ALGORITHM THEORETICAL BASIS DOCUMENT:
TRIPLE REDUNDANT ASPIRATED AIR TEMPERATURE

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1 DESCRIPTION

Contained in this document are details concerning the Triple Redundant Aspirated Air Temperature Sensors (TRAATS) used to determine tower top temperature at all NEON sites. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described. Temperature will be continuously monitored by NEON at tower sites. This document focuses on the Triple Redundant Aspirated Air Temperature Sensors (TRAATS) that will be used to determine tower top temperature.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 data product from Level 0 data, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by the TRAATS. 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 TRAATS are describe in this document. The temperature sensor employed is the Thermometrics Climate RTD 100 Ω Probe. Three Climate RTDs are housed in a Met One 076B fan aspirated radiation shield. The fan aspirated radiation shield reduces error from direct and indirect radiation. This document does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005004	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.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. 000385	C^3 Triple Aspirated Air Temperature
AD[09]	NEON.DOC.000723	Triple Point Temperature Calibration Fixture
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.000751	CVAL Transfer of standard procedure
AD[13]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values
AD[14]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products
AD[15]	NEON.DOC.002002	Engineering Master Location Sensor Matrix

2.2 Reference Documents

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

2.3 Acronyms

Acronym	**Explanation**
ATBD	Algorithm Theoretical Basis Document
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System
DP	Data Product
GRAPE	Grouped Remote Analog Peripheral Equipment
L0	Level 0
L1	Level 1
N/A	Not Applicable
NOAA	National Oceanic Atmospheric Administration
PRT	Platinum Resistance Thermometer
RPS	Revolutions Per Second
RTD	Resistance Temperature Detector
TRAATS	Triple Redundant Aspirated Air Temperature Sensor
TRT	Triple Redundant Temperature

2.4 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

Table 1 details the TRAATS-related L1 DPs provided by the algorithms disclosed in this ATBD.

Table 1. List of TRAATS-related L1 DPs that are produced in this ATBD, where TRT refers to Triple Redundant Temperature not to be confused with the SAATS measurements. Also '00n' represents the tower top level where the TRAAT where be located, see AD[15] for site specific details.

Data product	Averaging Period	Units	Data stream ID
1-minute Mean TRT ($Mean\_TRT_1$)	1-min	°C	NEON.DXX.XXX.DP1.00003.001.001.00n.001
1-minute Minimum TRT (Min_TRT_1)	1-min	°C	NEON.DXX.XXX.DP1.00003.001.002.00n.001
1-minute Maximum TRT (Max_TRT_1)	1-min	°C	NEON.DXX.XXX.DP1.00003.001.003.00n.001
1-minute TRT Variance ($\sigma^2\_TRT_1$)	1-min	°C^2	NEON.DXX.XXX.DP1.00003.001.004.00n.001
1-minute QA/QC TRT Summary ($Qsum\_TRT_1$)	1-min	N/A	NEON.DXX.XXX.DP1.00003.001.005.00n.001
1-minute TRT Averaging Quality Metric ($QM_A\_TRT_1$)	1-min	N/A	NEON.DXX.XXX.DP1.00003.001.006.00n.001
1-minute QA/QC TRT Report ($Qrpt\_TRT_1$)	1-min	N/A	NEON.DXX.XXX.DP1.00003.001.007.00n.001
30-minute Mean TRT ($Mean\_TRT_{30}$)	30-min	°C	NEON.DXX.XXX.DP1.00003.001.001.00n.002
30-minute Minimum TRT (Min_TRT_{30})	30-min	°C	NEON.DXX.XXX.DP1.00003.001.002.00n.002
30-minute Maximum TRT (Max_TRT_{30})	30-min	°C	NEON.DXX.XXX.DP1.00003.001.003.00n.002
30-minute TRT Variance ($\sigma^2\_TRT_{30}$)	30-min	°C^2	NEON.DXX.XXX.DP1.00003.001.004.00n.002
30-minute QA/QC TRT Summary ($Qsum\_TRT_{30}$)	30-min	N/A	NEON.DXX.XXX.DP1.00003.001.005.00n.002
30-minute TRT Averaging Quality Metric ($QM_A\_TRT_{30}$)	30-min	N/A	NEON.DXX.XXX.DP1.00003.001.006.00n.002

3.2 Input Dependencies

Table 2 details the TRAATS-related L0 DPs used to produce L1 DPs in this ATBD.

Table 2. List of TRAATS-related L0 DPs that are transformed into L1 DPs in this ATBD.

