NEON ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD)
HUMIDITY AND TEMPERATURE SENSOR

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1 DESCRIPTION

Contained in this document are details concerning relative humidity and accompanying temperature measurements made at all NEON sites. The quantity calculated from these measurements (i.e., the dew point/frost point temperature) will be used as a reference for NEON's sensor heating control. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 (L1) data products (DPs) from Level 0 (L0) data, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by Vaisala HUMICAP® Humidity and Temperature Probe HMP155 (NEON P/N: 031565000). It includes a detailed discussion of measurement theory and implementation, theoretical background, data product provenance, quality assurance and control methods used, assumptions, and a detailed estimation of uncertainty resulting in a cumulative uncertainty budget for this product.

1.2 Scope

This document describes the theoretical background and the end-to-end algorithmic process for creating L1 DPs from input data. It does not provide computational methodology to implement the details of the approaches presented here, except for cases where they stem directly from algorithmic/mathematical choices explained here.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY
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.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 De-spiking and time series analyses
AD[08]	NEON.DOC.000746	Evaluating Uncertainty
AD[09]	NEON.DOC.000850	NEON Sensor Command, Control, and Configuration-Humidity and Temperature Sensor
AD[10]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[11]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values[1]
AD[12]	NEON.DOC.001066	NEON Relative Humidity Calibration Fixture
AD[13]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products
AD[14]	NEON.DOC.000653	ATBD Barometric Pressure
AD[15]	NEON.DOC.001489	C^3 AQU Humidity and Temperature Sensor

2.2 Reference Documents

RD[01]	NEON.DOC.000008	NEON Acronym List
RD[02]	NEON.DOC.000243	NEON Glossary of Terms
RD [03]	Vaisala. 2012. User's Guide: Vaisala HUMICAP® Humidity and Temperature Probe HMP155, Manual Code: M210912EN-C	
RD [04]	Vaisala. Technical Note: What is dewpoint?	

2.3 Acronyms

Acronym	Explanation
A/D	Analog to Digital
ATBD	Algorithm Theoretical Basis Document
CI	NEON Cyber Infrastructure Project Team
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System

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[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.

DP	Data Product
FIU	Fundamental Instrument Unit
GRAPE	Grouped Remote Analog Peripheral Equipment
L0	Level 0
L1	Level 1
QA/QC	Quality Assurance/Quality Control

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 to distinguish the symbols of specific variables.

Symbol	**Internal Notation**	**Description**
$u_{A1,RH}$	U_CVALA1	Combined, standard calibration uncertainty of relative humidity (unitless)
$u_{A1,T}$	U_CVALA1	Combined, standard calibration uncertainty of temperature (°C)
$u_{A3,RH}$	U_CVALA3	Combined, standard calibration uncertainty (truth and trueness) of relative humidity (unitless)
$u_{A3,T}$	U_CVALA3	Combined, standard calibration uncertainty (truth and trueness) of temperature (°C)
${V_{eff}}_{A1,RH}$	U_CVALD1	Effective degrees of freedom relating to $u_{A1,RH}$ (unitless)
${V_{eff}}_{A1,T}$	U_CVALD1	Effective degrees of freedom relating to $u_{A1,T}$ (unitless)
${V_{eff}}_{A3,RH}$	U_CVALD3	Effective degrees of freedom relating to $u_{A3,RH}$ (unitless)
${V_{eff}}_{A3,T}$	U_CVALD3	Effective degrees of freedom relating to $u_{A3,T}$ (unitless)

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

Relative humidity and temperature related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file rhd_datapub_NEONDOC002886.txt.

3.2 Input Dependencies

A summary of the inputs required to produce the Level 1 data product are shown in Table 3-1.

Table 3-1: The relative humidity related L0 DPs that are transformed into L1DPs in this ATBD.

Description	Sample Frequency	Units	Data Product Number
Relative humidity (RH)	1 Hz	%	NEON.DOM.SITE.DP0.00098.001.01357.HOR.VER.000
Sensor Temperature (T)	1 Hz	°C	NEON.DOM.SITE.DP0.00098.001.01309.HOR.VER.000
Dew point/frost point temperature (T_d/f)	1 Hz	°C	NEON.DOM.SITE.DP0.00098.001.01358.HOR.VER.000
Sensor error flag (QF_E)	1 Hz	NA	NEON.DOM.SITE.DP0.00098.001.01359.HOR.VER.000

3.3 Product Instances

HMP155 sensors will be used at all NEON core and re-locatable sites. HMP155 sensors will be installed at the top level of the tower infrastructure, at the soil array and on the aquatic met station at a standard height above ground level. Individual instances of all HMP155-related L1 data products are displayed in the accompanying file rhd_datapub_NEONDOC002886.txt.

