Part No. 141.9510

CE 2018

USER'S GUIDE

for

MIDDLETON SOLAR

ACR-01

Absolute Cavity Radiometer

for operation with
Keysight Data Acquisition System

Date: Aug. 2022

Version: 2.4

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Solar Measurement Innovation since 1960

www.middletonsolar.com

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CONTENTS page

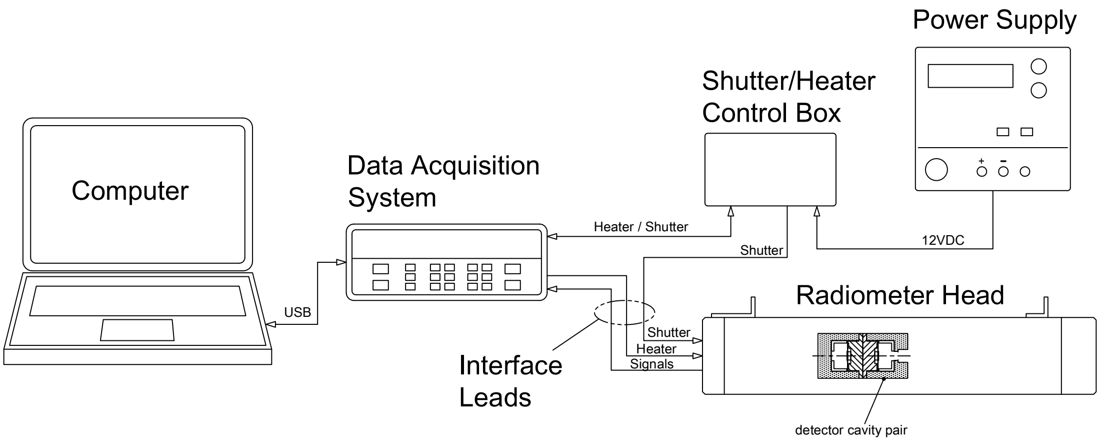
1 GENERAL

The ACR-01 is an Absolute Cavity Radiometer to measure solar Direct Normal Irradiance (DNI). It is suitable for use as a primary reference pyrheliometer. The ACR-01 is *absolute* in the sense that it has traceability to SI-units by using electrical power substitution to self-calibrate the detector sensitivity; operation is *passive* as electrical power is not maintained during solar measurement events[1]. The ACR-01 operates in a sequential cycle of Calibration > Measurement; an entrance shutter is closed for the Calibration mode (zero and self-calibration) and open for the Measurement mode (irradiance). The Calibration time is typically 6 minutes (3 min zero, then 3 min absolute calibration) and the Measurement time is typically 24 minutes.

2 SYSTEM DESCRIPTION

2.1 SYSTEM COMPONENTS

The ACR-01 consists of a Radiometer Head with Interface Cables and Shutter/Heater Control Box. A Data Acquisition System, with connected Computer and Power Supply, completes the arrangement.



System components supplied by Middleton Solar are:

- Radiometer Head
- Shutter/Heater Control Box (Configured for Keysight Switch Module)
- Power Supply 12VDC, 2A (for Shutter/Heater Control Box)
- Control Cables (Configured for Keysight Multiplexer Module)
- Interface Leads (to connect Data Acquisition System to Radiometer Head)
- ACR-01 Configuration file (for Benchlink Data Logger Pro software)

Other required system components are[2]:

- Keysight 34972A (or DAQ970A) Data Acquisition Unit[3]
- Keysight 34901A (or DAQM901A) Multiplexer Module
- Keysight 34903A (or DAQM903A) Switch Module
- Keysight Benchlink Data Logger Pro software
- USB Cable, type A to type B
- Computer (Windows 10 operating system)

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[1] *active* operation is where electrical heating is a dynamic part of measurement events

[2] the required items are MSolar available options, or User supplied

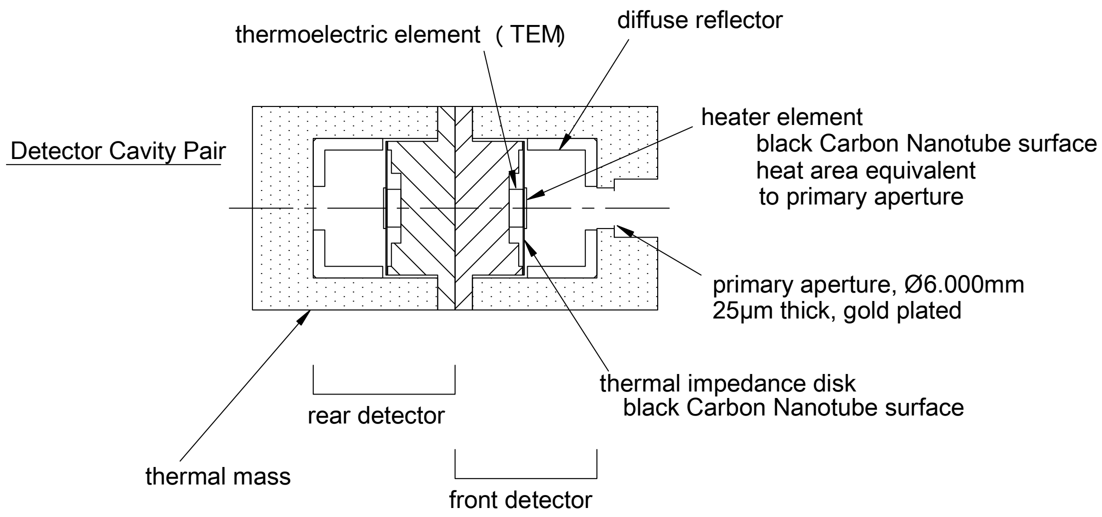
[3] Keysight was previously known as Hewlett Packard and as Agilent

Additional necessary equipment is:

Solar Tracker (to aim the Radiometer Head at the sun)

2.2 RADIOMETER HEAD

The Radiometer Head contains two identical black-body detector cavities inside a double-tube instrument body. Both detectors are enclosed by a thermal mass that is isolated from the instrument body. The front cavity can be exposed to solar irradiance via a shutter and a precision aperture. The blind rear (compensation) cavity is coupled to the front cavity to cancel any common-mode response due to temperature transients.



A thin heater resistance-element, equivalent in area to the primary aperture, is bonded to the thermoelectric element. In measurement mode, light entering the front cavity is absorbed by the black Carbon Nanotube surface of the detector causing a temperature rise that induces the thermoelectric element to produce a voltage proportional to the light intensity. The small proportion of light that is back-scattered is mostly returned to the detector surface by the reflector lining of the cavity (see Appendix D: Cavity Loss Analysis).

In self-calibration mode, current in the front heater resistance-element causes a temperature rise that induces the thermoelectric element to produce a voltage proportional to the electrical power. In both measurement and calibration mode, a small amount of energy is lost by net IR radiation exchange (10 μm CWL) from the receiver/heater surface to the slightly cooler cavity wall. This loss is equivalent in both modes, but contributes to uncertainty as ambient temperature varies (see Appendix F).

2.3 SENSITIVITY EQUIVALENCE

The sensitivity of the Radiometer Head to solar irradiance should be exactly equivalent to the absolute sensitivity from electrical heating, but in reality there are various subtle non-equivalence errors.

The main source of linear systematic error is un-recovered reflection from the receiver surface (see Appendix D). However, this loss is largely balanced by light diffraction into the cavity.

Other error sources include: unbalanced emission of IR radiation during illumination vs heating; inequality of the thermoelectric element response to solar heating versus electrical heating; parasitic heating from the wires to the heater element.

The deviation from ideal behaviour is expressed as a Correction Factor (CF) specific to each instrument.

CF = solar sensitivity / absolute sensitivity

ACR-01 CF (nominal) = 0.9980

In practice the CF is established for each ACR-01 instrument by comparing it to a radiometer that is directly traceable to the World Radiometric Reference (WRR)[4].

The CF for the ACR-01 represents the reciprocal of the 'WRR reduction factor' that is determined at International Pyrheliometer Comparison (IPC) events.

The current WRR is actually 0.34% higher than the SI radiometric scale so any instrument specific CF, if derived with respect to SI, will not exactly match the WRR.

Two additional sources of non-equivalence are electrical losses in the wires to the heating element, and accuracy of measurement of the area of the primary aperture. The heater lead correction resistance (Rc) and the primary aperture diameter (Ap) are provided for each instrument, and these parameters are not included in the assessment of the CF.

Application of the CF, the heater lead resistance (Rc), and the aperture diameter (Ap), is addressed in Section 5 of this document.

