ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD) GLOBAL, DIRECT, AND DIFFUSE RADIATION

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Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	08/02/2013	ECO-01054	Initial Release
B	10/23/2015	ECO-03110	Adjusted zenith angle threshold implemented standardized coverage factor of k=2 Moved consistency analyses outline to Future Plans / Modifications Sections
C	03/27/2020	ECO-06417	Removed mention of de-spiking algorithm. Added a note that the persistence test is only applied during local, daylight hours.

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1 DESCRIPTION

Contained in this document are details concerning measurements of global and diffuse shortwave radiation made at all NEON sites. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described. This document focuses on measurement of global, direct normal, and diffuse shortwave radiation by the Delta-T Devices SPN1 Sunshine Pyranometer. These measurements will be made at the tower top.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 data products from Level 0 data, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by the Delta-T Devices SPN1 Sunshine Pyranometer (i.e., global and diffuse shortwave radiation). It includes a detailed discussion of measurement theory and implementation, appropriate theoretical background, data product provenance, quality assurance and control methods used, approximations and/or assumptions made, and a detailed exposition of uncertainty resulting in a cumulative reported uncertainty for this product.

1.2 Scope

The theoretical background and entire algorithmic process used to derive Level 1 data from Level 0 data for the global and diffuse pyranometer are described in this document. The pyranometer employed is the Delta-T Devices SPN1 Sunshine Pyranometer. This document does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS, ACRONYMS AND VARIABLE NOMENLCATURE

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005004	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.002652	NEON Level 0 Data Products Catalog
AD[05]	NEON.DOC.000782	ATBD QA/QC Data Consistency
AD[06]	NEON.DOC.011081	ATBD QA/QC plausibility tests
AD[07]	NEON.DOC.000783	ATBD De-spiking and time series analyses
AD[08]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[09]	NEON.DOC.000610	C^3 Global and Diffuse Pyranometer
AD[10]	NEON.DOC.002002	Engineering Master Location Sensor Matrix
AD[11]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[12]	NEON.DOC.000751	CVAL Transfer of standard procedure
AD[13]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values[1]
AD[14]	NEON.DOC.000794	SPN1 Sunshine Pyranometer Calibration / Validation Procedure
AD[15]	NEON.DOC.000810	NEON ATBD-Primary Pyranometer
AD[16]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products

2.2 Reference Documents

RD[01]	NEON.DOC.000008	NEON Acronym List
RD[02]	NEON.DOC.000243	NEON Glossary of Terms

2.3 Acronyms

Acronym	Explanation
ATBD	Algorithm Theoretical Basis Document
CVAL	**NEON Calibration, Validation, and Audit Laboratory**
DAS	**Data Acquisition System**
DP	Data Product
GRAPE	Grouped Remote Analog Peripheral Equipment
L0	Level 0
L1	Level 1
WMO	World Meteorological Organization
SW	Short wave

2.4 Variable Nomenclature

[1] Note that CI obtains calibration and sensor values directly from an XML file maintained and updated by CVAL in real time. This report is updated approximately quarterly such that there may be a lag time between the XML and report updates.

The symbols used to display the various inputs in the ATBD, e.g., calibration coefficients and uncertainty estimates, were chosen so that the equations can be easily interpreted by the reader. However, the symbols provided will not always reflect NEON's internal notation, which is relevant for Cyberinfrastructure's (CI's) use, and or the notation that is used to present variables on NEON's data portal. Therefore a lookup table is provided in order to distinguish what symbols specific variables can be tied to in the following document.

Symbol	**Internal Notation**	**Description**
C_{d1}	CVALA1	CVAL Diffuse Radiation Scaling coefficient
C_{t1}	CVALA1	CVAL Global Radiation scaling coefficient
$u_{A1,DIF}$	U_CVALA1	Combined, relative uncertainty of diffuse irradiance associated with calibration (%)
$u_{A1,G}$	U_CVALA1	Combined, relative uncertainty of global irradiance associated with calibration (%)
$u_{A3,DIF}$	U_CVALA3	Combined, relative uncertainty (truth and trueness only) of diffuse irradiance calibration (%)
$u_{A3,G}$	U_CVALA3	Combined, relative uncertainty (truth and trueness only) of global irradiance calibration (%)

2.5 Verb Convention

"Shall" is used whenever a specification expresses a provision that is binding. The verbs "should" and "may" express non-mandatory provisions. "Will" is used to express a declaration of purpose on the part of the design activity.

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

Direct normal, diffuse, and global radiation-related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file dds_datapub_NEONDOC002870.txt.

3.2 Input Dependencies

Table 3-1: List of direct normal, global and diffuse radiation-related L0 DPs and associated data that are transformed into L1 DPs in this ATBD, where '00N' in the ninth field represents the uppermost tower level (i.e., tower top).

Description	Sample Frequency	Units	Data Product Number
Uncalibrated global shortwave radiation	1 Hz	W m^{-2}	NEON.DOM.SITE.DP0.00014.001.01332.HOR.VER.000
Uncalibrated diffuse shortwave radiation	1 Hz	W m^{-2}	NEON.DOM.SITE.DP0.00014.001.01333.HOR.VER.000
Sun presence flag	1 Hz	NA	NEON.DOM.SITE.DP0.00014.001.01334.HOR.VER.000
Sensor's Latitude	n/a	Degrees N	CI data store
Sensor's Longitude	n/a	Degrees W	CI data store

3.3 Product Instances

One Delta-T Devices SPN1 Sunshine Pyranometer will be deployed at each NEON tower site. The SPN1 Sunshine Pyranometer will be mounted on the tower top.

