THE CONTRIBUTION OF THE SOLCON INSTRUMENT TO THE LONG TERM TOTAL SOLAR IRRADIANCE OBSERVATION

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ABSTRACT

On century time scales, the variation in the total solar irradiance received by the earth is believed to be a major climate change driver. Therefore accurate and time stable measurements of the total solar irradiance are necessary. We present the latest contribution of the SOLar CONstant (SOLCON) instrument to these measurements, namely its measurements during the International Extreme Ultraviolet Hitchhiker (IEH) 3 space shuttle flight, and its results: the verification of the ageing of the Earth Radiation Budget Satellite (ERBS), and the measurement of the Space Absolute Radiometric Reference (SARR) adjustment coefficients for the Variability of solar IRradiance and Gravity Oscillations (VIRGO) radiometers.

INTRODUCTION

The influx of solar radiative energy is almost exclusively the only energy source for the earthern weather processes. Therefore the long term monitoring of the total solar irradiance is necessary for a correct approach to the "global climate change" question. The monitoring has to be precise in order to measure the solar climate forcing with an error that is at least one order of magnitude lower than the magnitude of the currently studied antropogenic climate forcings.

Making long term total solar irradiance measurements which which remain accurate, is very challenging. Indeed space instruments are subject to ageing, do not necessarily perform overlapping observations, and have limited absolute accuracy compared to the solar irradiance variations that have to be measured.. Therefore a strategy has actually been developed to help to improve this situation. Besides the radiometers operating for long time periods on unretrievable carriers, absolute radiometers have been used periodically for short term space fligths. The measurements of the short term measuring radiometers are used as reference points to verify the ageing of the long term measuring radiometers and to compare their observations.

Very fortunately 6 radiometers made simultaneous solar irradiance measurements during the ATLAS 2 flight period in April 1993. As the dispersion on the observed Total Solar Irradiance (TSI) by single instruments, $S_{instrument}(t)$, was mostly within the range of $\pm$ 0.1 percent, the Space Absolute Radiometric Reference (SARR) (ref. 1) could be defined through a set of instrument adjustment coefficients $a_{instrument}$, so that the adjusted measurements $a_{instrument}S_{instrument}(t)$ provide the same value for the different instruments.

Of these 6 radiometers 4 have been retrieved representing 6 radiometric channels. They can be compared before and after each flight by comparison on ground with absolute radiometers characterised for air and vacuum operation. This allows to control their stability and metrological coherence.
We present the results of the latest space shuttle flight of the SOLar CONstant (SOLCON) radiometer, which is one of the absolute radiometers that was retrieved after the ATLAS 2 space shuttle flight.

SYMBOLS

$S_{instrument}(t)$	time series of the Total Solar Irradiance (TSI) measurement of a single instrument
$a_{instrument}$	the Space Absolute Radiometric Reference (SARR) adjustment coefficient for a single instrument
σ	standard deviation
$S_{SARR}(t)$	SARR TSI time series (eq. 4)

THE SOLCON TYPE RADIOMETER

The SOLCON type radiometer (ref. 2) is a differential absolute solar radiometer developed at the Royal Meteorological Institute of Belgium .
Its radiometric core is formed by two blackened cavities constructed side by side on a common heat sink. In between each cavity and the heat sink a heat flux transducer is mounted. The difference between the two transducers' outputs gives a differential heat measurement, in which the common part of the thermal surrounding radiation seen by the two cavities is eliminated. By the symmetrical construction and good insulation thermal asymmetry is minimised.
Both cavity channels are equipped with a shutter in front of them, by which the sunlight can be kept away from (closed shutter) or allowed into (open shutter) the cavity. In the open shutter phase, solar radiative power flows into the cavity through a precision aperture and is absorbed at the bottom of the cavity. Besides solar radiative power, electrical resistive power can be dissipated in the cavity. During the design of the cavities, carefull attention has been paid to obtain maximally corresponding spatial locations and distributions for the solar and the electrical power.
Equilibrium between the two cavity heat fluxes is maintained by regulating, using a servo system, the electrical power in one of the two cavities. In the default measurement sequence a constant electrical power is fed into one cavity, the "reference" cavity, while its shutter remains closed. The electrical power in the other cavity, the "measurement" cavity, is regulated continuously, while its shutter sequentially opens and closes (both open and close phases take 90 seconds). When the instrument is pointed to the sun, the equilibrium electrical power in the measurement cavity drops proportional to the absorbed solar power when going from the closed to the open phase.
Accurate electrical power measurements are obtained by separate measurement of the voltage over and the current through both cavity heating resistors. The electrical measurement chains are calibrated continuously using six reference voltages, derived from a single, temperature stabilised, reference voltage. The resistance values of the heating resistors, which were choosen maximally stable with temperature, are used as quality indicators of the electrical measurements.
The basic measurement of the solar radiative flux is the drop in the measurement cavity electrical power divided by the precision aperture area. To this basic quantity corrections have to be applied for the optical characteristics of the cavity (e.g. diffraction around the precision aperture borders, absorption coefficient of the cavity, ...) and for the thermal emission of the shutters. The optical characteristics are part of the parameters determined during the pre-flight characterisation phase. The thermal emission of the shutters is measured in space during deep space pointing. The optical ageing of the instrument is verified in space by

