SOLAR IRRADIANCE VARIABILITY SINCE 1978

Revision of the PMOD Composite during Solar Cycle 21

C. FRÖHLICH (`cfrohlich@pmodwrc.ch`)
Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, CH–7260 Davos Dorf, Switzerland

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Abstract. Since November 1978 a set of total solar irradiance (TSI) measurements from space is available, yielding a time series of more than 25 years. Presently, there are three TSI composites available, called PMOD, ACRIM and IRMB, which are all constructed from the same original data, but use different procedures to correct for sensitivity changes. The PMOD composite is the only one which also corrects the early HF data for degradation. The results from the detailed analysis of the VIRGO radiometry allow a good understanding of the effects influencing the long-term behaviour of classical radiometers in space. Thus, a re-analysis of the behaviour of HF/NIMBUS-7 and ACRIM-I/SMM was indicated. For the former the situation is complicated by the fact that there are no in-flight means to determine changes due to exposure to solar radiation by comparison with a less exposed radiometer on the same spacecraft. The geometry and optical property of the cavity of HF is, however, very similar to the PMO6-type radiometers, so the behaviour of the PMO6V radiometers on VIRGO can be used as a model. ACRIM-I had to be revised mainly due to a henceforth undetected early increase and a more detailed analysis of its degradation. The results are not only important for solar radiometry from space, but they also provide a more reliable TSI during cycle 21. The differences between the revised PMOD composite and the ACRIM and IRMB are discussed by comparison with a TSI reconstruction from Kitt-Peak magnetograms. As the PMOD composite is the only one which has reliable data for cycle 21, the behaviour of the three solar cycles can now be compared and the similarities and differences discussed.

1. Introduction

Since late 1978 total solar irradiance (TSI) measurements were made by different radiometers in space, HF on NIMBUS 7, ACRIM I on SMM, ACRIM II on UARS, VIRGO on SOHO, ACRIM III on ACRIMSat and since 2003 TIM on SORCE (not used in the construction of the composites). Figure 1 shows these original time series and it is clear that not only the absolute values are quite different, especially at the beginning of the series, but there are also important differences between the series. This is e.g. obvious from comparison of early ACRIM-I with HF and is due to the fact that the original data from the HF radiometer cannot be corrected for degradation by internal means. These time series - either as they are and/or corrected for some effects not considered in the original data sets - can be used for the construction of a TSI composite by shifting each series to a common level and merging them together. Presently there are three composites available, the first one was presented in 1997 at the IAU General Assembly in Kyoto by Fröhlich

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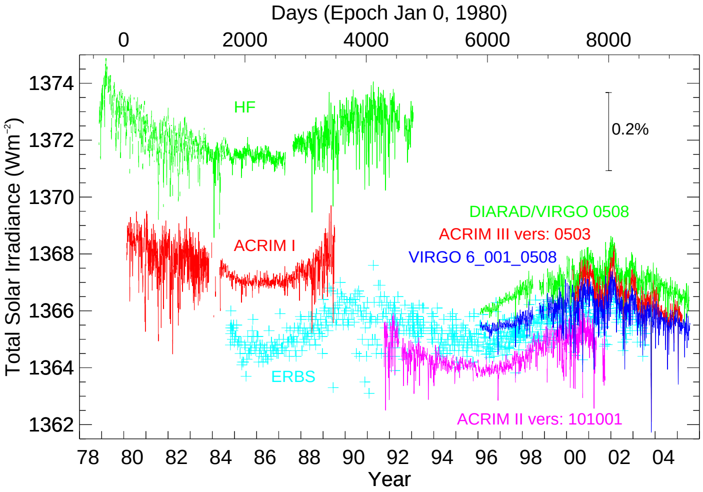

Figure 1. Compared are daily averaged values of the Sun's total irradiance from radiometers on different space platforms as published by the instrument teams since November 1978. Note, that the VIRGO TSI is determined from both VIRGO radiometers (PMO6V and DIARAD), whereas the DIARAD TSI is only based on this one.

and Lean (1998b) and is now called PMOD composite. A few month later the ACRIM composite was published by Willson (1997) which has been updated in 2003 (Willson and Mordvinov, 2003). Recently a third composite, called IRMB, was presented by Dewitte et al. (2004).

