Part No. 141.9510

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USER’S GUIDE

for

MIDDLETON SOLAR

ACR-01

Absolute Cavity Radiometer

for operation with
Keysight 34972A Data Acquisition / Switch Unit

Date: Jan. 2019

Version: 2.2

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Solar Measurement Innovation since 1960

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CONTENTS

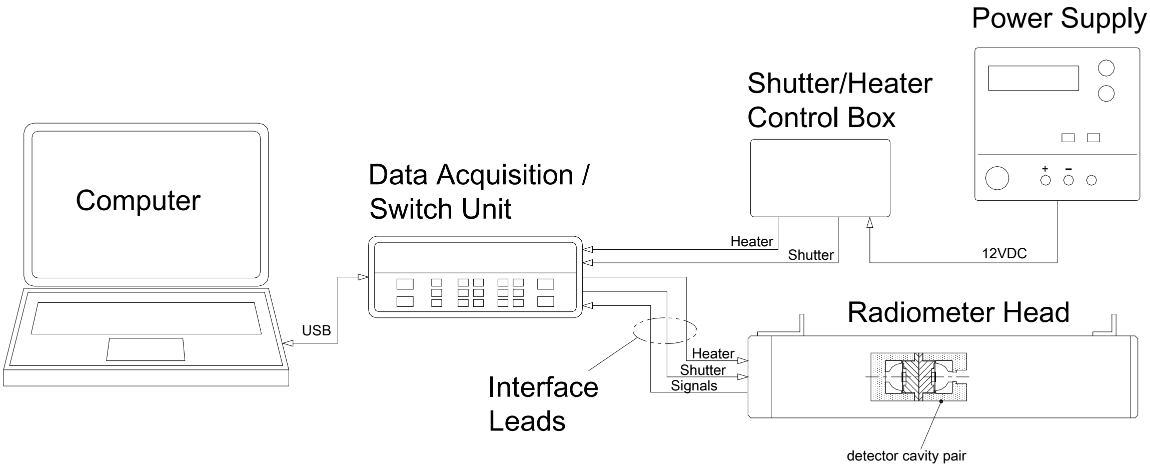
1 GENERAL

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 solar sensitivity; operation is *passive* as the solar measurements are taken between calibration events[1]. 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 Control Box. A Data Acquisition / Switch Unit with connected Computer and Power Supply completes the system.



System components supplied by Middleton Solar are:

- Radiometer Head
- Shutter/Heater Control Box (Configured for Keysight 34903A)
- Power Supply 12VDC, 2A (for Control Box)
- Control Cables (Configured for Keysight 34901A)
- Interface Leads (to connect Data Acquisition/Switch to Radiometer Head)
- ACR-01 Configuration file (for Control software)

Other required system components are[2]:

- Keysight 34972A Data Acquisition / Switch Unit[3]
- Keysight 34901A Control Multiplexer Module
- Keysight 34903A Control Switch Module
- Keysight 34830A Benchlink Data Logger Pro software
- USB Cable, type A to type B
- Computer (Windows 10 operating system)

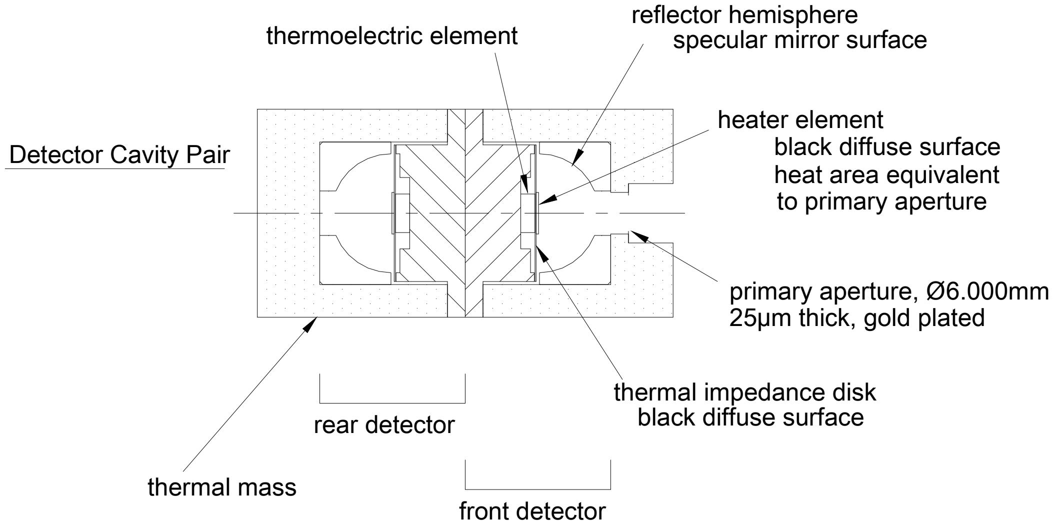
[1] *active* operation is where self-calibration is performed as part of solar measurement
[2] the required items are MSolar available options, or User supplied
[3] Keysight was previously known as Hewlett Packard and as Agilent

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 closed rear (compensation) cavity is coupled to the front cavity to cancel any common-mode response due to temperature transients.



