Measurement And Uncertainty Of The Long Term Total Solar Irradiance Trend

Steven Dewitte, Dominique Crommelynck, Sabri Mekaoui and Alexandre Joukoff
Royal Meteorological Institute of Belgium

July 1, 2004

Abstract. A possible long term trend of the total solar irradiance could be a natural cause for climate variations on Earth. Measurement of the total solar irradiance with space radiometers have started in 1978. We present a new total solar irradiance composite, with an uncertainty of +/- 0.35 W/m^2. From the minimum in 1995 to the maximum in 2002 the total solar irradiance increased by 1.6 W/m^2. In between the minima of 1987 and 1995 the total solar irradiance increased by 0.15 W/m^2.

Keywords: Total Solar Irradiance

1. Introduction

The solar energy input is the driving term in the Earth's energy budget. Possible long term variations of the Total Solar Irradiance (TSI) are therefore expected to result in climate changes on Earth. The monitoring of the long term TSI is thus necessary for climate change studies.

TSI measurements of acceptable quality for long term monitoring exist 'only' since 1978, which is relatively short compared to climate time scales. The currently available long term TSI measurements are summarised in table I.

Since the measurement periods for individual instruments are limited - see column 1 of table I - the TSI measurements of different instruments have to be composited in order to construct a long term TSI time series.

Different TSI composites have been proposed in (Crommelynck and Dewitte, 1997), (Froehlich and Lean, 1998) and (Willson and Mordvinov, 2003). The obtained composite TSI time series in these three studies show some substantial differences, e.g. (Willson and Mordvinov, 2003) find an increase of the 'quiet sun' irradiance level of 0.8 W/m^2 between the solar minima in 1986 and 1996, while (Froehlich and Lean, 1998) find no difference between the two minima.

The inherent uncertainty in the available TSI measurements has not been explicitely quantified so far.

Table I. Summary of available TSI measurements.

Period	Instrument	Satellite	Reference
1978-1993	ERB	Nimbus 7	(Hoyt et. al, 1992)
1980-1989	ACRIM 1	SMM	(Willson, 1994)
1984-...		ERBS	(Lee et al., 1995)
1991-2001	ACRIM 2	UARS	(Willson, 1994)
1992-2003	SOLCON	Space shuttle	(Crommelynck et al., 1994), (Dewitte et al., 2001)
1992-1993	SOVA 1	EURECA	(Crommelynck et al., 1994)
1992-1993	SOVA 2	EURECA	(Romero et al., 1994)
1996-...	DIARAD/VIRGO	SOHO	(Dewitte et al., 2004)
1996-...	PMO06/VIRGO	SOHO	(Froehlich, 2003)
2000-...	ACRIM 3	ACRIMSAT	(Willson, 2001)
2003-...	TIM	SORCE	(Lawrence et. al, 2000), (Kopp et. al, 2003)

The purpose of this publication is threefold: 1) construct a composite TSI time series - following the basic method proposed in (Crommelynck and Dewitte, 1997) - in which the TSI time series measured by the different instruments are adjusted relative to each other as well as possible, 2) quantify the uncertainty of the obtained composite TSI time series in an objective empirical way, 3) quantify the long term quiet sun irradiance trend.

2. SARR Adjustment Principle

The differences in absolute level measured by the different TSI instruments are larger or of the same order than the relative variations of the TSI with time that they measure. Therefore it is needed to bring the instruments to a common absolute level before compositing them. As common absolute level we use the Space Absolute Radiometric Reference (SARR) as defined in (Crommelynck et al., 1995). The SARR is defined as the average TSI of eight independent radiometers that were active during April 1992.

If the TSI measurements of instrument i as a function of time are denoted as $S_i(t)$, we define the *SARR adjusted time series* as $a_i S_i(t)$ where a_i is the *SARR adjustment factor* of instrument i. The SARR adjustment factor of an instrument can be determined by comparing it to the SARR adjusted time series $a_{ref} S_{ref}(t)$ of a reference instrument, by putting $\overline{a_i S_i(t)} = \overline{a_{ref} S_{ref}(t)}$ where $\overline{(.)}$ denotes the average over the comparison period.

As a prime reference we use the SOLCON instrument, which was active during the April 1992 period when the SARR was defined.

