NREL Comparison of Absolute Cavity Pyrgeometers, InfraRed Integrating Sphere, and Pyrgeometers Traceable to World Infrared Standard Group: September 25-October 6, 2023

Ibrahim Reda, Afshin Andreas, Martina Stoddard, Aaron Kepple, Shawn Jaker, and Aron Habte

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-1900-88171
November 2023

NREL Comparison of Absolute Cavity Pyrgeometers, InfraRed Integrating Sphere, and Pyrgeometers Traceable to World Infrared Standard Group: September 25-October 6, 2023

Ibrahim Reda, Afshin Andreas, Martina Stoddard, Aaron Kepple, Shawn Jaker, and Aron Habte

National Renewable Energy Laboratory

Suggested Citation
Reda, Ibrahim, Afshin Andreas, Martina Stoddard, Aaron Kepple, Shawn Jaker, and Aron Habte. 2023. *NREL Comparison of Absolute Cavity Pyrgeometers, InfraRed Integrating Sphere, and Pyrgeometers Traceable to World Infrared Standard Group: September 25-October 6, 2023*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-1900-88171. https://www.nrel.gov/docs/fy24osti/88171.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-1900-88171
November 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by NREL's Environment, Safety, Health, & Quality center (ESH&Q). The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Acknowledgments

We sincerely appreciate the support of Solar Radiance Research Laboratory (SRRL) staff and National Renewable Energy Laboratory (NREL) management, the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy/Solar Energy Technologies Program, Environmental Research/Atmospheric Radiation Measurement Program, and NREL's Environment, Safety, Health, & Quality center (ESH&Q).

Table of Contents

List of Figures

List of Tables

1 Introduction

The comparison of the absolute cavity pyrgeometers (ACPs) with the InfraRed Integrating Sphere (IRIS), Eppley Precision Infrared Radiometer (PIR) pyrgeometers, and Kipp & Zonen (KZ) pyrgeometers traceable to the World Infrared Standard Group (WISG) was held during NREL ACP and IRIS Comparisons (NAIC) from September 25 to October 6, 2023. Data from all instruments was collected during nighttime clear sky conditions only. The irradiance measured by the ACPs is collected in 30 seconds intervals during the measurement period of two hours, and 10 seconds intervals during the calibration period of 6 minutes.

During the comparison, the average (av) irradiance difference measured by ACPs and IRIS9 varied from -0.75 W/m^2 to 0.76 W/m^2, standard deviation (sd) from 0.78 W/m^2 to 1.04 W/m^2, and uncertainty U_{95} from 1.96 W/m^2 to 2.07 W/m^2. The average irradiance difference measured by ACP95F3 minus the irradiance measured by all pyrgeometers varied from 1.64 to 3.96 W/m^2, sd from 1.70 W/m^2 to 1.86 W/m^2, and uncertainty U_{95} from 3.78 W/m^2 to 5.42W/m^2. Note that from September 25th at 18:31 to September 29th at 5:30 ACP96F3 irradiance is calculated using Bruce, et al 2023 method.

Instrument List

- Absolute Cavity Pyrgeometer:
  - ACP20F3: DOE-Atmospheric atmospheric Radiation program (ARM)
  - ACP95F3: NREL
  - ACP96F3: Physikalisch-Meteorologisches Observatorium Davos—World Radiation Center (PMOD/WRC)
  - ACP10F3: Japan Meteorological Agency (JMA)
- InfraRed Integrating Sphere:
  - IRIS9: PMOD
- PIR pyrgeometer: 31197F3 (NREL)
- KZ pyrgeometer CGR4: 060881(NREL), 010567 (JMA, Japan), FT005(PMOD/WRC)

2 Measurement Equations

ACP

$$W = \frac{K_1 * V_{tp} + (2-\epsilon) * K_2 * W_r - (1+\epsilon) * W_c}{\tau}$$

Where,

- W is the atmospheric longwave irradiance ($W.m^{-2}$).
- K_1 is the reciprocal of the ACP's responsivity ($W.m^{-2}.uV^{-1}$).
- V_{tp} is the thermopile output voltage (uV).
- ϵ is the gold emittance.
- K_2 is the emittance of the black receiver surface.
- W_r is the receiver irradiance ($W.m^{-2}$) = σ * (T_{case} + 0.0007074 * V_{tp})^4, where T_{case} is the pyrgeometer case temperature in Kelvin.

- W_c is the concentrator irradiance ($W.m^{-2}$).
- τ is the ACP's throughput.