3.4 Temporal Resolution and Extent

One- and thirty-minute averages of global, direct normal, and diffuse SW radiation, as well as sunshine presence will be calculated to form L1 DPs.

3.5 Spatial Resolution and Extent

One Delta-T Devices SPN1 Sunshine Pyranometer will be deployed at each NEON tower site. See AD[10] for detail on sensor placement at a specific core site.

4 SCIENTIFIC CONTEXT

Solar radiation is a basic driver of many physical, chemical and biological processes, with the sun providing 99.98% of all energy reaching Earth. Direct horizontal and diffuse radiation between 400 nm and 2700 nm, comprise components of this global energy. Of the global incoming solar radiation reaching Earth, 30% is reflected back to space, 51% is absorbed by land and water, and the clouds and atmosphere absorb the remaining 19% (Rösemann 2011). Quantifying the diffuse radiation, global radiation and sunshine presence are critical to understanding energy balances, local climate and the drivers of many important ecological processes at NEON sites.

4.1 Theory of Measurement

The SPN1 Sunshine Pyranometer measures shortwave (SW) radiation between 400 nm and 2700 nm, outputting data in units of W m^{-2}. The sunshine status output (i.e., 'sunshine presence') indicates whether the energy in the direct horizontal beam exceeds the WMO standard threshold value of 120 W m^{-2}. The SPN1 has seven thermopile corrected sensors under cosine-corrected diffusers (Figure 1).

A note on radiation terms:

The terms direct beam (direct normal) irradiance, direct horizontal irradiance, diffuse irradiance, global irradiance, and total irradiance are commonplace in atmospheric science. Here, we provide definitions (as defined by Paulescu 2013) for each and also present which variables are measured and reported throughout the NEON Observatory.

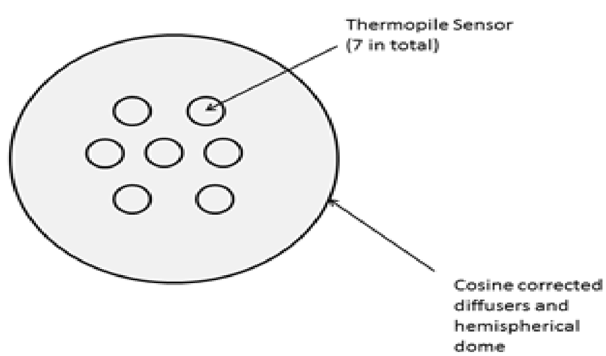

Figure 1. Depiction of the SPN1 sensor layout. Each of the seven thermopile sensors operates individually, and is housed under the hemispherical dome.

Direct beam irradiance (DIR) – the energy flux density of solar radiation measured at an angle perpendicular to the sun's rays.

Direct horizontal irradiance (DIR_{hor}) – solar radiation measured on a flat horizontal plane. The energy flux density on a horizontal plane is directly proportional to the cosine of the incidence angle:

$$DIR_{hor} = DIR * cos(z) \quad (1)$$

Diffuse irradiance (DIF) – the energy flux density of the solar radiation incoming from the entire sky dome on a horizontal surface (excluding direct beam irradiance).

Global irradiance (G) – solar radiation received from the entire 2π sky vault; the sum of direct horizontal and diffuse irradiance components.

$$G = DIR_{hor} + DIF = DIR * cos(z) + DIF \quad (2)$$

Total irradiance (T) – solar radiation received by a surface tilted with respect to the horizontal plane given by:

$$T = DIR_{hor} + DIF \cdot R_d + G_r \tag{3}$$

Where,

R_d = conversion coefficient

G_r = energy flux density reflected by the ground intercepted by the tilted surface.

Delta-t Devices uses the terms *total* and *global* radiation interchangeably (Delta-t Devices Ltd. 2007). However, as shown above there is an inherent difference in measurement techniques between the two.

The values output by the SPN1 sunshine pyranometer are diffuse irradiance, global irradiance, and sunshine presence (a binary variable indicating the presence/absence of sun). Direct normal irradiance is then calculated and output as a function of global and diffuse irradiance and the sun's zenith angle (Eq. (14) through (28)). Direct horizontal irradiance is not output to the end-user; however, the end-user could easily calculate direct horizontal irradiance by simply subtracting diffuse irradiance from global irradiance. A detailed description of the SPN1's processes is given below.

Direct horizontal SW radiation can be computed from these outputs as follows:

$$DIR_{SPN1} = G_{SPN1} - DIF_{SPN1} \tag{4}$$

The SPN1 makes a series of corrections *internally* to account for instrument bias. These are as follows:

$$SW_G = \text{MAX} + \text{MIN} \tag{5}$$

$$SW_{Diff} = 2 * \text{MIN} * 1.02 \tag{6}$$

Note: the 2% adjustment accounts for inherent instrument bias (Delta-t Devices Ltd. 2007).
If the corrected diffuse SW radiation is greater than the global SW radiation, diffuse SW radiation is set equal to the global SW radiation:

$$\textbf{IF } SW_{Diff} > SW_G \quad \textbf{THEN} \quad SW_{Diff} = SW_G \tag{7}$$

