The PREMOS/PICARD instrument calibration

2009 Metrologia 46 S202

(http://iopscience.iop.org/0026-1394/46/4/S13)

IOP Publishing Metrologia

Metrologia **46** (2009) S202–S206 doi:10.1088/0026-1394/46/4/S13

The PREMOS/PICARD instrument calibration

Werner Schmutz[1], André Fehlmann[1], Gregor Hülsen[1], Peter Meindl[2], Rainer Winkler[3], Gérard Thuillier[4], Peter Blattner[5], François Buisson[6], Tatiana Egorova[1], Wolfgang Finsterle[1], Nigel Fox[3], Julian Gröbner[1], Jean-François Hochedez[7], Silvio Koller[1], Mustapha Meftah[4], Mireille Meisonnier[4], Stephan Nyeki[1], Daniel Pfiffner[1], Hansjörg Roth[1], Eugene Rozanov[1], Marcel Spescha[1], Christoph Wehrli[1], Lutz Werner[2] and Jules U Wyss[1]

[1] Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC), Davos, Switzerland
[2] Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany
[3] National Physical Laboratory (NPL), Teddington, UK
[4] Service d'Aronomie du CNRS, Verrières-le Buisson, France
[5] Federal Office of Metrology, Bern, Switzerland
[6] CNES, Toulouse, France
[7] Royal Observatory of Belgium, Brussels, Belgium

Received 3 November 2008, in final form 23 March 2009
Published 2 June 2009
Online at stacks.iop.org/Met/46/S202

Abstract
PREMOS is a space experiment scheduled to fly on the French solar mission PICARD. The experiment comprises filter radiometers and absolute radiometers to measure the spectral and total solar irradiance. The aim of PREMOS is

(a) to contribute to the long term monitoring of the total solar irradiance,
(b) to use irradiance observations for 'nowcasting' the state of the terrestrial middle atmosphere and
(c) to provide long term sensitivity calibration for the solar imaging instrument SODISM on PICARD.

In this paper we describe the calibration of the instruments. The filter radiometer channels in the visible and near IR were characterized at PMOD/WRC and the UV channels were calibrated at PTB Berlin. The absolute radiometers were compared with the World Radiometric Reference at PMOD/WRC and a power calibration relative to a primary cryogenic radiometer standard was performed in vacuum and air at NPL.

1. Introduction

PICARD is a French micro satellite mission built by Centre National d'Etudes Spatiales (France), comprising three experiments: PREMOS, SODISM and SOVAP. The SOlar DIameter and Surface Mapper (SODISM) instrument will carry out solar diameter, solar asphericity, and helioseismologic observations; it will be provided by Service d'Aronomie du CNRS (France). The SOlar VAriability PICARD (SOVAP) instrument, provided by the Royal Meteorological Institute of Belgium (RMIB), will measure total solar irradiance. The experiment PREcision MOnitoring Sensor (PREMOS) is provided by PMOD/WRC (Switzerland) and measures total and spectral solar irradiance. Improved confidence in total solar irradiance (TSI) measurements can be achieved by simultaneously operating two radiometers of different designs. The goal of the PICARD mission is to investigate solar forcing on Earth's climate and the physics of the Sun that leads to solar irradiance variability [1].

The PREMOS package comprises two experiments, one measuring TSI with absolute radiometers, the other observing spectral irradiance at selected wavelengths with filter radiometers. The filter radiometers have 12 channels realized by three 4-channel instruments. The characteristics

Table 1. Wavelength characteristics of the PREMOS filter radiometers.

Central wavelength, λ/nm	210	215	266	535.69	607.16	782.26
Equivalent bandwidth, Δλ/nm	20	10	20	0.58	0.89	1.73

of the six different filters are given in table 1. Each filter is implemented in two channels in order to calculate sensitivity changes due to exposure of the filters to sunlight. One channel is operated continuously whereas the other is only occasionally exposed and compared with the operational channel. This double-instrument concept for assessing sensitivity changes in operation is also applied to TSI observations by having two absolute radiometers on PREMOS.