Data product	**Sample Frequency**	**Units**	**Data stream ID**
PRT resistance at temperature T (R_{t1})	1 Hz	Ω	NEON.DXX.XXX.DP0.00003.001.001.001.00n.001
PRT resistance at temperature T (R_{t2})	1 Hz	Ω	NEON.DXX.XXX.DP0.00003.001.001.001.00n.002
PRT resistance at temperature T (R_{t3})	1 Hz	Ω	NEON.DXX.XXX.DP0.00003.001.001.001.00n.003
Flow Rate	TBD	TBD	TBD
Heater Status	State Change	Binary	NEON.DXX.XXX.DP0.00003.001.004.001.001.001
Averaging Flag (QF_A)	1 Hz	8 Bit	NEON.DXX.XXX.DP1.00003.001.005.001.001.001

3.3 Product Instances

The TRAATS will be deployed at core and relocatable tower sites. TRAATS will be located on the top level of the tower infrastructure.

3.4 Temporal Resolution and Extent

One- and thirty- minute averages of temperature will be calculated to form L1 DPs.

3.5 Spatial Resolution and Extent

TRAATS will be affixed to the top level at all tower sites. Thus, observations reflect the point in space where the top of the tower is located. Site specific details are located in AD[15].

4 SCIENTIFIC CONTEXT

Temperature is one of the most fundamental physical measurements. It is a primary driving factor for countless physical, chemical, and biological processes. Temperature measurements will serve to provide NEON with ancillary data for numerous other environmental measurements.

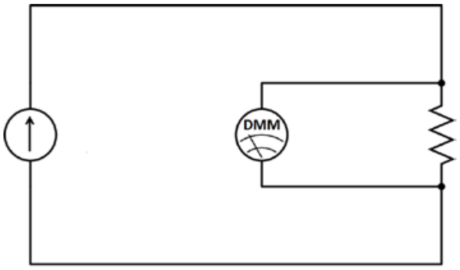

Figure 1. Four-wire measurement for PRT.

4.1 Theory of Measurement

Ultimately, temperature is derived from a PRT. Changes in the PRT resistance due to temperature are determined using a four-wire measurement. The four-wire measurement was chosen due to its decreased dependence on cable length and resistors over the four-wire bridge method. Using a fixed current source the four-wire measurement detects a voltage drop across a resistor using a digital multi-meter (DMM) with high impedance, shown in Figure 1. The voltage drop across the PRT is used, in conjunction with known current source, to calculate the PRT resistance. This measurement technique accomplished by a DMM (i.e. GRAPE) will acquire resistance for NEON operated PRTs.

4.2 Theory of Algorithm

The PRT is one of the most widely used RTD because platinum has the most linear relationship, for changes in resistance to temperature, over the greatest temperature range (−200 to 650 °C). Normally, when evaluating temperatures over the entire range of a PRT, the relationship between temperature and resistance is expressed by two equations due a divergence from linearity. However, NEON is concerned with only a fraction of the PRT's functional range. Thus, within NEON's desired temperature range, the relationship between temperature and resistance is simplified and temperature as a function of resistance can be expressed through a single equation (AD[09]):

$$T_{n,i} = C_{2n} {R_{T_{n,i}}}^2 + C_{1n} R_{T_{n,i}} + C_{0n} \tag{1}$$

Where:

$T_{n,i}$ = Individual (1 Hz) temperature each of the three PRTs (°C)
C_0 = Calibration coefficients provided by CVAL (°C)
C_1 = Calibration coefficients provided by CVAL (°C/Ω)
C_2 = Calibration coefficients provided by CVAL (°C/Ω^2)
$R_{T_{n,i}}$ = Individual (1 Hz) resistance at temperature T (Ω)
n = 3 (i.e. number of PRTs used in the TRAATS)

The TRAATS have three separate temperature measurements, (T_1, T_2, T_3), each obtained from one of the three separate PRT resistances (R_{t1}, R_{t2}, and R_{t3}). To determine how the three temperature measurements will be combined to calculate one temperature for the TRAATS, the following methods will be applied.

4.2.1 Pair-wise Differencing

First, the pair-wise differences among the three temperatures are determined:

$$\begin{aligned}\Delta T_{12} &= |T_1 - T_2| \\ \Delta T_{23} &= |T_2 - T_3| \\ \Delta T_{31} &= |T_3 - T_1|\end{aligned} \tag{2}$$

Due to potential differences in sample "pairing" of sensors with respect to their individual timestamps, "pairing" will be defined by the three measurements that occur within a one second period where time ∈ [0.000000, 1.000000) seconds.

