# TOTAL SOLAR IRRADIANCE FROM VIRGO ON SOHO

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## ABSTRACT

The long-term changes of the VIRGO radiometers on SoHO have been re-analyzed in detail. The exposure dependent changes can be described for both type of radiometers by a combination of an increase of the sensitivity and a degradation with time which depends on the dose of radiation from the sun. Also an exposure independent increase of the sensitivity has been detected which explains the early increase of the VIRGO $TSI$ which was since the beginning of the measurements a unresolved puzzle.

Key words: Total Solar Irradiance; Solar Radiometry; SoHO/VIRGO.

## 1. INTRODUCTION

The early increase of the VIRGO total solar irradiance ($TSI$) shortly after the minimum in 1996 was until recently an unresolved issue (Fröhlich & Lean 1998; Fröhlich 2000). Although this increase was incompatible with the empirical models based on the influence of sunspots, faculae and the network, the former being represented by the photometric sunspot index ($PSI$, see e.g Fröhlich et al. (1994)) and the later by the MgII index, the core-to-wing ratio of the MgII line (see e.g. Chandra et al. (1995)), there was no obvious reason not to believe the corrections for the long-term behavior of the VIRGO radiometry as proposed by Fröhlich et al. (1997); Anklin et al. (1999); Fröhlich & Anklin (2000). The corrections for the operational radiometers PMO6V-A and DIARAD-L were based on the assumption that changes depend only on the time exposed to solar radiation and thus can be determined by comparing the operational radiometers with the rarely exposed radiometers PMO6V-B and DIARAD-L. Moreover, the DIARAD-R was assumed to be constant, mainly because the DIARAD type radiometers showed much less degradation than the PMO6V radiometers. This was a first surprise of SoHO as during e.g. the EURECA mission both types showed a very similar degradation of roughly 1 part-per-million (ppm) per day similar to what other radiometers in space such as ACRIM show. As this increase was definitively not present in the empirical models the obvious conclusion was, that the sun seemed behaving differently than during the minima and early increase towards the maxima before. With increasing solar activity the irradiance achieved levels of the preceding activity maxima well before the maximum was reached. Both, the early increase and the high level before the maximum could obviously be explained by a steady increase of the sensitivity with time of the VIRGO radiometers. A simple linear upward trend of about 1 mWm$^{-2}$d$^{-1}$ up to the time of the SoHO vacations would in a first approach remove most of the problem. An obvious question, however, is what could be the physical reason for this behaviour and why have other radiometers of similar type in space not shown such a behaviour. Definitively the environment on SoHO is extraordinary stable and it was definitively the cleanliest spacecraft ever launched. The cleanliness, however, should not influence the radiometry too much, as cavities are used and exposure dependent changes – although very small – carefully monitored. The high stability of the thermal environment, however, could well result in a yet unobserved behaviour of the radiometers. The principle of these radiometer is based on thermal flux measurements and thus is inherently influenced by changes in the thermal environment at the level of a few parts-per-million.

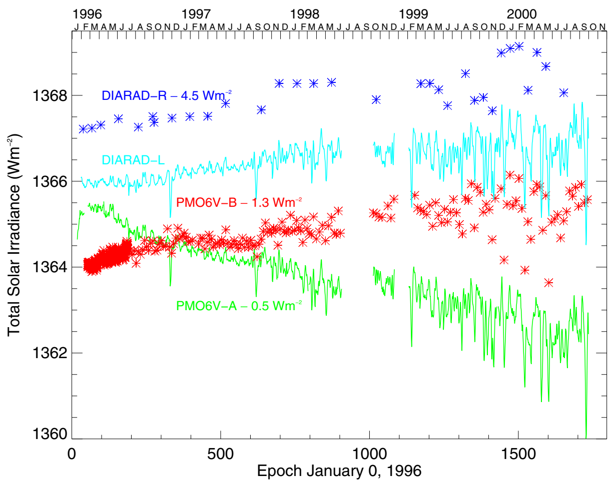


*Figure 1.* Time-series of the level-1 observations from the VIRGO radiometers PMO6V and DIARAD.

In the following we will describe the investigation of the

VIRGO radiometry which leads to an internally consistent picture of the behaviour although the details of the physical mechanisms are still to be understood. For a description of the principle of electrically calibrated radiometers and more specifically of the VIRGO radiometers we refer to Fröhlich et al. (1995).

