Active operation of a Hickey-Frieden (HF) radiometer

M. Suter[1], and J. Buchli[1]

[1] Davos Instruments AG, Davos Switzerland

Abstract

Electrical substitution radiometers are used as reference instruments for solar irradiance measurements. Thereby solar optical power is substituted by electrical power, which can be performed in a passive or an active mode.

Despite the fact that the Hickey-Frieden (HF) radiometer is normally operated in the passive mode (also known as the pacrad mode, it is possible to operate it in the active mode, similar to a PMO6/PMO8. An HF-radiometer has been operated in the active mode, using a slightly modified Linard-control unit from Davos Instruments.

While the passive mode allows to take readings of solar irradiance with an almost infinitely high cadence, the active mode traditionally allowed only one reading every two minutes. Using a fast digital controller loop, a measurement cadence of one reading every 30 seconds can be achieved which eliminates this limitation of the active mode.

A data set from summer 2021 is presented, the readings of the active HF are compared to different instruments run in parallel at PMOD/WRC, including instruments of the World Standard Group (WSG). Furthermore first results from the IPC-XIII are presented.

1 Introduction

Electrical substitution radiometers are usually divided into two groups: the actively operated instruments and the passively operated radiometers (WMO IOM Report No. 124). Prominent examples for the active instruments are: The "PMO" and "CROM" type, as well as the satellite based TIM and DARA type instruments. The well known passive radiometers are: PACRAD, TMI/MK and HF/AHF types. The HF and AHF (automated HF) radiometers are possibly the most widespread electrical substitution radiometers for solar irradiance.

1.1 Passive mode operation

In passive mode, the heat flux from the cavity to the heat sink of the radiometer is determined using a thermopile. The thermopile voltage is a measure of the heat flux, and similarly for the absorbed solar radiation. In order to calibrate the thermopile voltage to a cavity power, the cavity is electrically heated, while a shutter shades the cavity from solar radiation.

1.2 Active mode operation

In active mode, a reference cavity (in the dark) is electrically heated with a constant power that is higher than the expected solar power. The active (measurement cavity) is then also electrically heated by an active controller loop, so that these two cavities are at the same temperature, compared to the common heat sink. If the shutter is open, and the active cavity is illuminated, less electrical power is needed in order to balance the cavities. If the shutter is closed, more electrical power is needed to balance the cavities. Thus the difference of these two power levels corresponds directly to the contribution of the sun. The two operation modes are illustrated in Figure 1.

According to the AHF manual from the manufacturer Eppley Laboratory inc. it is possible to operate the AHF radiometer in active mode. However the manufacturer only provided control units capable of passive mode operation which is the recommended way of operation. The HF radiometer has, similar to the active radiometers a dark cavity. The thermopile measures the temperature difference between these two cavities. The dark cavity also features a heater that is however not needed in passive mode.

