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

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See configuration management system for approval history.

# Change Record

| REVISION | DATE | ECO # | DESCRIPTION OF CHANGE |
|---|---|---|---|
| A | 09/03/2015 | ECO-03108 | Initial Release |
| B | 12/18/2017 | ECO-05280 | Addition of AQU buoy mounted data products processing |
| C | 05/16/2022 | ECO-06813 | Revised logo |
| D | 06/28/2022 | ECO-06844 | • Revise QA/QC procedure to retain values failing the range test rather than remove them prior to averaging.<br>• Minor language updates. |

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|---|---|
| NEON Doc. #: NEON.DOC.000851    Author: N. Pingintha-Durden | Revision: D |

# 1    DESCRIPTION

Contained in this document are details concerning relative humidity and accompanying temperature measurements made at all NEON sites and buoys. 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 |
| AD[16] | NEON.DOC.001152 | Aquatic Sampling Strategy |
| AD[17] | NEON.DOC.003808 | $C^3$ Buoy meteorological station and submerged sensor assembly |
| AD[18] | NEON.DOC.004401 | Relative humidity and air temperature on-buoy ingest workbook |
| AD[19] | NEON.DOC.004402 | Relative humidity on-buoy publication workbook |
| AD[20] | NEON.DOC.004403 | Air temperature on-buoy publication workbook |
| AD[21] | NEON.DOC.002651 | NEON Data Product Numbering Convention |

### 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

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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.

| 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 |
| DP | Data Product |
| SCI | NEON Science Team |
| 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 (NEON.DP1.00098; tower).

Relative humidity and temperature related L1 DPs for relative humidity on-buoy (NEON.DP1.20271) and air temperature on-buoy (NEON.DP1.20046) can be found in the accompanying publication workbooks AD[19], RHBuoy_datapub_NEONDOC004402.txt and AD[20], airTempBuoy_datapub_NEONDOC004403.txt.

### 3.2    Input Dependencies

A summary of the inputs required to produce the Level 1 data products are shown in **Table 1** and **Table 2**.

**Table 1.** The relative humidity related L0 DPs that are transformed into L1 DPs (Relative humidity NEON.DP1.00098; tower measurements) 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 |

**Table 2.** Relative Humidity L0 DPs that are transformed into L1DPs (Relative humidity on-buoy NEON.DP1.20271) in this ATBD.

| Description | Sample Frequency | Units | Data Product Number |
|---|---|---|---|
| Relative humidity (RH) | ~ 1/min | percent | NEON.DOM.SITE.DP0.20271.001.01357.HOR.VER.000 |
| Sensor Temperature (sensorTemp) | ~ 1/min | celsius | NEON.DOM.SITE.DP0.20271.001.01309.HOR.VER.000 |
| Dew point/frost point temperature (dewPoint) | ~ 1/min | celsius | NEON.DOM.SITE.DP0.20271.001.01358.HOR.VER.000 |
| Sensor error flag (RHStatus) | ~ 1/min | NA | NEON.DOM.SITE.DP0.20271.001.01359.HOR.VER.000 |

\*\*Note: The HMP155 status is a non-numeric value. Currently the on-buoy software cannot parse non-numeric values. The LC will fill the data stream with -1 values. The sensor error cannot be tested due to the fact that the message cannot be parsed on the buoy datalogger.

**Table 3.** The relative humidity related L1 DPs (NEON.DP1.20271) that are published into other L1 DPs (Air temperature on-buoy NEON.DP1.20046) in this ATBD.