3.4 Temporal Resolution and Extent

One- and thirty-minute averages of relative humidity, temperature, and dew point/frost point temperature will be calculated to form L1 DPs.

3.5 Spatial Resolution and Extent

HMP155 sensors will be deployed at all core and re-locatable sites – one at the top level of the tower infrastructure, at the soil array and on the aquatic met station. Measurements at the tower's top level and aquatic met station will serve as a reference for heating control of NEON's sensors installed on the tower and aquatic met station, while those of the soil array will serve as a reference for heating control of NEON's sensor installed within the soil array.

4 SCIENTIFIC CONTEXT

Condensation occurs on a surface when its temperature is at or below the dew point temperature of the ambient air. Condensation that forms on the surface of sensors will cause erroneous measurements. Thus, to prevent condensation from forming on these sensors, the dew point temperature will be used as a proxy for heating control of NEON's sensor. In other words, it will be used to determine when the heater should be switched on or off.

4.1 Theory of Measurement/Observation

Dew point can be measured directly using traditional sensors (e.g., chilled-mirror hygrometer). Humidity measurements made with this type of sensor can offer the highest accuracy over a wide range of dew points. However, such sensors are very sensitive to dirt and dust, require regular maintenance, and are heavy on power consumption. Therefore, chilled-mirror hygrometers are usually used only when absolute accuracy is needed (e.g., in laboratories – see RD[04]; Campbell Scientific, 2000). An alternative method is to calculate dew point from measurements of relative humidity and temperature. While end results may not be quite as accurate as chilled-mirror hygrometers, they are acceptable for a wide range of applications (Campbell Scientific, 2000).

The HMP155 sensor *directly* measures i) relative humidity via a thin film polymer capacitor, and ii) temperature via a platinum resistance thermometer (RD[03]). The relative humidity measurement is dependent on the polymer's design, its ability to absorb and desorb water, and the temperature of the sensor (Smit *et al.* 2013).

The sensor also calculates dew point/frost point ($T_{d/f}$ RD[03]) from the temperature and relative humidity measurements. These calculations are detailed here as precursors to inform uncertainty estimates.

Dew/frost point:

$$T_{d/f} = \frac{237.3}{\left[\frac{7.5}{\log_{10}\left(\frac{P_{w_{W/I}}}{6.1078}\right)} - 1\right]} \tag{1}$$

Where,

$T_{d/f}$ = dew point (subscript "d") *or* frost point (subscript "f") (°C)

$P_{w_{W/I}}$ = water vapor pressure over water (subscript "W"), or ice (subscript "I") (hPa) and is calculated using:

$$P_{w_{W/I}} = \frac{P_{ws_{W/I}} * RH}{100} \tag{2}$$

Where,

$P_{ws_{W/I}}$ = saturation vapor pressure over water W, *or* ice I (hPa)
RH = the relative humidity (%)

At temperatures above the freezing point of water (0°C), the HMP155 reports the dew point temperature and the saturation vapor pressure as calculated over water, P_{ws_W}, using Eq. (3) and (4):

$$P_{ws_W} = \frac{e^{\left[\frac{b_0}{\Theta_w} + \sum_{i=1}^{4} b_i \Theta_w^{(i-1)} + b_5 \ln \Theta_w\right]}}{100} \tag{3}$$

where,

b_0 = -0.58002206 x 10^{4}
b_1 = 1.3914993
b_2 = -0.048640239
b_3 = 0.41764768 x 10^{-4}
b_4 = -0.14452093 x 10^{-7}
b_5 = 6.5459673
Θ_w = Virtual temperature (if T_K > 273.15 K)

The virtual temperature is calculated via:

$$\Theta_w = T_K - \sum_{i=0}^{3} C_i \, T_K^i \tag{4}$$

where,

T_K = Ambient temperature converted to Kelvin (K), i.e., $T + 273.15$
C_0 = 0.4931358
C_1 = -0.46094296 x 10^{-2}
C_2 = 0.13746454 x 10^{-4}
C_3 = -0.12743214 x 10^{-7}