NOTE: the Radiometer signal, and SI traceability of the electrical heating for self-calibration, is dependent on the measurement uncertainty of the Keysight Data Acquisition System. The User should ensure that the Keysight equipment is calibrated as recommended by Keysight (see Appendix F: Calibration Uncertainty)

[4] the WRR consists of the World Standard Group (WSG) of cavity radiometers located in Davos, Switzerland

3 SETTING UP

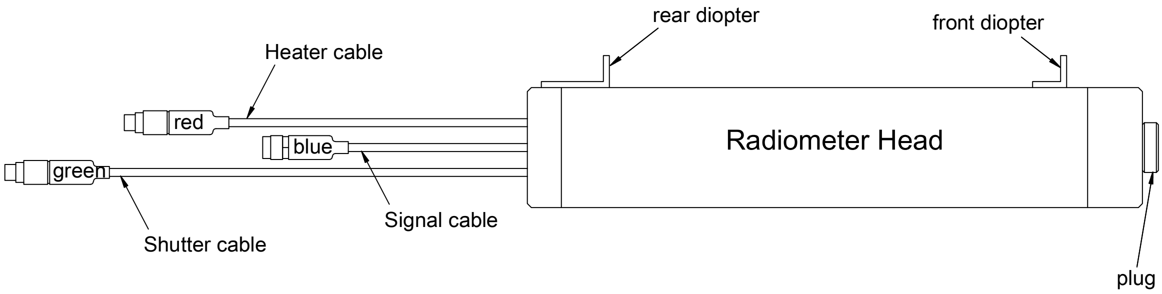
3.1 SITE CONDITIONS

The Radiometer Head should be placed outdoors and the Data Acquisition System, Computer, and Power Supply, should be located nearby and must be protected from exposure to inclement weather.

For the outdoor location select a site where obstructions do not exceed 25° elevation, in the daily path followed by the sun. To obtain accurate solar measurements it is recommended that there be no cloud or haze within 15° of the sun, total cloud cover be less than 1/8, wind speed be equal to or less than 4.5m/s, and AOD at 500nm equal to or less than 0.12.

3.2 RADIOMETER HEAD INSTALLATION

Fit the Radiometer Head to a suitable Solar Tracker System[5]. Adjust the alignment so the Head is aimed at the sun. The front diopter sight and rear diopter target have central "pinholes". When the Head is correctly aligned, direct sunlight passing through the front pinhole will centre on the rear pinhole.



The Radiometer Head has three short cable tails with colour-coded connectors. The three Interface Leads, each 6m long, should be coupled to the appropriate coloured tail connector; allow sufficient slack so the Interface Cables do not become taut during operation of the Solar Tracker.

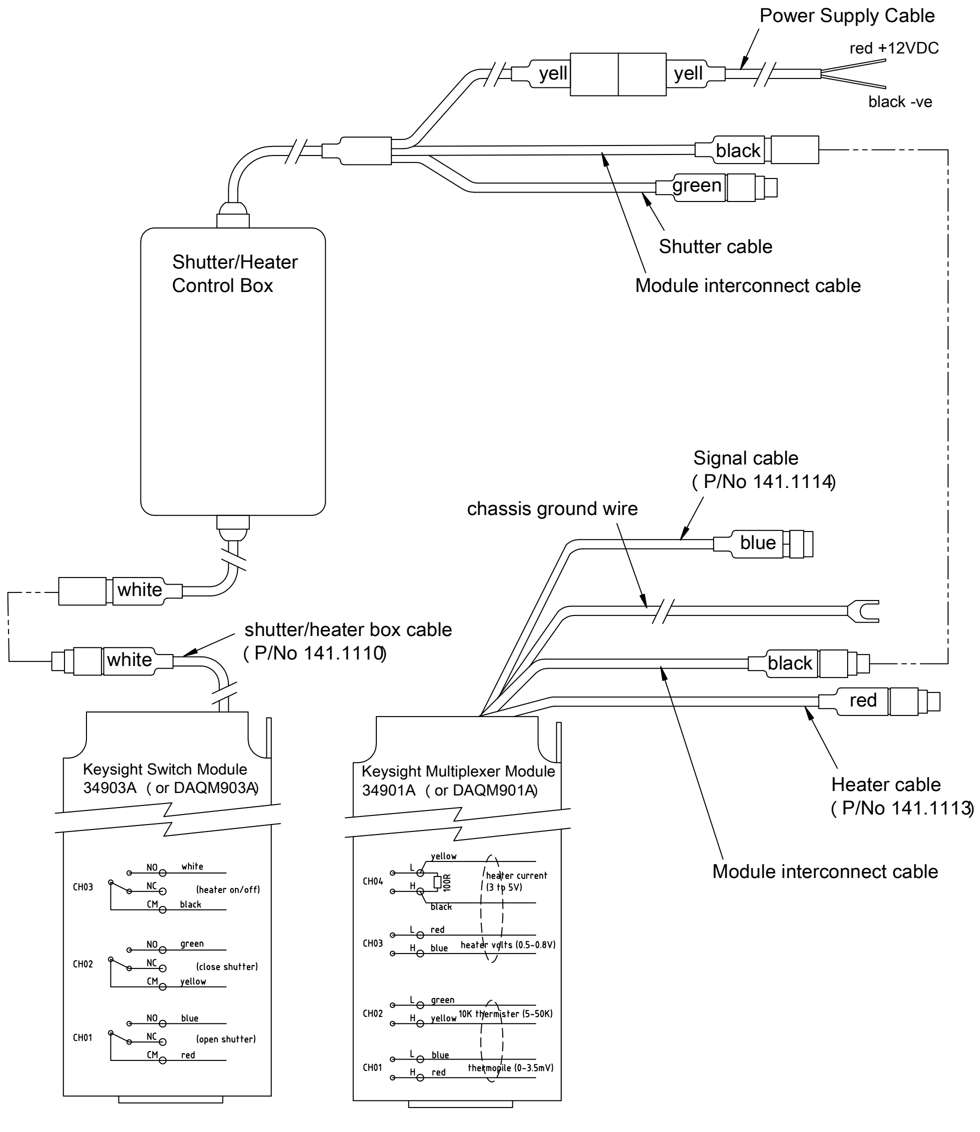
The Radiometer Head has a plug that protects the instrument interior from moisture and dust. This plug should be removed during use but should always be fitted when the instrument is idle.

[5] User provided, or available MSolar AST-02 Active Solar Tracker + PM02 Mount, or equivalent system

3.3 CONTROL INSTALLATION

Place the Computer, Data Acquisition System, Shutter/Heater Control Box, and Power Supply on a suitable bench or table, preferably indoors protected from the weather.

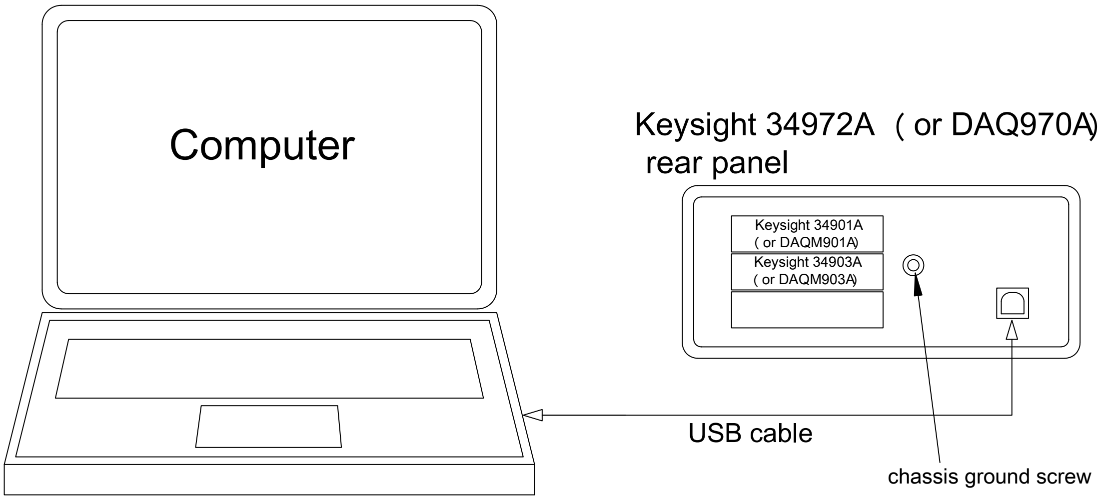
Ensure that the equipment is set to the correct line voltage for your location.



Fit the supplied Signal cable (P/No 141.1114) and Heater cable (P/No 141.1113) to the Keysight 34901A (or DAQM901A) Multiplexer Module. Fit the Shutter/Heater Box cable (P/No. 141.1110) to the Keysight 34903A (or DAQM903A) Switch Module.

Wiring schematics for the modules are in Appendix B. There are three relay controls required in the Switch Module: heater on/off; shutter open; shutter close.

There are four input signals monitored in the Multiplexer Module: thermopile output; detector temperature; heater current; heater volts.



Insert the two Modules into the Keysight Data Acquisition Unit. The Multiplexer Module (**901A) into the top slot, and the Switch Module (**903A) into the middle slot.

Connect the USB Cable to the Computer and to the Keysight Data Acquisition Unit.

Connect the Multiplexer Module to the Shutter/Heater Control Box with the Black Interconnect Cables.

Connect the Switch Module to the Shutter/Heater Control Box with the White Interconnect Cables.

Connect the chassis ground wire to the rear panel of the Keysight Data Acquisition Unit.

Connect the three Interface Leads, from the Radiometer Head, to the corresponding Red, Blue, and Green coloured Control Connector.

Connect the Power Supply Cable, of the Control Box, to the 12VDC Power Supply.

Connect the control equipment to mains power.

If the DAQ970A Data Acquisition Unit is used, then set it to emulate the Keysight 34972A Unit (see Section 3.4).