periodic comparison between measurements from both cavities. For this purpose, the total exposure to the sun of the right side cavity is systematically kept much lower than the one of the left side cavity.
Table 1 summarises the space flights of the RMIB radiometers. From these radiometers, SOLCON II and SOVA 1 have the same characteristics, summarised in Table 2.

OBSERVATIONS DURING THE IEH-3 MISSION

The International Extreme ultraviolet Hitchhiker (IEH) 3 payload on the STS-95 shuttle flight is the third of five flights dedicated to sun and earth observations. SOLCON was one of the experiments flown on the IEH-3 pallet from 29/10/1998 to 7/11/1998. The SOLCON timeline included 11 dedicated and 5 non dedicated solar observation periods. Deep space pointing, used by SOLCON for the shutter thermal emission measurement, was obtained before and after most of the solar measurements. With its sun pointing monitor SOLCON continuously measured the high quality of the space shuttle attitude control. During the sun observations mostly a pointing accuracy better than 1 degree was achieved.
The temperature of the base of the radiometer was maintained between 6 and 12 °C, the temperature of its top was never lower than 0 and never higher than 20 °C.
The thermal emission of the shutters is measured in space during deep space pointing. The temperature of the shutters varied between -25 and 25 °C.
One person operated SOLCON at the Goddard Space Flight Center supported by 6 collegues running the Space Remote Operation Centre of the Royal Meteorological Institute of Belgium around the clock. Operations included real time data reception and processing, monitoring of the results and issueing remote commands.
Data and voice communications happened through an ISDN line with internet as a backup for data communication.

DETERMINATION OF THE SARR ADJUSTMENT COEFFICIENTS OF THE VIRGO RADIOMETERS

Coincident with the SOLCON observations during IEH-3, the two types of radiometers which are part of the VIRGO(Variability of IRradiance and Gravity Oscillations)/SOHO(SOlar and Helioseismologic Observatory) package (ref. 3), the DIARAD (DIfferential Absolute RADiometer) and the PMO(Physikalisches-Meteorologisches Observatorium) radiometer types, made continuous measurements of the total solar irradiance.
Figure 1 shows the SARR adjusted SOLCON measurements together with the unadjusted level 1 DIARAD-L and level 2 PMO-VA measurements of the total solar irradiance. For DIARAD-L level 1 data - i.e. **absolute data without any correction defined after launch** - is used, for PMO-VA level 2 data - i.e. data obtained after the post-launch corrections defined in ref. 4 - is used. The SOLCON measurements are given as one mean value with a one sigma error bar for every solar period. The DIARAD-L and PMO-VA are given as hourly mean values.
The SARR coefficients of the VIRGO radiometers are estimated by comparison with the SARR adjusted SOLCON measurements. Since the DIARAD-L measurements have a lower variability than the PMO-VA measurements, in a first step this comparison is done for DIARAD-L.

