P6.31 LONG-TERM TOTAL SOLAR IRRADIANCE (TSI) VARIABILITY TRENDS: 1984-2004

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ABSTRACT

The incoming total solar irradiance (TSI), typically referred to as the "solar constant," is being studied to identify long-term TSI changes, which may trigger global climate changes. The TSI is normalized to the mean earth-sun distance. Studies of spacecraft TSI data sets confirmed the existence of 0.1 %, long-term TSI variability component with a period of 10 years. The component varied directly with solar magnetic activity associated with recent 10-year sunspot cycles. The 0.1 % TSI variability component is clearly present in the spacecraft data sets from the 1984-2004, Earth Radiation Budget Experiment (ERBE) active cavity radiometer (ACR) solar monitor; 1978-1993, Nimbus-7 HF; 1980-1989, Solar Maximum Mission [SMM] ACRIM; 1991-2004, Upper Atmosphere Research Satellite (UARS) ACRIM; 1996-2003, Solar and Heliospheric Observatory (SOHO)/VIRGO, Space Science (ATLAS), 2000-2004, ACRIMSAT; and 2003-2004 SOlar Radiation and Climate Experiment (SORCE) active cavity radiometer (ACR) missions. From October 1984, through March 2004, the ERBS/ERBE solar monitor was used to produce the longest continuous data set of total solar irradiance (TSI) variability measurements. The solar monitor is located on Shuttle Atmospheric Laboratory for Applications and the NASA Earth Radiation Budget Satellite (ERBS). Maximum TSI values occurred during the 1989-1991, and 1998-2002, time frames; while minimum [quiet sun] TSI levels occurred during 1986 and 1996. Recent ERBS measurements indicate that the TSI is decreasing to forecasted, minimum levels by 2006. Using the discontinuous non-operational Nimbus-7, SMM ACRIM, and UARS ACRIM mission TSI data sets, Wilson and Mordvinor (2003) suggested the existence of an additional long-term TSI variability component, 0.05 %, with a period longer than a decade. Analyses of the ERBS/ERBE data set do not support the Wilson and Mordvinor analyses approach because it used the Nimbus-7 data set which exhibited a significant ACR response shift of 0.7 Wm-2 (Lee *et al*,, 1995; Chapman *et al*., 1996).

In our current paper, analyses of the 1984-2004, ERBS/ERBE measurements, along with the other spacecraft measurements, are presented as well as the shortcoming of the ACRIM study. Long-term, incoming total solar irradiance (TSI) measurement trends were validated using proxy TSI values, derived from indices of solar magnetic activity. Typically, three overlapping spacecraft data sets were used to validate long-term TSI variability trends. During the years of 1978-1984, 1989-1991, and 1993-1996, three overlapping spacecraft data sets were not available to validated TSI trends. The TSI varies with indices of solar magnetic activity associated with recent 10-year sunspot cycles. Proxy TSI values were derived from least squares analyses of the measured TSI variability with the solar indices of 10.7-cm solar fluxes, and with limb-darkened sunspot fluxes. The resulting proxy TSI values were compared to the spacecraft ACR measurements of TSI variability to detect ACR instrument degradation, which may be interpreted as TSI variability. Analyses of ACR measurements and TSI proxies are presented primarily for the 1984-2004, ERBS/ERBE ACR solar monitor data set. Differences in proxy and spacecraft measurement data sets suggest the existence of another TSI variability component with an amplitude greater than or equal to 0.4 Wm-2 (0.03%) with a cycle of 20 years or more.

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1. INTRODUCTION

Total solar irradiance (TSI), normalized to the mean earth/sun distance, is the primary power source, which drives our climate system. In our earlier study (Lee *et al*., 2000), we outlined TSI variability derived from 1969-1999, spacecraft studies in order to identify long-term TSI variability. The study focused upon correlating irradiance variability with varying solar magnetic activity associated with the 11-year sunspot cycle. In addition, the study identified possible radiometer response shifts or drifts, which could be misinterpreted as natural TSI variability. We have extended our study to include the 2000-2004, Active Cavity Radiometer Irradiance Monitor Satellite (AcrimSat) (Wilson and Mordvinov, 2003) and the recently launched 2003-2004 SOlar Radiation and Climate Experiment (SORCE) spacecraft measurements (Kopp *et al*., 2003). In this paper, 1984-2004, ERBS/ERBE solar monitor measurements, along with the other spacecraft measurements, are analyzed to identify additional long-term TSI trends, which may trigger global climate changes.

