Solar radiometry

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Abstract

The classical radiometry for total solar irradiance (TSI) measurements is described using examples of the presently used four types of radiometer in space. The design, characterization and operation of these radiometers are described. Besides the instrumental characteristics determining the SI uncertainty, an important issue are possible long-term changes of the radiometers exposed to solar irradiance – especially in the EUV – and the space environment. A model for the degradation has been developed which can explain the behaviour of most radiometers in space. The TSI record since 1978 from different platforms and radiometers can be combined in a composite time series which demonstrates that although the SI uncertainty of the present state-of-the-art radiometers is insufficient, their short and long-term precision is good enough to produce a reliable time series of TSI over now almost 30 years.

Introduction

The term solar radiometry is mainly used for measurements of the 'solar constant', the total solar irradiance (TSI), integrated over all wavelengths and reduced to the mean Sun-Earth distance, 1 au; it is an observation of the Sun as a star. The Smithsonian Astrophysical Observatory initiated a ground-based programme for the determination of solar irradiance variability already in 1902, but they were not able to distinguish between solar and atmospheric effects [see e.g. Abbot, 1952; Aldrich and Hoover, 1954]. It was not so much a problem of solar radiometry - accurate pyrheliometers were known since the late 19th century [e.g. Fröhlich, 1991] - but of the atmospheric extinction. Measurements from outside the atmosphere, from rockets, high flying aircrafts and satellites started in the sixties and yielded first results about the inconstant solar constant (see e.g. Drummond et al. [1968]; Plamondon [1969]; Willson [1972] and for a review Fröhlich [1977]). But a reliable record of TSI started only in November 1978, when of NIMBUS7 was launched with an electrically calibrated radiometer (ECR) on board. All the measurements from the radiometers in space since then are shown in Figure 32.1, which illustrates the evolution of the state-of-the-art and the improvement in understanding solar radiometry.
Figure 32.1: Measurements of TSI since November 1978 are plotted as originally published. The absolute values of TSI varied especially at the beginning of the record; During the solar activity minimum in 1986 the three data sets ranged from (1364...1371) W m$^{-2}$, whereas during the next minimum in 1996 the range was already reduced to about 2 W m$^{-2}$. At that time, the measurements were within their stated SI uncertainty of the order of ±0.1% to ±0.2% and it was generally agreed that the characterization of the ECRs had improved, especially the determination of the aperture area. With the advent of the results from TIM on SORCE the community was faced with a serious problem: TIM was measuring almost 5 W m$^{-2}$ lower and it claimed an SI uncertainty of nearly ten times better than the classical radiometers.

In the following we will describe the classical radiometry for TSI measurements using examples of the presently used four types of radiometer in space. Besides the instrumental characteristics determining the SI uncertainty, an important issue is possible long-term changes of the radiometers exposed to solar irradiance and the space environment. A short discussion of the resulting composites - attempts to combine all the existing time series into a contiguous one - will conclude ‘Solar radiometry’.

**Principles and characterization of solar radiometry**

Solar radiometers are based on the conversion of radiation to thermal energy which is measured by an electrically calibrated thermal flux meter. Cavities are used to improve the absorption of solar radiation. They have an aperture, called ‘precision’ aperture, which determines the flux-defining area and a shutter, which opens and closes alternatively while the thermal flux to the heat sink is maintained constant; this is called the active mode of
operation, hence the name active cavity radiometer (ACR). Four types are currently used in space: ACRIM-III on ACRIM-Sat [Willson, 1979; Willson, 2001], PM06V and DIARAD within VIRGO on SOHO [Brusa and Fröhlich, 1986; Crommelynck et al., 1987; Fröhlich et al., 1995, 1997] and TIM on SORCE [Kopp and Lawrence, 2005; Kopp et al., 2005b]. These references may be consulted for details of the construction of the radiometers, of their characterization and on how the uncertainties are determined.

Figure 32.2: Schematic diagram of the PM06V radiometer with its control electronics. The shutter behind the view limiting aperture is a drum which can be closed by turning it by 90°. The electronics controls the active mode operation in which the heat flux (temperature difference across the thermal impedance of the front cavity) is maintained constant during the illuminated and reference phases.