3.4 DAQ970A DATA ACQUISITION UNIT

The Keysight DAQ970A is a replacement for the previous Keysight 34972A model. Keysight offer the *BenchVue Data Acquisition App* for the DAQ790A, but the older *Benchlink Data Logger Pro* software provides a superior control environment for the ACR-01 system. Use of *Benchlink Data Logger Pro* software requires that the DAQ970A be set to emulate the 34972A.

Procedure to implement 34972A emulation:

1) disconnect USB cable from the DAQ970A
2) turn power ON
3) press 'home' button on the front panel face
4) select 'User Setting' (via buttons below screen)
5) select 'I/O'
6) select 'SCPI ID'
7) select 'Agilent Tech'
8) select 'Model 34972A'
9) select 'Done'
10) turn power OFF
11) turn power ON (to initialize the selected emulation)
12) connect USB cable

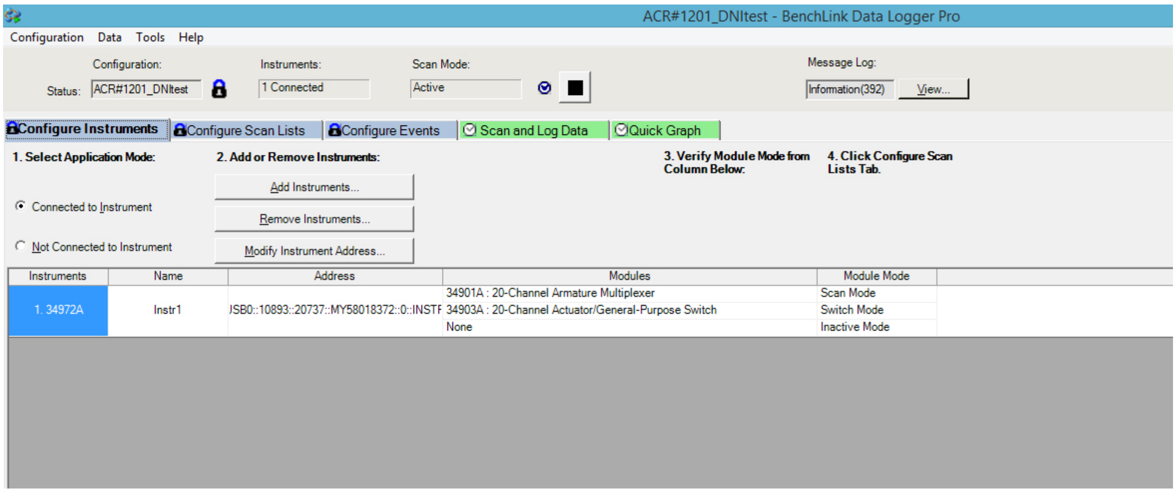
3.5 SOFTWARE CONFIGURATION

Obtain *Benchlink Data Logger Pro* software (available from keysight.com) and follow the instructions from Keysight to install on your computer. Become familiar with the operation of the software by using available Keysight tutorials.

A typical configuration template will have been loaded to the ACR-01 Data Acquisition Unit (if the DAQ was optioned at purchase). Otherwise request a template from Middleton Solar, or follow Keysight instructions to create a custom configuration to control the ACR-01. In the template there are four measured channels[6], four computed channels[7], and scripts to operate the Shutter and the Heater. The template can be readily duplicated and customized to suit User preferences.

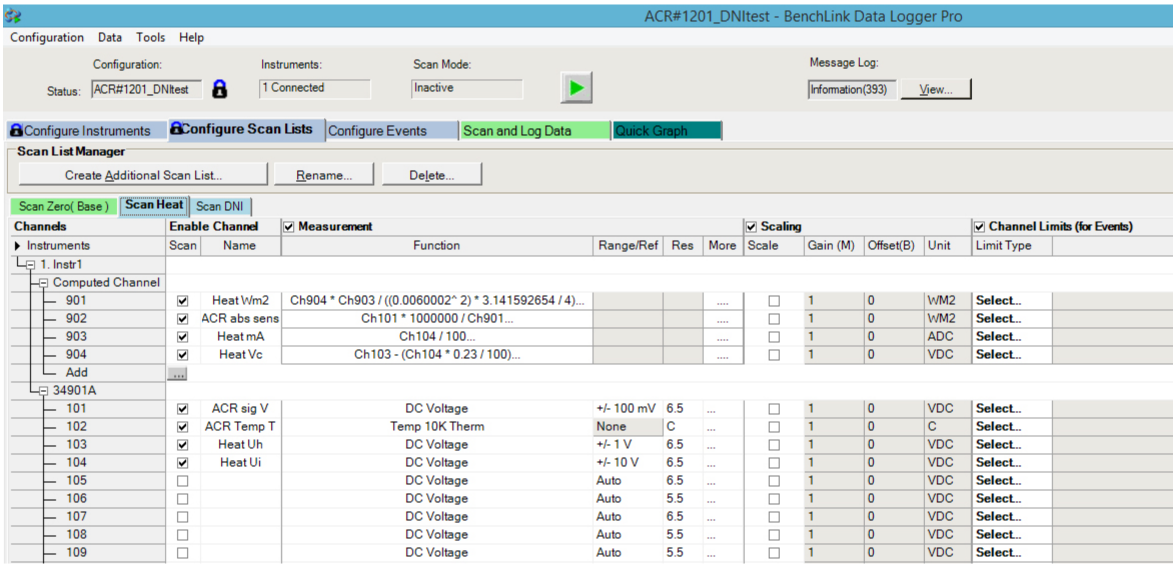
The four computed channels are *estimates* to confirm the recording of data is functioning correctly. The exact computations should be done later using the four measured channels.

The following screenshots illustrate the operation flow of the template.

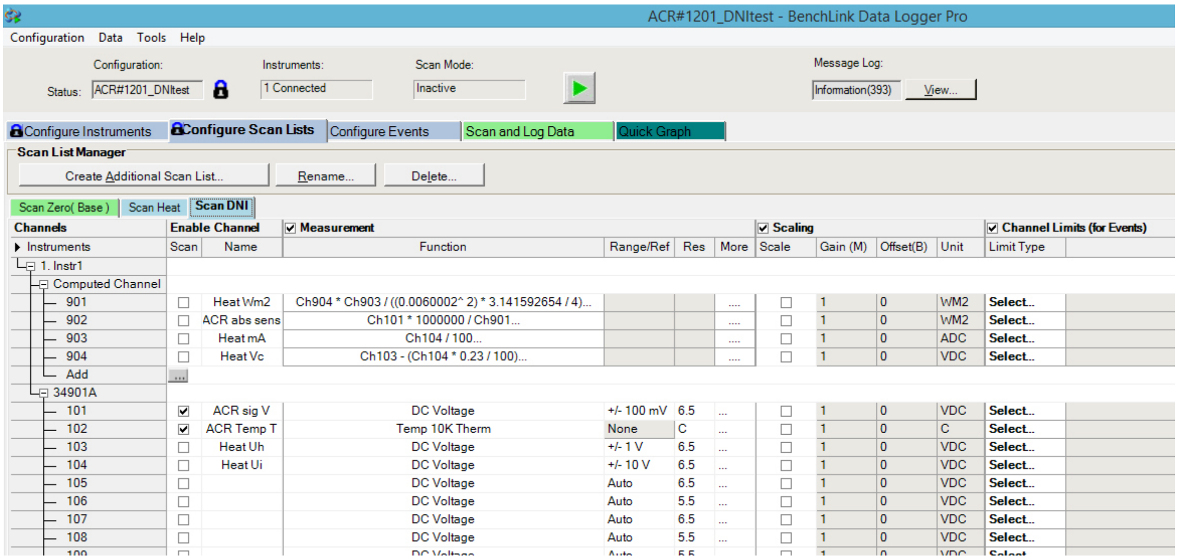


A) Configure the Data Acquisition Modules.

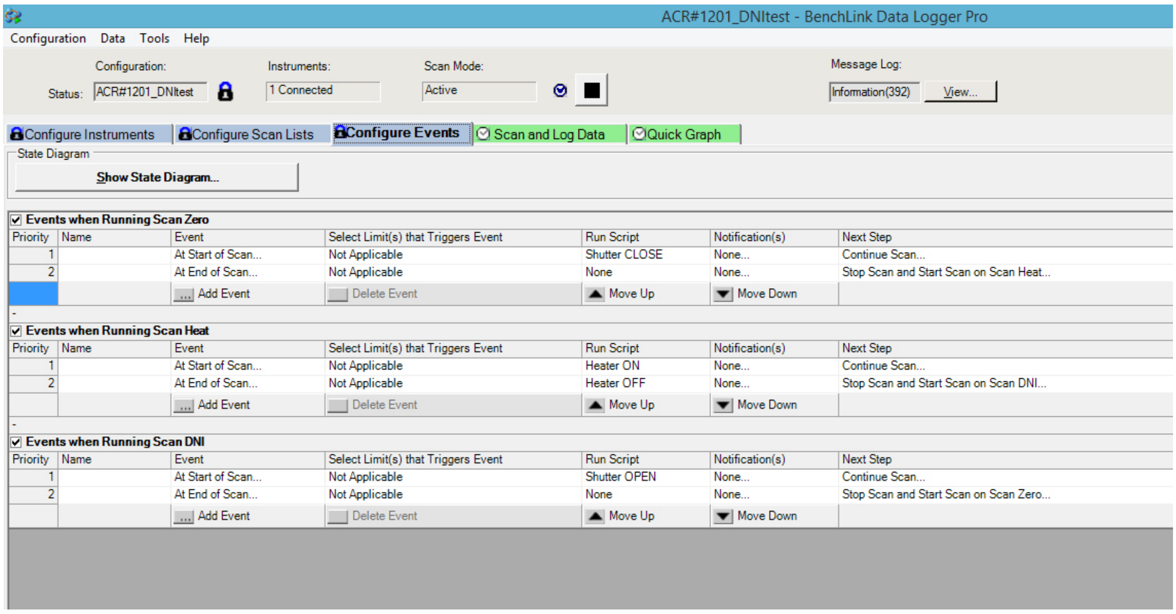
[6] The measured channels are designated 'ACR sig V', 'ACR Temp T', 'Heat Uh', 'Heat Ui'
[7] The computed channels are designated 'Heat Wm2', ACR abs sens', Heat mA', 'Heat Vc'