A further correction is required to adjust the spectral responses of the sensors for their different sensitivity to direct horizontal and diffuse light:

$$DIR_{SPN1} = (SW_G - SW_{Diff}) \cdot 0.99 \quad (8)$$

$$DIF_{SPN1} = SW_{Diff} \cdot 1.14 \quad (9)$$

$$G_{SPN1} = DIR_{SPN1} + DIF_{SPN1} \quad (10)$$

Where,

MAX	= largest thermopile reading of the seven thermopiles, adjusted for any calibration factors
MIN	= smallest thermopile reading of the seven thermopiles, adjusted for any calibration factors
SW_{Diff}	= uncorrected diffuse SW radiation measured by SPN1
SW_G	= uncorrected total SW radiation measured by SPN1
DIF_{SPN1}	= corrected diffuse SW radiation output from SPN1
DIR_{SPN1}	= direct horizontal SW radiation calculated from SPN1 outputs
G_{SPN1}	= corrected global SW radiation output from SPN1

Sunshine presence is then calculated using the ratio of Global and Diffuse, and is registered (set equal to 1) when the following criteria are met:

$$\textbf{IF } (G_{SPN1}/DIF_{SPN1}) > 1.35 \quad \textbf{AND} \quad G_{SPN1} > 24\, W\, m^{-2} \quad (11)$$

Otherwise, sunshine presence equals 0.

The 24 W m^{-2} threshold is used to acknowledge instances when direct horizontal sunshine is weak as a result of low sun angle, but the GLOBAL/DIFFUSE value may be high due to noise or offsets dominating the low reading values (Delta-t Devices Ltd. 2007). Sun presence undergoes no further calibrations or algorithmic processing prior to becoming an L1 DP.

4.2 Theory of Algorithm

Following internal sensor processing, values of global and diffuse irradiance measurements are exported in units of W m^{-2} and are further processed using the following equations:

$$DIF_i = DIF_{SPN1_i} * C_{d1} \quad (12)$$

$$G_i = G_{SPN1_i} * C_{t1} \quad (13)$$

Direct beam radiation is a function of global and diffuse radiation, as well as the zenith angle of the sun. NEON will follow the algorithms provided by MACC (2013) to quantify direct beam radiation:
CASE 1: IF $z_i < th\_1$:

$$DIR_i = \frac{G_i - DIF_i}{\cos(z_i)} \tag{14}$$

CASE 2: IF $th\_1 \leq z_i \leq 90°$:

$$DIR_i = (G_i - DIF_i) * \cos(th\_1) \tag{15}$$

CASE 3: IF $z_i > 90°$:

$$DIR_i = 0 \tag{16}$$

Where,

DIF_{SPN1_i}	=Individual (1 Hz) diffuse shortwave radiation (W m^{-2}); SPN1 output
DIF_i	=Individual calibrated diffuse shortwave radiation (W m^{-2})
DIR_i	=Individual direct beam shortwave radiation (W m^{-2})
C_{d1}	=Diffuse Radiation Scaling coefficient provided by CVAL
G_{SPN1_i}	=Global shortwave radiation measurement (W m^{-2}); SPN1 output
G_i	=Calibrated global shortwave radiation measurement (W m^{-2})
C_{t1}	=Global Radiation scaling coefficient provided by CVAL
th_1	=zenith angle threshold: 1.536 (radians)

Zenith angle is derived following the Michalsky (1988) approach for computing solar position. Because the majority of programming languages assume that trigonometric arguments are given in radians, Michalsky's formulas are modified to convert degrees to radians as necessary.

$$z_i = \cos^{-1}(\sin\emptyset \cdot \sin(\delta_i) + \cos\emptyset \cdot \cos(\delta_i) \cdot \cos(HA_i)) \tag{17}$$

Note that $\emptyset$ is given in radians, not degrees.

$$\delta_i = \sin^{-1}(\sin(\varepsilon_i) \cdot \sin(l_i)) \tag{18}$$

$$HA_i = \begin{cases} LMST_i - \alpha_i & \text{if } -\pi \leq LMST_i - \alpha_i \leq \pi \\ LMST_i - \alpha_i + 2\pi & \text{if } LMST_i - \alpha_i < -\pi \\ LMST_i - \alpha_i - 2\pi & \text{if } LMST_i - \alpha_i > \pi \end{cases} \tag{19}$$

$$LMST_i = \{[(GMST_i + L/15) \bmod 24] \cdot 15\} \cdot \frac{\pi}{180} \tag{20}$$

$$GMST_i = (6.697375 + 0.0657098242 \cdot JD_i + GMT_i) \bmod 24 \tag{21}$$

The right ascension is assigned to an angle between 0 and 2π radians. To accomplish this, a correction is made to the result of the inverse tangent function to account for its range of $\left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$:

$$\alpha_i = \begin{cases} \frac{\pi}{2} & x = 0, y > 0 \\ \frac{3\pi}{2} & x = 0, y < 0 \\ \left\{\left[\tan^{-1}\left(\cos(\varepsilon_i) \cdot \frac{y}{x}\right)\right] + 2\pi\right\} \bmod 2\pi & x > 0 \\ \left[\left(\tan^{-1}\left(\cos(\varepsilon_i) \cdot \frac{y}{x}\right)\right) + \pi\right] & x < 0 \end{cases} \tag{22}$$

Where,

$$x = \cos(l_i) \text{ and } y = \sin(l_i)$$

$$\varepsilon_i = (23.439 - 4 \cdot 10^{-7} \cdot JD_i) \cdot \frac{\pi}{180} \tag{23}$$

$$l_i = [(ML_i + 1.915 \cdot \sin(g_i) + 0.020 \cdot \sin(2 \cdot g_i)) \bmod 360] \cdot \frac{\pi}{180} \tag{24}$$

$$g_i = [(357.528 + 0.9856003 \cdot JD_i) \bmod 360] \cdot \frac{\pi}{180} \tag{25}$$

$$ML_i = (280.460 + 0.9856474 \cdot JD_i) \bmod 360 \tag{26}$$

$$JD_i = jd_i - 2{,}451{,}545 \tag{27}$$

$$jd_i = 2{,}432{,}916.5 + \big((Y_i - 1949) \cdot 365\big) + \mathrm{INT}\big((Y_i - 1949)/4\big) + d_i + (GMT_i/24) \qquad (28)$$

where GMT_i is the local hour and fraction thereof converted to the corresponding UTC hour, taking into consideration the day and year (e.g., local hours + minute/60 + number of hours from Greenwich). Note that $-12 \leq GMT_i < 36$ so that no further corrections need be made to the local year (Y_i) or day of the year (d_i).