## 2. EXPOSURE DEPENDENT CHANGES

We start with a description of the exposure dependent changes as they can be deduced from comparison of the radiometers with different exposures to the sun. Figure 1 shows the level 1 data as obtained after reducing the raw data to physical units and by applying all *a-priori* known instrumental effects such as electrical calibration and corrections for the thermal environment and operational corrections for distance and velocity to the sun. These data show a combination of the sun's irradiance variation and instrumental changes. It is also obvious that the two back-up instruments show more likely the irradiance changes whereas the operational ones are more influenced by instrumental behaviour. Already at this stage of evaluation the different long-term behaviour of PMO6V and DIARAD is very obvious, with the latter showing a much smaller difference between the operational and its back-up than the former. Also prominent is the early increase of the PMO6V radiometers during the first few days of exposure. This early increase by about 500 ppm must be an increase in the absorptivity of the black paint in the cavity. However, with a measured reflectivity of the cavity of some 300 ppm still another effect needs to amplify the observed increase. This is most probably related to a decrease of the non-equivalence between electrical and radiative heating. This is due to the radiation reflected onto the side wall of the cavity, from where a certain amount is lost to the environment and not measured by the heat-flux-sensor. Thus radiative heating of the cavity is less efficient than electrical heating, which is called non-equivalence. It is obvious that a decrease of the reflectivity of the paint leads to a proportional decrease in the non-equivalence (less radiation is falling on the side-wall). Assuming a change in reflectivity of the paint by a factor of 2 (e.g. from 0.06 to 0.03) the reflectivity will decrease by 150 ppm; in order to explain the full 500 ppm change the non-equivalence has to decrease by a factor of 2 also, yielding a value of the initial non-equivalence in space of about 700 ppm ($2\times[500-150]$) for the PMO6V radiometers. This value would correspond to a thermal conductivity of something like 4-5 $\mathrm{Wm^{-2}K^{-1}}$ if we believe the model calculations for the explanation of the behaviour of the PMO6 radiometers in air where we observe a non-equivalence of 3000 ppm and calculate a conductivity of ≈20 $\mathrm{Wm^{-2}K^{-1}}$ (Fröhlich 1988). Thus the loss of the side-wall would need to have an emissivity $\varepsilon \approx 0.7$ if the energy is transported by radiation only. This is much higher than $\varepsilon \approx 0.1$ which is expected for the actual side wall of the cavity which is gold plated outside and the black inside has a view-factor through the entrance aperture of the cavity of about 7%. Although the amount of the effect lacks a reasonable explanation it is observed not only for the PMO6V radiometers on SoHO, but also for HF on NIMBUS7 (Fröhlich & Lean 1998; Fröhlich 2000) and possibly also for ACRIM-II on UARS which all use the same paint.

To account for changes of the paint we assume a hyperbolic behaviour as function of exposure time. This choice

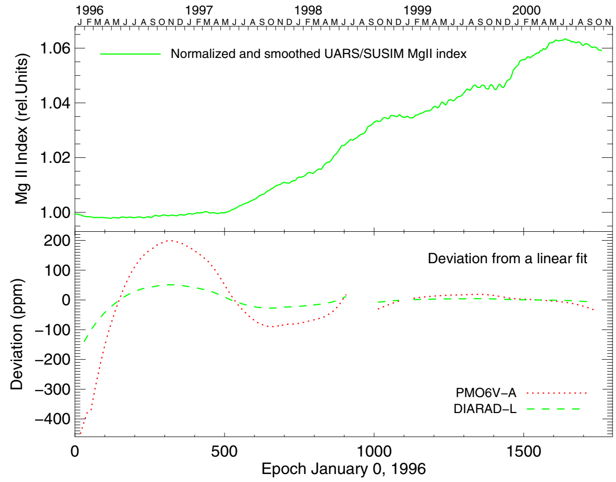


*Figure 2.* Top panel shows the MgII Index as used for determining the dose and the lower panel shows the result of the analysis of the ratio of the operational and back-up instruments.

is a result of the solution of the differential equation governing a change of the surface properties which in turn reduces the influence of the radiation as a function of the exposure time $t_{\mathrm{exp}}$. The increase $i(t_{\mathrm{exp}})$ due to a change in the paint's absorptivity is described by

$$i(t_{\mathrm{exp}}) = a\left(\left(1+\frac{t_{\mathrm{exp}}}{\tau}\right)^{-b}-1\right). \qquad (1)$$