For every time correspondent level 1 DIARAD-L measurement, $S_{DIARAD-L}(t_i)$, and SARR adjusted SOLCON measurement, $a_{SOLCON-L/R}S_{SOLCON-L/R}(t_i)$ [1] , an estimate $a_{SOLCON-L/R}S_{SOLCON-L/R}(t_i) \ S_{DIARAD-L}(t_i)$ of the DIARAD-L SARR adjustment coefficient is obtained.
From n time correspondent measurements, the best estimate of the DIARAD-L SARR adjustment coefficient, $a_{DIARAD-L}$, is the mean value of the individual estimates.

$$\mathbf{a_{DIARAD-L}} = \Sigma_{i=1,\ldots,n} \ a_{SOLCON-L/R}S_{SOLCON-L/R}(t_i) \ S_{DIARAD-L}(t_i) / n = \mathbf{1.000025} \tag{1}$$

The standard deviation, $\sigma_{DIARAD-L/SOLCON}$, around this mean value is given by equation 2 . This value is indicative of the noise on the comparison of instantaneous DIARAD-L and SOLCON measurements. It is constituted of DIARAD-L and SOLCON instrument noise, as well as coregistration noise.

$$\sigma_{\mathbf{DIARAD-L/SOLCON}}^{2} = \Sigma_{i=1,\ldots,n} (a_{SOLCON-L/R}S_{SOLCON-L/R}(t_i) \ S_{DIARAD-L}(t_i) - a_{DIARAD-L})^2 / n = \mathbf{0.000127}^{2} \tag{2}$$

The one sigma uncertainty $\sigma_{aDIARAD-L}$ with which $a_{DIARAD-L}$ is determined, is given by equation 3.

$$\sigma_{\mathbf{aDIARAD-L}}^{2} = \sigma_{DIARAD-L/SOLCON}^{2} / n = \mathbf{0.000010}^{2} \tag{3}$$

Table 3 lists the DIARAD SARR results when only the dedicated solar period measurements are used, when only the non dedicated solar period measurements are used, and when both are used.
The PMO-VA SARR adjustment coefficient is determined trough the mean ratio of DIARAD-L to PMO-VA. This mean ratio can be determined with low uncertainty if a large number of coincident measurements are used. For the eight full days during which SOLCON was active and during which complete DIARAD-L and PMO-VA were available the ratio of the mean TSI value measured by DIARAD-L and of the mean TSI value measured by PMO-VA was **1.000254** . The PMO-VA SARR adjustment, a_{PMO-VA} is determined as 1.000025 * 1.000254 = **1.000279** .

VERIFICATION OF THE ERBS SOLAR RADIOMETER STABILITY

The Earth Radiation Budget Satellite (ERBS) total solar irradiance monitor (ref. 5) has been used for long term solar measurements since 1985. Its SARR adjustment coefficient has been determined in April 1993 during the ATLAS 2 space shuttle flight. By re-comparison with the SARR adjusted SOLCON measurements during the IEH-3 space shuttle flight, it is possible to verify whether the ERBS sun monitor radiometer has been subject to ageing or drifts during the 5 year period between the ATLAS 2 and IEH-3 space shuttle flights. The comparison is done through the VIRGO radiometers for optimal time interpolation of the SARR SOLCON measurements.
Figure 2 shows the SARR adjusted ERBS, level 1 DIARAD-L and level 2 PMO-VA measurements of the total solar irradiance during the IEH-3 mission. The ERBS measurements are given as one mean value with a one sigma errorbar for every observation period. The DIARAD-L and PMO-VA are given as hourly mean values.

[1] The notation $a_{SOLCON-L/R}S_{SOLCON-L/R}(t_i)$ for a SARR adjustment SOLCON measurement is used to indicate either a SARR adjusted SOLCON-L measurement, $a_{SOLCON-L}S_{SOLCON-L}(t_i)$, or a SARR adjusted SOLCON-R measurement, $a_{SOLCON-R}S_{SOLCON-R}(t_i)$.

One can see that for all ERBS observation periods in figure 2, except for the first one, the SARR adjusted DIARAD-L and PMO-VA TSI values correspond to the SARR adjusted ERBS TSI values within the one sigma uncertainty interval of the ERBS measurements.

The comparison results are given in Table 4. The ratio of the SARR adjusted ERBS TSI measurements, with SARR coefficient determined in April 1993, to the SARR adjusted VIRGO TSI measurements, with the newly obtained SARR coefficient valid in November 1998, does not differ significantly from one. Thus the ERBS radiometer has not aged significantly from 1993 to 1998. The one sigma uncertainty level is 140 ppm in relative numbers, corresponding to 0.2 Wm^{-2} in absolute numbers.

