Long-term behaviour of space radiometers

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Abstract. Experience with the two types of radiometers in the experiment VIRGO on the ESA/NASA mission SOHO launched in December 1995 has revealed important information about the long-term behaviour of such radiometers in space. Exposure dependent changes can be determined from comparison of radiometers with different periods of exposure to the Sun, as it was done for e.g. the ACRIM series. The physical mechanisms for the long-term changes are not yet well understood. However, with the available data a model is developed which describes the temporal behaviour quite well and allows some inference of the mechanisms involved. The direct comparison of the two types of radiometers, after they have been individually corrected for the exposure dependent part, reveal changes which are independent of the exposure to solar radiation. From these comparison an upper limit for the uncertainty of the long-term changes can be deduced. The uncertainty of the composite TSI depends mainly on the uncertainty of the tracing of ACRIM II to I, which amounts together with the uncertainty of the HF correction during the gap between the two ACRIM experiments to ±62 ppm. Together with the result from a comparison with the independent record of ERBE the long-term uncertainty for the whole record from 1978 to present is estimated to ±85 ppm.

1. Introduction

Since the launch of NIMBUS7 in November 1978 total solar irradiance (TSI) has been observed from space by up to three simultaneous experiments on different platforms: more than 23 years of more or less continuous observations. All types of radiometers have electrically calibrated cavity receivers and are operated at $\sim$ 300 K and have an absolute uncertainty of the order of 0.15-0.3% . From the top panel of Fig. 1 it becomes clear that the absolute uncertainty has improved during the last decade, but obviously it is still not sufficient to trace TSI at the level of solar-cycle variability [16]. Nevertheless, a reliable composite could be constructed (see Fröhlich and Lean [9], Fröhlich [5]) mainly because always at least two different radiometer were simultaneously in space. A major source of uncertainty of the composite TSI are the long-term sensitivity changes, normally termed degradation. In order to assess the reliability of the composite it is important to improve the understanding of possible long-term changes. The continuous data sets from the two radiometers of VIRGO are an excellent basis for such an investigation.

In the first section the results of this investigation are discussed. In the following section the critical issues for the construction of the composite TSI are presented which will already give some insight of where the main uncertainties originate. The final assessment of the reliability of the present state-of-the-art radiometry in space is then presented.

2. Analysis of VIRGO/SOHO TSI

VIRGO has two types of radiometers, PMO6V and DIARAD, not only for redundancy, but also to enable a consistent determination of possible changes (e.g. degradation) during the mission. This was always stressed in the objectives of that investigation [11], and indeed the VIRGO radiometry is the first example of how the long-term behaviour can be investigated with simultaneous results from two types of radiometer. The evaluation starts with level-1 data (Fig. 2) which are transformed from the raw data into physical units using the radiometric constants and electrical calibrations and take into account all a priori known effects such as temperature, reduction to 1 AU, correction for radial velocity. The electrical calibration algorithm for DIARAD has recently been revised by Dewitte [4]. The main reason was the detection of a change of the observed heater resistance during open and closed phases of the radiometer operation. In 1996 a similar effect was identified in the PMO6V data and a new algorithm has then been devised using a constant heater resistance to evaluate the electrical power (see [7]). In the following we use these newly evaluated DIARAD data and the version of the VIRGO TSI is increased to 5 (here we use the the most recent data of version 5.004[1]). In comparison with earlier versions TSI is increased by ∼65

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1. The VIRGO data are available from ftp://ftp.pmodwrc.ch in the directory data/irradiance/virgo/TSI as daily and hourly values.