At temperatures below the freezing point of water the HMP155 reports frost point temperature (dew point over ice) and the saturation vapor pressure is calculated over ice, P_{ws_I}, by using Eq. (5) and (6):

$$P_{ws_I} = \frac{e^{\left[\frac{a_0}{\Theta_I} + \sum_{i=1}^{5} a_i \Theta_I^{(i-1)} + a_6 \ln \Theta_I\right]}}{100} \tag{5}$$

where:

a_0 = -0.56745359 x 10^4
a_1 = 6.3925247
a_2 = -0.96778430 x 10^{-2}
a_3 = 0.62215701 x 10^{-6}
a_4 = 0.20747825 x 10^{-8}
a_5 = -0.94840240 x 10^{-12}
a_6 = 4.1635019
Θ_I = Virtual temperature (if T_K ≤ 273.15 K)

The virtual temperature is calculated via:

$$\Theta_I = T_K. \tag{6}$$

4.2 Theory of Algorithm

The HMP155 sensor calculates dew point/frost point temperature internally. The HMP155 sensor outputs data in digital form (Table 3-1) through RS-485 connections, therefore, no analog to digital (A/D) conversion is necessary.

One- and thirty-minute averages of relative humidity, temperature, and dew point/frost point temperature will be determined accordingly to Eq. (7) and Eq. (8) to create the L1 DPs listed in file rhd_datapub_NEONDOC002886.txt:

$$\overline{\mathrm{X\_1}} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{X}_i. \tag{7}$$

where, for each minute average, n is the number of measurements over time t and the averaging period is defined as 0 ≤ t < 60 seconds and

$$\overline{\mathrm{X\_30}} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{X}_i \tag{8}$$

where, for each thirty-minute average, n is the number of measurements over time t and averaging periods are defined as 0 ≤ t < 1800 seconds; X denotes either temperature T, relative humidity RH, or dew point/frost point temperature $T_{d/f}$.

5 ALGORITHM IMPLEMENTATION

Data flow for signal processing of L1 data products will be treated in the following order.

1. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[06]. The details are provided below.
2. Time series analysis and signal de-spiking will be applied to the data stream in accordance with AD[07].
3. One- and thirty-minute averages of relative humidity, temperature, and dew point/frost point will be calculated using Eq. (7) and (8) and descriptive statistics (i.e., minimum, maximum, and variance) will be determined for both averaging periods.
4. Quality metrics, quality flags, and the final quality flag will be produced for one- and thirty-minute averages according to AD[13].

__QA/QC Procedure__:

1. **Plausibility Tests** AD[06] – All plausibility tests will be determined for relative humidity, temperature, and dew point/frost point temperature. Test parameters will be provided by FIU and maintained in the CI data store. All plausibility tests will be applied to the sensor's L0 DP and an associated quality flags (QFs) will be generated for each test.

2. **Sensor Test** – A sensor error flag as identified in the C^3 document (AD[09]) will be applied to L0 DPs while an error occurred (i.e., the sensor outputs stars asterisks (***) instead of measured values). One- and thirty-minute averages of quality metrics of the sensor flag will be produced according to AD[13].

3. **Signal De-spiking and Time Series Analysis** – The time series de-spiking 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 de-spiking analysis will be applied according to AD[07].

4. **Consistency Analysis** – Currently, there is no plan to run consistency analysis on the L1 DP for the Humidity and Temperature sensor. However, time series consistency analysis may be explored in the future.

5. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[13] – If a datum has failed one of the following tests it will not be used to create a L1 DP, sensor test, range, persistence, and step. 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 (***finalQF***), as detailed in AD[13]. 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 relative humidity measurements.

Flags
Range Flag
Persistence Flag
Step Flag
Null Flag
Gap Flag
Signal De-spiking Flag
Alpha Flag
Beta Flag
Final Quality Flag
Sensor Test

Table 5-2: Information maintained in the CI data store for the relative humidity sensor.

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 and Time Series Analysis	Time segments and threshold values
Calibration	CVAL sensor specific calibration coefficients
Sensor test flag	AD [09]
Uncertainty	AD[10]
Final Quality Flag	AD[13]

6 UNCERTAINTY

Uncertainty of measurement is inevitable (ISO 1995; Taylor 1997). It is imperative that uncertainties are identified and quantified to determine statistical interpretations about mean quantity and variance structure; both are important when constructing higher level data products (*e.g.,* L1 DPs) and modeled processes. This portion of the document serves to identify, evaluate, and quantify sources of uncertainty relating to L1 humidity DPs. It is a reflection of the information described in AD[10], and is explicitly described for Vaisala's HMP155 humidity and temperature probe and its assembly in the following sections.

