Validation of spacecraft active cavity radiometer total solar irradiance [TSI] long-term measurement trends using proxy TSI least squares analyses

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ABSTRACT

Long-term, incoming total solar irradiance (TSI) measurement trends were validated using proxy TSI values, derived from indices of solar magnetic activity. Spacecraft active cavity radiometers (ACR) are being used to measure long-term TSI variability, which may trigger global climate changes. The TSI, typically referred to as the "solar constant," was normalized to the mean earth-sun distance. Studies of spacecraft TSI data sets confirmed the existence of a 0.1 %, long-term TSI variability component within a 10-year period. The 0.1 % TSI variability component is clearly present in the spacecraft data sets from the 1984-2004 time frame. Typically, three overlapping spacecraft data sets were used to validate long-term TSI variability trends. However, during the years of 1978-1984, 1989-1991, and 1993-1996, three overlapping spacecraft data sets were not available in order to validate TSI trends. The TSI was found to vary 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-darked 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, Earth Radiation Budget Experiment (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 0.5 Wm-2 (0.04%), and with a cycle of 20 years or more.

Keywords: total solar irradiance, active cavity, radiometry, calibration, climate, ERBE, ERBS

1. INTRODUCTION

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 total solar irradiance (TSI), normalized to the mean earth/sun distance, is the primary power source, which drives our climate system. In our earlier studies,[1,2,3] we analyzed 1969-1999, spacecraft measurements in order to identify and verify long-term TSI variability. The studies 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 analyses of the 2000-2004, Active Cavity Radiometer Irradiance Monitor Satellite (AcrimSat),[4] and of the recently launched 2003-2004 SOlar Radiation and Climate Experiment (SORCE) spacecraft measurements.[5,6] In this paper, 1984-2004, Earth Radiation Budget Satellite (ERBS)/Earth Radiation Budget Experiment (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.

Our earlier studies[1,2,3] of long-term 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. In figure 1, the 0.1 % TSI variability component is clearly present in the spacecraft data sets from the 1984-2004, ERBE active cavity radiometer (ACR) solar monitor,[7] 1978-1993, Nimbus-7 HF; [8] 1980-1989, Solar Maximum Mission [SMM] ACRIM; [4] 1991-2004, Upper Atmosphere Research Satellite (UARS) ACRIM;[4] 1996-

2003, Solar and Heliospheric Observatory (SOHO)/VIRGO,[9,10] Space Science (ATLAS), 2000-2004, ACRIMSAT;[4] and 2003-2004 SORCE[5,6] missions. Note that the ERBS/ERBE solar monitor was used to produce the longest continuous data set of TSI variability measurements of 20 years, and of two sunspot cycles. The solar monitor is located on 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.

Typically, three overlapping spacecraft data sets were used to validate long-term TSI variability trends. As shown in figure 1, during the years of 1978-1984, 1989-1991, and 1993-1996, three overlapping spacecraft data sets were not available to validated TSI trends. During these gaps of overlapping 3-spacecraft data, TSI proxies were used to confirm TSI trends or to identify false trends which were caused by spacecraft sensor response shifts or drifts. It is known that the TSI varied with solar magnetic activity indices 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 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 a second long-term TSI variability component. It is estimated that the component has an amplitude greater than or equal to 0.5 Wm-2 (0.04%), and has a period of 20 years or more. In our earlier 1995 study[1], our analyses of the 1984-1995 solar monitor TSI measurement variability suggested a second irradiance component with an amplitude greater than 0.3 Wm^{-2} (0.02%), and with a period longer than 10 years. Recently, Willson and Mordvinor[11] suggested the existence of an additional long-term TSI variability component, 0.05 % (0.7 Wm^{-2}), with a period longer than a decade based upon analyses of the discontinuous, non-operational Nimbus-7, SMM ACRIM I, and UARS ACRIM II mission TSI data sets. Analyses of the ERBS/ERBE data set do not support the Willson and Mordvinor's analysis approach because the 1990 Nimbus-7 data set exhibited a significant ACR response shift of 0.8 Wm^{-2} according to Lee et al.[1] and Chapman et al.[12]