Already in the first versions of the PMOD composite corrections for the HF degradation were introduced (Fröhlich and Lean, 1998b; Fröhlich and Lean, 1998a). Due to the fact that the HF radiometer is similar to the PMO6V radiometers on VIRGO/SOHO the corrections were based on early results from VIRGO and used exponential functions to fit the changes due to an early increase and the degradation, and a linear trend to account for a gradual increase of the sensitivity. The origin of the latter effect is still unclear, but it was needed to explain the behaviour of HF up to about 1986. The so corrected data set was then used before the start of ACRIM-I and during the spin mode of SMM. Similarly, the degradation of ACRIM-I during its first year was corrected for the effect of the rather short exposure time during the spin mode which was not taken into account in the original treatment by Willson and Hudson (1991). The two time series with the corrections mentioned were the basis for the composite of Fröhlich and Lean (1998a) during the period before the end of ACRIM-I in 1989 and remained unchanged up to version d40_61_0502. The other two composites use the data as published during this period: HF up to 1980 and then ACRIM-I.

Another problem for all composite construction is how to bridge the so-called ACRIM gap between the end of ACRIM-I and the start of ACRIM-II, from June 1989 to October 1991. During this period daily values from HF and some 70 data points from ERBS with a sampling every 14 days are available. A detailed comparison of the two series by Lee III et al. (1995) revealed two slips in the HF data resulting in a total change of -0.68 Wm^{-2} over this period. This was confirmed by comparison with a model from the San Fernando group (Chapman et al., 1996). Fröhlich (2000) re-analyzed this period and the overall change was confirmed, but with a slightly different value of -0.58 Wm^{-2}. The date of the second slip was taken from Lee III et al. (1995) although it was difficult to really identify it. In Fröhlich and Lean (2002) it was first suggested that a gradual sensitivity increase of HF over the whole period together with a step at the first place would better represent the change. Moreover, it was recognized that the trend was very close to the one identified from comparison with ACRIM-I up to 1984 (Fröhlich and Lean, 1998a). The combination of a slip at 29 September 1989 after a switch-off of HF for four days (0.417 ± 0.043 Wm^{-2}) and a linear trend (0.349 ± 0.103 mWm^{-2}d^{-1}) was implemented in Fröhlich (2004) and yielded a total change over the gap of -0.84 ± 0.07 Wm^{-2}. The standard deviation of the ratio of HF to ERBS or the proxy model decreased by 45 and 60 ppm, respectively, or up to 20% with the corrections included. All these corrections were determined from data during the period of the ACRIM gap. As shown later, the new corrections for the HF are determined for the full time series from November 1978 until January 1993 at once, after a search and correction of glitches throughout the mission. Thus, these corrections are now internally consistent and there is no longer any need to treat the period of the ACRIM gap separately for the construction of the PMOD composite. The ACRIM composite neglects the corrections of the HF during the gap and this is the main reason for the claimed upward trend of TSI over the last 25 years. The IRMB composite traces ACRIM-II to I via ERBS and thus the difference between the two minima is also not significant, but only if the minimum value is calculated without the DIARAD data.

In the following sections we describe first the new procedure for ACRIM-I and HF, present the results and the new PMOD composite, discuss the differences to the earlier versions and compare it with the other two composites. Finally we compare the three solar cycles with a proxy model and discuss the similarities and differences between them.

2. Radiometric corrections

The most important effect influencing space radiometry is what is normally called degradation. As this effect depends on the time of exposure to solar radiation it can be determined by comparison with a less exposed back-up radiometer of the same type. Only the ACRIM and VIRGO radiometers have backups. As the backup measurements have to be scarce, a way to interpolate between the ratios has to be devised. For this the model developed during the detailed analysis of the PMO6V radiometry on VIRGO/SOHO is ideally suited. It is based on hyperbolic functions which take the dose of irradiation explicitly into account (a detailed description can be found in Fröhlich, 2003).

