Technical Report

International Intercomparison of Secondary Standard Pyranometers and Pyrheliometers

Laboratory of Radiometry and Photometry
Universidad de Santiago de Chile (USACh)
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Chapter 1

Introduction

This is one o of the first international intercomparison of secondary standard radiometers held in Latin America. It took place between 3 and 7 of September 2018 in the outdoor facilities of the Laboratory of Photometry and Radiometry of the Physics Department of the Universidad de Santiago de Chile at Santiago. The activity was hosted by Dr. Raúl Cordero and his collaborators and sponsored by PTB (Germany), represented by Ms. Imilce Zuta. Both global irradiance and direct irradiance measuring instruments where compared. The reference instruments for global irradiance measurements where provided by the World Radiation Center (WRC/PMOD) from Switzerland, represented by Dr. Wolgang Finisterle. The reference instrument for direct irradiance was a new absolute pirheliometer of the Laboratory of Photometry and Radiometery recently calibrated at PMOD with trazability to the World Radiation Reference (WRR).

Participants

Metrological institutes, research laboratories (some of them candidate delegate centers for calibration of radiometers) and one meteorological office have participated in this event with one or more instruments. Seven different countries are represented in this intercomparison. Table 1.1 lists the participating institutions and instruments.

Objectives of this activity

The general objective of the activity is to improve the metrological capacities in solar radiation measurements of the participating laboratories. In the case of LES, the specific objectives are:

- compare our secondary standard radiometers with the secondary standards provided by WRC, trazable to the World Radiometric Reference.

Center	Type	Country	Instruments	Brand	Model	Serial
USACh	research laboratory	Chile	pyranometer	Kipp & Zonen	SMP21	170007
			pyranometer	Kipp & Zonen	SMP22	160026
			pyrheliometer	Kipp & Zonen	SHP1	175112
			pyrheliometer	PMOD	PMO6	1602
LES UDELAR	research laboratory	Uruguay	pyranometer	Kipp & Zonen	CMP22	110282
			pyranometer	Kipp & Zonen	CMP22	120420
			pyheliometer	Kipp & Zonen	CHP1	120994
			pyheliometer	Kipp & Zonen	CHP1	150261
			data logger	Fischer Scient.	DT85	102813
INTI	Metrological Institute	Argentina	pyranometer	Kipp & Zonen	CMP11	152963
USP	research laboratory	Brazil	pyranometer	EKO	MS-80	16002013
			data logger	Agilent	34972A	49001867
LABE UNAL	research laboratory	Colombia	pyranometer	Kipp & Zonen	CMP10	141141
			pyranometer	EKO	MS-80	18003080
WRC PMOD	research lab	Switzerland	pyranometer	Kipp & Zonen	CM22	990010
			pyranometer	Hukseflux	SR25	2517
CENAM	metrological institute	Mexico	pyranometer	Kipp & Zonen	CMP21	140336
DMC	meteorological service	Chile	pyranometer	Kipp & Zonen	CMP3	164509
			data logger	Campbell Scient.	CR6	5204

Table 1.1: List of participating centers and instruments.

- compare two of our pirheliometers with the DNI measured by the absolute cavity radiometer PMO6 instrument, from USACh.
- test our implementation of the standards ISO-9847 and ISO-XXX.
- further test, against the standard ISO-9847 results, the alternative method used at LES for the data processing.
- standarize the way in which the uncertainties are computed and compare our results with those from the other participating laboratories.

General methodology

The general methodology was consensually agreed by the participants during the Santiago meeting. The instruments would be deployed in the outdoor measuring area during the whole measuring period (up to five days). During measurements, access to the platform was limited to two or three times a day, and a log of the interventions was kept. Four data aquisition systems where used (aside from the three listed in Table 1.1 , the control unit of the PMO6 was used for the USACh radiometers).

All the raw data was shared between the participants. Each laboratory provided the detailed information about its instruments, including the calibration certificates and the instrument condition and recent history (new, in storage, on field).

It was agreed that the ISO 9847:1992 standard *Calibration of field pyranometers by comparison to a reference pyranometer* should be followed as close as possible for the pyranometer calibrations [ISO92]. The reference instruments for the pyranometer calibrations would be those from the WRC and they where connected each to a different data logger. For the pyrheliometer calibration, the standard ISO 9059:1991 *Calibration of field pyrhe-*

liometers by comparison to a reference pyrheliometer should be followed as close as possible [ISO91] and the absolute cavity pirheliometer PMO6 from USACh would be used as the reference.

Each center would process the raw data according to its usual methods and report the results for the new sensitivity (or constant) of each participating radiometer with the corresponding uncertainty interval at P95 level of confidence. The calculation and expression of the uncertainties should follow the guidelines from the GUM [Joi08]. The results from WRC would be considered as the final values and they would not be disclosed until the end of the process. In this way, not only the instruments are tested but also the methods followed by each center are evaluated in this intercomparison.

On the scope of this report (disclaimer)

This technical report is the responsability of Laboratorio de Energía Solar (LES) alone. It reports the values of sensitivity obtained at LES for all the pyranometers and pyrheliometers that participated in this intercomparison when processed according to the methods described in the report. However, it is not ment to be a substitute of a proper calibration certificate for any of these instruments.

Its purpose is to document the detailed procedures followed by LES and the results obtained. It is not a report for the full intercomparison activity either. We hope that this complete report will be elaborated jointly by all participating centers in due time.

Chapter 2

Intercomparison of Pyranometers

The GHI calibration involved twelve pyranometers connected to three data acquisition systems (DAQ). The two pyranometers from WRC where used as reference instruments for the calibration, so only two DAQs had a reference pyranometer connected to them. The CR6 DAQ from the Meteorology Office (Chile) had only a single Second Class pyranometer, a CMP3 from Kipp & Zonen (see Table 1.1), which will not be taken into account in this report.

2.1 Setup of the instruments

The setup of the instruments on the outdoor platform of USACh (Fig. 2.1) was done during the first day.

Each team did the setup for its own instruments. Most instruments where organized in two dataloggers according to the details in Tables 2.1 and 2.2. The USACH instruments where connected to the PMO6 data aquisition system, running on a notebook computer indoors, as indicated in Table 2.3. The last calibration certificate of each instrument was provided, in all cases with trazability to the World Radiometric Reference (WRR). The DAQs details and calibration certificates (Fischer Scientific DT85 and Agilent 34972A) are provided in Appendix A. The requisites to be satisfied by the reference and the test radiometers, the site and the good practices recommended for recording the data, are described in [ISO92]. Simultaneous voltage signals from the standard and test radiometers where recorded every 30 seconds. Clocks in both DAQ systems where syncronized to an internet server on day 1. Data in DAQ3 (Table 2.3 was recorded at 3-min intervals, as this is the shortest interval at which the control unit could operate the PMO6 instrument. Day 1 was for setup and tests. The period of useful measurements extended from day 2 to day 5.

Figure 2.1: Outdoor platform at USACh before the deployment of the instruments.

instrument number	owner	model	serial number	sensitivity $\mu V/Wm^{-2}$	P95 uncertainty $\mu V/Wm^{-2}$	last calibration (center and date)	DAQ channel
5	LES	CMP22	110282	8.94	0.06	WRC 30/10/2012	1 ±
6	LES	CMP22	120420	8.97	0.19	LES 07/10/2017	3 ±
7	LES	CHP1	150261	7.24	0.08	KZ 06/02/2015	5 ±
8	LES	CHP1	120994	8.97	0.19	KZ 30/08/2012	7 ±
9	INTI	CMP11	152963	8.45	0.11	KZ 12/11/2015	9 ±
13	WRC	CM22	990010	11.410	0.057	WRC 28/08/2018	11 ±

Table 2.1: Instruments connected to Fischer Scientific DT85 from LES (DAQ1). KZ corresponds to Kipp & Zonen, with a manufacturer calibration certificate. Note that instruments 7 and 8 are pyrheliometers. P95 uncertainty is assumed with coverage factor 2 in this report.

inst. number	owner	model	serial number	sensitivity $\mu V/Wm^{-2}$	P95 uncertainty $\mu V/Wm^{-2}$	last calibration (center and date)	DAQ channel
10	USP	Eko MS80	16002013	11.500	0.078	EKO 22/4/16	111
11	UNAL	KZ CMP10	141141	8.81	0.12	KZ 10/12/14	106
12	UNAL	Eko MS80	18003080	9.700	0.063	Eko 10/05/18	104
15	CENAM	KZ CMP21	140336	9.22	0.19	CENAM 26/04/18	107
14	WRC	HK SR25	2517	10.93	0.15	WRC 28/08/2018	101

Table 2.2: Instruments connected to DAQ2 Agilent 34972A from USP. HK corresponds to Hukseflux, with a manufacturer calibration certificate. Pyranometer 10 had a channel change (102 → 111) due to grounding problems at the morning of day 2 (4/9).

2.2 Measurements

The requisites to be satisfied by the reference and the test radiometers, the site and the good practices recommended for recording the data, as described in [ISO92] where implemented. Maintenance (mainly cleaning of the domes and checking the horizontal level of the individual radiometers)

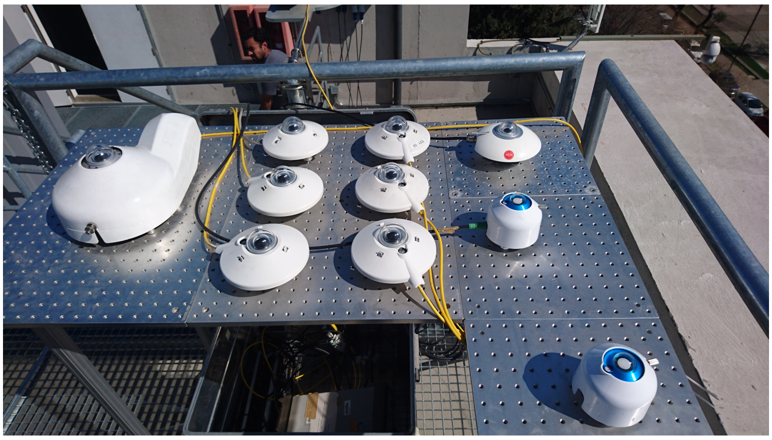

Figure 2.2: Pyranometers deployed.

Figure 2.3: [Left] LES Pyrheliometers mounted on a Kipp & Zonen Solys 2 tracker. [Right] USaCh Pyrheliometer and PMO6 absolute cavity pyrheliometer mounted on a Kipp & Zonen Gear-drive tracker.

inst. number	owner	model	serial number	sensitivity $\mu V/Wm^{-2}$	P95 uncertainty $\mu V/Wm^{-2}$	last calibration (center and date)
1	USACH	KZ SMP21-V	170007	10.25501	na	KZ 20/03/17
2	USACH	KZ SMP22-V	160026	9.91	0.08	KZ 13/04/16
3	USACH	KZ SHP1-V	175112	8.58	0.09	KZ 15/02/17
4	USACH	PMO 6	1602	51139.6 m^{-2}	31.5 m^{-2}	WRC 30/08/17

Table 2.3: Instruments with smart modbus sensor connected to the PMO6 control system (DAQ3) running on a PC kept indoors. Note that instruments 3 and 4 are pyrheliometers and inst. 4 is taken as the reference for DNI measurement.

was performed twice a day during the calibration. The USACh platform presented some stability problems if people walked frequently on it. During the first day (3/9), several instruments where found off-level several times. It was agreed that a single operator would check the leveling of all instruments three times a day (early morning, noon, late afternoon), this reduced transit in the platform and interferences with the measurements. Data for this first day was discarded. The period for measurements extended from noon day 2

DAQ	**Model**	**start**	**end**	Δt	N_{raw}
DAQ1	Fischer Sc. DT85	5/9 00:00:30	7/9 17:37:30	30 sec	7474
DAQ2	Agilent	4/9 11:25	7/9 17:36	30 sec	8429
DAQ3	PMO6 control unit	3/9 17:28:30	7/9 23:59:30	3 min	3463

Table 2.4: Data taking periods for the three DAQ's used. All dates are in the local timezone (UTC-3). In the case of DAQ1, data from days 1 and 2 (Mon, Tue) as well as part of data from day 4 (Thu) between 12:30 and 15:50 was omitted because improper levelling was detected in the reference instrument.

(4/9) to the afternoon of day 5 (7/9). In Table 2.4 we summarize the period for the measurements in each DAQ system.

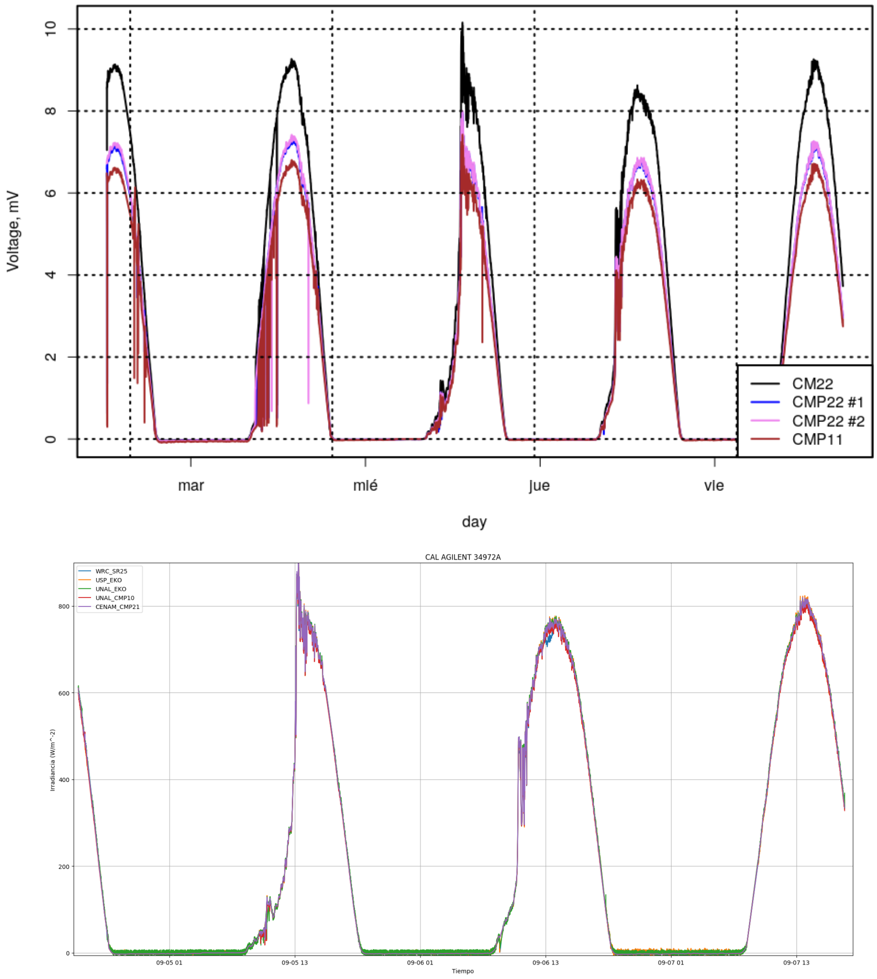

Figure 2.4: Raw data from DAQ1 (DT85, upper panel) and DAQ2 (Agilent, lower panel). In the case of DAQ1, data until noon of the third day was omitted from the analysis due to misalignment problems with the standard.