3. SARR Adjustment Of DIARAD, ACRIM 2, SOVA 1 And SOVA 2 Through SOLCON

From SOLCON as a prime reference, we derive the SARR adjustment factors of DIARAD, ACRIM 2, SOVA 1 and SOVA 2. ACRIM 2 and DIARAD will further be used as secondary references.

The SOLCON instrument has two radiometric channels, SOLCON-Left and SOLCON-Right. We use the SARR adjustment factors derived for SOLCON in (Crommelynck et al., 1995), $a_{\text{solcon-left}}$=0.999228 and $a_{\text{solcon-right}}$=0.999823.

For DIARAD we use the ageing corrected measurements as described in (Dewitte et al., 2004) as original measurements. We derive the DIARAD SARR adjustment factor by comparing it to the SOLCON reference instrument during the SOLCON International Extreme ultraviolet Hithchiker 3 (IEH-3) space shuttle flight in Oct-Nov 1998, yielding a_{diarad}=1.000295.

For ACRIM 2 we use the version 3 available from http://www.acrim.com. We derive the ACRIM 2 SARR adjustment factor by comparing it to the SOLCON reference instrument during the SOLCON ATmospheric Laboratory for Applications and Science 2 (ATLAS 2) space shuttle flight in April 1993, yielding a_{acrim2}=1.001295.

The top left part of figure 1 shows the SARR adjusted SOLCON, DIARAD and ACRIM 2 measurements. One can verify visually that the ACRIM 2 measurements (red curve) have been 'tied' to the SOLCON measurement in 1993 (second blue cross) and that the DIARAD measurements (green curve) have been 'tied' to the SOLCON measurements in 1998 (fourth blue cross). There is a good continuity between the TSI values measured by ACRIM2 before mid 1995 and the TSI values measured by DIARAD from 1996 onwards.

For SOVA 1, we use the measurements from (Crommelynck et al., 1994). For SOVA 2, we use the measurements from (Romero et al., 1994). We derive the SARR adjustment factors by comparison with SOLCON in 1993. We obtain a_{sova1}=1.000799 and a_{sova2}=0.999703.

4. SARR Adjustment Of PMO06, ACRIM 3 And TIM Through DIARAD

From DIARAD as a secondary reference, we derive the SARR adjustment factors of PMO06, ACRIM 3 and TIM.

For PMO06 we use the ageing corrected version as described in (Dewitte et al., 2004) as original measurements, and we find a_{pmo6}=1.000661.

For ACRIM 3 we use the version 0403 available from http://www.acrim.com as original measurements, and we find a_{acrim3}=1.000404.

For TIM we use the version 3 available from http://lasp.colorado.edu as original measurements, and we find a_{tim}=1.004137.

The top right part of figure 1 shows the SARR adjusted DIARAD, PMO06, ACRIM 3 and TIM measurements. One can verify visually that the PMO06 measurements (green curve), ACRIM 3 measurements (blue curve) and TIM measurements (pink curve) have been 'tied' to the DIARAD measurements (underlying red curve).

5. SARR Adjustment Of ERBS Through ACRIM 2, ACRIM 1 Through ERBS And Of ERB Through ERBS

From ACRIM 2 as a secondary reference, we derive the SARR adjustment factor of ERBS. ERBS is further used as a tertiary reference to derive the SARR adjustment factor of ACRIM 1. Finally ACRIM 1 is used as a quaternary reference to derive the SARR adjustment factor of ERB. The choice of the order of references is made based on the time periods when the instruments are available, not on their quality.

We use the ERBS meaurements from (Lee et al., 1995) as original measurements and we find a_{erbs}= 1.000536.

For ACRIM 1 we use the version 1 available from http://www.acrim.com as original measurements, and we find a_{acrim1}=0.999026.

The bottom left part of figure 1 shows the SARR adjusted ACRIM 2, ERBS and ACRIM 1 measurements. One can verify visually that the ACRIM 1 measurements (blue curve) have been 'tied' to the ERBS measurements (green points), which have in turn been 'tied' to the ACRIM 2 measurements (red curve).

For ERB we use the version from (Hoyt et. al, 1992). We use ACRIM 1 as a reference during the entire period of overlap, except in the period from December 1980 to February 1984 when the quality of the ACRIM

1 measurements was degraded due to the SMM 'spin mode'. We find a_{erb}=0.995867.

The bottom right part of figure 1 shows the SARR adjusted ACRIM 1 and ERB measurements. One can verify visually that the ERB measurements (green curve) have been 'tied' to the ACRIM 1 measurements (red curve) during the entire period of overlap except during the SMM spin mode period.