Before we discuss the differences and similarities of the different approaches we introduce the principle of solar radiometers with the PM06V radiometer as an example. Figure 32.2 from [Fröhlich et al., 1995] shows a cut through the radiometer and a block diagram of the control and measurement electronics. The front cavity is used to measure the radiation and the back looking one is the compensating part of the differential heat flux meter; in this configuration the back cavity cannot be used for radiation measurements. In contrast DIARAD and TIM have all cavities side by side which allows radiation measurements with any of them alternatively. The active mode operation with a shutter open-closed cycle of 60-60 s is realized with the control circuit consisting of a wheatstone bridge with the four wire-wound thermometers, a phase-sensitive detector (PSD) for the error signal, a proportional-integral (PI) control and a square-root circuit controlling the heater power in the front cavity. The value is set by the amount of power in the back cavity (REF). The electrical power in the front cavity is measured as voltage drop over the heater and a standard resistor.

First we will discuss the cavities and related effects of the non-equivalence between electrical and radiative heating. Figure 32.3 shows the cavities of ACRIM-III and PMO6-
Figure 32.3: Shown are the cavities of ACRIM-III (left) and PMO6-V (right). The electrical heaters (red) are wire-wound around the outside of the cone for ACRIM and a flexible printed circuit of Constantan glued to the inverted cone for PMO6-V. The temperature sensors (pink) are wire wound around the warm end of the thermal resistor, which is made of silver (ACRIM, light gray as the silver cone) and stainless steel (PMO6-V, dark gray); both are soldered to the heat sink.

V. The cone angle of ACRIM is 30° and the one of PMO6 60°; the black paint is in both cases specular. Ideally a ray parallel to the optical axis would undergo six and five reflections for ACRIM and PMO6, respectively, before it leaves the cavity. This would yield a reflectivity of the order of a few $10^{-6}$ (ppm). The measured ones, however, are of the order of 120 ppm and 300 ppm, for ACRIM and PMO6, respectively [Wilson, 1979; Brusa and Fröhlich, 1986]. The latter is larger because there is no measure to reduce the flat part of the tip of the cone of the PMO6 radiometers, whereas ACRIM prevents direct reflections from the bottom with the curved light trap. The thermal resistor of ACRIM is a silver tube soldered to the cone and to the heat sink at the bottom, the one of PMO6 is a stainless steel tube from the inverted cone to the heat sink. A thin copper wire (pink) wound around and glued to the warm end of the thermal resistor serve as temperature sensors for both radiometers. The electrical heater (red) is wire wound around the cone of ACRIM and covered with aluminized mylar to minimize radiative losses to the outside. The one of PMO6 is a flexible printed circuit made from an etched 5 μm Constantan foil forming a 90 Ω heater bonded to a 20 μm Kapton foil which is directly glued to the front side of the cone and then covered by the black paint. In both radiometers the heater covers the same area as illuminated on-axis through the ‘precision’ aperture, an indispensable measure to minimize the non-equivalence. Each radiometer has
two receivers in a back-to-back configuration, one for solar measurements and the other as reference of the differential heat-flow meter. The temperature sensor windings of both cavities are elements of a Wheatstone bridge the output of which regulates the electrical energy dissipated in the primary cavity in such a way that the temperature difference over the thermal resistor is maintained constant. In the case of PMO6V the reference cavity is heated with the same electrical power as used during the reference phase of the operational cavity so that the bridge output can be nulled and does not need to be offset to set the temperature difference.

The effects producing the non-equivalence of these two radiometers is quite different: due to the inverted cone of PMO6 the first reflected radiation does leave the electrically heated part, and produces an extra temperature gradient along the outer shield not present in the electrically heated case. In the case of ACRIM some of the electrical heater power may be lost to the outside; in vacuum the effect is probably small due to the radiation shield wrapped around the cone; but it is unknown and uncorrected. In air, however, it is quite large as ground comparison have shown. For PMO6 the effect is described in Brusa and Fröhlich [1986] and determined from the difference in sensitivity in air and vacuum with the argument, that the extra losses of the shield in vacuum and thus the non-equivalence are regarded as negligible due to the gold plating of the outside of the shield. This correction is rather high with values between (1500–4000) ppm. The results shown in Table II of Brusa and Fröhlich [1986] indicate, however, that these corrections are well determined, as they reduce the standard deviation of the comparison to PMO2 - one of the reference radiometer of the WRR - from (1120–580) ppm. Also the absolute value is changed by 2300 ppm, which corresponds roughly to the average of all the non-equivalence corrections. This turns out to be the most important correction for the PMO6 radiometers with a contribution to the overall $3\sigma$ uncertainty of more than one third (500 ppm). For space applications of the PMO6 radiometers this correction is used to transfer the WRR to space with the results of ground comparison performed in air. In vacuum a corresponding correction is neglected because the losses are only about 3%–5% of those in air yielding a small correction of less than 100 ppm.