z_i	= Zenith angle of the Sun (radians)
$\emptyset$	= Sensor's latitude stored in the CI data store (radians)
δ_i	= Solar declination (radians)
HA_i	= Hour angle (radians)
ε_i	= Obliquity of the ecliptic (Earth's tilt; radians)
L	= Sensor's longitude ($0 \leq L \leq 360$ degrees)
ML_i	= Mean Longitude ($0 \leq ML_i \leq 360$ degrees)
α_i	= Right Ascension (radians)
GMT_i	= Greenwich mean hour, including fractions thereof (unitless)
$GMST_i$	= Greenwich mean sidereal time ($0 \leq GMST_i \leq 24$; unitless)
$LMST_i$	= Local Sidereal time (radians)
JD_i	= Difference in date between current Julian Date and January 1st 2000, at 12 hours GMT; unitless)
l_i	= Ecliptic longitude (radians)
g_i	= Mean anomaly (radians)
Y_i	= Local year (unitless)
jd_i	= Current Julian Date (unitless)
d_i	= Local day of year (unitless)
$\mathrm{INT}(\cdot)$	= Integer portion of the argument

After the L0 DPs are corrected using scaling coefficients provided by CVAL, one- and thirty-minute global, diffuse, and direct normal radiation averages will be determined according to Eq. (29) and (30) to create the L1 DPs listed in file dds_datapub_NEONDOC002870.txt. Here we let 'X' represent both global, diffuse, and direct normal irradiance since they will be averaged the same way to create L1 DPs.

$$\bar{X}_1 = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad (29)$$

where, for each 1-minute average, n is the number of measurements during the averaging period and X_i is a 1-Hz radiation measurement taken during the 60-second averaging period [0, 60). For a 1-minute average, n = 60 if all data points are included.

Similarly,

$$\bar{X}_{30} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad (30)$$

where, for each 30-minute average, n is the number of measurements during the averaging period and X_i is a 1-Hz radiation measurement taken during the 1800-second averaging period [0, 1800).

One- and thirty-minute sun presence (S) will be calculated as follows:

If the SPN1 reports sun presence (i.e. Boolean value of 1) for ≥75% of the readings in a one minute period (i.e., ≥45 readings) S_1 will be recorded as present for that one minute period.

If the SPN1 reports sun presence (i.e. Boolean value of 1) for ≥75% of the readings in a thirty-minute period (i.e., ≥1350 readings) S_{30} will be recorded as present for that thirty minute period.

Note: The beginning of the first averaging period in a series shall be the nearest whole minute less than or equal to the first timestamp in the series.

5 ALGORITHM IMPLEMENTATION

Data flow for signal processing of L1 DPs shall be treated in the following way.

1. 1 Hz sensor outputs (W m^{-2}) shall be calibrated using NEON derived scaling coefficients provided by CVAL (Eq. (12) and (13))
2. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[06], details are provided below.
3. One- and thirty-minute global and diffuse averages will be calculated using Eq. (29) through (30). Sun presence for one- and thirty-minute periods will be calculated as described in section 4.2.
4. Descriptive statistics, i.e., minimum, maximum, and variance, will be determined for both one- and thirty-minute averages.
   Quality metrics, quality flags, and the final quality flag will be produced for one- and thirty-minute averages according to AD[16].

<u>**QA/QC Procedure**</u>:

1. **Plausibility Tests** AD[06] – All plausibility tests will be determined for global and diffuse radiation. Test parameters will be provided by FIU and maintained in the CI data store. All plausibility tests will be applied to the sensor's converted L0 DPs and associated quality flags (QFs) will be generated for each test.

2. **Sensor -** Delta-T Devices SPN1 Sunshine Pyranometer has no associated devices or sensor health related flags.

3. **Directional response flag [QF_Z]-** *Direct normal radiation* data will be flagged when:

$$z_i \geq 1.48$$

The Monitoring Atmospheric Composition and Climate group (2013) notes that the calculation of direct normal irradiance becomes somewhat unreliable when the Sun is close to the horizon (MACC 2013). As such, NEON is adopting their proposed zenith angle threshold of 1.48 to notify end-users of potentially unreliable direct normal irradiance data.

4. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[16]
If a datum has failed one of the following tests it will not be used to create a L1 DP, ***range, persistence***, and ***step.*** *The persistence test is only applied during local, daylight hours.* α and β QFs and QMs will be determined using the flags listed in Table 5-1. In addition, L1 DPs will have a QA/QC report and quality metrics associated with each flag listed in Table 5-1 as well as a final quality flag, as detailed in AD[16]. Ancillary information needed for the algorithm and other information maintained in the CI data store is shown in Table 5-2.

Table 5-1: Flags associated with the SPN1 pyranometer.

Tests
Range
Persistence
Step
Null
Gap
Sensor Test AD[09]
Final quality flag

Table 5-2: Information maintained in the CI data store for the SPN1 pyranometer.

