

LETTER TO THE EDITOR

Correlation of spectral solar irradiance with solar activity as measured by VIRGO[★]

C. Wehrli, W. Schmutz, and A. I. Shapiro

Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, 7260 Davos Dorf, Switzerland
e-mail: christoph.wehrli@pmo.dwr.ch

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ABSTRACT

Context. The variability of solar spectral irradiance (SSI) over the rotational period and its trend over the solar activity cycle are important for understanding the Sun–Earth connection as well as for observational constraints for solar models. Recently the Spectral Irradiance Monitor (SIM) experiment on the Solar Radiation and Climate Experiment (SORCE) has published an unexpected negative correlation with total solar irradiance (TSI) of the visible spectral range. It is compensated by a strong and positive variability of the near UV range.

Aims. We aim to verify whether the anti-correlated SIM-trend in the visible can be confirmed by independent observations of the Variability of solar IRadiance and Gravity Oscillations (VIRGO) experiment on the SOLar and Heliospheric Observatory (SOHO) satellite. The challenge of all space experiments measuring solar irradiance are sensitivity changes of their sensors due to exposure to intense UV radiation, which are difficult to assess in orbit.

Methods. We exclude the first six years prior to 2002 where one or more fast processes contributed to instrumental changes and analyse a ten-year timeseries of VIRGO sun photometer data between 2002 and 2012. The variability of SSI is correlated with the variability of the TSI, which is taken as a proxy for solar activity.

Results. Observational evidence indicates that after six years only one single long-term process governs the degradation of the backup sun photometer in VIRGO which is operated once a month. This degradation can be well approximated by a linear function over ten years. The analysis of the residuals from the linear trend yield robust positive correlations of spectral irradiance at 862, 500, and 402 nm with total irradiance. In the analysis of annual averages of these data the positive correlations change into weak negative correlations, but with little statistical significance for the 862 nm and 402 nm data. At 500 nm the annual spectral data are still positively correlated with TSI. The persisting positive correlation at 500 nm is in contradiction to the SIM results.

Key words. Sun: activity – solar-terrestrial relations – space vehicles – instrumentation: photometers

1. Introduction

The variability of solar irradiance was suspected long ago (Smyth 1855), but its connection with solar activity was not clear until the beginning of the satellite measurements of the total solar irradiance (TSI) in 1978. The measurements showed that TSI is positively correlated with solar activity, so generally when more sunspots are visible on the Sun, the TSI value is larger. The mean level of the TSI during the solar maximum is approximately 0.1% higher than during the solar minimum. This can be successfully explained by the current models (Lean et al. 2005; Krivova & Solanki 2008; Solanki & Krivova 2011), which attribute the solar variability on the 11-year time scale to the imbalance between the contributions from dark sunspots and bright active features (i.e. plages and bright network).

The understanding of the spectral solar irradiance (SSI) variability is significantly hampered by the lack of long-term measurements. The contrast between the bright features and quite Sun decreases with the wavelengths as the Planck function becomes less sensitive to the temperature changes (Shapiro et al. 2010). Therefore, most of the models (e.g. Lean et al. 2005; Krivova & Solanki 2008) predict inverse solar cycle changes (i.e. anticorrelation between the solar activity and irradiance)

in the IR, with the inversion point located between 1200 and 1600 nm. The UV and visible irradiance are predicted to positively correlate with the solar cycle (see review by Ermolli et al. 2013, for detailed intercomparison of the available models).

Strikingly, recent measurements by the Spectral Irradiance Monitor (SIM) showed a completely different picture of the solar variability in the UV and visible (Harder et al. 2009). The variability in UV measured by SIM is several times higher than all recent estimates. While 11-year variability of the UV and IR irradiance are in phase with the solar cycle, the variability of the visible irradiance (400–730 nm) is in antiphase. It was suggested that such this behaviour may be caused by a negative correlation of the continuum intensity with the magnetic field observed at some wavelengths (Topka et al. 1997) or by a change of the temperature gradient in the photosphere (see Harder et al. 2009; Fontenla et al. 2011 for more detailed discussion).