2. ERBE SOLAR MONITOR[7] AND ACTIVE CAVITY RADIOMETERS

The ERBE missions[13] were conducted from the NASA ERBS, and from the National Oceanic and Atmospheric Administration (NOAA) 9 and 10 spacecraft. The ERBS, NOAA-9, and NOAA-10 spacecraft were launched October 5, 1984, December 12, 1984, and September 17, 1986, respectively. Each spacecraft carried both a scanning[14] radiometric instrument package, and a separate nonscanning[15,16] ACR radiometric instrument package. Only on the ERBS spacecraft is the nonscanning ACR package still operating nominally. The other nonscanning and all of the scanning packages stopped transmitting useful measurements. Each scanning package consisted of three narrow field-of-view thermistor bolometers. The shortwave bolometer sensed earth-reflected total solar irradiance (TSI) in the 0.2 to 5 μm broadband spectral region, while the longwave bolometer measured earth-emitted irradiances in the 5 to 20 μm broadband spectral region. The third, "total" bolometer sensed both earth-reflected TSI and earth-emitted longwave irradiances in the 0.2 to 100 μm broadband spectral region.

2.1 ERBE Active cavity radiometer (ACR) instrument package
There are 5 ERBE nonscanning ACR modules: 2 total earth-viewing ACR's, 2 shortwave earth-viewing ACR's, and a sun-oriented, solar monitor (SM) ACR. All of the ACR's are electrical substitution absolute radiometers. The ERBE ACR's were built and calibrated by TRW (Redondo Beach, CA) under contract NAS-15900. The solar monitor ACR sensed the total amounts of TSI in the 0.2 to 100 μm broadband spectral region. The ERBE shortwave wide field-of-view (SWFOV) ACR measured earth-reflected total solar irradiances (TSI) in the 0.2 to 5.0 μm broadband spectral region while the total wide field-of-view (TWFOV) ACR measured both the earth-reflected TSI and the earth-emitted longwave irradiances in the 0.2 to 100 μm broadband region. The TWFOV and SWFOV ACR's were used to observe irradiances from the entire earth disc. The field-of-view limiters restricted their FOVs to the earth surrounded by approximately 2 angular degrees "space ring." The two remaining earth-viewing ACR's are called the shortwave medium field-of-view (SMFOV) and total medium field-of-view (TMFOV) radiometers. The TMFOV and SMFOV ACR's were used to measure earth irradiances from regions with diameters corresponding to 10-degrees, earth-centered angle. The 1984-1999 ERBE TWFOV, SWFOV, TMFOV, and SMFOV ACR's flight measurements and calibration results were documented by Lee et al (2002).[17] Lee et al (2003)[18] summarized the 2000-2003 calibration results. Lee et

al.[7] described the solar monitor's optical and physical properties, while Luther *et al.*[15,16] described the optical and physical properties of the ERBE TWFOV, SWFOV, TMFOV, and SMFOV ACR's.

3. PROXY TSI EMPIRICAL FIT

From October 1984, through the current date, the ERBE ACR solar monitor was used to produce a continuous 20-year data set of TSI variability measurements. The solar monitor is located on the NASA Earth Radiation Budget Satellite (ERBS). In our earlier studies,[1,2,3] we verified 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.[19] 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.[20,21] Faculae can be estimated from 10.7-cm solar radio flux (F10). In figure 2, the solar magnetic indices[22] of sunspot number, PSI, and 10.7-cm fluxes are presented as a function of time.

A proxy TSI empirical fit[1] was derived from least squares analyses of the NASA ERBS solar monitor[7] TSI measurements. From the 1985-1989 time frame, ERBS TSI measurements were used to calibrate the irradiance empirical fit. The resulting derived empirical fit for the total solar irradiance (I) is

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

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 $10^{-5} Wm^{-2}$. In this paper, the TSI proxies were calculated using equation 1 and 10.7-cm flux and PSI index.

4. IRRADIANCE MEASUREMENTS

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

Studies of ERBS/ERBE solar monitor TSI data set 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. In figures 1 and 3, 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 forecasted. 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 1986 period of minimum solar magnetic activity, the averaged 1986 TSI value was 1364.6±0.3 Wm^{-2}. During the 1996 period of minimum solar magnetic activity, the averaged 1996 TSI value was slightly higher at 1364.9±0.4 Wm^{-2} than the averaged 1986 TSI 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 existence of another TSI component with an amplitude equal to or greater than 0.5 Wm^{-2}, and with a period equal to 20 years or longer. The TSI level increased from 1364.9 Wm^{-2} to 1366.2 Wm^{-2} (1.3 Wm^{-2}) between 1996 and the 1999-2001 time frame. From 1996 to 1999-2001, the 1999-2001 increasing trend of 1.3 was similar in magnitude to the 1986 to 1989-1991 TSI increasing trend.