Target measurement uncertainties have been ambitiously set to 0.1 W m^{-2} or 70 ppm for the absolute accuracy of the absolute radiometers. The goal for the relative long term stability of the radiometers over the mission duration is 7 ppm per year. The absolute accuracy of spectral irradiance measurements is designed to be a few per cent while we aim for a relative long term stability of 5 ppm per year [1].

The optical and near IR filters are identical to those in the PICARD SODISM instrument as is the 215 nm filter, while the 210 nm filter was chosen to match the Herzberg filter implemented on LYRA/PROBA2 [2]. All UV filters have wavelengths that are of importance to ozone chemistry of the terrestrial atmosphere [3].

A PREMOS prototype was built and used to thoroughly test the integration of its components as well as the entire functionality of the electronics and mechanics. To verify the thermal analysis we conducted a thermal test that revealed an inconsistency with the modelled performance. As a result, we installed an additional heat pipe from the heat sink to the front plate of the package (see figure 1).

2. Characterization and calibration of the absolute radiometers

The PREMOS-PMO6 type radiometers were fully characterized as described in [4]. Since that publication we have found an additional effect that needs to be considered. PMO6 radiometers use resistance thermometers to measure the heat flux through the thermal impedance. The thermometers of the reference and the measuring cavity are combined into a Wheatstone bridge. The servo circuit regulates the bridge signal until it is zero by adjusting the heater power in the measuring cavity. Due to the fact that the front and rear radiometer cavities are not identical, a time-varying heat sink temperature results in a different bridge signal, and thus the power applied to the measuring cavity heater is altered. The resulting effect is small and only occurs with relatively fast changes in instrument temperature. It was found to produce a detectable effect in satellite data collected with PMO6 radiometers in the SOVIM experiment aboard the International Space Station. We are currently developing a model in order to correct past TSI observations made with PMO6 radiometers. The PREMOS software will correct for this effect.

Figure 1. The PREMOS experiment partly assembled. Filter radiometers are behind the upper three covers and two absolute radiometers are in the lower part of the instrument.

(This figure is in colour only in the electronic version)

2.1. PREMOS to SI vacuum calibration

The comparison of two PREMOS radiometers with the SI radiant power scale was performed from 7 to 18 April 2008 at NPL. The experimental set-up was similar to that of the past three comparisons between the World Radiometric Reference (WRR) and the SI reference as described by [6–8]. However, there was one fundamental difference: the comparison was conducted in vacuum rather than air as PREMOS radiometers will be operated in space. The advantage of a vacuum comparison is that it avoids the non-equivalence between radiative and electrical heating due to air conduction and convection. This non-equivalence results from different heat distribution and hence different heat losses to the surrounding air. During the phase of irradiation, cavity walls are heated by radiation reflected off the cone. This is different from the phase when the instrument shutter is closed, during which only the cone is electrically heated. As a result, the heat losses to ambient air are slightly higher during the irradiated phase.

A power comparison in vacuum with a beam that underfills the aperture only requires two parameters to characterize the instrument (see [4]): the reflective cavity losses and the lead heating. Our cavities have a reflectivity of 0.02% ± 0.013% at the laser wavelength ($\lambda = 632$ nm). The lead heating was determined to contribute 0.02% ± 0.007%. Table 2 lists the ratios of power as measured by both PREMOS radiometers

Table 2. Ratios of measured power and uncertainty ($k = 1.96$) of both PREMOS radiometers relative to the SI scale as realized by the cryogenic primary reference at NPL[a].

PREMOS-1/SI	0.9999	±0.0006
PREMOS-2/SI	1.0003	±0.0006

[a] Vacuum; under-filled aperture.

Table 3. Uncertainty budget for the power measurement comparison given in table 2.