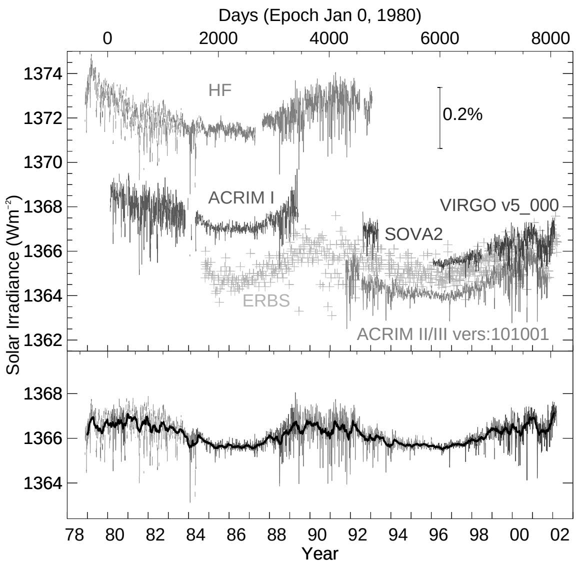

Figure 1. Top panel: Compared are daily averaged values of the Sun's total irradiance TSI from radiometers on different space platforms since November 1978: HF on Nimbus7 [12], ACRIM I on SMM [18], ERBE on ERBS [14], SOVA2 on EURECA [3], ACRIM II on UARS [19], VIRGO on SOHO [7], and ACRIM III on ACRIM-Sat [21]. The data are plotted as published. Note that only the results from the three ACRIM, the SOVA and VIRGO radiometers have inflight corrections for degradation. Bottom panel: Daily values of the composite (version 24.00) shown on the same scale as the original data above. Updated from [16]. As described in Section 3 the long-term uncertainty amounts to about ±90 ppm, which is a less than a tenth of the plotted error bar of 0.2%.

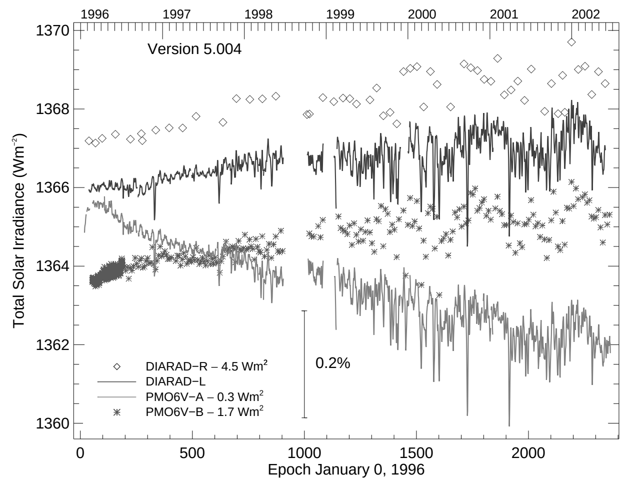

Figure 2. Level-1 data of the two type of radiometers on VIRGO, the DIARAD and PMO6V. Both types have redundant instruments (PMO6V-B) or channels (DIARAD-R) which are used only occasionally in order to assess the radiation dependent changes by comparison with the operational ones. Note the difference in the amount of degradation of PMO6V-A relative to DIARAD-L and the early increase of the PMO6V-A and B which depends obviously on the exposure to solar radiation.

ppm for the period before the SOHO vacations, and by ∼35 ppm after.

2.1. Corrections for exposure dependent changes

From Fig. 2 it is obvious that the long-term behaviour of the four 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 few weeks of exposure. From the comparison of a spare instrument of the same type with much less exposure to solar radiation changes due to exposure to the sun can be determined. The changes can be expressed as a hyperbolic function [6, 8] 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 and a subsequent decrease of the response to radiation exposure. The time dependent sensitivity change $\Delta S(t)$ is expressed as

$$\Delta S(t) = a\left[\left(1+\frac{1}{\tau}\int_0^{t_{\rm exp}} (\lambda M(t)+1)\,dt\right)^{-b} - 1\right] \quad (1)$$

with a, τ, b and the scaling λ as adjustable parameters and $M(t)$ the instantaneous UV radiation[2], normalized to 0 at solar minimum and 1 at solar maximum. The solar cycle amplitude ratio of the radiation involved (calculated from λ as $R_{\rm SC} = 1+\lambda$) depends strongly on wavelength. $R_{\rm SC}$ amounts to about 1.65 for Ly-α (see e.g. Rottman et al. [17]) and decreases gradually towards longer wavelength reaching the value of TSI of 1.001 in the near infrared.