| Description | Sample Frequency | Units | Data Product Number |
|---|---|---|---|
| tempRHMean | 1 minute | celsius | NEON.DOM.SITE.DP1.20271.001.00693.HOR.VER.001 |
| tempRHMinimum | 1 minute | celsius | NEON.DOM.SITE.DP1.20271.001.00694.HOR.VER.001 |
| tempRHMaximum | 1 minute | celsius | NEON.DOM.SITE.DP1.20271.001.00695.HOR.VER.001 |
| tempRHVariance | 1 minute | celsiusSquared | NEON.DOM.SITE.DP1.20271.001.00696.HOR.VER.001 |
| tempRHNumPts | 1 minute | number | NEON.DOM.SITE.DP1.20271.001.00697.HOR.VER.001 |
| tempRHExpUncert | 1 minute | celsius | NEON.DOM.SITE.DP1.20271.001.00698.HOR.VER.001 |
| tempRHStdErMean | 1 minute | celsius | NEON.DOM.SITE.DP1.20271.001.00699.HOR.VER.001 |
| tempRHRangeQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00700.HOR.VER.001 |
| tempRHPersistenceQAQ | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00701.HOR.VER.001 |
| tempRHStepQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00702.HOR.VER.001 |
| tempRHNullQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00703.HOR.VER.001 |
| tempRHGapQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00704.HOR.VER.001 |
| tempRHConsistencyQAQ | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00705.HOR.VER.001 |
| tempRHSpikeQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00706.HOR.VER.001 |
| tempRHAlphaQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00707.HOR.VER.001 |
| tempRHBetaQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.00708.HOR.VER.001 |
| tempRHRangeFailQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00709.HOR.VER.001 |
| tempRHRangePassQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00710.HOR.VER.001 |
| tempRHRangeNAQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00711.HOR.VER.001 |
| tempRHPersistenceFai | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00712.HOR.VER.001 |
| tempRHPersistencePas | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00713.HOR.VER.001 |
| tempRHPersistenceNAQ | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00714.HOR.VER.001 |
| tempRHStepFailQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00715.HOR.VER.001 |
| tempRHStepPassQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00716.HOR.VER.001 |
| tempRHStepNAQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00717.HOR.VER.001 |
| tempRHNullFailQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00718.HOR.VER.001 |
| tempRHNullPassQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00719.HOR.VER.001 |
| tempRHNullNAQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00720.HOR.VER.001 |
| tempRHGapFailQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00721.HOR.VER.001 |
| tempRHGapPassQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00722.HOR.VER.001 |
| tempRHGapNAQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00723.HOR.VER.001 |
| tempRHSpikeFailQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00724.HOR.VER.001 |
| tempRHSpikePassQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00725.HOR.VER.001 |
| tempRHSpikeNAQM | 1 minute | percent | NEON.DOM.SITE.DP1.20271.001.00726.HOR.VER.001 |
| tempRHConsistencyFai | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00727.HOR.VER.001 |
| tempRHConsistencyPas | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00728.HOR.VER.001 |
| tempRHConsistencyNAQ | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00729.HOR.VER.001 |
| tempRHAlphaQM | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00730.HOR.VER.001 |
| tempRHBetaQM | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00731.HOR.VER.001 |

| tempRHFinalQF | 1 minute | NA | NEON.DOM.SITE.DP1. 20271.001.00732.HOR.VER.001 |
|---|---|---|---|
| RHSensorErrorFailQM | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00959.HOR.VER.001 |
| RHSensorErrorPassQM | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00960.HOR.VER.001 |
| RHSensorErrorNAQM | 1 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00961.HOR.VER.001 |
| RHSensorErrorQAQCRpt | 1 minute | NA | NEON.DOM.SITE.DP1.20271.001.01152.HOR.VER.001 |
| tempRHMean | 30 minute | celsius | NEON.DOM.SITE.DP1. 20271.001.00693.HOR.VER.030 |
| tempRHMinimum | 30 minute | celsius | NEON.DOM.SITE.DP1. 20271.001.00694.HOR.VER.030 |
| tempRHMaximum | 30 minute | celsius | NEON.DOM.SITE.DP1. 20271.001.00695.HOR.VER.030 |
| tempRHVariance | 30 minute | celsiusSquared | NEON.DOM.SITE.DP1. 20271.001.00696.HOR.VER.030 |
| tempRHNumPts | 30 minute | number | NEON.DOM.SITE.DP1. 20271.001.00697.HOR.VER.030 |
| tempRHExpUncert | 30 minute | celsius | NEON.DOM.SITE.DP1. 20271.001.00698.HOR.VER.030 |
| tempRHStdErMean | 30 minute | celsius | NEON.DOM.SITE.DP1. 20271.001.00699.HOR.VER.030 |
| tempRHRangeFailQM | 30 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00709.HOR.VER.030 |
| tempRHRangePassQM | 30 minute | percent | NEON.DOM.SITE.DP1. 20271.001.00710.HOR.VER.030 |
| tempRHRangeNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00711.HOR.VER.030 |
| tempRHPersistenceFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00712.HOR.VER.030 |
| tempRHPersistencePassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00713.HOR.VER.030 |
| tempRHPersistenceNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00714.HOR.VER.030 |
| tempRHStepFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00715.HOR.VER.030 |
| tempRHStepPassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00716.HOR.VER.030 |
| tempRHStepNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00717.HOR.VER.030 |
| tempRHNullFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00718.HOR.VER.030 |
| tempRHNullPassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00719.HOR.VER.030 |
| tempRHNullNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00720.HOR.VER.030 |
| tempRHGapFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00721.HOR.VER.030 |
| tempRHGapPassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00722.HOR.VER.030 |
| tempRHGapNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00723.HOR.VER.030 |
| tempRHSpikeFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00724.HOR.VER.030 |
| tempRHSpikePassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00725.HOR.VER.030 |
| tempRHSpikeNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00726.HOR.VER.030 |
| tempRHConsistencyFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00727.HOR.VER.030 |
| tempRHConsistencyPassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00728.HOR.VER.030 |
| tempRHConsistencyNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00729.HOR.VER.030 |
| tempRHAlphaQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00730.HOR.VER.030 |
| tempRHBetaQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00731.HOR.VER.030 |
| tempRHFinalQF | 30 minute | NA | NEON.DOM.SITE.DP1.20271.001.00732.HOR.VER.030 |
| RHSensorErrorFailQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00959.HOR.VER.030 |
| RHSensorErrorPassQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00960.HOR.VER.030 |
| RHSensorErrorNAQM | 30 minute | percent | NEON.DOM.SITE.DP1.20271.001.00961.HOR.VER.030 |