IRIS

$$W = \frac{U * Cos(\theta)}{C(1 + dt(T - 293.15))} + k\sigma T^4$$

Where,

- U is the signal (V).
- Θ is the signal phase measure by the lock-in amplifier (°).
- C is the responsivity ($VW^{-1}m^2$).
- T is the IRIS temperature (K).
- k is the emissivity correction factor.
- dt is the temperature coefficient of the pyroelectric detector (K^{-1}).
- σ is the Stefan-Boltzmann constant ($W.m^{-2}$).

PIR&KZ (NREL)

$$W = K_1 * V_{tp} + K_2 * W_r + K_3 * (W_d - W_r)$$

Where,

- K_1 , K_2 , and K_3 are the calibration coefficients.
- W_d is the dome irradiance, in W/m^2.

KZ (PMOD)

$$W = \frac{V_{tp}}{C}(1 + K_1 * \sigma T_c^3) + K_2 * W_c - K_3 * (W_d - W_c)$$

Where C, K_1, and K_2 are the calibration coefficients, W_d and W_c are the dome and case irradiance.

3 Results

Figure 1 shows the irradiance of ACPs and IRIS9. Figure 2 shows ACP95F3 irradiance and irradiance measured by pyrgeometers. Figure 3 shows ACP95F3 thermopile output voltage. Figure 4 shows the water vapor content. Figure 5 is the water vapor content during the comparison. Table 1 shows that U_{95} varied from 1.96 W/m^2 to 2.07 W/m^2 for all ACPs and IRIS9, and U_{95} varied from U_{95} from 3.78 W/m^2 to 5.42W/m^2 for all pyrgeometers.