For the analysis of the two radiometers we assume a combination of a sensitivity increase and a decrease for the period before and after the SOHO vacations (loss of SOHO from end of June to early October 1998). The need to separate the two periods is quite obvious for DIARAD, as shown later. Otherwise, the analysis for DIARAD is straight forward as the spare channel is exposed very rarely (about once a month, yielding a total exposure time of about 1.4 days until 2002) and thus it can be assumed not to change due to exposure. The results of the analysis for DIARAD are shown in Fig. 3 and Table 1. The determined parameters may be influenced by factors which are not related the exposure dose and after the Soho vacations the magnitude of the corrections,

2. The MgII index taken from SUSIM/UARS is used as proxy and the data are available from susim.nrl.navy.mil in the directory /PUB/UARS/ as SUSIM_V19R5_MGII_INDEX.ASCII

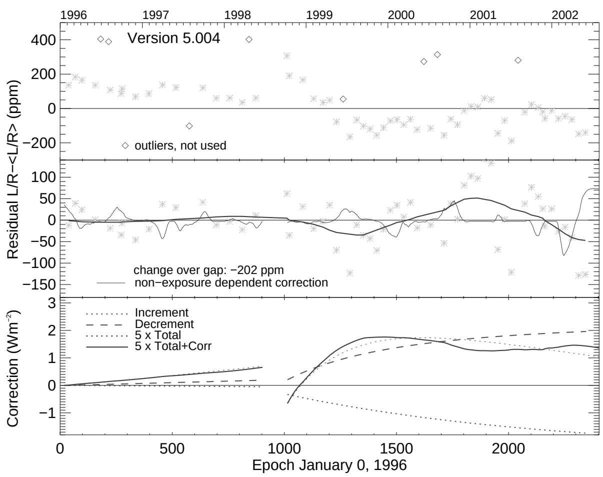

Figure 3. Top panel: Comparison of the DIARAD-L and R plotted as deviation from the mean. The points labelled with ◇ indicate outliers identified by a difference of the open/closed resistance ratio deviates by more than 0.03% from one [4]. Middle panel: Residuals after applying corrections from the fitted functions. Note the reduction of the standard deviation by at least a factor of five. Bottom panel: Correction functions determined from best fits (Total) together with the residuals (Corr).

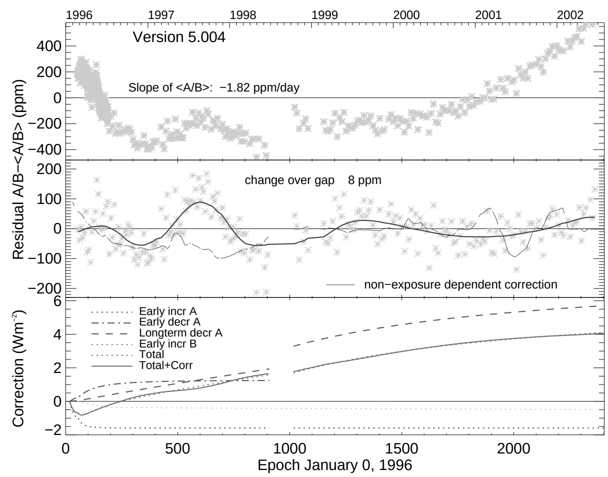

Figure 4. Top panel: Comparison of the PMO6V-A and B plotted as deviation from a linear regression with a slope of -1.87 ppm/day. All data have been used (no outliers removed). Middle panel: Residuals after applying corrections from the fitted functions. Bottom panel: Correction functions determined from best fits (Total) and together with the residuals (Corr).

Table 1. Summary of the parameters for the DIARAD corrections (a, b and τ (days) as of 1 and for $R_{\rm SC}$ see text); 'aft' and 'bef' mean after and before the SOHO vacations. For DIARAD we need to introduce a change of 188 ppm over the gap to fit the ratio before and after. The standard deviation of the residuals is reduced to 48 ppm.