Presently there is evidence both in favour and against the anticorrelation of the visible irradiance and activity reported by Harder et al. (2009). Preminger et al. (2011) showed that the analysis of the full-disk photometric images from the San Fernando Observatory indicates the opposite trends in the TSI and visible, which is in agreement with SIM measurements. At the same time Lean & DeLand (2012) suggested that SIM measurements are affected by the uncorrected sensitivity drifts. The clarification of this question is of crucial importance for climate modelling (Haigh et al. 2010; Shapiro et al. 2013).

[★] Appendix A is available in electronic form at <http://www.aanda.org>

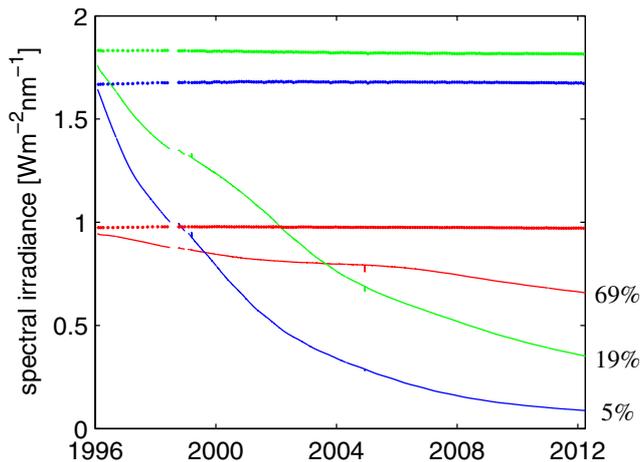


Fig. 1. Time series of SPM-A (line) and SPM-B (dots, horizontal) spectral irradiance at 862 nm (red), 500 nm (green), and 402 nm (blue).

In this paper we study the measurements of two sun photometers (SPM-A and SPM-B) in the Variability of solar IRadiance and Gravity Oscillations (VIRGO) experiment on the SOLar and Heliospheric Observatory (SOHO) searching for a qualitative statement about long-term correlation of SSI with solar activity between 2002 and 2012. In Sect. 2 we describe some technical background of the instrument, its operation, and in-flight performance that we deem necessary for understanding the data set. Section 3 addresses our approach to separate solar cycle variability from instrumental degradation and provides the results of straight forward correlation with and regression versus TSI observations. A summary and conclusion are given in Sect. 4.

2. Description of the instrument

The VIRGO SPM instruments are spectral radiometers with three channels centered at 402, 500, and 862 nm using interference filters of 5 nm FWHM bandwidth and silicon detectors. The filters are protected from energetic particle flux and UV radiation below 380 nm by a 3 mm thick front window of radiation resistant BK7-G18 glass. The optical compartment containing the filters and detectors is physically separated from the rest of the VIRGO experiment, and was permanently flushed with 5.5 grade nitrogen until launch. Further details about the VIRGO experiment are given in Fröhlich et al. (1995).

2.1. Operations

Both heaters of the SPM instruments were activated with their covers still closed on 6 December 1995 for an outgassing period of 46 days. The filter and detector compartments are constantly heated to a few degrees above ambient satellite temperature in order to reduce condensation of gaseous contaminants on their optical surfaces.

The cover of SPM-A was opened on 17 January 1996 and this instrument has since then continuously observed the Sun for more than 5900 days with the exception of the so called SOHO vacation from 25 June to 25 September, 1998. This covers the complete solar cycle 23 and the onset of cycle 24.

SPM-A is used primarily as a helioseismological instrument and is therefore operated continuously with a 60 s sampling rate; SPM-B is the radiometric instrument, intended to monitor the solar spectral flux and the degradation of SPM-A. During backup operations it is exposed for 20 min taking six samples of 60 s for each of its three channels sequentially. Until the end