A thin heater element, equivalent in area to the primary aperture, is bonded to the illuminated side of a thermoelectric element. In measurement mode, light entering the front cavity is absorbed by the black diffuse surface of the heater element 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 heater surface by the reflector hemisphere (see Appendix D: Cavity Losses from Reflection).

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. The small proportion of heater power that is emitted as IR radiation from the heater surface is mostly focused back onto the heater by the reflector hemisphere.

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 practice there are various subtle non-equivalence errors.

The major sources of linear systematic error are: un-recovered reflection from the receiver (heating element) surface; un-recovered emission of IR radiation from the heating element; inequality of the thermoelectric element response to solar heating versus electrical heating; scattered light from the precision aperture; light diffraction into the cavity; parasitic heating from the wires to the heater element.

The deviation from ideal behaviour is established by laboratory measurement and/or model calculations. This characterization results in the determination of a Correction Factor (CF) unique to each instrument.

CF = solar sensitivity / absolute sensitivity
typical CF = 0.99050

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].

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 so these parameters are not included in the assessment of the CF.

Application of the CF, the heater lead resistance, and the aperture diameter, is addressed in Section 5 of this Guide.

[4] the WRR is the World Standard Group located in Davos, Switzerland

3 SETTING UP

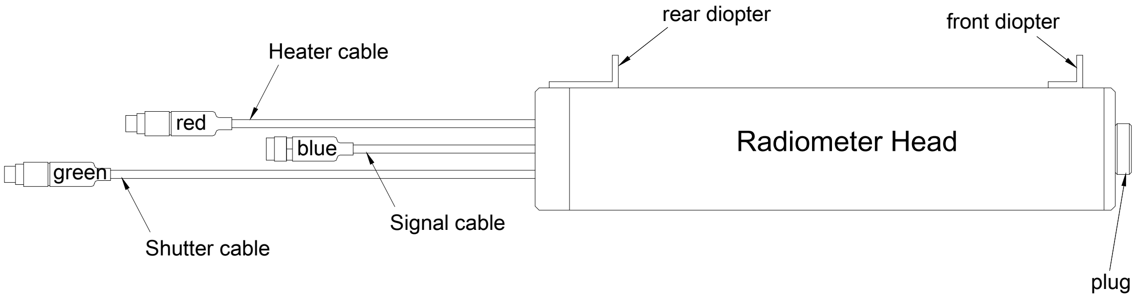
3.1 SITE CONDITIONS

The Radiometer Head should be located outdoors and the Data Acquisition / Switch Unit, 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° of elevation, in the daily path followed by the sun. To obtain accurate 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 also pass through the rear pinhole, and can be seen as a bright spot on a card held behind the diopter target.



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

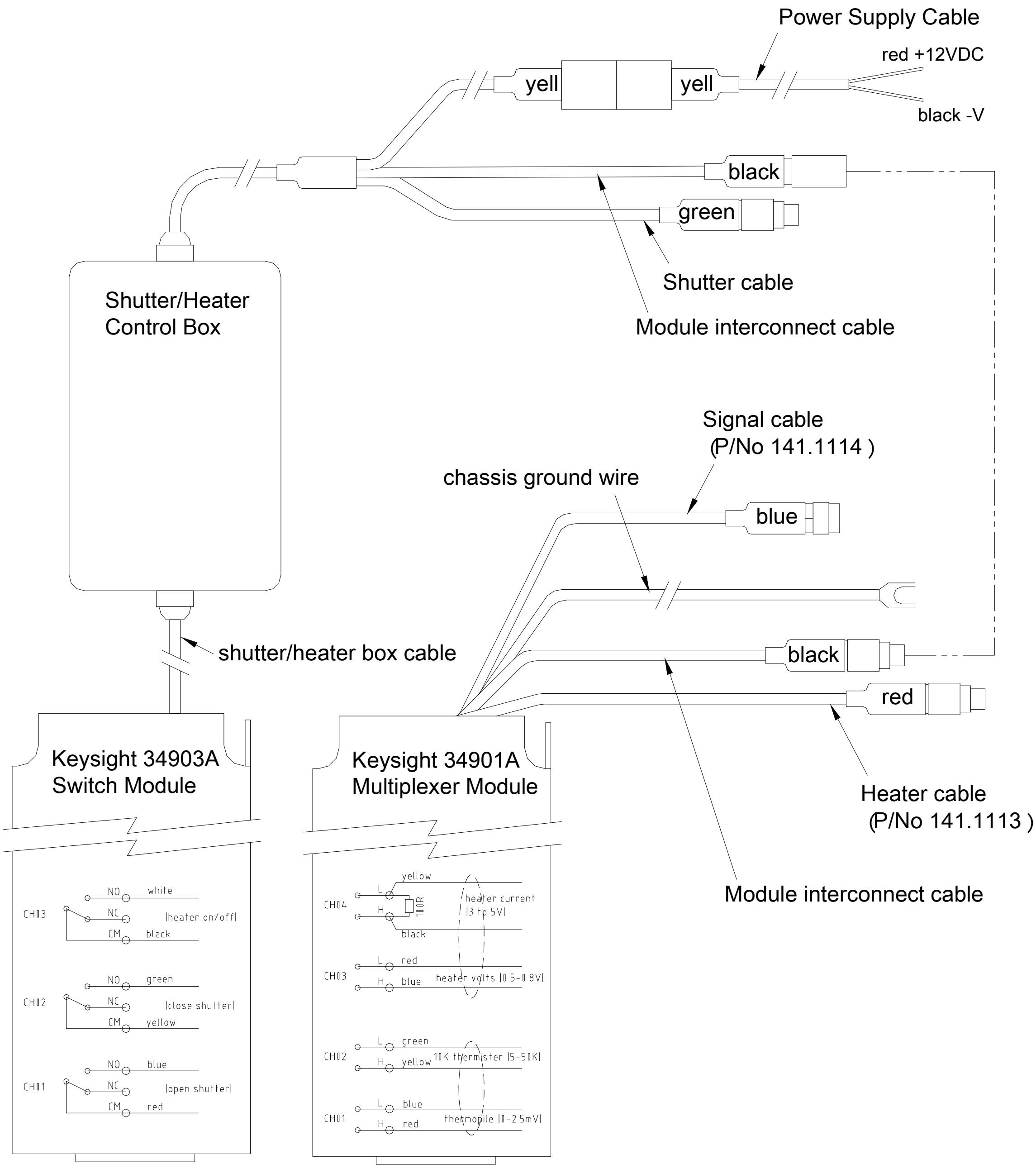
The Radiometer Head has a plug that protects the instrument interior from moisture and dust. This plug should be removed during use but must always be fitted when the instrument is idle.