DIARAD-L	a	b	τ	$R_{\rm SC}$
increase bef	0.229	1.74	2939	1.058
decrease bef	2.377	3.51	2487	1.110
increase aft	17.02	0.99	38231	1.042
decrease aft	2.210	1.79	479	1.069

as indicated by a, has substantially changed and furthermore, one of the two radiometers has changed by as much as 202 ppm. In this analysis it is assumed that the sensitivity of DIARAD-R does not change and therefore this change is fully attributed to the operational DIARAD-L, which is somewhat arbitrary. The other puzzle is the very low degradation of less than 0.1 ppm/d at the beginning, as compared to SOVA/EURECA when a similar sensor showed about 1 ppm/d [3]. The model does not really help and the final corrections could as well be simply determined from the ratio of DIARAD-L to R.

For PMO6V the analysis is more complicated as both radiometers show an early increase with a short time constant and PMO6V-B was exposed quite often at the beginning of mission (up to mission day 190 PMO6V-B had already 10.7 days of exposure. In this case the model is essential for the evaluation because both radiometers need to be corrected taking their individual exposure times into account. During the analysis it became clear, that some recovery may have occurred during the shaded periods of PMO6V-B; as a result $\tau_{\rm B}$ was set to $2.8 \times \tau_{\rm A}$ while a, b and $R_{\rm SC}$ are kept the same. The results are summarized in Fig. 4 and Table 2. Especially the results for the early

Table 2. Summary of the parameters for the PMO6V corrections (a, b and τ (days) as of 1 and for $R_{\rm SC}$ see text). 'aft' and 'bef' mean after and before the SOHO vacations. For PMO6V we determine a zero change over the SOHO gap. The standard deviation of the residuals is reduced to 50 ppm.

PMO6V-A	a	b	τ	$R_{\rm SC}$
increase bef	1.592	2.96	39.1	1.045
fast decrease bef	1.261	2.39	173.8	1.046
slow decrease bef	42.90	0.194	3308	1.217
decrease aft	5.08	0.755	1014	1.075

phase (during the first 300 days of measurements) may still be somewhat ambiguous as the parameters to be fitted are not really independent. As far as the slow decrease before and the one after the SOHO vacations are concerned, the corrections are not incompatible with one function for both periods. From the $R_{\rm SC}$ the early increase and the fast decrease are mainly influenced by radiation with a solar cycle variation of about 5%, corresponding to wavelength range centered around 200 nm. The slow decrease with about 22% of solar cycle variation would mainly be influenced by wavelengths around 130 nm, just longward of

Ly-α.

The result of this part of the analysis are two time series which are called level-1.8. As long as their differences are within their stated absolute uncertainties, there is good reason to accept that the measurements of the individual radiometers are consistent with the SI to within these uncertainties. For the VIRGO radiometers the average difference is about 0.09% which is an excellent result in terms of metrological radiometry. A linear fit to the residuals yields a slope of -9.3 ± 1.2 ppm/a over the whole period of observations, which seems to be systematic as shown in Fig. 5 (top panel). If these trends can be identified and removed, we will be able to improve the relative uncertainty, but obviously not the absolute accuracy.