Figure 32.4 shows the cavities of DIARAD and TIM. The DIARAD cavity has a flat bottom and uses a diffuse paint. The cone angle of TIM is $30^\circ$ and the black is not a paint, but an etched nickel phosphorous (NiP) layer deposited inside the silver cone. The measured reflectivity for solar radiation of the cavities are about 200 ppm for TIM and 250 ppm for DIARAD, which is compatible with the enhancement of such geometries under the assumption of diffuse reflections. In order to avoid direct reflections from the bottom of the cone of TIM a thin and pointed tungsten needle is inserted at the bottom which reflects the radiation back to the cone. The heater of TIM covers the illuminated area of nominal 0.5 cm$^2$. For DIARAD the heater covers a circular area 0.95 cm$^2$ of which only 0.5 cm$^2$ or slightly more than 50 % are illuminated by the Sun. The radiometers developed at Institut Royal Meteorologique de Belgique (IRMB) were the first to arrange both the operational and reference cavities side by side which allows to use both alternatively also for solar measurements - hence the name ‘Dual Irradiance Absolute RADiometer’. A further important advantage of this arrangement is that it provides a very similar thermal environment to both receivers which reduces substantially the sensitivity to changes of temperature and related gradients by e.g. eclipses during a low-Earth orbit which produces thermal waves from the front to the back. In TIM this arrangement is extended to two pairs which allows now simultaneous measurements and comparison of each of the two detector
pairs.

The effects of the non-equivalence for DIARAD and TIM are quite different. For DIARAD the non-equivalence is due to the difference in the area which is irradiated and electrically heated and due to radiation reflected from the bottom to the sidewall, a similar effect as for the PMO6 cavities. With results from mapping the sensitivity over the bottom of the cavity and along the sidewall with a laser beam a corresponding correction - called ‘efficiency’ [Crommelynck, 1988] - is estimated. In vacuum it amounts to 130 ppm for DIARAD on VIRGO/SOHO [Crommelynck and Dewitte, 2005].

The accurate knowledge of the size of the ‘precision’ aperture is obviously very important - it defines the area in which the solar radiation is collected. Figure 32.1 illustrates the importance very nicely as the differences in the early measurements were mainly due to the uncertainty of the aperture area. Both the manufacturing of precise and round apertures with short or zero land (cylindrical part of the aperture) and the measurement techniques have been substantially improved during recent years and allow now for uncertainties as low as 50-100 ppm [Johnson et al., 2003; Litorja et al., 2007] for apertures with diameters of 5 mm–8 mm. The apertures of ACRIM, PMO6-V and DIARAD are made of stainless steel and turned or milled to shape. The one of DIARAD is covered with a thin layer of

Figure 32.4: Shown are the cavities of DIARAD (left) and TIM (right). The electrical heaters (red) are wire-wound around the outside of the cone and encapsulated for TIM and a flexible printed circuit of Constantan glued to the upper face of the heat flow device (pink) for DIARAD, which is bonded to the heat sink with an indium foil. Three thermistors (pink) soldered to diamond flakes measure the temperature of the cavity for TIM. The thermal resistor to the heat sink is shown schematically as a ring (dark gray) of stainless steel, in reality it is spoked.
evaporated nickel, the surfaces of the others are as manufactured. The TIM aperture is made from nickel-covered aluminium which is diamond-turned to shape. In the classical radiometers the ‘precision’ apertures are placed directly in front of the cavities and a further aperture at about 100 mm–140 mm from the ‘precision’ aperture limits the field of view to approximately 5° full angle with an angle of 1° between the opening of the apertures, called slope. This is compatible with the view-limiting geometry of pyrheliometers used on ground for solar radiometry and allows direct comparison with e.g. the World Radiometric Reference [see e.g. Fröhlich, 1991], maintained at PMOD/WRC in Davos. TIM has the aperture geometry inverted with the ‘precision’ aperture (8 mm) at the front of the instrument and the viewing angle is limited by the diameter of the cavity entrance (16 mm at 104 mm behind the ‘precision’ aperture). This obviously needs a large cavity with a rather long time constant, which is, however, no problem for TIM as it is not operated in a quasi-steady-state mode as the classical radiometers.