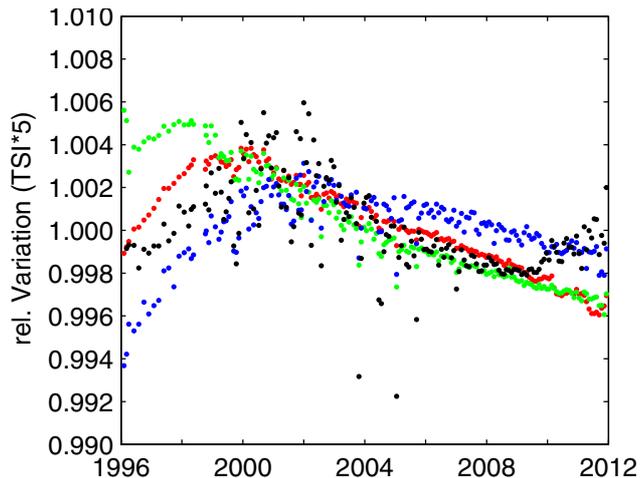


Fig. 2. Variations relative to their mean of VIRGO spectral (blue, green, and red) and total solar irradiance (black) during SPM-B backup measurements. The TSI relative variations are expanded by a factor of five.

of 1998 backup measurements were taken every 60 days, and since February 1999 the backup cadence was doubled to 30 days.

Level-1 are fully processed data with all a priori known corrections, e.g. conversion to physical units $\text{W m}^{-2} \text{nm}^{-1}$, temperature corrections, and normalization to Sun-Earth distance of 1 AU applied. Daily means are calculated for SPM-A, while SPM-B data represent averages over 6 min.

2.2. Instrument degradation

Since the start of operational measurements in January 1996 SPM-A has suffered a steady loss of sensitivity. After more than 15 years of continuous exposure the red channel signal is reduced to 70%, the green to 20%, and the blue to 5% of their initial values. Several processes may contribute to this degradation: contamination of the first optical surface, deterioration of filter glass and interference coatings, and loss of efficiency in the silicon photo detectors; SPM-B has maintained more than 99% of its sensitivity (see Fig. 1) thanks to its sparse operation cycle with an accumulated exposure time of less than three days versus more than 5900 days for SPM-A. Experience gained from similar instruments retrieved from the EURECA mission (Wehrli et al. 1995) led to much improved performance of the VIRGO spectral radiometer. Further speculations about the contribution of different processes leading to the sensitivity loss and their evolution in time are beyond the scope of this article.

3. Variability of VIRGO spectral irradiance

The VIRGO SPM time series represent the product of solar cycle variability and instrumental sensitivity changes that is difficult to factorize. The sensitivity rate of change is intricately related to solar activity as solar UV and energetic particle fluxes act on optical materials and semiconductor components to a largely unknown extent. Depending on the approach taken to fit an empirical model for the degradation through the observations, the solar cycle variability may be eliminated completely or be grossly overestimated.

The apparent stability of SPM-B signals suggests that an analysis of spectral solar irradiance variability over the solar cycle is possible. Figure 2 shows the relative variations of fluxes measured by SPM-B together with the variation of the TSI channel measured at corresponding dates, but magnified by a factor of five.

Table 1. Correlation coefficients between relative variations in TSI and SSI channels for monthly snapshot values (Cols. 2–4) and for annual averages (Cols. 5–7) are listed with 95% uncertainties in brackets.

	Monthly snapshots			Annual averages		
	SSI-862	SSI-500	SSI-402	SSI-862	SSI-500	SSI-402
TSI	0.25[0.08, 0.41]	0.87[0.83, 0.91]	0.48[0.33, 0.60]	−0.58[−0.88, 0.03]	0.91[0.68, 0.98]	−0.43[−0.82, 0.23]
SSI-862	1.0	0.45[0.30, 0.58]	0.55[0.42, 0.66]	1.0	−0.79[−0.94, −0.36]	0.65[0.09, 0.90]
SSI-500		1.0	0.68[0.58, 0.77]		1.0	−0.47[−0.82, 0.24]
SSI-402			1.0			1.0

Notes. The number of monthly and annual values are 124 and 11.

The 2σ variability in SSI observed by SPM-B between 1996 and 2009 is around $4\text{--}5 \times 10^{-3}$ or about five times larger than the corresponding TSI variation. From the general shape of the SSI variations common to all three channels, one would suspect an instrumental effect comprising at least two processes with different time constants, which can be modelled as the sum of 2 exponentials. Time constants of a bi-exponential fitted to the red and blue channel amount to 2–3 years for the fast component and more than 1000 years for the slow component. The bi-exponential does not fit the green channel well, probably because of a stronger solar component.

