IN-FLIGHT PERFORMANCE OF THE VIRGO SOLAR IRRADIANCE INSTRUMENTS ON SOHO

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(Received 19 March 1997; accepted 12 June 1997)

Abstract. The in-flight performance of the total and spectral irradiance instruments within VIRGO (Variability of solar IRradiance and Gravity Oscillations) on the ESA/NASA Mission SOHO (SOlar and Heliospheric Observatory) is in most aspects better than expected. The behaviour during the first year of operation of the two types of radiometers and the sunphotometers together with a description of their data evaluation procedures is presented.

1. Introduction

The aim of the VIRGO investigation (Variability of solar IRradiance and Gravity Oscillations) on SOHO (SOlar and Heliospheric Observatory) is to determine the characteristics of acoustic and internal gravity oscillations by observing irradiance and radiance variations, to measure the solar total and spectral irradiance and to quantify their variability over periods of days to the duration of the mission. The irradiance part of VIRGO contains two different active-cavity radiometers – DIARAD (DIfferential Absolute RADiometer) and PMO6-V (V indicating the VIRGO version of the PMO6-type radiometers) – for monitoring the solar 'constant', and two three-channel sunphotometers (SPM) for the measurement of the spectral irradiance at 402, 500, and 862 nm with a bandwidth of 5 nm, each.

SOHO was successfully launched on 2 December 1995 and VIRGO was switched on a few days later. The covers were released, but kept closed in order to outgas the experiment thoroughly during the following 7 weeks without having the optical surfaces exposed to the Sun. On Christmas Eve all covers were opened for a short period of time in order to test the performance of the instruments in a 'first light' experiment. Observations started mid-January for the radiometers and end of January 1996 for the sunphotometers.

The instrumentation of VIRGO has been described in detail by Fröhlich *et al.* (1995) and first results have been presented in Fröhlich *et al.* (1997); the observed in-flight performance and operational aspects of the irradiance observations are the subject of this paper.

Solar Physics **175:** 267–286, 1997.

2. Total Solar Irradiance Measurements

Absolute radiometers are based on the measurement of a heat flux by using an electrically calibrated heat flux transducer. The radiation is absorbed in a cavity which ensures a high absorptivity over the spectral range of the Sun. During practical operation of the instrument, an electronic circuit maintains the heat flux constant by controlling the power fed to the cavity heater. This is called the active mode of operation; hence also the name ‘active cavity radiometer’. As a first approximation the irradiance can be calculated from the shaded and irradiated electrical powers $P_{\rm s}$ and $P_{\rm i}$ according to: $S = C_{\rm rad} \times (P_{\rm s} - P_{\rm i})$, with $C_{\rm rad}$ being the reciprocal of the aperture area times a correction factor for the deviations from ideal behaviour.

Although the designs of both instruments – DIARAD and PMO6-V – are based on the same principle, the physical realization is different (for a general description of the VIRGO radiometers see Fröhlich *et al.* (1995), for details of DIARAD, Crommelynck and Domingo (1984), and for the PMO6, Brusa and Fröhlich (1986)). Major differences between them are the arrangements of the compensating cavities and the forms and coatings of the cavities. Moreover, in the DIARAD exists the possibility of assessing the quality of the electrical measurements in flight.

2.1. Operation

The left channel of DIARAD (DIARAD-L) has operated continuously since the beginning of the measurements on 18 January 1996, whereas the right channel (DIARAD-R) is used only from time to time (once every 60 days) to check for degradation of the left channel. DIARAD is operated with an alternately shaded and irradiated cycle of 90 s, providing a solar irradiance measurement every 3 min. The electrical signals are measured twice during 10 s at the end of each cycle. The two PMO6-V radiometers (PMO6-VA and PMO6-VB) were designed to operate with a shaded and irradiated phase of 60 s providing a solar irradiance measurement every 2 min. This normal operation of the PMO6-V radiometers, however, was used only during a short period of time, owing to the failure of the shutters. The shutter of PMO6-VB failed in mid January when normal operation was supposed to start. PMO6-VA was operated normally for about 2 weeks before its shutter failed also. The reason for the failure does not seem to be a mechanical problem of the actuator. The shutters of both PMO6-V radiometers can be opened, but when they are closed again the electronic fuse is triggered and automatic operation is inhibited. So a new operation mode had to be devised which uses the protective cover instead. Such covers are located in front of each instrument within VIRGO, and can be opened and closed by telecommand. In order to avoid an excessive number of cover operations by time tagged commands, we decided to close it for 21 min three times a day. The time of the closure is placed randomly within ± 2 hours around 4, 12, 20 hours of the day. The randomization softens the periodic

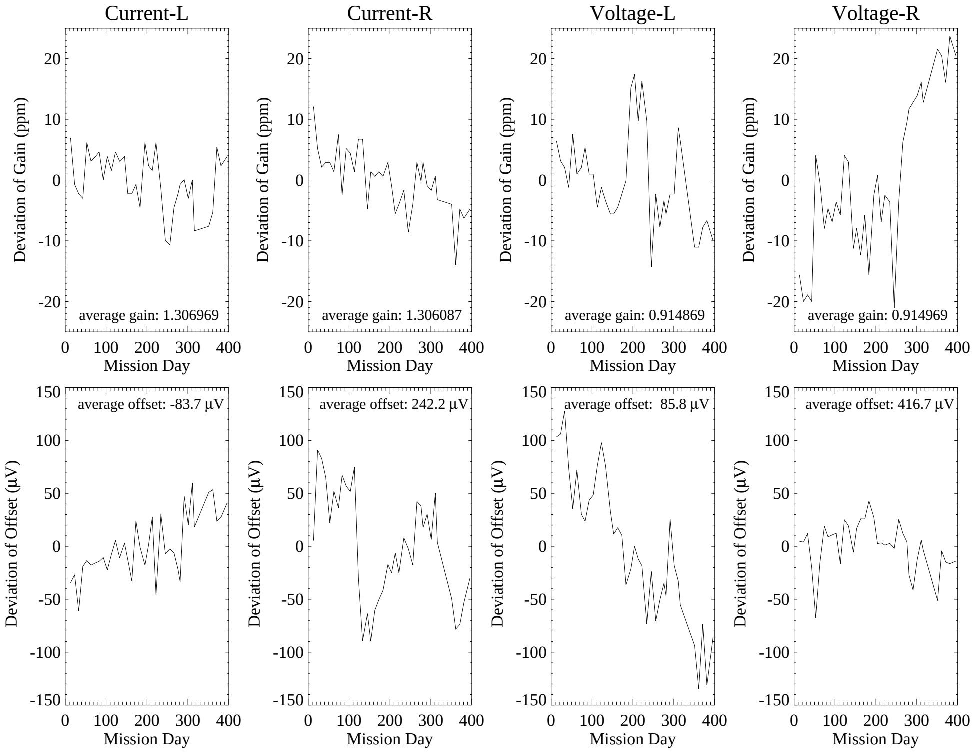

Figure 1. Gain and offset of the four electrical DIARAD channels during the first 400 days of the mission.

modulation of the time series. This mode of operation has the advantage of a 1-min sampling rate with a measurement during 20 s (duty cycle of 30%). It permits the measurements of p modes, although somewhat influenced by the low duty cycle. The rather infrequent reference phases, however, result in a somewhat increased noise at low frequency. This operation mode started on 23 February 1996 with a closed phase of PMO6-VA of 21 min, during which PMO6-VB was opened to fill the gaps. After some time it was realized that the gap filling was not really needed if the closed period of PMO6-VA was shortened. Thus, since 6 July 1996 the closure time of PMO6-VA has been reduced to 6 min and PMO6-VB takes only one measurement per week, which helps to keep its degradation low.