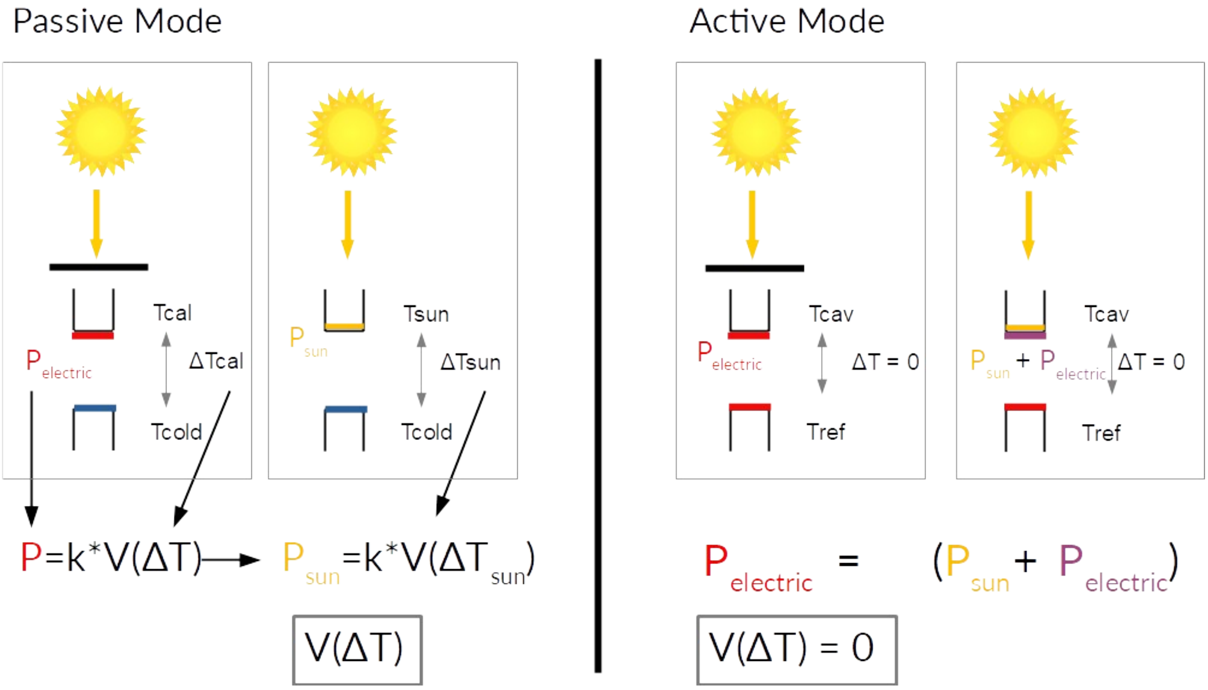

Figure 1 Passive and active mode operation of an electrical substitution radiometer. In the passive mode the thermopile signal serves as a measure of temperature difference. The thermopile is calibrated with an electric heat load during closed shutter phase (most left image). In the active mode the temperature of the measurement cavity is kept at constant temperature (the temperature of a reference cavity in the dark) by means of additional electrical heater power. In closed shutter phase the full amount of heating power is generated electrically, while in open shutter phase the amount of electric power is reduced by the sun's power.

2 Measurement Set-up

2.1 Equipment

For the active operation of the AHF radiometer the following equipment has been used.

2.1.1 AHF radiometer

The AHF radiometer S/N 29221, that has been manufactured by the Eppley Laboratory inc. in 1993.

2.1.2 Control unit Linard

The control unit Linard from Davos Instruments is designed to operate an active radiometer such as the PMO6 or the PMO8. A slight modification has been made: While the cavity balance of a PMO6/PMO8 is measured with an AC-measurement bridge, the cavity balance of the AHF is measured by means of a thermopile voltage. Thus the AC demodulation circuit needs to be bypassed.

2.1.3 Pre-Amplifier Module

Since thermopile reading is very crucial the signal must be carefully shielded against any noise pickup. With active mode operation, the thermopile signal is always regulated to zero, no absolute accuracy is needed, but a high sensitivity and low signal to noise ratio is important. Therefore a pre-apmlifier is placed close to the instrument. The pre-amplifier housing is built by the foot of a PMO8 radiometer, its plug also serves as a contact for the cable that connects to the control unit. The Pre-Amplifier is shown in Figure 3.

2.1.4 Shutter Module

In active mode much more shutter movements are necessary than in passive mode. While in passive mode the shutter is closed 2 to 3 times per hour, in the active mode 120 shutter cycles per hour are performed. Therefore it has been decided not to use the original (internal) shutter, but to place an external shutter on top of the radiometer structure. The external shutter consists of a PMO6 shutter, that is based on a stepper motor. The Shutter module is shown in Figure 2.