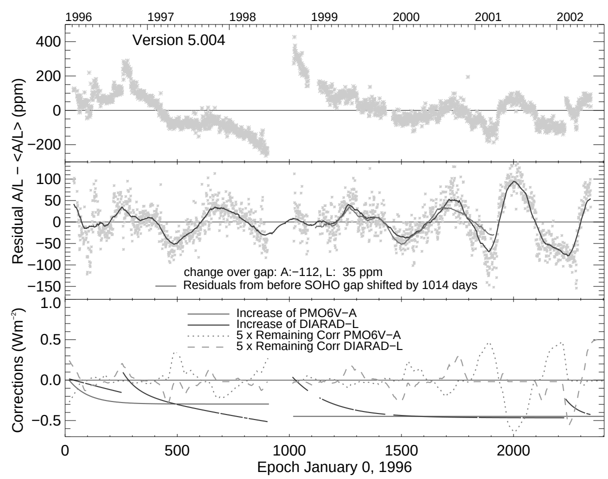

Figure 5. Top panel: Comparison of the PMO6V-A and DIARAD-L plotted as deviation from the mean. Middle panel: Residuals after applying corrections from the fitted functions. The blue dashed curve corresponds to the red one from day 100–900 shifted by 1012 days. Bottom panel: Correction functions determined from best fits, together with the allocation of the remaining residuals to each radiometer.

2.2. *Corrections for non-exposure dependent changes*

The removal of systematic trends is only possible if the temporal behaviour of the two radiometers is different enough for a sensible allocation of the share of the observed differences to each radiometer. The radiometers on VIRGO/SOHO meet this condition since the relevant time constants of the sensitivity changes differ by more than an order of magnitude (see Table 3). Moreover, DIARAD experiences a change in sensitivity after switch-off/on which was first detected after an accidental switch-off in September 1996 and now confirmed by the recent switch-off in February 2002 due to a reconfiguration of SOHO. This suggests that DIARAD may show a similar behaviour starting at the switch-on after launch and again after the extended period of switch-off during the SOHO vacation. As the origin of this effect is still unknown we assume a smooth recovery and use exponential functions to describe it. Although PMO6V does not show such an effect in September 1996 or in February 2002, we assume also an exponential sensitivity increase at the beginning. Indeed the resulting parameters for PMO6V show, that

Table 3. Summary of the parameters for the DIARAD and PMO6V corrections (a and τ (days) of the exponential function). These corrections reduce the standard deviation 98 to 38 ppm.

	DIARAD		PMO6V	
	a	τ	a	τ
Start of mission	1.279	1683	0.296	85.5
September 1996	0.258	64.8	-	-
SOHO vacation	0.514	169.2	-	-
February 2002	0.238	63.0	-	-

the determined function could be removed by reducing the ‘fast decrease’ of Table 2 by about 20%. This could mean that it is still an exposure-dependent effect, but not properly taken into account (see also Section 2.1.). The amplitudes of the DIARAD corrections for the two short switch-off are essentially the same, indicating that the effect is reproducible. With these corrections the residuals as shown in the middle panel of Fig. 5 are reduced by more than a factor of two. A closer look at these residuals shows an intriguing resemblence of the residuals after the SOHO vacation and at the beginning. The cross-correlation between the filtered residuals at the beginning shifted by 1012 days and the original ones afterwards is with $\rho = 0.952$ extremely high (see Fig. 5); no obvious explanation is available.

To determine how the daily values of the residuals $r_{\mathrm{PD}}(t)$ should be shared between the two radiometers some further information is needed. We use the composite ACRIM II and III record from Willson [21] as reference and calculate the filtered (55-day boxcar) ratio to ACRIM $\overline{R}_{\mathrm{PA}}$ and $\overline{R}_{\mathrm{DA}}$ for PMO6V and DIARAD, respectively. From the daily difference $D_{\mathrm{XA}} = \left|\overline{R}_{\mathrm{XA}} - \langle\overline{R}_{\mathrm{XA}}\rangle_{365\mathrm{d}}\right|$ and a threshold $\delta = 4 \times \mathrm{Stddev}(D_{\mathrm{XA}})$ a distribution function $0 \leq \alpha \leq 1$ is determined with $\alpha = 1$ for $D_{\mathrm{PA}} > D_{\mathrm{DA}} + \delta$, $\alpha = 0$ for $D_{\mathrm{DA}} > D_{\mathrm{PA}} + \delta$ and else $\alpha = 0.5$. After smoothing the residual correction is applied with $\alpha \times r_{\mathrm{PD}}(t)$ to PMO6V and $(1-\alpha) \times r_{\mathrm{PD}}(t)$ to DIARAD. Over the gap the determined correction of 147 ppm is distributed according to the ratios of PMO6V and DIARAD to ACRIM over 200 days before and after the gap. The final result is shown in the bottom part of Fig. 5. It is interesting to note that the repetition of the residuals with a lag of 1012 days is also repeated in the remaining corrections for both DIARAD and PMO6V.