Source of uncertainty	100 × Relative uncertainty
PMO6 reflectivity	0.0067
PMO6 lead heating	0.0034
Electrical power measurement	0.0013
Trap U	0.0012
Trap sensitivity	0.0100
Trap amplifier	0.0150
Beam-splitter	0.0256
Standard deviation	0.0022
Combined relative standard uncertainty	0.0323
Expanded ($k = 1.96$) uncertainty	0.0633

to the power measured by the cryogenic primary reference at NPL.

In table 3 we list the individual contributions to the uncertainty quoted in table 2. With the expanded uncertainties for reflectivity and lead heating, the radiometers should yield absolute power values to within 200 ppm. Both PREMOS radiometers agree with the SI scale well within this value.

The comparisons could be used to calibrate the instruments as the inverse of the values listed in table 2 are instrument calibration factors. Unfortunately, the expanded uncertainty of the comparison is not smaller than the uncertainty of the characterized radiometers. Fully characterized PMO6 radiometers have an uncertainty of 500 ppm [4] and PREMOS radiometers have appertures measured more accurately than assumed by [4]. It is therefore not possible to achieve a smaller measurement uncertainty by a calibration process for radiometers in space.

To further characterize PREMOS radiometers we also determined the non-equivalence of the instruments for under-filled apertures. The determination of this factor was conducted with the same set-up as for the power calibration at NPL except that we also measured the laser beam power with PREMOS radiometers operated in air. The non-equivalence factor is the ratio of the calibration factor (the inverse of the ratios of table 2) in air at ambient pressure to that in vacuum. Table 4 lists the non-equivalence factors of both PREMOS radiometers.

2.2. PREMOS to WRR calibration

For comparisons with the WRR in front of the Sun the apertures are over-filled. To account for the effect of the aperture being illuminated more correction factors need to be taken into account than for the under-filled SI comparisons as described above [4]:

lead heating 0.02% ± 0.007%;
cavity reflectance 0.03% ± 0.013%;
diffraction 0.11% ± 0.007%;
stray light 0.025% ± 0.02%.

Table 4. Non-equivalence factors and uncertainty ($k = 1.96$), i.e. air-to-vacuum ratios of both PREMOS radiometers. Measured for under-filled apertures but assumed to be valid for both under- and over-filled apertures.

PREMOS-1	1.0057	±0.0005
PREMOS-2	1.0070	±0.0005

Table 5. Ratios of measured solar irradiance from both PREMOS radiometers relative to the WRR scale as realized by the conventional primary reference at the World Radiation Center in Davos[a].

PREMOS-1/WRR	0.9997	±0.0014
PREMOS-2/WRR	1.0027	±0.0014

[a] Air; over-filled aperture.

Table 5 lists the ratios of irradiance as measured by both PREMOS radiometers to the irradiance measured by the World Standard Group at Davos, which realizes the WRR [5]. The agreement is satisfactory but to further improve the calibration status of PREMOS instruments, we plan to test the PREMOS-3 flight-spare instrument under laboratory conditions at the Total Solar Irradiance Radiometer Facility (TRF) at Boulder [9].

3. Characterization and calibration of the filter radiometers

3.1. UV filter radiometers

In total, eight UV filter radiometers, of which six will be used for PREMOS on the PICARD satellite, were characterized and absolutely calibrated at the Physikalisch-Technische Bundesanstalt (PTB). Four radiometers have a centre wavelength at about 215 nm and two radiometers at 266 nm. The filter bandwidth is 10 nm and 20 nm.

As a first step, the PTB characterized a set of suitable UV semiconductor detectors for use in the filter radiometers. The spatial homogeneity of the responsivity over the sensitive area of several detectors of different types was measured around the central wavelengths (210 nm and 268 nm) of each filter radiometer. Furthermore, spectral responsivity and temperature sensitivity were determined. The most suitable UV detectors were chosen for use in the filter radiometers. The second step was to calibrate the spectral irradiance responsivity of the assembled filter radiometers.

Calibration measurements were performed at the UV spectral responsivity calibration facility of the PTB [10]. To obtain a homogeneous beam profile a micro lens beam-homogenizer was applied in order to perform measurements of spectral irradiance. The beam profile of about $5 \times 5\,\text{mm}^2$ enabled the filter radiometers to be calibrated with respect to their spectral irradiance responsivity in the 190 nm to

Table 6. Uncertainty budget for the measurement of the spectral irradiance responsivity of filter radiometers at 212 nm and 268 nm.