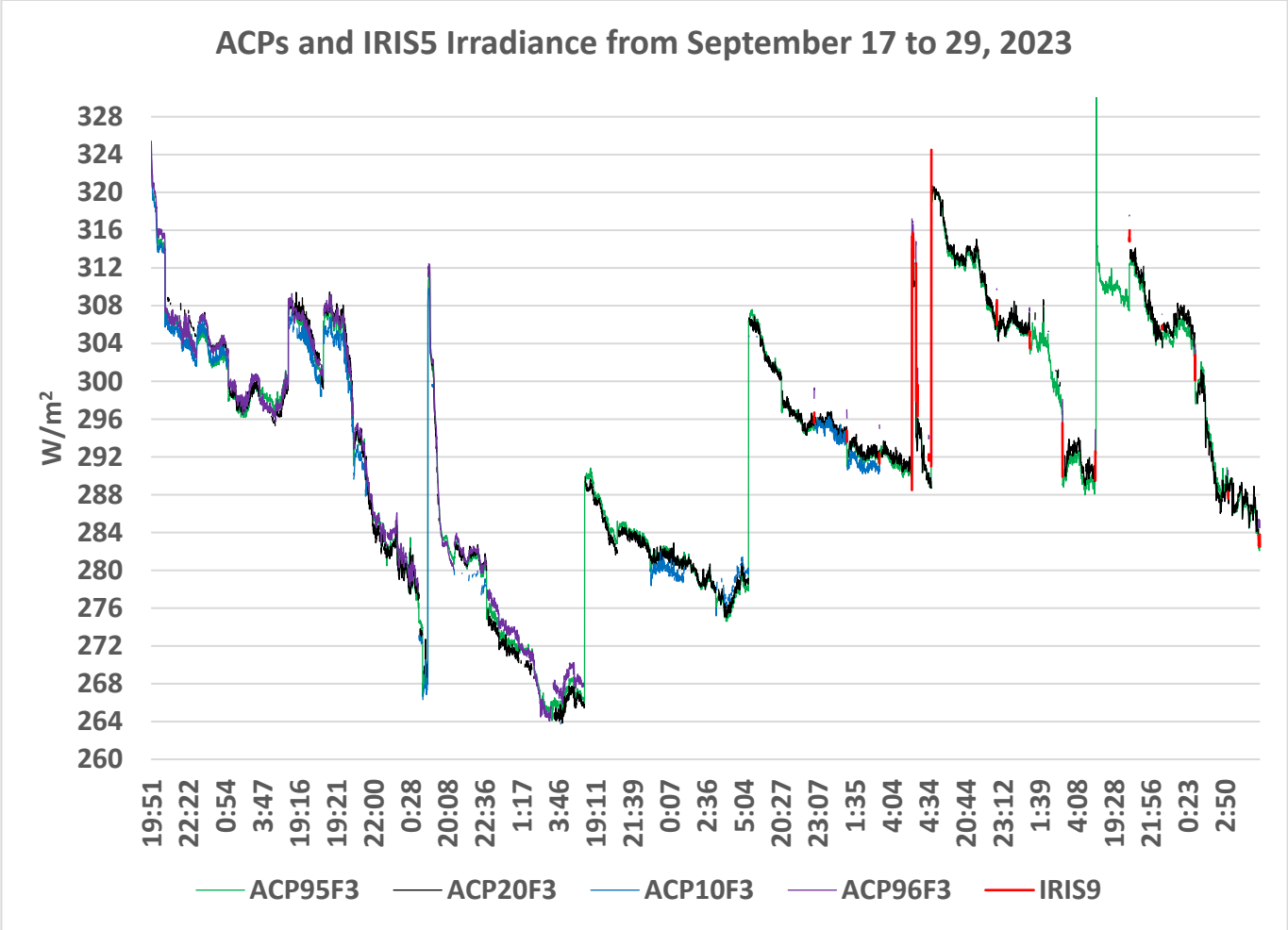

Figure 1. ACPs and IRIS9 irradiance

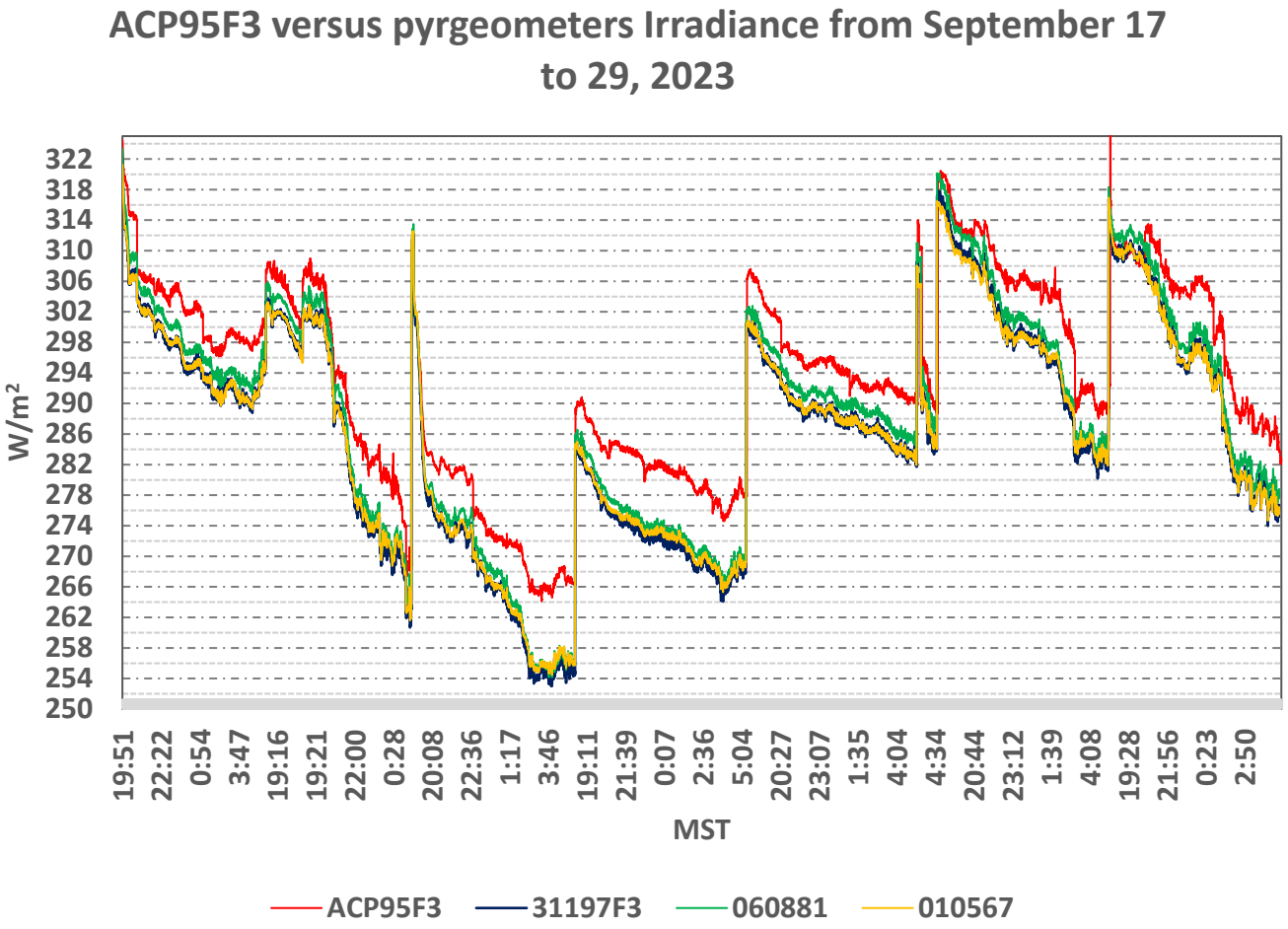

Figure 2. ACP95F3 irradiance and irradiance measured by pyrgeometers

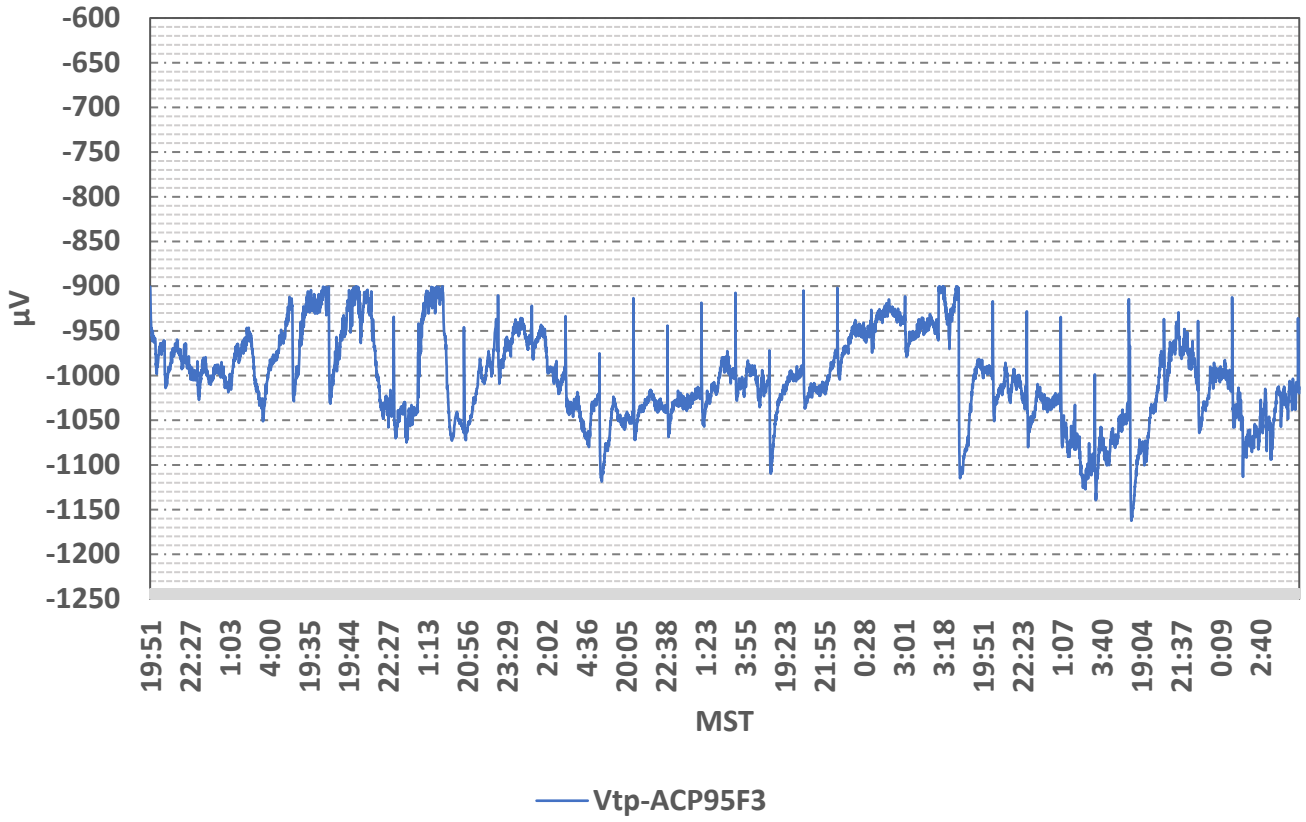

Figure 3. ACP95F3 thermopile output voltage*