UPDATED SARR TOTAL SOLAR IRRADIANCE DATA SET

With the newly obtained SARR adjustment coefficients for the VIRGO radiometers, the previously defined SARR total solar irradiance time series (ref. 6,7), can be extended. The daily mean SARR total solar irradiance time series, $S_{SARR}(t)$, is defined as the mean of all avilable daily mean SARR adjusted total solar irradiance measurements.

$$S_{SARR}(t)= \Sigma_{i=1,\ldots,n} a_i S_i \;/\; n \qquad (4)$$

Figure show the updated SARR TSI times series, including the VIRGO radiometer measurements SARR adjusted with their newly obtained SARR adjustment coefficients.

CONCLUSIONS

In order to reach the long term total solar irradiance monitoring stability required for climate change studies, a carefull observation strategy has to be implemented. Continuously observing instruments need to be combined with periodically used short term observing instruments.
The latest contributions of the periodically used short term observing SOLCON instrument are:

- The November 1998 level 1 DIARAD-L SARR adjustment coefficient is 1.000025 with a one sigma uncertainty of 10 ppm.
- The November 1998 level 2 PMO-VA SARR adjustment coefficient is 1.000279 with a one sigma uncertainty of 10 ppm.
- The ERBS TSI radiometer has not aged significantly since 1993 within the one sigma uncertainty level of 140 ppm.
- The daily mean SARR TSI time series has been extended until end 1998, using the newly obtained DIARAD-L and PMO-VA SARR coefficients.

As soon as the ACRIM II data will be available the same exercice as done for the ERBS sun monitor will be performed.

REFERENCES

1. D. Crommelynck, A. Fichot, R.B. Lee III and J. Romero, *First realisation of the Space Absolute Radiometric Reference (SARR) during the ATLAS 2 flight period*, Advances in Space Research, vol. 16 no. 8, pp. 17-23, 1995.
2. D. Crommelynck and V. Domingo, Solar irradiance observations, Science, vol. 225, pp. 180-181, 1984.

3. C. Fröhlich, D. Crommelynck, C. Wherli, M. Anklin, S. Dewitte, A. Fichot, W. Finsterle, A. Jimenez, A. Chevalier and H. Roth, *In-flight performance of the VIRGO solar irradiance instruments on SOHO*, Solar Physics, vol. 175, pp. 267-286, 1997.
4. M. Anklin, C. Fröhlich, W. Finsterle, D. Crommelynck and S. Dewitte, *Assesment of the degradation of the VIRGO radiometers onboard SOHO*, Metrologia, 1998.
5. R. B. Lee III, B. R. Barkstrom and R. D. Cess, *Characteristics of the earth radiation budget experiment solar monitors*, Applied Optics, vol. 26, pp. 3090-3096, 1987.
6. D. Crommelynck and S. Dewitte, *Solar constant temporal and frequency characteristics*, Solar Physics, vol. 173, pp. 171-191, 1997.
7. S. Dewitte, D. Crommelynck and A. Joukoff, *Maintenance of a long term solar irradiance data series*, Proceedings of 31st ESLAB conference, 1997.

TABLES

Table 1 : Space flights of the RMIB radiometers. SOVA 1 and SOLCON II are exact copies of each other.

Spacecraft	Date (number of days)	Mission	Instrument
STS-9	28/11/1983 (10)	Spacelab 1 (NASA/ESA)	SOLCON I
STS-45	24/03/1992 (9)	ATLAS 1 (NASA)	SOLCON II
STS-46/57	31/07/1992 - 21/06/1993	EURECA (ESA)	SOVA 1/SOVA
STS-56	07/04/1993 (9)	ATLAS 2 (NASA)	SOLCON II
STS-66	03/11/1994 (10)	ATLAS 3 (NASA)	SOLCON II
Atlas-IIAS	02/12/1995 (continues)	SOHO (ESA/NASA)	DIARAD/VIRGO
STS-85	07/08/1997 (13)	Hitchhiker/TAS-01 (NASA)	SOVA 1
STS-95	29/10/1998 (10)	Hitchhiker/IEH-03 (NASA)	SOLCON II

Table 2 : Characteristics of the SOVA 1 type radiometer (default measurement mode).