In figure 3, 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. Then, the monitor was turned back on after a few hours to as much as 6 days after the yaw 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 at approximately 1.3 Wm^{-2} (0.1%).

In figure 4, the operational October 25, 1984-August 2004 ERBS, ERBE solar monitor[6] TSI measurements are compared with other post-1991 spacecraft TSI mission data sets of (1) 1991-2001, UARS ACRIM II; (2) the February 7, 1996-April 20, 2004, SOHO/VIRGO, Differential Absolute RADiometer (DIARAD) [9] and PMO missions[10]; (3) April 4, 2000-June 9, 2004, AcrimSat ACRIM III;[4] and (4) the February 25, 2003–June 30, 2004 SORCE[5,6] spacecraft missions. In May 2001, the UARS/ACRIM II mission was terminated by the failure of its sensor instrument. The 1980-1989, SMM ACRIM I mission was terminated when the SMM spacecraft de-orbited. In our earlier studies,[1,2,3] data sets from the other pre-1995, spacecraft missions (Nimbus-7, SMM ACRIM I, and UARS ACRIM II) which are no longer operational, were presented, and analyzed for TSI variability, and examined for sensor response shifts and drifts using TSI proxies derived from solar magnetic indices. In this paper, we analyzed the TSI mission measurements, which were operational after 1995.

As shown in figures 1 and 4, the 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$\pm$0.7, 1372.0$\pm$0.7, 1367.5$\pm$0.7, 1364.4$\pm$0.5, 1366.0$\pm$0.5, 1366.6$\pm$0.5, and 1361.1$\pm$0.5 Wm^{-2}, respectively. The Nimbus 7 sensor was a transfer radiometer, not an absolute active cavity radiometer (ACR). The other mission sensors were ACR sensors. Not including the Nimbus-7 average, the mean of these ACR spacecraft data sets is 1365.2$\pm$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 TSI missions. Note that the Nimbus-7 sensor, and the other spacecraft TSI mission ACR's operated at ambient temperatures. The authors believe that the accuracies of ACR's can be determined best from measurement uncertainties of the Stefan-Boltzmann constant. Using room temperature ACR's, Kendall and Bergman[23] (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, spacecraft ACR 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[24] were able to measure the constant at the 0.01% accuracy level. Improvements in spacecraft ACR accuracies may be obtained by cooling the ACR's to cryogenic temperatures. At the lower temperatures, the ACR responses are faster, and the sensor noise decreases, increasing the signal-to-noise ratio.

In figures 1 and 4, 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, except during its first year in orbit. After the first year in-orbit, the ERBS solar monitor measurements did not exhibit any additional detectable irradiance-related response degradation. As previously stated, over the 1984 through 2004, measurement period, the ERBS solar monitor was exposed to direct solar radiation for approximately 2300 minutes (1.6 days), whereas the SMM/ACRIM I, UARS/ACRIM II, VIRGO, and AcrimSat reference ACR were exposed daily to direct radiation 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 irradiance-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. Therefore, the ERBS measurements are the best research source for defining long-term TSI variability because the ERBS solar monitor produced the longest continuous TSI data set with the least long-term instrument degradation.

5. COMPARISONS OF TSI MEASUREMENTS AND TSI PROXIES

In our earlier 1995 study[1], we suggested the existence of a second TSI variability component with an amplitude greater than 0.3 Wm^{-2}, and with a period longer than 10 years. Between 1986, minimum solar activity and sunspot number, and the 1989-1991 period, the TSI increased approximately 1.3 Wm^{-2} from the 1364.7 Wm^{-2} level to the 1366.0 Wm^{-2} level. Between the 1989-1991 period and 1994, the TSI decreased at a rate of 0.14 Wm^{-2} per year. This TSI decreasing rate indicated that the TSI would decreased by 1.0 Wm^{-2} from the 1989-1991 peak magnetic activity level of 1366 Wm^{-2} to a minimum activity level of 1365 Wm^{-2}. In figure 3, the 1996 TSI averaged measured value was 1365 Wm^{-2}. In our 1995 study,[1] we forecasted the 1365 Wm^{-2} TSI level for the 1996 period of minimum solar magnetic activity.