2.2. Electrical measurements

The electrical power (current and voltage) from the left and right channels of DIARAD are amplified with four differential amplifiers before being fed to the VIRGO data acquisition system (DAS). Knowledge of the gains and offsets is a crucial element in determining the accuracy of the observed solar irradiance. For this reason, the inputs of the four amplifiers are calibrated every few days

Table I

Gains and offsets for voltage (V) and current (C) channels of DIARAD and PMO6-V. For DIARAD the inflight measurements are listed with their standard deviations from Figure 1, and for PMO6-V the values determined before launch.

Channel	Gain (V/V)	Offset (μV)
DIARAD V left	0.914869 ± 7.1 ppm	85.8 ± 66.6
DIARAD V right	0.914969 ± 11.8 ppm	416.7 ± 22.6
DIARAD C left	1.306969 ± 6.1 ppm	− 83.7 ± 66.6
DIARAD C right	1.306087 ± 6.5 ppm	242.2 ± 51.5
PMO6-VA V	2.002530 ± 13.0 ppm	1319.5 ± 12.2
PMO6-VA C	3.027608 ± 12.6 ppm	−439.8 ± 7.3
PMO6-VB V	1.996693 ± 12.9 ppm	838.8 ± 13.2
PMO6-VB C	3.026542 ± 16.5 ppm	−380.8 ± 9.2

with an accurate voltage reference built into DIARAD (at the beginning this was performed every second day, since 3 August 1996 every 5 days). The measured gains and offsets are plotted in Figure 1 for the first 400 days of the mission, and the mean values with their standard deviations are shown in Table I. As the gain and offsets are quite stable, mean values are used for the evaluation of the DIARAD electrical signals, and any further development will be taken into account in the level-2 data. In summary, the uncertainty of the electrical measurements within DIARAD is about ±50 ppm, which is an excellent achievement in space.

The PMO6-V uses pre-launch calibrations for the gain and offsets as listed in Table I. During the data analysis it was realized that a problem with the offsets influences the calculated irradiance. The value of the heater resistance as a function of the heater power can be used to determine possible changes of the offsets. The observed $R_{\mathrm{o,c}} = u_{\mathrm{o,c}}/i_{\mathrm{o,c}}$ can be 'adjusted' by adding the same offsets $\Delta_{\mathrm{u,i}}$ to the measured open and closed signals $u_{\mathrm{o,c}}$ in order to achieve $\overline{R}_{\mathrm{o}} = \overline{R}_{\mathrm{c}}$:

$$\overline{R}_{\mathrm{o}} = \frac{u_{\mathrm{o}} + \Delta_{\mathrm{u}}}{i_{\mathrm{o}} + \Delta_{\mathrm{i}}} = \overline{R}_{\mathrm{c}} = \frac{u_{\mathrm{c}} + \Delta_{\mathrm{u}}}{i_{\mathrm{c}} + \Delta_{\mathrm{i}}} \,. \tag{1}$$

Here, the subscripts o and c denote open and closed, and u and i mean voltage and current. This assumes that only the offsets are subject to change, and not the gains. We assume also that the value of the heater resistor does not change between the open and closed readings. From the observed $R_{\mathrm{o,c}}$ one can determine one of the currently prevailing offsets Δu or Δi, assuming the other remains constant. Based on the analysis of PMO6-V radiometers, it was shown that the contribution of the U-channel to the offset is about an order of magnitude larger than the contribution of the I-channel. Accordingly we set $\Delta_{\mathrm{i}} = 0$, and Equation 1 is solved for Δ_{u}:

$$\Delta_{\mathrm{u}} = \Delta R \left(\frac{1}{i_{\mathrm{c}}} - \frac{1}{i_{\mathrm{o}}}\right)^{-1} \text{ with } \Delta R = R_{\mathrm{o}} - R_{\mathrm{c}}. \tag{2}$$

With these assumptions one can also calculate the difference in irradiance from the difference in the observed heater resistance

$$\begin{aligned}\Delta S \;&=\; S_{\text{corr}} - S = C_{\text{rad}}\left((u_{\text{c}} + \Delta_{\text{u}})i_{\text{c}} - (u_{\text{o}} + \Delta_{\text{u}})i_{\text{o}} - u_{\text{c}}i_{\text{c}} + u_{\text{o}}i_{\text{o}}\right) = \\ &=\; C_{\text{rad}}\Delta_{\text{u}}\,(i_{\text{c}} - i_{\text{o}}) = C_{\text{rad}}\Delta R\,(i_{\text{c}} - i_{\text{o}})\left(\frac{1}{i_{\text{c}}} - \frac{1}{i_{\text{o}}}\right)^{-1},\end{aligned} \tag{3}$$

which is plotted for the PMO6-VA in Figure 2. Note the small offset of about 0.02 W m^{-2}, corresponding to 15 ppm, at the beginning of the measurements indicating that the transfer from ground to space is indeed smooth. After the large excursion observed symmetrically around the greatest distance from the Sun around DoY96 200 (Day of the Year 1996) the curve is again smooth, but with a slightly different offset of 0.08 Wm^{-2} or about 60 ppm. The rms noise in the quiet periods is about $\pm$0.03 W m^{-2}, or 25 ppm, which is similar to the measured variance of the electrical channels of DIARAD. The reason for the large excursion is not understood, but it seems to be correlated with the increasing open electrical power in the cavity to compensate for the lower solar irradiance. It is, however, difficult to imagine how such a small change can influence the offset of the voltage channel so strongly, and in such a nonlinear fashion: increasing first up to DoY96 173 and then suddenly decreasing until the maximum of the electrical power is reached around DoY96 198; the whole is then repeated in the opposite direction. In order to cope with this problem, the electrical power in the cavity is calculated from the current, and the resistance value measured during the closed phase as $P_{\text{o,c}} = R_{\text{c}}i^2_{\text{o,c}}$, where P denotes power. The omission of the voltage signal in the open phase removes the strong excursion in the solar irradiance, as shown in Figure 3. Only some small remnants can be seen, e.g. between DoY96 220 and 230. The uncertainty of the electrical measurements in PMO6-V with this method is about $\pm$80 ppm.

2.3. Determination of the irradiance

The difference of the electrical power during the open and the mean of the two adjacent closed phases is converted into irradiance by the use of the individual radiometric constant C_{rad}, which will be discussed in Section 2.4.

As the cavity does not see the Sun alone, the measured irradiance has to be corrected for the changes in the infrared radiation of the thermal environment within the radiometer. The main advantage of the active operation is that the pace of the open/closed phases are short enough not to change the thermal environment of the radiometer. In the case of the DIARAD the influence of changing thermal conditions on the irradiance is mainly compensated by the symmetrical arrangement of the cavities, both seeing the same thermal environment. Thus only a correction for the shutter emission in the closed phase needs to be applied.