This function is normalized to zero at $t_{\mathrm{exp}}=0$. The decrease in sensitivity with exposure time $d(t_{\mathrm{exp}})$, normally termed as degradation, is assumed to be a decreasing linear function with time which is modulated by the dose of the received radiation weighted with a hyperbolic function in time. For the dose the MgII index from the SUSIM experiment on UARS is used as proxy and the change in sensitivity is described by

$$d(t_{\mathrm{exp}}) = a\int_0^t (MgII-o)\left(\left(1+\frac{t_{\mathrm{exp}}}{\tau}\right)^{-b}-1\right)dt + ct_{\mathrm{exp}}, \qquad (2)$$

with $o$ an offset determining the initial contribution to the slope and $c$ the slope of the linear function; again this function is normalized to zero at $t_{\mathrm{exp}}=0$. For the period before and after the SoHO vacations a reduction factor is introduced to reflect possible changes in the behaviour of the cavities. Also the slope of the linear function is reduced accordingly which could mean that an exponential function would probably better represent the long-term behaviour. But, because of the gap during the SoHO vacations it is difficult to follow the changes

*Table 1. Summary of the parameters determined for the long-term changes of the VIRGO radiometers*

| | Exposure dependent Corrections | | | | | | | | Exposure independent Corrections | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | increase | | | decrease | | | | | | | | |
| | $a$ | $\tau$ | $b$ | $o$ | $a$ | $\tau$ | $b$ | $c$ | $a$ | $\tau$ | $a_{\mathrm{after}}$ | offset |
| | $\mathrm{Wm}^{-2}$ | d | - | - | $\mathrm{Wm}^{-2}$ | d | - | $\mathrm{mWm}^{-2}\mathrm{d}^{-1}$ | $\mathrm{Wm}^{-2}$ | d | - | ppm |
| PMO6V | 1.40 | 22.22 | 1.2 | 0.9879 | 1.72 | 885 | 2.5 | 6.21 | 0.693 | 147.0 | 0.00087 | 0 |
| DIARAD | 1.27 | 54.64 | 0.3 | 0.9882 | 1.01 | 440 | 2.5 | 4.12 | 0.843 | 430.8 | 0.0956 | 275.7 |

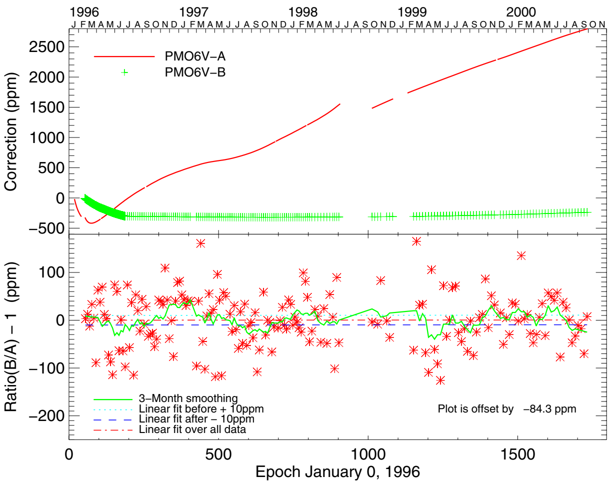


*Figure 3.* Corrections for PMO6V-A abd B (top panel) and the resulting ratio with the final corrections applied.

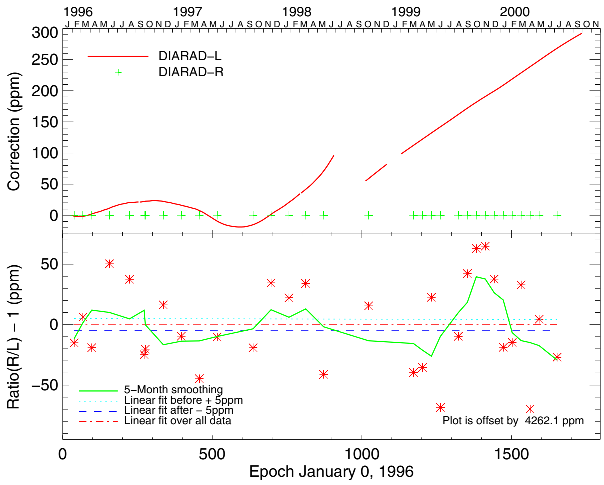


*Figure 4.* Corrections for DIARAD-L and R (top panel) and the resulting ratio with the final corrections applied.