6. TSI Composite And Uncertainty

After their SARR adjustment all the TSI instruments are 'tied' together at the same absolute level. Some differences in the detailed TSI time variations measured by the different instruments still exist. The final best estimate of the 'true' TSI variation is obtained as a composite TSI series. For a given day the value of the composite TSI is defined as the average of the SARR adjusted daily mean TSI measurements of all available instruments, with the exclusion of ERBS and SOLCON. For reference, the used SARR adjustment coefficients are compiled in table II.

The running yearly mean of the TSI composite reached a minimum of 1365.67 W/m^2 at the beginming of 1987, a maximum of 1367.08 W/m^2 during 1991, a minimum of 1365.82 W/m^2 at the end of 1995, and a maximum of 1367.42 W/m^2 at the end of 2001. Thus the TSI cycle amplitude was 1.4 W/m^2 and 1.6 W/m^2 for the last two solar cycles, and the change between the last two minima was 0.15 W/m^2.

The left part of figure 2 shows the composite time series (red curve), the ERBS measurements (green points) and the SOLCON measurements (blue crosses). As the ERBS measurements have been excluded in the composite TSI calculation, they can be used as partly independent measurements for an assesment of the uncertainty of the TSI composite. The independence is only partly because the ERBS measurements have been used to make the connection between the ACRIM 1 and ACRIM 2 measurements in section 5. The right part of figure 2 shows the difference (red curve) between the ERBS time series and the composite time series. To reduce the noise on the difference a 25 point running mean has been applied to the difference.

The strongest features visible in the ERBS minus composite difference are a decrease by about 0.75 W/m^2 from end 1989 to 1991, and an opposite increase by about 0.6 W/m^2 from 1992 to 1993. The increase correponds to the sudden disagreement between ERBS and ERB, which will be further discussed in the next section. The decrease corresponds

Table II. Summary of SARR adjustment coefficients.

Instrument	Version	SARR adjustment coefficient
SOLCON-Left	Original	0.999228
SOLCON-Right	Original	0.999823
DIARAD	(Dewitte et al., 2004)	1.000295
ACRIM 2	www.acrim.com, v.3	1.001295
SOVA 1	(Crommelynck et al., 1994)	1.000799
SOVA 2	(Romero et al., 1994)	0.999703
PMO06	(Dewitte et al., 2004)	1.000661
ACRIM 3	www.acrim.com, v.0403	1.000404
TIM	lasp.colorado.edu, v.3	1.004137
ERBS	Original	1.000536
ACRIM 1	www.acrim.com, v.1	0.999026
ERB	(Hoyt et. al, 1992)	0.995867

to the end of the lifetime of ERB, when it is no longer used in the composite.

95% of the ERBS-composite difference lie within -0.3 W/m^2 +/- 0.35 W/m^2 . Thus the 95% uncertainty on the shape of the variaton of the TSI with time, measured by comparing it with the independent ERBS measurements, is +/- 0.35 W/m^2. This means that it can not be concluded that the previously found solar minimum increase of 0.15 W/m^2 is significant.

7. Discussion And Conclusions

We have constructed a composite TSI time series and quantified its uncertainty using all available long term TSI measurements. We have adjusted the absolute level of the TSI measurements using the SARR adjustment principle as in (Crommelynck and Dewitte, 1997), applied through a cascade of references. After the adjustment of their absolute levels, all TSI instruments agree on the variation of TSI with time within +/- 0.35 W/m^2 for at least 95 % of the measurements.

For the changes at climate time scales, the long term trend of the 'quiet sun' irradiance levels in between two solar minima is the most relevant. In this study we find a measured trend of +0.15 W/m^2 +/- 0.35 W/m^2 over one solar cycle, so we can not conclude that this trend is significant.

Our results are different from (Willson and Mordvinov, 2003) who find a trend of 0.8 W/m^2 and from (Froehlich and Lean, 1998) who find no trend. The differences can be explained since we use the ERBS radiometer to bridge the gap between ACRIM 1 and ACRIM 2, while in the cited studies the ERB radiometer is used. We preferred not to use ERB, since it is believed (Lee et al., 1995) that ERB had a shift of about 0.8 W/m^2 after switch-off and switch-on between Sep. 1989 and May 1990. The ERB shift is visible in the right part of figure 2 as the increase of the ERBS minus composite difference by 0.8 W/m^2 around 1990. The ERB shift, which was corrected in (Froehlich and Lean, 1998) and not corrected in (Willson and Mordvinov, 2003), explains the difference between these two studies. In (Willson and Mordvinov, 2003) the decrease of the ERBS minus ERB difference from 1989 to 1991 is not interpreted as an upward shift of ERB, but as an ageing of ERBS.