2.2.1 Reference instruments

The two pyranometers from the WRC where used as reference instruments for the calibration of all other pyranometers (GHI). The Kipp & Zonen CM22 was connected to the DAQ1 system (DT85) and the Hukseflux SR25 was connected to the DAQ2 (Agilent). The sensitivities and P95 uncertainties for these instruments are listed in the bottom row of Tables 2.1 and 2.2, respectively. They have both been calibrated at WRC in 28/8/2018 with trazability to the WRR with P95 relative uncertainties are 0.5 % and 1.4%,

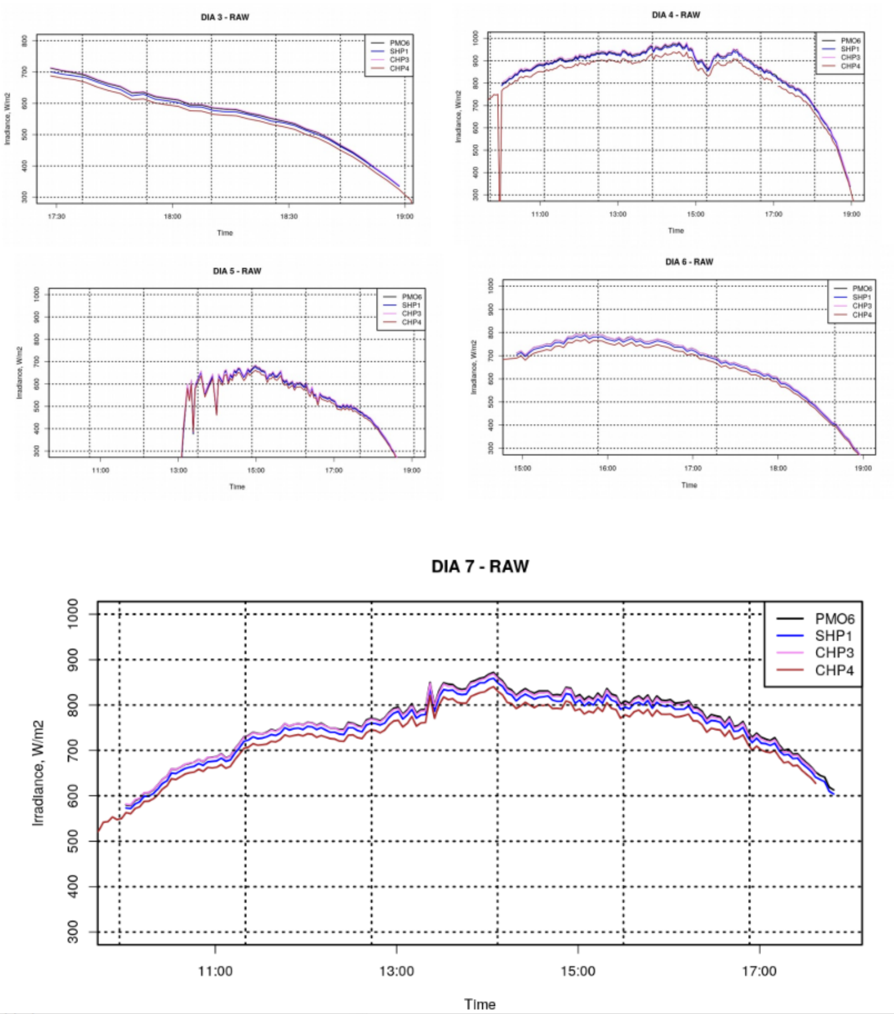

Figure 2.5: Raw data from DAQ3 (PMO6 control unit). Note that it is in terms of irradiance (W/m^2). The pyrheliometers CHP1 #3 and #4 where connected to DAQ1. The average 3-min DNI using the previous sensitivities listed Table 2.1 is shown here.

respectively.

DNI data for a calibration of pyrheliometers (two from LES and one from USaCh) has also been recorded. These instruments where mounted on precision solar trackers as shown in Fig. 2.3. The reference instrument for DNI was a PMO6 absolute cavity pyrheliometer mounted on its own precision tracker. This instrument was calibrated at PMOD in 30/08/17 with trazability to the WRR and the extremely low relative P95 uncertainty 0.06% . The USaCh pyrheliometers all use the automated DAQ and control unit of the PMO6 which measures DNI every 3 minutes, see Table 2.3. So the DNI comparison will be made on this time scale, after integrating the

30 second readings of the DT85 logger.

2.3 Methodology

The data processing as described in the ISO 9847:1992 standard involves grouping the data into series, each of them satisfying several criteria as described below. This processing involves a few steps which are not easy to automatize. At LES we use an alternative scheme for the data processing, which involves filtering out clear-sky data points and treating them statistically as part of a single set. This scheme has had an initial validation described in [AMS18]. This intercomparison provides an opportunity for further validation of the alternative method.

Below we describe the standard method (as described in [ISO92]) and the alternative method, with a focus in the parts in which it is different from the standard method.

2.3.1 Standard method

The data processing scheme in both methods can be separated into three stages:

1) a preliminary filtering stage which preserves daylight clear-sky data and arranges it into candidate series.

2) an outlier rejection stage.

3) the calculation of the new constant and its uncertainty from the filtered series.

Filtering stage

The raw data is first filtered according to the following criteria:

F1: Solar altitude, $\alpha_s \geq 20°$

F2: Diffuse fraction, $f_d \leq 0.20$

Filter F1 above is required by ISO-9487:1992. Usually low-sun data is affected by high directional errors (cosine error of the instruments) and other factors. The solar altitude can be calculated from local position (latitude and longitude), time and day of year [DB06]. This filter selects daytime data for which the sun is at least 20° above the horizon.

Filter F2 places an upper limit on the diffuse fraction f_d (the ratio of diffuse to global irradiance). In Uruguay, under clear-sky conditions, the diffuse fraction is usually lower, between 0.10 and 0.18, depending on the water and aerosol content in the atmosphere. Under a very cloudy sky, the sun is not directly visible and all irradiance is diffuse ($f_d = 1$). The standard ISO-9487:1992 states that *"the calibration of pyranometers to be employed in solar energy applications shall be performed only under conditions in which the sun is unobstructed by clouds throughout the data-taking period, with a minimum direct solar irradiance on a horizontal surface of 80% of the global horizontal irradiance"* and this implies a maximum diffuse fraction of 0.20, as indicated above.

Therefore, F1& F2 (logical AND) selects the data points corresponding to high sun and mostly clear sky conditions. Let N_1 be the number of data records that satisfy these conditions.[1]

Following the ISO-9487:1992 protocol, the N_1 data points are organized into N_s continuous series, each with $N(j)$ data points corresponding to a 10 to 20 minute time interval. Let the index j ($j = 1, 2, \ldots N_s$) refer to a given series and let the index i ($i = 1, 2, \ldots N(j)$) refer to a single measurement within series j. The series must span morning, noon and afternoon periods and must belong to at least two different days, to allow for diversity.

The following restrictions apply to the length and number of the final series,

i. $N(j) \geq 21$

ii. $N_s \geq 15$

That is, at least 15 series of 21 contiguous clear-sky data points are required [ISO92, Sec. 5.2.2.1].

Once the N_1 data records are arranged into N_s candidate series of $N(j)$ contiguous data points, a clear-sky selection filter is applied to each series. Actually the ISO 9847:1992 standard asks for *stable cloudless conditions*, without suggesting a quantitative objective set of criteria to automatically select these conditions in the data. Furthermore, in its Appendix B, the standard states that *no cloud formation shall be within* 30° *of the sun during the data taking period and in the case of automatic data acquisition this criterion can be replaced by a minimum irradiance threshold which indicates interference by clouds* [ISO92, Ap. B.2]. This wording suggests that the standard was intended mainly with a human observer present during the measurements, which was a common way to record solar data at the time (pre 1990).

In order to detect clear-sky conditions automatically, we use a normalized version of the clearness index [PISZ90],

$$k'_t = \frac{k_t}{0.1 + 1.031 \exp\left(\frac{-1.4m}{9.4+0.9m}\right)}, \tag{2.1}$$

[1] Filter F2 has not been applied in this intercomparison because diffuse radiation was not measured.

defined in terms of the air mass (calculated from the solar zenith angle θ_z as $m = 1/\cos\theta_z$ for data points which satisfy condition F1 above) and the clearness index k_t (the horizontal global irradiance normalized by horizontal extraterrestrial irrandiance). This is a dimensionless expression of global solar irradiance and for clear-sky conditions typically takes values around 0.85, as even the clearest atmosphere absorbs and disperses some fraction of the extraterrestrial irradiance. See for instance Ref. [DB06] for details on how to calculate these normalized quantities. The threshold $k_t' > 0.60$ proposed in [MD95] is used to detect clear-sky conditions. We use instead the additional requirement that $k_t > 0.60$. Furthermore, we use an upper limit for the clearness index ($k_t < 0.90$) to exclude overshoot events[2] which it is convenient to exclude since they usually include fast variations and atypical values for irradiance.

Summarizing, clear-sky records are selected on the basis of two conditions applied to the average values of the clearness index and the modified clearness index,

$$\mathrm{F3}: k_t'(j) \geq 0.60 \qquad \& \qquad \mathrm{F4}: 0.90 > k_t(j) > 0.60. \tag{2.2}$$

If after these filters are applied a series has less than 21 data points, it is discarded. The final stability of the surviving series is tested later, when outliers are discarded. The N_s series (with a total of N_2 ($N_2 < N_1$) data points) that satisfy the requirements F1 to F4 described above are subject to the following data processing in order to discard outliers and determine the new constant for the test instrument.

The simultaneous recorded values for the test (or field) and the reference instrument are indicated $V_F(i,j)$ and $V_R(i,j)$, respectively. Both quantities are expressed in units of mV. The constant of the reference instrument is indicated as F_R and that of the test instrument as F, both expressed in units of $\mathrm{Wm^{-2}/mV}$. A given irradiance measurement (in $\mathrm{W/m^2}$) is expressed as $G = F_R V_R = F V_F$.

If the reference instrument is well characterized, its constant will be corrected for the typical conditions (instrument temperature, solar incidence angle, solar azimuth) for a series j and will be expressed as $F_R(j)$.

For each of the N_s series, a test constant (in $\mathrm{Wm^{-2}/mV}$) is calculated as

$$F(j) = F_R(j)\,\frac{\sum_{i=1}^{N_r} V_R(i,j)}{\sum_{i=1}^{N_r} V_F(i,j)} = F_R \times \kappa(j). \tag{2.3}$$

where $\kappa(j) = \langle V_R\rangle / \langle V_F\rangle$ is the ratio of average voltages within the series and the second term assumes $F_R(j) = F_R = \mathrm{const}$.

[2]For certain white cloud configurations lasting a few minutes, the pyranometer can record irradiance values larger than the solar constant (the average solar irradiance incident or our planet's external atmosphere, conventionally $1367\,\mathrm{W/m^2}$).

Outlier rejection stage

For each measurement within series j, the individual factors

$$F(i,j) = F_R(j)\frac{V_R(i,j)}{V_F(i,j)} \tag{2.4}$$

are also calculated. Data records (i,j) for which the relative absolute deviations exceed more than 2% the series factor are discarded as outliers [ISO92, Sec. 5.4.1.3]. Explicitly, if the condition

$$F5: \quad \left|\frac{F(j) - F(i,j)}{F(j)}\right| < 0.02 \tag{2.5}$$

is not satisfied, the record (i,j) is rejected. After discarding these points, $N(j)$ and N_s are updated (if a series has less than 21 points, it is rejected). Finally, Eq. (2.3) is used to obtain the revised factors $F(j)$ for the remaining series.

A preliminary constant F for the field instrument is obtained as the simple average over the filtered series:

$$F = \frac{1}{N_s}\sum_{j=1}^{N_s} F(j) = F_R \times \langle\kappa\rangle \tag{2.6}$$

where the second expression assumes $F_R(j) = F_R$ (constant) and the average is over filtered series.

As a final statistical repeatability check, the standard requires that all series which include or are close to solar noon should have a standard deviation which is less than 0.5% of the final calibration factor F. For all series j for which the average solar angle satisfies $\omega(j) < 5°$ (20 minutes from solar noon), the standard deviation σ_j of $F(i,j)$ from its mean $F(j)$ is computed, and the condition

$$F6: \quad \sigma_j < 0.005\,F \tag{2.7}$$

is tested. Any series which does not comply is discarded and Eq. (2.6) is applied again to determine the new constant. Finally, the sensitivity s (in μV/Wm^{-2}) can be obtained from $s = 1000/F$.

New constant calculation

With the remaining series, provided $N_s > 15$, the final constant F is obtained from Eq. (2.6) and the standard deviation σ_F from this mean is also calculated and reported in the calibration certificate as it represents the variability throughout the calibration.

This organization of the data by series results in more complex programming schemes. However, it should be noted that the stability of solar irradiance is an important issue when comparing instantaneous readings from instruments with different response times, because this is a spurious cause for discrepancy (unrelated to the accuracy of the test instrument). This effect is present under conditions with high irradiance variability (due to mixed conditions with scattered clouds) and would increase the calibration uncertainty artificially. In order to minimize this effect, the standard demands stable sunshine conditions. And, of course, dividing data in N_s series has the benefit that the uncertainty is reduced by a factor $1/\sqrt{N_s}$, regardless of the distribution of the data.

2.3.2 Alternative method

The alternative implementation of the calibration procedure use at LES follows closely the norm ISO-9847:1992 outlined in the previous Section, but considers a different data processing based on robust regression techniques. The overall aim is to simplify the automatic data treatment while preserving the accuracy of the results. The initial data collection is the same in both cases, but in the alternative scheme the outlier rejection and the overall data organization differ.

Select clear-sky conditions

The data is not organized in series at all. Filters F1, F3 and F4 described in Subsection 2.3.1 are applied sequentially. Filter F2 is not applied because diffuse irradiance was not measured during the intercomparison. The set of N_2 points that satisfy these requirements is subject to the data processing described below in order to discard outliers.

Discard outliers

A linear relation $\hat{V}_F = A + BV_R$ is assumed between the test and reference signals. A two-stage fitting procedure is used to remove outliers and determine the calibration constant (F_R/B). An alternative procedure based on robust regression[3] was used but provided no significant advantages.

A standard linear regression fit is performed on the N_2 filtered points and preliminary parameters A' and B' are determined. The vector of residuals $\epsilon(i)$ $(i = 1, 2, \ldots N_2)$ is calculated for each pair (V_F, V_R) as

$$\epsilon = \hat{V}_F - V_F = (A' + B' \times V_R) - V_F. \tag{2.8}$$

The mean of the residuals, $\bar{\epsilon}$, and the standard deviation from the mean, σ, are also calculated. In this step, the $N_2 - N_3$ data points whose residual

[3] Robust regression is an alternative to least squares regression when data are contaminated with outliers or influential observations. In the alternative implementation, the robust linear fitting routine `rlm` of the MASS package of the R statistical software [R C18] was used. It is based on the iterated re-weighted least squares (IWLS) method [Mar93].

differs from the mean by more than one standard deviation are discarded as outliers. The residuals of the remaining N_3 points satisfy the condition

$$|\epsilon(i) - \bar{\epsilon}| < \sigma. \tag{2.9}$$

If a new regression is done with the "clean data" $(V_F(i), F_R(i) \times V_R(i))$, the resulting parameter B is the new constant for the test pyranometer.

However, in order to depart as minimum as possible from the standard method, the calibration factor is calculated from the N_c *clean* data points as the average:

$$F = \frac{1}{N_3} \sum_{i=1}^{N_c} F_R(i) \frac{V_R(i)}{V_F(i)} = F_R \times \langle \kappa(i) \rangle \tag{2.10}$$

where the second term applies if $F_R(i) = F_R = \text{const}$ and $\kappa(i) = V_R(i)/V_F(i)$ and the average is *over all clean data points*. Note that this is the only difference with Eq. (2.6) for the standard method.

The standard deviation from the mean, σ_F, is also calculated and reported. The reference pyranometer constant, F_R, is usually assumed invariant. However, if the information is available, one can correct the nominal constant F_R for systematic errors (such as variations in the instrument's temperature or in incidence angles) and then each data point will have a slightly different F_R. For this reason, it is left within the sum. In this intercomparison, F_R is assumed constant with all data points and systematic errors will contribute to the uncertainty in the final calibration constant.

2.3.3 Outline of the uncertainty calculations

Uncertainties are calculated and expressed following the GUM [Joi08]. Useful examples in the context of repetitive pairs of irradiance measurements are found in [Hye00, KH15]. In order to clarify notation: we shall use u_X for the *standard* uncertainty in variable X and $\delta_X = u_x/X$ for relative uncertainty in X.

We discuss first the standard method and later adapt the result for the alternative method. From Eq. (2.6), the relative (squared) uncertainty in F is

$$\delta_F^2 = \delta_R^2 + \delta_\kappa^2 \tag{2.11}$$

where δ_R is the *standard* relative uncertainty (either in sensitivity or in the constant) of the reference radiometer.

Reference instrument contribution

For the CM22 reference this is $\delta_{F_R} = 0.0025$ and for the SR25 reference it is $\delta_{F_R} = 0.0069$, using the expanded uncertainties (with coverage factor $k = 2$) from Tables 2.1 and 2.1.

Repeatability contribution

In the Standard method, κ is obtained as a simple average over the $\kappa(j)$ factor of N_s series. Therefore, it will be affected by a repeatability contribution $u_{\kappa,rep} = \sigma_\kappa/\sqrt{N_s}$, where σ_κ is the standard deviation from the mean in Eq. (2.6). The corresponding relative uncertainty is

$$\delta_{\kappa,rep} = \frac{u_{\kappa,rep}}{\langle\kappa\rangle} = \frac{\sigma_\kappa}{\sqrt{N_s}\langle\kappa\rangle} \tag{2.12}$$

where the average is over the N_s series, as in Eq. (2.6).

DAQ contribution

Each $\kappa(j)$ is a ratio of average voltages within a single series (Eq. (2.3)), $\kappa(j) = V_R(j)/V_F(j)$, where these are the *average* voltages of reference and field instrument within series j. These voltages are affected by the DAQ uncertainties. Assuming both instruments are connected to the same DAQ, it suffices to calculate one of them and multiply by $\sqrt{2}$ (for quadratic addition). Thus,

$$\delta^2_{\kappa,V} = \delta^2_{V_R} + \delta^2_{V_F} = 2\delta^2_V \tag{2.13}$$

where δ_V is an estimate of the relative error of the DAQ when measuring a voltage V. In Appendix A we include the relevant information about the DAQ systems used to measure GHI and show that for the DT85 $\delta_V = 0.001$, the nominal error of the 30 mV scale, is a reasonable estimate for the voltage contribution to the relative standard uncertainty with a typical voltage $V = 6\,\mathrm{mV}$. Since two voltages are measured, for the DT85 $\delta_{\kappa,V} \approx 0.0014$.

