Total Solar Irradiance from VIRGO Radiometry, an Update to Version 6.4

Claus Fröhlich
VIRGO Team, CH-7265 Davos Wolfgang Switzerland

Introduction

This poster is a summary of Fröhlich (2014) which is a working paper updated when ever new material becomes available. At present this new version of TSI is based on the level 1 data as available from the VDC. Especially the data of the PMO6V radiometer are still using the original procedure to produce level 1 data and thus show still the noise from inadequate interpolation of missing temperatures, such as the noise during the SOHO keyholes. Furthermore, the scale is still on the original WRR related value for PMO6V and on the original for DIARAD.

Corrections for the VIRGO PMO6V and DIARAD time series

For the analysis of the long-term behaviour of the radiometer an appropriate model is needed. It is based on the sunburn of quartz by dissociation of SiO_2 at the surface and described in detail in Fröhlich (2014). It depends on the dose during exposure for which the MgII index is used and on temperature. Moreover, it includes also a term for a possible recovery during non-exposure periods. The model used in the following analysis has a total of 6 coefficients.

The early behaviour of PMO6V is characterized by a rapid increase which is the result of a darkening of the illuminated part of the precision aperture, and hence a reduction of the reflected light into the baffle and an increase of a possible aperture heating. At first the explanation of this effect was difficult mainly because of its rather large value of about 500 ppm for PMO6V-A, 350 ppm for B, 590 ppm for ACRIM-I and about 1000 ppm for HF (Fröhlich, 2006). So, the scattered light from the precision aperture into the baffle and back to the receiver could be an explanation, the amount of which obviously changes with the reflectivity of the precision aperture. This effect was also suspected to explain the large difference in absolute values of about 0.3 % between the classical radiometers HF, ACRIM, PMO6V and DIARAD and TIM on SORCE. However, the corresponding correction was measured by Brusa and Fröhlich (1986) with a laser illuminating the precision aperture and measuring the radiation scattered back through the aperture with a Silicon detector; the result was of the order of 350–500 ppm - no way to explain a 0.3 % influence. With a reflectivity of about 60% the baffle receives about 40 mW which is mostly absorbed. Hence, the infrared radiation from the heated baffle could certainly be important and can possibly explain the effect. Comparison at TRF of spare radiometers of PMO6V and ACRIM with a cryogenic radiometer have shown that, indeed, the amount of scattered and infrared radiation from the baffle is large enough to explain the scale difference (e.g. Kopp et al., 2012). It is interesting, that DIARAD does not show an early increase and the recent TRF comparison confirm also that it has no effect of 'scattered' radiation. The fact that DIARAD has a curved precision aperture which focuses the radiation falling on it back into the view-limiting aperture and thus out of the radiometer, explains its nonsensitivity to 'scattered' radiation. The scale correction for DIARAD has a completely different reason due to the substantial difference in area covered by the electrical heater and the irradiance.

The level-1 VIRGO data are corrected for all known effects, such as electrical calibration, temperature, instrument-sun distance and radial velocity. The normal practice to correct level-1 data (Fig. 1) for degradation and other changes in space is based on the comparison of the measurements from the operational radiometers with those of the less exposed ones, the back-ups. For DIARAD this procedure is straightforward because the backup is exposed very little during the mission (about 10 days during the now 18 years in space) and can be assumed as having no degradation. The correction depends, however, on how the ratio DIARAD-R/L is determined. The present evaluation is directly based on the DIARAD level 1 files from the VDC (VIRGO Data Center at Tenerife, operated by the IAC). As the left and right channels of DIARAD cannot be operated at the same time, the algorithm calculates the ratio (or difference) from the linearly interpolated DIARAD-L values during that day and the average of DIARAD-R, shown as 'new R/L and 'new R/L outliers on Fig. 2. For the PMO6V radiometers this procedure is complicated by the fact that the shutters of both radiometers could no longer operated after about 70 days in space and had to be replaced by opening and closing the covers at 8-hour intervals (see e.g. Fröhlich et al., 1997). At the beginning of this new operational mode PMO6V-B was quite frequently exposed and thus these measurements need to be corrected for the early increase before they can be used to correct PMO6V-A. From mission days 83-218 the cover was normally closed and opened every 8 hours for 30 minutes, up to the SoHO vacation every 7 days and afterwards every 10 days.