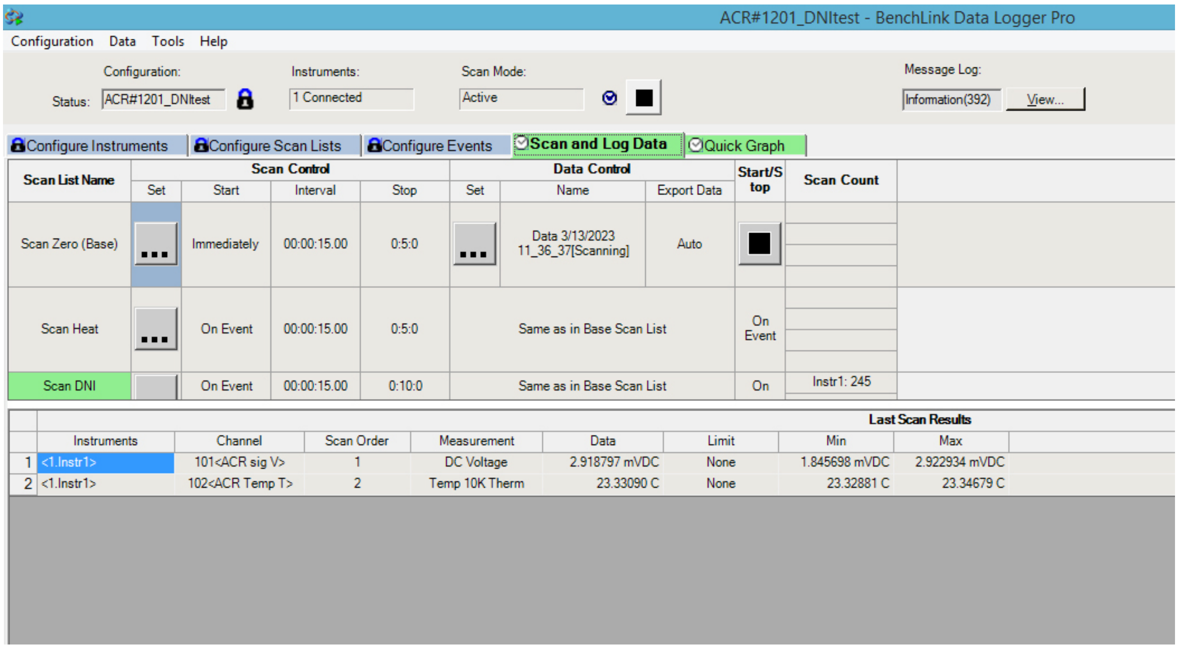
B) Configure the Scan Lists ('Scan Heat' is illustrated).



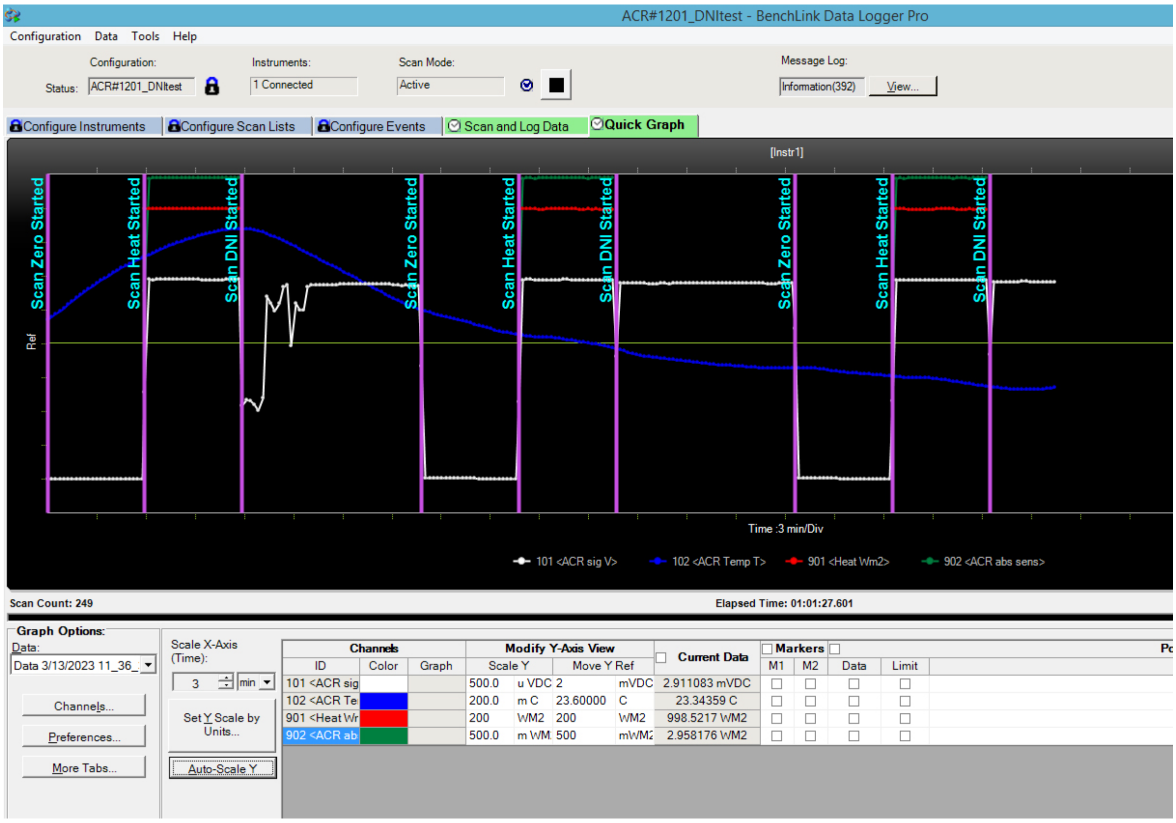
C) Configure the Scan Lists ('Scan DNI' is illustrated)



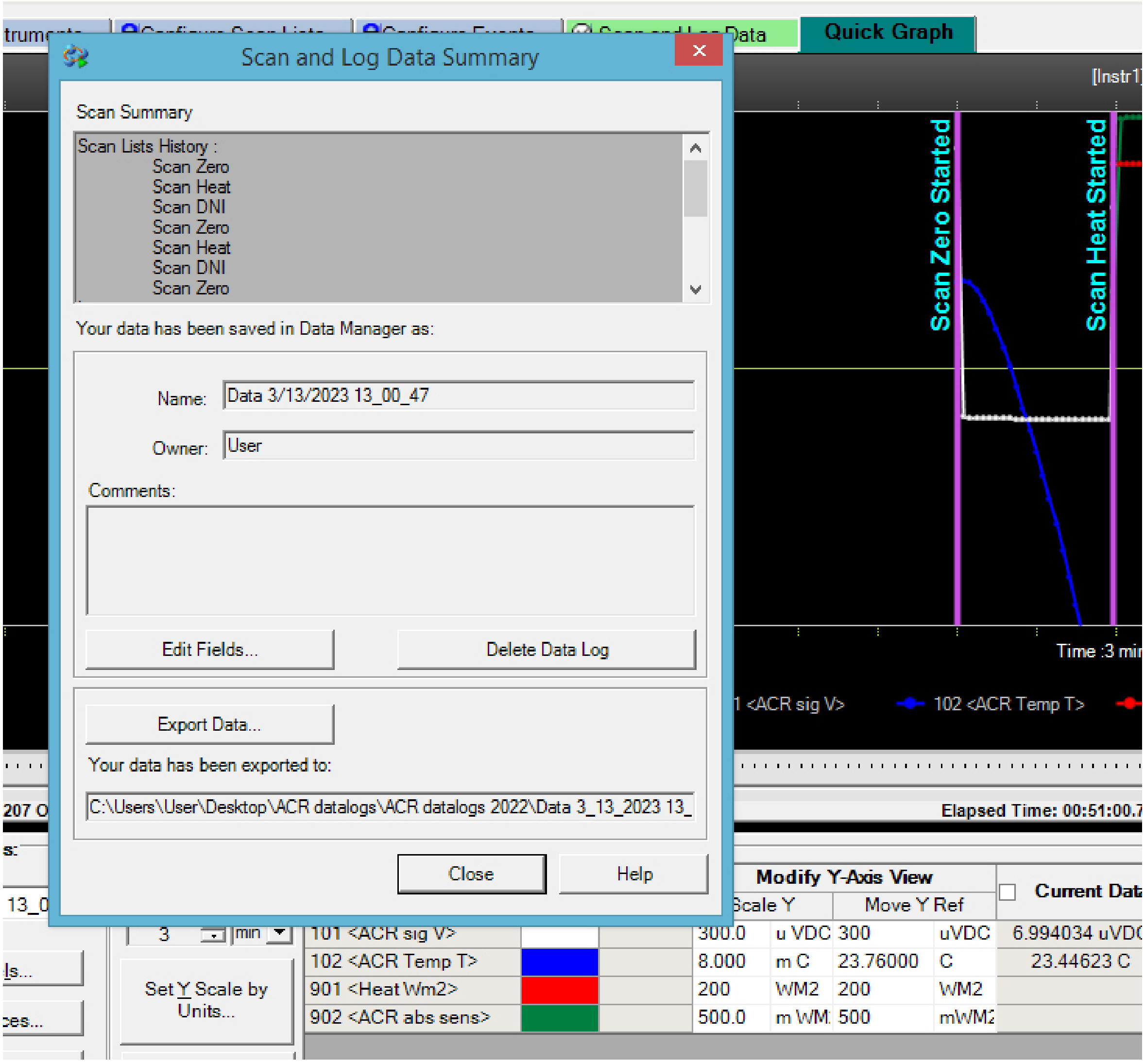
D) Configure the Events function.