Arguing that the fast processes of the instrumental effect have become insignificant after two time constants, i.e. after 2002, and that the slow components may be approximated by a linear function over a small fraction (1% of 1000 y) of its characteristic time, we propose to model the instrumental degradation since 2002 by a simple linear trend. Including data prior to 2002 would require more accurate modelling of the fast instrumental effects, which is beyond the scope of this paper.

The signature of SSI variability during the decline of solar cycle 23 and the rise of cycle 24 can be represented by the residuals of a linear function fitted to the SPM-B data and is related to the variability of TSI according to the PMOD composite (Fröhlich 2000). By our modest approach we eliminate most of the instrumental degradation and obtain an imperfect estimate of the solar variability. A statistical analysis of the spectral variability can then provide observational verification as to whether the anti-correlation of spectral versus total irradiance in the mid-visible wavelength range reported by Harder et al. (2009) and Preminger et al. (2011) can be confirmed by VIRGO measurements.

Figure 3 shows the variation of SSI since 2002 normalized to a robust linear least-squares fit (Holland & Welsch 1977) over the period shown. The 2σ variability is now in the order of 5×10^{-4} and comparable to the TSI variation shown in black. Solar activity shows up nicely on the rotational timescale, e.g. on 15 January 2005 with relative depressions of 0.9990 (Red), 0.9985 (TSI), 0.9979 (Green), and 0.9968 (Blue). The distinct signature of declining cycle 23 and rising cycle 24 seen in TSI variations is discernible in the detrended variation of the green (500 nm) channel, but is not obvious in the red (862 nm) and blue (402 nm) channels.

Table 1 (Cols. 2–4) lists the correlation coefficients of 124 simultaneous observations of solar spectral and total irradiance variations between January 2002 and March 2012. Numbers in brackets indicate the 95% confidence intervals of the correlation. The statistically robust correlation for the visible channel is further illustrated by Fig. A.1. From these correlations it can be concluded that a) all spectral channels show a positive correlation with TSI; b) correlations among the spectral channels are also positive; c) the correlation of the 500 nm channel with TSI

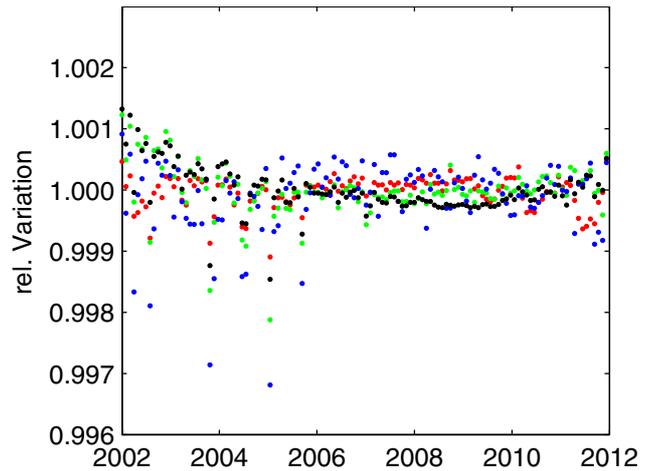


Fig. 3. VIRGO spectral solar irradiance variations (red, green, blue) normalized to their linear trends and total solar irradiance (black) normalized to its mean value.

is quite strong and robust as already seen in Fig. 3; and d) the confidence intervals of the weaker correlation for the channels at 402 nm and 862 nm are still entirely positive.

3.1. Correlation of annual means

Because of the sampling rate of 30 days for the SPM-B instrument, the positive correlation found in individual measurements represents a mixture of solar cycle and solar rotation activity. In order to isolate the solar cycle trend from contamination by rotating solar activity, we analysed annual means of SPM-B measurements from 2002 to 2012 (see Fig. A.2). In contrast to the all positive monthly correlations, the annual correlations (see Table 1, Cols. 5–7) become negative in red and blue channels. Corresponding p-values, indicating the probability that the given correlations might occur by chance, are 0.06 for 862 nm, <0.01 for 500 nm, and 0.19 for 402 nm. The signs of correlations remain within the uncertainties given in Table 1 when the data set is restricted to shorter periods, e.g. 2002–2010, 2004–2012, or 2004–2010, for example.