In the new operation mode of PMO6-V the stability of the thermal environment is degraded. Since the open phases last long enough for the instrument to reach its thermal equilibrium, the measurements, which are carried out shortly after the

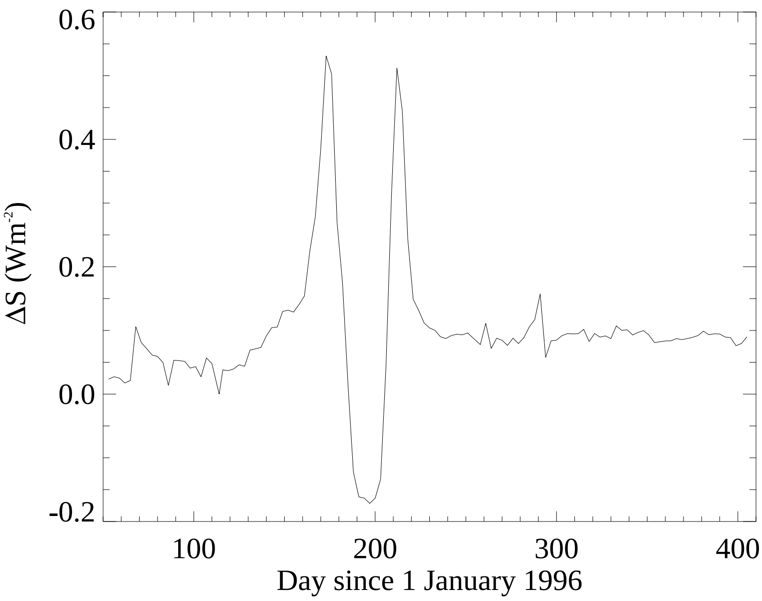

Figure 2. Change of solar irradiance caused by changes of the offset of the voltage channel of PMO6-VA during one year of the new operation.

opening of the cover, see a changing thermal environment which is different from that seen later. Consequently there are substantial relaxation tails in the irradiance time series whenever the cover changes its state. These changes can be accounted for by modelling the influence of the thermal environment seen by the cavity. The model uses five surfaces, taking into account their temperatures, their radiative properties and the view factors to estimate the contributions to the irradiance. The temperature within the radiometer is deduced from the two sensors in the heat sink and the front part; the temperature of the cover is calculated from an energy-balance model. The irradiance during the 8 hours of the open phase is calculated using a 'cover closed' value as reference, which is determined at each measurement in two steps. First, the closed values of the operational radiometer before and after the 8-hour period are linearly interpolated to the time of the observation. Secondly, small deviations of the power from the straight line are deduced from the closed (backup) radiometer, then smoothed and applied to the measurements of the open one.

The irradiance of the Sun as measured by the radiometer has to be normalized to a reference distance (1 AU) and zero velocity in order to reveal the proper variability of the Sun. The normalization to 1 AU is straightforward and is achieved by dividing the irradiance by the square of the heliocentric distance in AU. A Lorentz transformation reduces the irradiance to that in a frame at rest with respect to the Sun. The dependence of irradiance on orbital velocity was first illustrated by Hudson (1988) using SMM/ACRIM irradiance data (Willson, 1984). The correction factor given there as $(1+\beta^2)$ is incorrect; thus we give a brief derivation here. For a Planck radiating source $B_\nu(T)$ ($\sim \nu^3$) the irradiance is

$$S = B_\nu(T)\ \mathrm{d}\nu\ \mathrm{d}\Omega\ . \tag{4}$$

The Lorentz transformation changes ν and dΩ by a factor f and f^{-2}, respectively, where

$$f = \frac{1-\beta\cos\theta}{\sqrt{(1-\beta^2)}} \tag{5}$$

with $\beta = v/c$ and θ denoting the angle between the velocity and the line of sight. With $\beta_{\mathrm{r}} = c^{-1}\ \mathrm{d}r/\mathrm{d}t$ and the fact that S is proportional to ν^4 and $\beta \ll 1$ the reduced irradiance S_0 becomes

$$S_0 = S_{\mathrm{obs}}\frac{1}{(1-\beta_{\mathrm{r}})^2} = S_{\mathrm{obs}}(1+2\beta_{\mathrm{r}}). \tag{6}$$

For observations from SOHO this effect is rather small ($< \pm 0.2$ ppm), but for Earth-bound satellites with radial velocities of up to ± 9 km s^{-1} it is important (± 60 ppm). The heliocentric distance and velocities of SOHO provided by the spacecraft operations are used to perform this normalization.

2.4. Absolute Accuracy of the Solar Irradiance

The radiometric constant C_{rad} is the reciprocal of the aperture area times a correction factor for the deviations from ideal behaviour. The correction factor accounts for different effects such as the reflectivity of the cavity, the losses due to diffraction at the apertures, stray light in the view-limiting muffler, heating of leads, and the non-equivalence between electrical and radiative heating for PMO6-V and the air and vacuum cavity efficiency for DIARAD. The procedure for determining these factors is called characterization of the radiometer, and it provides both, the correction factors and their uncertainty, the sum of the latter determining the absolute accuracy of the radiometer. For the DIARAD and PMO6-V the accuracy is $\pm 0.15\%$ (Crommelynck, 1988) and $\pm 0.17\%$ (Brusa and Fröhlich, 1986). For measurements in space (vacuum) the uncertainty is reduced, as the correction factor for, e.g., the non-equivalence between electrical and radiative heating is much smaller or the cavity efficiency is better.

The DIARAD has been characterized in the radiometer characterization laboratory of IRMB, the PMO6-V at PMOD. For the evaluation of the DIARAD data the radiometric characterization constants as determined at IRMB are used. The evaluation of PMO6-V can be based on radiometric constants determined either by characterization (PMO6-VA: 50697.5 m^{-2}; PMO6-VB: 50687.4 m^{-2}) or by indirect comparison with cryogenic radiometers (Romero, Fox, and Fröhlich, 1996) on the ground (PMO6-VA: 50599.8 m^{-2}; PMO6-VB: 50681.1 m^{-2}). One way of

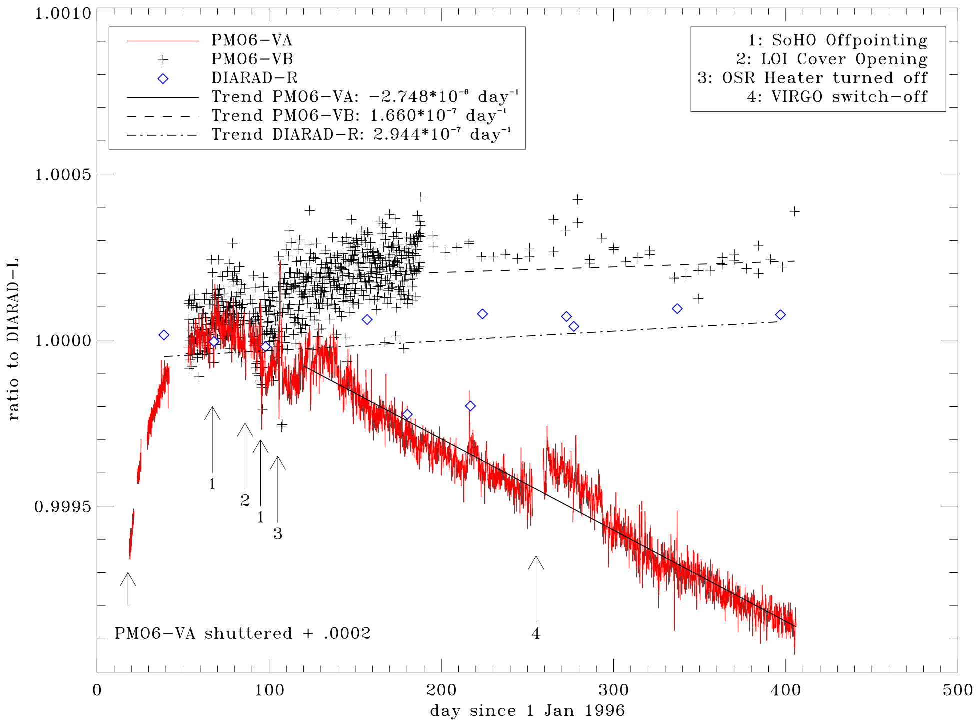

Figure 3. Comparison of the ratio of the solar irradiance measured by the four VIRGO radiometers to that measured by DIARAD-L. The labelled arrows show 3 major spacecraft events and No. 4 was the experiment switch-off due possibly to a hit by an energetic particle.