4.2.2 Comparisons

Second, true and false statements are used to determine if the PRTs within the TRAATS are operating normally. Under normal operation, the pair-wise differences for the temperature measurements from the three PRTs should not be greater than the average uncertainty of the two sensors being compared. Hence, a truth value of 'TRUE' is assigned if the statement is true if the difference between the two sensor measurements is less than or equal to the average uncertainty of the two sensors, and false otherwise:

$$\begin{aligned}
\mathrm{A} &= \left| \begin{matrix} \text{True} & \text{if} & \left(\Delta \mathrm{T}_{12} \le \dfrac{u(T_1) + u(T_2)}{2}\right) \\ \text{False} & \text{otherwise} & \end{matrix} \right. \\
\mathrm{B} &= \left| \begin{matrix} \text{True} & \text{if} & \left(\Delta \mathrm{T}_{23} \le \dfrac{u(T_2) + u(T_3)}{2}\right) \\ \text{False} & \text{otherwise} & \end{matrix} \right. \\
\mathrm{C} &= \left| \begin{matrix} \text{True} & \text{if} & \left(\Delta \mathrm{T}_{31} \le \dfrac{u(T_1) + u(T_3)}{2}\right) \\ \text{False} & \text{otherwise} & \end{matrix} \right.
\end{aligned} \tag{3}$$

4.2.3 Truth Tables

Third, results from Eq. (3) are applied to the following truth table to determine what averaging operator is used to compute the resulting, 1 Hz averaged temperature (TRT_i):

Table 3. Treatment of temperature sensor data based on results from pair-wise comparisons.

Inputs				
A	B	C	Averaging Operator	Averaging Flag (QF_A)
T	T	T	$\frac{1}{3}(T_1 + T_2 + T_3)$	0
T	T	F	$\text{median}(T_1, T_2, T_3)$	1
T	F	T	$\text{median}(T_1, T_2, T_3)$	2
T	F	F	$0.5(T_1 + T_2)$	3
F	T	T	$\text{median}(T_1, T_2, T_3)$	4
F	T	F	$0.5(T_2 + T_3)$	5
F	F	T	$0.5(T_1 + T_3)$	6
F	F	F	$\text{median}(T_1, T_2, T_3)$	7

Note: An eight bit averaging flag QF_A will accompany each averaged 1 Hz measurement. This averaging flag will be used for trouble shooting purposes and quality metrics for the eight different outcomes of the flag will be calculated according to AD[14] and included in the QM_A that accompanies a L1 DP.

4.2.4 Conversion to L1 Data Products

Once TRT at 1 Hz is determined from the three PRTs, one-minute ($\overline{TRT_1}$) and thirty-minute ($\overline{TRT_{30}}$) averages of the 1 Hz data will be determined to create L1 DPs for the TRAATS accordingly:

$$\overline{TRT_1} = \frac{1}{n}\sum_{i=x}^{n} TRT_i \qquad (4)$$

where, for each minute average, *n* is the number of measurements in the averaging period T, which is defined as 0 ≤ T < 60 seconds.

and;

$$\overline{TRT_{30}} = \frac{1}{n}\sum_{i=x}^{n} TRT_i \qquad (5)$$

where, for each thirty-minute average, *n* is the number of measurements in the averaging period T and averaging periods are defined as 0 ≤ T < 1800 seconds.

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. TRAATS's 1 Hz L0 DPs will be converted to temperature using Eq. (1) and PRT calibration coefficients provided by CVAL.
2. The averaging method will be applied to determine an individual (1 Hz) TRT_i value for the TRAATS from the three PRT measurements, as outlined in Section 4.2.
3. QA/QC Plausibility tests will be applied to TRT_i data (i.e., Table 3) in accordance with AD[06]. The details are provided below.
4. Signal de-spiking and time series analysis will be applied to TRT_i data (i.e., Table 3) in accordance with AD[07].
5. One- and thirty-minute temperature averages will be calculated using Eq. (4) and (5).
6. Descriptive statistics, i.e., minimum, maximum, and variance, will be determined for the one- and thirty-minute averages.
7. QA/QC consistency tests will be applied to one- and thirty-minute averages in accordance with AD[05].
8. QA/QC Summary (Q_{sum}) will be produced for one-and thirty-minute averages according to AD[14].