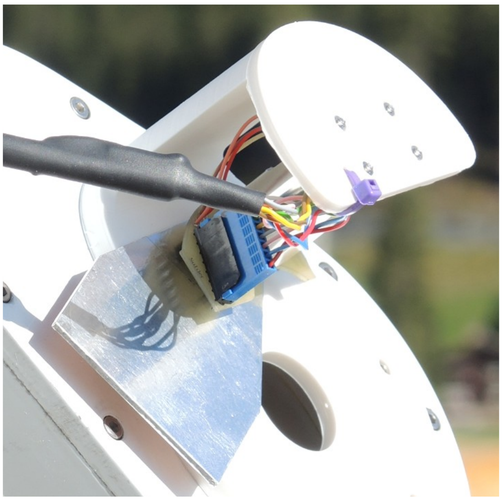

Figure 2 External shutter module

Figure 3 Pre-Amplifier

2.2 Schematics and wiring

Figure 4 shows a basic interconnection schematic of the different components. All signal wires are twisted pair, and cables are shielded

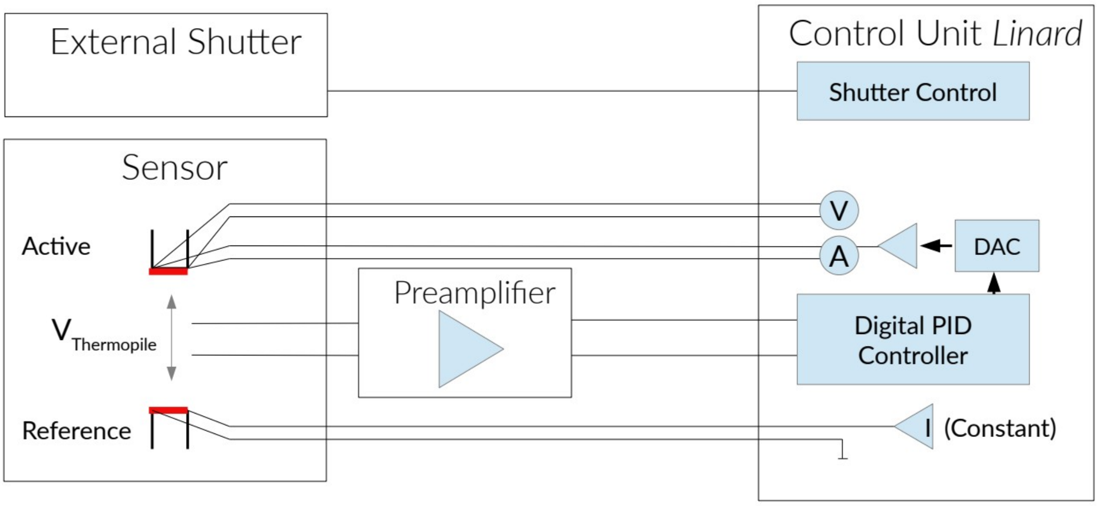

Figure 4 Wiring schematics of the measurement set-up.

2.3 Operation and Data Processing

The instrument is operated in an active mode with open and closed shutter cycles of 15s/15s respectively. Thus every 30 seconds a solar irradiance value can be derived. Figure 3 shows the thermopile output voltage that is fed into the PID controller in order to balance the cavities (thermopile voltage zero). Figure 6 shows the applied voltage to the heater element on the cavity. From the voltage and the simultaneously measured current through the heater element, the electrical heater power is derived. From the different power levels (open and closed phases) the contribution of the solar irradiance is derived as:

$$P_{Solar} = P_{Electic}(closed) - P_{electric}(open) \tag{1}$$

This is the standard equation for an active radiometer.

In order to get solar irradiance Irr, the power contribution of the sun is multiplied by the radiometric constant c.

$$Irr = C \cdot P_{Solar} \tag{2}$$

A well functioning controller loop is a requirement for the active radiometer operation. Low noise and fast settling times can be achieved with the described set-up. Figure 3 and Figure 6 show that the system can react adequately to the shutter switching. The balance of the cavity can be reestablished after a few seconds. The fast settling time indicates, that even higher measurement cadences than 30 s might be possible.