6.1 Uncertainty of Humidity Measurements

As noted in Section 4.1, the Vaisala HMP155 directly measures temperature and relative humidity. Dew/frost point is then calculated from those measurements. Because relative humidity and dew/frost point are dependent on ambient temperature, resulting measurement uncertainties are a function of the temperature measurement uncertainty.

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

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \right)^{\frac{1}{2}} \tag{9}$$

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 sources of uncertainty of HMP155's humidity, temperature, and dew/frost point measurements are discussed below.

6.1.1.1 DAS

The Vaisala HMP155 sensor has an internal Analog to Digital (A/D) converter and outputs data in digital form. Therefore, no data conversions occur within the DAS, and uncertainty introduced by the DAS can be considered negligible.

6.1.1.2 Passive Radiation Shield

The HMP155 is housed inside of a *passive* radiation shield i.e., one that relies on ambient wind for ventilation. Use of passive radiation shields can cause large, positive, temperature errors if ambient wind speed is low and incoming solar radiation is high (Brock *et al*. 1995; Lin *et al*. 2000). As noted in Section 4.1, the measurement of relative humidity via a thin film polymer capacitor is dependent on temperature (Smit *et al.* 2013), thus, relative humidity measurements (Tarara and Hoheisel 2007) are also affected by the radiation induced error. The same is true for dew/frost point measurements, as it is a function of temperature (refer to Eq. (3) through (6)). At this time, however, we cannot accurately quantify the extent of the uncertainty introduced by the passive radiation shield. As wind, insolation, and TRAAT measurements are collected and analyzed, measurement uncertainty resulting from the use of a passive shield may be quantified.

Note: Data will be flagged if ambient wind speed is below a threshold and insolation is above a threshold, thus notifying the end user where measurements may be biased due to radiation influences (please see AD[09]).

6.1.1.3 Calibration

NEON's CVAL will separately provide uncertainties for temperature and relative humidity measurements. These uncertainties (see Section 2.4) 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). Both are constant values that will be provided by CVAL, stored in the CI data store, and applied to all *individual temperature and relative humidity measurements* (that is, the uncertainty values 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[11,12].

6.1.1.4 Dew/frost point

The dew/frost point is directly related to the vapor content (e.g., vapor pressure) of the atmosphere. Despite this, Vaisala's HMP155 does not directly measure the vapor pressure of the atmosphere. Yet, the HMP155 i) empirically derives the dew/frost point of the atmosphere as a function of ambient temperature (virtual temperature) and RH, and ii) assumes RH and temperature to be independent of one another (the two atmospheric parameters are independently measured by the HMP155). Because the HMP155 derives dew/frost point $T_{d/f}$, from *independent* measurements of relative humidity RH, and temperature T_K, the uncertainties of relative humidity and temperature are treated *independently* within this document.

The derivative of dew/frost point with respect to temperature (Kelvin) can be partitioned as follows:

$$\frac{\partial T_{d/f_i}}{\partial T_{K_i}} = \frac{\partial T_{d/f_i}}{\partial P_{ws_{W/I_i}}} * \frac{dP_{ws_{W/I_i}}}{dT_{K_i}} \tag{10}$$

Where,

$\frac{\partial T_{d/f_i}}{\partial T_{K_i}}$ = derivative of Eq. (1) with respect to T_K (°C K^{-1})

$\frac{\partial T_{d/f_i}}{\partial P_{ws_{W/I_i}}}$ = partial derivative of Eq. (1), substituting Eq. (3) for P_{p_W} (Eq. (5) for P_{p_I}), with respect to P_{ws_W} (P_{ws_I}) (°C hPa^{-1}).