Tests/Values	CI Data Store Contents
Range	Minimum and maximum values
Persistence	Window size, threshold values and maximum time length
Step	Threshold values
Null	Test limit
Gap	Test limit
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[13]
Final Quality Flag	AD[16]

6 UNCERTAINTY

Uncertainty of measurement is inevitable; therefore, measurements should be accompanied by a statement of their uncertainty for completeness (JCGM 2008; Taylor 1997). To do so, it is imperative to identify all sources of measurement uncertainty related to the quantity being measured. Quantifying the uncertainty of TIS measurements will provide a measure of the reliability and applicability of individual measurements and TIS data products. This portion of the document serves to identify, evaluate, and quantify sources of uncertainty relating to individual, calibrated radiation measurements as well as L1 mean radiation data products. It is a reflection of the information described in AD[11], and is explicitly described for the radiation assembly in the following sections.

6.1 Uncertainty of Incoming Solar Radiation Measurements

Uncertainty of the global and diffuse pyranometer assembly is discussed in this section. Discussion is broken down into two topics informing the discrepancy between the two types of uncertainty presented within this document. The first subsection details the sources of *measurement* uncertainty, i.e., those associated with *individual measurements*. The second discusses uncertainties associated with temporally averaged data products. A diagram detailing the data flow and known sources of uncertainty is displayed in Figure 2.

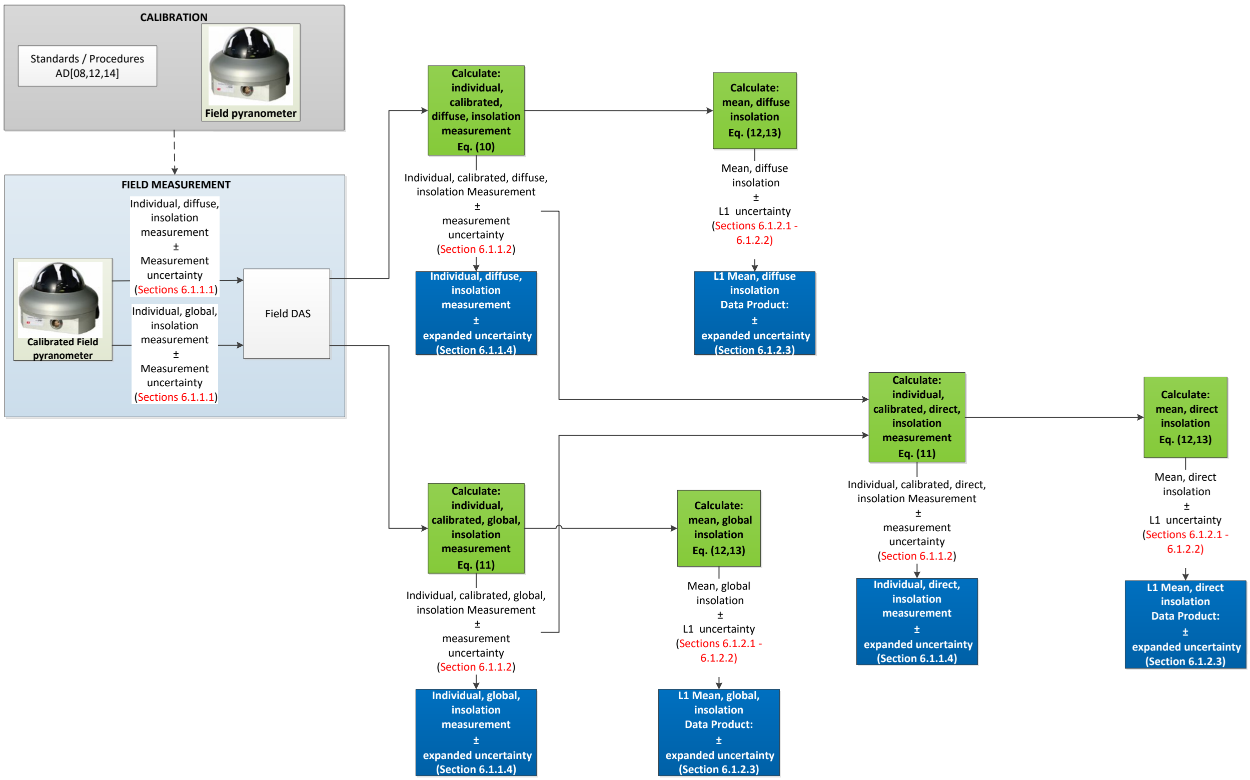

Figure 2: Displays the data flow and associated uncertainties of individual irradiance measurements and L1 irradiance DPs. For more information regarding the methods by which the pyranometer is calibrated, please refer to AD[08,12,14].

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with *individual observations*. It is important to note that the uncertainties presented in the following subsections are *measurement uncertainties*, that is, they reflect the uncertainty of an *individual* measurement. These uncertainties should not be confused with those presented in Section 6.1.2. We urge the reader to refer to AD[11] for further details concerning the discrepancies between quantification of measurement uncertainties and L1 uncertainties.

NEON calculates measurement uncertainties according to recommendations of the Joint Committee for Guides in Metrology (JCGM) 2008. In essence, if a measurand *y* is a function of *n* input quantities

$x_i\ (i = 1, \dots, n),\ i.e., y = f(x_1, x_2, \dots, x_n)$, the combined measurement uncertainty of *y*, assuming the inputs are independent, can be calculated as follows:

$$u_c(y) = \left(\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)\right)^{\frac{1}{2}} \tag{31}$$

where

$\frac{\partial f}{\partial x_i}$ = partial derivative of *y* with respect to x_i

$u(x_i)$ = combined standard uncertainty of x_i.

