PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 62 (2000) 1233–1250

Journal of
ATMOSPHERIC AND
SOLAR-TERRESTRIAL
PHYSICS

www.elsevier.nl/locate/jastp

The SOLAR2000 empirical solar irradiance model and forecast tool

W. Kent Tobiska[a, *], Tom Woods[b], Frank Eparvier[b], Rodney Viereck[c], Linton Floyd[d], Dave Bouwer[e], Gary Rottman[b], O.R. White[f]

[a] *FDC/JPL, MS 264-580, 4800 Oak Grove Dr., Pasadena, CA 91109, USA*
[b] *LASP, Univ. of Colorado, 1234 Innovation Dr., Boulder, CO 80309, USA*
[c] *NOAA/SEC, 325 Broadway, Boulder, CO 80303, USA*
[d] *Interferometrics, Inc., Chantilly, VA 20151, USA*
[e] *FDC/NOAA/SEC, 325 Broadway, Boulder, CO 80303, USA*
[f] *7690 County Road 39, Mancos, CO 81328, USA*

Received 1 July 1999; accepted 11 April 2000

Abstract

SOLAR2000 is a collaborative project for accurately characterizing solar irradiance variability across the spectrum. A new image- and full-disk proxy empirical solar irradiance model, SOLAR2000, is being developed that is valid in the spectral range of 1–1,000,000 nm for historical modeling and forecasting throughout the solar system. The overarching scientific goal behind SOLAR2000 is to understand how the Sun varies spectrally and through time from X-ray through infrared wavelengths. This will contribute to answering key scientific questions and will aid national programmatic goals related to solar irradiance specification. SOLAR2000 is designed to be a fundamental energy input into planetary atmosphere models, a comparative model with numerical/first principles solar models, and a tool to model or predict the solar radiation component of the space environment. It is compliant with the developing International Standards Organization (ISO) solar irradiance standard. SOLAR2000 captures the essence of historically measured solar irradiances and this expands our knowledge about the quiet and variable Sun including its historical envelope of variability. The implementation of the SOLAR2000 is described, including the development of a new EUV proxy, E10.7, which has the same units as the commonly used F10.7. SOLAR2000 also provides an operational forecasting and global specification capability for solar irradiances and information can be accessed at the website address of http://www.spacenvironment.net. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Solar spectrum; Solar irradiances; Solar EUV; SOLAR2000; Space weather forecasts

1. Scientific rationale for SOLAR2000

1.1. Solar irradiances

Understanding the solar–terrestrial interaction, including climatology and space weather, starts within the context of Earth's connection to the Sun's activity. The energy from nuclear fusion in the Sun's core is released and transported to the solar visible surface over millions of years by radiative and convective processes in the Sun's interior. This energy manifests in thermal and magnetic processes in the solar photosphere, chromosphere, and corona, giving rise to a highly ionized plasma in distinct features and layers and producing radiation throughout the electromagnetic spectrum. Solar radiation from radio waves and visible light to the ultraviolet, X-rays, and gamma-rays, arrives at Earth. Through interactions with the terrestrial environment, this radiation helps create short timescale space weather as well as the longer-term global climate.

* Corresponding author. Tel.: 1-818-393-7742; fax: 1-818-393-4530.

E-mail address: kent.tobiska@jpl.nasa.gov (W.K. Tobiska).

PII: S1364-6826(00)00070-5

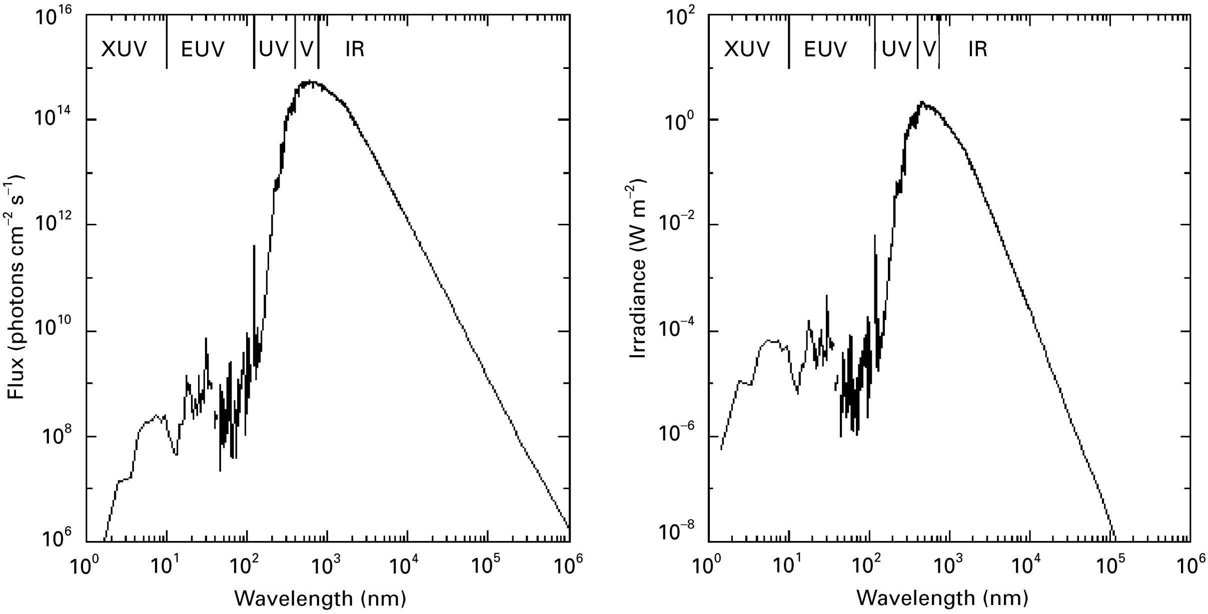

Fig. 1. Solar irradiance format for SOLAR2000 from the X-rays to the infrared adapted from Hinteregger et al. (1981), Woods (private communication, 1998), and ASTM E490. The total integrated irradiance in this spectrum is 1367.28±0.02 W m^{-2} including EUV variability.

Variations of the total solar irradiance (TSI), ultraviolet (UV), far ultraviolet (FUV), extreme ultraviolet (EUV), and soft X-rays (XUV) irradiances (Fig. 1) are the fundamental forcing mechanisms to the terrestrial atmosphere, land, and oceans. The Sun varies on all time scales and the magnitude of variability is a strong function of wavelength.

For example, the absolute amount of XUV–UV radiation is much smaller than the visible part of the spectrum though the solar cycle variability of this wavelength range is much greater than the rest of the spectrum. Emission lines in the XUV–EUV rise significantly above the blackbody spectrum and even above the continua emission. They form under non-local thermodynamic equilibrium (LTE) conditions in higher temperature layers of the outer solar atmosphere such as the chromosphere, transition region, and cool corona. The emissions are strongly related to magnetic activity of the Sun as seen, for example, in plage regions. Short-term variations, lasting from minutes to hours, are related to eruptive phenomena. Intermediate-term variations are modulated by the 27-day rotation period of the Sun. These are related to the appearance and disappearance of active regions, plage, and network on the solar disk. Long-term variability is related to the 22-year magnetic field cycle of the Sun. An accurate, long-term XUV–UV and TSI variation is still to be determined with satellite solar instruments. Examples of variability are factors of 10 or 20 or more between 1 and 10 nm, factors of 2 between 10 and 120 nm, 1–10% between 1 and 400 nm, and less than 1% for the TSI. Lean (1987, 1991), Rottman (1987), and Tobiska (1993) have provided recent reviews of solar XUV–UV variability.

For the TSI, the combination of Nimbus 7 and SMM instruments provided the first set of observations showing decadal solar irradiance variations on the order of 0.1% that were linked to solar cycle activity (Willson and Hudson, 1991; Hoyt et al., 1992). Fröhlich (1994) describes the times series from the Nimbus 7/ERB (HF), the SMM/ACRIM I, the UARS/ACRIM II, and the PMO6/SOVA 2 measurements with an unambiguous ~0.1% peak-to-peak variation in the total solar irradiance signal over a solar cycle. Although the relative impact of these solar variations on global climate change and weather is to be determined, we know that TSI variations directly force global surface temperatures and that solar UV variations modify ozone and the middle atmosphere structure (National Academy of Sciences, 1994).

1.2. Solar–terrestrial interactions

Solar emissions map from different source layers in the solar atmosphere to levels near unit optical depth in the terrestrial atmosphere as a function of wavelength and species cross section (Fig. 2). UV solar irradiances below 300 nm are completely absorbed by molecular oxygen and ozone and this radiation is both a dominant loss and source mechanism for stratospheric and lower mesospheric ozone. Solar emissions between 132 and 175 nm are absorbed by O_2 in the Schumann–Runge continuum and, at certain wavelengths between 175 and 205 nm, molecular oxygen cross sections are comparatively small. This allows solar UV to penetrate lower into the atmosphere and to be