5.1 TSI Proxy comparisons

Also in our 1995 study, we presented the differences between the TSI proxies and the spacecraft TSI measurements for the ERBS ERBE, Nimbus-7, SMM ACRIM I, and the UARS ACRIM II missions. As previously stated, the proxies were calculated from the solar magnetic indices of 10.7-cm solar flux and prompt photometric sunspot index (PPSI). In figures 1, 3, and 4, the spacecraft measurements appear to be slightly increasing relative to the TSI proxies. The proxies were calculated using solar magnetic indices with periods equal to approximately 10 years, the length of the sunspot cycle. Therefore, the proxies would not characterize TSI variability with periods greater than 11 years. The increasing TSI trend is stronger in the cases of the longer ERBS and Nimbus-7 mission data sets. In figure 5, the differences between the ERBS/ERBE solar monitor measurements and the TSI empirical fit proxies are presented with time. Applying least squares analyses to the TSI differences and time, the increasing rate is 0.0268 Wm^{-2} per year which implies an increase of 0.5 Wm^{-2} between 1984 and 2004. In figure 6, the differences between the post-1991 spacecraft measurements and the empirical fit are presented and compared with those corresponding to the ERBS/ERBE solar monitor minus fit differences. The increasing trends are present for all the spacecraft missions. The spacecraft TSI increasing trends indicate the existence of a second TSI irradiance variability component, in addition to the 0.1% variability component with a period of 10 years. Applying least squares analyses, the increasing rates were found to be 0.019, 0.0214, and 0.014 Wm^{-2} per year for the 1991-2001, UARS ACRIM I; SOHO/VIRGO; and ACRIMSAT, respectively. SORCE minus fit TSI differences were not presented because the data set is less than 3 years in duration. During the first year in orbit, ACR's exhibit some irradiance-related sensor response degradation. For example, the 1978-1980 Nimbus-7,[25,26] 1980-1981 SMM ACRIM I,[3] 1991-1992 UARS ACRIM II,[3] and 1996-1997 VIRGO[9] measurements were corrected for response changes. Sensor response corrections have not been incorporated in the 1984-1985, first orbital year, ERBS/ERBE solar monitor measurements.

Over the 1984-1993 time frame, the Nimbus-7 minus fit TSI differences[1] increased at a rate of 0.0988 Wm^{-2} per year.[27] The higher Nimbus-7 increasing rate was caused by instrumental sensor response shifts after the September 25, 1989 sensor failure when the sensor signal became saturated. On September 29, 1989, the Nimbus-7 sensor came back on scale and was no longer saturated. After September 29, 1989, the TSI measurements shifted upward by approximately 0.4 Wm^{-2}. The Nimbus-7 minus fit difference rate would be reduced to 0.0328 Wm^{-2} per year if the post September 1989 Nimbus-7 measurements were corrected for the September 25, 1989 response shift.

In figure 7, ERBS/ERBE solar monitor (SM) TSI measurements are compared with those from 1984-1999, ERBS/ERBE total wide field-of-view (TWFOV) and total medium field-of-view (TMFOV) ACR's. The SM, TWFOV, and TMFOV data sets exhibited the 0.1 % (1.3 Wm^{-2}) TSI variability component which varied in phase with solar magnetic activity, associated with the 10-year sunspot cycle. Note that the TWFOV measurements decreased approximately 0.08 % with time relative to the SM and TMFOV measurements. The TWFOV TSI decrease was caused by direct solar radiation degrading the sensor response. During the October 1984 through September 1999 time frame, the TMFOV ACR was exposed to direct solar radiation for approximately 1.1 days, while the SM exposure dosage was slightly higher at 1.2 days. The TWFOV exposure dosage was significantly higher at 337 days.

The averaged TMFOV TSI measurements were slightly higher by a few tenths of a Wm^{-2} during the 1996 period of minimum solar magnetic activity than the 1986 measurements, corresponding to the 1986 period of minimum solar activity. The TMFOV trend is similar to the increasing trend that was observed in the SM data set. This trend suggests the presence, again, of a second long-term TSI variability component which was present in the Nimbus-7, SMM, UARS, VIRGO, and ERBS spacecraft data sets.

6. CONCLUSIONS

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 0.5 Wm-2 (0.04%) with a cycle of 20 years or more. Comparisons of the ERBS TSI measurements and TSI proxies indicate the measurements were increasing relative to the proxies. The proxies were based upon a 0.1 % TSI variability component which was calculated from the solar magnetic indices of 10.7-cm solar flux and prompt photometric sunspot index (PPSI) with 10-year variability cycles. The fact that the measurements increased with time relative to the proxies suggests the existence of a second TSI variability component with an amplitude greater than 0.04% (0.5 Wm-2), and with a period greater or equal to approximately 20 years.