For the extrapolation of TSI measurements at climate time scales, see e.g. (Lean et al., 1995), an estimate of the long term quiet sun irradiance variation of 3.3 W/m^2 over 300 years - corresponding to an average trend of 0.11 W/m^2 per decade - has been used. To verify this estimate by measurements, would require a TSI record with an uncertainty lower than +/- 0.1 W/m^2 over one solar cycle, or with an uncertainty lower than +/- 0.2 W/m^2 over two solar cycles. Such low uncertainties on the long term TSI measurements have not been met so far, but it is not excluded that they can be met in the future, by extension of the time series and progress in technology. In this context it is promising to note that the radiometers DIARAD and TIM agree on the long term variation of the TSI over 1.5 years within +/- 0.1 W/m^2. Both radiometers have side by side cavity construction, which can explain their good stability. If both radiometers continue to function well and to agree well over the next few years, we can obtain a TSI record over one solar cycle with an uncertainty as low as +/- 0.1 W/m^2, which is the limit of what is needed.

Acknowledgements

We acknowledge the efforts of the VIRGO investigation on SOHO, a cooperative mission of ESA and NASA. We thank the NASA Small Shuttle Payloads Project Office for the SOLCON flight opportunities. We thank Richard Willson for the provision of the ACRIM data and Robert Lee III for the provision of the ERBS data. The work presented in this article was supported by the Belgian Science Policy office through the ESA PRODEX program.

References

Crommelynck, D., Domingo, V., Fichot, A. and Lee, R.B. Total Solar Irradiance Observations from the EURECA and ATLAS Experiments. In J. Pap et al., editors, *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, 63–69, Cambridge Univ. Press, New York, 1994.

Crommelynck, D., A. Fichot, R. B. Lee III and J. Romero, First realisation of the Space Absolute Radiometric Reference during the ATLAS 2 flight period. *Adv. Space Res.* 16:17–23, 1995.

Crommelynck, D. and S. Dewitte. Solar constant temporal and frequency characteristics. *Solar Physics*, 173:171–191, 1997.

Dewitte S., A. Joukoff, D. Crommelynck, R. B. Lee III, R. Helizon and R.S. Wilson. Contribution of the Solar Constant (SOLCON) program to the long term total solar irradiance observations. *Journal Geophysical Research*, 106(A8): 15759–15766, 10.1029/2000JA900160, 2001.

Dewitte S., D. Crommelynck and A. Joukoff. Total solar irradiance observations from DIARAD/VIRGO. *Journal Geophysical Research*, 109, A02102, doi:10.1029/2002JA009694, 2004.

Fröhlich, C., and J. Lean. The Sun's total irradiance: cycles and trends in the past two decades and associated climate change uncertainties. *Geophysical Research Letters*, 25:4377–4380, 1998.

Fröhlich, C. Long-Term Behaviour of Space Radiometers. *Metrologia*, 40:60–65, 2003.

Hoyt, D. V., H. L. Kyle, J. R. Hickey and R. H. Maschhoff. The Nimbus-7 solar total irradiance: a new algorithm for its derivation. *Journal Geophysical Research*, 97:51–63, 1992.

Kopp, G., Lawrence, G., and Rottman, G. Total Irradiance Monitor Design and On-Orbit Functionality. In *SPIE Proc.* 5171-4, 2003, in press.

Lawrence, G.M., G. Rottman, J. Harder and T. Woods. Solar Total Irradiance Monitor (TIM). *Metrologia*, 37:407–410 , 2000.

Lee, R. B., III, et al. Long-term total solar irradiance variability during sunspot cycle 22. *Journal Geophysical Research*, 100:1667–1675, 1995.

Lean, J., J. Beer and R. Bradley. Reconstruction of solar irradiance since 1610: Implications for climate change. *Geophysical Research Letters*, 22:3195–3198, 1995.