** ACP thermopile output voltage is a good indication of how clear the sky is.*

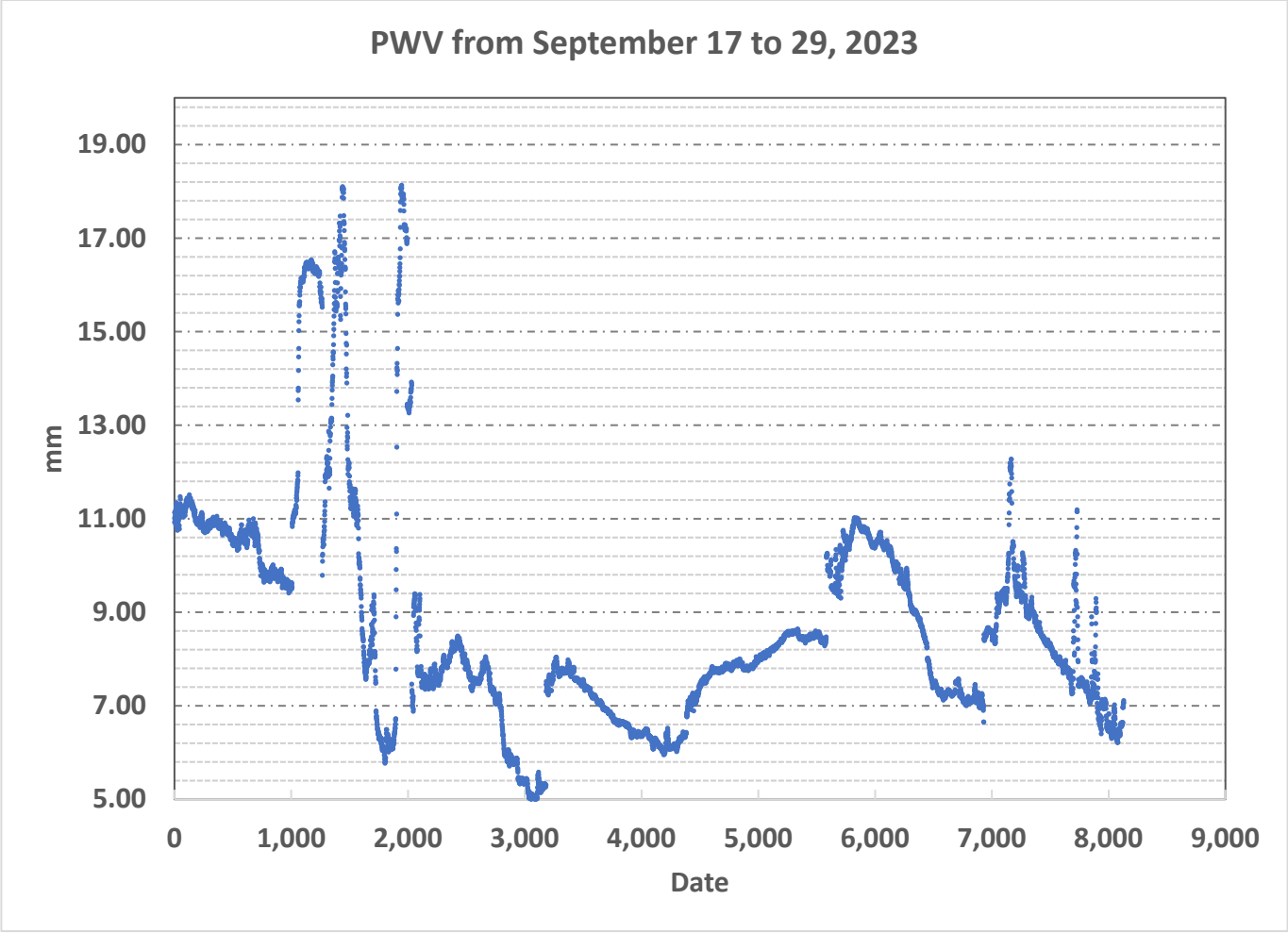

Figure 4. Water vapor content

Table 1. ACP95F3 Irradiance Minus the Irradiance Measured by all radiometers

W/m^2	ACP95F3-ACP20F3	ACP95F3-ACP10F3	ACP95F3-ACP96F3	ACP95F3-IRIS9	ACP95F3-31197F3	ACP95F3-060881	ACP95F3-010567	ACP95F3-FT005
av	-0.14	0.76	-0.75	0.04	3.78	1.64	3.96	3.38
sd	0.78	1.00	0.84	1.04	1.74	1.70	1.86	1.76
U_{95}	1.56	2.13	1.84	2.07	5.13	3.78	5.42	4.88
nrdg	6675	2062	3766	1402	1841	1841	1841	1841