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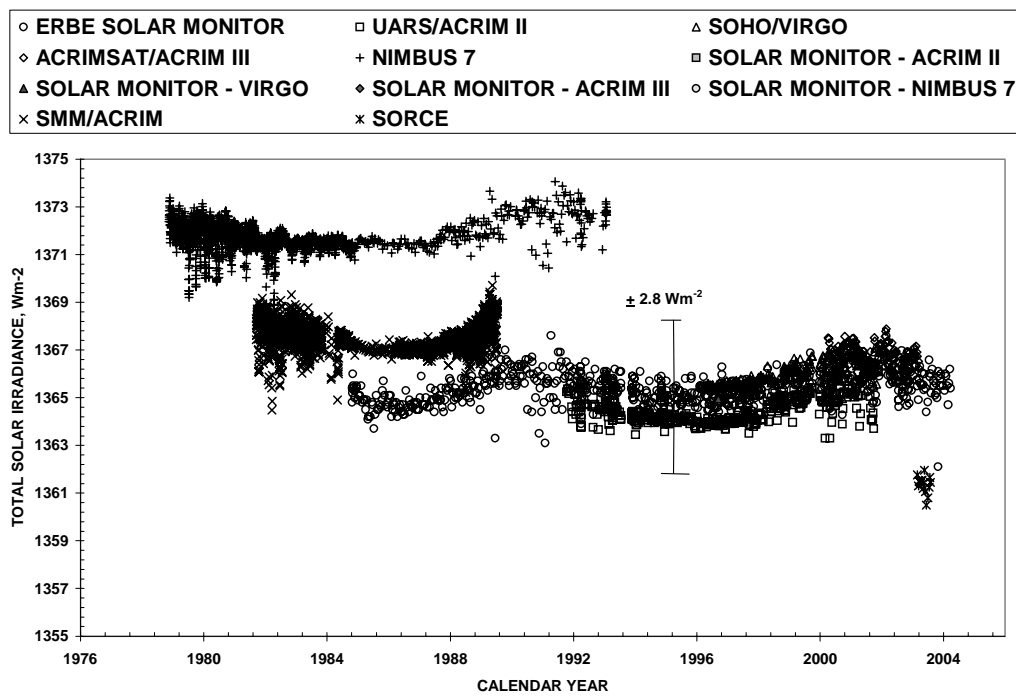
Fig. 1. 1979-2004, total solar irradiance (TSI) measurements are presented from long-term spacecraft missions. The measurements were normalized to the mean earth-sun distance.
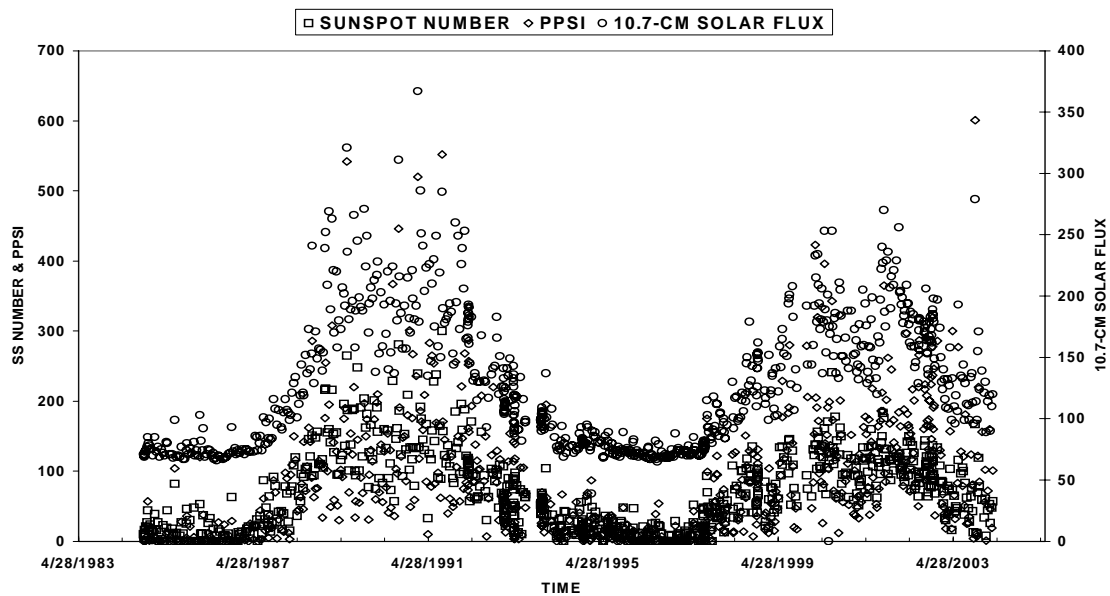