accurately. The parameters of these functions are determined for each type of radiometer assuming the same influence on each as a function of their exposure time. In the case of DIARAD-R the total exposure time is not even a day up to now (September 2000) and thus this instrument is assumed to have no exposure dependent change. For PMO6V-B, the exposure time was early in the mission quite important, and reached about 10 days when the cadence was changed from once every 8 hours to about once a week (around May 1996). The parameters are varied in such a way that the standard deviation from a linear fit to the ratio of the back-up to the operational radiometer readings is minimized. The constant $c$ is used to adjust the slope to zero. The result for the dose dependent corrections are shown as deviations from a linear trend in Fig. 2. The final values of the parameters as are listed in Table 1 for the two radiometer types. The ratios of the operational and back-up instruments with the final parameters are shown in Fig. 3 and 4. It is important to note that the dose dependent degradation was essential to achieve this low variation around the straight line (more than a factor of two lower than without). With a final precision of a few tens of ppm this demonstrates also how well it seems to describe the observed degradation. In the case of the DIARAD-L the corrections are such that the degradation at the beginning is masked by an increase in sensitivity as for the PMO6V radiometers, but with a much longer time constant. In parallel with this increase in absolute sensitivity an increase of the relative sensitivity to short-term variations by more than 30% is observed (see below). This was first observed during the passage of an active region without a sunspot in May 1996 as a difference in amplitude between DIARAD-L and PMO6V-A.

## 3. EXPOSURE INDEPENDENT CHANGES

The comparison of the time series of PMO6V-A and DIARAD-L corrected for the exposure dependent changes shows a trend which has to be exposure independent. Obviously, such a trend could never be determined from only one type of radiometer. As stated in the introduction the question is whether this effect can only be observed in a quiet thermal environment like on SoHO and has thus so far never been detected. As a model for this increase in sensitivity we propose an exponential function with a time constant $\tau$ and amplitude $a$; after the SoHO vacations the amplitude is multiplied by $a_{\mathrm{after}}$ which corresponds to a shift in time of the exponential function by $\tau \log a_{\mathrm{after}}$. Again we minimize the standard deviation from a regression line to the ratio PMO6V-A/DIARAD-L, first by varying the parameters $a$ and $\tau$ for the PMO6V-A. In a second step we minimize $\tau$ of DIARAD-L and then adjust its $a$ coefficient so that the slope becomes zero. This is done iteratively and the procedure converges to well defined parameters which are listed in Table 1 and shown in Fig. 5. Before the SoHO vacations the situation is straight forward and it converges towards a unique solution, mainly due to the fact that the time constants of the two radiometers are (fortunately) quite different. After the SoHo vacations the fit is done only for the period up to day 1430 when a change in the behaviour is observed (see

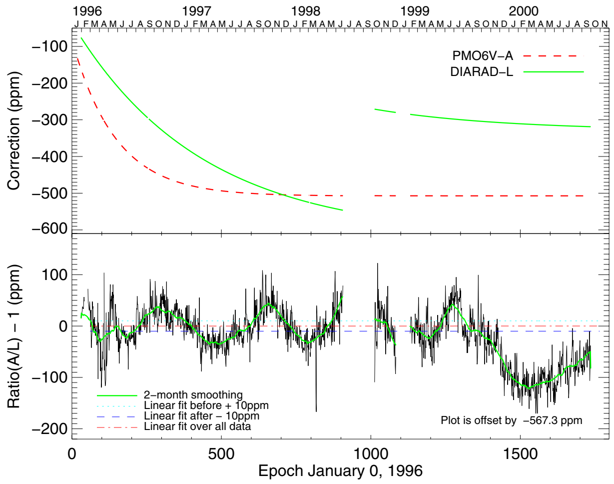


*Figure 5.* Corrections for the exposure independent behaviour of PMO6V-A and DIARAD-L (top pasnel) and the corrected ratio (lower panel).

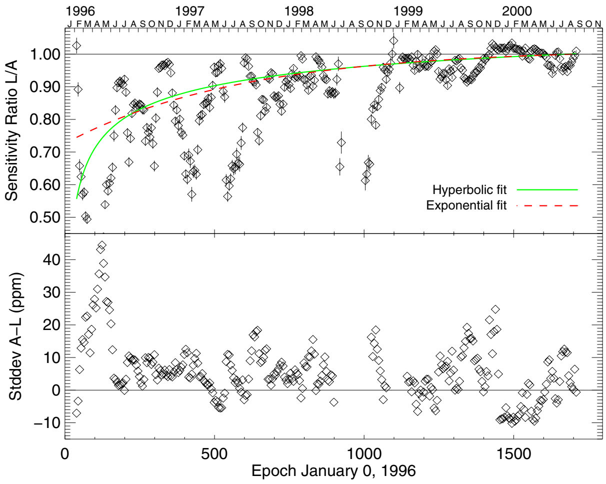


*Figure 6.* DIARAD sensitivity change as determined by comparing the variability around the mean value with the one of PMO6V-A (top panel). The lower panel shows the difference in standard deviation for the same periods as the sensitivity determinations. The parameters are determined from means over 41 days, shifted by 10 days.