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

3.3 CONTROL INSTALLATION

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

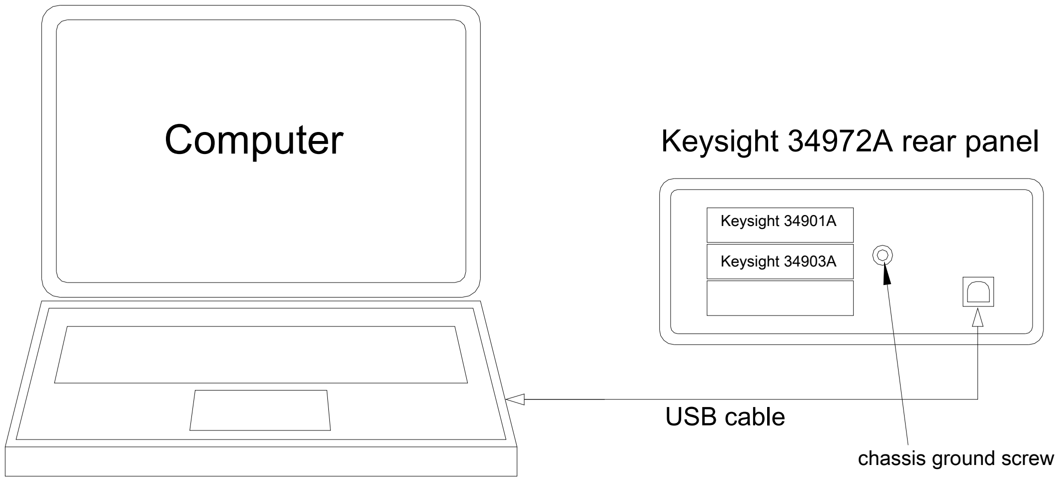
Ensure that the control equipment is set to the correct line voltage for your location.



Fit the supplied Signal cable (P/No 141.1114) and Heater cable (P/No 141.1113) to the Keysight 34901A Multiplexer Module. Fit the Shutter/Heater Box cable to the Keysight 34903A 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 34972A Data Acquisition / Switch Unit. The 34091A Module into the top slot, and the 34903A Module into the middle slot.

Connect the USB Cable to the Computer and to the Keysight 34972A Data Acquisition / Switch Unit.

Connect the Control Modules together with the black Module Interconnect Cables.

Connect the chassis ground wire to the rear panel of the Keysight 34972A Data Acquisition / Switch Unit.

Connect the three Interface Leads, from the Radiometer Head, to the corresponding red, blue, and green coloured Control Connector.

