ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD) - PRIMARY PYRANOMETER

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Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	08/28/2013	ECO-00979	Initial Release
B	10/23/2015	ECO-03110	Added revised L0 and L1 data product numbers Revised *Algorithm Implementation*, *Uncertainty*, and *Future Plans/ Modifications* sections. Implemented standardized coverage factor of k=2 Moved consistency analyses outline to Future Plans / Modifications Sections

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1 DESCRIPTION

1.1 Purpose

This document details the algorithms used for creating NEON L1 DP from L0 DP for tower-based measurements of incoming short wave (ISW) radiation, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by the pyranometer. 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 primary pyranometer are described in this document. It is expected that the primary pyranometer employed at all NEON core tower sites to measure SW radiation is the Kipp and Zonen CMP22. In addition, the Kipp and Zonen CV3 ventilation unit will accompany the CMP22 at all NEON sites. 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 NOMENCLATURE

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.002652	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.005005	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 QA/QC Time Series Signal De-spiking for TIS Level 1 Data Products
AD[08]	NEON.DOC.000800	CMP22 – Primary Pyranometer Calibration/Validation Procedure
AD[09]	NEON.DOC.000549	C^3 Primary Pyranometer
AD[10]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[11]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[12]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values[1]
AD[13]	NEON.DOC.002002	Engineering Master Location Sensor Matrix
AD[14]	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
FDAS	Field Data Acquisition System
GRAPE	Grouped Remote Analog Peripheral Equipment
ISW	Incoming Shortwave (i.e. Solar Radiation)
L0	Level 0
L1	Level 1
LW	Longwave (i.e. Far Infra-red Radiation)

[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.

PRT	Platinum Resistance Thermometer
SW	Shortwave (i.e. Solar Radiation)

2.4 Variable Nomenclature

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 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_1	CVALA1	CVAL calibration coefficient
u_{A1}	U_CVALA1	Combined, relative uncertainty of pyranometer (%)
u_{A3}	U_CVALA3	Combined, relative uncertainty (truth and trueness only) of pyranometer (%)
u_{V1}	U_CVALV1	Combined, relative uncertainty of Field DAS voltage measurements (%)
u_{V3}	U_CVALV3	Combined, relative uncertainty (truth and trueness only) of Field DAS voltage measurements (%)

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

Shortwave (SW) radiation-related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file psr_datapub_NEONDOC002882.txt.

3.2 Input Dependencies

Table 3-1 details the SW radiation-related L0 DPs used to produce L1 DPs in this ATBD.

Table 3-1: SW radiation-related L0 DPs that are used to produce L1 DPs via this ATBD.

Description	Sample Frequency	Units	Data Product Number
Pyranometer (P)	1 Hz	*V*	NEON.DOM.SITE.DP0.00022.001.01324.HOR.VER.000
Sensor Body Temperature	1 Hz	*Ω*	NEON.DOM.SITE.DP0.00022.001.01325.HOR.VER.000
Fan Tachometer Speed	1 Hz	*rpm*	NEON.DOM.SITE.DP0.00022.001.01326.HOR.VER.000
Heater Flag (QF_H1)	State Change	*NA*	NEON.DOM.SITE.DP0.00022.001.01327.HOR.VER.000
Heater Flag (QF_H2)	State Change	*NA*	NEON.DOM.SITE.DP0.00022.001.01328.HOR.VER.000

3.3 Product Instances

One primary pyranometer will be deployed at core tower sites only, see AD[13] for specific details.

3.4 Temporal Resolution and Extent

One- and thirty-minute averages of incoming SW radiation will be calculated to form L1 DPs.

3.5 Spatial Resolution and Extent

The primary pyranometer will be located at the top level at all core tower sites. Thus, observations reflect the point in space where pyranometer is affixed to the tower infrastructure, see AD[13] for specific details.