$\frac{dP_{ws_{W/I_i}}}{dT_{K_i}}$ = derivative of Eq. (3) or (5), substituting Eq. (4) for Θ_W or Eq. (6) for Θ_I, with respect to T_K (hPa K^{-1})

Total and partial derivatives are derived below.

$$\frac{\partial T_{d/f_i}}{\partial P_{ws_{W/I_i}}} = \frac{4719.72}{P_{ws_{I_i}}\left(\log_{10}\left(P_{ws_{W/I_i}} * RH_i\right) - 30.605\right)^2} \tag{11}$$

Saturation vapor pressure for calculating dew point

If T_{K_i} > 273.15 K *then*:

$$\begin{aligned} &\frac{dP_{ws_{W_i}}}{dT_{K_i}} \\ &= \frac{1}{100}\left(\left(-3c_3T_{K_i}^2 - 2c_2T_{K_i} - c_1 + 1\right)\left(b_2 \right.\right. \\ &+ \frac{1}{-c_3T_{K_i}^3 - c_2T_{K_i}^2 - c_1T_{K_i} + T_{K_i} - c_0}\left(\frac{-b_0}{-c_3T_{K_i}^3 - c_2T_{K_i}^2 - c_1T_{K_i} + T_{K_i} - c_0} - b_5\right) \\ &\left.+ \left(-c_3T_{K_i}^3 - c_2T_{K_i}^2 - c_1T_{K_i} + T_{K_i} - c_0\right)\left(2b_3 + 3b_4\left(-c_3T_{K_i}^3 - c_2T_{K_i}^2 - c_1T_{K_i} + T_{K_i} - c_0\right)\right)\right) \\ &\left. * \ e^{\frac{b_0}{-c_0 - c_1T_{K_i} - c_2T_{K_i}^2 - c_3T_{K_i}^3 + T_{K_i}} + \sum_{i=1}^{4} b_i - (c_0 - c_1T_{K_i} - c_2T_{K_i}^2 - c_3T_{K_i}^3 + T_{K_i})^{(i-1)} + b_5 \ln\left(-c_0 - c_1T_{K_i} - c_2T_{K_i}^2 - c_3T_{K_i}^3 + T_{K_i}\right)}\right) \end{aligned} \tag{12}$$

Saturation vapor pressure for calculating frost point

If T_{K_i} ≤ 273.15 K *then*:

$$\frac{dP_{ws_{I_i}}}{dT_{K_i}} = \frac{1}{100}\left(\left(\frac{-a_0}{{T_K}_i^2} + a_2 + 2a_3T_{K_i} + 3a_4{T_K}_i^2 + 4a_5{T_K}_i^3 + \frac{a_6}{T_{K_i}}\right) * e^{\left(\frac{a_0}{T_{K_i}} + \sum_{i=1}^{5} a_i {T_K}_i^{(i-1)} + a_6 \ln(T_{K_i})\ln\right)}\right) \tag{13}$$

The partial uncertainty of an individual dew/frost point temperature measurement with respect to ambient temperature is thus:

$$u_{T_K}\left({T_{d/f}}_i\right) = \left|\frac{\partial {T_{d/f}}_i}{\partial {T_K}_i}\right| u_{A1,T} \tag{14}$$

The partial uncertainty of an individual dew/frost point temperature measurement with respect to ambient relative humidity must also be derived.

Relative humidity:

$$\frac{\partial {T_{d/f}}_i}{\partial RH_i} = \frac{4719.72}{RH_i\left(\log_{10}\left(P_{ws_{W/I_i}} * RH_i\right) - 30.605\right)^2} \tag{15}$$

$$u_{RH}\left({T_{d/f}}_i\right) = \left|\frac{\partial {T_{d/f}}_i}{\partial RH_i}\right| u_{A1,RH} \tag{16}$$

Where,

$\frac{\partial T_{d/f_i}}{\partial RH_i}$ = partial derivative of Eq. (1) substituting Eq. (2) for P_{p_W} or P_{p_I}, with respect to RH (°C)

$u_{RH}\left({T_{d/f}}_i\right)$ = partial uncertainty of ${T_{d/f}}_i$ with respect to RH (°C)

6.1.1.5 Combined Measurement Uncertainty

Temperature and relative humidity:

Because the only *known, quantifiable* uncertainties are those provided by CVAL, the combined uncertainties of temperature and relative humidity are simply equal to the standard uncertainty values provided by CVAL (See Section 2.4).