A measure for the uncertainty of the long-term behaviour could be the standard deviation of the slope of the ratio of the two corrected VIRGO radiometers which amounts to $\sigma = 0.57$ ppm/a. This seems to be quite small, but it reflects the present state of the art of the knowledge of long-term trends under the conditions that observation are done with two type of radiometers within VIRGO on SOHO, a platform which has proven to be exceptionally stable.

3. Composite TSI

A detailed description of the procedures to construct the composite from the original data can be found in [10, 9, 5]. The composite is shown in the lower panel of Fig. 1 (version 24.00, updated until March 2002[3] with VIRGO Version 5.000 and with new ACRIM II data from Willson [21]). It relies mainly on the radiometers with internal corrections, namely ACRIM I on SMM in 1980 and after repair of the spacecraft in 1984, ACRIM II on UARS after an initial 'burn-in' and on VIRGO after the start of its TSI measurement in February 1996. For the discussion of the reliability mainly two issues are important: the correction for the early measurements of HF on NIMBUS 7 to account for its degradation and the tracing of ACRIM II back to ACRIM I by comparison with ERBE and HF. The deviations of the original data from the composite are shown in Fig. 6 which shows that the most important corrections of all radiometers have to be applied to the HF. Some strategy had to be devised to correct for the early behaviour of HF because this experiment has no spare instrument on board and thus no internal means to determine the irradiation-dependent degradation [12]. As described in [1, 8] the correction is based on the experience with PMO6V on VIRGO and we apply corrections for the HF radiometer degradation prior to 1982 by considering the behaviour of PMO6V and by utilizing comparison with ACRIM I. Moreover, we adjust HF data prior to the end of 1980 downwards, corresponding to a slip in the NIMBUS 7 orientation relative to the sun as described by Fröhlich and Lean [10].

The next important issue concerns two "glitches" - signal discontinuities - near 1 October, 1989 and 8 May, 1990 of -0.31 and -0.37 Wm^{-2} which [15] identified from comparison of HF and ERBE data, and [2] inferred from comparison with models based on ground-based solar observations. Both comparisons suggest changes in the sensitivity of the HF radiometer, although it is not clear that the changes occurred as proposed, in just two steps. The total irradiance increments corresponding to these two episodes in the HF data set are crucial for determining the long-term TSI record because they occurred during the gap between the two ACRIM experiments. A comparison

3. The composite is available from ftp://ftp.pmodwrc.ch in the directory data/composite as daily values.

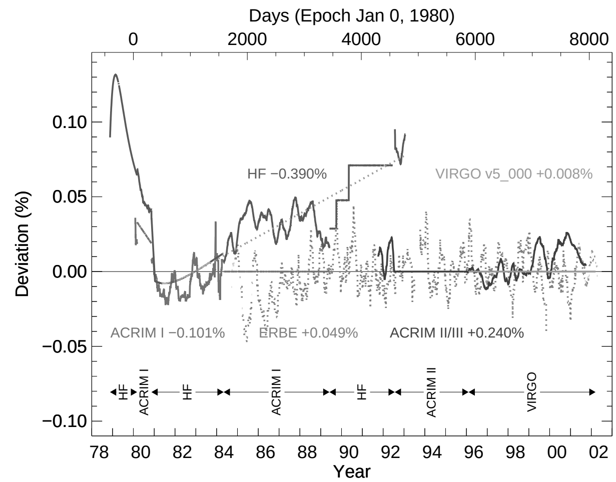

Figure 6. Comparison of the composite with the original data sets. Smooth lines indicate that the radiometer is the basis for the composite and if coincident with zero that no corrections other than an overall shift has been applied (ACRIM I after 1984, ACRIM II and VIRGO).The HF record needed the most important corrections as explained in the text. For the ACRIM I record in 1980 the original corrections as published by [22] needed also some revision as described in [9].