4 SCIENTIFIC CONTEXT

The sun's energy is emitted to the earth mainly in the form of incoming short wave (SW) radiation, with a small portion it falling LW radiation wavelengths. Pyranometers serve to quantify SW radiation and in turn provide a foundation for investigations of the Earth's climate. Incoming SW radiation, which is composed primarily of ultraviolet, visible, and a portion of infra-red wavelengths, is the primary driver for the Earth's climate. As such, the observations of incoming shortwave radiation are of great interest to the scientific and broader community in assessing the Earth's energy budget.

4.1 Theory of Measurement

The Kipp and Zonen CMP22 pyranometer is a passive sensor that uses a thermopile to detect incoming SW radiation flux (λ 200 to 3600 nm). The Kipp and Zonen CV3 ventilation unit will also be installed on each pyranometer, and includes both a fan and two five watt heaters. The ventilation unit will help to prevent temperature differentials and the buildup of precipitation (i.e., dew, frost, ice, etc.). The fan will always be operational, while the heaters will be activated based on the sensor body temperature according to AD[09].

The thermopile's surface is coated with a non-spectrally selective black paint that absorbs SW radiation. The sensing element for the thermopile is composed of numerous thermocouple junction pairs that are connected electrically in series. As the sensor absorbs SW radiation, active or 'hot' thermocouple junctions increase in temperature. The temperature differential between an active junction and a reference or 'cold' junction (i.e., kept at a fixed temperature) produces an electromotive force. This electromotive force is directly proportional to the temperature differential; known as a thermoelectric effect. Thus, the temperature difference across the thermal resistance of the detector (i.e., thermopile) is converted into a voltage that is a linear function of the absorbed solar irradiance. Since the physical properties of each thermopile and sensor will vary slightly, so will the sensitivity of each pyranometer. Therefore, for each pyranometer, even for the same model, it is necessary to determine unique sensor specific sensitivity calibration factors. Details on how these sensitivity calibration factors were determined can be found in AD[08].

4.2 Theory of Algorithm

4.2.1 Kipp and Zonen CMP22 Pyranometer and CV3 ventilation unit

An internal PRT 100 in the CMP22 will be used to control of the heater in the CV3 ventilation unit as described in AD[09]. The PRT signal must be converted from resistance to degrees Celsius prior to being used for heater control. The PRT signal will be converted to degrees Celsius according to Kipp and Zonen's specifications (Kipp and Zonen, 2010):

$$T = \frac{-\alpha\sqrt{\alpha^2 - 4\beta * \left(\frac{-R}{100} + 1\right)}}{2\beta} \qquad (1)$$

Where,

T = PRT 100 temperature (°C)
α = 3.9083*10^{-3}
β = -5.8019*10^{-7}
R = PRT 100 resistance (Ω)

4.2.2 Short-wave Radiation Measurement

The thermopile output from the pyranometer is converted from (V) to (W m^{-2}) as a function of sensor specific sensitivities; these will be determined by CVAL according to AD[08]. Using the sensor specific sensitivity and the output from the thermopile, incoming SW radiation is determined:

$$ISW_i = P_i * C_1 \qquad (2)$$

where,

ISW_i = Individual (1 Hz) incoming Short Wave Radiation (W m^{-2})
P_i = Individual pyranometer output (V)
C_1 = Pyranometer sensor specific sensitivity (W m^{-2} V^{-1}); provided by CVAL

After incoming SW radiation is determined and the QA/QC procedures explained in Section 5 have been implemented, one-minute and thirty-minute averages will be determined according to Eq. (3) and (4) to create the L1 DPs listed in the file psr_datapub_NEONDOC002882.txt. Individual calibrated measurements, i.e., 1 Hz incoming shortwave radiation, will be made available upon request.

$$\overline{ISW_1} = \frac{1}{n}\sum_{i=1}^{n} ISW_i \qquad (3)$$

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

Similarly,

$$\overline{ISW_{30}} = \frac{1}{n}\sum_{i=1}^{n} ISW_i \qquad (4)$$

where, for each 30-minute average, n is the number of measurements during the averaging period and ISW_i is a 1-Hz measurement taken during the 1800-second averaging period [0, 1800). 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 will be treated in the following order.