2. BACKGROUND

From October 1984, through March 24, 2004, the Earth Radiation Budget Experiment (ERBE) active cavity radiometer (ACR) solar monitor was used to produce a continuous 20-year data set of total solar irradiance (TSI) variability measurements. The solar monitor is located on the NASA Earth Radiation Budget Satellite (ERBS). In our earlier study, we indicated that irradiance variability is associated with solar magnetic activity located in the active photospheric regions of sunspots and faculae and in the quieter photospheric network (Chapman, 1987). Sunspots are relatively dark localized, photospheric areas, which emit less energy than surrounding photospheric areas. The impact of sunspots upon the irradiance can be characterized by the parameter photometric sunspot index (PSI). PSI represents the difference in irradiances emitted by limb-darkening sunspots and by equal areas of the undisturbed, quiet photosphere. Faculae are bright photospheric magnetic features that often occur in the vicinity of sunspots and in the photospheric network. Faculae irradiance brightening dominates sunspot irradiance darkening over long-term periods (Lean and Foukal, 1988; Foukal and Lean, 1990). Faculae can be estimated from 10.7-cm solar radio flux (F10).

We derived an empirical fit to the National Aeronautics and Space Administration (NASA) Earth Radiation Budget Satellite (ERBS) solar monitor (Lee *et al.,* 1987) TSI measurements (Lee *et al*., 1995). ERBS TSI measurements for the 1985-1989 time frame were used to calibrate the irradiance empirical fit. The resulting derived empirical fit for the total solar irradiance (I) is

$$I_{ERBS} = 1362.9 - [705.3 \times (PSI)] + [0.02953 \times 10^{22} \times (F10)] - [0.00005 \times 10^{44} \times (F10)^2] \quad (1)$$

where F10 is 10.7-cm solar radio flux, expressed in the solar flux unit (sfu) of $10^{-22} Wm^{-2} Hz^{-1}$), and PSI is expressed in the unit of $10^{-5} Wm^{-2}$.

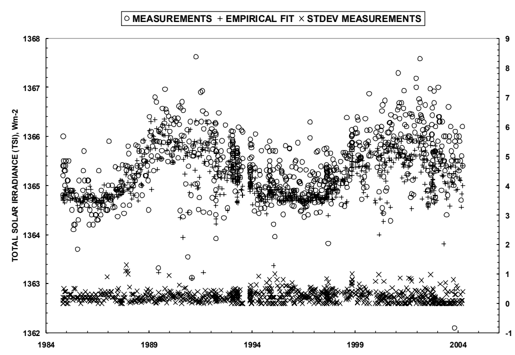

Fig. 1. Total solar irradiance (TSI) values are compared a TSI empircal fit for the October 25, 1984 through March 24, 2004 period, The TSI values were normalized to the mean earth-sun distance of 1.0 Astronomical Unit (AU). Measurement standard deviations are also presented.

3. IRRADIANCE MEASUREMENTS

In figure 1, the empirical fit is compared with October 25, 1984-March 24, 2004, ERBS measurements. The low frequency ERBS measurements were conducted weekly on Wednesdays over a 3-minute period during a single orbit. 765 ERBS TSI measurements are presented and compared with the fit. The 765 measurements represent less than 2 days, approximately 2300 minutes, 1.6 days, of exposure to direct solar radiation.

Studies of spacecraft TSI data sets confirmed the existence of a 1.3 Wm^{-2} (0.1 %), long-term TSI variability component with a 10-year period. The component varied directly with solar magnetic activity associated with recent 10-year sunspot cycles. The 0.1 % TSI variability component is clearly present in the 1984-2004 ERBS TSI measurements. The ERBS irradiance fit and measurements indicate TSI maxima in the 1989-1992, and 1999-2002 periods; while minimum levels existed during the years 1986 and 1996. The 2000-2004 measurements suggest that minimum TSI values should occur during 2006 when minimum solar magnetic activity is expected. The TSI peak periods correspond to periods of maximum solar magnetic activity indicated by large sunspot numbers and 10.7 solar flux levels. The minimum TSI levels correspond to periods of minimum solar activity. The TSI exhibited at least two maxima during each period of maximum activity. The TSI fit trends mimic the double peaks. The 1999-2002 TSI measurement peaks appear to be equal in magnitude to the 1989-1992 peaks. However, the fit indicates that the 1999-2002 peaks should be lower. During the 1996 period of minimum solar magnetic activity, the averaged 1996 TSI value was 1365.0 ± 0.4 Wm^{-2}. During the 1986 period of minimum solar magnetic activity, the averaged 1986 TSI value was slightly lower at 1964.6 ± 0.3 Wm^{-2} than the corresponding averaged 1996 value. This result suggests a TSI increase of 0.4 Wm^{-2}, which is beyond the 1.3 Wm^{-2} TSI variability component associated with the 11-year cycle of solar magnetic activity. This result indicates the possible existence of another TSI component with a amplitude equal to or greater than 0.4 Wm^{-2}, and with a period equal to 20 years or longer. In figure 1, it can be seen that the measurement noise increased after late 1993. Starting in late 1993, the solar monitor was turned off before each spacecraft yaw maneuver, at approximately 36-day intervals, and turned back on between a few hours to as much as 6 days after the completion of the hour-long maneuver. The monitor off-on events caused the resulting measurements to be noisier. Overall, between 1984 and 2004, it can be seen that the solar energy projected at the top of the atmosphere varied systematically approximately 1.3 Wm^{-2} (0.1%).