QA/QC Procedure:

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

2. **Sensor Test** – Sensor flags (i.e., flow rate and heater) are derived from L0 data products identified in the C^3 document (AD[08]). Any L0 DP (i.e., 1 Hz data) to which the heater and flow rate flags have been applied will not be used to compute L1 DPs. These flags will be combined with the other QA/QC flags and included in the L1 QA/QC summary (details below).
   a. Heater:

$$QF_H = \left| \begin{array}{l} 1 \ if \quad t_i < t < t_i + (1.5 * t_h) \\ \\ 0 \ otherwise \end{array} \right.$$

   Where:

   t = Current time
   t_i = Initial time that the heater turned on
   t_h = Amount of time that the heater stays on for one cycle

   The heater flag configuration tests for whether the heater is on or was on during the preceding time interval. Data will continue to be flagged after the heater shuts off for half of the time the heater was operating, to allow for heat to dissipate around the aspirated shield. The t_h time is described in AD[08] and kept in the CI data store.

   b. Flow Rate:

$$QF_F = \left| \begin{array}{l} 1 \ if \quad F < F_{min} \\ \\ 0 \ otherwise \end{array} \right.$$

   Where: F = Flow rate
   F_{min} = Minimum flow rate

   The flow rate flag indicates whether the sensor is adequately aspirated. F_{min} is a site specific variable that is described in AD[08], provided by ENG, and kept in the CI data store.

3. **Signal De-spiking and Time Series Analysis** – Time segments and threshold values for the automated despiking QA/QC routine will be specified by FIU and maintained in the CI data store. QFs from the despiking analysis will be applied according to AD[07].

4. **Consistency Analysis** – A QA/QC flag for data consistency will be applied according to the consistency analysis outlined in AD[05], and a pass/fail flag will be generated to reflect this activity. L1 DPs from a TRAATS ($TRT_{1\text{-}min}$ and $TRT_{30\text{-}min}$) will be compared to the L1 DPs of the SAATS on the tower level below it. A temperature difference between the TRAATS and the SAATS outside the defined limits, provided by FIU and maintained in the CI data store, will result in a failed test and the L1 DP will be flagged. L1 DPs that fail the consistency analysis will continued to be reported, but will have an associated failed flag that will be include in the QA/QC summary.

5. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[14] – If a datum has one of the following flags it will not be used to create a L1 DP, $\underline{QF_R}$, $\underline{QF_D}$, and $\underline{QF_H}$. α and β QFs and QMs will be determined for the following flags QF_R, QF_σ, QF_δ, QF_S, QF_N, QF_G, QF_D, and QF_H. All L1 DPs will have an associated final quality flag, QF_{NEON}, and quality summary, Qsum, as detailed in AD[16]. As stated in section 4.2.3, QMs for the QF_A will be created (i.e. $QM_{A,0}$, $QM_{A,1}$, $QM_{A,2}$, $QM_{A,3}$, $QM_{A,4}$, $QM_{A,5}$, $QM_{A,6}$, and $QM_{A,7}$). The QMs for the averaging flag will be and reported as a separate DP since this information is intended to be used for trouble shooting purposes only. Flags that may be associated with TRAAT measurements, as well as information maintained in the CI data store can be found below in Tables 4 and 5.

Table 3. Flags associated with TRAATS measurements.

Tests	**Flags**
Range	QF_R
Sigma (σ)	QF_σ
Delta (δ)	QF_δ
Step	QF_S
Null	QF_N
Gap	QF_G
Signal Despiking and Time Series Analysis	QF_D QF_o QF_I

Sensor Test (Heater Flag) AD[08]	QF_H QF_F
Consistency Analysis	QF_V
Final quality flag	QF_{NEON}
Averaging Flag	QF_A

Table 4. Information maintained in the CI data store for TRAATS.

Tests/Values	**CI Data Store Contents**
Range	Minimum and maximum values
Sigma (σ)	Time segments and threshold values
Delta (δ)	Time segment and threshold values
Step	Threshold values
Null	Test limit
Gap	Test limit
Signal Despiking and Time Series Analysis	Time segments and threshold values
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[13]
Sensor Test	QF_F and QF_H as described in AD[08]
Consistency Analysis	Test limits
Final Quality Flag	AD[14]

6 UNCERTAINTY

Uncertainty of measurement is inevitable (JCGM 2008, 2012; Taylor 1997). It is crucial 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 DP) and modeled processes. This portion of the document serves to identify, evaluate, and quantify sources of uncertainty relating to the L1 mean TRT DPs. It is a reflection of the information described in AD[13], and is explicitly described for the TRT assembly in the following sections.

