecast proxies on several time scales.

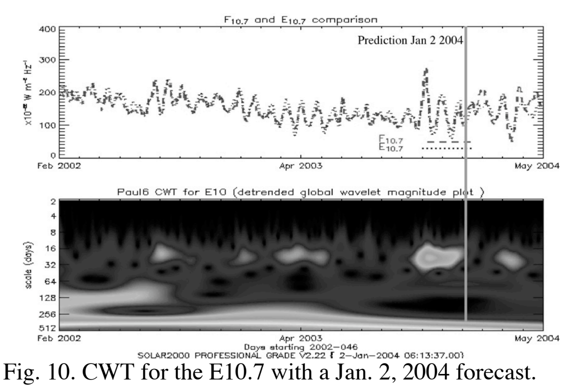

Fig. 10. CWT for the E10.7 with a Jan. 2, 2004 forecast.

Acknowledgements. Support has been provided by the NASA contracts NAG5-11408, NASW-02030, and NAS8-01117. SOLAR2000 is available at http://SpaceWx.com and is compliant with the ISO CD 21348 solar irradiance draft standard.