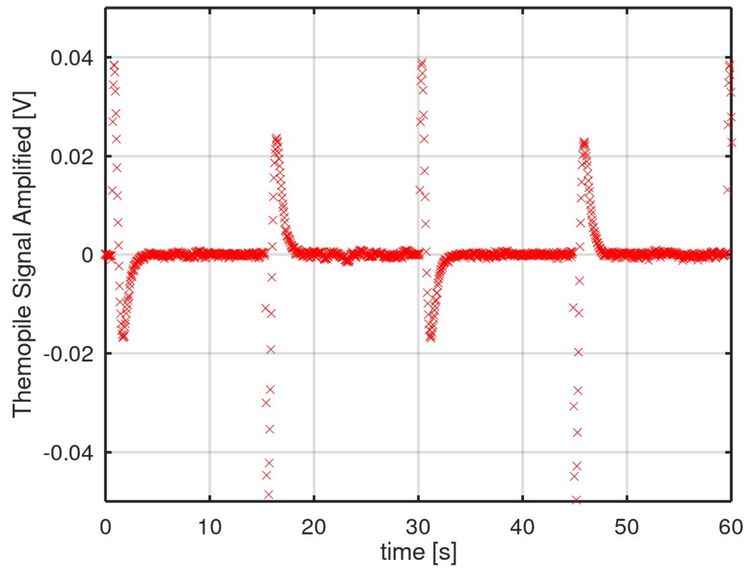

Figure 5 Thermopile signal (amplified by a factor of 2100) during active operation of the radiometer. At t=2 s, the shutter gets closed, at t=17 the shutter opens, and so forth. It can be seen how quickly the controller loop adjusts to the new situation and re-establishes thermal balance between the cavities.

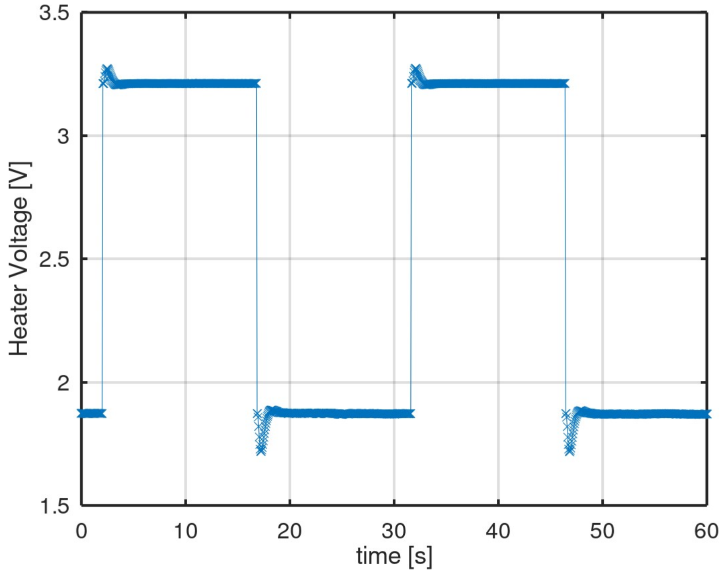

Figure 6 Heater Voltage raw signal over two shutter cycles. Two voltage levels can be identified, open shutter level at approx. 1.85 V and closed shutter level at 3.25 V. The wiggles at the beginning of each period result from a small imbalance after shutter operation.