below). The minimization works much better than for the full series and the result is quite interesting, as it indicates no change in behaviour after the gap, and the determined $a_{\mathrm{after}}$ indicate that the curves just continue from before. It is assumed that the effect starts with the switch-on of the instrument and is due to the slightly higher temperature of the cavity relative to the surroundings. Whether the effect was discontinued over the gap and conforms to the assumption cannot be decided because the effect is already quite small (10% in the case of DIARAD and less than 1% for PMO6V) and its detection marginal. The reason for the effect may again be a change of the non-equivalence through a change in e.g. the emissivity of the side-walls of the cavities (inside and outside). But, as for the early increase, the observed change of 500-600 ppm is larger than what could be expected. For DIARAD-L – and possibly also for PMO6V-A with a smaller amplitude – we need still another effect as it shows a kind of fall-back to a less sensitive mode when it is switched off. After the accidental switch-off of VIRGO in September 1996 this effect is well documented for DIARAD as it starts after switch-on with a sensitivity which is lower by about 200 ppm after the 3-day switch-off. After the SoHO vacations a value of 276 ppm is determined from the ratio to PMO6V-A by assuming that the change is due to DIARAD alone. This sounds reasonable as the Sun has increased during the SoHO vacations and the data from DIARAD are more or less constant over the gap (see Fig. 1). The 1996 event is presently corrected as suggested by the DIARAD team by shifting the data from just after the switch-on until 37 days later by 110 ppm upward, although we would prefer a correction which is consistent with both the events in September 1996 and after the SoHO vacations. As mentioned above there is a further problem encountered after mission day 1430 when the ratio of PMO6V-A/DIARAD-L changes; this coincides with the time when the MgII index increased abruptly (see Fig. 2). Also in Fig. 6 it is obvious that something happened around day 1430. This needs further investigation, and probably some irradiation tests of the black paint used in DIARAD, which has no heritage in long-term space radiometry other than on EURECA.

Another interesting observation is the modulation of the ratio with a period of about an year. In the ratio only the difference between the sensitivities of the two instruments is observed. However, the signal in the VIRGO irradiance is of similar magnitude; hence the fact that this signal vanishes after day 1430 may indicate that finally DIARAD has reached a sensitivity similar to the one of PMO6V. All this means that the precision and the sensitivity to the ‘‘main” part of the irradiance signal is accurate to only about 0.01% whereas changes of the short-term sensitivity up to that level are still possible. A similar effect was observed by comparison of HF and ACRIM-I during the solar minimum 1985.

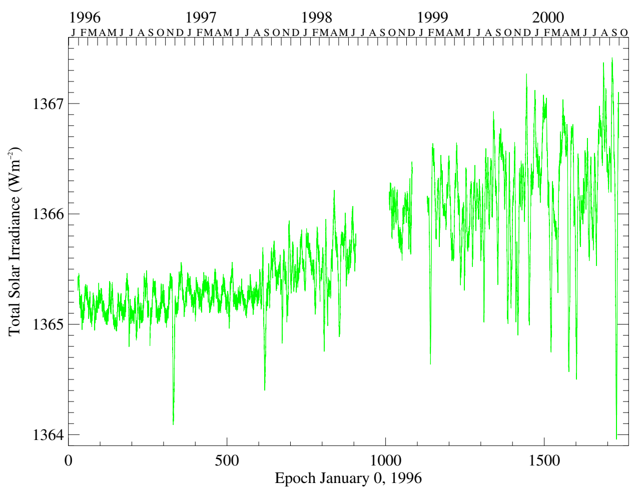


*Figure 7.* Time-series of the VIRGO $TSI$ from February 1996 until September 2000.