Measured quantity	Total irradiance (Wm^{-2})
Number of reference voltages	6
Cavity type	Cylindric, diffuse black
Diameter precision aperture	1 cm
Slope angle	2.5 °
Pointing device	4 quadrant
Solar sampling period	3 minutes
Duty cycle	50 %

Table 3.

Solar periods	n	$a_{DIARAD-L}$	$\sigma_{DIARAD-L/SOLCON}$	$\sigma_{aDIARAD-L}$
Dedicated	126	1.000026	0.000126	0.000011
Non dedicated	36	1.000024	0.000131	0.000022
Combined	162	1.000025	0.000127	0.000010

Table 4.

Number of observations	Mean ratio SARR ERBS to SARR DIARAD-L	Mean ratio SARR ERBS to SARR PMO-VA	Observed standard deviation	Uncertainty of ratio
13	0.99993	0.99995	0.00047	0.00014

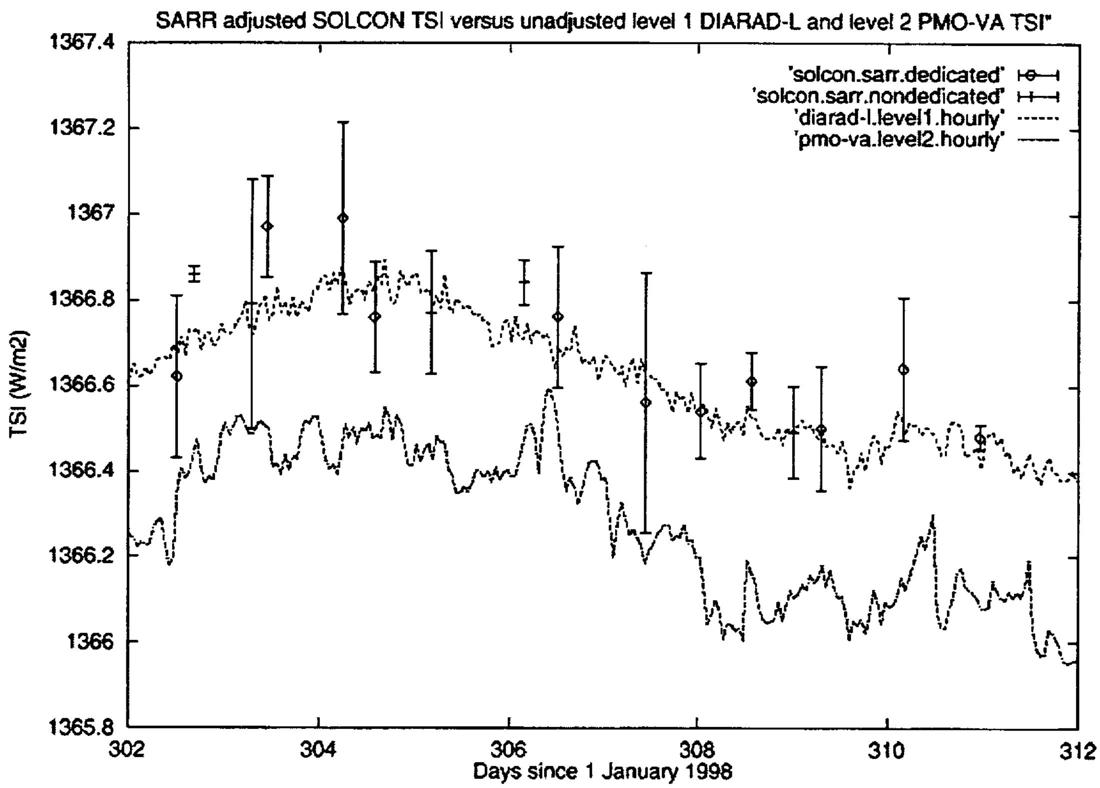

Figure 1 : Correspondent SARR adjusted SOLCON TSI measurements and unadjusted level 1 DIARAD-L and level 2 PMO-VA TSI measurements. The SOLCON measurements are given separately for the 11 dedicated and the 5 non dedicated solar observation periods during the IEH-3 space shuttle flight. During solar periods 2, 6 and 10 (partly) the right channel of SOLCON was used. During the rest of the solar periods the left channel of SOLCON was used. The hourly mean level 1 DIARAD-L measurements are given by the upper continuous curve, the hourly mean level 2 PMO-VA measurements are given by the lower continuous curve.