6.1 Uncertainty of Temperature Measurements

Uncertainty of the TRAATS assembly is discussed in this section. Sources of uncertainties include those arising from the calibration procedures, PRT sensors, heater, aspiration, and measurement noise (Figure 2).

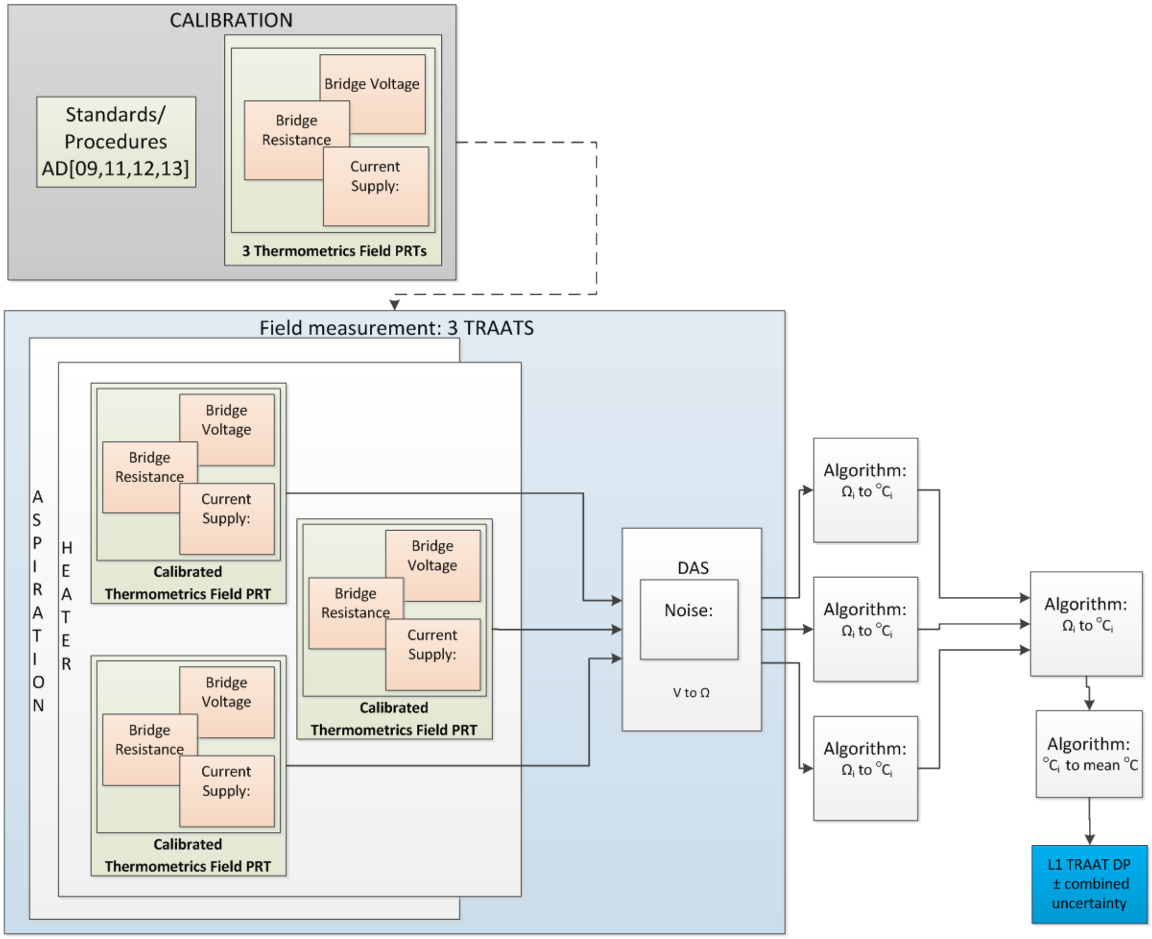

Figure 2: Displays the data flow and associated uncertainties of L1 mean TRT DPs. Salmon colored boxes represent direct measurement of temperature based on theory of PRT resistance. For a detailed explanation of the PRT calibration procedures, please refer to AD[09,11,12,13].

6.1.1 Calibration

Uncertainties associated with PRTs and their calibration processes are combined into an individual, standard uncertainty $u_c(T_{CVAL})$ by CVAL. This combined uncertainty represents i) the variation of an individual sensor from the mean of a sensor population, ii) uncertainty of the calibration procedures and

iii) uncertainty of coefficients used to convert resistance to calibrated station temperature (refer to Eq. (1)). It is a constant value that will be provided by CVAL (AD[15]), stored in the CI data store, and applied to all PRT measurements (that is, it does not vary with any specific sensor, DAS component, etc.).