Another effect is the early increase in sensitivity of radiometers in space which was first identified for the PMO6V radiometers on VIRGO and also for the HF, which is the main reason for the high values at the beginning of this record. This effect is important for all radiometers used in space missions which have their primary aperture directly in front of the cavity. It is due to a blackening of the primary aperture by the strong solar UV radiation in space which increases the temperature of the innermost part of the aperture and simulates an increased sensitivity by the extra IR radiation emitted into the cavity. Only apertures with a small cylindrical part are concerned, and thus, this effect is important for the HF, ACRIM, ERBS and PMO6 radiometers, but not for DIARAD which has a much larger land. During the evaluation of the PMO6V radiometers it was recognized that the early increase was followed by a short-term degradation (Fröhlich, 2003). The inspection of the SOVA-2 radiometers which were on the EURECA platform and retrieved after 10 month in space (Crommelynck et al., 1993) show that the early blackening is followed by a bleaching which explains the combination of the early increase and the short-term degradation of the PMO6V.

In the following we describe the newly determined corrections of ACRIM-I and HF, and discuss the differences to the early treatment.

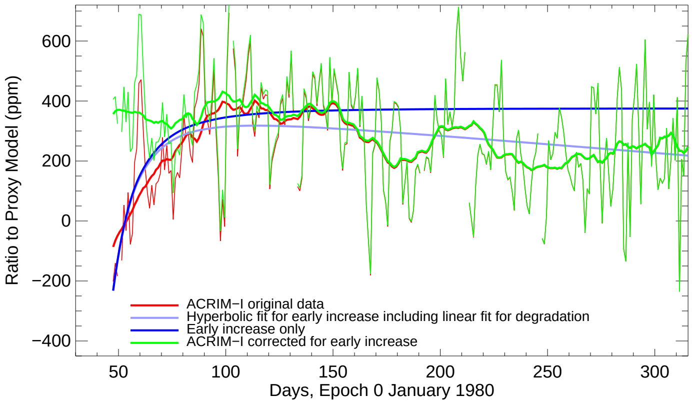

Figure 2. Shown are the early measurements of ACRIM-I together with a fit of a hyperbolic function describing the early increase and a linear fit taking the long-term degradation into account during the first few hundred days.

2.1. CORRECTIONS FOR ACRIM-I ON SMM

A first result of the re-analysis of ACRIM-I was the detection of an early increase with similar amplitudes as observed for PMO6V. As there are not enough data points available, however, only the blackening effect can be determined as shown in Figure 2; the neglect of the effect of the bleaching weakens the blackening somewhat and the remaining part is included in the overall degradation.

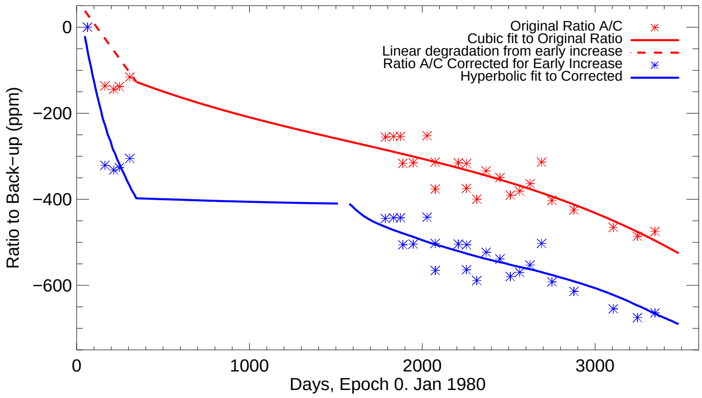

Figure 3. The original ratios of sensor A to sensor C (red symbols) of the ACRIM-I experiment on SMM are from Willson and Hudson (1991). The cubic fit corresponds to the correction originally applied and the dashed line includes the linear fit found by fitting the early increase. The blue symbols are corrected for the early increase and then fitted with a hyperbolic function.