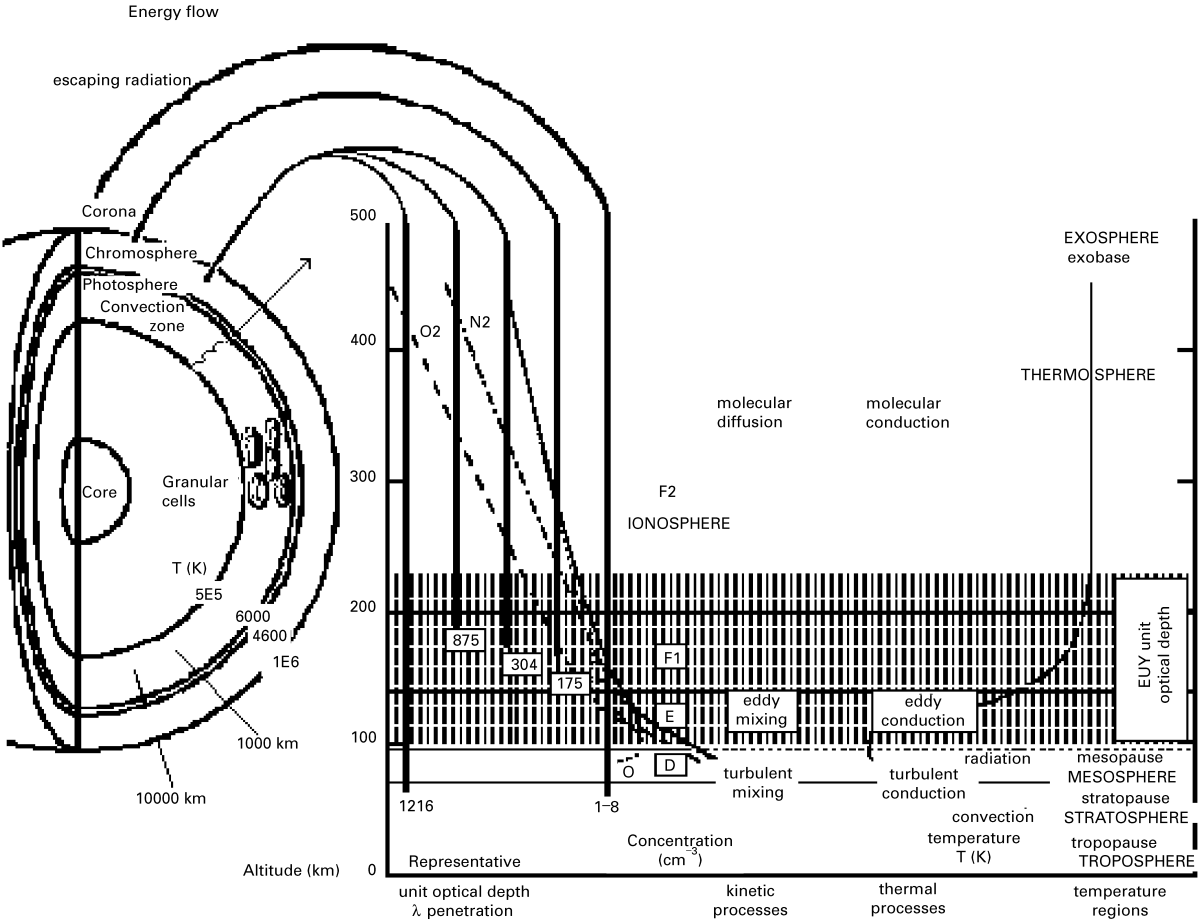

Fig. 2. Coupling of the solar–terrestrial environment. Solar irradiances from the photosphere, chromosphere, and corona are deposited at unique optical depths in the Earth's atmosphere (adapted from Brasseur and Solomon, 1984; Tobiska, 1988).

absorbed by O_2 in the Schumann–Runge Bands. Higher in the atmosphere, H Lyman-α photons at 121.6 nm pass through a window in the molecular oxygen cross section and penetrate to the mesosphere to photoionize nitric oxide and form the ionospheric D-region. Ozone photochemistry is affected by Lyman-α photons via the process of mesospheric water vapor dissociation that produces catalytically active hydroxyl radicals. Even higher in altitude, solar EUV emissions such as Lyman-β and X-rays from 0.1 to 0.8 nm compete in a complex way depending upon the level of solar activity and dominate energy deposition in the ionospheric D-region. He II 30.4 nm photons are the most important energy contributor to overall heating of the thermosphere at all solar activity levels.

Solar UV control of the middle atmosphere may couple with the Earth's biosphere. It is still unclear if solar EUV and XUV variability that effects the Earth's near-space environment also couples with the biosphere. However, one solar–terrestrial coupling phenomenon may be active. Anthropogenic carbon dioxide and methane may be convectively transported upwards from lower atmosphere layers and may have an effect upon the upper atmosphere hydrogen budget, cooling this region over long timescales.

The thermal balance of the Earth's atmosphere is largely determined by the 300–10,000 nm spectral region which contains about 99% of the total solar radiation. About 30% of this incoming radiation is reflected or scattered back to space but the remaining 70% is absorbed by the ocean and land surfaces. Variations in these spectral regions could have a major impact on global climate since the Earth's oceans, land surfaces, and atmosphere respond differently to heating by these wavelengths. For example, visible blue light penetrates the first 10-m mixed layer of the ocean while infrared radiation is absorbed by the topmost layer to a few millimeters. The transfer of heat from the ocean to the atmosphere is likely be affected significantly by the spectral distribution of irradiance changes.

1.3. Key scientific questions

Hence, the accurate characterization of a historical, self-consistent, empirical solar irradiance spectrum, extending from the soft X-rays through the infrared wavelengths (e.g., 1–1,000,000 nm), is important for answering key scientific questions. The need for this characterization motivates the development of SOLAR2000 which, in turn, contributes to answering such questions.

For example, solar variability in wavelengths from 1 to 200 nm may couple the Earth's upper atmosphere and near-space environment to the middle atmosphere and biosphere in a manifestation of space weather. Specifically,

- *Do we know the primary mechanisms by which solar UV, FUV, EUV, and XUV irradiance variations affect terrestrial global climate change and/or weather; if so, what is their significance and can we predict those variations?* SOLAR2000 self-consistent, daily solar spectra from 1 to 200 nm for multiple solar cycles provide short- and long-term historical and forecast solar irradiance variations.

Irradiances in the 200–400 nm range will help answer key questions regarding solar influences on global change. For example,

- *How does solar forcing compare with forcing from other sources such as increasing concentrations of radiatively active gases and atmospheric aerosols?* Daily solar irradiances at 1 nm spectral resolution between 200 and 400 nm can be used as inputs in atmospheric models providing realistic energy to compare species' concentrations and their variability.
- *How sensitive is the Earth's climate to solar radiation changes and what time scales of solar variability are significant to climate?* Daily to multiple solar cycle realistic irradiance estimates are necessary for climate sensitivity studies, are historically available from 1947 onwards, and are forecast into the next solar cycle.
- *How might solar variability affect global warming projections?* The self-consistent solar spectrum links historical irradiance databases and can be used in global warming studies to estimate the total radiation deposited from the surface to space in each terrestrial layer.
- *Are there signatures of solar influences distinct from anthropogenic effects?* The self-consistent solar spectrum has sufficient spectral resolution for depositing accurate energy in discrete atmospheric layers that will help discern non-solar, potentially anthropogenic effects.

Solar variability in wavelengths from 400 to 10,000 nm may couple with the terrestrial climate and biosphere. Irradiance knowledge in this spectral range will help answer key climate questions such as

- *What are the implications for humanity from solar influences to the terrestrial climate?* The extremes of our climate in historical times give reason for concern while the causes of paleoclimate changes are also unclear. An interesting relationship shows severe climate periods (e.g., temperatures in the "Little Ice Age") in comparison with possible climate markers (the percent change in $\Delta^{14}C$ from tree ring analysis) and solar forcing (solar cycle activity represented by Sunspot numbers) (National Academy of Sciences,1994). It is known that a continuous variability record of the total solar irradiance is required for studying solar influences on the global climate, for modeling the coupled Sun–Earth processes that can induce climate change, for understanding paleoclimate changes based on intercomparisons with solar irradiance analogs, and for predicting future climate perturbations. Of particular concern are predictions that the climate may warm by up to 3.5°C over the next 100 years as a result of increasing concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and chloroflourocarbons (Intergovernmental Panel on Climate Change, 1996). What role, if any, solar irradiance variations play in such a climate change is still unknown but solar-induced changes could significantly impact these predictions in either direction of temperature change. The current level of known solar cycle variability simply modulates the net anthropogenic increase in climate forcing. This model provides a solid basis for characterizing accurate, long-term TSI variations necessary for terrestrial climate studies.

1.4. Scientific goal and objective

The overarching scientific goal of SOLAR2000 is to contribute to the understanding of how the Sun varies, spectrally and through time, from the X-rays to the infrared wavelengths. Achieving this goal is accomplished, in part, by providing a solid, empirical irradiance variability foundation in order to help understand what solar interior dynamical mechanisms may cause this variability. This knowledge base will also help understand the way in which active regions, plage, and network evolve as a result of plasma–magnetic field interactions.

To understand and predict solar influences on global change, we must improve our knowledge of the variable Sun on multiple cycle, solar cycle, intermediate-term, 27-day, and shorter timescales. Ideally, all these solar irradiance variation measurements are made from space. However, measurements are not always available. As the alternative, solar irradiance models using ground- and space-based proxies or first principles have been developed to link diverse datasets and provide temporal and spectral continuity. However, there is not yet a solar irradiance variability model, empirical or first principles, that incorporates all the atmospherically relevant solar spectral regimes in a self-consistent manner and that varies with the observed solar emissions. Establishing such an empirical model is the primary scientific objective underlying the development of SOLAR2000.

The SOLAR2000 irradiance model is being developed from measured solar irradiances with geophysically relevant spectral resolution and time variability extending from the X-rays to the infrared wavelengths, i.e., 1–1,000,000 nm. The model is useful as a fundamental energy input into planetary atmosphere models for climate and energy process research. It can be used as a comparative model with numerical/first principles solar models to help explain solar physical processes. SOLAR2000 is also a tool to model or predict the solar radiation component of the space environment as part of space weather programs. As designed, it is compliant with the developing International Standards Organization (ISO) solar irradiance standard. SOLAR2000 captures the essence of historically measured solar irradiances and this information will expand our knowledge of the quiet and variable Sun. The model provides a comparative database for future studies of the Sun's changes and its historical envelope of variability.

SOLAR2000 provides an operational forecasting and solar irradiances specifications tool. These irradiances are able to couple with and help validate global ionospheric and thermospheric neutral density models. This capability supports US national agency programmatic goals that are relevant to solar irradiance specification.

1.5. Programmatic goals

1.5.1. US Global Change Research Program

The U.S. National Research Council (NRC) Board on Global Change, Commission on Geosciences, Environment, and Resources operates under the auspices of the United States Global Change Research Program (USGCRP). A recent panel of this Commission produced a report entitled *Solar Influences on Global Change* (National Academy of Sciences, 1994). It concluded that "solar variations directly force global surface temperature, solar variations modify ozone and the middle atmosphere structure, solar variability effects in the Earth's upper atmosphere (possibly) couple to the middle atmosphere and the biosphere '(it is unknown if) solar variability effects in the Earth's near-space environment couple to the biosphere' (and) we need to improve our knowledge of the variable Sun to understand and predict solar influences on global change."