From the beginning of absolute solar radiometry in the sixties one was concerned about possible heating of the ‘precision’ aperture directly in front of the cavity which would emit additional IR radiation into the cavity. This IR radiation is proportional to the solar irradiance and hence results in an increase of sensitivity. In the early seventies tests with electrical heaters were performed [see e.g. Geist, 1972], but no conclusive results were obtained, mainly because the emphasis was more how much the overall temperature of the aperture increased than on the detailed temperature distribution especially at the edge of the aperture. This edge has a short enough thermal time constant for the temperature to raise and fall during the shuttered operation and thus to contribute to the signal in the cavity whereas an overall temperature increase of the aperture does not influence the measurement. This effect is very difficult to determine experimentally. The problem came back with the detection of the early increase of the PMO6 radiometer in VIRGO/SOHO [Fröhlich et al., 1997], which can only be explained by a steadily increasing aperture heating due to e.g. a blackening of the aperture due to the strong solar UV radiation from e.g. Ly-α during the early exposure of the radiometer. This interpretation was confirmed by inspection of the apertures of the PMO6 type radiometers of SOVA-2 which were more than one year in space during the EURECA mission and then retrieved. The same effect is also present in the HF, ACRIMs and ERBE radiometer as shown by Fröhlich [2003, 2006]. So, the aperture heating seems be a substantial contribution to a yet uncorrected effect of the classical solar radiometers. Due to the nickel plating of the DIARAD aperture the early increase effect could be prevented, but this does not mean that the aperture heating does not also increase the sensitivity of DIARAD. For TIM the influence of aperture heating is negligible because of the very small view angle of the aperture from the cavity. Optical power measurements (with under-filled apertures) with PMO6 radiometers and a spare TIM and comparison with the cryogenic radiation scale at NPL [Romero et al., 1991, 1996] and NIST [Kopp and Rice, 2007], respectively, show agreement of their responsivity ratio to within < 0.1%. Thus, the difference in absolute values between the classical radiometers and TIM is most likely related to the arrangement of the apertures and more specifically to aperture heating of the radiometers with the aperture directly in front of the cavity. Thus, a detailed study of this effect in classical radiometers is needed in order to determine it accurately.

Diffraction is another effect which needs to be included in the corrections. This correction depends on the relative arrangement of the two apertures. If the larger aperture is in front of the radiometer its diffraction adds radiation through the ‘precision’ aperture
due to Babinet’s theorem. In the other case the ‘precision’ aperture in front diffracts radiation out of the viewlimiting aperture, reducing the received radiation. In other words the part diffracted out is greater than the one diffracted in. Thus the aperture arrangement of the classical radiometers increases the measured radiation by (200–1300) ppm depending on the size of their apertures and the distance between them and reduces it for TIM by 420 ppm [Brusa and Fröhlich, 1986; Kopp et al., 2005a; Shirley, 1998]. These corrections are calculated from theory which is based on exactly co-aligned and circular apertures; nevertheless, their uncertainty seem to be at the level of a few percent.

Another important aspect of solar radiometry is the influence of the immediate thermal environment seen by the detector. Most important is the difference in IR radiation received by the cavity during the shutter open and closed phases, respectively. Temperature sensors in the front part of the radiometers and on the shutter together with thermal models are used to estimate and correct these effects. An obvious test for these estimates is a measurement of the radiation from deep space. Other effects for the characterization like stray light and lead heating have been described in some detail [Willson, 1979; Brusa and Fröhlich, 1986; Crommelynck and Dewitte, 2005; Kopp and Lawrence, 2005] and will not be discussed further. Problems related to the electrical power measurements and their uncertainties are also not discussed here, but details from the VIRGO experiment as an example can be found in Fröhlich et al. [1995, 1997].