This finding is further corroborated by robust linear regressions of relative SSI versus TSI variations shown in Fig. 4. A statistically significant, positive slope of regression is thus found for the mid-VIS channel. Interestingly enough, both the near IR and near UV channels show the negative though less significant slopes given in Table A.1.

4. Discussion and conclusions

We have analysed a time series of solar spectral irradiance measured by the VIRGO experiment on the SOHO satellite in terms of spectral irradiance variation versus simultaneous

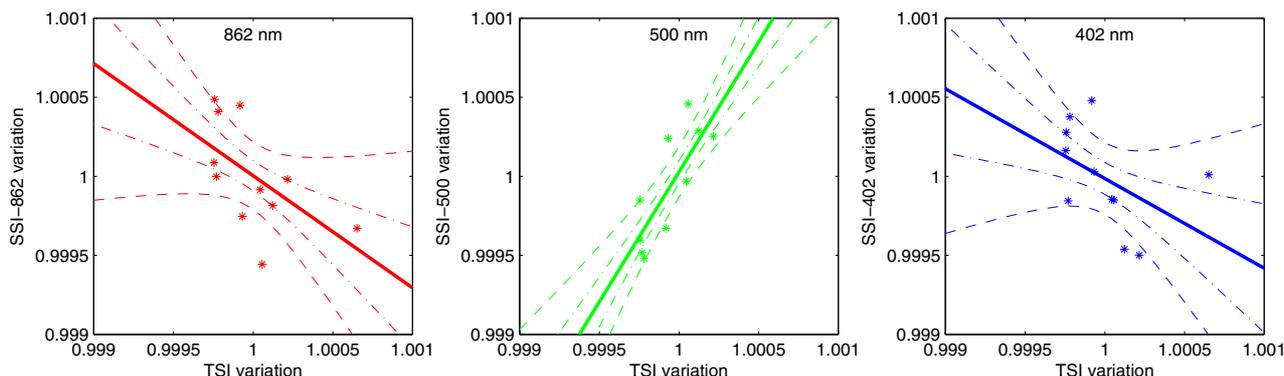


Fig. 4. VIRGO SSI (RGB) versus TSI variations based on annual means from 2002 to 2012. Solid lines indicate the robust linear regressions, the dash dot and dashed lines are, respectively, 1σ and 2σ uncertainties.

measurements of the total solar irradiance used as a proxy for solar activity. Monthly backup measurements of the SPM-B instrument are affected by small, but not negligible, ageing effects of the instrument that mask the signature of solar activity. We note that there are several processes (e.g. shift of the peak wavelengths of the filters due to the diffusion of the filter layers, development of spectral leaks, radiation damage of the silicon detector, etc.) that could influence the ageing and, in principle, would make it a non-monotonic function of time. Presently there is no reliable way to quantitatively characterize these processes or even to confirm their existence in the VIRGO/SPM data. Therefore, the only way to take these potential effects into account is to introduce a sophisticated empirical model of the degradation with a large number of free parameters. By adjusting these free parameters one is able to control the share of instrumental effects and solar signature in the observed variability even to the extreme case of attributing the full variability to either of the two possibilities. We note that the same is true for all available SSI measurements and there are a number of examples when different analyses of the same SSI measurements led to strikingly different results (see e.g. review by Ermolli et al. 2013).

The SPM-B instrument's daily averages were also analysed by Fröhlich¹ using a sophisticated model of the long-term behaviour of the instrument with 13 empirical parameters involving multiple time and temperature dependencies, as well as UV irradiance and TSI used as surrogates for the effects of solar activity effects. Fröhlich derives positive correlations at all three wavelengths, with cycle amplitude ratios of 0.5, 1.6, and 2.7 for the red, green, and blue channels with respect to TSI. Such a strong positive correlation would imply an even stronger negative correlation in the infrared tail of the spectrum in order to make the integrated SSI variability consistent with the observed TSI variability.