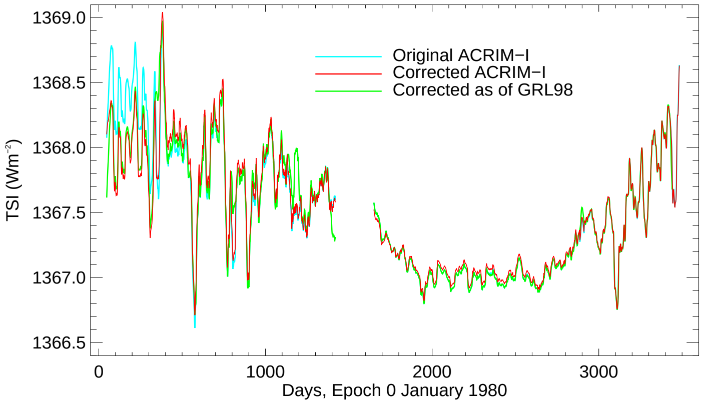

Figure 4. The original ACRIM-I record is compared to the corrected one as described in the text. Also plotted is the record as it was used in (Fröhlich and Lean, 1998a). The overall behaviour is very similar, the differences are in the details.

In a next step the degradation is re-analyzed. In Fröhlich and Lean (1998a) it was already realized that there is problem related to the fact that during the spin-mode operation of SMM (after failure of the pointing system of SMM in late 1980 until the spectacular repair in 1984 from the shuttle by astronauts) the exposure was drastically reduced. This effect was not accounted for in the original corrections by Willson and Hudson (1991) and the results of the improved degradation analysis are shown in Figure 3. The s-shape of the degradation curve illustrates the influence of the dose changing with solar activity from the maximum at the beginning through the minimum from days 2000–2600 into the ascending part of cycle 22. The flat part from days 320-1500 represents the spin-mode data with much less exposure. After the repair of SMM a further complication has been observed due to the rather long switch-off during the repair and a correction is determined by comparison with HF, ERBS and the proxy model, resulting in an exponential function with an amplitude of 88 ppm and a time constant of 80 days. Finally the corrected time series is presented in Figure 4.

2.2. CORRECTIONS FOR HF ON NIMBUS7

For the HF radiometer the situation is more complicated as there is no back-up instrument which can be used for in-flight corrections and there are many slips or glitches in the data which are thought to be due to operational changes on the spacecraft and have not been taken into account in the evaluation by Hoyt et al. (1992). An example is presented in Figure 5. Besides the three glitches shown in the figure, more than 15 have been identified in whole record by local comparison with a proxy model and/or ACRIM-I and were corrected. Also the famous one of 28 September 1989 (day 3559) is clearly identified in Figure 5.

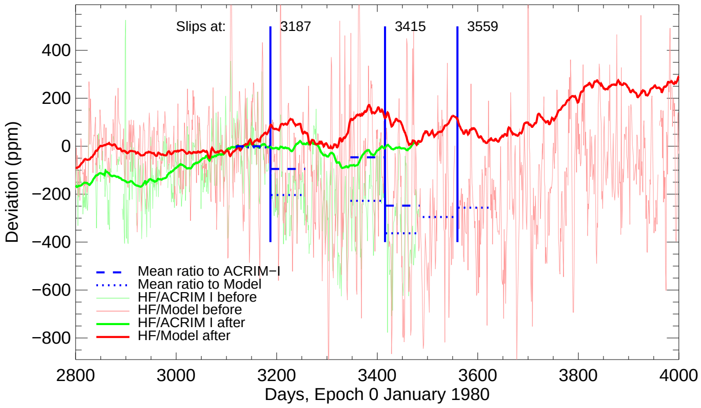

Figure 5. Shown is the period around the end of the ACRIM-I record with two slips of HF during ACRIM-I and one just after. The latter is the famous one responsible for the difference between the PMOD and ACRIM composite. 'Before' and 'After' mean before and after the corrections applied, with the 'Before' plotted as daily values and the 'After' as 81-day running means.