Other contributions, such as offset errors, directional errors, temperature dependence of the reference instrument, etc are not considered explicitly and will contribute to the overall uncertainty through the repeatability term and the uncertainty of the reference instrument.

Adding quadratically all contributions, Eq. (2.11), the relative combined standard uncertainty becomes

$$\delta_c = \sqrt{\delta^2_R + \delta^2_{\kappa,rep} + \delta^2_{\kappa,V}} = \sqrt{\delta^2_{F_R} + \frac{\sigma^2_\kappa}{N_s\langle\kappa\rangle^2} + 2\delta^2_V}. \tag{2.14}$$

Thus, the relative combined standard uncertainty can be evaluated from the standard uncertainties in the reference instrument, an estimate of the standard uncertainty in the voltage measurements, the number of series ($N_s \geq 21$, according to the ISO 9847:1992 standard) and the average of the series ratios $\kappa(j)$ and its variance σ^2_κ.

This is the relative uncertainty in both the field's instrument constant F and sensitivity s, so we can drop the variable reference and refer to a single relative *combined standard uncertainty* as

$$\delta_c = \delta_F = \delta_s \tag{2.15}$$

since these magnitudes are related by $s = 1000/F$. The standard combined uncertainties are readily obtained from

$$u_{s,c} = s \times \delta_c, \quad \text{and} \quad u_{F,c} = F \times \delta_c. \tag{2.16}$$

and, assuming a coverage factor $k = 2$ (infinite degrees of freedom) the expanded uncertainties are

$$u_s = 2s \times \delta_c, \quad \text{and} \quad u_F = 2F \times \delta_c. \tag{2.17}$$

Due to the repeatability contribution, this calculation must be done for each field instrument.

Expression for the Alternative method

When the alternative method is used, Eq. (2.10) replaces (2.6) and $\langle\kappa\rangle = \langle V_R/V_F\rangle$ where the average is now over all *clean* data points, i.e. those that passed all filters (F1 to F6). The analysis is the same as before, except for the repeatability contribution which is now simply $u_{\kappa,rep} = \sigma_\kappa$, where σ_κ is now the standard deviation within the N_c set. The relative uncertainty is

$$\delta_{\kappa,rep} = \frac{u_{\kappa,rep}}{\langle\kappa\rangle} = \frac{\sigma_\kappa}{\langle\kappa\rangle}. \tag{2.18}$$

Thus, in this case the final expression the relative combined standard uncertainty is

$$\delta_c = \sqrt{\delta_{F_R}^2 + \frac{\sigma_\kappa^2}{\langle\kappa\rangle^2} + 2\delta_V^2}. \tag{2.19}$$

However, the average and variance in Eqs. (2.14) and (2.19) *are not the same*. Once the relative combined uncertainty δ_c has been calculated, the rest of the calculations are as stated in Eqs. (2.15) to (2.17).

2.4 Results

The data from both DAQs was processed by both methods (Standard and Alternative). The results are reported in separate subsections.

2.4.1 Standard method

DAQ1: DT85

The instruments listed as number 5, 6 and 9 in Table 2.1 are calibrated against the reference instrument, number 13. The reference instrument (CM22 ns 990010 from WRC) has sensitivity $s = 11.41\,\mu\text{V}/\text{Wm}^{-2}$ and constant $F_R = 1000/s = 87.64\,\text{Wm}^{-2}/\text{mV}$ and the details for the last calibration of the field instruments can be found in this table. The data was processed and filtered according to the process described in Subsection 2.3.1 using code in Python language written by Andrés Monetta for this purpose. The details are different for each field pyranometer. The resulting series for the CMP22 ns 110282 (# 5 in Table 2.1), after outliers have been discarded, are listed in Table 4.2 as an example.

For this pyranometer, the average constant (obtained as the average of column $F(j)$ in Table 4.2) is $F = 112.02\,\text{Wm}^{-2}/\text{mV}$ and the new sensitivity $s = 1000/F = 8.93\,\mu\text{V}/\text{Wm}^{-2}$. This represents a small change (-0.11%) with respect to its previous sensitivity $s' = 8.94\,\mu\text{V}/\text{Wm}^{-2}$, see Table 2.1. The corresponding uncertainty is also calculated using the information in Table 4.2 and the procedure described in Subsection 2.3.3.

The filtering procedure started with $N_{raw} = 7474$ data points with simultaneous readings for the field and reference pyranometers and after filtering and discarding outliers, $N_f = 1435$ data points arranged in $N_s = 75$ series remain. The filtering details are given in Table 2.5 for clarity. The interval between readings was 30 seconds and no average was recorded. The outlier and satibility filters did not filter any data.

Filter	description	condition	data points	series
-	raw data	-	7474	-
F1	solar altitude	$\alpha_s \geq 20°$	2479	124
F3 & F4	clear-sky	Eq. 2.2	1435	75
F5	outliers	Eq. 2.5	1435	75
F6	stability	Eq. 2.7	1435	75

Table 2.5: Summary of the applied filters and evolution of the number of data points and series for the for the CMP22 ns 110282 (# 5 in Table 2.1) data. The results for the other two field pyranometers in DAQ1 are almost identical.

The same procedure is followed with the other instruments (# 6 and #9) but the resulting series are omitted for brevity. Detailed tables with series averages can be found for each instrument in Appendix B. Table 2.6 summarizes the results of the three calibrations. The variation in sensitivity for the two CMP22 field instruments is very small. The CM11 instruments has a 2% variation in sensitivity since its last (factory) calibration.

#	model, sn	F'	u'_F	s'	u'_s	s	u_s	Δ_s (%)
5	CMP22 110282	112.019	0.650	8.927	0.052	8.94	0.06	-0.15
6	CMP22 120420	111.465	0.645	8.971	0.052	8.97	0.19	0.00
9	CMP11 152963	120.842	0.708	8.275	0.048	8.45	0.11	-2.07
11	CM22 990010	reference	-	-	-	11.41	0.057	-

Table 2.6: Summary of results obtained from the standard method for the DAQ1 instruments listed in Table 2.1. Δ_s is the percent change in the new sensitivity s' relative to the previous sensitivity s. All constants are expressed in $\mathrm{Wm^{-2}/mV}$ and all sensitivities in $\mu\mathrm{V/Wm^{-2}}$.

Simplified expanded uncertainty calculation

The relative combined standard uncertainty is obtained from the second term in Eq. (2.14),

$$\delta_c = \sqrt{\delta_R^2 + \delta_{\kappa,rep}^2 + 2\delta_V^2} \tag{2.20}$$

where we choose to work with % to avoid leading zeros. For the CM22 reference (Table 2.1), assuming a coverage factor $k = 2$,

$$\delta_R = \frac{100}{k} \times \frac{u_{s_R}}{s_R} = 100 \times \frac{1}{2} \times \frac{0.057}{11.41} = 0.25\%. \tag{2.21}$$

As mentioned in Subsection 2.3.3, the nominal error for the 30 mV scale of the DT85 datalogger

$$\delta_V = 0.10\% \tag{2.22}$$

is a conservative estimate of the standard uncertainty for voltage measurements in this scale, based on an average of ≈ 6 mV.

#	model, sn	N_s	$\langle V_R \rangle$ mV	$\langle V_F \rangle$ mV	$\langle \kappa \rangle$	σ_κ	$\delta_{\kappa,rep}(\%)$
5	CMP22 110282	75	7.471	5.844	1.2782	0.0047	0.043
6	CMP22 120420	75	7.471	5.873	1.2718	0.0041	0.037
9	CMP11 152963	75	7.471	5.418	1.3788	0.0069	0.058

Table 2.7: Summary of the statistics of the voltage ratios for each field pyranometer. The relative standard repeatability uncertainty is calculated from Eq. (2.12).

The repeatability error is specific for each pyranometer and can be calculated from the statistics of the voltage ratios, as summarized in Table 2.7. This data has been summarized from tables such as 4.2 for each field radiometer. Table 2.8 summarizes the uncertainty budget for thre three pyranometers connected to DAQ1. Repeatability is the only contribution that is instrument specific, and it is the smallest one in this case. As a consequence, the three expanded uncertainties are very similar, about 0.6%. The three instruments are secondary standards and this may explain the high stability of the series and corresponding low uncertainties.

#	model, sn	δ_R	$\sqrt{2}\delta_V$	$\delta_{\kappa,rep}$	δ_c	δ_{exp}
5	CMP22 110282	0.25	0.14	0.043	0.290	0.580
6	CMP22 120420	0.25	0.14	0.037	0.289	0.579
9	CMP11 152963	0.25	0.14	0.058	0.293	0.586

Table 2.8: Uncertainty budget for instruments connected to DAQ1. All values are in %.

As far as comparison with previous sensitivities (see Table 2.6), very small changes (0.15% and 0.02%) are observed for the two CMP22 pyranometers which are used as secondary standards for Uruguay and are kept in their boxes except during the calibrations of field instruments. These changes are smaller than the uncertainties in their sensitivities so they are not significant. In the case of the CMP11 pyranometer, a 2% reduction in sensitivity with respect to the factory calibration is found. This is a significant difference. This instrument has been reported by its owner to be in storage, so degradation is not expected. The factory calibration was done indoors with a solar simulator, perhaps this is behind the discrepancy with this outdoor calibration.

DAQ2: Agilent

The instruments listed as number 10, 11, 12 and 15 in Table 2.2 are calibrated against the reference instrument, number 14. The reference instrument (Hukseflux SR25 ns 2517 from WRC) has sensitivity $s = 10.93\,\mu\text{V}/\text{Wm}^{-2}$ and constant $F_R = 1000/s = 91.49\,\text{Wm}^{-2}/\text{mV}$ and the details for the last calibration of the field instruments can be found in this table. The data was processed and filtered according to the process described in Subsection 2.3.1 using code in Python language written by Andrés Monetta for this purpose and the details are different for each field pyranometer.

The filtering procedure is summarized in Table 2.9 below.

Filter	**description**	**condition**	**data points**	**series**
-	raw data	-	8429	-
F1	solar altitude	$\alpha_s \geq 20°$	2801	143
F3 & F4	clear-sky	Eq. 2.2	1551	82
F5	outliers	Eq. 2.5	1550	82
F6	stability	Eq. 2.7	1550	82

Table 2.9: Summary of the applied filters and evolution of the number of data points and series for the for the EKO MS80 sn: 16002013 (# 10 in Table 2.2) data. The results for the other field pyranometers in DAQ2 are identical, except for small variations in F5.

The same procedure is followed with the other instruments (# 11, 12 and # 15) but the resulting series are omitted for brevity. Detailed tables with series averages can be found for each instrument in Appendix B. Table 2.10 summarizes the results of the four calibrations.

Model and serial number	#	F'	u'_F	s'	u'_s	s	u_s	Δ_s (%)
EKO MS80 ns 16002013	10	86.77	1.21	11.525	0.161	11.500	0.078	0.2
KZ CMP10 ns 141141	11	114.58	1.60	8.728	0.122	8.81	0.12	-0.9
EKO MS80 ns 18003080	12	102.48	1.43	9.758	0.136	9.700	0.063	0.6
KZ CMP21 ns 140336	15	107.93	1.50	9.265	0.129	9.22	0.19	0.5
HK SR25 ns 2517	14	reference				10.93	0.15	

Table 2.10: Summary of results obtained from the standard method for the DAQ2 instruments listed in Table 2.2. Δ is the percent change in sensitivity relative to the previous sensitivity s. All constants are expressed in $\mathrm{Wm^{-2}/mV}$ and all sensitivities in $\mu\mathrm{V/Wm^{-2}}$.

Variations with respect to the previous sensitivities are small (below 1 %) for all instruments.

Simplified expanded uncertainty calculation

The uncertainty is calculated from Eq. (2.14) with the following relative standard uncertainties.

For the reference instrument, Hukseflux SR 25, we have

$$\delta_R = \frac{100}{k} \times \frac{u_{s_R}}{s_R} = 100 \times \frac{1}{2} \times \frac{0.15}{10.93} = 0.69\%. \tag{2.23}$$

As mentioned in Appendix A, the typical error for DC voltage measurements in the 100 mV scale of the Agilent datalogger is

$$\delta_V = 0.07\% \tag{2.24}$$

This is used as an estimate of the standard uncertainty for voltage measurements in this scale, based on an average of $\approx 6\,\mathrm{mV}$.

The repeatability error is specific for each pyranometer and can be calculated from the statistics of the voltage ratios (see Appendix B for listings of all series for each instrument). The relevant information is summarized in Table 2.11. Table 2.12 summarizes the uncertainty budget for the four pyranometers connected to DAQ2.

The uncertainty budget shows that the dominant contribution is the uncertainty of the reference instrument. Since it is much larger than the repeatablity uncertainty (the only instrument-specific contribution) the four instruments end up with a very similar expanded uncertainty of 1.40%. Note that the expanded uncertainty of this reference instrument is 1.37%.

Once the relative expanded ($k = 2$) uncertainty for each instrument has been determined (Table 2.12), the uncertainty in sensitivity and in the constant factor are calculated and listed in Table 2.10. In spite of being of

#	Model and serial number	N_s	$\langle V_R \rangle$	$\langle V_F \rangle$	$\langle \kappa \rangle$	σ_κ	$\delta_{\kappa,rep}(\%)$
10	EKO MS80 ns 16002013	82	7.46	7.87	0.948	0.0080	0.093
11	KZ CMP10 ns 141141	82	7.46	5.96	1.252	0.0103	0.091
12	EKO MS80 ns 18003080	82	7.46	6.66	1.120	0.0060	0.059
15	KZ CMP21 ns 140336	82	7.46	6.32	1.180	0.0070	0.066

Table 2.11: Summary of the statistics of the voltage ratios for each field pyranometer. Voltages are in mV. The relative standard repeatability uncertainty is calculated from Eq. (2.12). See Appendix B for the series listings.

similar quality, the expanded relative uncertainties assigned to these instruments is more than twice that of the instruments connected to DAQ1. This is a consequence of the relatively high uncertainty of the reference instrument (SR25, with 1.37%) as compared to the reference instrument in DAQ1 (CM21, with 0.5%). Thus, the uncertainty in these constants can probably be reduced if they are compared to the DAQ1 reference.

The changes in sensitivity of the four instruments are all within 1% (relative to the previous sensitivity) and therefore, are not significant within the assigned uncertainty.

#	model, sn	δ_R	$\sqrt{2}\delta_V$	$\delta_{\kappa,rep}$	δ_c	δ_{exp}
10	EKO MS80 ns 16002013	0.686	0.099	0.093	0.699	1.40
11	KZ CMP10 ns 141141	0.686	0.099	0.091	0.699	1.40
12	EKO MS80 ns 18003080	0.686	0.099	0.059	0.696	1.39
15	KZ CMP21 ns 140336	0.686	0.099	0.066	0.696	1.39

Table 2.12: Uncertainty budget for instruments connected to DAQ1. All values in %.

2.4.2 Results from the alternative method

In the alternative method, as in the standard method, the filters described as F1 to F4 in Subsection 2.3.1 (see Eqs. (2.2)) are applied to the data from the reference pyranometer. Only complete (V_R, V_F) pairs are considered. However, in the alternative method the data *is not* divided into continuous series. A linear regression is done on the data and the residuals are examined and outliers are rejected, as described in Subsection 2.3.2. A new linear regression provides $V_F = A + BV_R$ and the new constant is $F = F_R/B$. Alternatively, one can invert this relation to obtain the new sensibility as $s = s_R \times B$.

DAQ1: DT85

The filtering stage includes stages F1 to F4 in Table 2.5. The raw reference data (7474 records) is filtered with the results indicated in Table 2.13 (note that % are with respect to the initial raw data in all cases).

Filter	description	condition	data points	% of raw data
-	raw data	-	7474	100
F1	solar altitude	$\alpha_s \geq 20°$	2492	33.3
F3	clear-sky	k_t, Eq. 2.2	2413	32.3
F4	clear-sky	(Perez) Eq. 2.2	2474	33.1
All			1961	26.2

Table 2.13: Summary of the applied filters for the DAQ1 data.

For each field pyranometer, a linear regression is applied on the 1961 filtered data pairs . Figure 2.6 shows, as an example, the statistics for the CMP22 ns 110282 pyranometer. With a 5% threshold 321 data pairs are discarded as outliers and the final regression is made on 1634 data points. The number of outliers is specific of each field pyranometer, so it is not shown in Table 2.13

For each pyranometer, the final data pairs are used to report several variable ranges during the calibration and this information is included in the calibration certificate. As an example, Fig. 2.7 shows the conditions for the CMP22 ns 110282 dataset. The final results for the three field pyranometers are shown in Table 2.14. The expanded uncertainties are calculated from Eq. (2.19) as described at the end of Subsection 2.3.3.