6.1.2 DAS

To quantify DAS noise, a *relative* uncertainty value, $u_r(\mathrm{R}_{DAS})$ will be provided by CVAL and stored in the CI data store. This value must be converted into a *standard* uncertainty value:

$$u\left(\mathrm{R}_{DAS_i}\right) = \left(u_r(\mathrm{R}_{DAS}) * R_{T_i}\right) + O_{DAS} \quad [\Omega] \tag{6}$$

Where $u\left(\mathrm{R}_{DAS_i}\right)$ represents the standard uncertainty of an *individual,* raw, resistance measurement, R_{T_i}, and O_{DAS} is the offset imposed by the DAS. The offset accounts for readings of 0.00 Ω; its value will be provided by CVAL and maintained in the CI data store. This individual, standard uncertainty is then multiplied by the absolute value of Eq. (1)'s partial derivative:

$$\frac{\partial T_i}{\partial R_{T_i}} = 2C_2 R_{T_i} + C_1 \tag{7}$$

$$u_{R_T}(T_i) = \left|2C_2 R_{T_i} + C_1\right| u\left(R_{T_i}\right) \quad [^{\circ}\mathrm{C}] \tag{8}$$

Where, $u\left(R_{T_i}\right) \equiv u\left(\mathrm{R}_{DAS_i}\right)$

6.1.3 Heater

Throughout NEON's Observatory, the exteriors of aspirated shields are partially wrapped in heating material. This material will be turned on during times when ice buildup causes a potential threat to the aspiration within the shield. When the heater is on, it is hypothesized that a portion of the thermal energy will conduct through the aluminum shield, thus altering the internal temperature of the shield and result in large measurement errors.

At this time, the extent to which the heater will affect the measurement uncertainty is unclear. Because of this, any measurements recorded during times of heating, and for a specified time after the heater is turned off (refer to Section 5), will be flagged. This is an example of an uncertainty that can be identified, but cannot be quantified at this time.

6.1.4 Aspiration

The WMO (2006) argues that aspirated shields result in more accurate temperature measurements than naturally ventilated (passive) shields. However, aspirated shields offer minimal natural ventilation given their design (i.e., non-perforated sides hinder natural ventilation), and large temperature errors may be possible if aspiration ceases.

Met One (1997) states that their 076B aspirated shield minimizes temperature errors to $< 0.05\ °F \approx 0.028$ °C, if flow rate within the shield is $500\ F^3\ min^{-1} \approx 0.236\ m^3\ s^{-1}$. This statement may be somewhat misleading, as Met-One hints that temperature errors are solely a function of aspiration. However, studies involving both passively ventilated and fan-forced (aspirated) shields show that temperature errors are a function of ventilation/aspiration *and insolation* (e.g., Brock *et al*. 1995; Lin *et al*. 2000; Tarara and Hoheisel 2007). Brock *et al*. (1995) noted that when ventilation fell below 2 m s^{-1} and insolation rose above 700 W m^2, temperature errors were > 2°C for multi-plate, passively ventilated shields. Tarara and Hoheisel (2007) found that non-perforated, tube-shaped, aspirated shields were prone to larger temperature errors than naturally ventilated shields when aspiration/ventilation ≤ 1 m s^{-1} and insolation ≥ 600 W m^{-2}. On the contrary, the authors also showed that temperature errors were *negligible* when ventilation/aspiration was ≤ 1 m s^{-1} and insolation < 200 W m^{-2}, for any type of shield, whether passively ventilated or aspirated. These findings suggest that it may be inappropriate to assign an aspiration rate independent of insolation.

Given the findings of the previous authors it seems plausible that large temperature may be possible if aspiration of Met One's 076B shield completely ceases while insolation is > 200 W m^2. However, the magnitude of these errors is currently unknown. In the future it may be possible to derive sufficient aspiration rates as a function of insolation. For instance, following Tarara and Hoheisel (2007), aspiration ≤ 1 m s^{-1} may be acceptable if insolation is < 200 W m^2, however, aspiration should be ≥ 4.0 m s^{-1} to minimize temperature errors during periods when insolation is ≈ 800 W m^2.