SOLAR2000 irradiances between 1 and 400 nm are designed to help understand how solar variations force global surface temperatures, modify the middle atmosphere structure, and create the ionosphere. The model will contribute to understanding whether or not solar variability effects upon the Earth's upper atmosphere and near-space environment also couple to the middle atmosphere and the biosphere.

The scientific goal and objective of SOLAR2000 broadly incorporates the NRC panel's specific recommendations. The panel determined that the scientific basis for global change policy-making must, in part, "understand and characterize, through analysis of solar images and surrogates, the sources of solar spectral (and hence total) irradiance variability." In addition, to understand potential coupling mechanisms, it is important to "monitor continuously, with improved accuracy and long-term precision, the ultraviolet radiation reaching the Earth's surface (as well as) monitor the solar extreme ultraviolet spectral irradiance (at wavelengths less than 120 nm) for sufficiently long periods of fully assess the long term variation." The SOLAR2000 self-consistent empirical solar spectrum incorporates two decades of ground and satellite measurements. As such, it is designed to preserve the information in historical datasets and will help improve knowledge of the variable Sun to understand and predict solar influences on terrestrial global change.

1.5.2. National Polar-orbiting Operational Environmental Satellite System

Beginning early in the 21st Century, NASA's Earth Observing System (EOS) and the Departments of Defense and Commerce National Polar-orbiting Operational Environmental Satellite System (NPOESS) will monitor and provide global and regional weather data including solar-geophysical information. These data will also help monitor space weather and answer "What critical measurements and scientific understanding will improve solar variability forecasting and will enable the protection of technological systems from space weather? Can we enable a reliable forecast of harmful solar activity effects on vulnerable societal systems?"

Major NPOESS elements are not yet in place. For example, a method of efficiently integrating large datasets and disseminating value-added data products has not been planned. In addition, the structure for research support that is necessary to achieve operational climate and space environment products is only now beginning to be developed. SOLAR2000 assists this programmatic evolution by providing a method of organizing and preserving information content in solar irradiance measurements, data integration and dissemination.

1.5.3. National Space Weather Program

SOLAR2000 significantly contributes to the US National Space Weather Program (NSWP). The NSWP seeks to improve our understanding of the physical space environment by encouraging the development of empirical and physics-based models that adequately forecast and specify that environment.

Space weather is organized by domain within the NSWP. Included are coronal mass ejections, solar activity/flares, solar and galactic energetic particles, solar UV/FUV/EUV/XUV irradiances, solar radio noise, solar wind, magnetospheric particles and fields, geomagnetic disturbances, radiation belts, aurora, ionospheric properties, ionospheric electric fields, ionospheric disturbances, ionospheric scintillation, and the neutral upper atmosphere (thermosphere and mesosphere). In the near-term, this model contributes to the solar UV, FUV, EUV, and soft X-ray irradiances domain. In the long term, the full TSI variations will be included in SOLAR2000.

The NSWP goal of improved understanding can be achieved when the representation of space weather is coupled into a seamless system from the Sun to the Earth. In working toward this goal, the NSWP supports the continued development, integration, and validation of improved models of the solar-terrestrial system. In general, the NSWP supports the evolution from empirical models through semi-empirical to coupled physical models. Ideally, all models will eventually be self-consistently coupled so that changes in the system driving forces can be communicated through the different regions of space. SOLAR2000 provides the first self-consistent, empirical solar XUV-IR operational forecast and specifications tool and is a starting point in an eventual chain of coupled models that will reduce risks from space weather.

1.6. Mitigating space environment effects

Much as modern weather forecasts help to mitigate the costs of destructive storms, space weather forecasts attempt to mitigate the impact of solar activity on human technology. Enterprises already known to be affected directly or indirectly by the Sun's radiative effects include cellular telephone service, weather satellite operation, fusion and carbon dating experiments, global positioning system (GPS), ozone measurement program, commercial TV relays, communication satellite systems, satellite reconnaissance and remote-sensing systems, submarine detection, manned space program, interplanetary satellite experiments, VLF navigation systems (OMEGA, Loran, etc.), over-the-horizon radar, solar–terrestrial research and applications, satellite orbit prediction, balloon and rocket experiments, ionospheric rocket experiments, and short-wave radio propagation. There are two major risk-mitigation paths and SOLAR2000 contributes to both.

First, knowledge of past solar irradiance behavior and range of variability allows engineers to incorporate features into system designs that can shield our technology from worst-case scenarios. SOLAR2000 is a tool for technology system designers who are interested in protection against dissociating and ionizing solar radiation under a range of solar activity conditions.

Second, risk is sometimes judged acceptable in return for substantial cost-reduction benefits. In this case, technological systems may operate satisfactorily during nominal solar activity but may suffer temporary or catastrophic failure under abnormally active solar conditions. To address this risk, SOLAR2000 contributes short-term forecasts and long-term global specifications for solar irradiances.

1.7. Operational capability

The SOLAR2000 model offers a way to transfer research results into operational systems. A first example is that the NOAA Space Environment Center in Boulder will evaluate SOLAR2000 for irradiance specification through its Rapid Prototyping Center. This evaluation and validation process will eventually provide daily nowcast solar irradiances. These irradiances may then be coupled with first-principles thermosphere–ionosphere–plasmasphere models such as CTIP (Fuller-Rowell et al., 1996; Millward et al., 1996) or other models to provide upper atmosphere neutral mass densities/electron profile nowcasts or forecasts. A second example is a new solar EUV proxy, E10.7, which is described in Section 2.7 and is a direct application of research knowledge to operational systems.

Commercial development in space has significantly increased the applications for the operational capability of this solar irradiance specification tool. Near real time, minutes to hours, solar irradiance and thermospheric density knowledge allows satellite operators to respond to rapidly changing conditions in the next orbit for single satellites, reentry vehicles, or satellite constellation station keeping. Forecasts from days to months, based on forecast irradiances, are useful for scheduling satellite activities such as maneuvers, station-keeping operations, and reentry planning. SOLAR2000 irradiances also provide months-to-years climatological estimates that are useful for LEO satellite mission design activities or interplanetary spacecraft trajectory design using Earth gravity assists. Historical irradiances are also commercially useful. Applications include anomaly post-analysis and resolution, as-flown archival of satellite ephemeredes, and validation of operational algorithms.

For operational centers using ionospheric densities, improved solar flux can provide more accurate electron density and total electron content. For example, near real-time information from forecast solar irradiance-derived electron densities can provide a knowledge base for algorithms to accurately correct GPS signals that are perturbed by scintillation. Intense scintillation events may create intermittent or even persistent disruption of GPS signals for extended periods. Predictive information, showing that conditions are ripe for scintillation events, can be used to avoid reliance on those systems during times when disruption is likely. Table 1 outlines the SOLAR2000 applications by time scales of solar phenomena and human needs.

An operational version of SOLAR2000 is being installed on a continuously operating, 24/7 server that autonomously downloads the most recent proxies, ingests the data, performs trend analysis, and provides warning and nowcast capability. The code development uses an object-oriented (OO) approach addressing the architectural software design questions "What are the objects and what are the interfaces?" The code design and implementation of the architecture has

Table 1
SOLAR2000 applications[a]

Human time-scale Solar time-scale	Past	Present	Future
Multiple solar cycles	Sun-climate studies (r)		Sun-climate studies (r)
Solar cycle	Global warming studies (r)		Global warming (r) Mission planning (c, g, m)
Months	Solar–terrestrial studies (r) Post-analysis (c, g, m)		Scheduling (c, g, m) Reentry (c, g, m)
Weeks	Solar–terrestrial studies (r) Post-analysis (c, g, m)		Scheduling (c, g, m) Reentry (c, g, m)
Days	Post-analysis (c, g, m)		Station Keeping (c, g, m) Reentry (c, g, m)
Hours	Post-analysis (c, g, m)	RT ops (c, g, m) Reentry (c, g, m)	Station Keeping (c, g, m) Docking (c, g, m) GPS (c, g, m)
Minutes	Post-analysis (c, g, m)	RT ops (c, g, m) Reentry (c, g, m) GPS (c, g, m) HF freq (c, g, m)	Station Keeping (c, g, m) Docking (c, g, m) HF usable freq (c, g, m)

[a] Application code: c (commercial), r (research), m (military), g (government agency).

four parts:

(1) description of what the model will do by developing "Use Cases" and including scenarios that end users will typically follow;
(2) code diagramming where the objects and their interactions are created;
(3) code proof-of-concept prototyping that targets risk areas, i.e., the most potentially difficult algorithms, and implements the writing of classes, methods, and test cases for each object that is specified; and
(4) fix the deficiencies discovered in the initial end-to-end alpha version to deploy a beta release that has sufficient robustness and function to pass a detailed set of tests in the test plan document.

The Use Cases represent six classes of users that SOLAR2000 can serve, including:

(1) *education/public outreach* where the most recent daily average solar spectrum for education and public outreach is provided;
(2) *research-grade* for scientific and engineering research where a user may generate historical daily solar irradiances;
(3) *contract-grade* for scientific and engineering research using historical and climatological daily irradiances that are coupled with other models;
(4) *operations-grade* for support of operations and forecast facilities such as NOAA/SEC. This model grade incorporates dedicated runs, specific proxy input, specific "push" technology output, and restricted distribution solely to the forecast center. The nowcast daily irradiance output is validated and then released publicly by a forecaster;
(5) *commercial-grade* for secure local or remote use of high time resolution, validated irradiance products coupled with other models or linked directly to a commercial product; and
(6) *server developer* assistance for developers of remote, coupled models that are linked to SOLAR2000.