Dew/frost point:

The combined uncertainty for the dew/frost point measurement is simply:

$$u_c\left(T_{d/f_i}\right) = \left(u^2_{T_K}\left(T_{d/f_i}\right) + u^2_{RH}\left(T_{d/f_i}\right)\right)^{\frac{1}{2}} \tag{17}$$

6.1.1.6 Expanded Measurement Uncertainty

The expanded measurement uncertainty for any variable is a function of the effective degrees of freedom for that particular variable. The effective degrees of freedom for temperature $V_{eff_{A1,T}}$, and relative humidity $V_{eff_{A1,RH}}$, will be provided by CVAL (please see Section 2.4). The effective degrees of freedom for dew/frost point are calculated via:

$$V_{eff_{T_{d/f_i}}} = \frac{u^4_c\left(T_{d/f_i}\right)}{\frac{u^4_{T_K}\left(T_{d/f_i}\right)}{V_{eff_{A1,T}}} + \frac{u^4_{RH}\left(T_{d/f_i}\right)}{V_{eff_{A1,RH}}}} \tag{18}$$

The expanded measurement uncertainty for each variable can then be calculated via:

$$U_{95}(x_i) = k_{95,V_{eff_x}} * u_c(x_i) \tag{19}$$

Where:

$U_{95}(x_i)$ = expanded measurement uncertainty of variable x at 95% confidence. Variable x represents temperature, relative humidity or dew/frost point temperature.

$k_{95,V_{eff_x}}$ = coverage factor of variable x obtained with the aid of Table 5 in AD[10]

$V_{eff_{A1,T}}$ = effective degrees of freedom relating to quantification of temperature sensor calibration uncertainty

$V_{eff_{A1,RH}}$ = effective degrees of freedom relating to quantification of relative humidity sensor calibration uncertainty

6.1.2 Uncertainty of the 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 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:

$$u_{NAT}(\bar{X}) = \frac{s(X)}{\sqrt{n}} \tag{20}$$

Where,

$u_{NAT}(\bar{X})$ = standard error of the mean (natural variation)

$s(X)$ = experimental standard deviation of individual observations for the defined time period

n = number of observations made during the defined time period

6.1.2.2 Calibration

The calibration uncertainty for a L1 mean DP is similar to that described in Section 6.1.1.1. However, the uncertainties provided by CVAL (see Section 2.4) do not account for i) individual sensor repeatability, or ii) the variation of sensors' responses over a population (reproducibility). These components estimate the uncertainties 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. Both values (i.e., temperature and relative humidity) are constant values that will be provided by CVAL and stored in the CI data store. Please refer to AD[10] for further justification regarding evaluation and quantification of this combined uncertainty.

The temperature and relative humidity uncertainties provided by CVAL will propagate through to the dew/frost point temperature. These propagations are identical to those shown in Section 6.1.1.4, however, the uncertainties shown in Eq. (14) and (16) are replaced with $u_{A3,T}$, and $u_{A3,RH}$, respectively, such that:

$$u_{TT_{T_K}}(\overline{T_{d/f}}) = \left|\frac{\partial T_{d/f}}{\partial T_K}\right|_{MAX} u_{A3,T} \tag{21}$$

$$u_{TT_{RH}}\left(\overline{T_{d/f}}\right) = \left|\frac{\partial T_{d/f}}{\partial RH}\right|_{MAX} u_{A3,RH} \tag{22}$$

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

$$MAX = \{i: u_c(x_i) = \max[u_c(x_1), \dots, u_c(x_n)]\}. \tag{23}$$

6.1.2.3 Combined Uncertainty

Temperature and relative humidity:

The combined uncertainty for our L1 mean data products $u_c(\bar{X})$, is computed by summing the uncertainties from Section 6.1.2.1 and the CVAL provided uncertainty ($u_{A3,T}$ or $u_{A3,RH}$) in quadrature:

$$u_c(\bar{X}) \ = \left(u_{NAT}^2(\bar{X}) + u_{A3,X}^2\right)^{\frac{1}{2}} \tag{24}$$

Where, X represents temperature or relative humidity.