	100 × Relative uncertainty	
Source of uncertainty	At 212 nm	At 268 nm
Repeatability	1.00	1.00
Positioning in the beam	0.60	0.60
Spectral responsivity of secondary standard	0.59	0.17
Spectral bandwidth effect	0.50	0.15
Aperture area of secondary standard	0.10	0.10
Stray light	0.10	0.10
Inhomogeneity of beam profile	0.10	0.10
Signal noise	0.020	0.020
Electrical measurements	0.005	0.005
Combined relative standard uncertainty	1.4	1.2

400 nm wavelength range. The spectral irradiance at the flat of the beam was about 0.084 W m^{-2} nm^{-1} at 215 nm and 0.174 W m^{-2} nm^{-1} at 268 nm. The spectral bandwidth was 1 nm. The associated uncertainty due to an inhomogeneous beam profile is less than 0.1%.

The filter radiometers were calibrated against a PtSi trap detector which is a PTB spectral responsivity standard for UV radiant power. This trap detector was provided with a precision aperture of 3 mm diameter to obtain a standard for spectral irradiance. The stability of this standard was monitored by comparing its responsivity against a third working standard several times during the calibration campaign. The spectral radiant power responsivity of the standard was measured against a cryogenic radiometer before and after the filter radiometer calibration campaigns. In this way, the calibration of filter radiometers was traceable to SI units.

The filter radiometers were calibrated during two calibration campaigns which had a six-month interval. The relative standard uncertainty of a responsivity measurement is about 1.4% at 212 nm and 1.2% at 268 nm and is calculated at the spectral maximum of the responsivity (table 6).

The repeatability of measurements (about 1.0%) is the dominant contribution to the uncertainty budget. The positioning of the detectors in the beam direction is a further important contribution to the uncertainty of about 0.6%. Equally important is the uncertainty of the spectral responsivity of the secondary standard that was used. This uncertainty includes the calibration uncertainty with respect to a cryogenic radiometer, the temporal stability of the secondary standard and a temperature correction for the responsivity. The spectral bandwidth during the calibration was 1 nm. Therefore, bandwidth effects have to be considered that account for the spectral shape of the filter transmittance. Other uncertainty contributions such as stray light do not have a significant impact on the combined uncertainty.

The effective wavelength of the radiation has a systematic uncertainty of 30 ppm. This uncertainty is strongly correlated over the sensitive spectral range of the filter radiometer. For this reason, this wavelength uncertainty does not significantly affect the shape and the amplitude of the spectral responsivity but only the spectral location of the responsivity bandpass. The responsivities of the filter radiometers were measured at temperatures around 21 °C. The temperature of each single measurement was monitored. A temperature correction has to be carried out if the operating temperature differs from 21 °C. However, due to the properties of the interference filter a change in temperature mainly affects the spectral location of the responsivity.

Table 7. Relative loss of spectral irradiance responsivity for UV channels at the maximum of sensitivity.

Head	Channel	Wavelength/nm	100 × Relative change
A	1	212	−6.5
A	4	268	−3.5
B1	1	212	−5.9
B1	3	213	−7.4
C	1	212	−6.4
C	4	269	−4.2

The sensitivities of the instrument heads A, B1 and C were calibrated in September/October 2007 as well as in March/April 2008. We observed a decrease in responsivity of the UV filter radiometers that significantly exceeds the measurement uncertainty: up to about 8% degradation of the peak responsivity within six months. Table 7 gives the relative changes in the six UV filters which were calibrated twice. A fourth head, B2, which has two UV filters with a centre wavelength at 215 nm, was only measured in March/April 2008. Head B2 replaces head B1 in the PREMOS flight model.

Further investigations with the spare instrument head, B1, will be performed to identify the reasons for this drift. The spectral characteristics of the degradation indicate that the most likely cause is instability of the interference filters.