A comparison with the results from the standard method (Table 2.6) shows that the differences between both methods are in the order of 1/10 of the assigned uncertainties, and therefore are not significant. However, the uncertainty from the standard method is about half as the one obtained from the alternative method, due to the difference in the repeatability uncertainty.

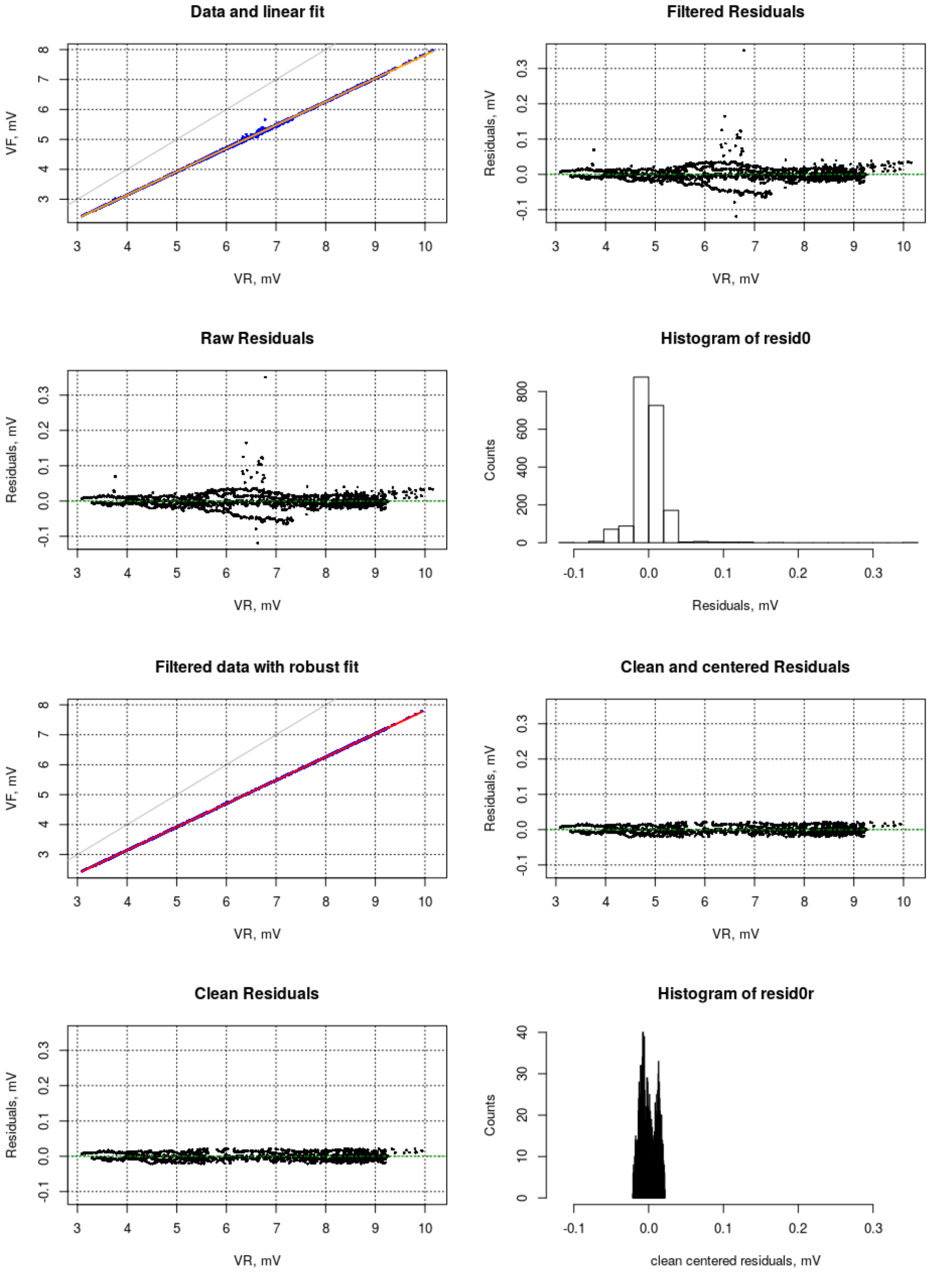

Figure 2.6: Statistics for the CMP22 ns 110282. The first four panels correspond to the 1961 data points that passed the filters. The last four correspond to "clean" data without outliers. Within each set, the top-left is V_F vs V_R, the bottom-left is a plot of the residuals. The top-right corresponds to centered residuals and bottom-right is a histogram of the residuals.

```
Piranometro:  ./P01/ZWF01.bin -- Software: Calibra version:  3.5
===============================================================
Constante Final: (cobertura k=2) KF = 111.93          Wm-2/mV
Sensibilidad: s =  8.93  mu V/Wm-2

Máximos, mínimos y promedios:
 GHI: 871.4 270.7 597.6  W/m2
Theta_z: 69.9 39.8 51.5  degrees
TA: -Inf Inf NaN  deg C
W: 60.4 -60.8 8.6  deg
Número de datos conforme a norma:  1961 ; Número de datos sin outliers:  1634
Se usaron  29.2 % de datos matutinos (W < 15 deg)
Se usaron  46.9 % de datos cercanos a mediodía
Se usaron  23.9 % de datos vespertinos (W > 15 deg)
===============================================================

 Success. Results in Result.txt y Stats.txt
```

Figure 2.7: Conditions (global horizontal irradiance, zenith angle, ambient temperature, hour angle) during the calibration for the CMP22 ns 110282 (text output from the calibration program).

#	model, sn	Ndata	F'	u'_F	s'	u'_s	s	u_s	Δ_s (%)
5	CMP22 110282	1634	111.93	1.33	8.93	0.11	8.94	0.06	-0.07
6	CMP22 120420	1581	111.35	1.25	8.98	0.10	8.97	0.19	0.12
9	CMP11 152963	1917	120.80	1.66	8.28	0.11	8.45	0.11	-2.03
11	CM22 990010	-	reference	-	-	-	11.41	0.057	-

Table 2.14: Summary of results obtained from the alternative method for the DAQ1 instruments listed in Table 2.1. Ndata is the number of data points after outlier removal. Δ is the percent change in sensitivity relative to the previous sensitivity s'. All constants are expressed in $\mathrm{Wm}^{-2}/\mathrm{mV}$ and all sensitivities in $\mu\mathrm{V}/\mathrm{Wm}^{-2}$.

This is the price one must pay for a simpler data processing.

DAQ2: Agilent

The same procedure is applied to the pyranometers connected to the Agilent DAQ. The results of the filtering stage are summarized in Table 2.15.

Filter	description	condition	data points	% of raw data
-	raw data	-	8429	100
F1	solar altitude	$\alpha_s \geq 20°$	2915	34.6
F3	clear-sky	k_t, Eq. 2.2	2916	34.6
F4	clear-sky	(Perez) Eq. 2.2	2999	35.6
All			2394	28.4

Table 2.15: Summary of the applied filters for the DAQ2 data.

For each field pyranometer, a linear regression is applied on the 2394 filtered data pairs. With a 5% threshold for the residuals, outliers are discarded. As an example, for the pyranometer EKO MS80 ns 16002013 (# 10) 567 data pairs are discarded as outliers and the final regression is made on 1827 data points. The number of outliers is specific of each field pyranometer, so it is not shown in Table 2.15.

Model/ serial number	#	Ndata	F'	u'_F	s'	u'_s	Δ_s (%)
EKO MS80 ns 16002013	10	1827	86.66	2.77	11.54	0.23	0.35
KZ CMP10 ns 141141	11	1873	114.42	3.49	8.74	-0.8	
EKO MS80 ns 18003080	12	1925	102.21	3.21	9.78	0.19	0.8
KZ CMP21 ns 140336	15	1969	107.86	3.19	9.27	0.14	0.5
HK SR25 ns 2517	14	reference	-	-	10.93	0.15	-

Table 2.16: Summary of results obtained from the alternative method for the DAQ2 instruments listed in Table 2.2. Ndata is the number of data points after outlier rejection. The last column shows the % change in sensitivity, from the alternative method. All constants are expressed in $\mathrm{Wm^{-2}/mV}$ and all sensitivities in $\mu\mathrm{V/Wm^{-2}}$.

Comparison with Table 2.10 shows that both methods produce consistent results to within the assigned uncertainties. The dominant component in the uncertainty is the uncertainty in the constant of the reference instrument. Since the SR25 reference has a higher uncertainty (1.4%) compared with the CM22 reference (0.5%) this reflects in higher uncertainties for the DAQ2 field instruments.

Chapter 3

Intercomparison of Pyrheliometers

The intercomparison for pirheliometers is made following the guidelines of the standard ISO 9059:1991 [ISO91], although the data treatment is done using the alternative method described in Section 2.3.2.

The participating pirheliometers, their constants, sensibilities, uncertainties (P95) and the last calibration dates are listed in Table 3.1. These instruments where compared to a PMO6 absolute cavity radiometer (ns 1602) from USACh which was used as the reference instrument. This instrument measures DNI from a difference in electrical power with its aperture closed (P_c) or open (P_o),

$$G_b = C \times (P_c - P_o), \tag{3.1}$$

and electrical power is measured with negligible error, so the uncertainty in G_b (the reference DNI) is determined by the uncertainty in the aperture constant C. The PMO6 was calibrated at the WRC/PMOD at 28/08/2018 with trazability to the WRR and $C = 51\,139.6\,\mathrm{m}^{-2}$ and $u_C = 31.5\,\mathrm{m}^{-2}$ (P95 uncertainty). Accordingly, its relative uncertainty is

$$\delta_C = \delta_{F_R} = 100 \times \frac{u_C}{C} = 0.06\%, \tag{3.2}$$

which is an order of magnitude smaller than the typical uncertainties in single-cavity thermopyle commercial pirheliometers. Data from the PMO6 has a minimum time interval of 3 minutes, because the control unit requires 90 seconds for each open/close phase, thus the reference DNI data was recorded every three minutes by its own control/DAQ unit.

3.1 Setup of the instruments

The instruments from USACh (SHP1 and PMO6) where mounted on a Kipp & Zonen Gear Drive solar tracker and those from LES (both CHP1) where

#	instrument	owner	F $\mathrm{Wm^{-2}/mV}$	u_F $\mathrm{Wm^{-2}/mV}$	s $\mu\mathrm{V/Wm^{-2}}$	u_s $\mu\mathrm{V/Wm^{-2}}$	δ %	last cal. date
3	SHP1 ns 175112	USACh	116.6	1.2	8.58	0.09	1.0	15/02/2017
8	CHP1 ns 120994	LES	138.1	1.5	7.24	0.08	1.1	30/08/2012
7	CHP1 ns 150261	LES	120.5	1.7	8.30	0.12	1.4	01/02/2015

Table 3.1: Pirheliometers participating in the intercomparison. All instruments where last calibrated at the factory (Kipp & Zonen) with trazability to the WRR.

mounted on one side of a Kipp & Zonen SOLYS2 solar tracker using an extension bracket (see Fig. 2.3). The SHP1 instrument was connected to a computer with SmartExplorer software from Kipp & Zonen through a Modbus RS48 protocol. Data from this instrument was recorded every 30 seconds, and later integrated to 3 minute intervals.

Both CHP1 instruments where connected to the Fischer Scientific DT85 DAQ system as described in Table 2.1. Measurements where recorded every 30 seconds and later integrated to three-minute intervals. The intercomparison was made on this time scale (3 minutes) since it is determined by the PMO6 reference instrument.

3.2 Measurements and pre-processing

Data was recorded during the days 3 to 7 de september 2019 at USACh's TARP-05 facility at Santiago de Chile (latitude = −33.45, longitude = −70.68). USach provided a file with the 3-minute integration of all pirheliometers and the reference PMO6 instrument's readings. A plot of the raw DNI data is shown in Fig. 2.5.

The filtering procedure follows the recommendations of Norm ISO-9859:1990 (Solar Energy – Calibration of filed pyrheliometers by comparison to a reference pyrheliometer) [ISO91]. Accordingly, for each instrument, the following filters were applied to the 3-min data of the reference instrument:

F0) Complete pairs: (DNI_R, DNI_F)

F1) Diurnal data: $\cos\theta_z > 0$

F2) Linke turbidity: $T_L < 6.0$ (see below, requested by [ISO91])

F3) Minimum DNI: $DNI_R > 300\,\mathrm{W/m^2}$ & $DNI_F > 300\,\mathrm{W/m^2}$. Norm ISO-9859:1990 suggests this threshold when the value $700\,\mathrm{W/m^2}$ leaves removes to many data points, which was the case here.

3.3 Methodology

The Linke Turbidity is a dimensionless parameter which can be interpreted as the number of clean, dry (Raleigh) atmospheres which are equivalent to

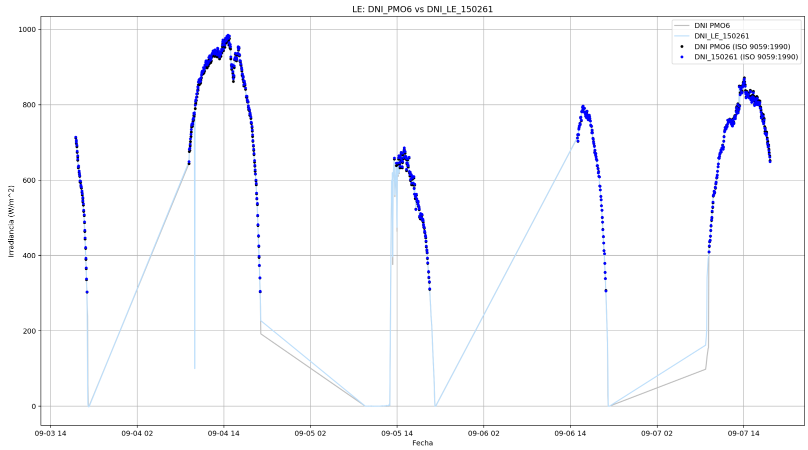

Figure 3.1: Selected data for pyrheliometer # 7 ns 150261 (blue dots) compared to the DNI reference data (black dots).

the real atmosphere. Even though it is a function of air mass m, the Linke factor T_L is conventionally referred to $m = 2$. The Linke turbidity is the single parameter in the European Solar Radiation Atlas (ESRA) clear-sky solar radiation model [RBW00], where DNI is expressed as

$$DNI = G_{sc} f_n \, e^{-0.8662 \times T_L \delta_R(m) \times m}. \tag{3.3}$$

Here, $G_{sc} = 1367\,\mathrm{W/m^2}$ is the conventional value of the solar constant[1], $f_n = (r_0/r)^2$ is the orbital eccentricity daily correction factor (see [Iqb83] for useful parametrizations), m is the refraction-corrected air mass [KY89] and $\delta_R(m)$ is the Rayleigh optical thickness as parametrized in [RBW00]. The numerical factor 0.8662 is unimportant, since it appears as a consequence of a shift in definitions of T_L over time, see [Kas96] for details. An estimate for the current T_L can be readiliy obtained from Eq. (3.3) using the reference DNI measurement.The total number of raw 3-minute data was 14399 records. From these, 585 valid pairs of diurnal data (which passed filters F0, F1 and F2) are considered. The results of the filtering procedure are summarized in Table 3.2.

3.3.1 Statistical methodology

The satistical methodology follows closely the one used for GHI and described as the Alternative method in Section 2.3.2. For the pre-selected points (column F3 in Table 3.2) a first linear regression between DNI_R and

[1]The mean solar irradiance at the top of the atmosphere when the Earth is at its mean distance from the Sun r_0.

#	instrument	pass F2	pass F3	all	pass F4	f
3	SHP1 ns 175112	585	574	562	467	1.0117
8	CHP1 ns 120994	585	570	558	465	1.0384
7	CHP1 ns 150261	585	573	561	470	1.0007

Table 3.2: Filtering procedure applied to the initial 585 diurnal data records above 300 W/m^2. F4 is the outlier rejection filter, explained below. The $F4$ column is the number of clean records (N_c) used to determine the new constant for each instrument and the final column is the assigned correction factor f, such that $F'_F = f \times F_F$.

DNI_F is performed and the standard deviation of the residuals, σ_r, is computed. Then all records whose residuals are larger than σ_r are discarded as outliers (filter F4 in Table 3.2). A second linear regression is computed on the N_c clean points to obtain the new correction factor f for the constant of each instrument, $F'_F = f \times F_F$. Both linear regressions are forced to go through the point (0,0). This procedure results in the correction factors assigned in Table 3.2, which are under 1% except for the instrument # 8, which had a change of almost 4% in its constant.