**Operation of solar radiometers**

The classical radiometers are operated in a quasi-stationary mode with shutter cycles of 60 s to 90 s and at the end of each phase the electrical power is read and the irradiance $S$ evaluated according to

$$S = \frac{C}{A} (P_{\text{closed}} - P_{\text{open}})$$

(32.1)

with $A$ the area of the ‘precision’ aperture, $C$ the total correction factor as determined by characterization, $P_{\text{closed}}$ and $P_{\text{open}}$ are the closed and open electrical power readings. This operation relies on a rather short time constant which is improved with the overall gain of the servo loop which is typically between three and five. So an open-loop or natural $1/e$ time constant of about 20 s is reduced to 4 s to 7 s. Normally, there is not only one measurement before the end of a phase, but a few, so that the servo loop characteristics can also be checked in flight. In contrast to this classical active mode operation TIM uses phase sensitive detection at the fundamental shutter period. This avoids many problems with effects at higher frequencies. For the behaviour of the non-equivalence in the classical case one needs to take into account all contributions from up to frequencies of at least ten times the shutter frequency because a full square wave has to be reconstructed. The TIM radiometer is operated in the same way as the classical radiometers, that is the electrical power is always adjusted so that the temperature difference - or the heat flux - remains constant. The electrical power is derived from a constant voltage source with pulse-width modulation. The evaluation of the phase sensitive signal is somewhat more complicated because most terms are complex phasor components representing the amplitude and phase of sinusoidal variations (indicated as bold-type symbols). With $A$ for the aperture area and $\alpha$ for the absorptivity of the cavity the irradiance $S$ is evaluated from the time series of the
fraction $D$ of the electrical power $P_0$ as

$$S = \frac{P_0}{\alpha A_{\text{real}}} \left[ -\frac{Z_{\text{el}}}{Z_{\text{rad}}} \frac{1}{T} \left( D + \frac{D - F}{G} \right) \right],$$

(32.2)

which corrects also for the complex servo system gain $G$, the shutter timing $T$, and the equivalence as ratio of the corresponding impedances $Z_{\text{el}}/Z_{\text{rad}}$ and the applied feed-forward values $F$ at the shutter frequency. This latter effect accelerates the control system with the information of the last shutter open values feeded forward. The time series of the instantaneous fraction of power fed to the cavity $D$ is generated from pulse-width modulator controlled by a digital signal processor maintaining the thermal balance of the cavity. This signal is sampled at 100 Hz and transmitted to ground as numbers from 0 . . . 64 000, representing the fraction $q = D/64 000$ of $P_0$. The advantage of the transmission of $D$ is obviously that one can also analyse other frequency terms for diagnostics by choosing a different $T$. The final $S$ is convoluted with a gaussian filter of about 400 s length. This means that fluctuations due to e.g. $p$ modes cannot be resolved, but for the objective of TSI for Sun-Earth connections this seems justified. Due to the fact that the result is a true integral the aliases due to such higher frequency variations are suppressed anyway.

The value of TSI as determined from the above algorithms include all known instrumental effects. It has to be normalized to 1 au, the mean Sun-Earth distance, by multiplying the measured value by $r_E^2$, the actual value of the Sun-instrument distance $r_E$. The corrections varies between $\pm 3\%$ and can be done to a relative uncertainty of at least 0.1 ppm from the ephemeris of the spacecraft. A further correction is needed for the Doppler effect due to the radial velocity between the source and the radiometer. The correction is discussed in Chapter 2 and is proportional to $(1 - 2v_r/c_0)$ with $v_r$ being positive away from the Sun. For a low-orbit satellite this correction can amount to up to $\pm 60$ ppm with radial velocities of up to $\pm 9$ km s$^{-1}$.

**Long-term behaviour of solar radiometers in space**

From Figure 32.5 it is obvious that the long-term behaviour of the four VIRGO radiometers differs substantially from each another and important corrections are needed to deduce a reliable TSI from these data. Already at this stage of the evaluation the different long-term behaviour of the operational PMO6V and DIARAD is very obvious. Also prominent is the early increase of the PMO6V radiometers during the first weeks of exposure. From the comparison of a backup instrument of the same type with much less exposure to solar radiation changes due to exposure to the Sun can be determined. But these data are sparse and we need a reliable way to interpolate between the reference measurements in order to enable a continuous correction of the operational radiometer. One may use fitting of polynomials of higher degrees [Willson and Hudson, 1991; Willson and Helixon, 2005] or one can use some other means as e.g. running means [Dewitte et al., 2004a]. A much better way is to use a model which also helps to understand the physical mechanisms behind. Such a model is based on a hyperbolic function [e.g. Fröhlich and Anklin, 2000; Fröhlich and Finsterle, 2001; Fröhlich, 2006] which is the solution of the differential equation describing the ‘siliconizing’ of a quartz window exposed to UV radiation, that is a change of the optical properties due to the formation of silicon at the surface with a subsequent decrease of the response of the underlying quartz to radiation.
exposure. The time dependent sensitivity change $\Delta S(t)$ with $t$ for the exposure time can be described as