assessing the uncertainty of the transfer of the instruments to space is by comparing the relative instrument readings during ground tests and in space. The ratio DIARAD-L/DIARAD-R was 0.994645 on the ground and 0.995790 in space; there a difference of +1145 ppm is observed, which is within the uncertainty of the ground comparison. The ratio PMO6-VA/PMO6-VB changed from 1.000000 on the ground (both adjusted to the cryogenic scale) to 0.999330 in space, differing by −670 ppm, which is also within the uncertainty. Thus, the radiometers have not changed significantly during the integration, test and launch.

The relations between the four radiometers during DoY96 52–61 are presented in Table II. Adjusted time series are plotted as ratios to DIARAD-L in Figure 3. The most obvious deviation is in the early phase of the PMO6-V data. These data were taken in the shuttered mode. Relative to DIARAD the PMO6-V radiometer shows an increase, which seems to be exponentially damped with a time constant of about 40 days. There is no obvious reason for such behaviour, but it could be related to the non-equivalence of the PMO6-V radiometers which is slowly decreasing, due, e.g., to a change in the IR-emissivity of the outside wall of the cavity. The values of the shuttered operation differ from the later ones by about 200 ppm, with

Table II
Ratio of the four VIRGO radiometers to the mean value of DIARAD-L and PMO6-V determined during DoY96 52–61

Radiometer	Factor
DIARAD-L	1.000339
DIARAD-R	1.004569
PMO6-VA	0.999995
PMO6-VB	0.999325

the former being lower. In Figure 3 the shuttered data have been moved up by this amount. In view of the substantial change in operation, this is a rather small difference, and confirms the fact that the thermal model adopted for the cover mode is satisfactory. The observed difference of 0.423% between the two channels of DIARAD is unusual and certainly outside the uncertainty. The higher reading on the right channel may be due to an unidentified internal reflection on the right side of DIARAD. To maintain the independent character of the left and right channels, DIARAD-R is used only to measure the aging of DIARAD-L.

Besides the degradation discussed in Section 2.5, there are several other differences between the radiometers. These are mostly related to operations, such as the change of DIARAD after the switch-off in September 1996 (DoY96 255–261, see also Figure 5) which relaxes after about a month. It is not clear what caused this effect; though, some changes in gains, offsets and/or DAS references could be responsible. The variation in the PMO6-V value around DoY96 210–220 may be still some remnant of the offset problem discussed in Section 2.2.

The absolute value of the irradiance will be compared with measurements of similar radiometers on a planned stratospheric balloon flight in spring/summer 1998 and in August 1997 with the experiment SOLCON on board STS 85 with the NASA Hitchhiker Program (Crommelynck *et al.*, 1996). These comparisons will be complemented by a detailed study of the time series of simultaneous measurements of DIARAD-L and PM06-VA in VIRGO and ACRIM-II on the Upper Atmosphere Research Satellite (UARS). These comparisons will also permit us to refer the VIRGO observations to the Space Absolute Radiometer Reference (SARR) as defined by Crommelynck *et al.* (1995).

In summary the evaluation of DIARAD and PMO6-V signals is a straightforward conversion from measured pulses to voltages, taking into account the electrical calibration of the data acquisition system, which are then transformed into electrical power using the electrical calibration for each radiometer. The power difference between the open and the mean of the two adjacent closed measurements is used together with VIRGO housekeeping data in the DIARAD and PM06-V algorithms to obtain total irradiance values in $\mathrm{W\,m^{-2}}$. These raw irradiances are then reduced

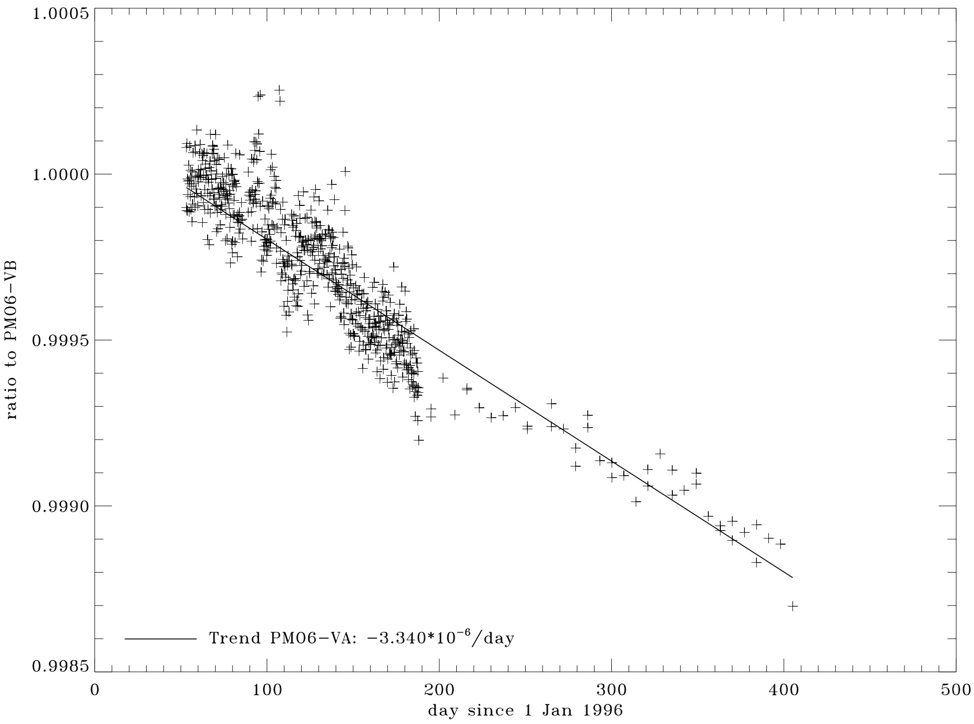

Figure 4. Determination of the degradation from the ratio of PMO6-VA/PMO6-VB irradiance for the first year of operation. Note that PMO6-VB is also corrected for its own time-dependent exposure degradation.

to 1 AU and corrected for the radial velocity as described in Section 2.3, using SOHO ancillary data.

2.5. Determination of the Degradation

The continuously exposed DIARAD left channel shows a very low degradation which was not measurable up to about the end of 1996. Data comparison between DIARAD-L and DIARAD-R over the full year shows a trend of -0.29 ppm day^{-1} deduced from linear regression of the ratio. For the PMO6-VA the rate of change is -3.34 ppm day^{-1} from the comparison of PMO6-VA and PMO6-VB shown in Figure 4. It is interesting to note that radiometers of both types (DIARAD and PMO6-V) on EURECA showed a degradation similar to that of the VIRGO PMO6-V, if referred to the same exposure times, whereas on SOHO the DIARAD behaves quite differently.