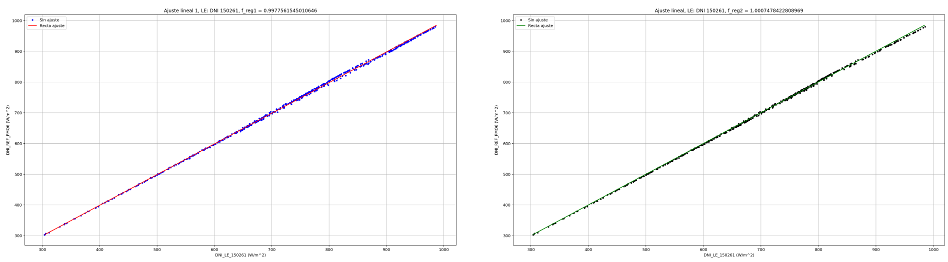

Figure 3.2: (a) First linear regression fit (slope = f = 0.997756) and (b) final linear regression fit after 91 outliers are removed (slope = f = 1.000748). The example is for pyrheliometer # 7 ns 150261.

The new assigned constants and sensitivities, together with their uncertainties are summarized in Table 3.4 below. The calculation of the uncertainties is explained below.

Conditions during calibration

Conditions during calibration (after outlier removal) are reported based on the reference measurement as follows:

Other data, such as diffuse irradiance, dry bulb air temperature, atmpospheric pressure or relative humidity where not available.

	DNI_R (W/m^2)	T_L
minimum	310.0	2.29
maximum	980.0	5.86
average	751.5	na

Table 3.3: DNI and Linke turbidity conditions during DNI calibration (after outlier removal). Data with $T_L > 6.0$ was filtered out.

3.3.2 Uncertainty calculation

Calculation of relative combined standard uncertainties is based on Eq. 2.19, which we reproduce here with a minor modification,

#	model, sn	F	u_F	s	u_s	F'	u'_F	s'	u'_s	Δ_s (%)
3	SHP1 ns 175112	116.6	1.2	8.58	0.09	117.9	0.8	8.48	0.06	-1.2
8	CHP1 ns 120994	138.1	1.5	7.24	0.08	143.4	1.1	6.97	0.06	-3.7
7	CHP1 ns 150261	120.5	1.7	8.30	0.12	120.6	1.0	8.29	0.07	-0.1

Table 3.4: Summary of results obtained in the pyrheliometer calibration. Δ_s is the percent change in sensitivity relative to the previous sensitivity. All constants F are expressed in Wm^{-2}/mV and all sensitivities s in μV/Wm^{-2}.

$$\delta_c = \sqrt{\delta_{F_R}^2 + \frac{\sigma_\kappa^2}{\langle\kappa\rangle^2} + \delta_V^2}. \tag{3.4}$$

The factor of 2 in the voltage uncertainty has been omitted because, as explained before, the PMO6 reference signal was measured with negligible electrical error. The field instruments voltage was measured with the DT85 DAQ system in the case of instruments # 7 and 8. Instrument # 3 had its own DAQ which we will assume has a similar error as the DT85 DAQ. Therefore for the three field pyrheliometers, $\delta_V = 0.10\%$, as explained in Appendix A. The fractional uncertainty of the PMO6 reference is, see Eq. 3.2, $\delta_{F_R} = 0.06\%$.

#	instrument	$<\kappa>$	σ_κ	δ_κ (%)	δ_c (%)	δ_e (%)
3	SHP1 ns 175112	1.0114	0.0031	0.31	0.33	0.66
8	CHP1 ns 120994	1.0375	0.0038	0.37	0.39	0.78
7	CHP1 ns 150261	0.9989	0.0038	0.38	0.40	0.80

Table 3.5: Calculation of the expanded combined uncertainty $\delta_e = 2 \times \delta_c$ from Eq. (3.4).

The statistical (or repeatability) uncertainty term is referred to the ratios $\kappa_i = (DNI_R/DNI_F)_i$ for $i = 1, 2 \ldots N_c$. The average value of this ratio $<\kappa>$ and its standard deviation σ_κ are recorded for each instrument.

Table 3.5 lists these values and the corresponding repeatability uncertainties $\sigma_\kappa / < \kappa >$ which are quadratically combined (Eq. 3.4) to produce the combined standard uncertainty and the expanded uncertainty (using a cover factor of $k = 2$ appropiate to a large number of degrees of freedom). Table 3.4 lists the final assigned constants and sensitivies with their absolute expanded uncertainties (confidence level P95).

Chapter 4

Summary

This intercomparison was sponsored by the german metrological institute (Physikalisch-Technische Bundesanstalt - PTB) as the activity “Strengthening the Capabilities for the Calibration of Pyranometers and Pyrheliometers for Use in Solar Radiation Measurements” as part of the broader PTB project “Quality Infrastructure for Energy Efficiency and Renewable Energy”. The measurements where hosted by the Applied Optics group of the Physics Departament of Universidad de Santiago de Chile (USACh) and took place in Santiago, Chile between 3 and 7 September 2018. The objective of this activity is two fold: (i) to provide training in calibration of secondary standard pyranometers and pyrheliometers following the relevant ISO standards and (ii) to perform an intercomparison of secondary standards and calibration practices used by the participating laboratories.

Seven laboratories from universities and metrological institutes of seven countries (six from Latin America and one from Europe) have participated in the intercomparison with one or more secondary standard pyranometers or pyrheliometers (acording to standard ISO9060 [ISO90]. The complete list of participating laboratories and instruments can be found in Table 1.1. The World Radiation Center participated providing two secondary standard pyranometers calibrated at WRC with trazability to the World Radiation Reference (WRR). An absolute cavity pyrheliometer (PMO6) from USaCh, recently fabricated and calibrated at the WRC, was used as a trazable reference instrument for the pyrheliometric measurements. This technical report summarizes the procedures followed by the staff from the Laboratorio de Energía Solar (LES - UDELAR) to obtain and process the measurements and informs the results obtained for all participating pyranometers and pyheliometers. In the case of pyranometers, data was processed by LES both according to the ISO 9847:1992 standard and also using an alternative method based on linear regression techniques, as a form of validation of this alternative method. Consistent results where obtained in both cases, as shown in Table 4.1. The two pyranoemters from USACH where connected to the

PMO6 control unit, and data for these instruments was recorded every three minutes. As a consequence no 30-second data was available for them and they where not calibrated.

#	owner	brand & model	serial number	previous sensitivity	last cal. date	standard method	alternative method
8	LES	KZ CHP1	120994	7.24 ± 0.08	8/2012	na	6.97 ± 0.06
7	LES	KZ CHP1	150261	8.30 ± 0.12	2/2015	na	8.29 ± 0.07
3	USACH	KZ SHP1-V	175112	8.58 ± 0.09	1/2017	na	8.48 ± 0.06
4	USACH	PMO 6	1602	51139.6 ± 31.6	8/2017	reference	reference
5	LES	KZ CMP22	110282	8.94 ± 0.06	4/2014	8.93 ± 0.05	8.93 ± 0.11
6	LES	KZ CMP22	120420	8.92 ± 0.09	1/2012	8.97 ± 0.05	8.98 ± 0.10
9	INTI	KZ CMP11	152963	8.45 ± 0.11	11/2015	8.28 ± 0.05	8.28 ± 0.11
10	USP	Eko MS80	16002013	11.50 ± 0.08	4/2016	11.53 ± 0.16	11.54 ± 0.23
11	UNAL	KZ CMP10	141141	8.81 ± 0.12	12/2014	8.73 ± 0.12	8.74 ± 0.15
12	UNAL	Eko MS80	18003080	9.70 ± 0.06	5/2018	9.76 ± 0.14	9.78 ± 0.19
15	CENAM	KZ CMP21	140336	9.22 ± 0.19	4/2018	9.27 ± 0.13	9.27 ± 0.14
13	WRC	CM22	990010	11.41 ± 0.06	8/2018	reference	reference
14	WRC	HK SR25	2517	10.93 ± 0.15	8/2018	reference	reference

Table 4.1: Sensitivities for all participating instruments (in μV/Wm^{-2}) reported according to both methods, when applicable. In the case of the PMO6 absolute cavity pirheliometer, the aperture area is reported, in m^{-2}. The corresponding uncertainties are combined, expanded at P95 confidence level ($k = 2$).

Conclusions

- Results from both methods (standard and alternative) are consistent within the stated uncertainties. The alternative method yields equivalente results and it is simpler in terms of data processing, but it has a higher uncertainty than the standard method, since the data is not organized into series of uniform conditions.
- The pyranometers connected to the DAQ2 (Agilent) had the HK SR25 secondary standard as a reference. This instrument was calibrated with higher relative uncertainty than the CM21 secondary standard and this propagates into higher uncertainties assigned to these pyranometers.
- The typical calibration uncertainty for DAQ1 instruments was below 1%. Usually, changes in sensitivity under 1% are observed, with some exceptions as for the CMP11 instrument from INTI which showed a 2% change.

This activity was important as it allowed our laboratory to compare and validate its methods for the first time with those from other laboratories in the region, as well as those used by the World Radiation Center. The comparative analysis of the results from each laboratory are the subject of the global intercomparison report which is currently beign prepared. We thank PTB for supporting the activity and hope that similar activities can take place with fixed and known periodicity.

Appendix A
Details for the dataloggers

DAQ1: DT85

The datalogger used for the intercomparison is a model DT85-3 with serial number 102813. It was calibrated at the factory on 22 August 2014. In Fig. 4.1 we reproduce its calibration certificate.

Pyranometer voltages are in the range 0 to 20 mV, so the 30 mV scale was used for all voltage measurements. For this scale, the user manual reports a maximunm error (in mV) $u_V = 0.0005V + 0.003$ where V is the measured voltage in mV. In relative terms

$$\delta_V = \frac{u_V}{V} = 0.0005 + \frac{0.003}{V} \tag{4.1}$$

so relative error is larger for smaller voltages, as expected. The calibration certificate in Fig. 4.1 shows that the actual error for this scale was -0.013% while the nominal error is $\pm 0.1\%$ for a temperature range 5 °C to 40 °C. This corresponds to a voltage $V = 6\,\text{mV}$, which is close to the observed average voltages during calibration (see Table 4.2 for actual values), so we shall use

$$\delta_V = 0.001 \tag{4.2}$$

(or 0.10%) as the typical relative error for voltage measurements.

This nominal error has a square (or uniform) distribution centered at V with semi-width $a_V = 0.001V = 6\,\mu\text{V}$. Thus, the standard uncertainty would be $u_V = a_V/\sqrt{3} = 3.4\,\mu\text{V}$. However, we are not certain that the tenmperature of the DAQ has been within the specified range at all times and we should allow for connection resistances as well. To be on the safe side, the standard uncertainty assigned to the voltage measurements with the DT85 is

$$u_V = \frac{a_V}{\sqrt{3}} = 6\,\mu\text{V}. \tag{4.3}$$

and the corresponding relative uncertainty is $\delta_V = u_V/V = 0.001$ or 0.1%, the nominal error for this scale.

dataTaker

Certificate of Traceable Calibration

Product Description

Model: DT85-3
Serial: 102813

Kernel Assembly: AS1238C1 1663-002
Terminal Assembly: AS1218C1 1670-009
Firmware: 85 Version 9.10.4890

Calibration Details

Calibration Date: 2014/08/22 11:41:02
Test Location: Apptek, Unit 7, 2 Pinacle Street Brendale QLD 4500
Ambient Temperature: 27.2 °C
NATA Certified Reference: Fluke 8840A Serial 5141011
Calibration Reference: DT8x Tester JIG-274 Version 1.50.0001, Calibrated 2014/07/28 10:24:22

Calibration Results

The following table lists measurements performed against traceable references.

Range	Channel(options)	Reference	Actual Reading	Allowable Error[1]	Error	Status
+30 V	1+HV(GL30V)	+10.0000 V	+9.9981	± 0.1 %	-0.019 %	PASS
+3000 mV	1*V(GL3V)	+2500.3 mV	+2500.3	± 0.1 %	-0.001 %	PASS
+300 mV	1+V(GL300MV)	+250.00 mV	+250.03	± 0.1 %	0.011 %	PASS
+30 mV	1-V(GL30MV)	+24.995 mV	+25.002	± 0.1 %	0.027 %	PASS
-30 V	1+HV(GL30V)	-10.0000 V	-9.9981	± 0.1 %	-0.019 %	PASS
-3000 mV	1*V(GL3V)	-2500.1 mV	-2500.4	± 0.1 %	0.012 %	PASS
-300 mV	1+V(GL300MV)	-249.99 mV	-249.99	± 0.1 %	0.000 %	PASS
-30 mV	1-V(GL30MV)	-25.001 mV	-24.998	± 0.1 %	-0.013 %	PASS
10 k Ω	1R(4W,I)	100.0000 Ω	100.007	± 0.2 %	0.007 %	PASS

[1] Allowable Error indicates the maximum allowable difference between the Reference and the Actual Reading, specified as a percentage of the Actual Reading, when the ambient temperature is between 5°C and 40°C.

The product covered by this certificate meets or exceeds the required performance specified by Thermo Fisher Scientific Australia Pty. Ltd.

The measurements performed to generate this certificate are traceable to Australian national standards of measurement.

This product has been manufactured under an ISO9001:2008 quality system.

Figure 4.1: Calibration certificate of the DT85 DAQ.

DAQ2: Agilent 34972A datalogger

The specifications for this instrument's DC readings are shown below in Fig. 4.2.

± (% of reading + % of range) [1]
Includes measurement error, switching error, and transducer conversion error

Function	Range[3]	Test Current or Burden Voltage	24 Hour[2] 23 °C ± 1 °C	90 Day 23 °C ± 5 °C	1 Year 23 °C ± 5 °C	Temperature Coefficient /°C 0 °C - 18 °C 28 °C - 55 °C
DC Voltage	100.0000 mV		0.0030 + 0.0035	0.0040 + 0.0040	0.0050 + 0.0040	0.0005 + 0.0005
	1.000000 V		0.0020 + 0.0006	0.0030 + 0.0007	0.0040 + 0.0007	0.0005 + 0.0001
	10.00000 V		0.0015 + 0.0004	0.0020 + 0.0005	0.0035 + 0.0005	0.0005 + 0.0001
	100.0000 V		0.0020 + 0.0006	0.0035 + 0.0006	0.0045 + 0.0006	0.0005 + 0.0001
	300.000 V		0.0020 + 0.0020	0.0035 + 0.0030	0.0045 + 0.0030	0.0005 + 0.0003

Figure 4.2: Specifications for DC voltage readings with the Agilent data logger.

In its smallest scale ($FS = 100\,\mathrm{mV}$) the maximum error for a reading V within a 90 day period is estimated as $\pm(0.004\%V + 0.004\% \times (FS))$. For an average voltage $V = 6\,\mathrm{mV}$ we have

$$\varepsilon_V = \frac{0.004 \times 6}{100} + \frac{0.004 \times 100}{100} = 4.24\,\mu\mathrm{V} \tag{4.4}$$

and a typical relative error (%) of

$$\delta_V = 100 \times \frac{\varepsilon_V}{V} = 100 \times \frac{4.24}{6000} = 0.07\% \tag{4.5}$$

This relative error assumes a temperature range of 18 °C to 28 °C for the datalogger, which seems compatible with the ambient temperatures during the calibration. This error is comparable to the typical 0.10% error of the DT85 in its 30 mV scale.

The certificate of calibration for the Agilent datalogger is included in Fig. 4.3.

Certificate Of Calibration

Certificate No: 34972AMY49001867

Manufacturer: Agilent Technologies
Model No: 34972A
Options Installed With Specifications: N/A

Description: LXI Data Acquisition / Switch Unit
Serial No: MY49001867

Date of Calibration: 4 Aug 2010
Temperature: (23 +/-5)C
Procedure: 34972A / 214705671112

Humidity: (20 to 80)% RH

This certifies that the above product was calibrated in compliance with a quality system registered to ISO 9001:2008, using applicable Agilent Technologies' procedures.

As Received: Factory tested. No incoming data available.

As Shipped Conditions: At the completion of the calibration, measured values were IN SPECIFICATION at the points tested.

These calibration procedures and test points are those recommended in a procedure developed by Agilent.