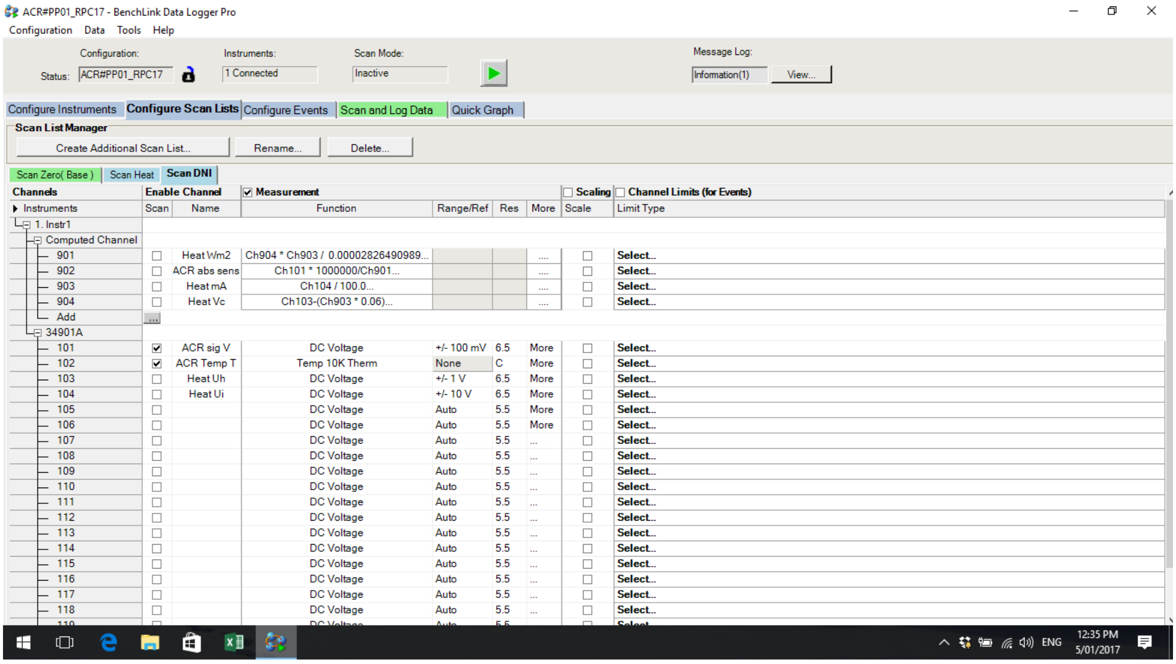
Connect the Power Supply Cable, of the Control Box, to the supplied Power Supply.

Connect the control equipment to mains power.

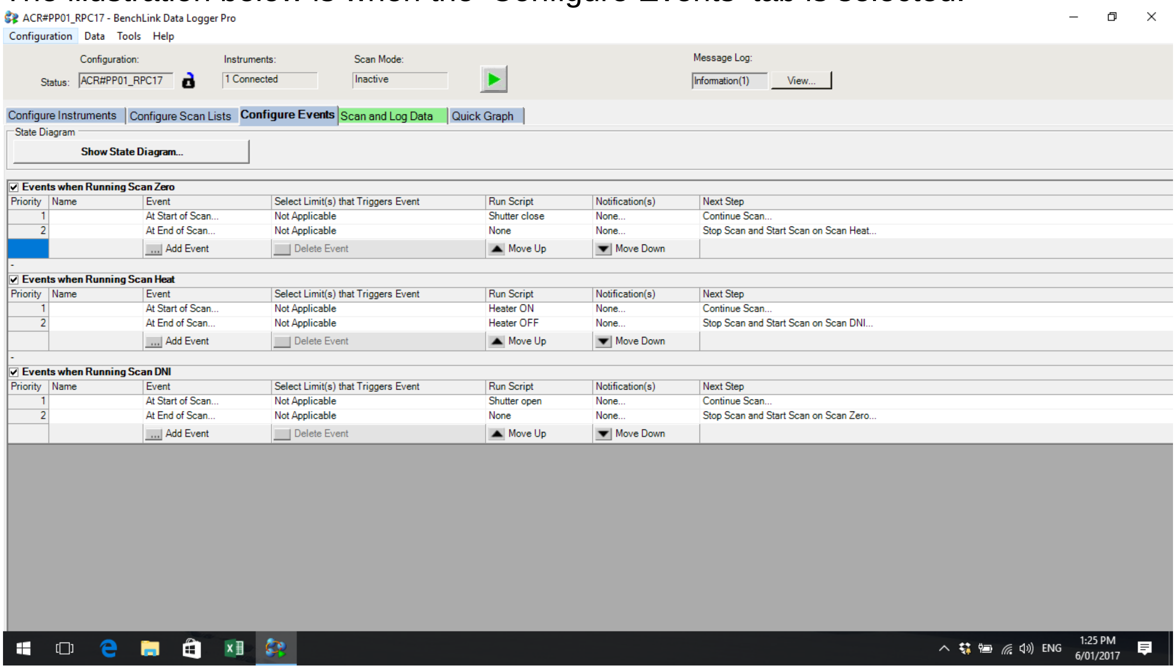
3.4 SOFTWARE CONFIGURATION

Load the Keysight 34830A Benchlink Data Logger Pro software, and associated Keysight Application Files, to the Computer. Follow the instructions available from Keysight. Load the ACR-01 Configuration File, supplied with your instrument, to the Benchlink software. The Configuration File is a 'template' data logger programme to control the operation of the ACR-01 System. There are four measured channels, four computed channels, and scripts to operate the Shutter and Heater. The Configuration File can be readily customized to suit User preferences.

The Computer screen will typically appear as illustrated below when the 'Configuration Scan Lists' tab is selected.



The illustration below is when the 'Configure Events' tab is selected.



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 to measurement uncertainty.

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 should be adjusted 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, and 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.

Ap, primary aperture diameter (typically 6.0E-3 meter)
Rh, precision shunt resistor to measure heater current (typically 100 Ω)
Rc, heater leads correction resistance (typically 0.06 Ω)
CF, correction factor for non-equivalence (typically 0.99050)

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

Ve, thermopile output (typically 1.5E-3 volts, for S = 1,000 $W.m^{-2}$)
Vo, thermopile zero off-set (typically 2E-6 volts)
Uh, voltage across heater element
(typically 0.7 volts, for S = 1,000 $W.m^{-2}$)
Ui, voltage across heater current shunt resistor Rh
(typically 4 volts, for S = 1,000 $W.m^{-2}$)

There is one optional quantity obtained from the data acquisition Computer.