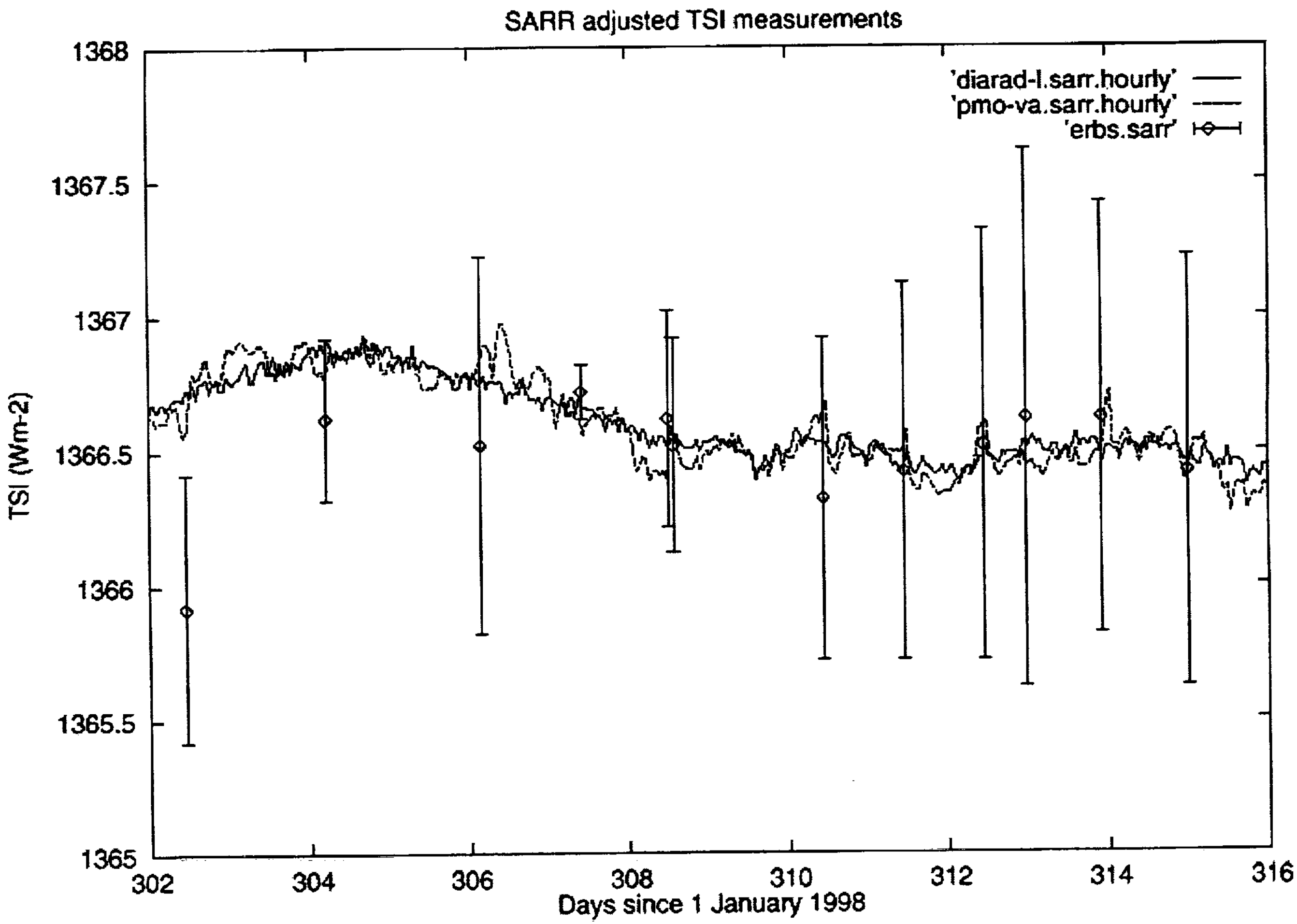

Figure 2 : Correspondent SARR adjusted hourly mean DIARAD-L, PMO-VA and instantaneous ERBS TSI measurements. For the DIARAD-L and PMO-VA radiometers the newly obtained SARR adjustment coefficients have been used. For the ERBS radiometer the SARR adjustment defined during the ATLAS 2 space shuttle flight period (April 1993) has been used.