After having removed the slips and glitches we need to correct for the exposure dependent early increase, the degradation, and for an increase of the sensitivity which may not be exposure dependent. As there is no backup instrument we need a reference for the early observations. This reference is built from the proxy model calibrated against the corrected ACRIM-I and used to extrapolate ACRIM-I back to November 1978, the start of NIMBUS-7. For the period after February 1980 we use

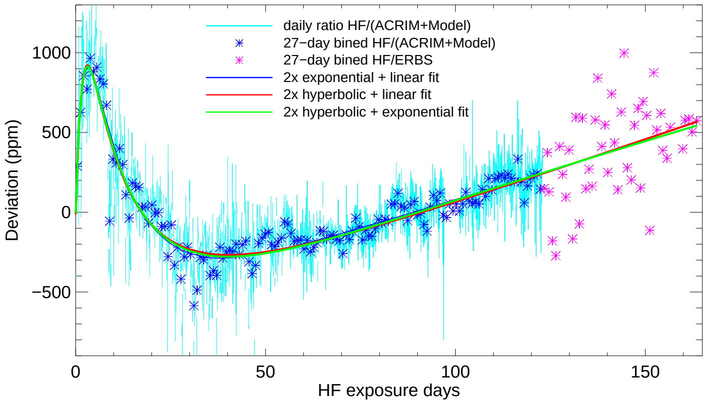

Figure 6. Shown is the ratio of HF, corrected for glitches, to the reference TSI. Corrections are needed for an early increase, for degradation, which may also include the bleaching of the aperture, and for a long-term increase of the sensitivity. The latter can be modelled with different functions, in the following the exponential one is preferred.

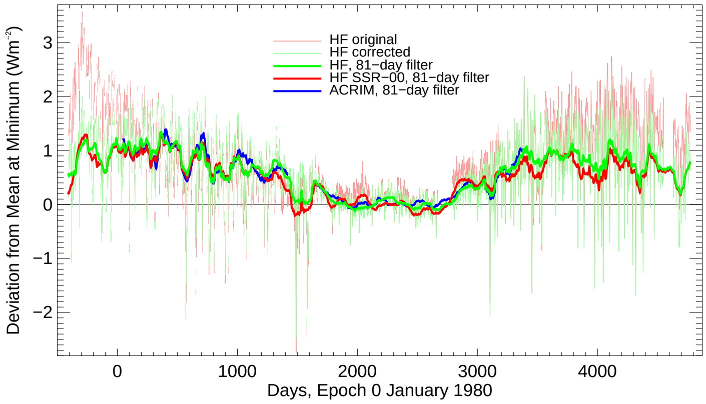

Figure 7. The final result of the HF after corrections is compared to the original data set and to ACRIM-I. Differences between the corrected and original data is up to 1 Wm^{-2}. Also plotted is the corrected HF as used in Fröhlich (2000).

the corrected ACRIM-I data until their end and then ERBS data. Figure 6 illustrates the procedure and the results. The non-exposure dependent effect is modelled with an exponential function as it is similar to the one found for DIARAD/VIRGO by Fröhlich (2003). So the corrections during the ACRIM gap need no longer to be determined by comparison with ERBS and a proxy model as in Fröhlich (2000). The final result of the corrected HF data set is shown in Figure 7 which demonstrates how important these corrections are (up to 1 Wm^{-2}). Moreover, the internal consistency of the corrections prove their reliability, and also their need.

2.3. CORRECTIONS FOR ACRIM-II ON UARS AND VIRGO ON SOHO

ACRIM-II needs also some corrections which have been determined in Fröhlich (2004) and are not changed since. Finally, we use version 6_001_0508 for the VIRGO data, updated to July 2005. The corrections to get from level-1 to level-2 data are described in Fröhlich (2003) and on `http://www.pmodwrc.ch/pmod.php?topic=tsi/virgo` from where the hourly and daily TSI data from VIRGO can be downloaded.

3. The PMOD composite

Having applied all the described corrections we are almost ready to construct the composite. We need to refer ACRIM-II to ACRIM-I which is done by a weighted average of the ratios of ACRIM-I to the corrected HF and ERBS data and the corresponding average ratios to ACRIM-II. The result is shown in Figure 8. Note, that this result depends on the corrections applied to HF and ACRIM-I and II. The correction of ACRIM-II changed by only about 30 ppm with the new HF compared to the one used by Fröhlich (2000).