1.8. State of observations and models

1.8.1. Measurements

Following the first solar UV rocket in 1946, EUV rocket observations were made and provided absolute flux estimates for specific solar conditions. Reviews by Tousey (1961), Timothy (1977), Schmidtke (1984), Lean (1987, 1991), Rottman (1988), and Tobiska (1993) detail the early history.

EUV satellite observations exist since 1962. These provide insights into wavelength-dependent daily, solar rotational, active region evolution, and solar cycle variations. Satellites in this period include OSO 1 (1962), OSO 3 (1967), OSO 4 (1967–69), OSO 6 (1969), AEROS A (1972), AE-C (1974–75), AEROS B (1974–75), AE-E (1977–80), SOLRAD 11 (1977–79), PROGNOZ 7–10 (1978–85), San Marco 5 (1988), PHOBOS 1& 2 (1988–89), YOHKOH (1991-), CORONAS-I (1994), INTERBALL-1 (1995–96), ELECTRO (1995–98), and SOHO (1995–). Future XUV-EUV measurements are planned on TIMED (2001-), ISS (2003-), GOES (2004-), and Solar Patrol (2004-). Sounding rockets have made spectral, image, and

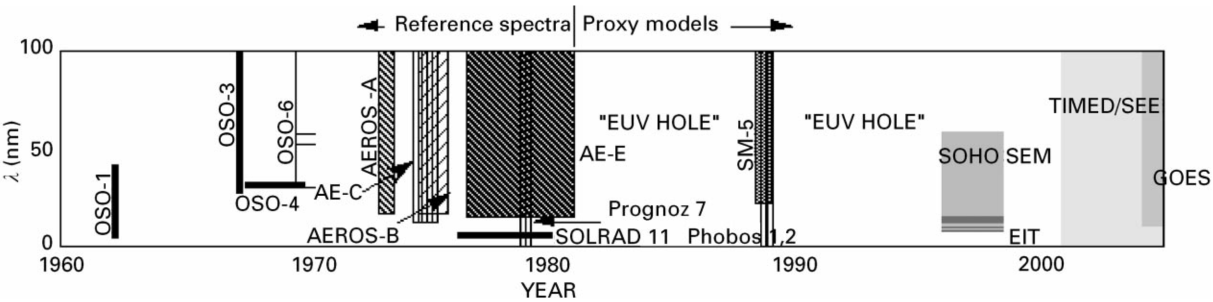

Fig. 3. Timeline showing intermittent XUV/EUV satellite observations since the 1960s, reference spectra development during early observations (1970–1990), and empirical model appearance starting in the "EUV holes" (1980–2000) (adapted from Schmidtke, private communication, 1992).

integrated bandpass observations throughout the EUV, especially during the "EUV Holes" (Fig. 3). They include USC (1982, 1983, 1988, 1996), LASP (1988, 1989, 1993, 1994, 1996, 1998), and GSFC (1989).

Solar UV satellite observations have been made by AEROS A (1972), AE-C (1974–75), AEROS B (1974–75), AE-E (1977–1980), Nimbus 7 (1978–1987), SME (1981–1989), NOAA 9,11 (1985-), ATLAS 1,2 (1992,1993), UARS (1991-), and GOME (1995-). NOAA 14 (2000-), TIMED (2001-), EOS/TSIM (2002-), and ISS (2003-) will provide future measurements in the UV spectral range.

Following the inconclusive efforts to measure variations in the solar constant from ground and airborne platforms, satellite instruments were developed. Researchers anticipated greater precision by reducing the effect of atmospheric interference. The first successful long-term irradiance measuring experiment using a thermopile-based radiometer, commonly called the H-F type, was launched on Nimbus 7 as the Earth Radiation Budget Experiment (ERB). It began successful measurements on November 16, 1978 (Hickey et al., 1988,1989) and continued to early 1993. Shortly after the Nimbus 7 launch, an active cavity radiometer irradiance monitor (ACRIM I) was flown on the Solar Maximum Mission (SMM) and conducted measurements from February 14, 1980 (Willson, 1979) to June 1, 1989.

Currently, the ERBS and UARS/ACRIM II instruments are returning TSI data although ERBS does not measure on a daily basis and UARS is facing significant problems in its power subsystem. The PMO6-V and the Differential Absolute Radiometer (DIARAD) on the joint ESA/NASA SOlar Heliospheric Observatory (SOHO) Variability of solar IRradiance and Gravity Oscillations (VIRGO) instruments launched in 1995 are also returning data (Fröhlich et al., 1995).

1.8.2. Reference spectra

The 1-nm reference spectrum in Fig. 1 is a composite spectrum. Hinteregger (1985, private communication) provided the SC21REFW reference spectrum between 1.8 and 15.5 nm, Woods (private communication, 1998) provided a solar spectrum between 15.5 and 119.5 nm. The ASTM E490 reference solar spectrum provides solar irradiances longward of 119.5 nm.

Reference spectra have been particularly useful for characterizing the highly variable XUV–EUV spectral range. Prior to AE-E, reference XUV–EUV spectra were developed from rocket observation. Several spectra have been widely used. For example, the Donnelly and Pope (1973) moderate solar activity ($F10.7 = 150$) reference spectrum was a composite of several rocket observations with a wavelength bin size is 0.3–1 nm. Several discrete, important lines are included and this was the first reference solar spectrum in the EUV.

Hinteregger et al. (1981) provided a reference spectrum for low solar activity ($F10.7 = 68$) from a composite of rocket and satellite observations with a wavelength bin size of 0.1–0.2 nm. All discrete, important lines are included in this reference spectrum (SC#21REFW). AFGL reference spectrum (F79226) for high solar activity and (F79050N) for anomalously high solar activity have also been used in the literature (Hinteregger, private communication, 1985).

Schmidtke et al. (1992) have provided a moderate solar activity ($F10.7 = 150$) composite of rocket (LASP) and satellite (ASSI) observations with a wavelength bin size of 1.0 nm. All discrete, important lines are included within each bin.

The ASTM E490 composite spectrum is used by SOLAR-2000. In it, UARS/ATLAS-2 moderate solar activity spectra are used between 119.5 and 379.5 nm which are averages of the SUSIM and SOLSTICE measurements (Woods et al., 1996). These data were scaled by 0.96843 to match the Neckel and Labs (1984) data between 330 and 410 nm. Thuillier et al. (1998a,b) provided a spectrum that is used above 379.7 nm. However, the 410–825 nm range values come from the McMath Solar Telescope (Neckel and Labs, 1984). Between 825 nm and 4.0 μm, the ASTM E490 spectrum is from a high-resolution solar atlas (Kurucz, 1993). Here the data are smoothed to the composite spectrum resolution and scaled by 1.00085 to match the Neckel and Labs (1984) data at 825 nm. Between 4.0 and 1000 μm, the spectrum is the logarithmic irradiance versus wavelength fit reported by Smith and Gottlieb (1974) which is then scaled by 0.99437 to match the Kurucz (1993) data at 4.0 μm. The entire composite spectrum was then scaled by 0.99745 to make the integrated total irradiance equal to the solar constant (Fröhlich and Lean (1998)).

Beyond reference spectra, and post AE-E, the "EUV holes" (a period devoid of continuous measurements) have forced the development of empirical solar EUV models. All empirical solar EUV irradiance models, i.e., SERF1, Nusinov, SERF2, EUV91, SERF3, EUVAC, and EUV97 derive from AE-E data. There has only been one rigorous comparison made between EUV models (Lean, 1990) where SERF1 and SERF2 were compared with the data used to derive those models. Comparisons have been made using coupled solar-ionospheric models with ionospheric electron content or densities and these comparisons have pointed to areas requiring model improvement. A short description of the EUV empirical models demonstrates the state of empirical modeling, with the exception that SERF3 has not yet been published (Donnelly, private communication, 1998).

*SERF*1: Hinteregger et al. (1981) provided a model where Lyman-β is used as a proxy for chromospheric emissions during the AE-E timeframe. Fe XVI is used as a proxy for coronal emissions. Outside of AE-E, F10.7 is used as the sole proxy.

Nusinov: Nusinov (1984) developed a model with an empirically determined active-region background component, Fb, which incorporated modeled physical features. It is combined with daily F10.7 to produce full-disk irradiances.

EUVAC: Richards et al. (1994a,b) describe a solar EUV flux model which reproduces the integrated EUV flux and the shape of the measured photoelectron flux spectrum in 37 wavelength bins. It is based on the measured F74113 solar EUV reference spectrum and the solar cycle variation of the flux measured by the AE-E satellite.

EUV97 model: Tobiska and Eparvier (1998) upgraded a model for aeronomical and space environment uses with heritage from SERF2 (Tobiska and Barth, 1990) and EUV91 (Tobiska, 1991). Lyman-α is used as the chromospheric proxy and F10.7 is used as the coronal proxy. EUV97 models daily irradiances from 1947 to the end of solar cycle 23 in 39 wavelength lines or bins.

UV and FUV models: Three solar UV models have been developed which represent the spectral range of 120–200 nm, i.e., fluxes that originate in the solar photosphere and chromosphere. Cook et al. (1980) developed a two-component model that used a parameterization of the daily sunspot number to provide plage region and quiet region emission. Lean et al. (1982) improved upon the long-term absolute irradiance variation with a three-component model that incorporates flux contributions from the quiet Sun, moderately bright active network, and bright plage areas. Worden (1996) used improved UARS/SOLSTICE FUV irradiances to develop a similar three-component model as well as an empirical model based on a Lyman-α plage-index proxy.

None of the XUV/EUV/FUV/UV models provides a self-consistent, full solar spectrum, an operational version, a proxy of the EUV, nor a forecast capability. None are compliant with a developing ISO solar standard. These issues are additional motivating factors for the development of SOLAR2000.

1.9. ISO solar standard compliance

The International Standards Organization (ISO) Technical Committee 20, SubCommittee 14 (Space Systems and Operations), Working Group 4 (Space Environment, natural and artificial) (ISO TC20/SC14/WG4) is drafting a solar irradiance standard. The scope of the standard specifies the representations of solar irradiances and is applicable to measurements, reference spectra, empirical models, and first-principles models. Its purpose is to provide a standard specification of all solar irradiances for use by space systems materials and environment.