T, temperature of detector assembly (°C)

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
$DNI = (Ve - Vo) * 1E6 / CF / K$

6 SPECIFICATIONS

ACR-01 Radiometer Head	
full opening angle	5°
slope angle	1°
limit angle	4°
irradiance	0 - 1,400 W/m^2
time constant (63%)	< 2 sec
front aperture	∅10 mm
primary aperture (typical)	∅6,000 ±0.5μm; 25μm thick; gold plated
aperture separation	114.5 mm
absolute sensitivity (typical)	1.5 μV/ $W.m^{-2}$, at 20°C
non-linearity	< 0.001%, for 700 -1,400 W/m^2
temperature response	+0.14%/°C
Correction Factor (CF)	> 0.99
operating temperature	-10 to +40°C
heater type & resistance	constantan wire, 16Ω (nominal)
shutter	multi-blade, bi-stable, 1 sec response
construction	aluminium & stainless steel
size	∅60 x 286 mm
weight	1.25kg (radiometer head)

ACR-01 Control	
Shutter/Heater Control Box	Configured for Keysight 34903A
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
Interface Leads	6m, PU: Heater; Shutter; Signals
ACR-01 Configuration File	to suit Keysight 34830A Benchlink Data Logger Pro software

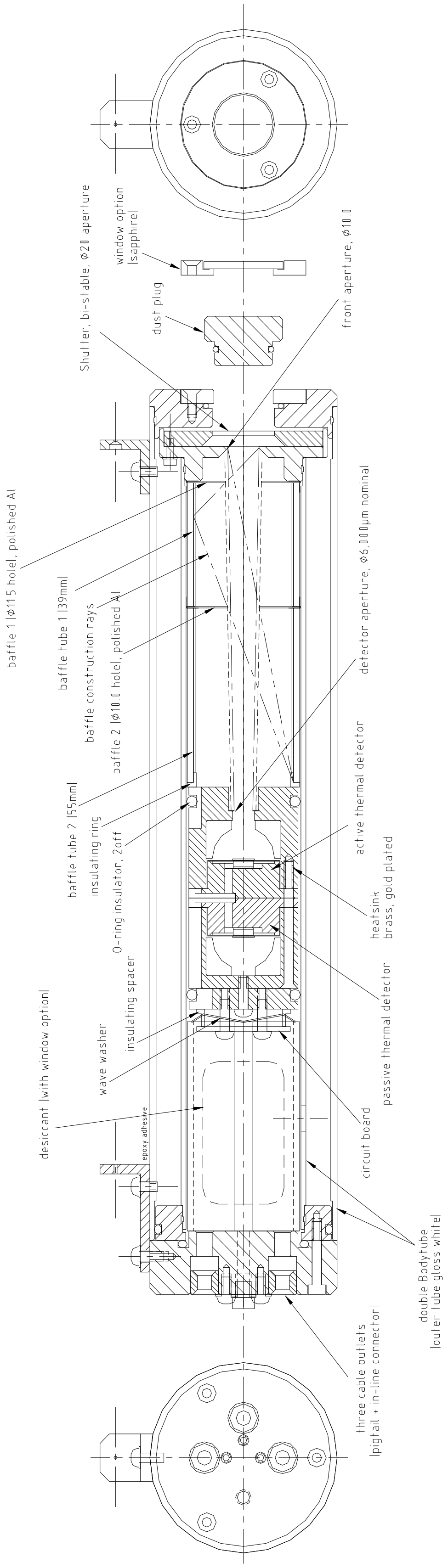
Required Options[6]	
Data Acquisition / Switch	Keysight 34972A
Control Multiplexer Module	Keysight 34901A
Control Switch Module	Keysight 34903A
Control Software	Keysight 34830A Benchlink Data Logger Pro
USB Cable	USB type A to type B
Computer	Notebook PC; Windows 10