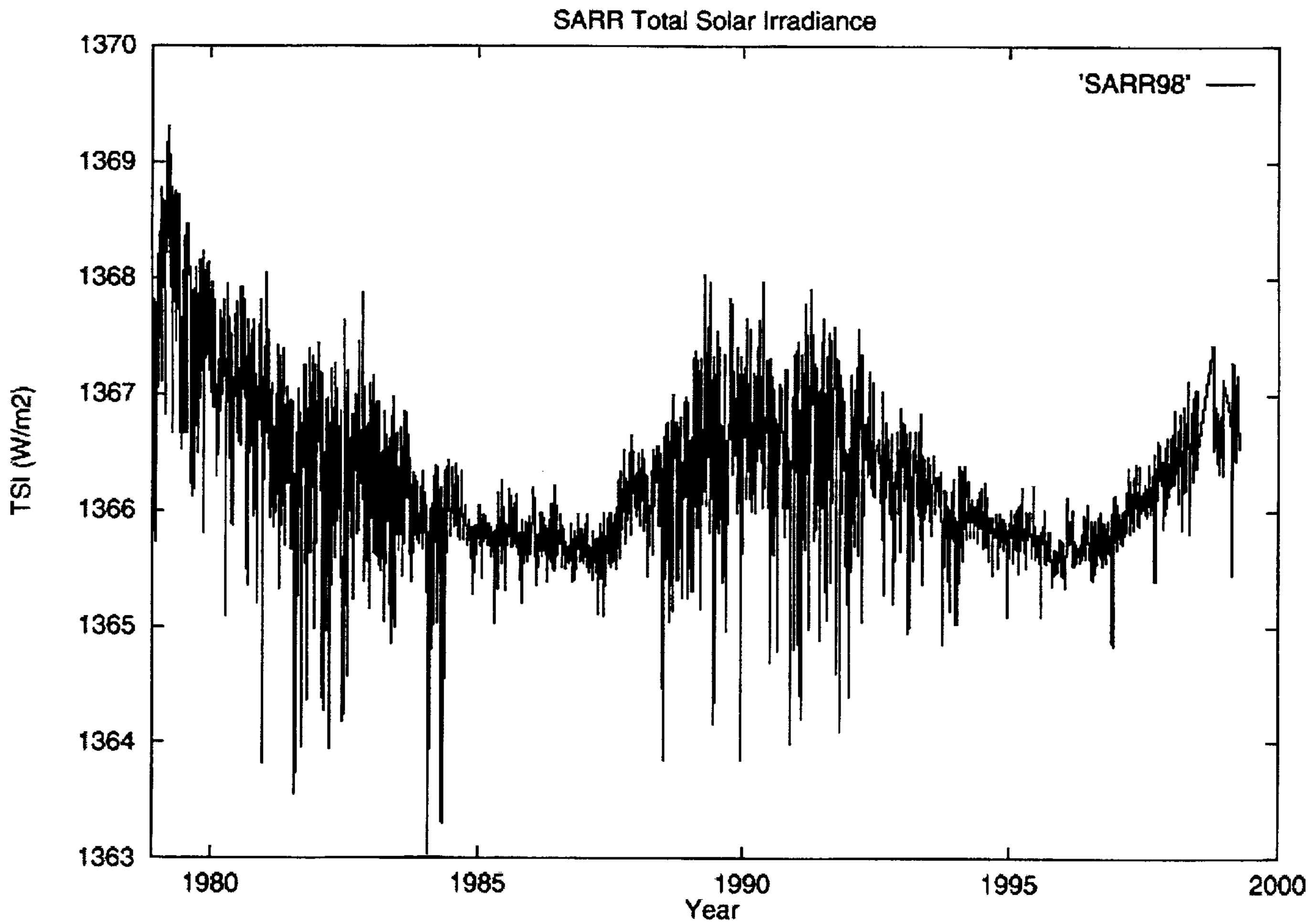

Figure 3 : Updated SARR total solar irradiance series. DIARAD-L and PMO-VA have been added using the newly obtained SARR adjustment coefficients. The data set can be obtained on request at http://estirm2.oma.be.