Remarks or special requirements:

Traceability Information: Traceability is to the International System of Units (SI), consensus standards or ratio type measurements through national standards realized and maintained by the NIST U.S., NRC Canada, NMIJ Japan, KRISS Korea, Euramet members (NPL, PTB, etc.), NML-SIRIM in Malaysia or other National Measurement Institutes signatories to the CIPM MRA. Supporting documentation relative to traceability is available for review by appointment. This report shall not be reproduced, except in full, without prior written approval of the calibration facility

Calibration Equipment Used:

Date Used: Date equipment used in this Calibration

Model Number	Model Description	Trace Number	Date Used	Cal Due Date
5720A	Fluke Calibrator	7605208	4 Aug 2010	27 May 2011
5725A	Fluke Amplifier	6775002	4 Aug 2010	27 May 2011

Print Date: 04-Aug-10

Tay Eng Su
Quality Manager

TEST REPORT

TEST DESCRIPTION	READING	ERROR	1 YEAR SPEC
DCV +.1V on .1V Range	0.0999997	-0.0004%	+/-0.0090%
DCV +1V on 1V Range	0.9999998	+0.0000%	+/-0.0047%
DCV +10V on 10V Range	9.9999990	+0.0000%	+/-0.0040%
DCV +.1V on 10V Range	0.1000000	+0.0000%	+/-0.0535%
DCV -10V on 10V Range	-10.000005	+0.0000%	+/-0.0040%
DCV +100V on 100V Range	100.00006	+0.0001%	+/-0.0051%
DCV +300V on 300V Range	299.99908	-0.0003%	+/-0.0075%
ACV .01V 1KHZ on .1V Range	0.0099998	-0.0018%	+/-0.4600%
ACV .1V 1KHZ on .1V Range	0.1000004	+0.0004%	+/-0.1000%
ACV .1V 50KHZ on .1V Range	0.0999919	-0.0081%	+/-0.1700%
ACV 1V 1KHZ on 1V Range	0.9999944	-0.0006%	+/-0.1000%
ACV 1V 50KHZ on 1V Range	0.9995691	-0.0431%	+/-0.1700%
ACV 10V 10HZ on 10V Range	10.000002	+0.0000%	+/-0.3900%
ACV 10V 1KHZ on 10V Range	9.9997830	-0.0022%	+/-0.1000%
ACV 10V 20KHZ on 10V Range	10.000260	+0.0026%	+/-0.1000%
ACV 10V 50KHZ on 10V Range	9.9974940	-0.0251%	+/-0.1700%
ACV 10V 100KHZ on 10V Range	9.9972490	-0.0275%	+/-0.6800%
ACV 10V 300KHZ on 10V Range	10.058529	+0.5853%	+/-4.5000%
ACV 100V 1KHZ on 100V Range	00100	+0.0000%	+/-0.1000%
ACV 100V 50KHZ on 100V Range	100.01083	+0.0108%	+/-0.1700%
ACV 300V 1KHZ on 300V Range	299.99978	-0.0001%	+/-0.1400%
ACV 300V 50KHZ on 300V Range	300.03372	+0.0112%	+/-0.2400%
4W OHMS 100OHMS on 100OHMS Range	99.999820	-0.0002%	+/-0.0140%
4W OHMS 1KOHMS on 1KOHMS Range	1000.0003	+0.0000%	+/-0.0110%
4W OHMS 10KOHMS on 10KOHMS Range	10000.007	+0.0001%	+/-0.0110%
4W OHMS 100KOHMS on 100KOHMS Range	100000.02	+0.0000%	+/-0.0110%
4W OHMS 1MOHMS on 1MOHMS Range	1000006.2	+0.0006%	+/-0.0110%
4W OHMS 10MOHMS on 10MOHMS Range	9999777	-0.0022%	+/-0.0410%
DCI 10mA on 10mA Range	0.0100000	-0.0003%	+/-0.0700%
DCI 100mA on 100mA Range	0.1000000	+0.0000%	+/-0.0550%
DCI 1A on 1A Range	0.9999890	-0.0011%	+/-0.1100%
ACI 10mA 1KHZ on 10mA Range	0.0099996	-0.0036%	+/-0.1400%
ACI 100mA 1KHZ on 1A Range	0.1000208	+0.0208%	+/-0.5000%
ACI 1A 1KHZ on 1A Range	1.0000460	+0.0046%	+/-0.1400%
FREQ 1V 10KHZ on 1V Range	10000	+0.0000%	+/-0.0100%

Figure 4.3: Calibration certificate of the Agilent datalogger.

Appendix B
Series statistics used for the standard method

In this Appendix we simply list the series statistics for each pyranometer connected to DAQ1 or DAQ2. Average values of the series can be considered as preliminary estimates leading to the new constant.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ Wm^{-2}/mV	$s(j)$ $\mu V/Wm^{-2}$
1	20	9.65	0.32	7.57	0.25	1.275	111.76	8.95
2	20	9.28	0.54	7.28	0.42	1.275	111.74	8.95
3	20	8.80	0.18	6.90	0.14	1.276	111.84	8.94
4	19	8.42	0.18	6.59	0.14	1.277	111.95	8.93
5	17	8.49	0.34	6.64	0.27	1.278	112.03	8.93
6	17	8.51	0.27	6.65	0.21	1.279	112.08	8.92
7	20	8.74	0.12	6.83	0.09	1.279	112.07	8.92
8	20	8.50	0.09	6.65	0.07	1.279	112.13	8.92
9	20	8.46	0.14	6.61	0.11	1.280	112.19	8.91
10	20	8.29	0.11	6.48	0.09	1.280	112.15	8.92
11	20	8.21	0.24	6.41	0.19	1.281	112.28	8.91
12	20	8.10	0.11	6.32	0.08	1.282	112.31	8.90
13	20	7.84	0.12	6.12	0.10	1.281	112.26	8.91
14	20	7.68	0.09	5.99	0.07	1.282	112.39	8.90
15	20	7.53	0.11	5.88	0.08	1.280	112.15	8.92
16	20	7.11	0.08	5.55	0.06	1.280	112.20	8.91
17	20	6.89	0.10	5.39	0.06	1.278	111.97	8.93
18	20	6.65	0.07	5.25	0.14	1.266	110.99	9.01
19	20	6.32	0.13	4.98	0.13	1.269	111.26	8.99
20	16	5.98	0.11	4.67	0.08	1.280	112.18	8.91
21	12	5.64	0.09	4.41	0.07	1.279	112.08	8.92
22	14	5.43	0.13	4.27	0.10	1.273	111.59	8.96
23	13	6.82	0.04	5.34	0.03	1.278	112.03	8.93
24	13	7.07	0.06	5.54	0.05	1.278	111.97	8.93
25	11	7.22	0.09	5.64	0.07	1.282	112.32	8.90
26	20	7.51	0.13	5.87	0.11	1.279	112.08	8.92
27	20	7.76	0.12	6.05	0.09	1.282	112.32	8.90
28	20	7.98	0.03	6.24	0.02	1.279	112.06	8.92
29	20	7.23	0.07	5.60	0.05	1.291	113.13	8.84
30	20	6.95	0.09	5.39	0.06	1.290	113.06	8.84
31	20	6.65	0.10	5.15	0.07	1.290	113.07	8.84
32	20	6.31	0.13	4.90	0.10	1.288	112.91	8.86
33	20	6.01	0.08	4.68	0.06	1.285	112.60	8.88
34	20	5.66	0.11	4.41	0.09	1.284	112.50	8.89
35	20	5.28	0.12	4.13	0.09	1.281	112.23	8.91
36	20	4.94	0.14	3.86	0.10	1.281	112.27	8.91
37	17	4.59	0.10	3.59	0.08	1.280	112.21	8.91
38	10	6.12	0.05	4.82	0.04	1.269	111.19	8.99
39	16	6.44	0.12	5.07	0.09	1.269	111.22	8.99
40	20	6.80	0.08	5.35	0.06	1.271	111.43	8.97
41	20	7.09	0.09	5.57	0.06	1.273	111.59	8.96
42	20	7.37	0.10	5.78	0.08	1.275	111.75	8.95
43	20	7.60	0.06	5.96	0.05	1.276	111.80	8.94
44	20	7.78	0.06	6.10	0.04	1.275	111.78	8.95
45	20	7.95	0.02	6.22	0.02	1.277	111.88	8.94
46	20	8.04	0.05	6.30	0.04	1.276	111.82	8.94
47	20	8.24	0.01	6.46	0.01	1.276	111.80	8.94
48	20	8.42	0.06	6.60	0.05	1.276	111.80	8.94
49	20	8.53	0.11	6.69	0.09	1.276	111.79	8.95
50	20	8.66	0.06	6.78	0.05	1.276	111.86	8.94
51	20	8.72	0.06	6.83	0.05	1.277	111.88	8.94
52	20	8.92	0.15	6.98	0.12	1.278	112.01	8.93
53	20	9.11	0.07	7.12	0.06	1.279	112.12	8.92
54	20	9.06	0.07	7.08	0.05	1.280	112.22	8.91
55	20	9.14	0.05	7.15	0.04	1.280	112.15	8.92
56	20	9.15	0.04	7.15	0.03	1.280	112.22	8.91
57	20	9.02	0.07	7.04	0.06	1.281	112.24	8.91
58	20	8.88	0.06	6.94	0.04	1.281	112.23	8.91
59	20	8.81	0.03	6.87	0.02	1.282	112.33	8.90
60	20	8.70	0.04	6.79	0.03	1.281	112.28	8.91
61	20	8.57	0.07	6.69	0.06	1.281	112.26	8.91
62	20	8.35	0.06	6.52	0.05	1.282	112.32	8.90
63	20	8.23	0.06	6.42	0.04	1.282	112.32	8.90
64	20	8.09	0.10	6.31	0.07	1.281	112.25	8.91
65	20	7.77	0.04	6.07	0.03	1.280	112.21	8.91
66	20	7.61	0.06	5.95	0.05	1.279	112.08	8.92
67	20	7.32	0.08	5.73	0.06	1.277	111.96	8.93
68	20	7.05	0.09	5.53	0.07	1.276	111.86	8.94
69	20	6.79	0.09	5.33	0.07	1.275	111.71	8.95
70	20	6.43	0.13	5.05	0.10	1.274	111.65	8.96
71	20	6.12	0.11	4.81	0.08	1.272	111.50	8.97
72	20	5.76	0.13	4.53	0.10	1.271	111.41	8.98
73	20	5.39	0.12	4.24	0.09	1.271	111.41	8.98
74	20	5.05	0.11	3.97	0.09	1.272	111.44	8.97
75	20	4.68	0.13	3.68	0.10	1.271	111.36	8.98
Av	19.1	7.47	0.11	5.48	0.08	1.28	112.02	8.93

Table 4.2: Final series for **CMP22 ns 110282 in DAQ1**. N_j is the number of data points in series j. Reference (V_R) and field (V_F) pyranometer average voltages and their standard deviations. $\kappa(j) = \langle V_R \rangle / \langle V_F \rangle$. The constant $F(j)$ and sensitivity $s(j)$ from each series are also shown.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ $\mathrm{Wm}^{-2}/\mathrm{mV}$	$s(j)$ $\mu V/Wm^{-2}$
1	20	9.65	0.32	7.60	0.25	1.27023111435434	111.33	8.98
2	20	9.28	0.54	7.31	0.42	1.26954500939231	111.27	8.99
3	20	8.80	0.18	6.94	0.14	1.26944179885218	111.26	8.99
4	19	8.42	0.18	6.63	0.14	1.27013066603663	111.32	8.98
5	17	8.49	0.34	6.68	0.27	1.27061344178304	111.36	8.98
6	17	8.51	0.27	6.69	0.21	1.27054661449432	111.35	8.98
7	20	8.74	0.12	6.88	0.09	1.27027533941934	111.33	8.98
8	20	8.50	0.09	6.69	0.07	1.27059670715521	111.36	8.98
9	20	8.46	0.14	6.66	0.11	1.27095698516451	111.39	8.98
10	20	8.29	0.11	6.52	0.09	1.2702673106841	111.33	8.98
11	20	8.21	0.24	6.46	0.19	1.2711747858226	111.41	8.98
12	20	8.10	0.11	6.37	0.08	1.27127144503195	111.42	8.98
13	20	7.84	0.12	6.17	0.10	1.27074878787967	111.37	8.98
14	20	7.68	0.09	6.04	0.07	1.27205044140452	111.49	8.97
15	20	7.53	0.11	5.93	0.08	1.27015950110425	111.32	8.98
16	20	7.11	0.08	5.60	0.06	1.27049344441443	111.35	8.98
17	20	6.89	0.10	5.43	0.07	1.26978310103589	111.29	8.99
18	20	6.65	0.07	5.26	0.06	1.26533943053826	110.90	9.02
19	20	6.32	0.13	4.99	0.12	1.26580980803209	110.94	9.01
20	16	5.98	0.11	4.71	0.09	1.27097830310167	111.39	8.98
21	12	5.64	0.09	4.44	0.07	1.27001397782573	111.31	8.98
22	14	5.43	0.13	4.28	0.10	1.26752999429125	111.09	9.00
23	13	6.82	0.04	5.36	0.04	1.273196974696	111.59	8.96
24	13	7.07	0.06	5.56	0.05	1.2727029972194	111.54	8.97
25	11	7.22	0.09	5.66	0.07	1.27682957115065	111.90	8.94
26	20	7.51	0.13	5.89	0.10	1.27482480631725	111.73	8.95
27	20	7.76	0.12	6.07	0.09	1.27824106068826	112.03	8.93
28	20	7.98	0.03	6.26	0.02	1.2758272095297	111.82	8.94
29	20	7.23	0.07	5.64	0.06	1.28289150703342	112.44	8.89
30	20	6.95	0.09	5.41	0.07	1.2836522840811	112.50	8.89
31	20	6.65	0.10	5.18	0.08	1.28435605232238	112.56	8.88
32	20	6.31	0.13	4.92	0.10	1.28288925593727	112.44	8.89
33	20	6.01	0.08	4.70	0.06	1.27983689000042	112.17	8.92
34	20	5.66	0.11	4.43	0.09	1.27757999987975	111.97	8.93
35	20	5.28	0.12	4.15	0.09	1.27222207131083	111.50	8.97
36	20	4.94	0.14	3.89	0.10	1.27122840754046	111.41	8.98
37	17	4.59	0.10	3.61	0.08	1.27093041635618	111.39	8.98
38	10	6.12	0.05	4.83	0.04	1.26638102726983	110.99	9.01
39	16	6.44	0.12	5.08	0.09	1.26667192882319	111.01	9.01
40	20	6.80	0.08	5.36	0.06	1.26900559510299	111.22	8.99
41	20	7.09	0.09	5.58	0.06	1.27044364345803	111.34	8.98
42	20	7.37	0.10	5.80	0.08	1.27143956712386	111.43	8.97
43	20	7.60	0.06	5.98	0.05	1.27185161261302	111.47	8.97
44	20	7.78	0.06	6.12	0.04	1.27144433728672	111.43	8.97
45	20	7.95	0.02	6.25	0.02	1.27192672127862	111.47	8.97
46	20	8.04	0.05	6.33	0.04	1.27115379368475	111.41	8.98
47	20	8.24	0.01	6.48	0.01	1.27082483110413	111.38	8.98
48	20	8.42	0.06	6.62	0.05	1.27087898126604	111.38	8.98
49	20	8.53	0.11	6.71	0.09	1.27076947258993	111.37	8.98
50	20	8.66	0.06	6.81	0.05	1.27153586340974	111.44	8.97
51	20	8.72	0.06	6.86	0.05	1.27155965547966	111.44	8.97
52	20	8.92	0.15	7.01	0.12	1.2730765336689	111.58	8.96
53	20	9.11	0.07	7.14	0.06	1.27446840392129	111.70	8.95
54	20	9.06	0.07	7.11	0.05	1.27501306695683	111.75	8.95
55	20	9.14	0.05	7.18	0.04	1.27396114384595	111.65	8.96
56	20	9.15	0.04	7.18	0.03	1.27443865218399	111.69	8.95
57	20	9.02	0.07	7.08	0.06	1.27375039592417	111.63	8.96
58	20	8.88	0.06	6.98	0.04	1.27349960836662	111.61	8.96
59	20	8.81	0.03	6.91	0.02	1.27407402038993	111.66	8.96
60	20	8.70	0.04	6.83	0.03	1.2731453938075	111.58	8.96
61	20	8.57	0.07	6.74	0.06	1.27277395019513	111.55	8.96
62	20	8.35	0.06	6.56	0.05	1.27284693205434	111.56	8.96
63	20	8.23	0.06	6.47	0.04	1.27246526023612	111.52	8.97
64	20	8.09	0.10	6.36	0.08	1.27148708532795	111.44	8.97
65	20	7.77	0.04	6.11	0.04	1.27117080146391	111.41	8.98
66	20	7.61	0.06	5.99	0.05	1.27052559815169	111.35	8.98
67	20	7.32	0.08	5.76	0.06	1.27054325371629	111.35	8.98
68	20	7.05	0.09	5.55	0.08	1.27129968060834	111.42	8.98
69	20	6.79	0.09	5.34	0.07	1.27067919209749	111.37	8.98
70	20	6.43	0.13	5.06	0.10	1.27047614182815	111.35	8.98
71	20	6.12	0.11	4.82	0.09	1.26934797708143	111.25	8.99
72	20	5.76	0.13	4.54	0.10	1.26780936488619	111.11	9.00
73	20	5.39	0.12	4.26	0.09	1.26500137696069	110.87	9.02
74	20	5.05	0.11	4.00	0.09	1.26317854190123	110.71	9.03
75	20	4.68	0.13	3.71	0.10	1.26238997940411	110.64	9.04
Av	19.1	7.47	0.11	5.87	0.08	1.27184635863133	111.47	8.97