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

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

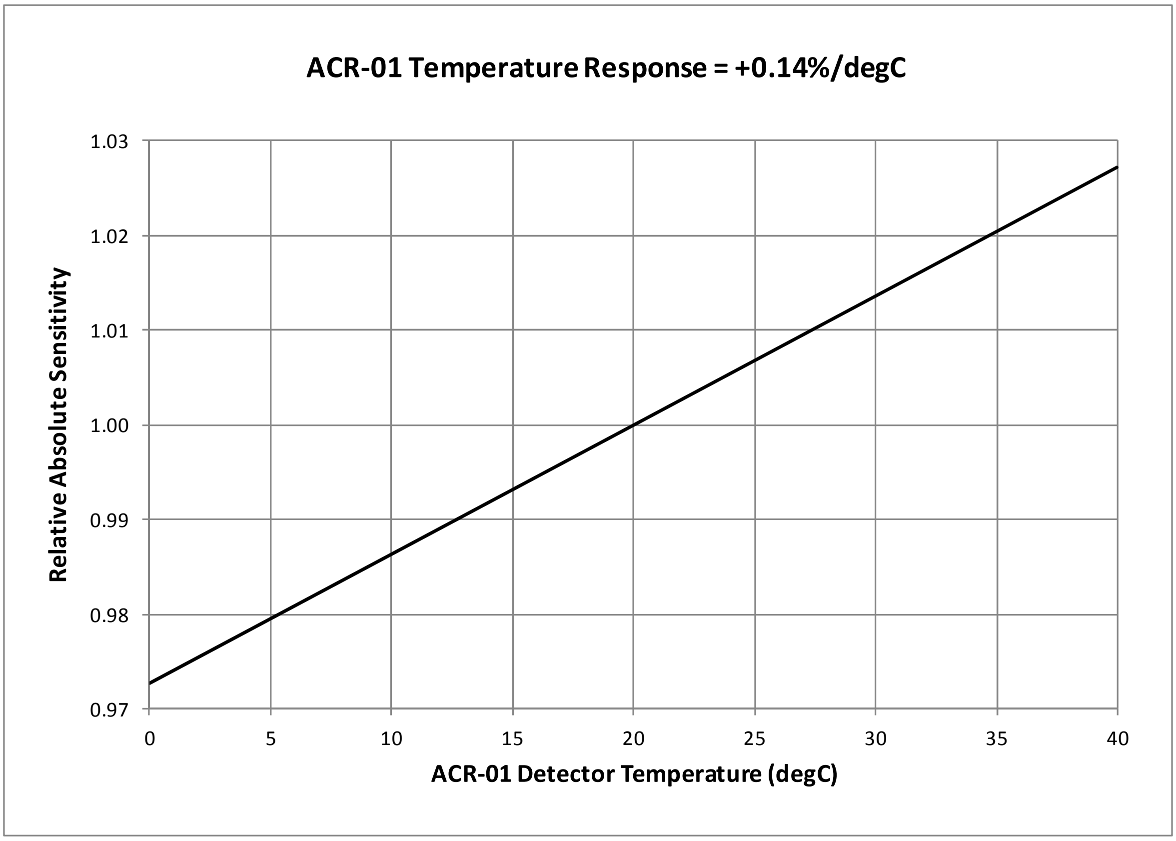
7 SERVICE

The ACR-01 radiometer head has no User serviceable components. Contact the manufacturer for any servicing or repairs.