For version 6.4 a new algorithm has be developed for the interpolation between the rarely measured back-up data. It is based on splines (in IDL use the functions `spl_init` and `spl_interp`) which yields values for the final corrections of L or A which now show also some variations related to temperature because they are less smoothed. For DIARAD the result is shown on Fig. 2 as 'new from R/L. DIARAD has also some changes related to the switch-off of the experiment during the mission, which extended for 2 to 3 days six times during the 18-year operation due to Emergency Sun Re-acquisition (ECR) of SoHO and once due to a latch-up-induced switch-off of the VIRGO power supply. After the event in September 1996 it became clear that DIARAD showed a slow recovery after the experiment was switched on again and a similar recovery was also identified after the SoHO vacations. The later events, however, were no longer as clear as the ones before. Both the corrections for versions up to 6.002 and for 6.004 are shown in Fig. 2 as 'old' and 'new switch-off'. With all these corrections the DIARAD level 1.8 values can be determined. In the course of the mission it became clear that the DIARAD must have also a non-exposure-dependent change of its sensitivity, both from comparison with PMO6V and other radiometers in space, and it was likely that this change can be modeled by an exponential. In the present version the difference between the level 1.8 DIARAD and the level 1 PMO6V-B is fitted to the model for the early-increase for PMO6V-B and to an exponential for DIARAD. The coefficients for PMO6V-B are then used to correct it and by comparison with ACRIM the change over the SoHO vacations is determined. The procedure and the results are shown in Fig. 3 and it is quite interesting that PMO6V-B does not show any significant change over the SoHO interruption. These changes may have the same reason as the long-term sensitivity change, namely a change of the thermal contact of the cavity and the heat-flux meter (probably due to exposure to the space environment), and hence a change in the non-equivalence due to the difference in area covered by electrical substitution heater which is larger than the irradiated area by a factor of about 2.5. Normally these two area are the same size and coincident by design and hence, there is no influence of a change of the thermal resistance for 'normal' radiometers. With the coefficients of the exponential the final DIARAD level 2 values can now also be determined.

Before we can determine the level 2 PMO6V-A we need to correct the A values at the beginning for the early increase. For this early increase correction we need TSI values to compare with. As DIARAD starts at mission day 68 only, we expand these data with the proxy model back to mission day 48. For fitting the model a further parameter is added, representing the typical degradation of 2 ppm/day. The result is shown in Fig. 4. With the level 2 PMO-B series the corrections for PMO-A over the whole mission can be determined and interpolated by the method of splines to the hourly values as shown in Fig. 5 and the change over the SoHO interruption is determined by comparison with ACRIM (top plot). Again, the PMO-A has not changed significantly during SOHO vacations as PMO-B.

VIRGO TSI is defined as the average of the PMO6V and DIARAD values and is determined by weighting. The weights are deduced from the difference of the variances, the standard deviation squared, of PMO6V minus the one of DIARAD, each determined from a 81-day-running period and shown by the green line on the top panel of Fig. 6, again smoothed with a 131-day boxcar. It is normalized in such a way that the absolute maximum is set to 0.5 and a positive difference means that the noise of PMO6V is higher and its weight correspondingly lower and a negative one that the noise of DIARAD is higher. So, the derived weights 0 . . . 1 are shown as red and blue dashed lines (on the left hand scale). DIARAD has in general less noise than PMO6V with e.g. the spikes during the keyholes due to the fact that still the original level 0-to-1 algorithm. For the moment, it seemed, however, more important to have an internally consistent way to produce level 2 data, than improving on the noise of PMO6V.

As far as the absolute value is concerned VIRGO TSI is still on its original scale, because the detailed analysis of the absolute scale of PMO6V and DIARAD data is not yet completed, but new values will be available soon. Besides the absolute value, the major results can be summarized as follows:

- Relative to TIM VIRGO TSI has a downward trend of 13.1 ± 1.9 ppm/a which would yield a difference of about 150 ppm over a solar cycle.
- Relative to ACRIM 3 VIRGO TSI has during the period of TIM an upward trend of 20.2 ± 1.9 ppm/a.
- VIRGO TSI has still the artefact during the keyholes of SOHO which are coming from the PMO6V data due to some inadequate temperature interpolation of missing values in the present level 0-to-1 evaluation. In general the PMO6V values have less medium- to long-term deviations relative to TIM than DIARAD, but the noise of PMO6V is higher. This is already seen in the comparison of DIARAD with PMO-B (see Fig. 3).

The new VIRGO TSI is certainly more reliable from a VIRGO-only point of view. No other time series are used besides ACRIM 2 to bridge the gap during the summer vacations of SOHO. However, we found that both PMO6V do not show a significant change - so *a posteriori* we could use this fact in the evaluation and leave out all the tests with ACRIM 2.