E) Configure the Scan and Log Data function.



F) Graph the data as it is logged.



G) Download the data to your computer.

4 OPERATION

Setup the ACR-01 System as per Section 3 of this Guide.

Switch the Power Supply to ON.

Allow at least 30 minutes for the Radiometer Head to reach equilibrium with ambient temperature after it is mounted to the Solar Tracker.

The ACR-01 has an output signal for detector heatsink temperature. It is recommended this signal be monitored as it is desirable that the detector heatsink temperature be stable during a Calibration > Measurement cycle so that the temperature response does not contribute unduly to the uncertainty budget (Appendix F). Reject the data if the temperature change exceeds 0.5 °C during a Calibration > Measurement cycle, or apply a temperature response correction.

The heat flux (Absolute Irradiance) in self-calibration mode can be adjusted by changing settings inside the Shutter/Heater Control Box (see Appendix C). The Absolute Irradiance has been adjusted during manufacture to approximately match the Solar Irradiance. The match does not have to be precise because the detector non-linearity is negligible.

Record sequential cycles of *Zero Measurement/ Absolute Calibration / Solar Measurement* using the *Benchlink Data Logger Pro* software.

Download the recorded datafiles to a spreadsheet programme, such as MS Excel. Calculate the Corrected Direct Normal Irradiance (DNI) as per Section 5 of this Guide.

5 CALCULATIONS

There are four fixed quantities that are specific to each ACR-01. The values for these quantities are listed on the Rating Label attached to the Radiometer Head, and on the associated Calibration Certificate.

Ap, primary aperture diameter (typically 6.0E-3 meter)
Rh, precision shunt resistor to measure heater current (100 Ω)
Rc, heater leads correction resistance (nominally 0.25 Ω)
CF, correction factor for non-equivalence (nominally 0.9980)

There are four measured quantities obtained from the data acquisition Computer.

Ve, thermopile output (typically 2.9E-3 volts, for S = 1,000 $W.m^{-2}$)
Vo, thermopile zero off-set (typically 3E-6 volts)
Uh, voltage across heater element (typically 0.7 V, for S = 1,000 $W.m^{-2}$)
Ui, voltage across heater resistor Rh (typically 4 V, for S = 1,000 $W.m^{-2}$)

There is one optional quantity obtained from the Radiometer Head.

T, temperature of detector assembly (°C)[8]

5.1 SHUTTER CLOSED

Calculation of Absolute Irradiance, S ($W.m^{-2}$)

S = heater power / primary aperture area
S = heater current ∗ corrected heater volts / primary aperture area
$S = (Ui / Rh) * (Uh - \{Ui * Rc / Rh\}) / (Ap^2 * \pi / 4)$

Calculation of Absolute Sensitivity, K ($\mu V/W.m^{-2}$)

K = thermopile voltage / absolute irradiance
$K = (Ve - Vo) * 1E6 / S$

5.2 SHUTTER OPEN

Calculation of Uncorrected Direct Normal Irradiance, DNI_u ($W.m^{-2}$)

DNI_u = thermopile voltage / absolute sensitivity
$DNI_u = (Ve - Vo) * 1E6 / K$

Calculation of Corrected Direct Normal Irradiance, DNI ($W.m^{-2}$)

DNI = thermopile voltage / Correction Factor / absolute sensitivity
$DNI = (Ve - Vo) * 1E6 / CF / K$

5.3 ALTERNATE COMBINED FORMULA

Calculation of Corrected Direct Normal Irradiance, DNI ($W.m^{-2}$)

DNI = C * sun resp / heater resp * heater current * corrected heater volts
$DNI = C * (\{Ve_{open} - Vo\} / \{Ve_{close} - Vo\}) * (Ui / Rh) * (Uh - \{Ui * Rc / Rh\})$
where Calibration Characteristic, $C = 4 / (CF * Ap^2 * \pi)$
typical $C \approx 35440$

[8] reject the data, or consider applying a temperature response correction of +0.14%/°C to Ve, if the temperature change exceeds 0.5°C during a Calibration > Measurement cycle

6 SPECIFICATIONS

ACR-01 Radiometer Head	
full opening angle	5°
slope angle	1°
limit angle	4°
irradiance	0 - 1,400 W/m^2
response time (95%)	2.5 sec.
front (view limiting) aperture	∅10 mm
primary aperture (typical)	∅6,000 ±0.5μm; 25μm copper; gold plated
detector surface black coating	carbon nanotube
aperture separation	114.5 mm
sensitivity (typical)	2 - 3μV/ W.m^{-2}, at 20°C
non-linearity	< 0.001%, for 700 -1,400 W/m^2
temperature response	+0.14%/°C
Correction Factor (CF)	0.9980 (nominal)
operating temperature	-10 to +40°C
heater type & resistance	constantan wire, 16Ω (nominal)
shutter	rotary, bi-stable, 0.2 sec response
construction	aluminium & stainless steel
size	∅60 x 307 mm
weight	1.25kg (Radiometer Head)

ACR-01 Control	
Shutter/Heater Control Box	Configured for Keysight 34903A / DAQM903A
Power Supply	12VDC, 2A, for Shutter/Heater Control Box
Heater cable (P/No 141.1113) Signal cable (P/No 141.1114)	Configured for Keysight 34901A / DAQM901A
Interface Leads	6m, PU: Heater; Shutter; Signals
ACR-01 Configuration File template	to suit Keysight Benchlink Data Logger Pro software

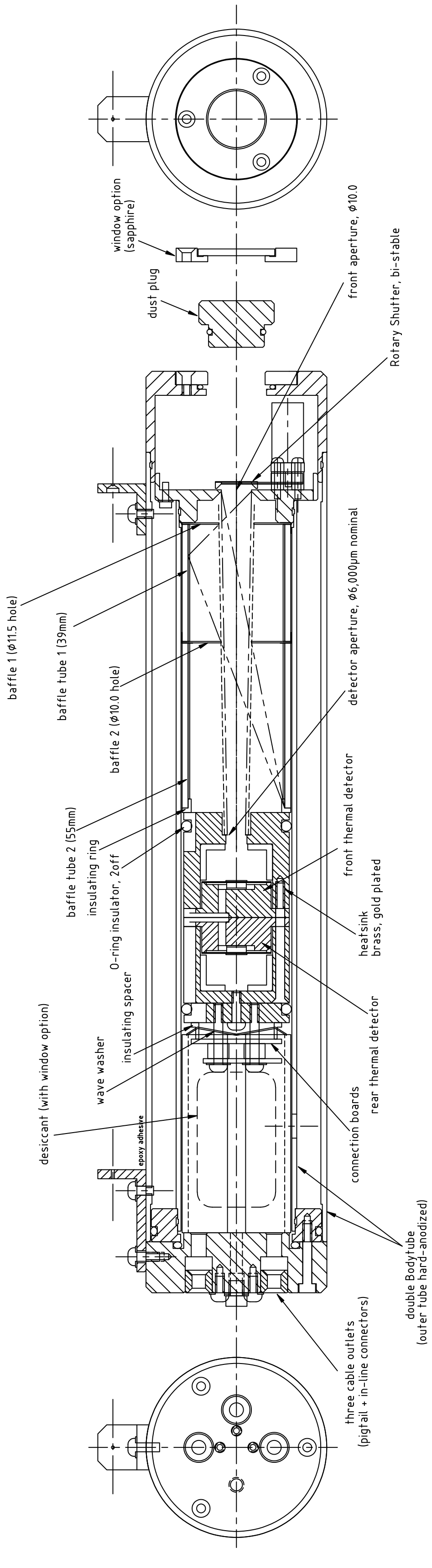
Required Control Options[9]	
Data Acquisition Unit	Keysight 34972A or DAQ970A
Control Multiplexer Module	Keysight 34901A or DAQM901A
Control Switch Module	Keysight 34903A or DAQM903A
Control Software	Keysight Benchlink Data Logger Pro
USB Cable	USB type A to type B
Computer	PC; Windows 10