1. SW radiation will be determined from the L0 DPs through Eq. (2).
2. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[06], details are provided below.
3. Signal de-spiking will be applied to the data stream in accordance with AD[07].
4. One- and thirty-minute incoming shortwave radiation averages will be calculated using Eq. (3) and (4).
5. Descriptive statistics, i.e., minimum, maximum, and variance, will be determined for both averaging periods.
6. Quality metrics, quality flags, and the final quality flag will be produced for one- and thirty-minute averages according to AD[14].

QA/QC Procedure:

1. **Plausibility Tests** AD[08] -- All plausibility tests will be determined for the primary pyranometer. Test parameters will be provided by FIU and maintained in the (Cyberinfrastructure) 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 Test** – The two five watt heaters in the CV3 venation unit are operated according to the C^3 document, AD[09]. When the heaters are operational, flags will be set and applied to the L0 DPs. Due to the nature of SW radiation, the heaters should theoretically only induce minimal variability in measurements, which is further discussed in Section 6.1.3. Flags from the heaters may be used to enhance uncertainty estimates and to provide ancillary information that may be useful for troubleshooting. Here, both L0 heater flags will be lumped into a single quality flag which will collectively inform if at least one heater was active when data were observed. The heater flag will be combined with the other quality flags to form the L1 QA/QC summary.

3. **Signal Despiking** – The time series despiking routine will be run according to AD[07]. Test parameters will be specified by FIU and maintained in the CI data store. Quality flags resulting from the despiking analysis will be applied according to AD[07].

Quality Flags (QFs) and Quality Metrics (QMs) AD[14] – If a datum has failed one of the following flags it will not be used to create a L1 DP, ***range***, ***persistence***, and ***step***. α and β QFs and QMs will be determined for all of the flags with the exception of the ***heater*** flag. In addition, all L1 DPs will have a QA/QC report and quality metric 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 primary pyranometer measurements.

Flags
Range
Persistence
Step (hard)
Null
Gap
Heater
Signal De-spiking
Alpha
Beta
Sensor Test AD[09]
Final quality flag

Table 5-2: Information maintained in the CI data store for the primary 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
Signal De-spiking	Time segments and threshold values
Calibration	AD[08]
Uncertainty	AD[12]
Sensor Test	AD[09]
Final Quality Flag	AD[14]

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 short-wave radiation measurements as well as L1 mean DPs. It is a reflection of the information described in AD[10], and is explicitly described for the primary pyranometer assembly in the following sections.

6.1 Uncertainty of Insolation Measurements

Uncertainty of the pyranometer assembly is discussed in this section. The section is broken down into two topics. The first informs the sources of *measurement* uncertainty, i.e., those associated with *individual measurements*. The second details uncertainties associated with temporally averaged data products. A diagram detailing the data flow and known sources of uncertainty are displayed in Figure 2.