The concept of an ISO solar irradiance standard starts with the assumption that there will be continued technical improvements in the accuracy and precision of measurements as space-based instrumentation uses new detectors, filters, and computer hardware/software. There is also the expectation of continual improvements to reference spectra, empirical, and first-principles models. In addition, there will be an evolving solar standard user community that is still not fully defined.

Because of these anticipated changes, the ISO solar irradiance standard is being written as a process-based standard. In other words, a solar irradiance product can be developed to comply with the standard rather than adopting one spectrum or one model as the sole standard.

The standard as it is being developed contains a compliance list with four overarching requirements that are common to radiation state measurements, reference spectra, empirical models, and first-principles models. These requirements are:

(1) Solar irradiances are reported in SI units of Watts per square meter corrected to 1 AU.
(2) The method of determining irradiances is documented and, where appropriate, includes data collection, processing, archiving, validation, accuracy, and precision methodology and/or algorithms information as well as:
  (a) for measurements (e.g., space-based satellite observations or rocket experiment datasets), a description of the instrumentation used to obtain and return the fluxes as well as the instrument calibration technique and heritage,
  (b) for reference spectra (e.g., the mean of spectra over several solar cycles, spectra for low, moderate, or high solar activity conditions, or spectra based on rocket flights), a description of the measurement set(s) and reference to the instrumentation used to obtain the data, the method of resolving discrepan-

cies between data, and the rationale for specification of the data as a reference,

(c) for empirical models (e.g., code based on one or many space-based measurement sets), a description of the proxies and independent datasets used in the derivation including references, the mathematical formulation of the model and a description of its derivation as well as application, and the rationale for use of the proxies selected, and

(d) for first-principles models (e.g., models of solar LTE and non-LTE processes), a description of the physical principles upon which the model is based, the numerical algorithms and their derivations as well as application, and the rationale for the mathematical approach used.

(3) The irradiances documented in item (2) are published in an internationally available journal which uses scientific or discipline-area peer review in the publication process. For all irradiances, the published article can point to a permanent electronic archival where the actual archived measurements, spectra, or models can be found.

(4) The irradiances documented in items (2) and published in item (3) are archived in a method consistent with current technology that ensures international accessibility.

SOLAR2000 is compliant with this developing ISO solar irradiance standard.

2. Implementation of SOLAR2000

SOLAR2000 has a five-phase development process: (1) model definition and design; (2) modeling of soft X-rays (XUV) and extreme ultraviolet (EUV) irradiances; (3) modeling of far ultraviolet (FUV) irradiances; (4) modeling of UV irradiances; and (5) representation of visible, infrared, and the total solar irradiance (TSI). This implementation process ensures that a time-variable, spectrally self-consistent empirical solar model evolves to meet scientific goals and objectives over the next five years. The initial emphasis is on the most variable part of the spectrum, i.e., the XUV and EUV.

Besides improving the accuracy of historical modeling, a capability that is already found in current models, SOLAR2000 is designed to provide accurate forecasts and state specifications of the solar spectrum. There are five identified forecast timescales, each with a unique derivation method. These timescales can also be associated with technology requirements motivating solar irradiance forecasting and specification:

(1) For a 1–72 hour forecast, neural-net algorithms can be employed for irradiance estimates that are useful for helping determine thermospheric densities relevant to next several orbits satellite docking, station keeping, and reentry operations. This timescale is also important for forecasting ionospheric conditions related to GPS and HF states at specific geographic locations. This forecast algorithm will use, for example, broadband, high time resolution solar XUV-EUV measurements from GOES EUV detectors. The algorithm assumes that non-flare irradiances continue their recent trends.

(2) For a 3–14 day forecast, solar image processing can provide irradiance information to help determine thermospheric densities important for daily operational satellite docking, reentry, and scheduling. Forecasting ionospheric conditions relevant to GPS and HF states can be done on this timescale. Solar images, e.g., Ca II K, show contributions from plage and enhanced network structures distributed over the entire surface of the Sun. These images contribute information for evolving plage, enhanced network, and a derived active network compared to the reference quiet Sun and provide emission knowledge of these persistent features during the current solar rotation.

(3) For a 14–28 day forecast, interplanetary hydrogen backscatter measurements, such as the type obtained by SOHO/SWAN or from a future STEREO-type mission, will provide a proxy of solar far-side Lyman-α that can be used to forecast solar irradiances. These forecasts will continue to help determine thermospheric densities important for near-term satellite docking, reentry, and scheduling operations as well as for forecasting ionospheric conditions relevant to GPS and HF states or scheduling. Newly forming bright active regions can be detected early and forecast by assuming persistence of these features through a solar rotation.

(4) For a 1–6 month forecast, the use of FFT non-stationary periodicities can provide an estimate of solar irradiances that is useful for helping determine thermospheric densities relevant to long-term satellite scheduling and mission planning, for planning ionospheric campaigns, and for estimating GPS/HF quality periods. This method assumes that an active region timescale for evolution and decay exists over several months. Although the energy in a solar region varies with time and emitting solar atmosphere layer (hence, wavelength), the FFT method can estimate wavelength-dependent timescales based on persistence.

(5) for a 1/2–11 year forecast, statistical methods for estimating 10.7 cm flux are already used to specify solar cycle activity. The irradiances produced from this method are useful for helping estimate thermospheric densities important to satellite mission planning, lifetime, and spacecraft design criteria. Ionospheric, GPS, and HF climatology and potential Sun-climate changes can be estimated using this statistical method.

2.1. Phase I

Model definition and design is complete. In this phase, the scientific goals, objectives, and implementation strategy were defined. The baseline datasets and proxies have been

Table 2
SOLAR2000 development phases

Φ	λ	Source data	Timeframe	Proxies
2	XUV	SOLRAD	1977–1980	*Coronal*:
	1–10 nm	Rockets	1976–1998	1-8 Å
		YOHKOH	1991–?	F10.7
		SNOE	1998–?	Cor. hole images
		TIMED	*2001–?*	
2	EUV	SOLRAD	1977–1980	*Coronal*:
	10–120 nm	AE-E	1977–1980	F10.7
		rockets	1976–1998	*Chromospheric*:
		SOHO	1995–?	Lyman-α
		TIMED	*2001–?*	He I 10830 EW
		ISS	*2003–?*	Mg II c/w
		GOES	*2004–?*	GOES 5 bands
				Ca II K images
3	FUV	AE-E (Ly-α only)	1977–1980	*Chromospheric*:
	120–200 nm			Lyman-α
		Nimbus 7	1978-1987	He I 10830 EW
		SME	1981–1989	Mg II c/w
		rockets	1976–1998	Ca K 1 Å
		NOAA 9,11,14	1985–?	Ca II K images
		ATLAS 1,2	1992,1993	*Photospheric*:
		UARS	1991–?	PSI
		GOME	1995–?	
		TIMED	*2001–?*	
		EOS	*2002–?*	
		ISS	*2003–?*	
4	UV	Nimbus 7	1978–1987	*Chromospheric*:
	200–400 nm	SME	1981–1989	Lyman-α
		rockets	1976–1998	He I 10830 EW
		NOAA 9,11,14	1985–?	Mg II c/w
				Ca K 1 Å
		ATLAS 1,2	1992,1993	Ca II K images
		EURECA	1992–1993	*Photospheric*:
		UARS	1991–?	PSI
		GOME	1995–?	
		EOS/TSIM	*2002–?*	
		ISS	2003–?	
5	VIS-IR	ATLAS 1,2	1992,1993	*Photospheric*:
	400–1,000,000 nm	*EOS/TSIM*	*2002–?*	PSI
		ISS	*2003–?*	

identified (Table 2), as have the default 1 nm wavelength bin baseline template with daily time resolution. The model algorithm (Eqs. (1) and (2)) and the uncertainty (1σ specification of measurement error which includes data-proxy correlation uncertainty) is established. The algorithm produces an irradiance integrated over a spectral bin based on the solar source layer components (coronal, chromospheric, and photospheric). The irradiances are ratioed to their quiet Sun values with both daily and 81-day proxy components used in the algorithm. One notes that $a_0(\lambda, k)$ is the baseline coefficient of the multiple linear regression at a specified wavelength, λ, for $k = 1, 2, 3$ (coronal, chromospheric, photospheric), $a_1(\lambda, k)$ is the 81-day proxy coefficient, and $a_2(\lambda, k)$ is the daily minus 81-day proxy coefficient, P is the daily proxy value, and P_{81} is the 81-day proxy value. To prevent the occurrence of negative solar minimum values for a derived flux, z is a power term that revises the solar cycle maximum/minimum proxy ratio to the same as the flux data ratio for a defined time frame.

$$\frac{I(\lambda,k,t)}{I_0(\lambda,k,t)}-1=F(\lambda,k_{=2},t)_{\text{corona}}+F(\lambda,k_{=1},t)_{\text{chromosphere}}+F(\lambda,k_{=0},t)_{\text{photosphere}}, \quad (1)$$

where

$$I(\lambda,k,t)=\sum_{k=1}^{3}\{a_0(\lambda,k)+a_1(\lambda,k)P_{81}(k,t)^z+a_2(\lambda,k)[P(k,t)-P_{81}(k,t)]\}, \quad (2)$$

The source code language is Interactive Data Language (IDL® from RSI, Inc.) using a modular architecture that allows rapid upgrades with new datasets. The core architecture, initial dataset objects, model "wrappers", and WWW access, i.e., a dedicated FTP server and JAVA GUI applet server, are in development. The architecture enables the model to be extensible and portable for easy user access, distribution of model results, and retention of legacy files and programs. The web interface and distribution architecture, using remote JAVA components and an FTP site, is designed for a nowcast and forecast capability. SOLAR2000, through all phases of development, is on the web at http://www.spacenvironment.net. As part of ISO solar standard compliance, SOLAR2000 rationale for individual proxies and dataset weighting, detailed description of the mathematical formulation and its derivation, unique applications, and proxy/dataset references will be described in a separate document.