Other Available Options	
Solar Tracking System	Middleton Solar AST-02 or AST-03
Window, optical sapphire	spectral range = 0.2 – 5.5μm; *T* = 86%

[9] required items are available from MSolar, or from a third party, or can be User provided

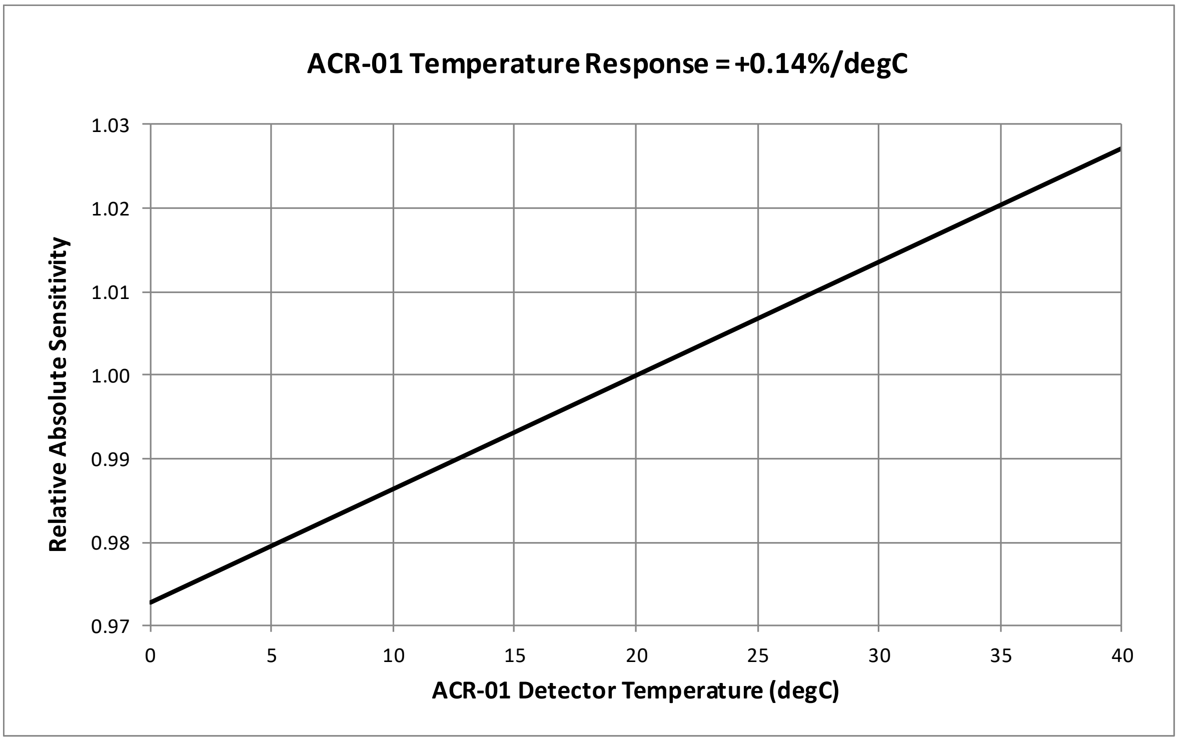
7 SERVICE

The ACR-01 Radiometer Head has no User Serviceable components. Contact Middleton Solar for any servicing or repairs.

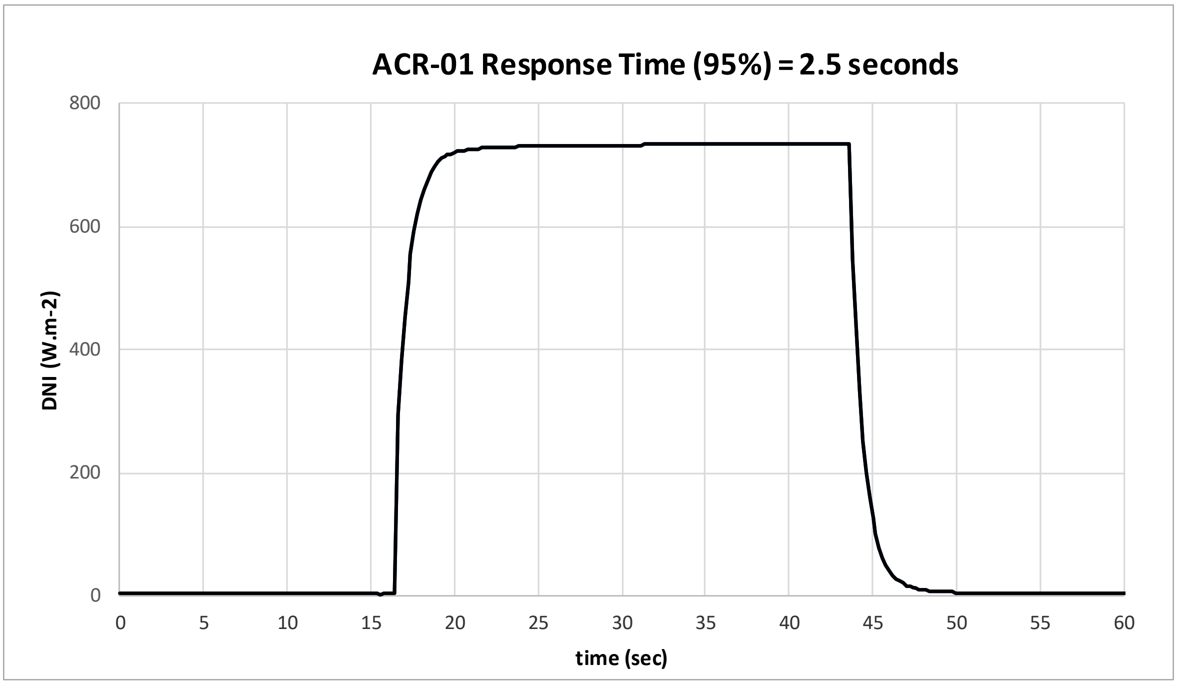


Appendix A: TEMPERATURE & TIME RESPONSE

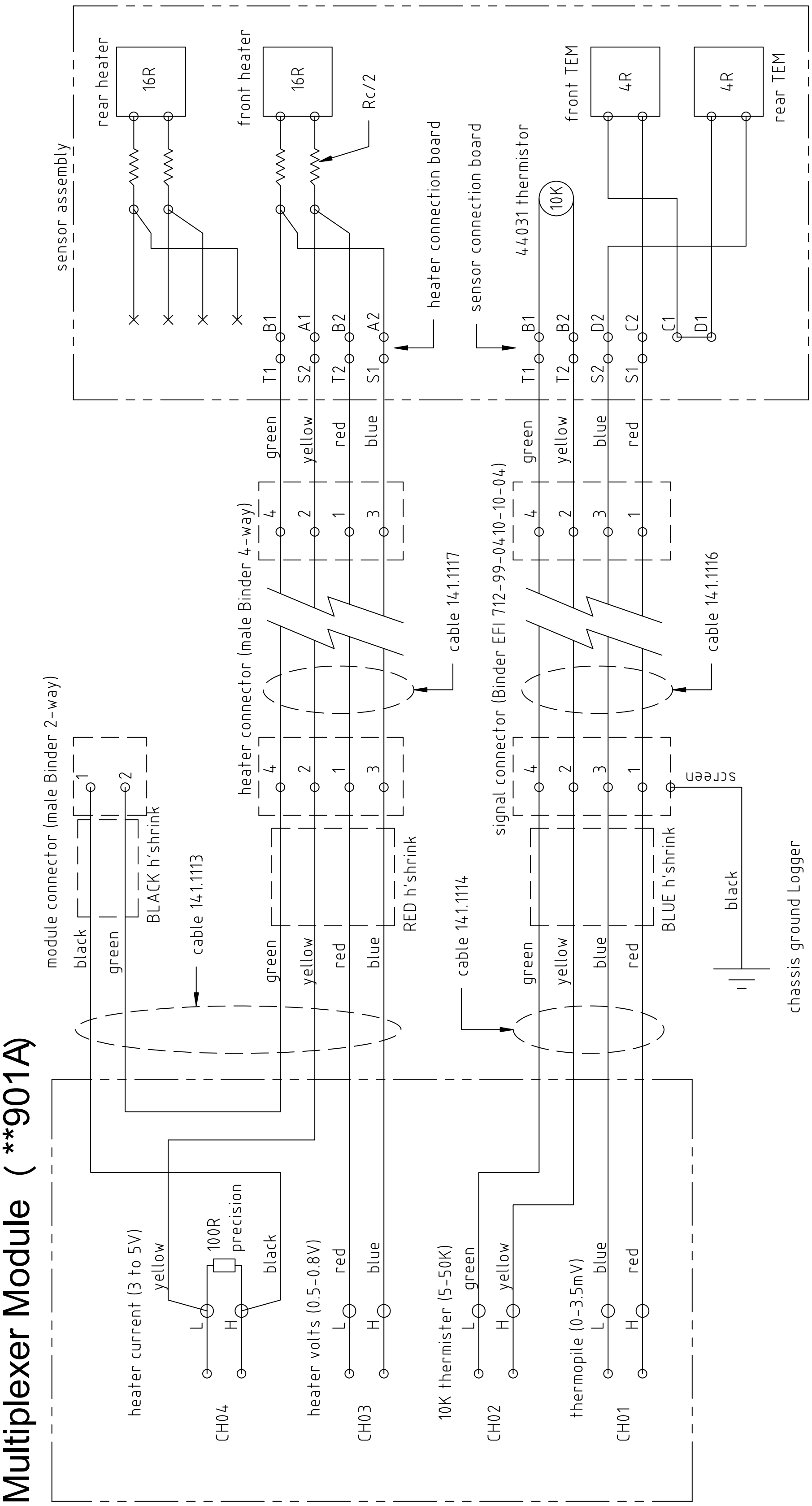
The ACR-01 does not have embedded temperature compensation. The temperature response is determined by the properties of the thermoelectric elements used in the detector. The temperature response is linear with respect to the temperature of the detector heatsink.