Dew/frost point temperature:

$$u_c\left(\overline{T_{d/f}}\right) \ = \left(u_{NAT}^2\left(\overline{T_{d/f}}\right) + u_{TT_{T_K}}^2\left(\overline{T_{d/f}}\right) + u_{TT_{RH}}^2\left(\overline{T_{d/f}}\right)\right)^{\frac{1}{2}} \tag{25}$$

6.1.2.4 Expanded Uncertainty

To derive an expanded measurement uncertainty for our L1 mean DP, the effective degrees of freedom of the data product must first be computed

Temperature and relative humidity:

$$V_{eff_{\bar{X}}} = \frac{u_c^4(\bar{X})}{\frac{u_{NAT}^4(\bar{X})}{n-1} + \frac{u_{A3,X}^2}{V_{eff_{A3,X}}}} \tag{26}$$

Dew/frost point temperature:

$$V_{eff_{\overline{T_{d/f}}}} = \frac{u_c^4\left(\overline{T_{d/f}}\right)}{\frac{u_{NAT}^4\left(\overline{T_{d/f}}\right)}{n-1} + \frac{u_{TT_{T_K}}^4\left(\overline{T_{d/f}}\right)}{V_{eff_{A3,T}}} + \frac{u_{TT_{RH}}^4\left(\overline{T_{d/f}}\right)}{V_{eff_{A3,RH}}}} \tag{27}$$

Where,

$V_{eff_{\bar{X}}}$ = effective degrees of freedom relating to quantification of the combined, standard, uncertainty (unitless)

$n-1$ = effective degrees of freedom relating to quantification of the natural variation (standard error) of the L1 mean data product; n= number of measurements used to calculate $\bar{X}$ (unitless)

$V_{eff_{A3,X}}$ = effective degrees of freedom relating to quantification of sensor calibration uncertainty (not including repeatability or sensor variation amongst a population of sensors; unitless)

Next, the expanded uncertainty is calculated:

$$U_{95}(\bar{X}) = k_{95,V_{eff_{\bar{X}}}} * u_c(\bar{X}) \tag{28}$$

Where:

$U_{95}(\bar{X})$ = expanded L1 mean data product uncertainty at 95% confidence

$k_{95,V_{eff_{\bar{X}}}}$ = coverage factor obtained with the aid of Table 5 in AD[10]

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. Uncertainties denoted in this budget are either derived within this document or will be provided by other NEON teams (e.g., CVAL) and stored in the CI data store.

Table 6-1: Uncertainty budget for individual measurements. 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** [°C]	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ [°C]	**Degrees of Freedom**
Temperature	$u_{A1,T}$	AD[11]	n/a	n/a	$V_{eff\,A1,T}$
Relative humidity	$u_{A1,RH}$	AD[11] [unitless]	n/a	n/a	$V_{eff\,A1,RH}$
Dew/frost point	$u_c\left(T_{d/f_i}\right)$	Eq. (17)	n/a	n/a	Eq. (18)
Temperature	$u_{A1,T}$	AD[11]	Eq. (10)	Eq. (14)	$V_{eff\,A1,T}$
Relative humidity	$u_{A1,RH}$	AD[11] [unitless]	Eq. (15)	Eq. (16)	$V_{eff\,A1,RH}$

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

Source of uncertainty	**uncertainty component** $u(x)$	**uncertainty value** [°C]	$\frac{\partial f}{\partial x_i}$	$u_{u_{x_i}}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ [°C]	**Degrees of Freedom**
Temperature	$u_c(\overline{T})$	Eq. (24)	n/a	n/a	Eq. (26)
Calibration	$u_{A3,T}$	AD[11]	n/a	n/a	$V_{eff\,A3,T}$
Natural variation	$u_{NAT}(\overline{T})$	Eq. (20)	n/a	n/a	$n-1$
Relative humidity	$u_c(\overline{RH})$	Eq. (24) [unitless]	n/a	n/a	Eq. (26)
Calibration	$u_{A3,RH}$	AD[11] [unitless]	n/a	n/a	$V_{eff\,A3,RH}$
Natural variation	$u_{NAT}(\overline{RH})$	Eq. (20) [unitless]	n/a	n/a	$n-1$
Dew/frost point	$u_c(\overline{RH})$	Eq. (25)	n/a	n/a	Eq. (27)
temperature	$u_{A3,T}$	AD[11]	Eq. (10)	Eq. (21)	$V_{eff\,A3,T}$
Relative humidity	$u_{A3,RH}$	AD[11] [unitless]	Eq. (15)	Eq. (22)	$V_{eff\,A3,RH}$
Natural variation	$u_{NAT}(\overline{T})$	Eq. (20)	n/a	n/a	$n-1$

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream and included in the QA/QC summary DP ($Qsum_{1min}$ and $Qsum_{30min}$) that summarizes any flagged data that went into the computation of the L1 DP.

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