From the final result we can determine the change of PMO6V over the SOHO gap as 13.3 ± 27.6 ppm and for DIARAD as 288.7 ± 15.7 ppm. These results can be used to determine the 1-σ uncertainty as less than 30 ppm due to the SOHO gap. Together with the uncertainty of the slope to TIM over cycle 24 of $12 \times 1.9 = 23$ ppm (from Fig. 7), an estimate of the uncertainty of the difference between the last two minima in 1996 and 2008 by summing the two components amounts to 50 ppm or if we use the rms value to 35 ppm. This value is lower than the 92 ppm reported in Fröhlich (2009) and makes the change between the minima of now 124 ppm more significant. However, the present value is smaller than the one reported in (Fröhlich, 2011) of 168 ppm for version 6_002_1110).

Acknowledgements

I would like to thank W Finsterle and A. Fehlmann for many helpful discussions. Thanks are extended to the VIRGO and SOHO teams, without their continuous efforts this work would never have been possible. SOHO is a cooperative mission of ESA and NASA, launched on 2nd December 1995, more than 18 years ago - and is still going strong.

References

R. W. Brusa and C. Fröhlich. Absolute radiometers (PMO6) and their experimental characterization. Appl. Opt., 25: 4173–4180, 1986. doi: {10.1364/AO.25.004173}.

C. Fröhlich. Solar irradiance variability since 1978: Revision of the PMOD composite during solar cycle 21. Space Sci. Rev., 125:53–65, 2006. doi: 10.1007/s11214-006-9046-5.

C. Fröhlich. Evidence of a long-term trend in total solar irradiance. A&A, 501:L27–L30, 2009. doi: {10.1051/0004-6361/200912318}.

C. Fröhlich, D. Crommelynck, C. Wehrli, M. Anklin, S. Dewitte, A. Fichot, W. Finsterle, A. Jiménez, A. Chevalier, and H. J. Roth. In-flight performances of VIRGO solar irradiance instruments on SOHO. Sol. Phys., 175:267–286, 1997. doi: {10.1023/A:1004929108864}.

Claus Fröhlich. Total solar irradiance observations. *Surveys in Geophysics*, 33:453–473, 2011. doi: 10.1007/s10712-011-9168-5.

Claus Fröhlich. Degradation of radimeters in space: Application to VIRGO TASI and SSI. Technical report, VIRGO Team, CH-7265 Davos Wolfgang, Switzerland, 2014. This is a working paper and the present version is available from `ftp://ftp.pmodwrc.ch/pub/Claus/VIRGO-TSI/VIRGO_TSI_6004.pdf`.

G. Kopp, A. Fehlmann, W. Finsterle, D. Harber, K. Heuerman, and R. Willson. Total solar irradiance data record accuracy and consistency improvements. *Metrologia*, 49: 29, 2012. doi: 10.1088/0026-1394/49/2/S29.

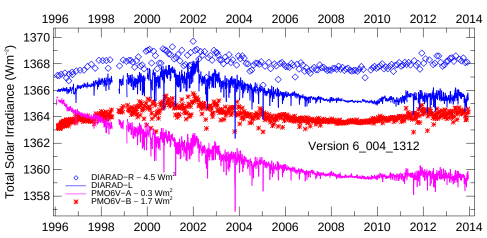

Figure 1: *Measurements (Level 1) of the two operational radiometers, PMO6V-A and DIARAD-L and their back-ups, PMO6V-B and DIARAD-R.*

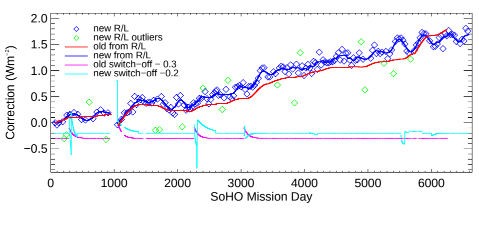

Figure 2: *Corrections of DIARAD-L from comparision with DIARAD-R for degradation and with PMO6V-A for switch-offs for both versions, the 'old' 6.002 and the 'new' 6.004.*