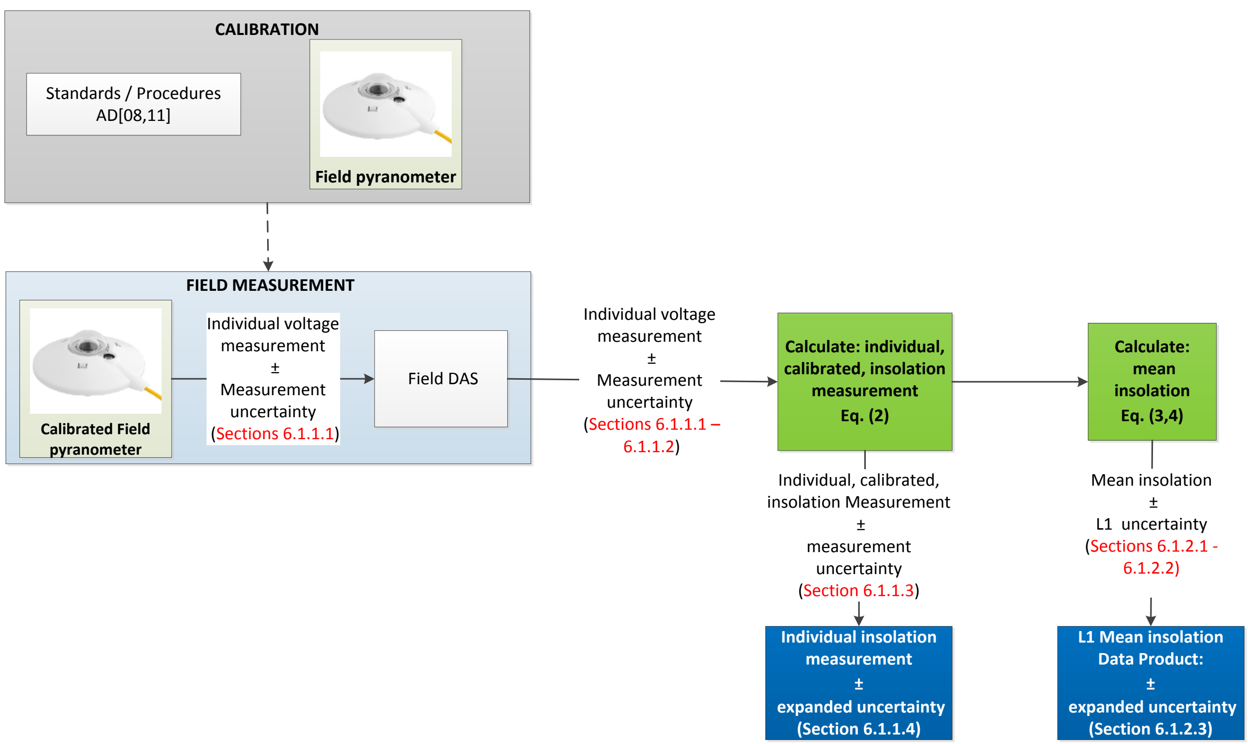

Figure 1: Displays the data flow and associated uncertainties of individual insolation measurements and L1 insolation DPs. For a detailed explanation of pyranometer calibration procedures, please refer to AD[08,11].

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with *individual radiation 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* radiation measurement. These uncertainties should not be confused with those presented in Section 6.1.2. We urge the reader to refer to AD[12] for further details concerning discrepancies between quantification of measurement uncertainties and L1 data product 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 $x_i\ (i = 1, \ldots, n),\ i.e., y = f(x_1, x_2, \ldots, x_n)$, the combined measurement uncertainty of *y*, assuming the inputs are independent, can be calculated as follows:

$$u_c(y) = \left(\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)\right)^{\frac{1}{2}} \quad (5)$$

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 be 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 propagate into a combined, relative, measurement uncertainty. This combined uncertainty, u_{A1}, represents 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. (2)). It is a relative value [%] that will be provided by CVAL (AD[12]) and stored in the CI data store. After converting from [%] to measurement units, it will be applied to all individual measurements (that is, it does 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[08,11].

The combined, standard, measurement uncertainty is calculated as follows:

$$u_{CVAL}(ISW_i) = u_{A1} * ISW_i. \quad (6)$$

6.1.1.2 Ventilation Unit

Pyranometer performance can be improved by using a well-designed ventilation unit (i.e., a fan and two heaters), as it helps prevent temperature differentials and buildup of moisture (Kipp and Zonen 1999). Although use of the Kipp and Zonen ventilation unit improves measurement accuracy, 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 thus we cannot quantify related uncertainties. However, with sufficient operational experience, such uncertainties may be better estimated.