Thus, the uncertainty of the measurand can be found by summing the input uncertainties in quadrature. The calculation of these input uncertainties is discussed below.

6.1.1.1 Calibration:

Uncertainties associated with the calibration process of global and diffuse irradiance propagate into two separate, combined, standard measurement uncertainties. These uncertainties, $u_{A1,DIF}$ and $u_{A1,TOT}$ represent i) the repeatability and reproducibility of the sensor and the lab DAS and ii) uncertainty of the calibration procedures and coefficients including uncertainty in the standard (truth) (refer to Eq. (1)). Both are relative values that will be provided by CVAL (AD[13]), stored in the CI data store and, after converting to measurement units, applied to all individual *global and diffuse* irradiance measurements (that is, they do not vary with any specific sensor, DAS component, etc.). A detailed summary of the calibration procedures and corresponding uncertainty estimates can be found in AD[09,10,13].

The standard measurement uncertainty is calculated as follows:

$$u_{CVAL}(X_i) = u_{A1,X} \cdot X_i. \tag{32}$$

Note: $u_{A1,X}$ is used in the following sections to represent $u_{A1,DIF}$ and $u_{A1,G}$, while $u_{CVAL}(X_i)$ is used to represent $u_{CVAL}(DIF_i)$ and $u_{CVAL}(G_i)$. A calibration uncertainty is not provided for *direct* irradiance measurements, as they are a derived function of global and diffuse irradiance (See Section 6.2)

6.1.1.2 Accuracy (Zenith Angle)

Michalsky (1988) states that his formula for calculating the zenith angle of the sun is accurate to 0.01^{o} through year 2050. Thus, we will assume the following uncertainty for the calculated zenith angle of the sun:

$$u(z_i) = 0.01^0 = 0.0001745 \text{ rad} \tag{33}$$

6.1.1.3 DAS

SPN1 pyranometers have an internal Analog to Digital (A/D) converter and output data in digital form. Thus, uncertainty related to measurement noise of the field DAS can be considered negligible. Please refer to AD[11] for further information.

6.1.1.4 Heater

The SPN1 pyranometer is equipped with an internal heater to prevent frost and condensation buildup. The heater is automatically controlled and operates (powered) as a function of ambient temperature (Delta-T Devices 2007). Although use of the heater improves measurement accuracy by preventing moisture buildup, it affects the variability of the measurement, thus adding uncertainty to the measurement. At this time we cannot quantify the extent of this variability and related uncertainties because there is no way of determining when the heater is actually on or off. Thus, even with sufficient operational experience, uncertainties introduced by the heater will most likely remain unquantifiable.

6.1.1.5 Combined Uncertainty

Global and diffuse irradiance:
The sole measurement uncertainties for *global* and *diffuse* irradiance measurements, are simply, $u_{CVAL}(G_i)$ and $u_{CVAL}(DIF_i)$, respectively.

Direct normal irradiance:
The calculation of direct normal irradiance is a function of global and diffuse radiation, as well as the sun's zenith angle. As a result, the following equations must be derived to calculate the combined uncertainty of *direct irradiance*.

$$\frac{\partial DIR_i}{\partial G_i} = \frac{1}{\cos{(z_i)}} \tag{34}$$

$$u_{TOT}(DIR_i) = \left|\frac{\partial DIR_i}{\partial G_i}\right| u_{CVAL}(G_i) \tag{35}$$

$$\frac{\partial DIR_i}{\partial DIF_i} = \frac{-1}{\cos{(z_i)}} \tag{36}$$

$$u_{DIF}(DIR_i) = \left|\frac{\partial DIR_i}{\partial DIF_i}\right| u_{CVAL}(DIF_i) \tag{37}$$

$$\frac{\partial DIR_i}{\partial z_i} = (G_i - G_i) \cdot \tan(z_i) \cdot \sec{(z_i)} \tag{38}$$

$$u_z(DIR_i) = \left|\frac{\partial DIR_i}{\partial z_i}\right| u(z_i) \tag{39}$$

Where,

$\frac{\partial DIR_i}{\partial G_i}$ = partial derivative of Eq. (14) with respect to *global* irradiance (unitless)

$u_G(DIR_i)$ = partial uncertainty of direct normal irradiance as a function of global irradiance (W m^{-2})

$\frac{\partial DIR_i}{\partial DIF_i}$ = partial derivative of Eq. (14) with respect to *diffuse* irradiance (unitless)

$u_{DIF}(DIR_i)$ = partial uncertainty of direct normal irradiance as a function of diffuse irradiance (W m^{-2})

$\frac{\partial DIR_i}{\partial z_i}$ = partial derivative of Eq. (14) with respect to zenith angle (unitless)

$u(z_i)$ = uncertainty of zenith angle (radians)

$u_z(DIR_i)$ = partial uncertainty of direct normal irradiance as a function of zenith angle (W m^{-2})

The combined uncertainty is then:

$$u_c(DIR_i) = \left(u_G^2(DIR_i) + u_{DIF}^2(DIR_i) + u_z^2(DIR_i)\right)^{\frac{1}{2}} \tag{40}$$

Note: Here, the derivation of direct normal irradiance uncertainty for CASE 1 is also used to represent direct normal irradiance for CASE 2 (see Section 4.2).

