ARM TR-027

Ground Radiation (GNDRAD) Handbook

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Tables

1. General Overview

The Ground Radiation (GNDRAD) collection of radiometers provides each Atmospheric Radiation and Cloud Station (ARCS) with continuous measurements of broadband shortwave (solar) and longwave (infrared) irradiances for upwelling components. These 1-minute data are collected from a network of stations to help determine the total radiative energy exchange within the Tropical Western Pacific.

2. Contacts

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2.2 Instrument Developer

This section is not applicable to this instrument.

3. Deployment Locations and History

The GNDRAD is operational at the North Slope of Alaska and Tropical Western Pacific sites.

4. Near-Real-Time Data Plots

Barrow, Alaska Quicklooks

Atqasuk, Alaska Quicklooks

5. Data Description and Examples

See Near-Real-Time Data Plots, Section 4, and Data Quality Health and Status, Section 6.1.

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

The following *broadband* irradiance measurements are available from the GNDRAD platform:

UPWELLING SHORTWAVE (0.3 TO 3.0 micrometers)

1. Reflected irradiance measured by an inverted pyranometer with a hemispheric field of view.

UPWELLING LONGWAVE (4.0 to 50 micrometers)

2. Irradiance measured by an inverted pyrgeometer with a hemispheric field of view.

5.1.1.1 Definition of Uncertainty

Estimating radiometer measurement uncertainties continues to be a topic for additional research. Based on experiences with these and similar instruments for renewable energy applications, the following estimated measurement uncertainties in Table 1 conservatively apply to SKYRAD and GNDRAD measurement platforms.

Table 1.

Measurement	Abbreviation	Radiometer Model	Typical Responsivity ($\mu V/Wm^{-2}$)	Estimated Measurement Uncertainty*
Direct Normal (beam)	DNI	NIP	8.0	±3.0% or 4 Wm^{-2}
Diffuse Horizontal (sky)	DD	PSP	9.0	±6.0% or 20 Wm^{-2}
Downwelling Shortwave (global)	DS	PSP	9.0	±6.0% or 10 Wm^{-2}
Downwelling Longwave (atmospheric)	DIR	PIR	4.0	±2.5% or 4 Wm^{-2}
Upwelling Shortwave (reflected)	US	PSP	9.0	±6.0% or 15 Wm^{-2}
Upwelling Longwave (terrestrial)	UIR	PIR	4.0	±2.5% or 4 Wm^{-2}

*Field measurement uncertainties include the uncertainties associated with instrument calibration, installation, operation and maintenance.

5.1.2 Secondary/Underlying Variables

This section is not applicable to this instrument.

5.1.3 Diagnostic Variables

This section is not applicable to this instrument.

5.1.4 Data Quality Flags

GNDRAD Data Object Design Changes for ARM netCDF file header descriptions.

5.1.5 Dimension Variables

This section is not applicable to this instrument.

5.2 Annotated Examples

This section is not applicable to this instrument.

5.3 User Notes and Known Problems

This section is not applicable to this instrument.

5.4 Frequently Asked Questions

None.

6. Data Quality

6.1 Data Quality Health and Status

The following links go to current data quality health and status results.

- DQ HandS (Data Quality Health and Status)
- NCVweb for interactive data plotting using.

The tables and graphs shown contain the techniques used by ARM's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

6.2 Data Reviews by Instrument Mentor

This section is not applicable to this instrument.

6.3 Data Assessments by Site Scientist/Data Quality Office

All DQ Office and most Site Scientist techniques for checking have been incorporated within DQ HandS and can be viewed there.

6.4 Value-Added Procedures and Quality Measurement Experiments

Many of the scientific needs of the ARM Program are met through the analysis and processing of existing data products into "value-added" products or VAPs. Despite extensive instrumentation deployed at the ARM CART sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the program. Conversely, ARM produces some VAPs not in order to fill unmet measurement needs, but instead to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces "best estimate" VAPs. A special class of VAP called a Quality Measurement Experiment (QME) does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks, comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth. For more information, see the VAPs and QMEs web page.

7. Instrument Details

7.1 Detailed Description

7.1.1 List of Components

The following radiometers manufactured by The Eppley Laboratory, Inc., in Table 2 are used at each GNDRAD.

Table 2.

Measurement	Radiometer Model	Mounting Arrangement	Typical Responsivity ($\mu V/Wm^{-2}$)	Typical Calibration Uncertainty*
Upwelling Shortwave	PSP	Inverted w/o ventilation	9.0	±3.0% or 10 Wm^{-2}
Upwelling Longwave	PIR	Inverted w/o ventilation	4.0	±2% or 2 Wm^{-2}

*Field measurement uncertainties are larger and include the uncertainties associated with instrument calibration, installation, operation and maintenance.