The irradiance measures of the radiometers DIARAD-L and PMO6-V, individually corrected for degradation, are shown in Figure 5. The agreement between the two time series is very good, especially after DoY96 270, when the standard deviation between the two time series is less than 40 ppm. As expected from the new operation mode, the PMO6-V has more low frequency noise, and for the period before DoY96 150 its behaviour is still dominated by the slowly levelling off of the increase observed since the beginning of the measurements. It should also be noted that the amplitude of the activity-related modulation of the solar irradiance measured by PMO6-V is larger than that observed by DIARAD by up to 20%. This may suggest that DIARAD is less sensitive to UV-EUV irradiance. The mean ratio DIARAD-L/PMO6-V for the whole period shown in Figure 5 amounts to 1.000573, which is very close to the original ratio of 1.000674 determined between DoY96 53 and 62. This difference of 100 ppm reflects the fact that the PMO6-V radiometer still increased slightly during the first 100 days. The correlation between the two radiometers at the 3-min sampling level is 0.8421 for the whole period and 0.8949 for the last 5 months (after switch-off/on in September).

The observations of DIARAD-L and PMO6-V are an excellent basis for studies of the solar variability on time scales longer than a few hours. The DIARAD-L, with its low degradation is best suited for keeping the long time record, and the PMO6-V may yield more complete information on the active-region related variability, if it turns out that the higher amplitude is indeed due to UV-EUV radiation. This is an excellent basis for producing an unbiased estimate of the solar irradiance time series for the study of the medium and long-term variability, as it was set forth as VIRGO science objective by having two different radiometers. The production of such a time series is based on the two series individually corrected for degradation as described in this Section. The VIRGO irradiance is composed of the PMO6-VA values ‘adjusted’ to the long-term behaviour of the DIARAD-L. This is performed by fitting a smooth curve to the ratios PMO6-VA/DIARAD-L during periods of quiet Sun. This time dependent ratio is then used to adjust each value of PMO6-VA for its long-term changes. These are then normalized to VIRGO values by using the corresponding factor in Table II. The use of only quiet-Sun periods prevents the correction from being influenced by the different sensitivity of the two radiometers to medium and short-term solar variability (see above). This is certainly feasible during periods of low activity, as prevailing now. With increasing activity, however, this method may need some modification. The level-2 VIRGO irradiance data contain the three time series (hourly or daily values): VIRGO, PMO6-V and DIARAD-L.

For studies of the high-frequency behaviour of the total irradiance (above about 25 μHz) the level-1 PMO6-VA values should be used. In the 5-min range, e.g., the noise level of the PMO6-VA data is only slightly higher than the one of the SPM data (Fröhlich *et al.*, 1997). This means that the PMO6-VA noise in this range is only limited by the low sampling duty cycle (30%) of the originally actively operated radiometer. Towards lower frequencies this influence decreases and the observed noise becomes predominately solar.

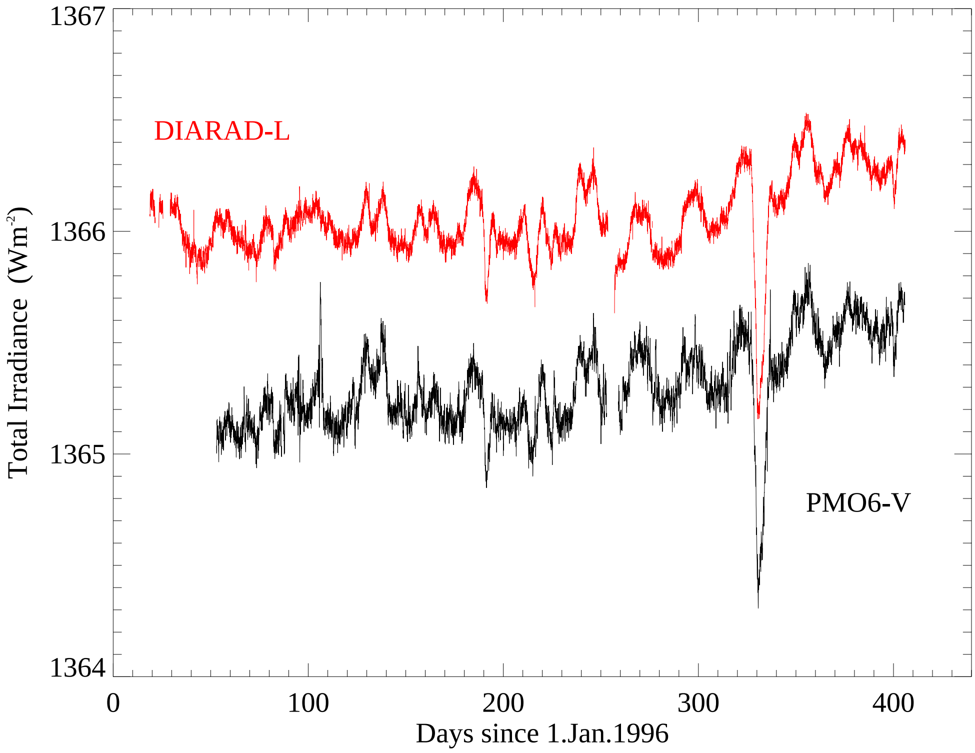

Figure 5. Time series of DIARAD-L and PMO6-V after removing their individually determined rate of degradation.

3. Spectral Irradiance Measurements

The spectral irradiance measurements within VIRGO are performed with two sun-photometers (SPM), SPMA and SPMB. These are spectral radiometers with three channels with 5nm bandwidth centered at 402, 500, and 862 nm, using interference filters and silicon photodiode detectors. Two apertures of 3.0 and 6.9 mm diameter on each channel define the radiometric area and the view geometry (4° full view and 1° slope angle). The filters and detectors are heated to a few degrees above the temperature of the heat sink to reduce condensation of gaseous contaminants on the optical surfaces. The SPM is not intrinsically an absolute radiometer, as it is not self-calibrating, but calibrated by two FEL irradiance standard lamps traceable to the National Institute of Standards and Technology (NIST) to an accuracy of 2–3%. A detailed description of the SPM instrument and its calibration is given by Wehrli and Fröhlich (1991) and their implementation in VIRGO by Fröhlich *et al.* (1995).

Table III
Temperature coefficients (TC) of the SPM as determined in space

	862 nm	500 nm	402 nm
TC in 0.1% K^{-1}	1.774	1.054	1.056

3.1. Corrections for temperature and pointing

SPMA is operated continuously with a 1-min cadence, while SPMB is exposed briefly every few weeks to check the degradation of the primary instrument. In addition, SPMB may be used as a backup in the event of a failure of SPMA. The actual detector temperature is monitored by two thermometers and used to correct the sensitivity during evaluation of the data. After launch, the SPM heaters were fully on during the outgassing period, and the sensor temperature was 6.5 K above ambient. When SPMA's cover was opened on 17 January 1996, its temperature rose by another 3 K due to solar irradiance absorbed by the radiometric aperture. On 2 February 1996 the heater power for SPMA was reduced to $\frac{1}{3}$, resulting in a temperature drop of 7.5 K. This temperature step was then used to determine the temperature dependence of the SPM *in situ*. The results are listed in Table III. They are quite different from the ones which were determined on the ground. Partly, this is due to the fact that they were measured in a seperate setup and not in the VIRGO sensor package with its data aquisition and its specific thermal environment. In the data evaluation the coefficients from the space determination (Table III) are used. Because the degradation rate showed a temperature dependence, at least for the 862 nm channel, the heater for SPMB was also switched off completely on DoY96 92. Thanks to solar heating, SPMA still remains 3 K above the heat sink temperature. SPMB is only 0.7 K warmer than the heat sink, but its entrance is protected by the cover. Outgassing should be low after 4 months in space. Figure 6 shows the course of the temperature of the SPM and of the VIRGO sensor package to illustrate the quiet thermal environment on SOHO.