of the ratios HF/ERBE before and after the glitches provides an independent assessment of the amount of change in the total irradiance [5]. Figure 6 suggests that the two glitches may reflect the continuation of a general increase in the sensitivity of the HF radiometer of about 70 ppm/a, already identified by comparison with ACRIM I between 1980 and 1984. This explanation would account for the difficulty in identifying the glitches as local events, especially since there were no changes in the orientation of the spacecraft at these periods with which to explain the glitches. The assumption of continual, rather than isolated, HF sensitivity changes modifies only the short-term irradiance variability during this period, not the scaling of ACRIM II and I. The slope of the ratio of the corrected HF to ERBE over the gap amounts to -1.1 ± 24 ppm/a. If the uncertainty of the slope is used as an estimate for the uncertainty of the correction we get ± 56 ppm for 2.3 years. With the result of the tracing of ACRIM I to II as a correction of ACRIM II by 2176 ± 26 ppm we get a total (rms) uncertainty of ± 62 ppm. With this uncertainty the correction of HF of about 480 ppm is different from zero at the 7.5σ confidence level. Nevertheless, Willson [20] neglects this correction (see also the comment of Kerr [13]) and so he concludes that TSI during the solar minimum in 1996 was higher than during the earlier minimum by 0.04% which corresponds roughly to the correction of HF.

An estimate for the uncertainty of the long-term behaviour of the composite TSI can be deduced from comparison with the independent ERBE data for the three periods (starting at the beginning of ERBE, UARS and VIRGO) from 24 October 1984, 6 October 1991 and 7 February 1996 until 20 March 2002. The slopes of the ratio ERBE to TSI amount to 13.2±2.4, 10.1±4.5 and 18.2±10.3 ppm/a respectively. As the standard deviations depend on the length of the data set we may estimate the uncertainty of a possible trend to be about ±2.5 ppm/a for periods longer than the 17 years of the ERBE observations. This uncertainty implies a possible change of ±58 ppm over the 23 years of the observations. If we add the uncertainties related to the tracing of ACRIM-II to I together with the related HF correction we get a total (rms) of ±85 ppm. The observed change of the composite TSI as difference between the two solar minima of 7.2 ppm can be regarded as zero with a very high level of confidence.

ERBE, on the other hand, shows for the full period an increase of 13.2 ppm/a relative to the composite which amounts to a total change over the 17 years of 230 ppm. Until March 2002 the ERBE radiometer was exposed to the sun for only 2.3 days, which corresponds to an increase of ∼10 ppm per exposure day. This increase could be to due to an early increase similar to the ones observed for the PMO6V radiometers, which show at the beginning about 70 and 35 ppm per exposure day for the A and (less exposed) B sensors, respectively. As ERBE has even longer recovery periods between measurements than PMO6V-B a further reduction to 10 ppm seems reasonable.

4. Conclusions

The observed change of TSI, determined from the difference between the minimum around 1986 to the one around 1997 amounts to an increase of 7.2 ppm over 10.5 years. Compared to the overall uncertainty of ±85 ppm over the period of 23 years, this means that the TSI has no trend with a very high level of confidence (nearly 6σ).

From the more recent data it is also clear that the uncertainty of the long-term trend has been improved by a factor of at least two, which is also reflected by the lower spread of the data since about 1990. In spite of these improvements the problem of absolute accuracy and determination of the long-term stability remains an important issue [16]. The main reason that we could produce such a reliable time series of TSI is that we had always at least two independent experiments simultaneously in space. Although the plans of space agencies for the next years show that we still may have more than one experiment at a time, the plans for the distant future, however, are vague. Thus, we still need measurements with an accuracy of space radiometry at least a factor of 10 better and we need them soon as a benchmark for future measurements which may not be as continuous as needed for accurate traceability.