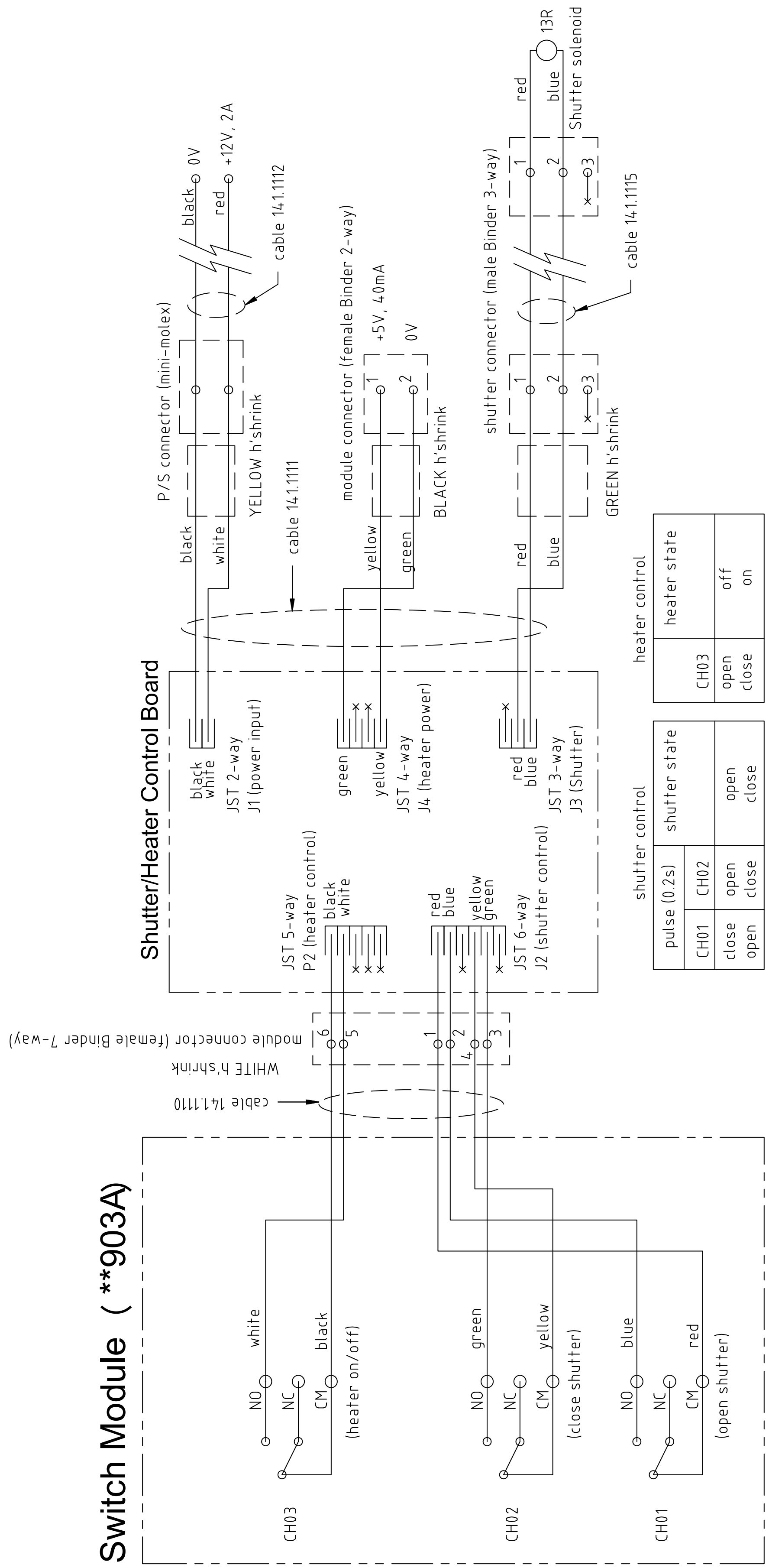


The time response of the ACR-01 is determined by the thermal properties of the combined detector assembly.



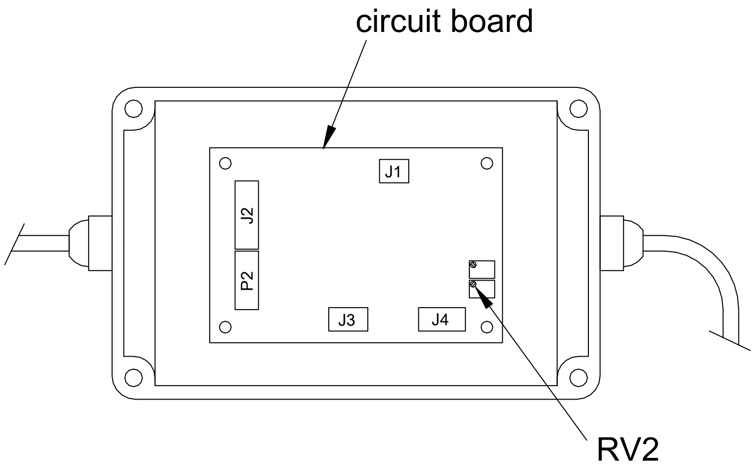
Appendix B: CONTROL MODULE WIRING SCHEMATICS




Switch Module (**903A)
Shutter/Heater Control Board
CH03
CH02
CH01
NO
NC
CM
white
black
(heater on/off)
green
yellow
(close shutter)
blue
red
(open shutter)
cable 141.1110
WHITE h'shrink
module connector (female Binder 7-way)
JST 5-way
P2 (heater control)
JST 6-way
J2 (shutter control)
JST 2-way
J1 (power input)
JST 4-way
J4 (heater power)
JST 3-way
J3 (Shutter)
cable 141.1111
P/S connector (mini-molex)
YELLOW h'shrink
cable 141.1112
0V
+12V, 2A
module connector (female Binder 2-way)
BLACK h'shrink
+5V, 40mA
shutter connector (male Binder 3-way)
GREEN h'shrink
cable 141.1115
13R
Shutter solenoid
shutter control
pulse (0.2s)
CH01
CH02
shutter state
close
open
open
close
open
close
heater control
CH03
heater state
open
close
off
on

Appendix C: SHUTTER/HEATER CONTROL BOX

Remove the lid from the Control Box to gain access to the circuit board.



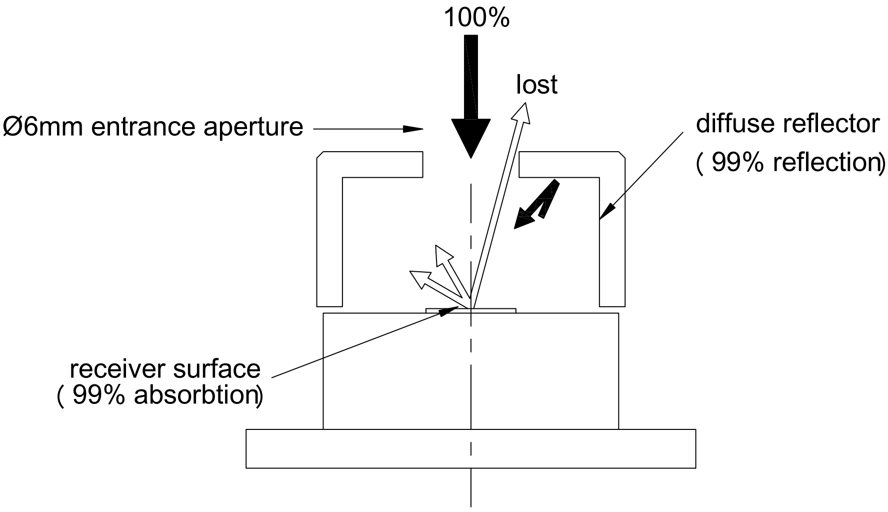
The heater power is set using potentiometer RV2.
The recommended nominal heater power is 1,000 W.m-2.
The available adjustment range is approximately 950 to 1,100 W.m-2.

P2 and J2 are switch inputs for shutter control and heater control from the Keysight *903A Switch Module; the two shutter relays should be turned on for 0.2 seconds, then turned off, to operate the respective shutter function. The relay for heater function toggles the heater operation on/off.