Romero, J., Wehrli, C. and Fröhlich, C. Solar total irradiance variability from SOVA2 on board EURECA. *Solar Physics*, 152: 23–29, 1994.

Willson, R. C. Irradiance observations of SMM, Spacelab 1, UARS and ATLAS experiments. In J. Pap et al., editors, *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, 54–62, Cambridge Univ. Press, New York, 1994.

Willson, R. C. The ACRIMSAT/ACRIM3 experiment-Extending the Precision, Long-Term Total Solar Irradiance Climate Database, *Earth Observer*, 13:14–17, 2001.

Willson, R.C., A.V. Mordvinov. Secular total solar irradiance trend during solar cycles 21-23. *Geophysical Research Letters*, 30(5):1199, doi:10.1029/2002GL016038, 2003.

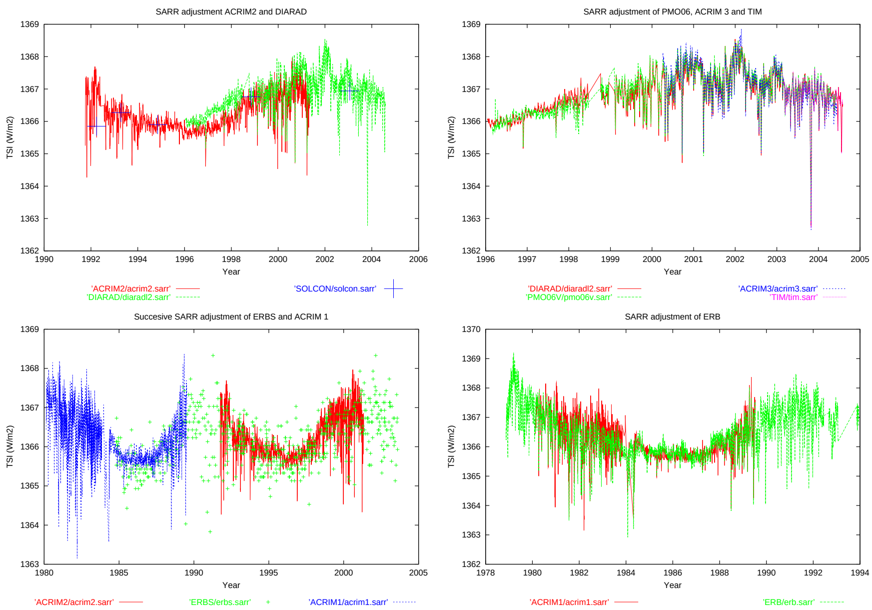

Figure 1. Top left: SARR adjusted SOLCON measurements (blue curve), DIARAD measurements (green curve) and ACRIM 2 measurements (red curve). Top right: SARR adjusted DIARAD measurements (red curve), PMO06 measurements (green curve), ACRIM 3 measurements (blue curve) and TIM measurements (pink curve). Bottom left: SARR adjusted ACRIM2 measurements (red curve), ERBS measurements (green points) and ACRIM 1 measurements (blue curve). Bottom right: SARR adjusted ACRIM1 measurements (red curve), and ERB measurements (red curve).

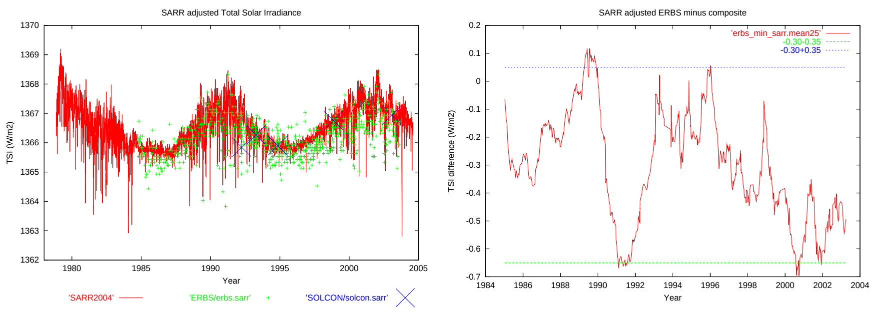

Figure 2. Left: SARR adjusted TSI composite (red curve), ERBS TSI measurements (green points) and SOLCON TSI measurements (blue crosses) Right: SARR adjusted ERBS TSI minus SARR adjusted TSI composite (red curve) + upper limit (blue line) and lower limit (green line) of the 95% interval of this difference.