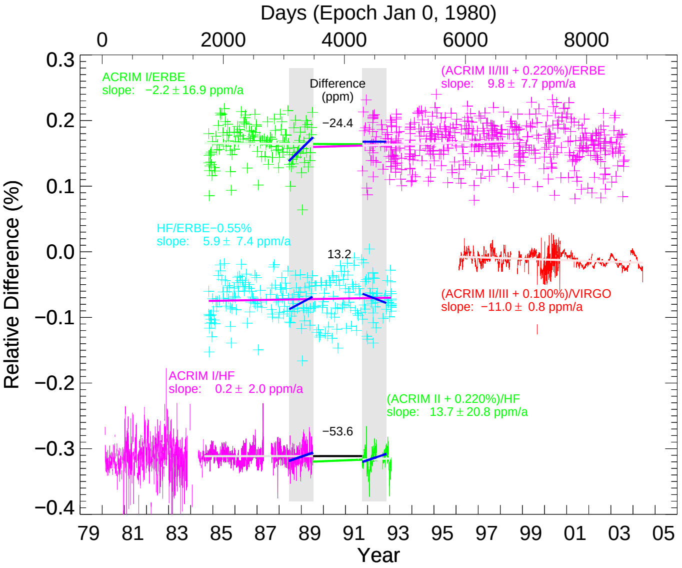

Figure 8. This plot illustrates the tracing of ACRIM-II to ACRIM-I. The change of the ACRIM-II level is determined by a weighted average of the comparison of ACRIM-I and II with HF and ERBS during the periods indicated by shading.

Having done this scaling the rest is straight-forward and consists in adjusting the HF and VIRGO measurements to the ACRIMs leaving them at their respective levels. For practical reasons the result is then scaled to SARR (Crommelynck

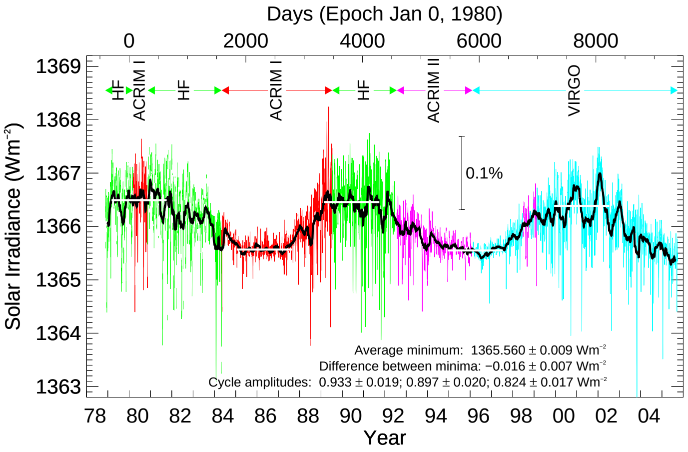

Figure 9. Shown is the final version of the PMOD composite. Compared to the earlier versions the maximum of cycle 21 is at about the level as before, but has less noise, especially in the early part. This may indicate that the early HF corrections have indeed been improved. Finally, the difference between the minima has also not changed. The dates of the maxima are 26/03/1979 – 25/12/1981, 28/04/1989 – 21/02/1992 and 19/01/2000 – 18/02/2003 and of the minima 13/04/1985 – 07/06/1987 and 05/05/1995 – 02/08/1997.

et al., 1995) and is shown in Figure 9. The differences to the earlier versions have been shown in the Figures 4 and 7 and lie more in the details than in the overall behaviour. Thus the final result does not change the trend or the amplitudes significantly. Overall it is a more reliable time series mainly due to the fact that the corrections of the different records are based on the same type of model.