Additional information is available from http://www.eppleylab.com, http://www.nrel.gov/srrl/, and http://rredc.nrel.gov.

7.1.2 System Configuration and Measurement Methods

GNDRAD instruments provide two broadband radiometric measurements:

US = Upwelling Shortwave (reflected solar) Irradiance
UIR = Upwelling Infrared (terrestrial) Irradiance.

The data acquisition system is a Coastal Environmenal Systems Model ZENO®-3200 Datalogger. The data system is inside a weather-resistant enclosure that is mounted above ground. The system is designed to operate over the full range of environmental conditions anticipated for the network of ARCS stations (see http://www.coastal.org for detailed measurement and environmental specifications).

7.1.3 Specifications

Selected theoretical measurement parameters of the SKYRAD and GNDRAD radiometers are listed below in Table 3.

Table 3.

Measurement	Radiometer Field of View	Wavelength Range (microns)	Minimum Irradiance (Wm^{-2})	Maximum Irradiance (Wm^{-2})
Direct Normal (beam) [DNI]	5.7°	0.3 to 3.0	0.0	1100
Diffuse Horizontal (sky) [DD]	2π sr	0.3 to 3.0	0.0	600
Downwelling Shortwave (global) [DS]	2π sr	0.3 to 3.0	0.0	1400
Downwelling Longwave (atmospheric) [DIR]	2π sr	4.0 to 50	50	800
Upwelling Shortwave (reflected) [US]	2π sr	0.3 to 3.0	0.0	1100
Upwelling Longwave (terrestrial) [UIR]	2π sr	4.0 to 50	100	800

Field of View and Angular Response

The SKYRAD pyrheliometer (Eppley Laboratory, Inc., Model NIP) field of view was designed to meet the World Meteorological Organization's design requirements circa 1960. Without the scattering effects of a clear atmosphere, the solar disc would appear to be about 0.5° at the earth's surface. The NIP geometry allows for solar tracker alignment tolerances possible at the time of the WMO specification and includes, therefore, an amount of circumsolar (forward scatter) radiation.

The SKYRAD and GNDRAD pyranometers (Eppley Laboratory, Inc., Model PSP) have unique angular response characteristics that can be determined and verified with calibration (see separate section). The angular response of the pyranometer is a major contributor to the estimated measurement uncertainty for the various shortwave irradiance elements.

Spectral Response

The spectral response of the SKYRAD and GNDRAD radiometers listed above are nominal values. The precise values vary with instrument model.

Thermal Offsets

Shortwave radiometers should produce a null signal in the absence of solar radiation. However, all commercially available pyranometers based on thermoelectric transducers, exhibit a non-zero output signal in the absence of solar radiation. These signals are believed to be a result of thermal gradients within the pyranometer.

The Eppley Laboratory, Inc., Model PSP is a thermoelectric, single-black detector design with well-established performance characteristics **[Zerlaut, 19??].** As shown in **Figure 4**, the two Schott Glass hemispheres protect the thermopile detector from the weather. These inner and outer domes are used to also reduce the thermal exchange between the detector, or thermopile "hot" junction, and the environment. The body of the instrument is a relatively massive bronze casting that is used to control the "cold" or reference junction of the thermopile. Recent studies of this and other models of pyranometers suggest thermal offsets are producing as much as 30 Wm^{-2} during clear-sky, nighttime conditions. Similarly, daytime measurements of downwelling diffuse shortwave irradiance must be corrected for thermal offsets. ARM will use a correction method based on correlations with the net infrared and observed diffuse irradiances **[Dutton, et al, 2001]**.

7.2 Theory of Operation

Shortwave Irradiance

Three pyranometers are positioned to measure the hemispheric irradiance fields:

DS Unshaded, ventilated, and mounted in horizontal orientation
US Inverted, unventilated and mounted 10m above the ground level
DD Shaded, ventilated, and mounted on automatic solar tracker in horizontal orientation.

A single pyrheliometer is mounted on an automatic solar tracker and aligned to the sun's disc.