$$\Delta S(t) = a \left[ 1 + \frac{1}{b \tau_C} \int_0^{t_{\text{exp}}} (\lambda m(t) + 1)dt \right]^{-b} - 1$$  \hspace{1cm} (32.3)

with $\frac{1}{b \tau_C}$, $b$, $a$ and $\lambda$ as adjustable parameters. The $b$ is included in $\tau_C$ because it then corresponds to a $1/e$ time constant because the hyperbolic function transforms to an exponential one for large $b$ which has then one parameter less:

$$\Delta S(t) = a \left[ \exp \left( -\frac{1}{\tau_C} \int_0^{t_{\text{exp}}} (\lambda m(t) + 1)dt \right) - 1 \right].$$  \hspace{1cm} (32.4)

For $b < 20$ the differences are substantial and the hyperbolic function should be used. Only if $b$ starts to increase during the fitting process, the hyperbolic function can be replaced with the exponential one. The integral corresponds to the dose received during the exposure time and for $m(t)$ the Mg II index is used as surrogate for the UV radiation, normalized to $-0.5 \ldots 0.5$. The fitted parameter $\lambda$ provides the information about the wavelength responsible for the effect as it is proportional to the cycle variability of

Figure 32.5: Level-1 data of the two radiometers on VIRGO: DIARAD-L and R and PMO6V-A and B. Note the difference in the amount of degradation of PMO6V relative to DIARAD-L and the early increase of the PMO6V-A and B.
the corresponding wavelength and $2\lambda$ corresponds to the cycle amplitude of that radiation. Thus, for e.g. Ly-\(\alpha\) with a solar cycle variation of (0.06...0.10) mW m\(^{-2}\) [Rottman et al., 2004] $\lambda = \frac{1}{2} \lambda_{\odot} = 0.83$. This analysis can not only explain the dose dependence of the changes, but also provides information about the physical mechanisms behind it.

In the case of VIRGO this analysis works only for the PMO6V radiometers, mainly because the changes of DIARAD are a mixture of exposure dependent and also non-exposure dependent changes. For an illustration of the method the behaviour of ACRIM-I is shown in Figure 32.6 and the hyperbolic functions of the degradation explains the behaviour quite well. The correction of the early increase is not shown here, for details of this corrections see Figure 2 of Fröhlich [2006]. It shows also how important the dose is, and that neither the exposure time alone nor a simple polynomial fit is sufficient - especially if the activity level is changing during the period analysed.

![Figure 32.6](image_url)

**Figure 32.6:** 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 (not shown). The blue symbols are corrected for the early increase and then fitted with a hyperbolic function. Note the dose dependent change over the period of the spin mode and after the solar minimum of 1986. Adapted from Figure 3 of Fröhlich [2006].