A 3-D graphical timeline of the design, phases, and components of SOLAR2000, based on funding and proxy usage considerations, is shown in Fig. 4. This representation attempts to capture the flavor of the multiple dimensions of the SOLAR2000 model.

2.2. Phase II

Modeling of the XUV/EUV irradiances is complete. SOLAR2000 version 1.03a is based on the non-italicized datasets in Table 2. Future inclusions of SNOE/XUV, TIMED/SEE, ISS/SOL-ACES, and GOES/EUV data, for example, will complete this phase. There will be additional rocket data and other international satellite datasets, i.e., Russian and Japanese, in this wavelength range that can be incorporated into future versions. The XUV/EUV empirical irradiance code utilizes knowledge and experience from previous XUV/EUV models including SERF1, Nusinov, SERF2, EUV91, SERF3, EUVAC, and EUV97. A default 1 nm wavelength bin template is used although subroutines provide extracted prominent lines as well as user-defined grids, e.g., the SC21REFW format (~1 Å) and the SERF1 ... EUV97 37/39 wavelength ranges/lines.

SOLAR2000 version 1.03a uses traditional proxies of F10.7 for coronal emissions and Lyman-α for chromospheric emissions based on the experience of SERF1, EUV91, and EUV97 where proxies from a solar source layer best represent other emissions from the same layer. Mg II cwr and He I 1083 nm EW proxies will be incorporated in future versions. Ca II K images will eventually be incorporated as a proxy for 30.4 nm (Worden et al., 1999) where the images will also be correlated with He I 1083 nm EW and Lyman-α to link to the AE-E heritage. Maturing proxies such as the Precision Solar Photometric Telescope (PSPT) solar images, SOHO images, and planned ISOON images will eventually be incorporated in future versions. It may also be possible to use the two-temperature Mewe code model of SOLRAD data (Eparvier, private communication, 1996) for coronal proxies correlated with the GOES five XUV/EUV bands (Fig. 5).

In Phase II, the time and distance resolution, i.e., daily average irradiances at 1 AU, are used and the overall software architecture is being refined and upgraded. A JAVA GUI server has been designed that will implement client/server architecture and utilizes servlets, RMI, and CORBA. The architecture will eventually interconnect with other computer systems for data sources and destinations.

2.3. Phase III

This phase for modeling FUV irradiances has been started and is developing an FUV empirical irradiance model utilizing the knowledge and experience from previous FUV models (Worden, 1996). This modeling is being linked to the XUV/EUV code. Using the identified datasets (Table 2) and the 1 nm wavelength bin template, subroutines allow for user-created special formats. Established and new proxies such as F10.7, He I, Lyman-α, Mg II cwr, Ca K 1 Å, and PSI will be incorporated into future versions of SOLAR2000 for this wavelength region. The same time and distance resolutions are used as in other wavelength regions.

2.4. Phase IV

This phase has also been initiated to model UV irradiances based on knowledge and experience from previous FUV (Worden, 1996) and UV (Lean et al., 1982) models. Table 2 identifies the datasets anticipated for inclusion into this wavelength region of SOLAR2000. Using the same 1 nm wavelength bin grid and daily time resolution at 1 AU as other wavelength regions, this spectral range will use proxies outlined in Table 2.

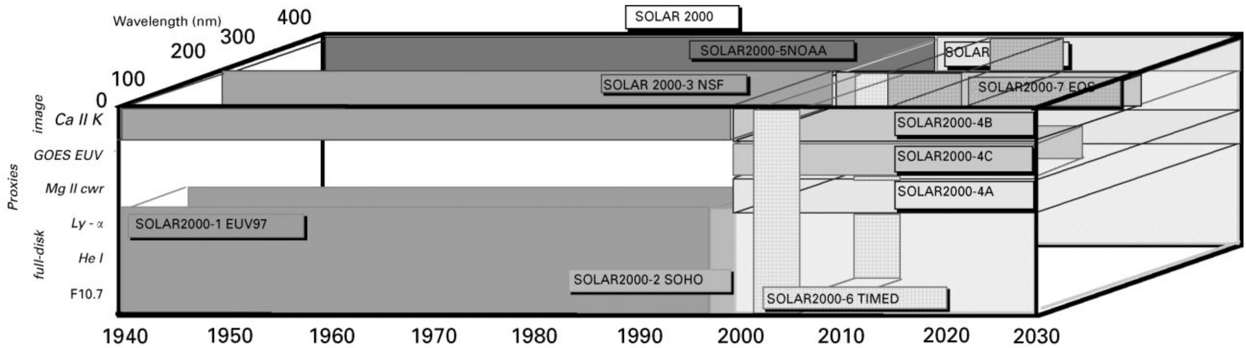

Fig. 4. Timeline of SOLAR2000 model definition and design through all phases of potential funding and proxy usage.

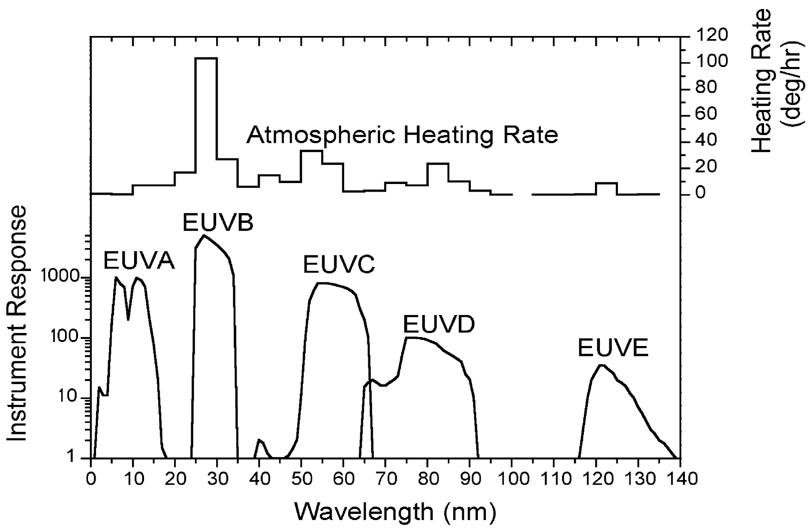

Fig. 5. Five GOES EUV broadband photometers are scheduled to fly later this decade. Their coverages are shown in relation to the thermospheric heating rate by wavelength (R. Viereck, private communication, 2000). Thermospheric heating rates vary by solar activity, altitude (density of atmosphere), species' absorption cross section, and irradiance wavelength. During both solar maximum and solar minimum the 30.4, 85–90, and 15–20 nm wavelengths produce the greatest heating rates. Five distinct bands (EUV-A: 1–20 nm; EUV-B: 24–35 nm; EUV-C: 38–68 nm; EUV-D: 64–93 nm; EUV-E: 115–139 nm) will be measured every 10 s beginning in 2004.

2.5. Phase V

This phase for representation of the visible, infrared, and total solar irradiances has begun and uses the ASTM E490 composite reference spectrum in version 1.03a. Future work in this phase will utilize knowledge and experience from other models based on sunspot irradiance deficiencies. While using the 1 nm wavelength bin grid and daily time resolution at 1 AU as other wavelength regions, new proxies will be developed for this modeling.

2.6. SOLAR2000 versions

SOLAR2000 version 1.03a (February 2000) uses short- and long-term variations of Lyman-α to represent chromospheric emissions and F10.7 to represent coronal emissions in the XUV-EUV wavelength range. In wavelength regions longward of Lyman-α, a reference spectrum is used as described in Section 1.8 (reference spectra) and Fig. 1. Subsequent versions of SOLAR2000 will incorporate additional proxies and additional wavelength range variability. SOLAR2000, in all versions, provides irradiance output in several formats depending on user specification. Example formats include 1 nm resolution (default), 37 (or 39) wavelength bins and lines (Torr et al., 1979; Tobiska and Eparvier, 1998), and the SC#21REFW ~0.1 nm spectrum (Hinteregger, private communication, 1985). The total energy content of the full spectrum remains the same regardless of format and is the solar constant. The model provides a new EUV proxy, E10.7.

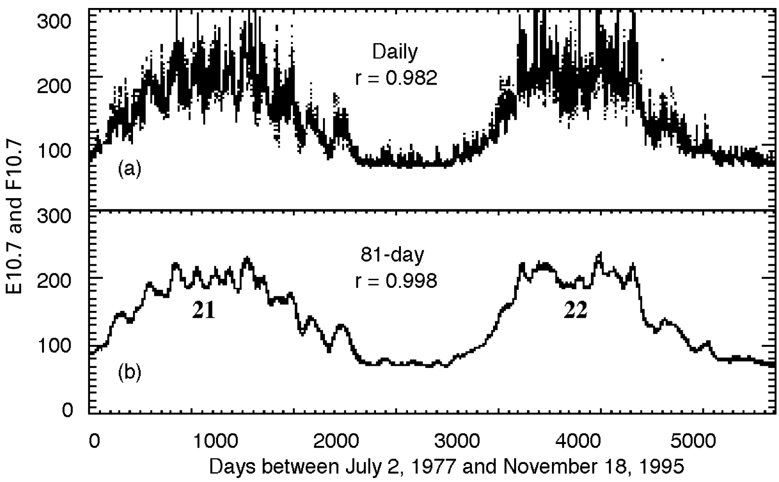

Fig. 6. Daily (panel (a)) and 81-day (panel (b)) E10.7 and F10.7 for 6714 days in solar cycles 21 and 22. The units of both are $\times 10^{-22}$ W m^{-2} Hz^{-1}. The calculation of panel (b) is shown in Eqs. (4) and (5) where E10.7 is the solid line and F10.7 is the dotted line (almost identical).

2.7. E10.7 proxy

A new solar proxy has been developed and is generated as an output product of the SOLAR2000 model. It is termed E10.7 as a proxy for the actual EUV energy arriving at 1 AU and is reported in the same units as a historical proxy, the 10.7 cm radio flux.