6.1.1.3 Field DAS

To quantify the uncertainty introduced by the Field DAS (FDAS), the following equations are computed.

$$u_{FDAS}(P_i) = (u_{V1} * P_i) + O_V \tag{7}$$

Where,

$u_{FDAS}(P_i)$ = combined, standard uncertainty introduced by the Field Das (V)
P_i = Sensor output (insolation; V)

u_{V1} = combined, relative Field DAS uncertainty for voltage measurements, provided by CVAL (unitless)

O_V = offset imposed by the FDAS, provided by CVAL (V)

$$\frac{\partial ISW_i}{\partial P_i} = C_1 \tag{8}$$

$$u_{FDAS}(ISW_i) = \left|\frac{\partial ISW_i}{\partial P_i}\right| u_{FDAS}(P_i) \tag{9}$$

Where,

$\frac{\partial ISW_i}{\partial P_i}$ = partial derivative of Eq. (2) with respect to P_i (W m^{-2})

C_1 = calibration coefficient provided by CVAL (W m^{-2} V^{-1})

$u_{FDAS}(ISW_i)$ = converted, combined, standard uncertainty introduced by the Field DAS (W m^{-2})

6.1.1.4 Combined Measurement Uncertainty

The combined, standard, measurement uncertainty for an individual pyranometer measurement, $u_c(ISW_i)$, is given in units of W m^{-2} and computed by summing the individual uncertainties in quadrature:

$$u_c(ISW_i) = \left(u_{CVAL}^2(ISW_i) + u_{FDAS}^2(ISW_i)\right)^{\frac{1}{2}} \quad (10)$$

6.1.1.5 Expanded Measurement Uncertainty

The expanded measurement uncertainty is calculated as:

$$U_{95}(ISW_i) = k_{95} * u_c(ISW_i) \quad (11)$$

Where:

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

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

6.1.2 Uncertainty of L1 Mean Data Product

The following subsections discuss uncertainties associated with 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 quantify the uncertainty attributable to random effects, the distribution of the individual measurements is used. Specifically, the *estimated standard error of the mean (natural variation)* is computed. This value reflects the repeatability of insolation measurements for a specified time period:

$$u_{NAT}(\overline{ISW}) = \frac{s(ISW_i)}{\sqrt{n}} \quad (12)$$

Where,

$u_{NAT}(\overline{ISW})$ = standard error of the mean (natural variation) (W m^{-2})

$s(ISW_i)$	= experimental standard deviation of individual observations for the defined time period (W m^{-2})
n	= number of observations made during the defined time period. (unitless)

6.1.2.2 Calibration

The uncertainty detailed here is similar to that described in Section 6.1.1.1. However, this combined, relative uncertainty, u_{A3}, does not account for i) individual sensor repeatability, or ii) the variation of sensors' responses over a population (reproducibility). This component of uncertainty estimates the uncertainty due to accuracy of the instrumentation in the form of *Truth* and *Trueness*, a quantity which is not captured by the standard error of the mean. It is a relative value [%] that will be provided by CVAL (AD[12]) and stored in the CI data store. After converting to measurement units, the uncertainty will be calculated using the *maximum* insolation value observed during the averaging period.

$$u_{CVAL(TT)}(\overline{ISW}) = u_{A3} * ISW_{MAX} \quad (13)$$

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

$$MAX = \{i: u_c(ISW_i) = \max[u_c(ISW_1), \dots, u_c(ISW_n)]\}. \quad (14)$$

And,

$u_{CVAL(TT)}(\overline{ISW})$	= combined, standard *Truth* and *Trueness* uncertainty due to the sensor calibration process (W m^{-2})
ISW_{MAX}	= ISW measurement observed at MAX index (W m^{-2})
u_{A3}	= Combined, relative uncertainty (*Truth* and *Trueness* only) of pyranometer, provided by CVAL (unitless)

Please refer to AD[10] for further justification regarding evaluation and quantification of using the maximum index for quantification of these L1 mean data product uncertainties.

6.1.2.3 Field DAS

Since the L1 mean DP is a function of the individual measurements, any measurement bias introduced by the Field DAS will be reflected in the L1 mean data product. Here, the raw measurement that maximizes the combined uncertainty of an individual measurement (Eq.(10)) is used in the calculation of the L1 mean DP uncertainty. Uncertainty components due to random effects, whether a function of the environment or the measurement assembly, are quantified via the natural variation of the mean (see Section 6.1.2.1).). For more information regarding the justification of this approach, please see AD[10].