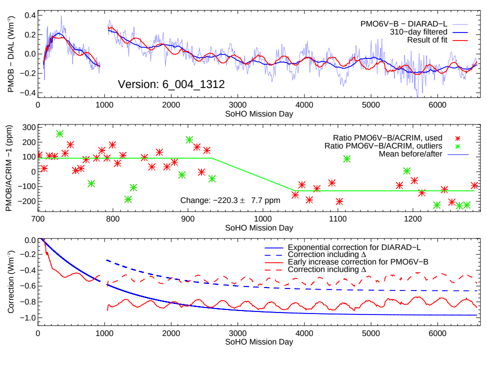

Figure 3: *The top panel shows the difference between PMO6V-B and DIARAD level-1.8 used to fit the early increase and the exponential model. The middle panel shows the comparison of the corrected PMO6V-B with ACRIM-II to determine the change over the SoHO vacations, and the bottom panel the corrected data as dashed lines.*

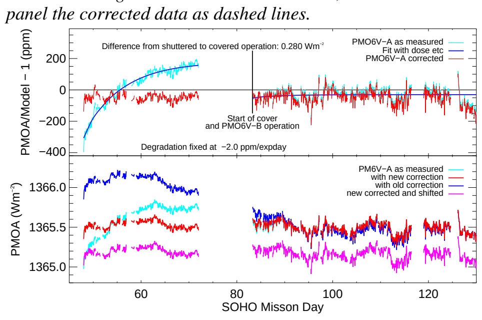

Figure 4: *Top panel: Ratio of the irradiance of PMO6V-A to a combination of the proxy model and DIARAD. The change of absolute values due to change from shuttered to covered operation of -0.280 Wm^{-2} is also determined. Bottom panel: Corrected PMO6V-A values 'with new corrections' compared to the former ones as 'with old corrections'.*

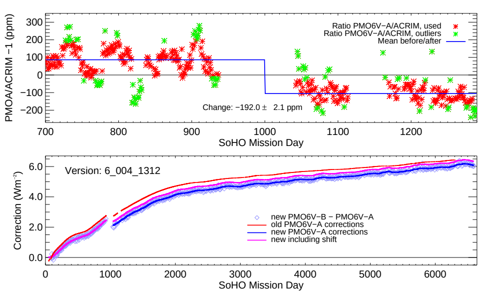

Figure 5: *The bottom panel shows the corrections for both versions, the 'old' 6.002 and the 'new' 6.004 of PMO-A from comparison with the corrected PMO-B and the top panel the comparison with ACRIM for the determination of the change over the gap.*

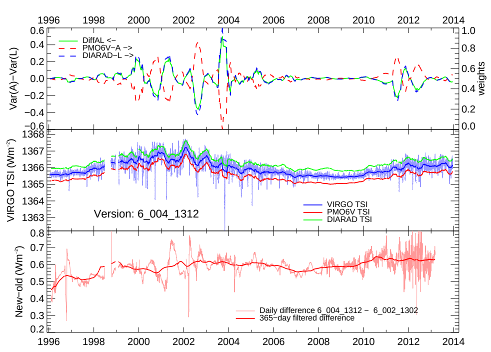

Figure 6: *The top panel shows the variance of DIA-L and PMO-A as used to weight each for the average VIRGO value. The middle panel shows the three final time series and the bottom panel the difference between the new version 6_004 and the old one 6_002.*

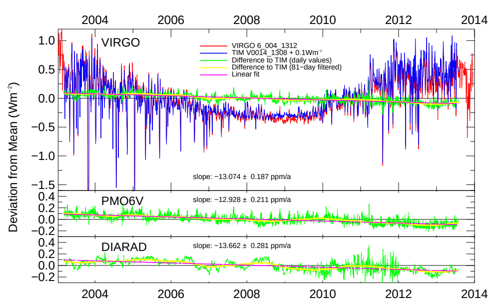

Figure 7: *The top panel shows the time series of VIRGO and TIM and their difference and the bottom panels the difference to PMO6V and DIARAD respectively. DIARAD shows less short-term noise than PMO6V, on the other hand PMO6V has less longer term deviations relative to TIM.*

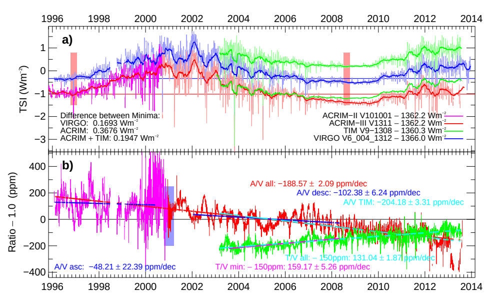

Figure 8: *VIRGO TSI is compared to ACRIM and TIM. The ACRIM values are on the scale of ACRIM 3 (version 1311). It is interesting to note that the slope relative to ACRIM for the whole period and for the TIM period only are very similar, although the ACRIM time series is composed of ACRIM 2 and 3.*