The idea for developing a new EUV proxy was proposed at least two decades ago by Schmidtke (1976), who suggested an EUV proxy summed over wavelength bands. At the June 1999 TIGER symposium (St. Petersburg, Russia), there was renewed support for such a proxy. It was acknowledged that many empirical models, across many disciplines, use the 10.7 cm flux as a proxy for solar irradiances. Participants noted that it is much easier to develop a new proxy as input into those models rather than to change the models.

Ideally, one would like a new proxy to reflect the time-dependent (t) solar heating of the thermosphere as a function of EUV energy by wavelength (λ), heating efficiency, unit optical depth ($\tau(\lambda,z)$), and absorption cross section of each neutral species ($\sigma_i(\lambda)$). Fig. 5 shows an example of this heating. Physically, this can be thought of as the volume-heating rate per unit mass in the thermosphere, $q_i(\lambda,z,t)$. In the derivation of E10.7, the daily integrated volume-heating rate per unit mass, $Q(t)$, where

$$Q(t) = \sum_i \sum_\lambda \sum_z q_i(\lambda,z,t) \tag{3}$$

for $i = 1,\ldots,8$ constituents, $\lambda = 1.8$–105.0 nm, and $z = 120,\ldots,1000$ km, was derived for each day over 20 years (6714 days between July 2, 1977 (1977-183) and November 18, 1995 (1995-322)) using a first principles thermospheric model (Tobiska, 1988). The results were then compared with a simpler approximation, i.e., the integrated solar EUV flux at the top of the Earth's atmosphere, $E(t)$. There are only minor differences when these two quantities are compared as discussed below. Hence, the second quantity has been adopted for derivation of the E10.7 proxy based on its ease of calculation.

E10.7 is the time-dependent, integrated solar EUV flux at the top of the Earth's atmosphere reported in 10.7 cm radio flux units. An example of its calculation is Eqs. (4) and (5), i.e., the 81-day average value of E10.7,

$$E_{10.7}(t) = 19 + 20.8E(t) \tag{4}$$

and

$$E(t) = \sum_{\lambda=m}^{n} E(\lambda,t), \tag{5}$$

where $E(t)$ is the time-dependent integrated solar EUV energy flux (ergs cm^{-2} s^{-1}) from the EUV97 model between the wavelengths ($\lambda = m,\ldots,n$) for $m = 1.86$ nm and $n = 105.0$ nm. The coefficients 19 and 20.8 are derived from a first degree least-squares polynomial fit between the 81-day $E(t)$ and F10.7 adjusted values for the 6714 days described above. The correlation coefficient from this regression is 0.99 and covers two solar cycles. Fig. 6 shows the E10.7 proxy compared with F10.7 during this period for both the daily flux values and the 81-day values (Eqs. (4) and (5)).

The verification of E10.7 magnitude and variability was accomplished with two separate tests. The first test compares the standard deviations from several cases of least-squares fit proxy derivations and the second test compares E10.7 and F10.7 when both are used in calculating satellite orbit decay.

In the first test, the E10.7 mean 1σ percentage, $\langle\sigma_{\%}\rangle$ in Eq. (6), was calculated and compared to other least-squares polynomial fit proxies. Table 3 shows these comparisons

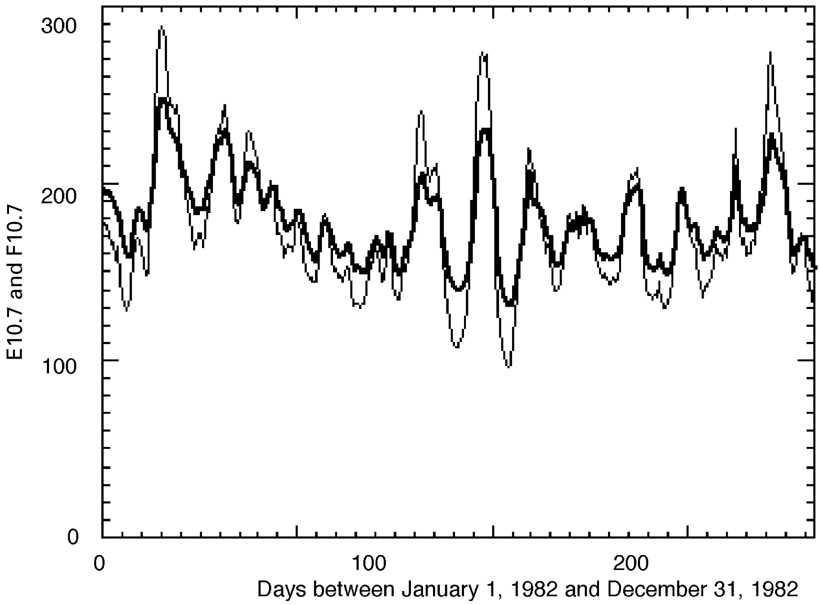

Fig. 7. E10.7 and F10.7 during 1982 in units of $\times 10^{-22}$ W m^{-2} Hz^{-1}. The E10.7 is the dark line and F10.7 is the light line. Differences in the daily variations, through several solar rotations, are apparent and can reach approximately $\pm 20\%$ with the F10.7 over- and underestimating the total EUV energy deposition.

Table 3
EUV proxy comparisons

Ind. var.	Dep. var.	T	r	$\langle \sigma_{\%} \rangle$
$E(t)$	F10.7	81-day	0.998	0.023
$Q(t)$	F10.7	81-day	0.997	0.027
$Q(t)$	Lyman-α	81-day	0.940	0.055
$E(t)$	Lyman-α	81-day	0.936	0.057
$Q(t)$	F10.7	daily	0.979	0.060
$E(t)$	F10.7	daily	0.982	0.062
$Q(t)$	Lyman-α	daily	0.900	0.075
$E(t)$	Lyman-α	daily	0.896	0.075

based on two independent variables (energy flux $E(t)$ and volume heating rate per unit mass $Q(t)$), two dependent variables (F10.7 and Lyman-α), two time frames (T, daily or 81-day), the correlation coefficient (r), and the mean 1σ percentage ($\langle \sigma_{\%} \rangle$). The 81-day E10.7, derived from the energy flux, $E(t)$, and F10.7, had the smallest mean 1σ percentage although it is nearly identical to the proxy values for the 81-day $Q(t)$ and F10.7:

$$\langle \sigma_{\%} \rangle = \frac{E_{10.7}(1\sigma)}{(1/6714)\sum_{t=1}^{6714} E_{10.7}(t)}. \quad (6)$$

In all the longer-term physical variations, such as the solar cycle and active region growth/decay, E10.7 is nearly identical to F10.7. However, in daily variations of a solar rotation or less, there are important differences where the F10.7 tends to be more variable than the E10.7. The F10.7 represents the coronal emissions while the E10.7, based on the total integrated EUV including both chromospheric and coronal emissions, varies less dramatically. In July 1982, the differences are on the order of $\pm 20\%$ as seen in Fig. 7.

The second test for verifying E10.7 as a solar proxy compared both F10.7 and E10.7 when they were used as inputs to the JPL-developed Long-term Orbit Propagator (LOP) to generate satellite altitude decay profiles (Tobiska, 1988). LOP, coupled with a Jacchia 71 (J71) thermospheric model for this study, used interpolated daily F10.7 or E10.7 values from monthly averages to determine a density at the satellite altitude.

The case of the Solar Mesosphere Explorer (SME) was examined where SME was in a Sun-synchronous orbit at approximately 540 km altitude starting in 1981. Actual SME altitude data for a year and a half were compared with LOP predicted altitudes using the monthly means of F10.7 and E10.7. The orbit prediction started on March 31, 1982 (1982-090) and ended on October 1, 1983 (1983-274). At the end, there were 200–300 m difference between the actual and predicted altitudes, z, based on a mean equatorial radius of the Earth of 6378.164 km. Table 4 summarizes the LOP comparison by orbit data source, start altitude (km), and end altitude (km). Fig. 8 demonstrates the results graphically where the dark line shows the actual SME orbit altitude, the thin solid line shows the F10.7 from LOP and the dotted line shows the E10.7. Non-EUV energy inputs to the atmosphere, e.g., Joule heating in the polar thermosphere, were not considered in this study. Some of the discrepancy

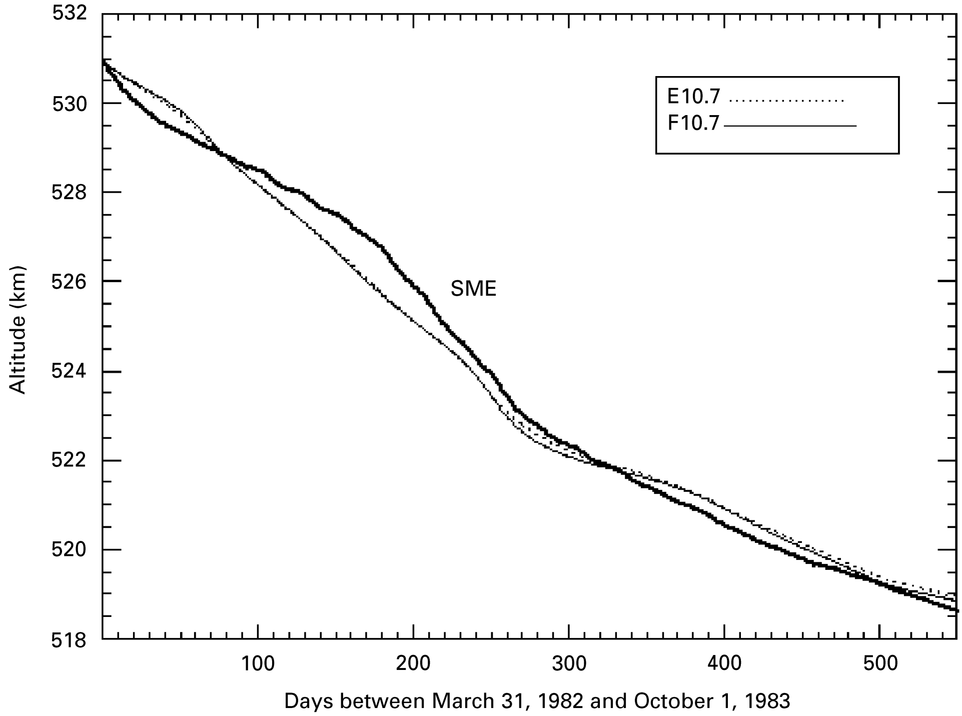

Fig. 8. SME orbit altitude comparison. SME actual altitude is the dark line, LOP coupled with J71 using a daily flux interpolated from the monthly mean F10.7 (light line), and LOP coupled with J71 using a daily interpolation from the monthly mean E10.7 (dotted line).