The accuracy of the Field DAS in the form of *Truth* and *Trueness* propagates through to the uncertainty of the mean DP similarly to how the Field DAS uncertainty associated with a raw voltage propagates through to the uncertainty of the measurement attributable to the Field DAS (Eqs. (7)-(9)).

$$u_{FDAS(TT)}(P_{MAX}) = (u_{V3} * P_{MAX}) + O_V \tag{15}$$

where:

$u_{FDAS(TT)}(P_{MAX})$ = Field DAS *Truth* and *Trueness* uncertainty of P_{MAX} (V)
P_{MAX} = individual irradiance measurement observed at MAX index (V)
u_{V3} = combined, relative, Field DAS *Truth* and *Trueness* uncertainty for voltage measurements, provided by CVAL (%)
O_V = offset imposed by the FDAS for voltage measurements provided by CVAL (V)

Thus, analogous to Eq. (9),

$$u_{FDAS(TT)}(\overline{ISW}) = \left|\frac{\partial ISW_i}{\partial P_i}\right|_{P_{MAX}} u_{FDAS(TT)}(P_{MAX}) \tag{16}$$

Where:

$\left|\frac{\partial ISW_i}{\partial P_i}\right|_{P_{MAX}}$ = partial derivative of ISW_i with respect to P_i (Eq. (8)) evaluated at P_{MAX} (W m^{-2})

C_1 = calibration coefficient provided by CVAL (W m^{-2})

$u_{FDAS(TT)}(\overline{ISW})$ = *Truth* and *Trueness* uncertainty of the mean DP introduced by the Field DAS (W m^{-2})

6.1.2.4 Combined Uncertainty

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

$$u_c(\overline{\text{ISW}}) = \left(u^2_{NAT}(\overline{ISW}) + u^2_{CVAL(TT)}(\overline{ISW}) + u^2_{FDAS(TT)}(\overline{ISW})\right)^{\frac{1}{2}} \quad (17)$$

6.1.2.5 Expanded Uncertainty

The expanded uncertainty is calculated as:

$$U_{95}(\overline{\text{ISW}}) = k_{95} * u_c(\overline{\text{ISW}}) \quad (18)$$

Where:

$U_{95}(\overline{\text{ISW}})$ = expanded L1 mean data product uncertainty at 95% confidence (W m^{-2})

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

6.1.3 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 insolation 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**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\|\frac{\partial f}{\partial x_i}\right\| u(x_i)$ $[W\ m^{-2}]$
1 Hz ISW	$u_c(ISW_i)$	Eq. (10) $[\text{W m}^{-2}]$	n/a	n/a
Sensor/calibration	$u_{CVAL}(ISW_i)$	Eq. (6) $[\text{W m}^{-2}]$	1	Eq. (6)
Field DAS	$u_{FDAS}(ISW_i)$	Eq. (7) [V]	Eq. (8)	Eq. (9)

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

Source of uncertainty	Uncertainty component $u(x_i)$	Uncertainty value	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\|\frac{\partial f}{\partial x_i}\right\| u(x_i)$ [$\mu mol\ m^{-2}\ s^{-1}$]
L1 mean insolation	$u_c(\overline{ISW})$	Eq. (17) [μmol m^{-2} s^{-1}]	n/a	n/a
Natural variation	$u_{NAT}(\overline{ISW})$	Eq. (12) [μmol m^{-2} s^{-1}]	1	Eq. (12)
Sensor/calibration	$u_{CVAL(TT)}(\overline{ISW})$	Eq. (13) [μmol m^{-2} s^{-1}]	1	Eq. (13)
Field DAS	$u_{FDAS(TT)}(\overline{ISW})$	Eq. (15) [V]	Eq. (8)	Eq. (16)

7 FUTURE PLANS AND MODIFICATIONS

Details concerning the evaluation and quantification of Sensor and Field DAS drift will be added to the uncertainty section.

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

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