Fig. 2. Solar magnetic indices[15] of sunspot number, PSI, and 10.7-cm fluxes are presented as a function of time for the October 1984 through March 2004 time frame
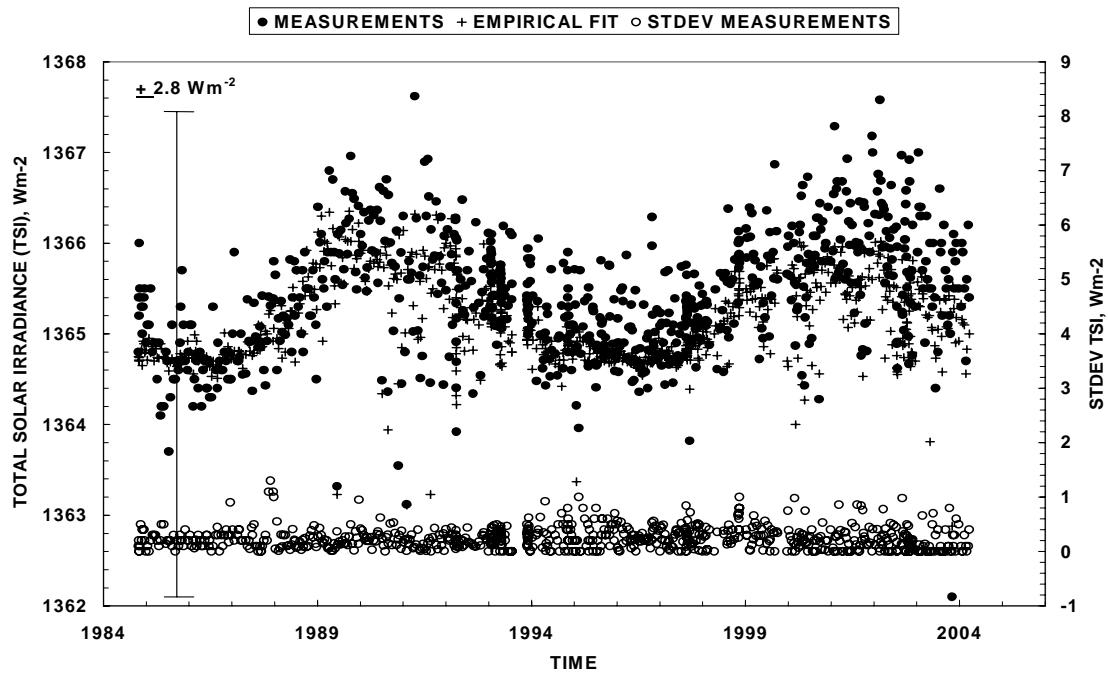
Fig. 3. ERBS solar monitor total solar irradiance (TSI) values are compared with a TSI empircal fit for the October 25, 1984 through March 2004 time frame. The TSI values were normalized to the mean earth-sun distance of 1.0 Astronomical Unit (AU). Measurement standard deviations are also presented.