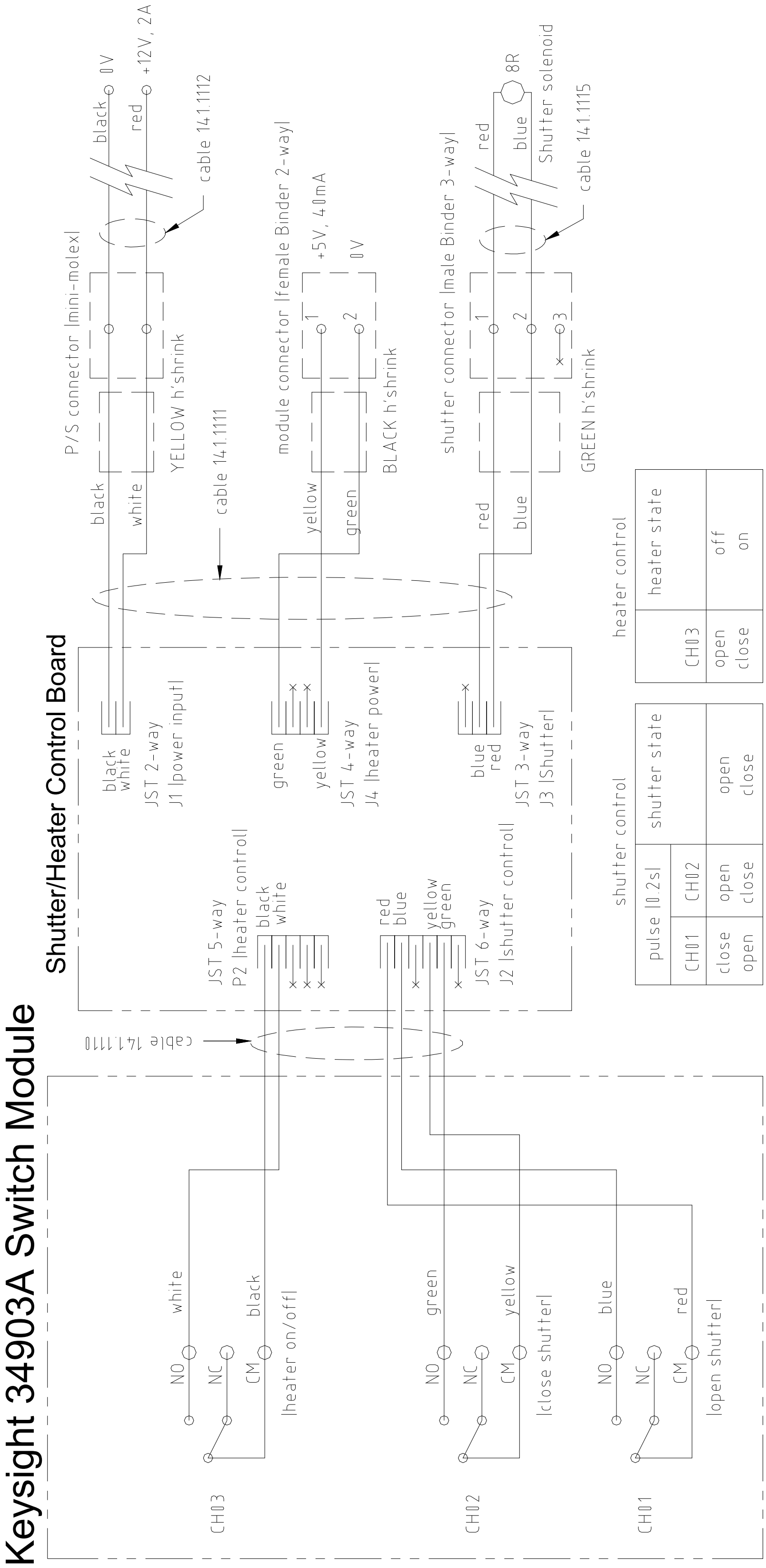


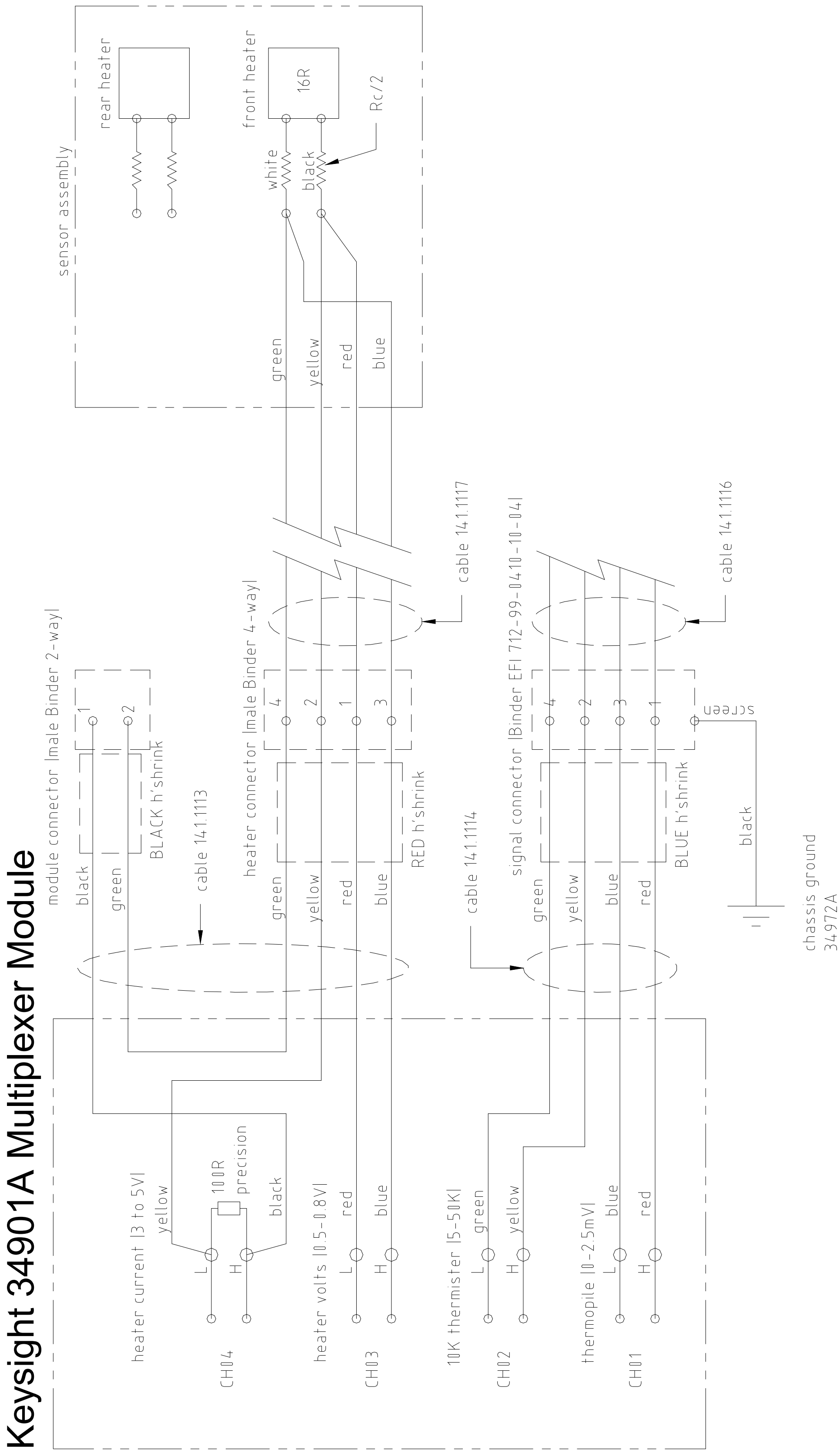
Appendix A: TEMPERATURE RESPONSE

The temperature response of the ACR-01 is determined by the properties of the thermoelectric element used in the detector. The temperature response is linear with respect to the temperature of the detector heatsink.