3.2. *The visible and near IR filter radiometers*

The visible channels of four PREMOS filter radiometer heads (one is a spare head) were calibrated at PMOD/WRC, using two tungsten–halogen irradiance standards (1000 W FEL type) traceable to the primary spectral irradiance standard of the PTB. F300 and F301 were calibrated relative to BB3200pg on 2 December 2004 and 14 May 2007, respectively.

The optical entrance of the PREMOS heads limits the field-of-view to about ±1.5°. To ensure that the irradiation from the lamp is entirely received by the sensor, the distance to the lamp must be large enough and its alignment towards the lamp must be of high accuracy. This was verified by a field-of-view measurement. The result is that at a 2 m distance from the lamp reference plane to the head reference plane (sensor surface) and an alignment uncertainty of ±0.5° the emitted radiation is entirely received by the sensors.

All PREMOS heads were illuminated using the reference lamp, F301. The calibration was verified using the lamp, F300, at heads B and B2. The variability in calibration by using F300 and F301 is between −0.7% and +1.9%. The difference of the actual distance from the sensor surface to the lamp reference plane (approximately 2 m) to the distance stated in the calibration certificate of the primary standard lamps

Table 8. Uncertainty budget for irradiance measurement of the PREMOS radiometers in space.

Source of uncertainty	100 × Relative uncertainty
Reflectivity	0.0067
Lead heating	0.0034
Aperture area	0.0025
Stray light	0.0115
Diffraction	0.0040
Combined relative standard uncertainty	0.0153
Expanded ($k = 1.96$) uncertainty	0.0300

(700 mm) was taken into account. The absolute calibration provides calibration factors for all visible filter channels and the total expanded uncertainty[8] of the measurement $u = \pm 4\%$.

4. Conclusions

The PREMOS experiment will carry the first absolute radiometers into space that were calibrated in vacuum against the SI radiant power scale. In order to transfer the SI calibration into space for irradiance measurements we will have to apply additional corrections for diffraction and stray light, due to the apertures being over-filled during operation. In table 8 we give the uncertainty budget of both PREMOS radiometers for irradiance measurements in space.

The intended goal, to obtain radiometer calibrations with an uncertainty of less than 100 ppm, was not attained because a beam-splitter for the NPL comparison had to be used. Determination of the splitting value of the beam-splitter dominates the uncertainty budget.

Although the filter radiometers have now been finally calibrated, it is not yet clear whether further degradation of the UV channels has to be taken into account. We will follow the development of the responsivity of the spare instrument head in order to arrive at a conclusion.

The flight model was delivered in June 2008 and the integration took place in July 2008. The tests were successfully passed and the PREMOS experiment is now ready for launch, which is at present scheduled for the end of the year 2009.

References

[1] Thuillier G, Dewitte S, Schmutz W and the PICARD team 2006 *Adv. Space Res.* **38** 1792

[2] Hochedez J-F *et al* 2006 *Adv. Space Res.* **37** 303

[3] Rozanov E, Egorova T, Fröhlich C, Haberreiter M, Peter T and Schmutz W 2002 *ESA SP* **508** 181

[4] Brusa R and Fröhlich C 1986 *Appl. Opt.* **25** 4173

[5] 1979 *Technical Regulations WMO* No 49, Geneva

[6] Romero J, Fox N P and Fröhlich C 1991 *Metrologia* **28** 125

[7] Romero J, Fox N P and Fröhlich C 1995 *Metrologia* **32** 523

[8] Finsterle W, Blattner P, Moebus S, Rüedi I, Wehrli C, White M and Schmutz W 2008 *Metrologia* **45** 377

[9] Kopp G, Heuerman K, Harber D and Drake G 2007 *Proc. SPIE* **6677** 667709

[10] Meindl P, Klinkmüller A E, Werner L, Johannsen U and Grützmacher K 2006 *Metrologia* **43** 72

---

[8] The reported expanded uncertainty of measurement u is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%.