Table 4.3: Final series for **CMP22 ns 120420 in DAQ1**.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ $\mathrm{Wm}^{-2}/\mathrm{mV}$	$s(j)$ $\mu V/Wm^{-2}$
1	20	9.65	0.32	7.05	0.24	1.370	120.034	8.331
2	20	9.28	0.54	6.76	0.40	1.373	120.312	8.312
3	20	8.80	0.18	6.40	0.13	1.376	120.605	8.292
4	19	8.42	0.18	6.11	0.13	1.379	120.837	8.276
5	17	8.49	0.34	6.15	0.26	1.381	121.002	8.264
6	17	8.51	0.27	6.16	0.20	1.380	120.964	8.267
7	20	8.74	0.12	6.34	0.09	1.379	120.839	8.275
8	20	8.50	0.09	6.17	0.07	1.379	120.872	8.273
9	20	8.46	0.14	6.13	0.10	1.380	120.965	8.267
10	20	8.29	0.11	6.01	0.08	1.380	120.907	8.271
11	20	8.21	0.24	5.94	0.18	1.383	121.219	8.250
12	20	8.10	0.11	5.86	0.08	1.383	121.205	8.250
13	20	7.84	0.12	5.68	0.09	1.381	121.015	8.263
14	20	7.68	0.09	5.55	0.06	1.384	121.284	8.245
15	20	7.53	0.11	5.46	0.08	1.378	120.809	8.278
16	20	7.11	0.08	5.15	0.06	1.381	121.026	8.263
17	20	6.89	0.10	5.02	0.07	1.372	120.245	8.316
18	20	6.65	0.07	4.78	0.59	1.391	121.879	8.205
19	20	6.32	0.13	4.66	0.16	1.354	118.688	8.425
20	16	5.98	0.11	4.35	0.08	1.377	120.676	8.287
21	12	5.64	0.09	4.10	0.06	1.375	120.480	8.300
22	14	5.43	0.13	3.96	0.10	1.370	120.069	8.329
23	13	6.82	0.04	4.93	0.04	1.384	121.256	8.247
24	13	7.07	0.06	5.12	0.04	1.382	121.099	8.258
25	11	7.22	0.09	5.20	0.07	1.388	121.671	8.219
26	20	7.51	0.13	5.43	0.10	1.382	121.097	8.258
27	20	7.76	0.12	5.60	0.08	1.386	121.438	8.235
28	20	7.98	0.03	5.79	0.02	1.379	120.860	8.274
29	20	7.23	0.07	5.18	0.05	1.397	122.417	8.169
30	20	6.95	0.09	4.98	0.06	1.394	122.197	8.183
31	20	6.65	0.10	4.76	0.07	1.396	122.371	8.172
32	20	6.31	0.13	4.52	0.09	1.396	122.321	8.175
33	20	6.01	0.08	4.32	0.06	1.391	121.879	8.205
34	20	5.66	0.11	4.07	0.08	1.390	121.808	8.210
35	20	5.28	0.12	3.81	0.09	1.386	121.456	8.233
36	20	4.94	0.14	3.57	0.09	1.386	121.438	8.235
37	17	4.59	0.10	3.32	0.07	1.383	121.186	8.252
38	10	6.12	0.05	4.45	0.03	1.375	120.501	8.299
39	16	6.44	0.12	4.69	0.09	1.374	120.391	8.306
40	20	6.80	0.08	4.94	0.06	1.375	120.544	8.296
41	20	7.09	0.09	5.15	0.06	1.376	120.627	8.290
42	20	7.37	0.10	5.36	0.07	1.376	120.631	8.290
43	20	7.60	0.06	5.52	0.04	1.377	120.704	8.285
44	20	7.78	0.06	5.65	0.04	1.377	120.688	8.286
45	20	7.95	0.02	5.76	0.02	1.379	120.861	8.274
46	20	8.04	0.05	5.84	0.04	1.378	120.777	8.280
47	20	8.24	0.01	5.98	0.01	1.377	120.710	8.284
48	20	8.42	0.06	6.11	0.05	1.378	120.732	8.283
49	20	8.53	0.11	6.19	0.08	1.377	120.717	8.284
50	20	8.66	0.06	6.28	0.05	1.379	120.840	8.275
51	20	8.72	0.06	6.33	0.05	1.377	120.719	8.284
52	20	8.92	0.15	6.47	0.12	1.380	120.911	8.271
53	20	9.11	0.07	6.59	0.06	1.381	121.011	8.264
54	20	9.06	0.07	6.57	0.06	1.381	120.992	8.265
55	20	9.14	0.05	6.64	0.04	1.377	120.667	8.287
56	20	9.15	0.04	6.64	0.04	1.378	120.797	8.278
57	20	9.02	0.07	6.54	0.05	1.378	120.754	8.281
58	20	8.88	0.06	6.45	0.04	1.378	120.740	8.282
59	20	8.81	0.03	6.38	0.02	1.380	120.965	8.267
60	20	8.70	0.04	6.31	0.03	1.379	120.826	8.276
61	20	8.57	0.07	6.22	0.06	1.379	120.842	8.275
62	20	8.35	0.06	6.05	0.05	1.380	120.944	8.268
63	20	8.23	0.06	5.96	0.04	1.379	120.896	8.272
64	20	8.09	0.10	5.87	0.07	1.378	120.773	8.280
65	20	7.77	0.04	5.64	0.03	1.378	120.740	8.282
66	20	7.61	0.06	5.53	0.04	1.375	120.539	8.296
67	20	7.32	0.08	5.33	0.05	1.374	120.415	8.305
68	20	7.05	0.09	5.13	0.07	1.374	120.459	8.302
69	20	6.79	0.09	4.95	0.07	1.372	120.232	8.317
70	20	6.43	0.13	4.69	0.09	1.372	120.250	8.316
71	20	6.12	0.11	4.47	0.08	1.369	120.018	8.332
72	20	5.76	0.13	4.21	0.09	1.369	119.951	8.337
73	20	5.39	0.12	3.94	0.09	1.368	119.897	8.341
74	20	5.05	0.11	3.69	0.08	1.370	120.036	8.331
75	20	4.68	0.13	3.42	0.09	1.368	119.875	8.342
Av	19.1	7.47	0.11	5.42	0.09	1.379	120.845	8.275

Table 4.4: Final series for **CMP11 ns 152963 in DAQ1**.

j	N_j	$\langle V_R \rangle$	σ_{VR}	$\langle V_F \rangle$	σ_{VF}	$\kappa(j)$	$F(j)$	$s(j)$
		mV	mV	mV	mV		Wm^{-2}/mV	$\mu V/Wm^{-2}$
1	20	6.54	0.08	6.82	0.12	0.958	87.672	11.406
2	20	6.19	0.11	6.45	0.11	0.960	87.863	11.381
3	20	5.82	0.12	6.09	0.12	0.955	87.338	11.450
4	15	5.52	0.07	5.76	0.07	0.959	87.703	11.402
5	20	5.25	0.10	5.35	0.14	0.981	89.721	11.146
6	17	4.88	0.09	4.97	0.10	0.982	89.813	11.134
7	16	3.78	0.08	3.93	0.10	0.960	87.849	11.383
8	19	9.08	0.35	9.59	0.35	0.947	86.619	11.545
9	20	9.16	0.44	9.74	0.46	0.941	86.061	11.620
10	18	8.62	0.23	9.11	0.25	0.946	86.526	11.557
11	18	8.29	0.17	8.76	0.20	0.946	86.572	11.551
12	12	8.33	0.23	8.80	0.28	0.946	86.584	11.549
13	12	8.31	0.19	8.74	0.22	0.951	86.981	11.497
14	18	8.32	0.20	8.79	0.21	0.947	86.649	11.541
15	20	8.30	0.10	8.75	0.12	0.949	86.797	11.521
16	20	8.17	0.08	8.62	0.07	0.948	86.697	11.534
17	20	7.99	0.16	8.43	0.17	0.948	86.725	11.531
18	17	8.01	0.13	8.44	0.14	0.949	86.837	11.516
19	20	7.89	0.12	8.27	0.13	0.954	87.245	11.462
20	20	7.66	0.11	8.05	0.13	0.951	87.028	11.490
21	20	7.47	0.04	7.80	0.05	0.958	87.675	11.406
22	20	7.28	0.07	7.65	0.06	0.951	87.049	11.488
23	20	7.00	0.19	7.37	0.20	0.950	86.961	11.499
24	19	6.74	0.06	7.06	0.07	0.954	87.283	11.457
25	11	5.14	0.09	5.48	0.11	0.937	85.706	11.668
26	20	7.51	0.06	7.94	0.09	0.946	86.569	11.552
27	14	7.58	0.03	8.09	0.05	0.937	85.744	11.663
28	18	7.82	0.07	8.26	0.12	0.946	86.542	11.555
29	18	7.94	0.06	8.48	0.11	0.937	85.687	11.670
30	10	8.08	0.05	8.77	0.06	0.922	84.314	11.860
31	20	8.13	0.08	8.74	0.08	0.931	85.141	11.745
32	20	8.34	0.08	8.81	0.07	0.947	86.612	11.546
33	20	8.24	0.05	8.73	0.06	0.944	86.408	11.573
34	19	8.22	0.09	8.70	0.09	0.944	86.411	11.573
35	20	8.18	0.09	8.65	0.11	0.946	86.515	11.559
36	20	8.04	0.10	8.51	0.09	0.945	86.420	11.571
37	20	7.97	0.07	8.42	0.07	0.947	86.610	11.546
38	20	7.79	0.09	8.26	0.11	0.943	86.293	11.588
39	20	7.72	0.06	8.15	0.07	0.947	86.613	11.546
40	20	7.53	0.09	7.97	0.09	0.945	86.488	11.562
41	20	7.40	0.12	7.83	0.12	0.945	86.493	11.562
42	20	7.29	0.06	7.71	0.09	0.945	86.481	11.563
43	20	7.10	0.07	7.49	0.13	0.949	86.808	11.520
44	20	6.89	0.09	7.25	0.12	0.950	86.873	11.511
45	18	6.59	0.09	6.96	0.08	0.947	86.628	11.544
46	20	6.36	0.09	6.69	0.14	0.951	86.966	11.499
47	20	6.05	0.13	6.36	0.18	0.952	87.061	11.486
48	20	5.75	0.09	6.06	0.10	0.948	86.759	11.526
49	17	5.47	0.10	5.76	0.14	0.950	86.882	11.510
50	18	6.75	0.07	7.13	0.09	0.946	86.555	11.553
51	20	7.00	0.08	7.37	0.10	0.950	86.921	11.505
52	20	7.25	0.06	7.70	0.10	0.942	86.170	11.605
53	20	7.43	0.06	7.88	0.09	0.943	86.271	11.591
54	20	7.62	0.05	8.04	0.06	0.949	86.796	11.521
55	20	7.71	0.05	8.16	0.08	0.946	86.510	11.559
56	20	7.90	0.06	8.36	0.10	0.945	86.448	11.568
57	20	8.06	0.09	8.53	0.10	0.945	86.419	11.572
58	20	8.14	0.07	8.64	0.07	0.942	86.173	11.605
59	20	8.34	0.04	8.85	0.10	0.942	86.187	11.603
60	16	8.37	0.05	8.89	0.10	0.942	86.154	11.607
61	20	8.48	0.16	9.01	0.22	0.941	86.094	11.615
62	20	8.65	0.11	9.13	0.13	0.947	86.601	11.547
63	20	8.77	0.07	9.25	0.12	0.948	86.718	11.532
64	20	8.76	0.06	9.24	0.13	0.948	86.688	11.536
65	20	8.76	0.04	9.27	0.10	0.945	86.450	11.567
66	20	8.74	0.10	9.22	0.12	0.948	86.770	11.525
67	20	8.53	0.08	9.03	0.09	0.945	86.424	11.571
68	20	8.48	0.06	8.97	0.09	0.945	86.477	11.564
69	20	8.37	0.08	8.84	0.10	0.946	86.570	11.551
70	20	8.25	0.07	8.69	0.10	0.950	86.883	11.510
71	18	8.12	0.09	8.56	0.10	0.949	86.788	11.522
72	20	7.95	0.05	8.36	0.11	0.950	86.943	11.502
73	20	7.85	0.06	8.25	0.09	0.952	87.128	11.477
74	20	7.60	0.13	7.98	0.16	0.953	87.148	11.475
75	20	7.39	0.06	7.76	0.09	0.952	87.078	11.484
76	20	7.20	0.09	7.55	0.11	0.952	87.145	11.475
77	20	6.94	0.08	7.26	0.11	0.956	87.477	11.432
78	20	6.68	0.07	7.01	0.11	0.954	87.241	11.463
79	20	6.41	0.10	6.72	0.15	0.955	87.353	11.448
80	20	6.07	0.07	6.36	0.12	0.955	87.413	11.440
81	20	5.77	0.09	6.03	0.12	0.957	87.580	11.418
82	13	5.43	0.06	5.75	0.08	0.944	86.388	11.576
Av	18.9	7.46	0.10	7.87	0.12	0.948	86.771	11.525

Table 4.5: Final series for **Eko MS80 ns 16002013 in DAQ2**.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ Wm^{-2}/mV	$s(j)$ $\mu V/Wm^{-2}$
1	20	6.54	0.08	5.15	0.08	1.270	116.229	8.604
2	20	6.19	0.11	4.88	0.09	1.269	116.136	8.611
3	20	5.82	0.12	4.60	0.09	1.265	115.695	8.643
4	15	5.52	0.07	4.36	0.05	1.267	115.902	8.628
5	20	5.25	0.10	4.15	0.11	1.265	115.710	8.642
6	17	4.88	0.09	3.85	0.08	1.269	116.133	8.611
7	16	3.78	0.08	2.92	0.07	1.296	118.539	8.436
8	19	9.08	0.35	7.33	0.27	1.239	113.345	8.823
9	20	9.16	0.44	7.41	0.37	1.236	113.052	8.845
10	18	8.62	0.23	6.90	0.19	1.249	114.246	8.753
11	18	8.29	0.17	6.63	0.14	1.250	114.399	8.741
12	12	8.33	0.23	6.66	0.21	1.251	114.414	8.740
13	12	8.31	0.19	6.62	0.18	1.255	114.812	8.710
14	18	8.32	0.20	6.65	0.18	1.251	114.484	8.735
15	20	8.30	0.10	6.62	0.09	1.254	114.743	8.715
16	20	8.17	0.08	6.54	0.04	1.249	114.244	8.753
17	20	7.99	0.16	6.38	0.11	1.251	114.482	8.735
18	17	8.01	0.13	6.39	0.11	1.253	114.627	8.724
19	20	7.89	0.12	6.26	0.09	1.259	115.212	8.680
20	20	7.66	0.11	6.12	0.09	1.251	114.466	8.736
21	20	7.47	0.04	5.93	0.02	1.260	115.268	8.675
22	20	7.28	0.07	5.82	0.04	1.251	114.473	8.736
23	20	7.00	0.19	5.60	0.15	1.249	114.293	8.749
24	19	6.74	0.06	5.37	0.05	1.254	114.685	8.720
25	11	5.14	0.09	4.25	0.07	1.208	110.522	9.048
26	20	7.51	0.06	6.00	0.09	1.252	114.544	8.730
27	14	7.58	0.03	6.13	0.03	1.237	113.164	8.837
28	18	7.82	0.07	6.26	0.08	1.249	114.263	8.752
29	18	7.94	0.06	6.41	0.07	1.239	113.313	8.825
30	10	8.08	0.05	6.59	0.02	1.225	112.114	8.920
31	20	8.13	0.08	6.56	0.05	1.240	113.454	8.814
32	20	8.34	0.08	6.64	0.03	1.255	114.840	8.708
33	20	8.24	0.05	6.59	0.04	1.252	114.541	8.731
34	19	8.22	0.09	6.57	0.07	1.252	114.555	8.729
35	20	8.18	0.09	6.52	0.08	1.255	114.858	8.706
36	20	8.04	0.10	6.41	0.06	1.254	114.735	8.716
37	20	7.97	0.07	6.36	0.04	1.252	114.549	8.730
38	20	7.79	0.09	6.23	0.07	1.250	114.369	8.744
39	20	7.72	0.06	6.15	0.05	1.256	114.905	8.703
40	20	7.53	0.09	6.03	0.07	1.250	114.336	8.746
41	20	7.40	0.12	5.92	0.08	1.251	114.474	8.736
42	20	7.29	0.06	5.82	0.04	1.253	114.621	8.724
43	20	7.10	0.07	5.63	0.07	1.262	115.463	8.661
44	20	6.89	0.09	5.47	0.06	1.260	115.301	8.673
45	18	6.59	0.09	5.27	0.06	1.251	114.452	8.737
46	20	6.36	0.09	5.05	0.07	1.260	115.249	8.677
47	20	6.05	0.13	4.79	0.10	1.264	115.622	8.649
48	20	5.75	0.09	4.58	0.06	1.255	114.858	8.706
49	17	5.47	0.10	4.34	0.08	1.261	115.354	8.669
50	18	6.75	0.07	5.43	0.06	1.243	113.687	8.796
51	20	7.00	0.08	5.63	0.07	1.242	113.669	8.797
52	20	7.25	0.06	5.83	0.04	1.243	113.745	8.792
53	20	7.43	0.06	5.98	0.05	1.243	113.740	8.792
54	20	7.62	0.05	6.09	0.03	1.251	114.484	8.735
55	20	7.71	0.05	6.17	0.02	1.250	114.344	8.746
56	20	7.90	0.06	6.32	0.04	1.250	114.347	8.745
57	20	8.06	0.09	6.44	0.07	1.250	114.409	8.741
58	20	8.14	0.07	6.52	0.04	1.248	114.160	8.760
59	20	8.34	0.04	6.67	0.05	1.251	114.412	8.740
60	16	8.37	0.05	6.70	0.05	1.250	114.329	8.747
61	20	8.48	0.16	6.80	0.14	1.248	114.137	8.761
62	20	8.65	0.11	6.89	0.09	1.255	114.790	8.712
63	20	8.77	0.07	6.98	0.06	1.256	114.940	8.700
64	20	8.76	0.06	7.01	0.06	1.250	114.375	8.743
65	20	8.76	0.04	7.04	0.03	1.245	113.867	8.782
66	20	8.74	0.10	6.97	0.06	1.254	114.703	8.718
67	20	8.53	0.08	6.86	0.06	1.243	113.765	8.790
68	20	8.48	0.06	6.78	0.03	1.251	114.431	8.739
69	20	8.37	0.08	6.72	0.05	1.245	113.917	8.778
70	20	8.25	0.07	6.62	0.04	1.246	113.989	8.773
71	18	8.12	0.09	6.48	0.06	1.253	114.610	8.725
72	20	7.95	0.05	6.33	0.03	1.255	114.839	8.708
73	20	7.85	0.06	6.27	0.05	1.253	114.660	8.721
74	20	7.60	0.13	6.06	0.10	1.254	114.706	8.718
75	20	7.39	0.06	5.89	0.03	1.254	114.707	8.718
76	20	7.20	0.09	5.73	0.07	1.257	114.978	8.697
77	20	6.94	0.08	5.52	0.07	1.257	115.033	8.693
78	20	6.68	0.07	5.31	0.05	1.258	115.115	8.687
79	20	6.41	0.10	5.10	0.08	1.258	115.107	8.688
80	20	6.07	0.07	4.82	0.05	1.260	115.277	8.675
81	20	5.77	0.09	4.59	0.08	1.257	115.035	8.693
82	13	5.43	0.06	4.32	0.05	1.258	115.096	8.688
Av	18.9	7.46	0.10	5.96	0.08	1.252	114.579	8.728