## 4. VIRGO $TSI$ AND COMPOSITE UPDATE

From this analysis a new version (3.50) of the VIRGO $TSI$ can be constructed. The VIRGO irradiance is a composite of the results from the corrected data of DIARAD-L and PMO6V-A. An average of the data from the two radiometers is not a good way to produce the best $TSI$. The short-term sensitivity change of the DIARAD has to be corrected first, which is possible from the determinations shown in Fig. 6, the exponential curve is used to rise the sensitivity to the same level as PMO6V. This is done until the SoHO vacations and no further corrections are applied afterwards yet. At the beginning of the

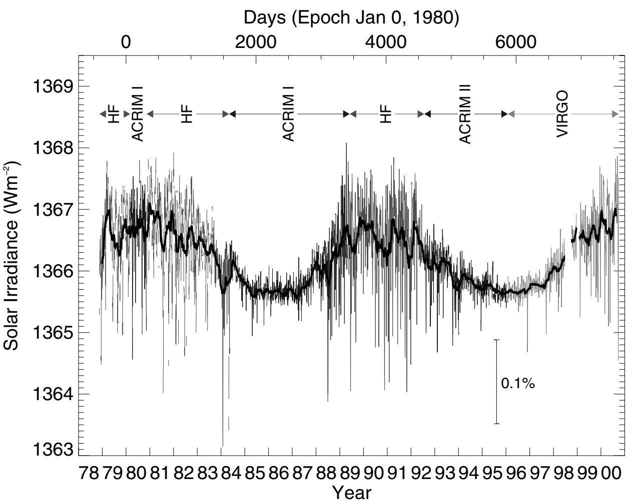


*Figure 8.* Composite $TSI$ updated with the VIRGO Version 3.50 data.

mission the PMO6V data are less reliable, partly due to the early increase which cannot be determined very accurately as PMO6V-B was only operative after the major increase of PMO6V-A was over, and partly due to the new type of operation which was needed after the failure of the shutters (Fröhlich et al. 1997). Thus, before mission day 195 the PMO6V data are discarded. During the periods when both radiometers are available the average of PMO6V-A and the short-term corrected DIARAD-L is used. If only one radiometer is available it is multiplied or divided by the average ratio from Fig. 5. For the data after day 1430 the average is taken, although the data are expected to change when the results of a more detailed investigations are available. Figure 7 shows the $TSI$ from February 1996 until September 2000 (Version 3.50); they are also available as daily and hourly values from `www.pmodwrc.ch` in files with an explaining header and three columns with the VIRGO, PMO6V and DIARAD level-2 values.

With the new VIRGO $TSI$ we have also updated the composite which is shown in Fig. 8 and is also available from the PMOD/WRC web server as version 19. This composite is now compared to the model calibrated over the full period of the composite as described in Fröhlich (1999). The result is shown in Fig. 9 and the onset into the new cycle 23 has no longer the pronounced difference due to the early increase of the VIRGO radiometry.

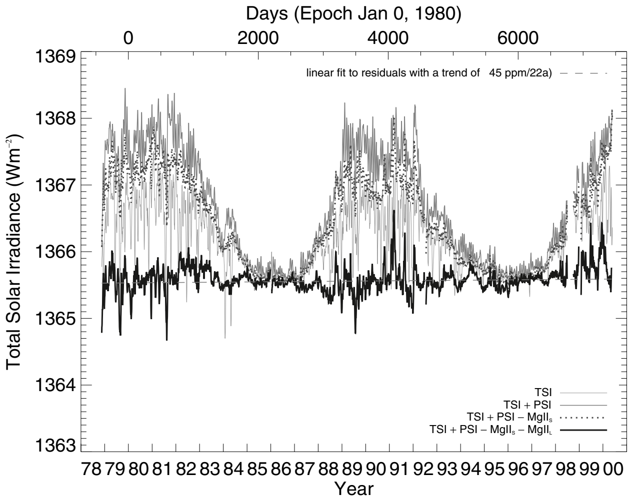


*Figure 9.* Comparison of the composite with the new VIRGO data with the model composed of $PSI$ and a long a short-term MgII index.

## 5. CONCLUSIONS

The detailed investigation of the behaviour of the VIRGO radiometers allows to determine the long-term changes in an internally consistent and unambiguous way. The most important message is that there are changes which cannot be determined by comparing differently exposed radiometers, because the effects do not dependent on exposure to the sun as detected for the VIRGO radiometers. It is quite possible that this exposure independent behaviour could only be detected in an environment as stable as the one on SoHO. Some of the yet unexplained fluctuations of other space radiometers may be due to such effects, but the substantial changes of the thermal environment do not allow to reach a steady state as on SoHO.

The comparison of the composite with the model shows now reasonable agreement for the increase of $TSI$ towards the maximum of cycle 23.

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