The following relationships are expected from the SKYRAD and GNDRAD measurement systems for the various broadband shortwave irradiance elements.

$$DS = DNI * Cos(Z) + DD$$
$$US = DS * \rho$$
$$DS \leq ETR$$
$$DNI \leq ETRN$$

where,

DS = Downwelling Hemispheric Shortwave (Global) Irradiance
DNI = Direct Normal Shortwave (Beam) Irradiance
Z = Solar Zenith Angle (sunrise/sunset = 90°)
DD = Downwelling Diffuse Shortwave (sky) Irradiance
US = Upwelling Diffuse Shortwave (reflected) Irradiance
ρ = Surface Shortwave Albedo (typically 0.2 for vegetation, 0.8 for fresh snow)
ETR = Extraterrestrial (exo-atmospheric) Radiation on horizontal surface
ETRN = Extraterrestrial Radiation Normal (beam) to the sun (1366 ±5 Wm^{-2} **[REF??]**).

Longwave Irradiance

Elements of the pyrgeometer measurements are used to compute the infrared:

$$IR = T_{tp} * C_1 + \sigma T_C^4 - C_2 \sigma (T_d^4 - T_c^4)$$

where,

IR = Infrared Irradiance (W/sq m)
T_{tp} = PIR thermopile voltage (mV)
T_c = PIR case temperature (K)
T_d = PIR dome temperature (K)
C_1 = PIR Calibration Factor (W/sq m per mV)
C_2 = PIR Dome Correction Factor (4.0 = default for all PIRs)
σ= Stephan-Boltzman Constant = 5.67E-08 $W/m^2\ K^4$.

7.3 Calibration

7.3.1 Theory

The calibration of all ARM *shortwave* radiometers (pyrheliometers and pyranometers) is traceable to the World Radiometric Reference (WRR) maintained by the World Radiation Center (WRC) for the World Meteorological Organization. Calibrations are performed at the SGP Radiometer Calibration Facility (RCF-see separate entry) using the Broadband Outdoor Radiometer CALibration (BORCAL) methods developed at NREL. A group of three electrically self-calibrating absolute cavity radiometers is maintained by NREL as the reference standards for the U.S. Department of Energy (DOE) and ARM. WRR calibration traceability of these reference standards is maintained for all DOE programs by participation in the International Pyrheliometer Comparisons (IPC) held every five years at the WRC. IPC-IX was completed in October 2000.

The calibration of all ARM *longwave* radiometers (pyrgeometers) are traceable to temperature standards maintained by the National Institute of Standards and Technology (NIST). ARM pyrgeometers will be calibrated in the new Pyrgeometer Blackbody Calibration System developed by The Eppley Laboratory, Inc. for the ARM Program and/or by outdoor comparisons with transfer standards. Standard operating procedures are currently under development at NREL for later use at the RCF to provide routine pyrgeometer calibrations.

Shortwave Radiometer Calibrations

The *Component Summation Method* used for all BORCAL events is a modified version of the shading method described in the American Society for Testing and Materials (ASTM) Standard E913-82, "Standard Method for Calibration of Reference Pyranometers with Axis Vertical by the Shading Method."

The direct normal (beam) irradiance is measured with one or two absolute cavity radiometers, and the diffuse (sky) irradiance is measured with one or two pyranometers shaded with a tracking disk. The output voltage of these standards and the radiometers under test are measured at approximate 30-second intervals throughout each day during clear-sky conditions (no clouds near the solar disk).

The responsivity for a pyrheliometer is calculated for each data point by dividing the value of the instrument's output signal (microvolts) by the mean value of the absolute cavity radiometer(s) output (W/sq m).

The responsivity for a pyranometer is calculated by dividing the value of the instrument's output signal (microvolts) by the computed reference global horizontal irradiance (W/sq m). The computed reference irradiance is the sum of the diffuse radiation and the vertical component of the direct beam irradiance (cavity radiometer irradiance multiplied by the cosine of the solar zenith angle at the time of measurement). This assumes that the pyranometer has a perfect angular response. The solar zenith angle calculations are corrected for atmospheric refraction effects at the calibration facility.

During a calibration event, one or more pyranometers (The Eppley Laboratory, Inc., Model PSP) and pyrheliometers (The Eppley Laboratory, Inc., Model NIP) are used as control standards to monitor the calibration process. The results from these instruments are reviewed to monitor the calibration process and compare the results of different BORCAL events.

Uncertainty Calculations

The uncertainty of a measurement result is a parameter that characterizes the spread of the values that could be reasonably attributed to the measurement. The evaluation of the uncertainty in the derived BORCAL responsivity of each instrument is based on the guidelines of the International Standards Organization "Guide to the Expression of Uncertainty in Measurements" [9], similar guides prepared by and available from national standardizing laboratories [8,10] and previous NREL experience [11].