Table 4
SME orbit decay comparison (km)

Orbit source	*z* (1982-090)	*z* (1983-274)
SME actual	530.939	518.646
LOP (F10.7)	530.920	518.854
LOP (E10.7)	530.920	518.950

between predicted and actual orbit decay is likely due to non-solar effects.

These results validate E10.7 as a surrogate for F10.7. Why would one use E10.7 instead of F10.7? There are four general advantages of using E10.7 versus F10.7:

(1) *Nowcast*: E10.7, as produced by SOLAR2000, will be available as high time resolution data (minutes) for real-time operational applications while F10.7 will continue to be reported as daily average values. F10.7 is often used as an adjusted, rather than observed, value meaning that adjusted F10.7 is reported days or weeks after the measurement. E10.7 needs no adjustment and is available immediately. E10.7, at the highest time resolution, will capture the rise and decay of large solar flare events, a capability that does not exist with F10.7.

(2) *Forecast*: E10.7 will improve its forecast accuracy based on planned data from new missions such as TIMED, ISS Solar Platform, and GOES. The forecast accuracy of F10.7 will remain static. In addition, SOLAR2000 will provide forecasting in five distinct time regimes from 1 hour to a solar cycle.

(3) *Physics*: E10.7 characterizes the actual solar irradiance that deposits energy in the upper atmosphere while F10.7 has no physical connection to the atmosphere.

(4) *Solar spectrum*: E10.7, as produced by SOLAR2000, characterizes a subset of a broader, self-consistent solar spectrum from 1 to 1,000,000 nm while F10.7 is the single emission from one solar atmosphere layer.

In summary, E10.7 can be used in any application that uses F10.7, including empirical thermospheric models, ionospheric models, and general representations of solar activity ranging from climate research to engineering applications.

2.8. Conclusions

SOLAR2000 is a new empirical model of the full solar spectrum. Irradiances are modeled at 1 nm resolution between 1 and 1,000,000 nm and reported in SI units of W m^{-2} at 1 AU. The integrated model spectrum is the solar constant and the model is compliant with the developing ISO solar irradiance standard.

The model derivation comes from requirements for a self-consistent solar spectrum to help address important scientific questions, achieve agency programmatic goals, and mitigate space environment risks to technological systems. To fulfill these requirements, SOLAR2000 is designed to provide the first solar irradiance operational capability as well as research, contract, and commercial capabilities. It provides daily historical irradiances and will produce minutely to daily nowcast and forecast irradiances over five timescales from 1 hour to a solar cycle. The model generates a new EUV proxy, E10.7, that is the integrated EUV energy at the top of the Earth's atmosphere reported in units of 10.7 cm radio flux. This proxy is reported at all the same timescales as the model irradiances and is valid in any application that requires F10.7 for representation of solar irradiances.

SOLAR2000 is being developed in five design phases and four broad wavelength ranges. In version 1.03a, released in February 2000, the XUV–EUV spectral ranges are time variable while longer wavelengths are represented by reference spectra. SOLAR2000 documentation is located at http://www.spacenvironment.net.

Acknowledgements

Much appreciated support for this work has been provided by the NASA TIMED contract NAS5-97179 (APL Contract 774017, UCB SPO BS0059849), by the NASA SOHO contract NAS5-98172, and by the NATO EST.CLG 975301 collaborative travel grant. R.F. Donnelly has provided useful comments.

References

Brasseur, G., Solomon, S., 1984. Aeronomy of the Middle Atmosphere. D. Reidel Publ. Co., Dordrecht, Holland.
Cook, J.W., Brueckner, G.E., Vanhoosier, M.E., 1980. Journal of Geophysical Research 85, 2257.
Donnelly, R.F., Pope, J.H., 1973. Technical Report ERL 276-SEL 25, NOAA, Boulder.
Fröhlich, C. 1994. In: Pap, J.M., Fröhlich, C., Hudson, H.S., Solanki, S.K. (Eds.), The Sun as a Variable Star: Solar and Stellar Irradiance Variations, Cambridge Univ. Press, Cambridge, p. 28.
Fröhlich, C. et al, 1995. In: Fleck, B., Domingo, V., Poland A.I. (Eds.), SOHO Mission, from Solar Physics 162, 101.
Fröhlich, C., Lean, J., 1998. Geophysical Research Letters 25, 4377.
Fuller-Rowell, T.J., Rees, D., Quegan, S., Moffett, R.J., Codrescu, M.V., Millward, G.H., 1996. In: Schunk, R.W. (Eds.), Solar–Terrestrial Energy Program: Handbook of Ionospheric Models, p. 217.
Hickey, J.R., Alton, B.M., Kyle, H.L., Major, E.R., 1988. Advances in Space Research 8 (7), 5.
Hickey, J.R., Alton, B.M., Kyle, H.L., Hoyt, D.V., 1989. Space Science Reviews 48, 321.
Hinteregger, H.E., Fukui, K., Gilson, B.R., 1981. Geophysical Research Letters 8, 1147.
Hinteregger, H.E., 1985. Private communication to the Solar Electromagnetic Radiation Flux Study (SERFS)/World Ionosphere Thermosphere Study (WITS).
Hoyt, D.V., Kyle, H.L., Hickey, J.R., Maschhoff, R.H., 1992. Journal of Geophysical Research 97, 51.
Intergovernmental Panel on Climate Change, 1996. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995: The Science of Climate Change, Cambridge University Press, Cambridge.
Kurucz, R.L., 1993. ATLAS9 Stellar Atmosphere Programs and 2 km/s Grid. Harvard-Smithsonian Center for Astrophysics CD-ROM No. 13.
Lean, J., 1987. Journal of Geophysical Research 92, 839.
Lean, J.L., 1990. Journal of Geophysical Research 95, 11 933.
Lean, J., 1991. Reviews in Geophysics and Space Physics 29, 505.
Lean, J.L., White, O.R., Livingston, W.C., Heath, D.F., Donnelly, R.F., Skumanich, A., 1982. Journal of Geophysical Research 87, 10 307.
Millward, G.H., Moffett, R.J. Quegan, S., Fuller-Rowell, T.J. 1996. In: Schunk, R.W. (Ed.), Solar–Terrestrial Energy Program: Handbook of Ionospheric Models. p. 239.
National Academy of Sciences, 1994. Solar Influences on Global Change. National Research Council, National Academy of Press, Washington DC.
Neckel, H., Labs, D., 1984. Solar Physics 90, 205.
Nusinov, A.A., 1984. Geomagnetism and Aeronomy 24, 439.
Richards, P.G., Fennelly, J.A., Torr, D.G., 1994a. Journal of Geophysical Research 99, 8981.
Richards, P.G., Fennelly, J.A., Torr, D.G., 1994b. Journal of Geophysical Research 99, 13 283.
Rottman, G.J., 1987. In: Foukal, P. (Ed.), Proceedings of a Workshop on Solar Radiative Output Variation. Cambridge Research and Instrumentation, Inc., p. 71.
Rottman, G.J., 1988. Advances in Space Research 8, 53.
Schmidtke, G., 1976. Geophysical Research Letters 3, 573.
Schmidtke, G., 1984. In: Flugge, S. (Ed.), Handbuch der Physik, Vol. XLIX/7, Geophysics III. Part VII. Springer-Verlag, Berlin, p. 1.
Schmidtke, G., Woods, T.N., Worden, J., Rottman, G.J., Doll, H., Wita, C., Solomon, S.C., 1992. Geophysical Research Letters 19, 2175.
Smith, E.V.P., Gottlieb, D.M., 1974. Space Science Reviews 16 (5/6), 771.
Thuillier, G., Hersé, M., Simon, P.C., Labs, D., Mandel, H., Gillotay, D., Foujols, T., 1998a. Solar Physics 177, 41.
Thuillier, G., Hersé, M., Simon, P.C., Labs, D., Mandel, H., Gillotay, D., 1998b. Metrologia 35, 689.
Timothy, J.G., 1977. In: White, O.R., The Solar Output and Its Variation. Colo. Assoc. University Press, Boulder, p. 133.
Tobiska, W.K., 1988. Ph.D. Dissertation, University of Colorado, Boulder, CO.
Tobiska, W.K., 1991. Journal of Atmospheric and Terrestrial Physics 53, 1005.
Tobiska, W.K., 1993. Journal of Geophysical Research 98, 18 879.
Tobiska, W.K., Barth, C.A., 1990. Journal of Geophysical Research 95, 8243.
Tobiska, W.K., Eparvier, F.G., 1998. Solar Physics 177, 147.
Torr, M.R., Torr, D.G., Ong, R.A., Hinteregger, H.E., 1979. Geophysical Research Letters 6, 771.
Tousey, R., 1961. Journal of the Optical Society of America 51, 384.
Willson, R.C., 1979. Applied Optics 18, 179.

Willson, R.C., Hudson, H.S., 1991. Nature 351, 42.
Woods, T.N., Prinz, D.K., Rottman, G.J., London, J., Crane, P.C., Cebula, R.P., Hilsenrath, E., Brueckner, G.E., Andrews, M.D., White, O.R., VanHoosier, M.E., Floyd, L.E., Herring, L.C., Knapp, B.G., Pankratz, C.K., Reiser, P.A., 1996. Journal of Geophysical Research 101 (D6), 9541.
Worden, J.R., 1996. Ph.D. Dissertation, University of Colorado, Boulder, CO.
Worden, J., Woods, T.N., Neupert, W.M., Delaboudiniere, J.-P., 1999. Astrophysical Journal 511, 965.