During a joint observing program the spacecraft was depointed by 3.3 arc min south and a slight increase was detected in the red channel and not in the other channels. After the original pointing direction was restored, the red signal returned back to its original value, indicating that this channel shows a non-negligible sensitivity to pointing. From 3–5 April 1996 the spacecraft performed an off-pointing exercise sweeping from $10'$ north to $10'$ south and then from $10'$ east to $10'$ west braced by rapid excursions to $20'$ in each direction. Relative variations of the red channel, determined by subtracting a linear fit and dividing by the mean value, were fitted for both angular directions by cubic polynomials in the depointing angle. These coefficients are listed in Table IV, and can be used to correct the red channel's signal. Incidentally, the N/S sensitivity is almost exactly 1 per radian,

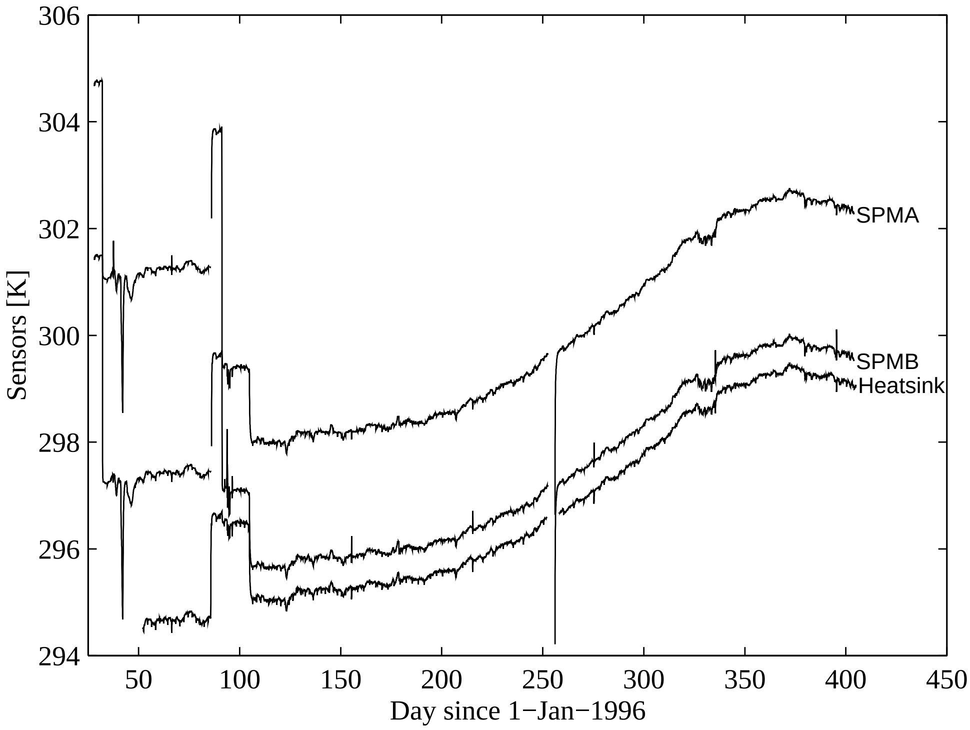

Figure 6. Temperature of the SPM sensors and the VIRGO sensor package during the first year of operation.

Table IV

Coefficients of the third-order polynomial $a_{0\ldots3}$ used to correct the pointing sensitivity of the red channel of SPMA with the angular deviation in radians (positive towards N and E, respectively)

Direction	a_0	a_1	a_2	a_3
N/S	-6.4861×10^{-5}	$+1.1022$	$+46.915$	-3.4962×10^{4}
E/W	-1.0482×10^{-4}	$+0.2712$	$+22.249$	-1.4660×10^{4}

which is easy to remember. The absolute pointing offsets for SPMA amount to $-13''$ in pitch and $-22''$ in yaw angle. On 17 April 1996 the SOHO pitch offset adjustment of 9.6 mrad caused a signal change of 10^{-3}, which could be corrected to an accuracy of a few ppm. Both other channels are much less sensitive and need no correction.

3.2. Determination of the spectral irradiance

During the 'first light' experiment, all three spectral irradiances were about 2.9% below the values of the spectrum of Neckel and Labs (1984) as listed in Table V.

Table V

Calibration and 'first light' results from SPMA and SPMB compared with Neckel and Labs (1984) values. Calibration values are in A m^{-2} nm^{-1}, and irradiances in W m^{-2} nm^{-1}.

	SPMA			SPMB		
	862 nm	500 nm	402 nm	862 nm	500 nm	402 nm
Calibration	0.280	0.515	0.507	0.270	0.507	0.511
N&L irradiance	0.995	1.900	1.705	0.995	1.900	0.705
'1st light' irradiance	0.967	1.844	1.661	0.964	1.836	1.665
Difference	−2.8%	−3.0%	−2.6%	−3.1%	−3.4%	−2.3%

While this is still within the combined errors of the NIST spectral irradiance scale (NBS-1973: 1.5–1.7%), lamp scatter (<0.3%) and the reference spectrum (r.m.s. <1%), the general lower values hint at a systematic error during calibration. A possible reason is that the calibrations were performed in the clean room which has bright walls, rather than in the optics laboratory with dark curtains and more baffles. Any additional stray light measured would have decreased the calibrated response, and would therefore have led to a systematically lower value of solar irradiance measurements. The ratios SPMA/SPMB during the 'first light' experiment were 1.0031, 1.0043, and 0.9976 for the red, green and blue channels. They agree within less than 0.5%, which indicates that their calibrations have been transferred to space with very good accuracy.

The absolute values will be checked during the stratospheric balloon flight planned for 1997 by comparing with a similar SPM calibrated before and after the flight. These calibrations will be based on the recently developed, very accurate radiometric method (e.g., Friedrich, Fischer, and Stock, 1995) rather than on sources such as standard lamps.

In summary, the evaluation of SPM signals is a straightforward conversion from measured pulses to voltages, taking into account the electrical calibration of the data acquisition system, which are then multiplied by a calibration factor (Table V) to obtain spectral irradiance values in W m^{-2} nm^{-1}. These raw irradiances are corrected for temperature, normalized to 1 AU and corrected for the radial velocity as for the radiometers (Section 2.3) using VIRGO housekeeping and SOHO ancillary data. Additionally the red channel is corrected for its pointing sensitivity if needed.