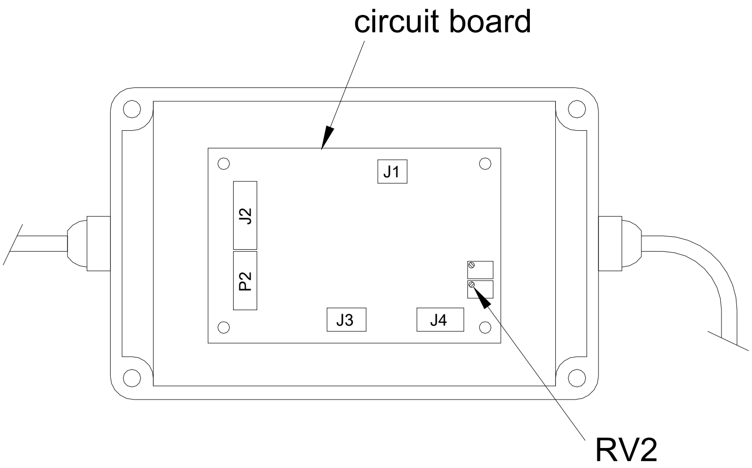
Appendix B: CONTROL MODULE WIRING SCHEMATICS




Keysight 34901A Multiplexer Module
sensor assembly
rear heater
front heater
16R
Rc/2
white
black
green
yellow
red
blue
cable 141.1117
cable 141.1116
module connector (male Binder 2-way)
heater connector (male Binder 4-way)
signal connector (Binder EFI 712-99-0410-10-04)
screen
black
green
BLACK h'shrink
RED h'shrink
BLUE h'shrink
cable 141.1113
cable 141.1114
chassis ground
34972A
heater current (3 to 5V)
yellow
100R
precision
black
heater volts (0.5-0.8V)
red
blue
10K thermister (5-50K)
green
yellow
thermopile (0-2.5mV)
blue
red
CH04
CH03
CH02
CH01
L
H

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.

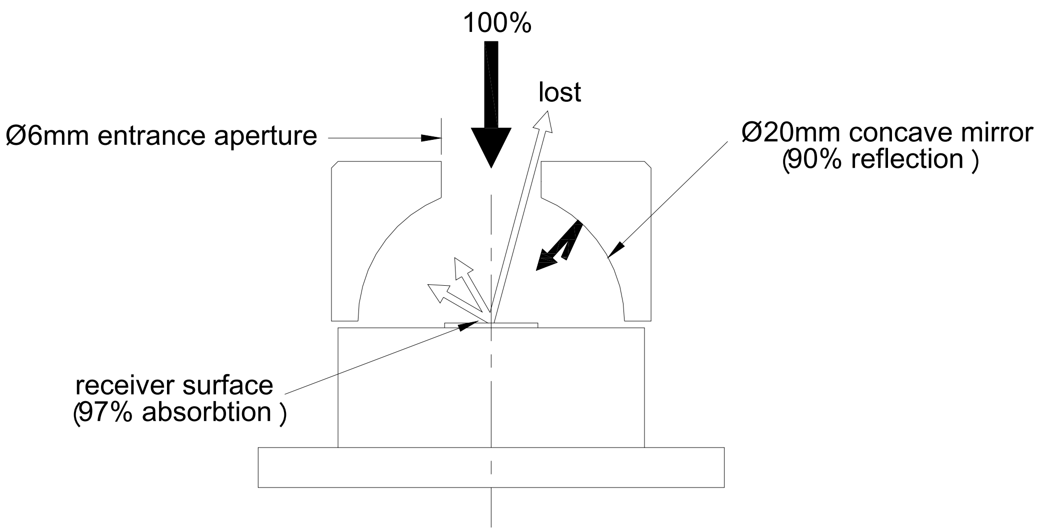
P2 and J2 are relay inputs for shutter control and heater control from the Keysight 34903A Switch Module; the two shutter relays should be turned on for 0.2 seconds, then turned off, to operate the respective shutter function. The relay for heater function toggles the heater operation on/off[7].

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

[7] P2 and J2 can be re-configured as TTL control inputs for interface to other types of control setup

Appendix D: CAVITY LOSSES FROM REFLECTION

Estimate of solar irradiance loss in measurement mode.



Of the 100% solar radiation entering the front detector cavity, approximately 97% is captured (absorbed) by the blackened receiver surface, and 3% is back-scattered in a lambertian manner. Some of the back-scattered radiation is lost through the entrance aperture, and 90% of the remainder is specular reflected (focused) back to the receiver surface by the concave mirror hemisphere. This reflected radiation is in turn 97% captured, and 3% back-scattered, ad infinitum.

Entrance aperture area = π x 6 x 6 /4 = 28mm^2
Concave mirror area = π x 20 x 20 /2 = 628mm^2
Back-scatter loss through entrance aperture = 28 / 628 = 0.045

Primary capture = 0.97
Secondary capture = 0.03 x (1-0.045) x 0.9 x 0.97 = 0.025
Tertiary capture = 0.025 x 0.025 = 0.0006

Total capture = 0.97 + 0.025 + 0.0066 + n………
$\approx$ 0.996

Front cavity loss from un-recovered reflection = 1 – 0.996
$\approx$ 0.4%

Likewise in measurement or calibration mode, the small proportion of energy that is emitted as IR radiation from the receiver/heater surface, is mostly recovered.

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

YSI 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