The mean responsivity (Rs) is multiplied by a "base uncertainty" (1.3%, or 0.013, derived below) and added to 1/2 the RANGE of responsivities over any region (a bin, 45/55 bin, or composite) to provide the uncertainty in terms of µV/W/sq m. Dividing this value by the mean Rs and multiplying by 100 provides the percent uncertainty. The rationale for this approach is described below.

Sources of uncertainty are identified in the reference instrumentation, the process of data collection and computation, and derived from the data empirically after processing. The sources are classified as "type A" (random), and "type B" (non-random). Type A sources are attributable to processes assumed to have a known distribution, typically normal or gaussian. Type B (sometimes referred to as systematic or bias errors) have unknown or non-gaussian distributions. The later require robust, non-statistically based estimates of their magnitude. See the references for detailed discussions of estimating Type B uncertainty sources.

Our uncertainty analysis of the reference instrumentation and data processing techniques results in a "base" uncertainty equal to ± 1.3% in each individual responsivity computation. The sources of uncertainty in these processes include uncertainty in:

- the World Radiometric Reference (WRR) [12] (0.3%)
- transfer of WRR to NREL Working Standards (0.2%)
- data logger accuracy (0.2%)
- incidence angle computations (0.64%).

These are all considered to be 2 sigma, random, Type A sources of uncertainty which have been added together to produce an overall 1.3% "base" uncertainty.

The approach applied here is described in Paragraph 4.6 of Section 4 ("Type B Evaluation of Standard Uncertainty") in National Institute of Standards and Technology Technical Note 1297 [10]. This procedure requires estimating the lower (a-) and upper (a+) limits for the value (a) in question such that the "probability that the value lies in the interval from (a-) to (a+) is for all practical purposes 100%"[10]. Section 2.0 Statistical Tables above describes the procedure for computing the responsivity, Rs. Responsivities and uncertainty within the bins of solar zenith angles are provided to assist the user in understanding the limitations of the instruments, particularly with respect to angular response.

-Cautionary Note –

This approach asserts that the "probability that the value lies in the interval (a-) to (a+) is for all practical purposes 100%" [10] ONLY for the empirically derived values during the BORCAL event. Only a LIMITED portion of the angular response of the pyranometers is mapped out as the result of the solar zenith and azimuth angles available during the calibration period. However, since the range of incidence angles encountered generally includes a significant part of those possible throughout the year, for an instrument mounted horizontally, the uncertainty quoted for the composite responsivity (if computed) is probably reasonable for general applications.

Applying the Responsivities

To derive irradiance in Watts per square meter from a radiometer's output voltage, divide the voltage (in microvolts) by the instrument's responsivity (µV/W/sq m).

Example:

Output voltage: 0.00624 V (6240 µV)
Responsivity: 7.34 µV/W/sq m ± 2.7%
Irradiance: 6240 / 7.34 = 850.1 W/sq m ± 2.7%.

Thus, with 99% certainty, the true irradiance lies between 827.1 and 873.1 W/sq m, given the cautionary note above in the Uncertainty Calculations section.

7.3.2 Procedures

This section is not applicable to this instrument.

7.3.3 History

This section is not applicable to this instrument.

7.4 Operation and Maintenance

7.4.1 User Manual

This section is not applicable to this instrument.

7.4.2 Routine and Corrective Maintenance Documentation

This section is not applicable to this instrument.

7.4.3 Software Documentation

ARM netCDF file header descriptions may be found at GNDRAD Data Object Design Changes.

7.4.4 Additional Documentation

In order to provide research-quality irradiance measurements, the radiometers are re-calibrated annually. The existing radiometer inventory allows for 100% spares, reducing the down time for station operation due to calibration. Maintenance of the SKYRAD and GNDRAD equipment is performed during maintenance visits to the ARCS facilities. Detailed information is available from the Tropical Western Pacific (TWP) web site (http://www.dmf.arm.gov/index.html).

7.5 Glossary

Broadband Irradiance
Pyranometer
Pyrgeometer
Pyrheliometer

Also see the ARM Glossary.

7.6 Acronyms

CART: Cloud and Radiation Testbed
NIP: normal incidence pyrheliometer
PIR: precision infrared radiometer
PSP: precision spectral pyranometer
SIRS: Solar Infrared Station
Also see the ARM Acronyms and Abbreviations.

7.7 Citable References

Iqbal, M. 1983. *An Introduction to Solar Radiation*. Academic Press, New York, New York. ISBN 0-12-373750-8 (ISBN 0-12-373752-4 for paperback), pp. 390.

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