6.1.1.6 Expanded Uncertainty

The expanded measurement uncertainties are respectively calculated as:

$$U_{95}(Y_i) = k_{95} * u_c(Y_i) \tag{41}$$

Where,

$U_{95}(Y_i)$ = respective expanded measurement uncertainty at 95% confidence (W m^{-2})

k_{95} = 2 (unitless); coverage factor for 95% confidence

6.1.2 Uncertainty of L1 Mean Data Product

The following subsections discuss uncertainties associated with temporally averaged, i.e., L1 mean, data products. As stated previously, it is important to note the differences between the *measurement uncertainties* presented in Section 6.1.1 and the uncertainties presented in the following subsections. The uncertainties presented in the following subsections reflect the uncertainty of a time-averaged mean value, that is, they reflect the uncertainty of a distribution of measurements collected under non-controlled conditions (i.e., those found in the field), as well as any uncertainties, in the form of *Truth* and *Trueness*, related to the accuracy of the field assembly.

6.1.2.1 Repeatability (natural variation)

To determine the validity of the L1 mean irradiance DP, its uncertainty must be calculated. The distribution of the individual measurements is used as a metric to quantify this uncertainty. Specifically, the *estimated standard error of the mean (natural variation)* is computed. This value reflects the repeatability of irradiance measurements for a specified time period:

$$u_{NAT}(\bar{X}) = \frac{s(X_i)}{\sqrt{n}} \tag{42}$$

Where,

$u_{NAT}(\bar{X})$ = standard error of the mean (natural variation) for *global, diffuse, or direct* irradiance (W m^{-2})

$s(X_i)$ = experimental standard deviation of individual observations (i.e., *global, diffuse, or direct* irradiance) for the defined time period (W m^{-2})

n = number of *global, diffuse, or direct* irradiance observations made during the defined time period. (unitless)

6.1.2.2 Calibration

The uncertainties detailed here are similar to that described in Section 6.1.1.1. However, these combined, relative uncertainties, $u_{A3,DIF}$ and $u_{A3,G}$ do not account for i) individual sensor repeatability, or ii) the variation of sensors' responses over a population (reproducibility). These components of uncertainty estimate uncertainty due to the accuracy of the instrumentation in the form of *Truth* and *Trueness*, a quantity which is not captured by the standard error of the mean. They are relative values that will be provided by CVAL (AD[13]) and stored in the CI data store. After converting to measurement units, the uncertainty will be calculated using the *maximum* irradiance value observed during the averaging period.

$$u_{CVAL(TT)}(\bar{X}) = u_{A3,X} * X_{MAX} \tag{43}$$

Where, the subscript "MAX" represents the index, i, where the *maximum*, combined, standard, measurement uncertainty of an individual irradiance measurement is observed over a set (averaging period) of observations. Mathematically, this can be defined as:

$$MAX = \{i: u_c(X_i) = \max[u_c(X_1), \dots, u_c(X_n)]\}. \tag{44}$$

And,

$u_{CVAL(TT)}(\bar{X})$	= combined, standard *Truth* and *Trueness* uncertainty due to the sensor calibration process (*diffuse or global* irradiance; W m^{-2}) and zenith angle (radians)
X_{MAX}	= Irradiance (W m^{-2}) or zenith angle (radians) observed at MAX index
$u_{A3,X}$	= Combined, relative uncertainty (*Truth* and *Trueness* only) of *diffuse or global* irradiance (%) provided by CVAL

Please refer to AD[11] for further justification regarding evaluation and quantification of using the maximum index for quantification of these L1 mean data product uncertainties.

Note: $u_{CVAL(TT)}(\bar{X})$ is used in the following sections to represent $u_{CVAL(TT)}(\overline{DIF})$, and $u_{CVAL(TT)}(\bar{G})$.

Because the zenith angle is calculated using equations that vary only with respect to time at a given location, the uncertainty associated with this calculation propagates in its entirety to the L1 mean DPs.

A calibration uncertainty is not provided for *direct* irradiance measurements, as they are a derived function of global and diffuse irradiance (See Section 6.2)

6.1.2.3 Combined Uncertainty

Global and diffuse irradiance:

The combined uncertainty for our L1 mean irradiance data product, $u_c(\bar{\mathrm{X}})$, given in units W m^{-2}, is computed by summing the uncertainties from Sections 6.1.2.1 through 6.1.2.3 in quadrature:

$$u_c(\bar{\mathrm{X}}) = \left(u_{NAT}^2(\bar{X}) + u_{CVAL(TT)}^2(\bar{X})\right)^{\frac{1}{2}} \tag{45}$$

Direct irradiance:

The calculation of direct irradiance is a function of global and diffuse radiation, as well as the Sun's zenith angle. As a result, Eq. (34) - (39) are used to calculate the combined uncertainty of L1 mean, direct irradiance DPs. However, since we only wish to quantify the uncertainty associated with truth and trueness, $u_{CVAL}(G)$ and $u_{CVAL}(DIF)$ terms must be replaced with $u_{CVAL(TT)}(\bar{G})$ and $u_{CVAL(TT)}(\overline{DIF})$ terms. For brevity, only the propagating terms are displayed.

$$u_{TOT(TT)}(\overline{DIR}) \equiv \left|\frac{\partial DIR}{\partial G}\right|_{G_{MAX}} \cdot u_{CVAL(TT)}(\bar{G}) \tag{46}$$

$$u_{DIF(TT)}(\overline{DIR}) \equiv \left|\frac{\partial DIR}{\partial DIF}\right|_{DIF_{MAX}} \cdot u_{CVAL(TT)}(\overline{DIF}) \tag{47}$$

$$u_z(\overline{DIR}) \equiv \left|\frac{\partial DIR}{\partial z}\right|_{z_{MAX}} \cdot u(z) \tag{48}$$