## 3.3    Product Instances

HMP155 sensors will be used at all NEON core and gradient 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.

With a slightly different configuration, an additional HMP155 sensor will be deployed at all lake and river sites where the sensor will be installed on the buoy. The buoy HMP155 is also used for the air temperature on-buoy data product (DP1.20046). The air temperature data will be published from level 1 relative humidity on-buoy data (DP1.20271). So, no additional processing will be done for the air temperature data product (DP1.20046), the data published on the portal will be a subset of the relative humidity data.

## 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 gradient sites – one at the top level of the tower infrastructure, at the soil array, on the aquatic met station, and on the buoy. Measurements at the tower's top level, aquatic met station, and on the buoy will serve as a reference for heating control of NEON sensors installed on the tower, aquatic met station and buoy, 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 on a surface occurs when the surface temperature is at or below the ambient dew point temperature. When condensation forms on the surface of certain sensors it can cause erroneous measurements. To prevent condensation from forming on sensor infrastructure, the dew point temperature, as measured by the HMP155, will be used as a proxy for heating control of NEON sensors, i.e., it will inform when a 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. The latter approach is not as accurate as chilled-mirror hygrometers but is an acceptable alternative 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

$\Theta_w$ = 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

$\Theta_I$ = Virtual temperature (if $T_K \leq$ 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 and outputs data in digital form (Table 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 and RHBuoy_datapub_NEONDOC004402.txt :

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

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

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

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 $T_{d/f}$.

The buoy mounted HMP155 returns data at about 1 measurement per minute. Because of the communication system at the buoys (AD[17]), it is possible that zero or more than one (probably 2 or 3 maximum) measurements will be returned per minute. Thus, for the on-buoy HMP155 the number of values that are averaged may not be a consistent value. Usually, 1-minute mean will be just one instantaneous measurement and 30-minute mean will be a mean of 30 measurements. When zero measurements are returned for a given minute, a timestamp and data may not be published to users.

## 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 SCI 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 SCI 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: persistence and step.  α and β QFs and QMs will be determined using the flags listed in **Table 4**. Since Dew Point is a function of Relative Humidity and Temperature, all flags from those streams will propagate to Dew Point. In addition, L1 DPs will have a QA/QC report and quality metrics associated with each flag listed in **Table 4** 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**.

**Table 4.** 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.** 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

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

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

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 $\Theta_w$ or Eq. (6) for $\Theta_I$, 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*:

$$\frac{dP_{ws_{W_i}}}{dT_{K_i}} = \frac{1}{100}\left(1 - \sum_{j}^{3} j\, C_j T_{k_i}^{(j-1)}\right)\left(-\frac{b_0}{\theta_{w_i}^2} + \sum_{j=2}^{4}(j-1)b_j\theta_{w_i}^{(j-2)} + \frac{b_5}{\theta_{w_i}}\right)$$
$$* e^{\left[\frac{b_0}{\theta_{w_i}} + \sum_{j=1}^{4} b_j\theta_{w_i}^{(j-1)} + b_5 \ln\theta_{w_i}\right]} \tag{12}$$

**Saturation vapor pressure for calculating frost point**

*If $T_{K_i}$ ≤ 273.15 K then*:

$$\frac{dP_{ws_{I_i}}}{dT_{K_i}} = \frac{1}{100}\left(\left(\frac{-a_0}{T_{K_i}^2} + a_2 + 2a_3T_{K_i} + 3a_4T_{K_i}^2 + 4a_5T_{K_i}^3 + \frac{a_6}{T_{K_i}}\right)\right.$$
$$\left. * e^{\left(\frac{a_0}{T_{K_i}}+\sum_{j=1}^{5} a_jT_{K_i}^{(j-1)}+a_6\ln(T_{K_i})\right)}\right) \tag{13}$$