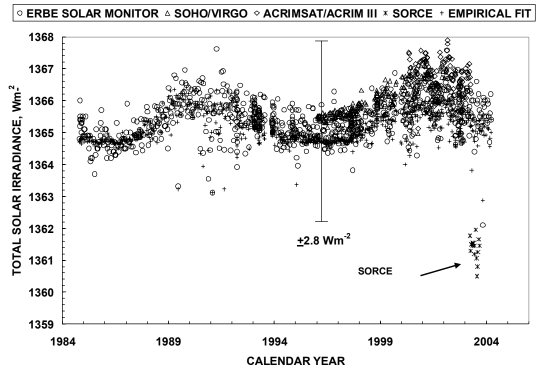

Fig. 2. 1984-2004, total solar irradiance measurements of the ERBS, VIRGO, AcrimSat, and SORCE operational spacecraft missions are presented and normalized to the mean earth-sun distance.

In figure 2, the operational October 25, 1984-March 24, 2004 Earth Radiation Budget Satellite (ERBS), Earth Radiation Budget Experiment (ERBE) solar monitor (Lee *et al.*, 1995) TSI data set is compared with other spacecraft TSI data sets. The February 7, 1996-April 20, 2004, Solar and Heliospheric Observatory (SOHO)/ Variability of solar IRradiance and Gravity Oscillations (VIRGO), Differential Absolute RADiometer (DIARAD) (Dewitte *et al.* 2001) and PMO missions (Frohlich and Anklin, 2000); April 4, 2000-June 9, 2004, Active Cavity Radiometer Irradiance Monitor Satellite (AcrimSat) ACRIM III; and the February 25, 2003–June 30, 2004 SOlar Radiation and Climate Experiment, SORCE (Kopp *al.*, 2003; Lawrence *et al.*, 2003)) spacecraft missions produced long-term data sets. In May 2001, the UARS/ACRIM II data set was ended by the failure of its sensor instrument. In our earlier study (Lee *et al.,* 2000), data sets were presented and discussed from the other pre-1995, spacecraft missions (Nimbus-7, SMM ACRIM I, and UARS ACRIM II) which are no longer operational.

As shown in figure 3, ERBS data set is the longest continuous spacecraft TSI set available. The ERBS, Nimbus-7, SMM, UARS, VIRGO, AcrimSat and SORCE averaged TSI values were found to be 1365.4 ± 0.7, 1372.0 ± 0.7, 1367.5 ± 0.7, 1364.4 ± 0.5, 1366.0 ± 0.5, 1366.6 ± 0.5, and 1361.1 ± 0.5 Wm^{-2}, respectively. The Nimbus 7 sensor was a transfer radiometer; it was not an absolute active cavity radiometer (ACR). The other mission sensors were ACR sensors. Not including the Nimbus-7 average, the mean of these ACR spacecraft data sets is 1365.2±2.1 Wm^{-2}, which is within 0.2 Wm^{-2} of the ERBS averaged value. The UARS, VIRGO, and AcrimSat data sets have estimated SI uncertainties of the order of 1.4 Wm^{-2} (0.1%) with daily measurement precisions better than 0.1 Wm^{-2} (0.01%). For each ERBS instantaneous measurement, the instantaneous measurement accuracy and precision are 2.8 Wm^{-2} (0.2%) and 0.2 Wm^{-2} (0.02%), respectively. The SORCE mean TSI measurements were found to be approximately 4 Wm^{-2} (0.3%) lower than the averaged TSI values for the other missions. The SORCE estimated absolute accuracy is quoted at the 0.14 Wm^{-2} (0.01%) level. The differences between the SORCE TSI values and those of the other ACR missions exceed quoted estimated uncertainties of the ACR's. Note that the Nimbus-7 sensor and the other spacecraft TSI mission ACR have operated at ambient temperatures. The authors believe that the accuracies of ACR's are best demonstrated by the accuracies, which can be determined from measurement uncertainties of the Stefan-Boltzmann constant. Using room temperature, ACR's Kendall and Berdahl (1970) and Bergman (1970) were able to measure the Stefan-Boltzmann constant at the 0.3% accuracy level. At the 1365.2 Wm^{-2} TSI level, the 0.3% accuracy level would correspond to a 4.1 Wm^{-2} uncertainty in the room temperature ACR, spacecraft TSI measurements. Therefore, the fact that the SORCE averaged TSI value is approximately 4 Wm^{-2} (0.3%) lower than the ERBS averaged 1365.2 Wm^{-2} averaged value is not unrealistic. Using a cryogenic ACR, Quinn and Martin (1984) were able measure the constant at the 0.01% accuracy level. Improvements in ACR accuracies were obtained by cooling the ACR's to cryogenic temperatures where the ACR responses was faster, and its signal-to-noise ratio was increased by reducing the sensor noise.