Where,

$\left|\frac{\partial DIR}{\partial G}\right|_{G_{MAX}}$ = partial derivative of DIR with respect to G evaluated at G_{MAX} (radians)

$u_{TOT(TT)}(\overline{DIR})$ = *Truth* and *Trueness* uncertainty of the L1, mean, direct irradiance DP as a function of truth and trueness of *global* irradiance (W m^{-2})

$\left|\frac{\partial DIR}{\partial DIF}\right|_{DIF_{MAX}}$ = partial derivative of DIR with respect to DIF evaluated at DIF_{MAX} (radians)

$u_{DIF(TT)}(\overline{DIR})$ = *Truth* and *Trueness* uncertainty of the L1, mean, direct irradiance DP as a function of truth and trueness of *diffuse* irradiance (W m^{-2})

$\left|\frac{\partial DIR}{\partial z}\right|_{z_{MAX}}$ = partial derivative of DIR with respect to z evaluated at z_{MAX} (radians)

$u_z(\overline{DIR})$ = Uncertainty of the L1, mean, direct irradiance DP as a function of *zenith angle* (W m^{-2})

The combined uncertainty for the L1, mean, direct irradiance DP is:

$$u_c(\overline{DIR}) = \left(u_{NAT}^2(\overline{DIR}) + u_{G(TT)}^2(\overline{DIR}) + u_{DIF(TT)}^2(\overline{DIR}) + u_z^2(\overline{DIR})\right)^{\frac{1}{2}} \tag{49}$$

6.1.2.4 Expanded Uncertainty

The expanded measurement uncertainties are respectively calculated as:

$$U_{95}(\bar{Y}) = k_{95} * u_c(\bar{Y}) \tag{50}$$

Where,

$U_{95}(\bar{Y})$ = respective expanded uncertainty at 95% confidence (W m^{-2})

k_{95} = 2 (unitless); coverage factor for 95% confidence

6.1.2.5 Communicated Precision

L1 average global, direct, and diffuse radiation data products will be reported to 0.1 W m^{-2}. The resolution of the SPN1 Sunshine Pyranometer is 0.6 W m^{-2}. Lab-measured repeatability of the global and diffuse radiation components are on the order of 0.71% and 1.47%, respectively.

6.2 Uncertainty Budget

The uncertainty budget is a visual aid detailing i) quantifiable sources of uncertainty, ii) means by which they are derived, and iii) the order of their propagation. Uncertainty values denoted in this budget are either derived within this document or are provided by other NEON teams (e.g., CVAL), and stored in the CI data store.

Table 6-1: Uncertainty budget for an individual irradiance measurement. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of measurement uncertainty	Measurement uncertainty component $u(x_i)$	Measurement uncertainty value $[W\ m^{-2}]$	$\frac{\partial f}{\partial x_i}$	$u_i(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ $[W\ m^{-2}]$
1 Hz dif. irradiance	$u_{CVAL}(DIF_i)$	Eq. (32)	n/a	n/a
1 Hz glob. irradiance	$u_{CVAL}(G_i)$	Eq. (32)	n/a	n/a
1 Hz dir. irradiance	$u_c(DIR_i)$	Eq. (40)	n/a	n/a
1 Hz glob. irradiance	$u_G(DIR_i)$	$u_{CVAL}(G_i)$	Eq. (34)	Eq. (35)
1 Hz dif. irradiance	$u_{DIF}(DIR_i)$	$u_{CVAL}(DIF_i)$	Eq. (36)	Eq. (37)

1 Hz zenith angle	$u_z(DIR_i)$	$u_c(z_i)$ (radians)	Eq. (38)	Eq. (39)

Table 6-2: Uncertainty budget for L1 mean irradiance measurements. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of uncertainty	**Uncertainty component** $\boldsymbol{u(x_i)}$	**Uncertainty value** $[\boldsymbol{W\ m^{-2}}]$	$\boldsymbol{\frac{\partial f}{\partial x_i}}$	$\boldsymbol{u_i(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)}$ $[\boldsymbol{W\ m^{-2}}]$
L1 dif. irradiance	$u_c(\overline{DIF})$	Eq. (45)	n/a	n/a
Natural variation	$u_{NAT}(\overline{DIF})$	Eq. (42)	1	Eq. (42)
Sensor/calibration	$u_{CVAL(TT)}(\overline{DIF})$	Eq. (43)	1	Eq. (43)
L1 glob. irradiance	$u_c(\bar{G})$	Eq. (45)	n/a	n/a
Natural variation	$u_{NAT}(\bar{G})$	Eq. (42)	1	Eq. (42)
Sensor/calibration	$u_{CVAL(TT)}(\bar{G})$	Eq. (43)	1	Eq. (43)
L1 dir. irradiance	$u_c(\overline{DIR})$	Eq. (49)	n/a	n/a
Natural variation	$u_{NAT}(\overline{DIR})$	Eq. (42)	1	Eq. (42)
tot. irradiance (TT)	$u_{G(TT)}(\overline{DIR})$	Eq. (43)	Eq. (34)	Eq. (46)
dif. Irradiance (TT)	$u_{DIF(TT)}(\overline{DIR})$	Eq. (43)	Eq. (36)	Eq. (47)
Zenith angle	$u_z(\overline{DIR})$	Eq. (43) (radians)	Eq. (38)	Eq. (48)

7 FUTURE PLANS AND MODIFICATIONS

Details concerning the evaluation and quantification of Sensor and Field DAS drift may be added to the uncertainty section of this ATBD

QA/QC tests may be expanded to include consistency analyses among similar measurement streams.

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