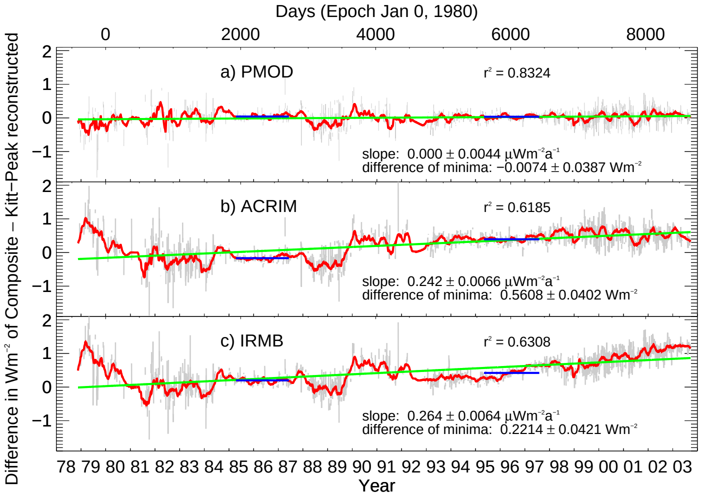

Figure 10. The comparison of the three composites with a reconstruction of TSI from Kitt-Peak magnetograms by Wenzler (2005)

In Figure 10 the PMOD, ACRIM (Willson and Mordvinov, 2003) and IRMB (Dewitte et al., 2004) composites are compared to a reconstruction of TSI from Kitt-Peak magnetograms by Wenzler (2005). These reconstructions are based on the identification of sunspot (umbra, penumbra and pores) pixels from white light images and of quiet, network and facular pixels from the magnetograms (see e.g. Wenzler et al., 2005). Together with a contrast from e.g. Fligge et al. (2000) the radiance of each pixel is determined and summed up to yield the irradiance. For the bright pixels a filling factor is defined which depends linearly on the magnetic field in the pixel up to a saturation field after which it is set to one. This saturation field is the only free parameter in the reconstruction which is determined by calibration against the PMOD composite as 340 G for the Kitt-Peak magnetograms (Wenzler, 2005). The best agreement is with the PMOD composite explaining 83% of the variance, an unexpectedly high correlation for the rather simple assumptions on which the reconstruction is based. For the ACRIM and IRMB composites this reconstruction explains only 62 and 63% of the variance. For the former the low value is mainly due to the difference between the two minima due to the neglect of the HF corrections during the ACRIM gap. For the latter the main reason is that the IRMB evaluation of DIARAD does neglect the non-exposure dependent changes, which explains also the difference between the minima due to the increase from the beginning of the measurements in early 1996. Furthermore, the low correlation of both composites is also due to the missing correction of HF for degradation during the maximum of cycle 21 and the noise due to the uncorrected glitches during the

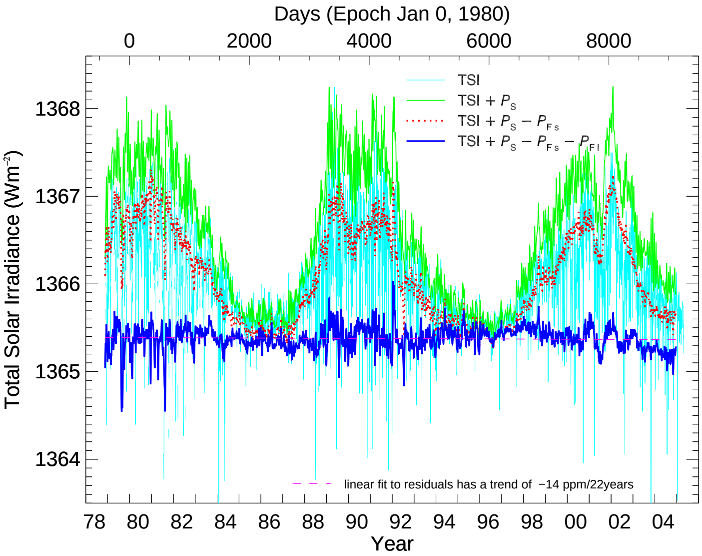

Figure 11. The comparison of the PMOD composite with a 3-component model (PSI P_S, short- P_{Fs} and long-term MgII P_{Fl}). This model has been calibrated against the composite for each cycle separately which makes the overall trend of the residuals approximately zero.

ACRIM gap. There are also some differences – although much smaller – between the reconstruction and the PMOD composite, especially at the maxima of cycle 21 and 22 which are probably due to the noisier NSO-512 magnetograms, but could also be partly due to mistaken corrections applied to the TSI records for the PMOD composite.