2.4 Treatment of the Lead Heating Effect

The radiometric constant c is in first order the inverse of the defining aperture area. The radiometric constant c also accounts for minor effects, such as diffraction, non-equivalences of electrical and radiative heating of the cavity, and lead heating effects (Brusa and Fröhlich, 1986; Suter 2015). In the context of this work the lead heating effects needs special attention. Although the effect is similar in active and passive mode, it has been treated differently by the different user groups. While the characterization of the PMO6 (classic active cavity radiometer) by Brusa and Fröhlich (1986) includes the lead heating effect in the radiometric constant c, the HF manual proposes a different treatment of the lead heating effect, that consists of a correction that is proportional to the square of the current. From these two sources of information it is concluded that the point of voltage measurement at the PMO6 is directly on the cavity, whereas in the HF radiometer it is farther away, and only the current carrying lead is attached to the cavity. Therefore in the PMO6 the electrical heating is slightly underestimated and in the HF the electrical heating power is overestimated. In both case a correction is foreseen.

For this work the correction described in the AHF manual is converted into a correction that can be integrated into the radiometric constant c, similar to Brusa and Fröhlich (1986) treatment.

The original HF formula (The Eppley Laboratory inc.,1992) describes the relation between electrical calibration and solar irradiance for equal thermopile signals in calibration and measurement phase:

$$Irr = C_{hf} \cdot I \cdot \left(V - I \cdot R_{leads} \right) \quad (3)$$

Where I can be substituted, where R_{heater} is the resistance of the cavity heater:

$$Irr = C_{hf} \cdot I \cdot \left(V - \frac{V}{R_{Heater}} \cdot R_{leads} \right) = Chf \cdot I \cdot V \left(1 - \frac{1}{R_{heater}} \cdot R_{leads} \right) = C_{brusa} \cdot I \cdot V \quad (4)$$

this leads to:

$$C_{brusa} = C_{hf} \left(1 - \frac{R_{leads}}{R_{heater}} \right) \quad (5)$$

Table 7 shows the values for the involved symbols. Thus C_{brusa} can be derived from c_{hf}, and the solar irradiance can simply be derived as described in 2.3 using C_{brusa}.

R_{heater}	R_{leads}	C_{hf} (Factofy Calibration)	C_{brusa} (applied in active mode)
153.3 Ω	0.066 Ω	20009 m^{-2}	20000 m^{-2}

Table 7 Values for heater and leads resistance and radiometric constants for AHF 29221, derived from the instruments factory calibration sheet.

2.5 Data Collection

The AHF 29221 has been installed on the WSG tracking platform at the World Radiation Centre (WRC) in Davos Switzerland in July 2021. During 13 days between 18. July and 24.September data has been collected.

During IPC-XIII the instrument has been placed at a separate solar tracker on the WRC premises. Data has been collected according to the IPC schedule.

3 Data Evaluation and Comparison

The AHF raw data is processed internally in the control unit Linard, similar to an evaluation of a PMO8, using the active radiometer equations (1) and (2) from section 2.3 in order to derive solar irradiance. Quality flags are assigned according to stability criteria applied to the raw signals.

AHF 29221 irradiance data has been compared to different available reference instruments, such as WSG members and another AHF radiometer available the WRC in Davos. Figure 8 shows the collected irradiance data in comparison to the irradiance data collected by the AHF 32455 radiometer for the pre-IPC period in summer 2021. Table 9 shows comparison results to several other radiometers, before and during IPC 2021. All other radiometers are corrected by their WRR factor, in order to represent WRR. The absolute value of the AHF 29221 is lower than the WRR by approximately 1500 ppm. The AHF 29221 has no WRR factor to date since it has not been part of a comparison since its original factory calibration in 1993. The new comparison result would yield a WRR factor of approximately 1.0015, that is comparable to the factor of AHF 32455 that is 1.00138 (IPC-XII).

Consulting the IPC-XII Report (WMO IOM Report No. 124) it can be seen that a WRR correction of 1500 ppm to the factory calibration is in the usual range for an AHF radiometer.

Apart from the absolute values (ratio to WRR) in Table 9 it is worthwhile to have a look at the standard deviations of the ratio. While the standard deviation of the ratio to older radiometers such as the PMO2 is clearly higher than the standard deviation in the case of the two PMO8 radiometers, where the standard deviation is remarkably low. It means that the active AHF 29221 performs low noise measurements and is a very stable radiometer.