Until NEON data are analyzed and aspiration-insolation correlations are derived for Met One's 076B shield, we are unable to quantify the extent in which temperature measurements will be affected if aspiration diminishes or ceases. Until such tests are completed, we will assume that any temperatures measured when aspiration is $< 0.236\ m^3\ s^{-1}$ are accompanied by an unquantifiable systematic uncertainty. Thus, during these instances, data will be flagged and will not be used to calculate L1 DPs. Even when the flow rate is sufficient, data are still accompanied by a random temperature uncertainty:

$$u(A_s) = \pm\, 0.028\ [°\text{C}] \qquad If\ flow\ rate\ \approx\ 0.236\ \text{m}^3\ \text{s}^{-1} \tag{9}$$

6.2 Combined Uncertainty

The calculation of uncertainty for 1 Hz data (TRT_i) will be contingent on the results of the pair-wise differencing tests (Table 3). Ultimately, two scenarios can arise; to avoid ambiguity, each scenario is displayed below:

SCENARIO 1
If QF$_A$ = 0, 3, 5 or 6:

$$u_c(T_{n,i}) = \left(u_{R_T}{}^2(T_{n,i}) + u_c{}^2(T_{CVAL}) + u^2(A_s)\right)^{\frac{1}{2}} \quad [\text{°C}] \tag{10}$$

Where, $T_{n,i}$, is a 1 Hz temperature measurement from each PRT, n. The resulting value is multiplied by the partial derivative of the appropriate equation from Table 3:

$$\frac{\partial TRT_i}{\partial T_{n,i}} = \frac{1}{n} \tag{11}$$

Where n represents the number of valid observations made at 1 Hz. The absolute value of Eq. (11) is then multiplied by Eq. (10):

$$u_{T_{n,i}}(TRT_i) = \left|\frac{1}{n}\right| u_c(T_{n,i}) \quad [\text{°C}] \tag{12}$$

The combined uncertainty for this scenario is simply:

$$u_c(TRT_i) = \left(\sum_{i=1}^{n} u_{T_{n,i}}{}^2(TRT_i)\right)^{\frac{1}{2}} \quad [\text{°C}] \tag{13}$$

SCENARIO 2
If QF$_A$ = 1, 2, 4 or 7:

$$u_c(T_{M,i}) = \left(u_{R_T}{}^2(T_{M,i}) + u_c{}^2(T_{CVAL}) + u^2(A_s)\right)^{\frac{1}{2}} \quad [\text{°C}] \tag{14}$$

Where, $T_{M,i}$ is the median temperature value of the three (i.e., $T_{1,i}, T_{2,i}, T_{3,i}$) 1 Hz temperature measurements. Given that only *one* temperature measurement (i.e., the median), the resulting combined uncertainty is simply:

$$u_c(TRT_i) = u_c(T_{M,i}) \quad [\text{°C}] \tag{15}$$

The combined uncertainty of the L1 mean TRT DPs is then calculated via two simple steps. Firstly, the uncertainties of individual 1 Hz temperature data (TRT_i) are multiplied by the partial derivative (shown in Eq. (16)) of the L1 DP averaging equation:

$$\frac{\partial \overline{TRT}}{\partial TRT_i} = \frac{1}{n} \tag{16}$$

$$u_{TRT_i}(\overline{TRT}) = \left|\frac{1}{n}\right| u_c(TRT_i) \quad [°\mathrm{C}] \tag{17}$$

Finally, the resulting values are summed in quadrature:

$$u_c(\overline{TRT}) = \left(\sum_{i=1}^{n} {u_{TRT_i}}^2(\overline{TRT})\right)^{\frac{1}{2}} \quad [°\mathrm{C}] \tag{18}$$

<u>Note</u>: In some applications the environmental (natural) variation of temperature may be of equal or greater interest than the measurement uncertainty (i.e., combined uncertainty derived in Eq. (18)). Because of this, the natural variation of the mean is presented:

$$u(\overline{TRT}) = \left(\frac{s^2(TRT_i)}{n}\right)^{\frac{1}{2}} \quad [°\mathrm{C}] \tag{19}$$

Where, $s^2(TRT_i)$ is the variance DP (NEON.DXX.XXX.DP1.00002.001.004.00n.00X) and n are the number of observations used to generate the DP. It should be noted that such an equation *assumes* the data are normally distributed.

6.3 Expanded Uncertainty

The expanded uncertainty for the L1 mean TRT DPs can be derived in a few steps. Contingent on the results of the pair-wise difference tests, the first step is to derive the effective degrees of freedom for each 1 Hz datum of the appropriate PRT(s).