4. Comparison with a 3-component proxy model

Multiple regression of a 3-component proxy model against TSI is used to 'calibrate' it and explains somewhat less than 80 % of the variance. This is slightly less than what the magnetogram based reconstruction is able to do. The three components of this proxy model are the photometric sunspot index as represented by PSI (P_S) and a short- and long-term MgII index ($P_\mathrm{Fs,Fl}$) as described in e.g. Fröhlich and Lean (2004). The corresponding coefficients are determined by multiple regression with TSI. This can be done over the full period or for each cycle separately. The results of the latter method are shown in Figures 11 and 12. The coefficients for the short and long-term MgII ($P_\mathrm{Fs,Fl}$) vary at most by ±10% between the cycles which may not be significant in terms of representativeness of the model. It is interesting to note that P_Fs is lowest for cycle 21, whereas P_Fl is highest. The opposite situation is found for cycle 23. The highest coefficients for $P_\mathrm{Fs,Fl}$ are observed for cycle 22. The residuals show a rather strong downward trend during cycle 23. This deviation

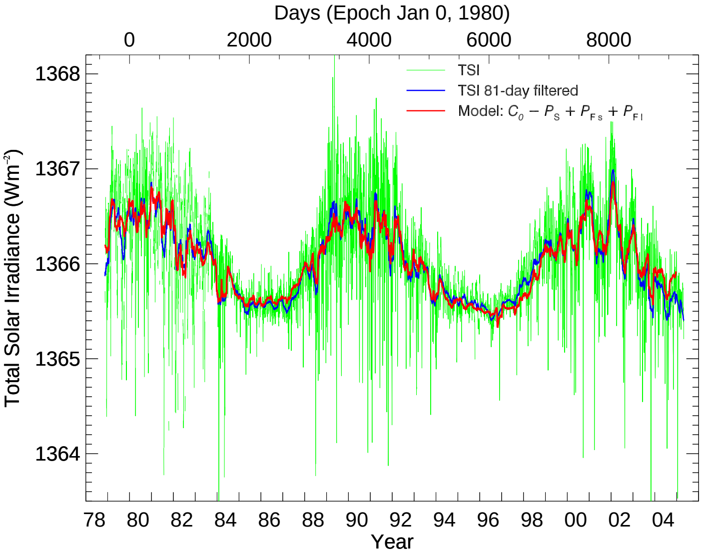

Figure 12. Shown is the comparison of the proxy model with the PMOD composite. Although some discrepancies are obvious, the overall fit is quite impressive. Note the rather large deviation at the end of the time series which may be related to a possible influence of sunspots on the MgII index (see text).

could also be due to the MgII index having some still uncorrected degradation. Another explanation may be some influence of sunspots on MgII index which confuse the facular part and should be removed. This may be indicated by the trend of the ratio of the MgII index to the 10.7cm radio flux as indicated by Figure 6 of Viereck et al. (2004). Also the rather large deviations during the maxima of cycle 22 and 23 could be for the same reason. The overestimation of TSI by the proxy model towards the end of descending part of cycle 23 may also be related to such an effect, when the measurements show already values as low as those observed during the last minima and the model is still higher.

5. Conclusions

The presented corrections are based on the improved understanding of the short and long-term changes of classical radiometers in space, and have substantially improved the reliability of the composite. Overall, the changes are small and do not change the earlier conclusions about a non-existing long-term trend or the amplitudes of the cycles. A detailed error analysis shows that the PMOD composite has a long-term uncertainty of less than about 90 ppm per decade (Fröhlich, 2004), which makes the observed difference between the minima not significantly different from zero. The close agreement with the reconstruction from Kitt-Peak magnetograms by Wenzler (2005), and with the 3-component proxy model supports the PMOD composite as the most reliable representation of the solar irradiance variability for the last 25 years.

The PMOD composite is available from `http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant`, the ACRIM and IRMB composites from `http://www.acrim.com/Data\%20Products.htm` and `http://remotesensing.oma.be/solarconstant/sarr/SARR.txt` respectively.

Acknowledgements

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Address for Offprints: Claus Fröhlich, Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, CH-7260 Davos Dorf, Switzerland, cfrohlich@pmodwrc.ch