Here, we explicitly refrain from sophisticated speculations about the nature and strength of these instrumental effects and search for the least number of free parameters. Observational data indicate that the VIRGO ageing may be summarized by a fast process (2–3 years) and a slow process (≈ 1000 y) that are exponential in time, and that the fast processes have decayed after six years; the ten-year period from January 2002 to March 2012 was empirically approximated by a linear function in time.

Based on monthly snapshots, positive correlations of SSI with TSI were found at all three wavelengths. In the analysis of annual averages, the correlations at 862 nm and at 402 nm become negative. A negative correlation for the IR channel is more likely real ($R^2 = 0.22$) than for the UV channel ($R^2 = 0.01$), but both are not significant at the $2\text{-}\sigma$ level. However, the robust ($R^2 = 0.79$) positive correlation of monthly snapshots at 500 nm remains statistically significant at the $5\text{-}\sigma$ level after smoothing out the solar rotation period. This result based on VIRGO observations clearly contradicts previous reports (Harder et al. 2009) of anti-correlated spectral irradiance at the peak of the solar spectral energy distribution with the solar cycle.

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References

- Ermolli, I., Matthes, K., Dudok de Wit, T., et al. 2013, *Atmos. Chem. Phys.*, 13, 3945
- Fontenla, J. M., Harder, J., Livingston, W., Snow, M., & Woods, T. 2011, *J. Geophys. Res. (Atmospheres)*, 116, 20108
- Fröhlich, C. 2000, *Space Sci. Rev.*, 94, 15
- Fröhlich, C., Romero, J., Roth, H., et al. 1995, *Sol. Phys.*, 162, 101
- Haigh, J. D., Winning, A. R., Toumi, R., & Harder, J. W. 2010, *Nature*, 467, 696
- Harder, J. W., Fontenla, J. M., Pilewskie, P., Richard, E. C., & Woods, T. N. 2009, *Geophys. Res. Lett.*, 36, 7801
- Holland, P. W., & Welsch, R. E. 1977, *Communications in Statistics: Theory and Methods A*, 6, 813
- Krivova, N. A., & Solanki, S. K. 2008, *JA&A*, 29, 151
- Lean, J., & DeLand, M. 2012, *J. Climate.*, in press
- Lean, J., Rottman, G., Harder, J., & Kopp, G. 2005, *Sol. Phys.*, 230, 27
- Preminger, D. G., Chapman, G. A., & Cookson, A. M. 2011, *ApJ*, 739, L45
- Shapiro, A. I., Schmutz, W., Schoell, M., Haberleiter, M., & Rozanov, E. 2010, *A&A*, 517, A48
- Shapiro, A. V., Rozanov, E. V., Shapiro, A. I., et al. 2013, *J. Geophys. Res. (Atmospheres)*, 118, 3781
- Smyth, C. P. 1855, *MNRAS*, 16, 1
- Solanki, S. K., & Krivova, N. A. 2011, *Science*, 334, 916
- Topka, K. P., Tarbell, T. D., & Title, A. M. 1997, *ApJ*, 484, 479
- Wehrli, C., Fröhlich, C., & Romero, J. 1995, *Metrologia*, 32, 653

¹ Poster at SORCE meeting 2011, available from ftp://ftp.pmodwrc.ch/pub/Claus/SORCE_2011/SPM_poster_cf.pdf

Appendix A: SSI variations at 500 nm versus TSI variations

A robust linear regression analysis of monthly snapshot variations of SSI at 500 nm versus TSI confirms the positive correlation reported here. The lowest irradiance values occur during sun spot passages, the largest values during the active mid-term of cycle 23. Thus, data points shown in the lower-left corner of Fig. A.1 ($x, y < 1$) represent measurements taken during passage of sunspots over the solar disc while those shown in the upper-right corner represent observations during the declining phase of solar cycle 23 and rising phase of cycle 24. All data points are weighted by a bi-square function of their regression residues, and so the leverage of outliers, e.g. transit of large sun spots, on regression is minimized. We note that the regression slope is clearly dominated by the number of data points (green) with positive correlation, specifically by those in the upper-right corner representing higher solar activity.