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References

1. M. Anklin, C. Fröhlich, W. Finsterle, D. A. Crommelynck, and S. Dewitte. *Metrologia*, 1998, 35, 686–688.
2. G. A. Chapman, A. M. Cookson, and J. J. Dobias. *J.Geophys.Res.*, 1996, 101, 13541–13548.
3. D. Crommelynck, V. Domingo, A. Fichot, C. Fröhlich, B. Penelle, J. Romero, and Ch. Wehrli. *Metrologia*, 1993, 30, 375–380.
4. S. Dewitte. New evaluation procedure for the DIARAD electrical calibration. private communication, 2002.
5. C. Fröhlich. *Space Science Reviews*, 2000, 94, 15–24.
6. C. Fröhlich and M. Anklin. *Metrologia*, 2000, 37, 387–391.
7. C. Fröhlich, D. Crommelynck, C. Wehrli, M. Anklin, S. Dewitte, A. Fichot, W. Finsterle, A. Jiménez, A. Chevalier, and H. J. Roth. *Sol. Phys*, 1997, 175, 267–286.
8. C. Fröhlich and W. Finsterle. VIRGO radiometry and total solar irradiance 1996-2000 revised. In: *Recent Insights Into the Physics of the Sun and Heliosphere: Highlights from SOHO and Other Space Missions* (edited by P. Brekke, B. Fleck, and J. B. Gurman), ASP Conference Series, IAU Symposium, Vol. 203, 2001, 105–110.
9. C. Fröhlich and J. Lean. *Geophys. Res. Let.*, 1998, 25, 4377–4380.
10. C. Fröhlich and J. Lean. Total solar irradiance variations: The construction of a composite and its comparison with models. In: *IAU Symposium 185: New Eyes to See Inside the Sun and Stars* (edited by F. L. Deubner, J. Christensen-Dalsgaard, and D. Kurtz), Kluwer Academic Publ., Dordrecht, The Netherlands, 1998, 89–102.
11. C. Fröhlich, J. Romero, H. Roth, C. Wehrli, B. N. Andersen, T. Appourchaux, V. Domingo, U. Telljohann, G. Berthomieu, P. Delache, J. Provost, T. Toutain, D. Crommelynck, A. Chevalier, A. Fichot, W. Däppen, D. O. Gough, T. Hoeksema, A. Jiménez, M. Gómez, J. Herreros, T. Roca Cortés, A. R. Jones, and J Pap. *Sol. Phys.*, 1995, 162, 101–128.
12. D. V. Hoyt, H. L. Kyle, J. R. Hickey, and R. H. Maschhoff. *J.Geoph.Res.*, 1992, 97, 51–63.
13. R. Kerr. *Science*, 1997, 277, 1923–1924.
14. R. B. Lee III, B. R. Barkstrom, and R. D. Cess. *Appl. Opt.*, 1987, 26, 3090–3096.
15. R. B. Lee III, M. A. Gibson, R. S. Wilson, and S. Thomas. *J. Geoph.Res.*, 1995, 100, 1667–1675.
16. T.J. Quinn and C. Fröhlich. *Nature*, 1999, 401, 841.
17. G. Rottman. *Space Sci. Rev.*, 2000, 94, 83–91.
18. R. C. Willson. *Space Sci. Rev.*, 1984, 38, 203–242.
19. R. C. Willson. Irradiance observations from SMM, UARS and ATLAS experiments. In: *The Sun as a Variable Star, Solar and Stellar Irradiance Variations* (edited by J. Pap, C. Fröhlich, H. S. Hudson, and S. Solanki), Cambridge University Press, Cambridge UK, 1994, 54–62.
20. R. C. Willson. *Science*, 1997, 277, 1963–1965.
21. R. C. Willson. ACRIM II and ACRIM III data products (version 10/10/01). http://www.acrim.com/ in the directory Data%20Products.htm, 2001.
22. R. C. Willson and H. S. Hudson. *Nature*, 1991, 351, 42–44.

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