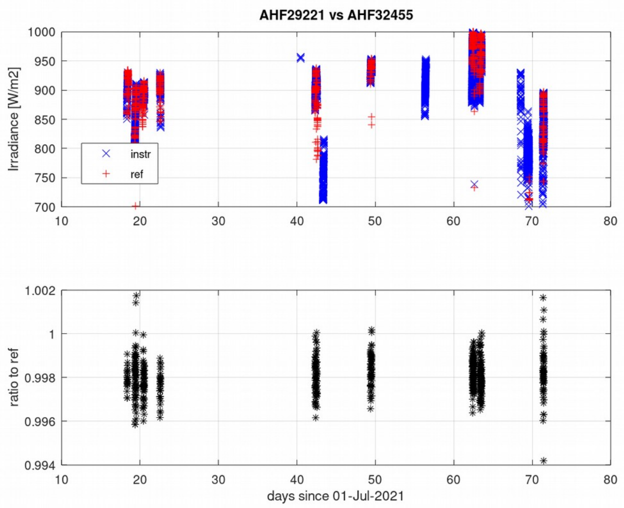

Figure 8 Collected solar irradiance data during July, August and September 2021, compared to the data of AHF 32455. AHF 32455 has an WRR factor of 1.00138 applied.

Reference Instrument	Period	Mean ratio to reference	Standard deviation (ratio to reference)
AHF 32455	Pre IPC (Jul-Sep 2021)	0.9981	0.00084
PMO2	Pre IPC (Jul-Sep 2021)	0.99827	0.00099
HF18784	Pre IPC (Jul-Sep 2021)	0.9976	0.00097
WRR Preliminary	IPC	0.9985	0.00073
PMO2	1. October	0.99859	0.00085
HF30497	1. October	0.99862	0.00068
TMI68018	1. October	0.99846	0.00079
F201-001 (PMO8)	1. October	0.99847	0.00044
F201-002 (PMO8)	1. October	0.99858	0.00039

Table 9 Comparison of AHF29221 irradiance data to other instruments. All of the compared instruments have WRR factors applied, and represent WRR. The Period indicates the time period that has been used to retrieve the respective result. The results from 1. October are from a single day, instruments belong to participants of the IPC

4 Conclusion and Outlook

It could be shown that the AHF radiometer is suitable for active operation. An operational controller loop could be established, using mostly off the shelf components. The preamplifier for the thermopile signal as well as proper shielding turned out to be the key for smooth operation.

A measurement cadence of 30 s has been achieved, the results indicate, that even igher cadences seem feasible.

Low standard deviation (400 ppm) in the irradiance ratios to modern PMO8 radiometer indicate that the active mode is performing well, and the noise level is low.

Comparing the absolute irradiance values to WRR, it is found that the AHF reads 1500 ppm lower than WRR. This difference is within the expected range, as the comparison is based on the factory calibration that is almost 30 years past. Although there is no indication of inconsistency it would be desirable to validate the results of the active HF mode to the passive mode of the same instrument within a short period of time and accurate equipment, that would lead to lower uncertainties.

Acknowledgements

Davos Instruments acknowledges the support form the Deutsche Wetterdienst (DWD), PMOD/WRC and the Eppley Laboratory inc.

References

Brusa, R.W. and C. Fröhlich, 1986: Absolute Radiometers (PMO6) and their Experimental Characterisation. Applied Optics, 25:4173–4180.

Suter, M, 2015: Advances in Solar Radiometry, PhD thesis, Universität Zürich.

The Eppley Laboratory inc.,1992: Instruction and Information Manual For Model H-F Self-Calibrating Cavity Pyrheliometer and Model 405A Radiometer Control Unit.

World Meteorological Organization, 2016: International Pyrheliometer Comparison IPC-XII (W. Finsterle, ed.). WMO IOM Report No. 124.