3.3. Determination of the Degradation

The sensitivity of the main instrument has slowly degraded with mean rates of about −64 ppm day^{-1} for the 862 nm, −313 ppm day^{-1} for the 500 nm and −620 ppm day^{-1} for the 402 nm channel as shown in Figure 7. These rates are determined by fitting a straight line to the data of Figure 7, which is the same as assuming a constant solar irradiance over the period of evaluation. The total decrease of sensitivity during the first year of operation amounts to 3, 12, and 23%

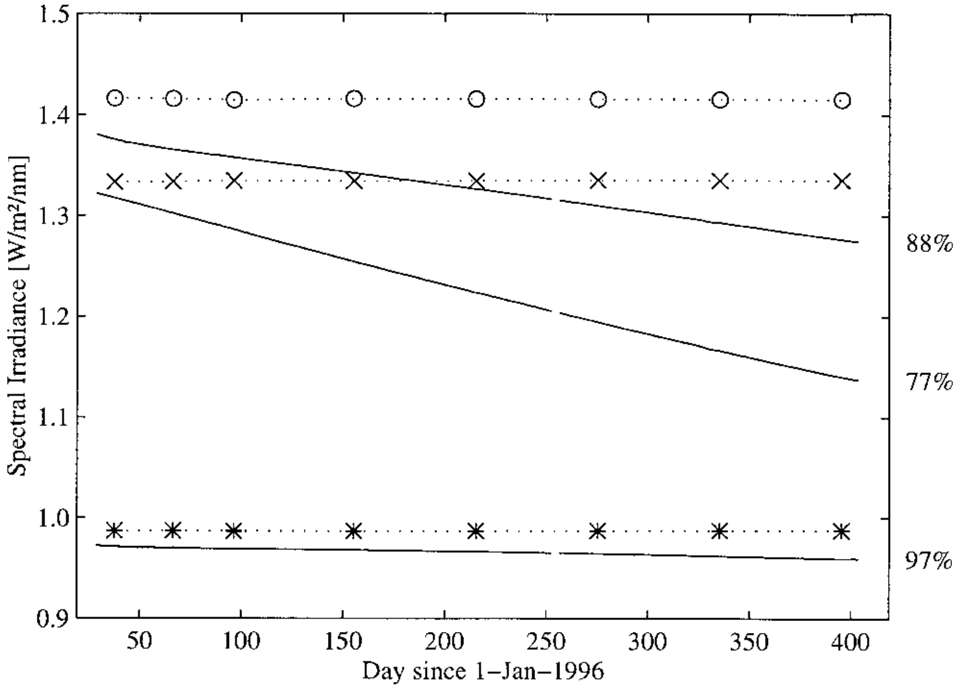

Figure 7. Summary of the measurements of the SPMA and SPMB for the first year of operation. The full lines are for the operational instrument and the dotted lines connect the measurements of the back-up channels. The lines starting below the symbols and the symbols correspond to the following channels: $\circ$ green, $\times$ blue, and $\star$ red (from top to bottom).

for the red, green, and blue channels, respectively. The degradation is one order of magnitude lower than what was experienced by similar SPM instruments on EURECA or PHOBOS; more stable filters and strict cleanliness control during construction of VIRGO and the spacecraft have indeed paid off. It is interesting to note that the three channels have very different initial degradation. It was already noted during the EURECA flight that the first few hours of exposure can decrease the sensitivity substantially more severely than later on. This effect is strongest in the green channel with 4.8% change between 1st light and first comparison with SPMB. It is 3.8% for the red and only 1.6% for the blue.

During this first year the spare instrument (SPMB) has been exposed only 8 times for 21-min intervals each plus 406 min during the off-pointing tests. The measurements are plotted in Figure 8. The red and blue channels show increases similar to the one observed in total irradiance (Figure 5); in contrast, the green channel decreased slightly. These differences in behaviour may be explained with an initial rapid decrease in sensitivity as observed in SPMA for the green channel. These data are obviously not accurate enough to be used to correct the SPMA for degradation to a level of 100 ppm needed to assess the long-term solar changes.

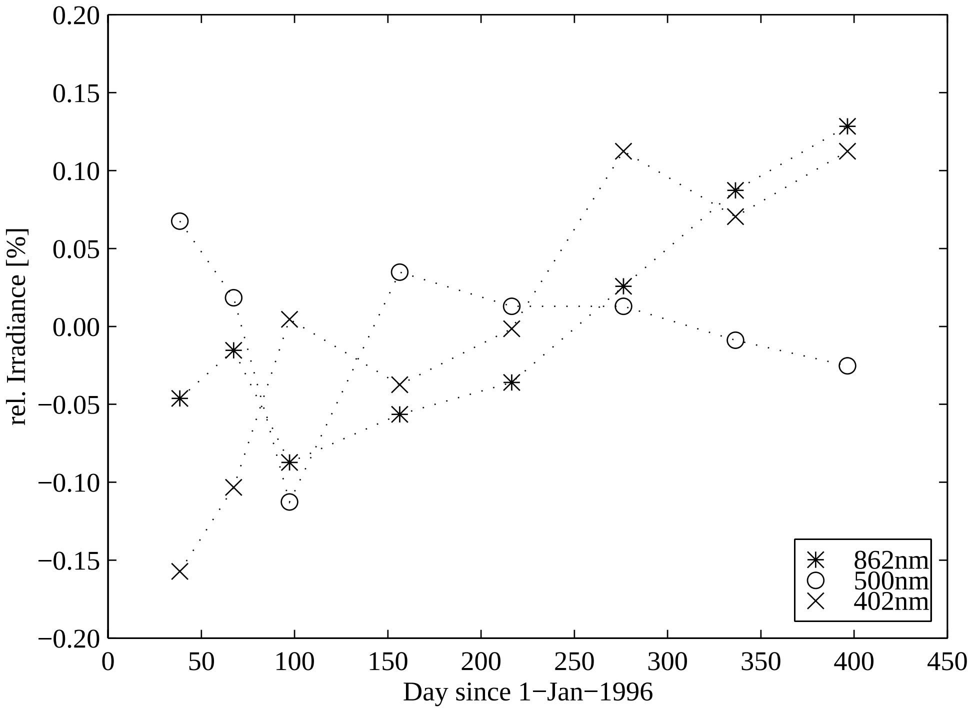

Figure 8. Measurements of SPMB for the first year of operation.

More detailed studies and possibly a longer time series are needed. For the analysis of solar oscillations and the variability on time scales of up to a few months, detrending by polynomials or cubic splines is adequate as shown in Figure 9. Such time series are the basis for level-2 SPM data. As the mission goes on and more data are gathered, the whole time series may have to be updated, resulting in a new version level-2 data.

4. Data Products

The VIRGO Data Centre (VDC) at IAC in Tenerife receives the data from the SOHO Operation Center (SOC) at Goddard Space Flight Center (GSFC) near Washington D.C. and produces and archives level-0, level-1, and level-2 data. The data can be accessed by the VIRGO team according to the rules of the Data Rights (Fröhlich *et al.*, 1995). The level-0 data are files containing the original counts, but sorted by instrument together with the VIRGO HK data needed for the evaluation of this instrument. The level-1 data are time series which are corrected for all *a priori* known effects such as the influence of temperature and pointing, instrument-Sun distance and relative velocity, and are calculated according to the algorithms developed by the instrument co-investigators and described in Sections 2 and 3.