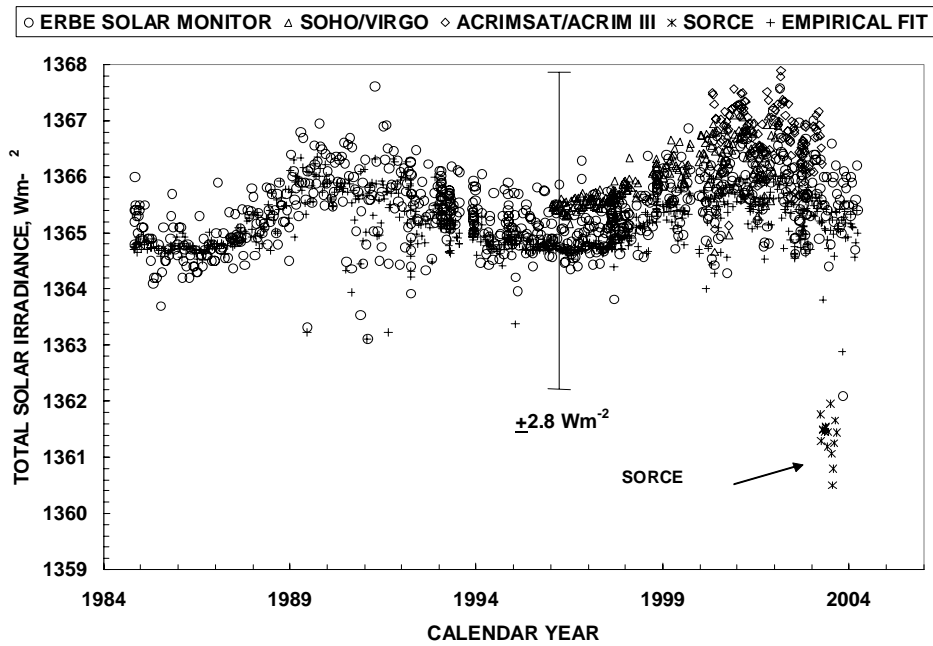
Fig. 4. 1984-2004, total solar irradiance measurements of the ERBS, VIRGO, AcrimSat, and SORCE operational spacecraft missions are presented and normalized to the mean earth-sun distance.
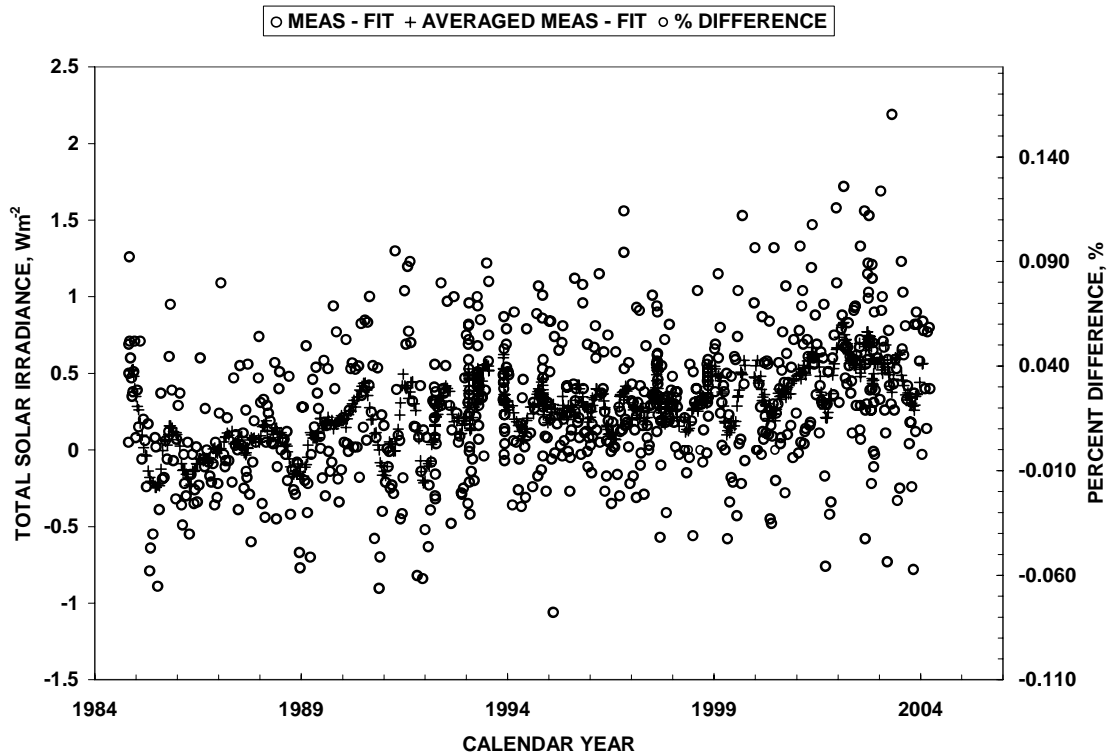
Fig. 5. Differences between ERBS TSI measurements and the TSI empircal fit are presented as a function of time.
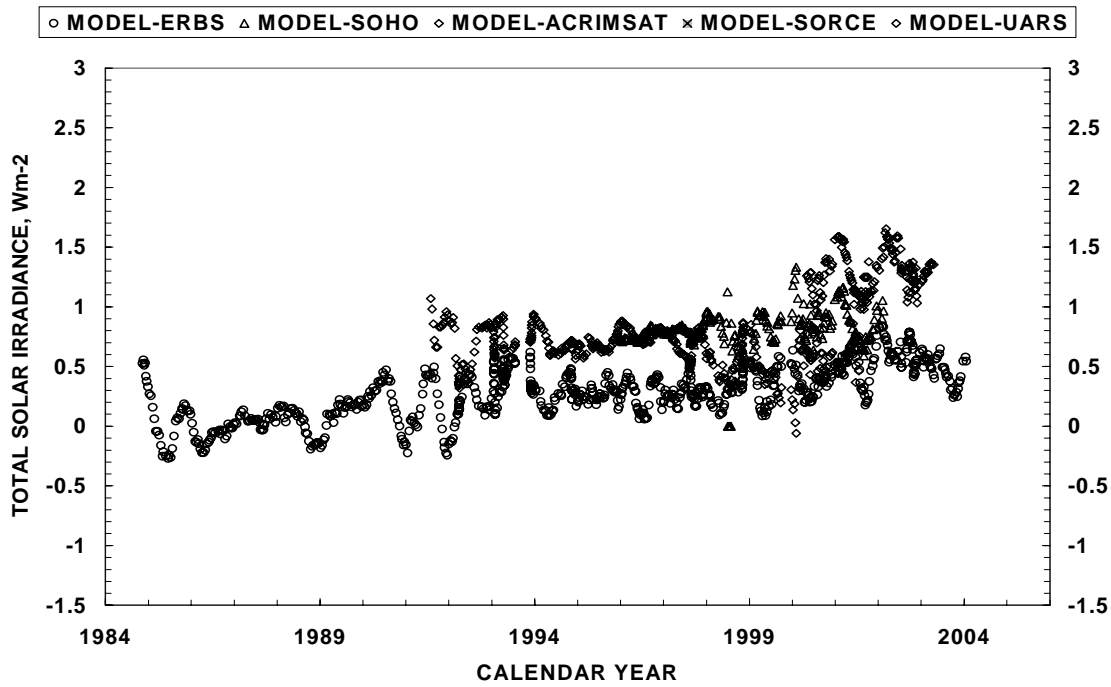