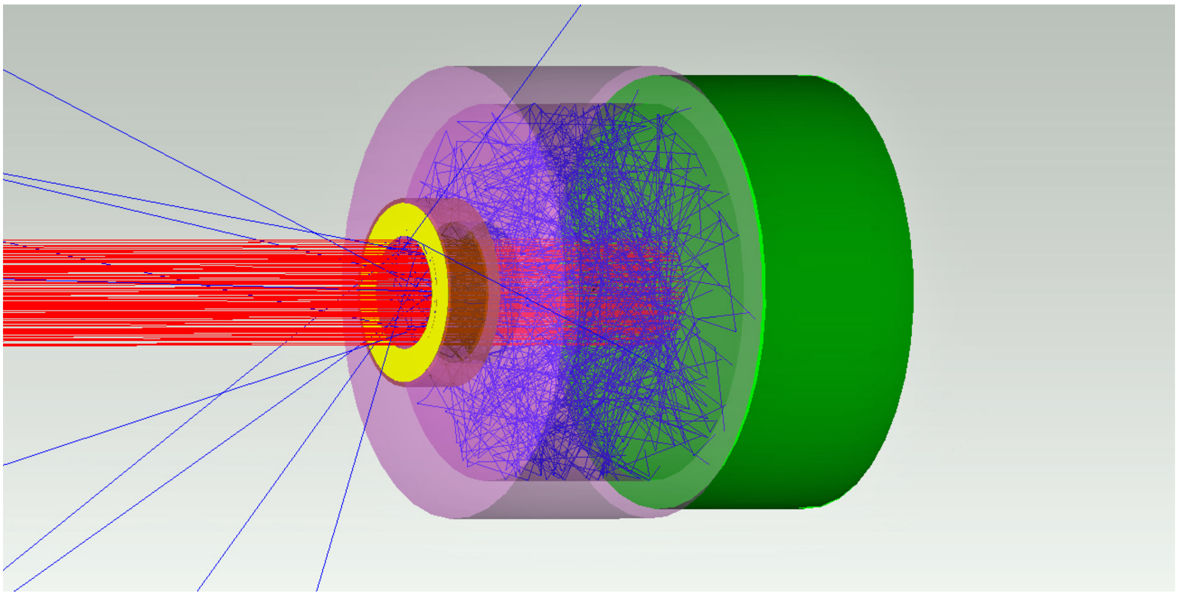
The shutter open & shutter close operations have a duration of 1 second. This duration is set in the Control Box firmware.

Appendix D: CAVITY LOSS ANALYSIS

In measurement mode, some incoming light is lost by reflection back through the entrance aperture.

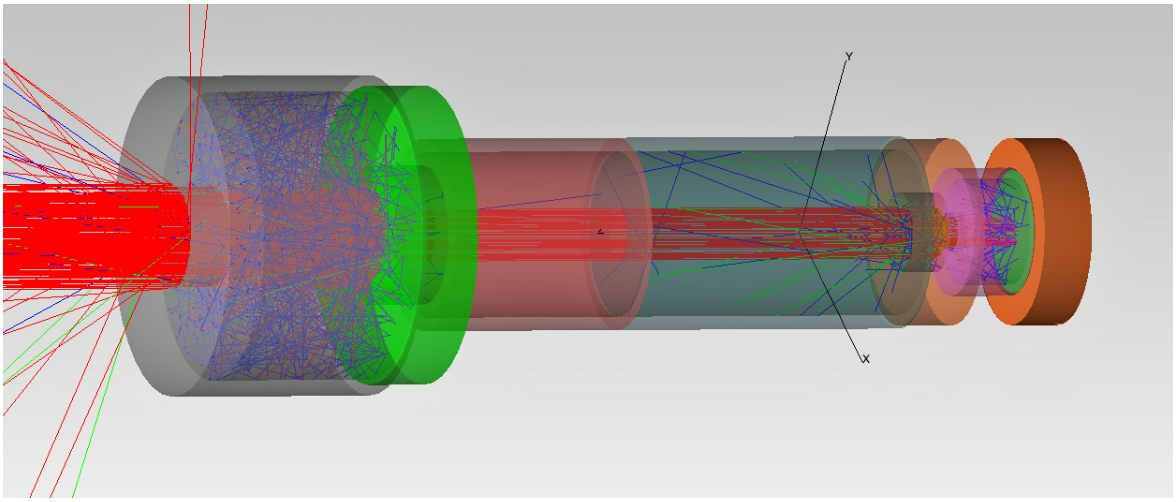


Of the solar radiation entering the front detector cavity, approximately 99% is absorbed by the black Carbon Nanotube receiver surface, and 1% is back-scattered[10]. Some of the back-scattered radiation is lost through the entrance aperture, and most of the remainder is returned to the receiver surface by the reflector.



The above image is a simplified 150-ray computer simulation of a model of the detector cavity; it illustrates the ray trajectories in the cavity.

[10] the Carbon Nanotube receiver surface has a BRDF (ABg model) scatter pattern



The above image is a simplified 300-ray simulation of a model of the complete ACR-01 Radiometer Head; it illustrates the ray trajectories in the whole instrument.

This model of the complete ACR-01 was analyzed using an 1,000,000-ray Monte Carlo computer simulation[11].

If the effect of diffraction is ignored, the computed absorptance of the receiver surface is 0.998320.

The cavity reflection loss is thus 1 - 0.998320 ≈ 1,680ppm ≈ 0.17%

However, diffraction at the Primary Aperture (∅6 mm) causes a small additional cavity loss, and diffraction at the View Limiting Aperture (∅10 mm) causes a significant cavity gain.

When diffraction is included, the computed absorptance of the receiver surface is 0.998750.

Thus, the cavity reflection+diffraction net loss is:
1 – 0.998750 ≈ 1,250ppm ≈ 0.13%

The uncertainty of cavity loss evaluation is 330ppm (see Appendix F).

[11] TracePro Standard opto-mechanical simulation software

Appendix E: TEMPERATURE vs THERMISTOR RESISTANCE for ACR-01 detector heatsink temperature

44031 Thermistor (accuracy = ±0.2ºC)

Temperature (ºC)	Resistance (Ω)	Temperature (ºC)	Resistance (Ω)
-30	135,200	15	15,130
-29	127,900	16	14,500
-28	121,100	17	13,900
-27	114,600	18	13,330
-26	108,600	19	12,790
-25	102,900	20	12,260
-24	97,490	21	11,770
-23	92,430	22	11,290
-22	87,660	23	10,840
-21	83,160	24	10,410
-20	78,910	25	10,000
-19	74,910	26	9605
-18	71,130	27	9227
-17	67,570	28	8867
-16	64,200	29	8523
-15	61,020	30	8194
-14	58,010	31	7880
-13	55,170	32	7579
-12	52,480	33	7291
-11	49,940	34	7016
-10	47,540	35	6752
-9	45,270	36	6500
-8	43,110	37	6258
-7	41,070	38	6026
-6	39,140	39	5805
-5	37,310	40	5592
-4	35,570	41	5389
-3	33,930	42	5193
-2	32,370	43	5006
-1	30,890	44	4827
0	29,490	45	4655
1	28,150	46	4489
2	26,890	47	4331
3	25,690	48	4179
4	24,550	49	4033
5	23,460	50	3893
6	22,430	51	3758
7	21,450	52	3629
8	20,520	53	3504
9	19,630	54	3385
10	18,790	55	3270
11	17,980	56	3160
12	17,220	57	3054
13	16,490	58	2952
14	15,790	59	2854

Appendix F: CALIBRATION UNCERTAINTY

Radiometer Head, SI calibration uncertainty = 0.13% (K=1)

Keysight DAQ, SI calibration uncertainty = 0.30% (K=1)

Combined (Head plus DAQ) SI uncertainty = 0.33% (K=1)

The uncertainty is valid for an operating temperature of 20°C $^{+20,\,-30}$ (-10 to +40°C).

Table of main items that contribute to ACR-01 System uncertainty budget:

Item	**Term**	**Uncertainty (ppm)**
primary aperture	Ap	1000
shunt resistor	Rh	60
heater tails	Rc	440
non-equivalence	CF	330
temperature response	-	700
other	various (IR, etc)	100
Keysight data acquisition	Ve (solar)	2100
	Ve (elect. heating)	2100
	Total (RSS)	3260 (= 0.33%)

Component tolerance range contributes approximately 90% of the total uncertainty, and thermal coefficients contribute the remainder.

The Radiometer Head contributes approximately one third of the uncertainty, and the Keysight data acquisition system contributes the remainder.

Appendix G: BIBLIOGRAPHY

Publications that may be useful to understanding the application and use of an absolute cavity radiometer.

ASTM E816-15. Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers.
(note: this publication is technically equivalent to ISO 9059:1990)

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

World Meteorological Organization, 2018: Fourth Regional Pyrheliometer Comparison of RAII (M. Omori, Et al.). WMO IOM Report No. 130.
(note: this publication includes an ACR-01 instrument)

Characterization of absolute cavity radiometers for traceability to SI of solar irradiance (J. L. Balenzategui, Et al.) Meas. Sci. Technol. 33 (2022) 115009 (15pp)

Uncertainty in the Calibration Transfer of Solar Irradiance Scale: From Absolute Cavity Radiometers to Standard Pyrheliometers (J. L. Balenzategui, Et al.) Solar 2022, 2, 158-185