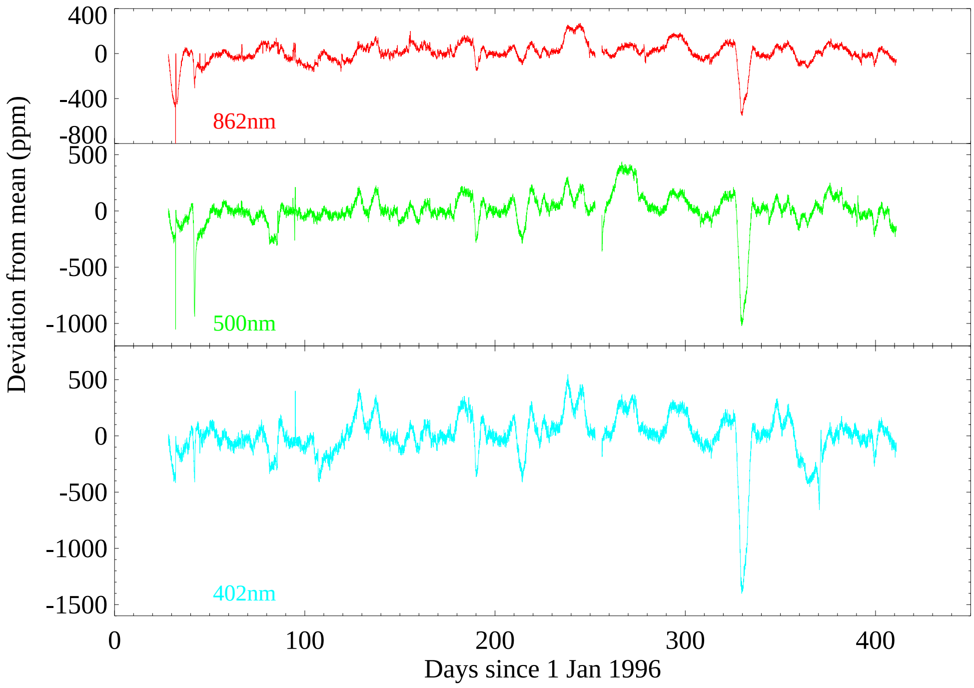

Figure 9. Spectral solar irradiance for the first year of operation from the 3 SPMA channels. The degradation is taken out by fitting cubic splines.

They are stored in daily FITS files with the 3-min data of DIARAD and the 1-min data of PMO6-V and SPM. For medium-term time series analysis to up to a month these data can be used directly. For analysis of longer periods, level-2 data should be used. The production of these data depends strongly on the reliability of the knowledge of the degradation. As stated in Section 2.5, this is well established for the total irradiance. The problems with spectral irradiance are discussed in Section 3.3 and only preliminary level-2 data are produced. The level-2 data as hourly means are stored in monthly FITS files for the total irradiance (VIRGO, DIARAD-L and PMO6-VA values) and the spectral irradiance (RED, GREEN and BLUE) separately. According to data release rules (Fröhlich *et al.*, 1995) these data are only available to the VIRGO team (including guest-investigators) until the end of the second year, when the first year of data will be released. A time series of daily means of the total solar irradiance will be made available to the public soon.

5. Conclusions

The irradiance instruments in the VIRGO package work very well with performances in general exceeding expectation. The total irradiance data show solar variability on all time scales with a precision of a few ppm down to periods of hours, and continuing well below in the 5-min range. Owing to the low degradation, the present high precision can possibly be maintained into the solar maximum. The values of DIARAD-L with their excellent precision together with the PMO6-V data with the higher sensitivity to the overall spectrum are the basis for the VIRGO total irradiance data base as set forward in the science objective by having two different radiometers. The very good signal-to-noise ratio of the PMO6-V at frequencies above about 25 μHz can be used for studies of solar oscillations, supergranulation, mesogranulation and granulation. The spectral irradiance observations with the SPM have excellent signal-to-noise ratio in the 5-min range, where the instrumental noise is at least one order of magnitude below the solar noise (Fröhlich *et al.*, 1997). The stability for periods over a month, however, is not yet established, as the detailed understanding of the degradation mechanisms is still lacking. In summary, the excellent performance, the very quiet environment of SOHO and the continuity of the observations enables us to obtain time series of a quality never previously achieved. The first results presented by Fröhlich *et al.* (1997) demonstrate the potential of these data.

Acknowledgements

VIRGO is an investigation on the Solar and Heliospheric Observatory, SOHO, which is a mission of international cooperation between ESA and NASA. The experiment is a cooperative effort of many individual scientists and engineers at several institutes in Europe and the USA as listed by Fröhlich *et al.* (1995). Without the continuous and concerted efforts of the team this experiment would never have reached the success it demonstrates today. Thanks are extended to various members of the VIRGO science and technical team for many helpful discussions during the compilation of the material for this paper. The irradiance part of the VIRGO team has been supported by several national and international funding agencies which are gratefully acknowledged: The PMOD/WRC by the Swiss National Science Foundation under grants 2.860−0.88, 20–28779.90, 20–33941.92, 20−40589.94, 20−47039.96 and PRODEX, the IRMB by the Fonds de la Recherche Fondamentale Collective d'Initiative Ministérielle and PRODEX, the IAC by the CICYT through PNIE under grants ESP88–0354 and ESP90−0969.

References

Brusa, R. W. and Fröhlich, C.: 1986, *Appl. Optics* **25**, 4173.
Crommelynck, D.: 1988, in N. Fox (ed.), *New Developments and Applications in Optical Radiometry*, Inst. Phys. Conf. Ser. 92, London, p. 19.
Crommelynck, D. and Domingo, V.: 1984, *Science* **225**, 180.

Crommelynck, D., Fichot, A., Lee III, R. B., Romero, J.: 1995, *Adv. Space Res.* **16**, (8), 17.
Crommelynck, D., Fichot, A., Domingo, V., Lee III, R. B.: 1996, *Geoph. Res. Letters* **23**, 2293.
Friedrich, R., Fischer, J., and Stock, M.: 1996, *Metrologia* **32**, 509.
Fröhlich, C., Romero, J., Roth, H., Wehrli, C., Andersen, B. N., Appourchaux, T., Domingo, V., Telljohann, U., Berthomieu, B., Delache, P., Provost, J., Toutain, T., Crommelynck, D., Chevalier, A., Fichot, A., Däppen, W., Gough, D. O., Hoeksema, T., Jiménez, A., Gómez, M., Herreros, J., Roca-Cortés, T., Jones, A. R., Pap, J., and Willson, R. C.: 1995, *Solar Phys.* **162**, 101.
Fröhlich, C., Andersen, B., Appourchaux, T., Berthomieu, G., Crommelynck, D. A., Domingo, V., Fichot, A., Finsterle, W., Gómez, M. F., Gough, D. O., Jiménez, A., Leifsen, T., Lombaerts, M., Pap, J. M., Provost, J., Roca Cortés, T., Romero, J., Roth, H., Sekii, T., Telljohann, U., Toutain, T., Wehrli, C.: 1997, *Solar Phys.* **170**, 1.
Hudson, H. S.: 1988, *Ann. Rev. Astron. Astrophys.* **26**, 473.
Neckel, H. and Labs, D.: 1984, *Solar Phys.* **90**, 205.
Romero, J., Fox, N., and Fröhlich, C.: 1996, *Metrologia* **32**, 523.
Wehrli, Ch. and Fröhlich, C.: 1991, *Metrologia* **28**, 285.
Willson, R. C.: 1984, *Space Sci. Rev.* **38**, 203.