Fig. 6. Differences between ERBS TSI measurements and the TSI empircal fit are presented as a function of time.
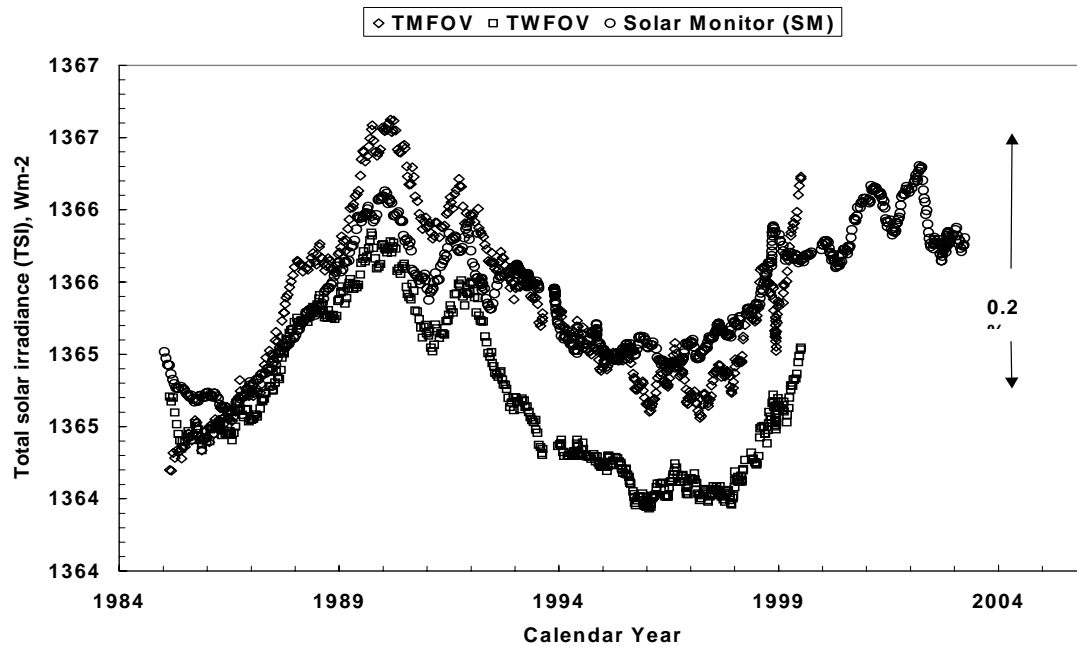
Fig. 7. October 25, 1984 through September 30, 1999, ERBS solar monitor total solar irradiance (TSI) values are compared with ERBS ERBE total wide field-of-view (TWFOV) and total medium field-of-view (TMFOV) active cavity TSI measurements. The TSI values were normalized to the mean earth-sun distance of 1.0 Astronomical Unit (AU).