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:

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

### 6.1.1.6    Expanded Measurement Uncertainty

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

$$U_{95}(x_i) = k_{95} * u_c(x_i) \tag{18}$$

Where:

$U_{95}(x_i)$ = respective expanded measurement uncertainty at 95% confidence

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

### 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:

$$u_{NAT}(\bar{X}) = \frac{s(X)}{\sqrt{n}} \tag{19}$$

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[11] 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:

$$u_{TT_{T_K}}\left(\overline{T_{d/f}}\right) = \left|\frac{\partial T_{d/f}}{\partial T_K}\right|_{MAX} u_{A3,T} \tag{20}$$

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

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:

$$MAX = \{i\colon u_c(x_i) = \max[u_c(x_1), \dots, u_c(x_n)]\}. \tag{22}$$

### 6.1.2.3   Combined Uncertainty

**Temperature and relative humidity:**

The combined uncertainty for our L1 mean data products $u_c(\bar{Y})$, 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:

$$u_c(\bar{Y}) = \left(u_{NAT}^2(\bar{Y}) + u_{A3,Y}^2\right)^{\frac{1}{2}} \tag{23}$$

Where, $Y$ represents temperature or relative humidity.

**Dew/frost point temperature:**

$$u_c(\overline{T_{d/f}}) = \left(u_{NAT}^2(\overline{T_{d/f}}) + u_{TT_{T_K}}^2(\overline{T_{d/f}}) + u_{TT_{RH}}^2(\overline{T_{d/f}})\right)^{\frac{1}{2}} \tag{24}$$

### 6.1.2.4 Expanded Uncertainty

The expanded uncertainties are calculated as:

$$U_{95}(\overline{X}) = k_{95} * u_c(\overline{X}) \tag{25}$$

Where:

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

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

### 6.1.2.5 Communicated Precision

L1 average relative humidity data products will be reported to 0.01%. Lab-measured repeatability of the relative humidity is on the order of 0.006%. L1 average temperature and dew point temperature data products will be reported to 0.001 °C. Lab-measured repeatability of the temperature is on the order of 0.004 °C.

## 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.** 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] | $\dfrac{\partial f}{\partial x_i}$ | $u_{x_i}(Y) \equiv \left\lvert\dfrac{\partial f}{\partial x_i}\right\rvert u(x_i)$ [°C] |
|---|---|---|---|---|
| Temperature | $u_{A1,T}$ | AD[11] | n/a | n/a |
| Relative humidity | $u_{A1,RH}$ | AD[11] [unitless] | n/a | n/a |

| Dew/frost point | $u_c\left(T_{d/f_i}\right)$ | Eq. (17) | n/a | n/a |
|---|---|---|---|---|
| Temperature | $u_{A1,T}$ | AD[11] | Eq. (10) | Eq. (14) |
| Relative humidity | $u_{A1,RH}$ | AD[11] [unitless] | Eq. (15) | Eq. (16) |

**Table 6.** 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 [℃] | $\dfrac{\partial f}{\partial x_i}$ | $u_{u_{x_i}}(Y) \equiv \left\lvert\dfrac{\partial f}{\partial x_i}\right\rvert u(x_i)$ [℃] |
|---|---|---|---|---|
| Temperature | $u_c(\overline{T})$ | Eq. (24) | n/a | n/a |
| Calibration | $u_{A3,T}$ | AD[11] | n/a | n/a |
| Natural variation | $u_{NAT}(\overline{T})$ | Eq. (20) | n/a | n/a |
| Relative humidity | $u_c(\overline{RH})$ | Eq. (24) [unitless] | n/a | n/a |
| Calibration | $u_{A3,RH}$ | AD[11] [unitless] | n/a | n/a |
| Natural variation | $u_{NAT}(\overline{RH})$ | Eq. (20) | n/a | n/a |
| Dew/frost point | $u_c(\overline{T_{d/f}})$ | Eq. (25) | n/a | n/a |
| temperature | $u_{A3,T}$ | AD[11] | Eq. (10) | Eq. (21) |
| Relative humidity | $u_{A3,RH}$ | AD[11] [unitless] | Eq. (15) | Eq. (22) |
| Natural variation | $u_{NAT}(\overline{T_{d/f}})$ | Eq. (20) | n/a | n/a |

## 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.

The HMP155 status is a non-numeric value. Currently the on-buoy software cannot parse non-numeric values. The LC will fill the data stream with -1 values. The sensor error cannot be tested due to the fact that the message cannot be parsed on the buoy datalogger.

Calibration tests (i.e., valid calibration) may be included in the future to check whether calibration coefficients are valid for a given time period.

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