We also note that all points (magenta) that correspond to anti-correlation between the TSI and SSI-500 are located very close to the (1, 1) point in Fig. A.1. This means that all cases of anti-correlation occur when the amplitude of the cycle is small

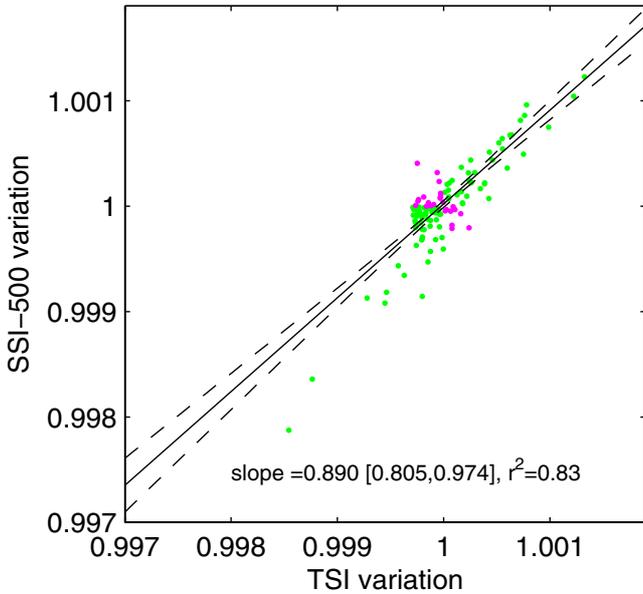


Fig. A.1. SSI variation at 500 nm versus TSI variation for the period from 2001 to 2012 with robust linear regression. Green dots ($n = 104$) have positive correlation; magenta dots ($m = 21$) are anti-correlated with TSI.

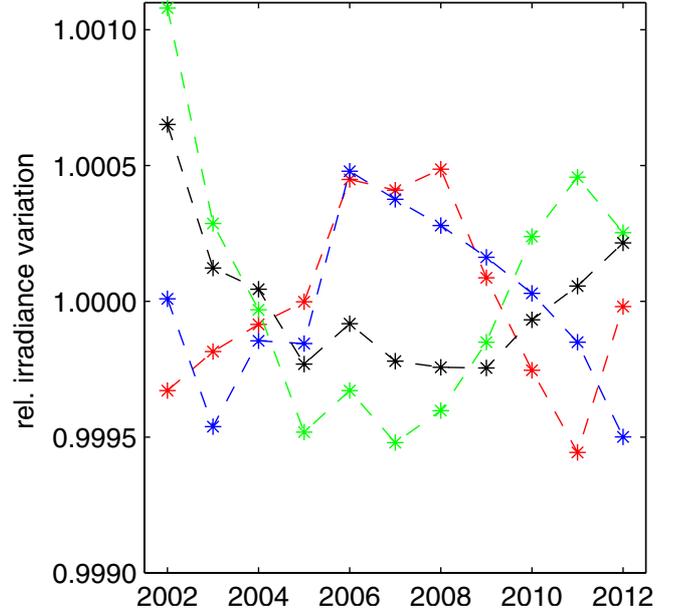


Fig. A.2. The same as Fig. 3 but for annual mean values.

Table A.1. Slopes of the linear regression (shown in Fig. 4) between relative variations in the annual means of the VIRGO TSI and SSI monthly snapshots.

Channel	Slope	2- σ uncertainty	1- σ uncertainty	R^2
SSI-862	-0.71	[-1.55, 0.13]	[-1.08, -0.34]	0.22
SSI-500	1.65	[1.02, 2.27]	[1.37, 1.92]	0.79
SSI-402	-0.57	[-1.45, 0.32]	[-0.96, -0.17]	0.01

and comparable to the uncertainty of the degradation correction. Therefore, these points are the most sensitive to small deviations in the degradation correction and accordingly the least reliable. When the data are restricted to the central cluster (within a square region of 1 ± 0.0005), the slope is reduced to $+0.561$ [0.436, 0.686], but remains strictly positive.

The trend of annual-mean data shown in Fig. A.2 is apparent to the eye: the green curve (500 nm) resembles the black (TSI) while the red (862 nm) and blue (402 nm) lines almost correspond to images of TSI mirrored at normalization level 1.0. We note that the temporal position of the extrema of SSI variations may be affected by the choice of the selected period. However the sign of the correlation remains unaffected (see Sect. 3.1).