SCENARIO 1

If QF$_A$ = 0, 3, 5 or 6:

$$V_{eff\,T_{n,i}} = \frac{u_c{}^4(T_{n,i})}{\frac{u_{R_T}{}^4(T_{n,i})}{Veff_{R_{DAS}}} + \frac{u_c{}^4(T_{CVAL})}{Veff_{T_{CVAL}}} + \frac{u^4(A_s)}{Veff_{A_s}}} \tag{20}$$

Where $Veff_{R_{DAS}}$ and $Veff_{T_{CVAL}}$ are functions of the number of tests conducted by CVAL during calibration – their values will be stored in the CI data store; $Veff_{A_s}$ results from a Type B evaluation and its value will be 100 (please refer to AD[10] for further justification).

Second, the effective degrees of freedom must be calculated for the 1 Hz mean temperature DP (TRT_i):

$$V_{eff\,TRT_i} = \frac{u_c{}^4(TRT_i)}{\sum_{i=1}^{n}\left(\frac{(u_c(T_i)/n)^4}{V_{eff\,T_{n,i}}}\right)} \tag{21}$$

SCENARIO 2

If QF$_A$ = 1, 2, 4 or 7:

$$V_{eff\,T_{M,i}} = \frac{u_c{}^4(T_{M,i})}{\frac{u_{R_T}{}^4(T_{M,i})}{Veff_{R_{DAS}}} + \frac{u_c{}^4(T_{CVAL})}{V_{eff T_{CVAL}}} + \frac{u^4(A_S)}{Veff_{A_s}}} \tag{22}$$

The explanation for Eq. (20) can be applied here, with the exception that this scenario deals with a median value. Because of this, it can be stated that $V_{eff\,TRT_i} = V_{eff\,T_{M,i}}$ for scenario 2.

The effective degrees of freedom for the L1 mean TRT DPs is given by:

$$V_{eff_{\overline{TRT}}} = \frac{{u_c}^4(\overline{TRT})}{\sum_{i=1}^{n}\left(\frac{(u_c(TRT_i)/n)^4}{V_{eff_{TRT_i}}}\right)} \tag{23}$$

Finally, the expanded uncertainty is calculated:

$$U_{95}(\overline{TRT}) = k_{95} * u_c(\overline{TRT}) \quad [°C] \tag{24}$$

Where k_{95} is the coverage factor obtained with the aid of:

- Table 5 from AD[10]
- $V_{eff}(\overline{TRT})$

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

Table 2: Uncertainty budget for L1 mean TRT DPs. Shaded rows denote propagation (from lightest to darkest) of uncertainties.

Source of uncertainty	**Standard uncertainty component u(X_i)**	**Type of eval.**	**Value of standard uncertainty [°C]**	$c_i \equiv \frac{\partial f}{\partial x_i}$	$u_i(Y) \equiv \lvert c_i \rvert u(x_i)$ **[°C]**	**Degrees of Freedom**
L1 TRAATS DP	$u_c(\overline{TRT})$	A	Eq. (18)	N/A	N/A	Eq. (23)
SCENARIO 1: 1 Hz TRAATS	$u_c(TRT_i)$	A,B[1]	Eq. (13)	Eq. (16)	Eq. (17)	Eq. (21)
1 Hz PRT	$u_c\left(T_{n,i}\right)$	A,B[1]	Eq. (10)	Eq. (11)	Eq. (12)	Eq. (20)
Sensor/calibration	$u_c(T_{CVAL})$	AD[13]	AD[13]	1	AD[13]	AD[13]
Noise (DAS)	$u\left(R_{T_{n,i}}\right)$	AD[13]	Eq. (6) [Ω]	Eq. (7)	Eq. (8)	AD[13]
Aspiration	$u(A_s)$	B[1]	Eq. (9)	1	Eq. (9)	100
SCENARIO 2: 1 Hz TRAATS	$u_c(TRT_i)$	A,B[1]	Eq. (15)	Eq. (16)	Eq. (17)	Eq. (22)
1 Hz PRT	$u_c\left(T_{M,i}\right)$	A,B[1]	Eq. (14)	1	Eq. (14)	Eq. (20)
Sensor/calibration	$u_c(T_{CVAL})$	AD[13]	AD[13]	1	AD[13]	AD[13]
Noise (DAS)	$u\left(R_{T_{n,i}}\right)$	AD[13]	Eq. (6) [Ω]	Eq. (7)	Eq. (8)	AD[13]
Aspiration	$u(A_s)$	B[1]	Eq. (9)	1	Eq. (9)	100

k_{95}: $v_{eff_{\overline{TRT}}}$ & Table 5 of AD[10]

$U_{95}(\overline{TRT})$: Eq. (24)

[1] Met One (1997)

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream and included in the QA/QC summary.

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