For the PMO6V on VIRGO this analysis is complicated by the fact that also the back-up instrument was exposed more than normally due to the change in operations [Fröhlich et al., 1997]. Thus, it shows a significant early increase which has to be corrected before the back-up can be used for the determination of the exposure-dependent changes of PMO6V-A. The principles of these dose dependent corrections are described in Fröhlich [2003], however, for version 5. Since then the exposure dependent changes of PMO6V have been revised for version 6 as well as the corresponding non-exposure dependent changes of DIARAD. This has improved the internal consistency of the corrections substantially. The most recent VIRGO results (still version 6, updated to end of April 2008)
are shown in Figure 32.1, they are the basis for the PMOD composite. Also included in Figure 32.1 is the DIARAD time series which is determined from the DIARAD-L and R alone [updated from Dewitte et al., 2004a]. Their analysis assumes arbitrarily that there is no change over the SOHO vacations which is not confirmed by comparison with e.g. ACRIM-II and ERBE. Besides this obvious misinterpretation, the overall behaviour shows a much stronger decrease over solar cycle 23 than any other time series during this period. This is due to the neglect of the non-exposure dependent increase of sensitivity which cannot be assessed by analysing the operational and the backup radiometer alone. It can only be detected by comparison with an independent radiometer, e.g. PMO6V. Albeit this effect was not anticipated before launch, the reason for having two different radiometers within VIRGO was: "Although the designs of both radiometers are based on the same principle, the physical realization is different" [from Fröhlich et al., 1995]. The residuals of the comparison of DIARAD and PMO6V, both corrected for exposure dependent changes (level-1.8), can now be fitted to an exponential function which describes the long-term sensitivity change. Comparisons with ACRIM-II or ERBE instead of PMO6V yield essentially the same results, indicating that it is indeed a sensitivity change of DIARAD. A similar effect is also found for the HF as shown in Fröhlich [2006]. So, these two radiometers show an increase of sensitivity which is independent of exposure to radiation and fortunately no such effect is present in ACRIM, ERBE and PMO6 radiometers. Thus, the DIARAD/VIRGO data as published by Dewitte et al. [2004a] and Dewitte et al. [2004b] are confusing and are not correctly representing the irradiance from the Sun during solar cycle 23.

Results and discussion of solar radiometry

With the VIRGO TSI data for solar cycle 23 and the data from HF, ACRIM-I and II for the period before 1996 we can construct a composite TSI as described in Fröhlich [2006] and in Figure 32.7 the so-called PMOD composite is shown as an example. There are two other composites from the ACRIM [Willson and Mordvinov, 2003] and IRMB [Dewitte et al., 2004b] teams. The differences between these and the PMOD composite have been discussed extensively in Fröhlich [2006, 2009] and Lockwood and Fröhlich [2007, 2008] where also detailed information about the reasons for the differences can be found. Figure 32.7 shows very interesting results of solar variability during the last three solar cycles and most importantly the most recent minimum is lower than the previous ones, and the length of this last solar cycle also much longer than the previous ones. The results show that overlapping measurements from different platforms enable to construct a reliable TSI record, demonstrating that the relative precision of the individual radiometers is much higher than their SI uncertainty. The result also shows that only a detailed understanding of the degradation helps to correct the data over longer periods than the 11-year solar cycle. Comparison with simultaneous TSI measurements from ACRIM-II and III and TIM/SORCE indicate that VIRGO may overestimate this trend [Fröhlich, 2009], but a change of at least 18% (instead of the 26% stated in Figure 32.7) can be confirmed. With a long-term uncertainty between ±35 ppm/decade [Fröhlich, 2004] and ±50 ppm/decade [Fröhlich, 2009] the presently observed low value of TSI is highly significant but different from what is observed in spectral irradiance (see Figure 2.3 of Chapter 2) which show essentially no change between minima. This means that there are different
Figure 32.7: Shown is the PMOD composite (version 41_61_0805), updated to end of April 2008. The minima values as 1-year averages amount to (1365.57, 1365.50, 1365.23) W m\(^{-2}\) with an average of 1365.44 W m\(^{-2}\) and the amplitudes of three cycles as difference of the 3-year average at maximum to the adjacent minima to (0.922, 0.921, 1.029) W m\(^{-2}\). In contrast to cycles 21 and 22 there is a substantial trend over cycle 23 with a difference between the two adjacent minima amounting to a change of 26% relative to the amplitude of this cycle [see e.g. Fröhlich, 2009], which is a very interesting and important new result.

physical mechanisms responsible for the trend in TSI and the cycle variation of TSI and SSI. The former may be due to a long-term change in the photospheric temperature which is only marginally influencing UV radiation of the Sun.

Another, still unsolved problem of solar radiometry is the absolute value of TSI which differs between the classical radiometers and TIM/SORCE (see Figure 32.1) which differ by more than 4 W m\(^{-2}\).

Acknowledgements

The author would like to thank Greg Kopp, LASP at University of Colorado, Steven Dewitte and Andre Chevalier, Institut Royale Meteorologique de Belgique, Richard Willson, Columbus University, for many helpful discussions about their radiometers. And last but not least all these results would not have possible without the continuing support of the Swiss Nation Science Foundation, the SOHO and VIRGO Teams which is gratefully acknowledged. SOHO is a cooperative mission of ESA and NASA.
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