Table 4.6: Final series for **KZ CMP10 ns 141141 in DAQ2**.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ $\mathrm{Wm}^{-2}/\mathrm{mV}$	$s(j)$ $\mu V/Wm^{-2}$
1	20	6.54	0.08	5.80	0.10	1.126	103.054	9.704
2	20	6.19	0.11	5.52	0.09	1.122	102.653	9.742
3	20	5.82	0.12	5.22	0.13	1.114	101.928	9.811
4	15	5.52	0.07	4.92	0.07	1.123	102.740	9.733
5	20	5.25	0.10	4.67	0.10	1.126	102.982	9.710
6	17	4.88	0.09	4.34	0.09	1.124	102.824	9.725
7	16	3.78	0.08	3.35	0.09	1.127	103.144	9.695
8	19	9.08	0.35	8.11	0.28	1.120	102.508	9.755
9	20	9.16	0.44	8.21	0.39	1.116	102.068	9.797
10	18	8.62	0.23	7.69	0.21	1.121	102.559	9.750
11	18	8.29	0.17	7.39	0.15	1.122	102.675	9.739
12	12	8.33	0.23	7.43	0.24	1.121	102.544	9.752
13	12	8.31	0.19	7.38	0.19	1.126	102.976	9.711
14	18	8.32	0.20	7.41	0.17	1.123	102.760	9.731
15	20	8.30	0.10	7.38	0.10	1.125	102.936	9.715
16	20	8.17	0.08	7.28	0.07	1.122	102.628	9.744
17	20	7.99	0.16	7.11	0.14	1.124	102.815	9.726
18	17	8.01	0.13	7.12	0.12	1.125	102.897	9.718
19	20	7.89	0.12	7.00	0.10	1.127	103.156	9.694
20	20	7.66	0.11	6.81	0.10	1.125	102.968	9.712
21	20	7.47	0.04	6.60	0.05	1.132	103.611	9.651
22	20	7.28	0.07	6.47	0.08	1.125	102.930	9.715
23	20	7.00	0.19	6.24	0.18	1.123	102.701	9.737
24	19	6.74	0.06	5.98	0.06	1.126	103.053	9.704
25	11	5.14	0.09	4.66	0.08	1.102	100.787	9.922
26	20	7.51	0.06	6.71	0.08	1.119	102.348	9.771
27	14	7.58	0.03	6.83	0.05	1.111	101.615	9.841
28	18	7.82	0.07	6.99	0.08	1.119	102.363	9.769
29	18	7.94	0.06	7.17	0.08	1.107	101.262	9.875
30	10	8.08	0.05	7.40	0.05	1.091	99.825	10.018
31	20	8.13	0.08	7.36	0.06	1.104	101.039	9.897
32	20	8.34	0.08	7.44	0.05	1.121	102.581	9.748
33	20	8.24	0.05	7.36	0.05	1.119	102.421	9.764
34	19	8.22	0.09	7.34	0.07	1.120	102.433	9.763
35	20	8.18	0.09	7.30	0.09	1.120	102.514	9.755
36	20	8.04	0.10	7.18	0.07	1.119	102.391	9.766
37	20	7.97	0.07	7.11	0.06	1.121	102.543	9.752
38	20	7.79	0.09	6.97	0.09	1.117	102.201	9.785
39	20	7.72	0.06	6.90	0.06	1.120	102.433	9.762
40	20	7.53	0.09	6.74	0.08	1.118	102.256	9.779
41	20	7.40	0.12	6.63	0.09	1.117	102.241	9.781
42	20	7.29	0.06	6.52	0.06	1.117	102.175	9.787
43	20	7.10	0.07	6.34	0.08	1.120	102.446	9.761
44	20	6.89	0.09	6.15	0.08	1.120	102.458	9.760
45	18	6.59	0.09	5.91	0.06	1.115	102.035	9.801
46	20	6.36	0.09	5.69	0.09	1.117	102.216	9.783
47	20	6.05	0.13	5.41	0.12	1.119	102.367	9.769
48	20	5.75	0.09	5.16	0.07	1.114	101.959	9.808
49	17	5.47	0.10	4.90	0.10	1.115	102.019	9.802
50	18	6.75	0.07	6.05	0.07	1.115	102.030	9.801
51	20	7.00	0.08	6.25	0.08	1.120	102.455	9.760
52	20	7.25	0.06	6.49	0.07	1.117	102.151	9.789
53	20	7.43	0.06	6.66	0.07	1.116	102.101	9.794
54	20	7.62	0.05	6.80	0.04	1.121	102.553	9.751
55	20	7.71	0.05	6.89	0.04	1.120	102.510	9.755
56	20	7.90	0.06	7.06	0.07	1.120	102.472	9.759
57	20	8.06	0.09	7.20	0.08	1.120	102.462	9.760
58	20	8.14	0.07	7.29	0.05	1.117	102.163	9.788
59	20	8.34	0.04	7.47	0.06	1.117	102.202	9.785
60	16	8.37	0.05	7.49	0.06	1.118	102.271	9.778
61	20	8.48	0.16	7.60	0.16	1.116	102.084	9.796
62	20	8.65	0.11	7.71	0.10	1.122	102.626	9.744
63	20	8.77	0.07	7.79	0.08	1.126	102.987	9.710
64	20	8.76	0.06	7.79	0.07	1.124	102.819	9.726
65	20	8.76	0.04	7.81	0.05	1.122	102.682	9.739
66	20	8.74	0.10	7.77	0.09	1.126	103.014	9.707
67	20	8.53	0.08	7.61	0.06	1.121	102.558	9.751
68	20	8.48	0.06	7.56	0.06	1.122	102.655	9.741
69	20	8.37	0.08	7.46	0.06	1.121	102.537	9.753
70	20	8.25	0.07	7.35	0.07	1.122	102.619	9.745
71	18	8.12	0.09	7.23	0.07	1.124	102.823	9.725
72	20	7.95	0.05	7.06	0.06	1.125	102.971	9.711
73	20	7.85	0.06	6.97	0.06	1.126	103.032	9.706
74	20	7.60	0.13	6.75	0.12	1.126	103.000	9.709
75	20	7.39	0.06	6.57	0.06	1.124	102.863	9.722
76	20	7.20	0.09	6.40	0.08	1.125	102.935	9.715
77	20	6.94	0.08	6.17	0.08	1.125	102.945	9.714
78	20	6.68	0.07	5.95	0.07	1.124	102.807	9.727
79	20	6.41	0.10	5.71	0.10	1.123	102.704	9.737
80	20	6.07	0.07	5.41	0.08	1.123	102.741	9.733
81	20	5.77	0.09	5.14	0.09	1.123	102.725	9.735
82	13	5.43	0.06	4.87	0.05	1.116	102.066	9.798
Av	18.9	7.46	0.10	6.66	0.09	1.120	102.483	9.758

Table 4.7: Final series for **Eko MS80 ns 18003080 in DAQ2**.

j	N_j	$\langle V_R \rangle$ mV	σ_{VR} mV	$\langle V_F \rangle$ mV	σ_{VF} mV	$\kappa(j)$	$F(j)$ $\mathrm{Wm}^{-2}/\mathrm{mV}$	$s(j)$ $\mu V/Wm^{-2}$
1	20	6.54	0.08	5.49	0.08	1.190	108.892	9.183
2	20	6.19	0.11	5.21	0.10	1.188	108.731	9.197
3	20	5.82	0.12	4.91	0.10	1.184	108.354	9.229
4	15	5.52	0.07	4.65	0.06	1.186	108.541	9.213
5	20	5.25	0.10	4.42	0.09	1.187	108.612	9.207
6	17	4.88	0.09	4.12	0.09	1.185	108.432	9.222
7	16	3.78	0.08	3.14	0.08	1.204	110.169	9.077
8	19	9.08	0.35	7.75	0.29	1.171	107.153	9.332
9	20	9.16	0.44	7.84	0.39	1.168	106.878	9.356
10	18	8.62	0.23	7.30	0.20	1.180	107.931	9.265
11	18	8.29	0.17	7.02	0.15	1.181	108.071	9.253
12	12	8.33	0.23	7.05	0.23	1.181	108.076	9.253
13	12	8.31	0.19	7.02	0.19	1.185	108.378	9.227
14	18	8.32	0.20	7.04	0.19	1.181	108.094	9.251
15	20	8.30	0.10	7.01	0.09	1.184	108.319	9.232
16	20	8.17	0.08	6.93	0.04	1.179	107.890	9.269
17	20	7.99	0.16	6.76	0.12	1.181	108.062	9.254
18	17	8.01	0.13	6.77	0.12	1.182	108.183	9.244
19	20	7.89	0.12	6.64	0.09	1.187	108.643	9.204
20	20	7.66	0.11	6.49	0.09	1.180	107.973	9.262
21	20	7.47	0.04	6.29	0.03	1.188	108.695	9.200
22	20	7.28	0.07	6.17	0.04	1.180	107.971	9.262
23	20	7.00	0.19	5.94	0.16	1.179	107.864	9.271
24	19	6.74	0.06	5.70	0.05	1.183	108.207	9.242
25	11	5.14	0.09	4.47	0.08	1.148	105.075	9.517
26	20	7.51	0.06	6.36	0.09	1.181	108.091	9.251
27	14	7.58	0.03	6.49	0.03	1.168	106.881	9.356
28	18	7.82	0.07	6.63	0.08	1.180	107.914	9.267
29	18	7.94	0.06	6.79	0.08	1.169	106.955	9.350
30	10	8.08	0.05	7.00	0.02	1.155	105.640	9.466
31	20	8.13	0.08	6.96	0.05	1.168	106.838	9.360
32	20	8.34	0.08	7.05	0.03	1.183	108.211	9.241
33	20	8.24	0.05	6.99	0.04	1.180	107.949	9.264
34	19	8.22	0.09	6.97	0.07	1.180	107.914	9.267
35	20	8.18	0.09	6.92	0.09	1.182	108.164	9.245
36	20	8.04	0.10	6.81	0.07	1.181	108.045	9.255
37	20	7.97	0.07	6.76	0.04	1.179	107.843	9.273
38	20	7.79	0.09	6.62	0.07	1.177	107.699	9.285
39	20	7.72	0.06	6.53	0.06	1.183	108.191	9.243
40	20	7.53	0.09	6.40	0.07	1.177	107.687	9.286
41	20	7.40	0.12	6.28	0.08	1.179	107.823	9.274
42	20	7.29	0.06	6.17	0.04	1.180	107.959	9.263
43	20	7.10	0.07	5.98	0.07	1.188	108.694	9.200
44	20	6.89	0.09	5.81	0.06	1.186	108.474	9.219
45	18	6.59	0.09	5.59	0.06	1.178	107.750	9.281
46	20	6.36	0.09	5.37	0.07	1.185	108.424	9.223
47	20	6.05	0.13	5.10	0.10	1.188	108.675	9.202
48	20	5.75	0.09	4.87	0.07	1.180	107.977	9.261
49	17	5.47	0.10	4.61	0.09	1.185	108.400	9.225
50	18	6.75	0.07	5.73	0.06	1.177	107.658	9.289
51	20	7.00	0.08	5.95	0.07	1.177	107.645	9.290
52	20	7.25	0.06	6.16	0.04	1.177	107.707	9.284
53	20	7.43	0.06	6.31	0.05	1.177	107.718	9.283
54	20	7.62	0.05	6.44	0.04	1.183	108.266	9.236
55	20	7.71	0.05	6.53	0.03	1.182	108.108	9.250
56	20	7.90	0.06	6.69	0.04	1.181	108.066	9.254
57	20	8.06	0.09	6.82	0.07	1.181	108.051	9.255
58	20	8.14	0.07	6.91	0.04	1.178	107.800	9.276
59	20	8.34	0.04	7.07	0.05	1.180	107.976	9.261
60	16	8.37	0.05	7.10	0.06	1.178	107.814	9.275
61	20	8.48	0.16	7.21	0.15	1.176	107.618	9.292
62	20	8.65	0.11	7.32	0.10	1.182	108.110	9.250
63	20	8.77	0.07	7.41	0.07	1.183	108.222	9.240
64	20	8.76	0.06	7.44	0.06	1.177	107.706	9.285
65	20	8.76	0.04	7.47	0.03	1.173	107.298	9.320
66	20	8.74	0.10	7.41	0.06	1.180	107.990	9.260
67	20	8.53	0.08	7.28	0.07	1.171	107.134	9.334
68	20	8.48	0.06	7.20	0.04	1.177	107.714	9.284
69	20	8.37	0.08	7.14	0.04	1.172	107.271	9.322
70	20	8.25	0.07	7.04	0.04	1.172	107.269	9.322
71	18	8.12	0.09	6.89	0.06	1.178	107.809	9.276
72	20	7.95	0.05	6.73	0.03	1.181	108.006	9.259
73	20	7.85	0.06	6.66	0.06	1.179	107.824	9.274
74	20	7.60	0.13	6.45	0.10	1.179	107.848	9.272
75	20	7.39	0.06	6.27	0.04	1.179	107.824	9.274
76	20	7.20	0.09	6.09	0.08	1.181	108.031	9.257
77	20	6.94	0.08	5.88	0.07	1.181	108.071	9.253
78	20	6.68	0.07	5.65	0.06	1.182	108.136	9.248
79	20	6.41	0.10	5.43	0.09	1.182	108.118	9.249
80	20	6.07	0.07	5.13	0.05	1.183	108.276	9.236
81	20	5.77	0.09	4.89	0.08	1.182	108.122	9.249
82	13	5.43	0.06	4.59	0.06	1.183	108.237	9.239
Av	18.9	7.46	0.10	6.32	0.08	1.180	107.937	9.265

Table 4.8: Final series for **KZ CMP21 ns 140336 in DAQ2**.

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