In figure 3, the comparisons among data sets emphasize that the ERBS measurements characterized irradiance variability fairly well, although the ERBS measurement frequency was very low, weekly over a 3-minute period during a single orbit. Also, comparisons among the ERBS and other spacecraft measurements indicated that the ERBS measurements were not affected by sensor response degradation with the exception during its first year in orbit, the 1984-mid1985 period. After the first year in-orbit, the ERBS solar monitor measurements did not exhibit any additional detectable irradiance-related response degradation. Over the 1984 through 2004, measurement period, the ERBS solar monitor was exposed to direct solar radiation for approximately 2300 minutes (1.6 days). Wheras the SMM/ACRIM I, UARS/ACRIM II, VIRGO, and AcrimSat reference ACR are exposed daily between 860 and 1440 minutes per day. The non-reference UARS/ACRIM II, VIRGO, AND AcrimSat data sets were corrected as much as 4 Wm^{-2} (0.3%) for radiation-related response degradations using the reference ACR's to assess the irradaince-related degradation. However, the reference ACRIM ACR's were not corrected for irradiance-related response degradation which is probably 20 times greater than any possible radiation-related ERBS response degradation.

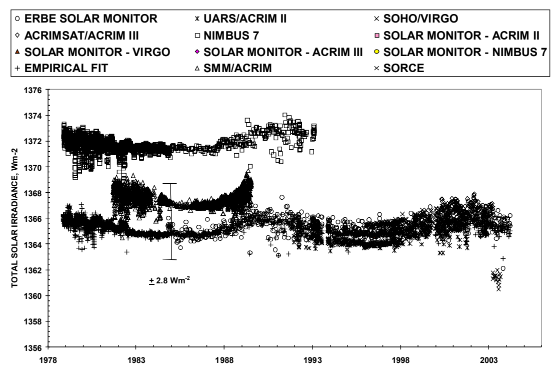

Fig. 3. 1979-2004, total solar irradiance measurements of the operational and of the non-operational Nimbus-7, and SMM ACRIM I, UARS ACRIM II spacecraft missions are presented and normalized to the mean earth-sun distance.

Therefore, the ERBS data set is the best research source for defining long-term TSI variability because the ERBS solar monitor was used to produce the longest continuous TSI data set with the least long-term instrument degradation.

4. CONCLUSIONS

Total solar irradiance (TSI) variability was investigated using 1984-2004 ERBS TSI spacecraft measurements. The investigation confirms the existence of a 10-year irradiance variability component. This component is correlated with solar magnetic activity associated with the 11-year sunspot cycle and with an amplitude of approximately 1.3 Wm^{-2} (0.1%).

The current, on-going 1984-2004, ERBS irradiance spacecraft mission has produced the longest total solar irradiance data set. Comparisons between an empirical irradiance model fit [based upon 10.7-cm solar radio flux (F10) and photometric sunspot index (PSI)], and ERBS TSI measurements indicate that there were no irradiance-related detectable ACR response shifts or drifts in the ERBS/ERBE solar monitor TSI data set which could be falsely identified as TSI trends.

The 2000-2004 ERBS TSI measurements indicate that the TSI will to decrease to minimum levels by the year 2006 as solar magnetic activity is projected to decrease minimum levels.

Differences between the ERBS TSI averaged measurements during the 1986 and 1996 periods of minimum solar magnetic activity suggest the existence of another TSI variability component with an amplitude greater than or equal to 0.4 Wm-2 (0.03%) with a cycle of 20 years or more.

5. ACKNOWLEDGEMENTS

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