NEON ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD) - TRIPLE REDUNDANT ASPIRATED AIR TEMPERATURE

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Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	08/02/2013	ECO-00797	Initial Release
B	10/23/2015	ECO-03110	Updated document to reflect L0 and L1 data product renumbering Revised *Algorithm Implementation* and *Uncertainty* Sections. Implemented standardized coverage factor of k=2 Moved consistency analyses outline to Future Plans / Modifications Sections
C	04/20/2022	ECO-06809	• Update to reflect change in terminology from relocatable to gradient sites • Revised logo • Added Neon to document title

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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. Temperature measurements shall be made along a vertical profile using Single Aspirated Air Temperature Sensors (SAATS; those at low- and mid-levels of the tower) and Triple Redundant Aspirated Air Temperature Sensors (TRAATS; those used to determine *tower top temperature).* This document focuses on the latter.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 data products from Level 0 data, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by the 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 ACRONYMS AND VARIABLE NOMENCLATURE

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.002652	NEON Level 1, Level 2, and Level 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[1]
AD[14]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products
AD[15]	NEON.DOC.002002	Engineering Master Location Sensor Matrix
AD[16]	NEON.DOC.000807	ATBD 3D Wind-Turbulent Exchange
AD[17]	NEON.DOC.000780	ATBD 2D Wind Speed and Direction

2.2 Reference Documents

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

2.3 Acronyms

Acronym	Explanation
ATBD	Algorithm Theoretical Basis Document
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System
DP	Data Product
FDAS	Field Data Acquisition System

[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.

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 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. Therefore a lookup table is provided in order to distinguish what symbols specific variables can be tied to in the following document.

Symbol	**Internal Notation**	**Description**
C_0	CVALA0	CVAL PRT calibration coefficient
C_1	CVALA1	CVAL PRT calibration coefficient
C_2	CVALA2	CVAL PRT calibration coefficient
O_R	U_CVALR4	offset imposed by the FDAS for resistance readings, provided by CVAL (Ω)
u_{A1}	U_CVALA1	Combined, relative uncertainty of PRT sensor (%)
u_{A3}	U_CVALA3	Combined, relative uncertainty (truth and trueness only) of PRT sensor (%)
u_{R1}	U_CVALR1	Combined, relative uncertainty of Field DAS resistance readings (%)
u_{R3}	U_CVALR3	Combined, relative uncertainty (truth and trueness only) of Field DAS resistance readings (%)

2.5 Verb Convention

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

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

The single aspirated air temperature related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file tat_datapub_NEONDOC002876.txt.

3.2 Input Dependencies

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

Table 1. List of TRAATS-related L0 DPs that are transformed into L1 DPs in this ATBD.

Data product	Sample Frequency	Units	Data Product Number
PRT resistance at temperature T (R_{T1})	1 Hz	Ω	NEON.DOM.SITE.DP0.00003.001.01325.HOR.VER.101
PRT resistance at temperature T (R_{T2})	1 Hz	Ω	NEON.DOM.SITE.DP0.00003.001.01325.HOR.VER.102
PRT resistance at temperature T (R_{T3})	1 Hz	Ω	NEON.DOM.SITE.DP0.00003.001.01325.HOR.VER.103
Turbine Speed (S_T)	1 Hz	rpm	NEON.DOM.SITE.DP0.00003.001.01330.HOR.VER.000
Heater Status (H)	State Change	NA	NEON.DOM.SITE.DP0.00003.001.01319.HOR.VER.000
3D Sonic Anemometer U component (*U*)	TBD	m s^{-1}	NEON.DOM.SITE.DP0.XXXXX.001.XXXXX.HOR.VER.000
3D Sonic Anemometer V component (*V*)	TBD	m s^{-1}	NEON.DOM.SITE.DP0.XXXXX.001.XXXXX.HOR.VER.000
*2D Sonic Anemometer U component (*U*)	1 Hz	m s^{-1}	NEON.DOM.SITE.DP0.00001.001.01306.HOR.VER.000
*2D Sonic Anemometer V component (V)	1 Hz	m s^{-1}	NEON.DOM.SITE.DP0.00001.001.01307.HOR.VER.000

* The 2D wind speed from the level below tower top, represented as 'n-1', will be initially used until such time that wind speed observations from the 3D sonic anemometer become available.

3.3 Product Instances

The TRAATS will be deployed at core and gradient 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.

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.

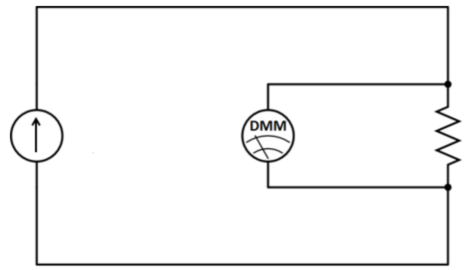

Figure 1. Four-wire measurement for PRT.

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]):

$$T_{k,i} = C_{k,2} * (R_{T_{k,i}}{}^2) + C_{k,1} * (R_{T_{k,i}}) + C_{k,0} \quad (1)$$

Where:

$T_{k,i}$ = Individual (1 Hz) temperature each of the three PRTs (°C)
$C_{k,0}$ = Calibration coefficients for kth PRT provided by CVAL (°C)
$C_{k,1}$ = Calibration coefficients for kth PRT provided by CVAL (°C/Ω)
$C_{k,2}$ = Calibration coefficients for kth PRT provided by CVAL (°C/Ω^2)
$R_{T_{k,i}}$ = Individual (1 Hz) resistance from kth PRT at temperature *T* (Ω)
k = 1, 2 or 3

The TRAATS have three separate temperature measurements, (T_1, T_2, T_3), each obtained from one of the three separate PRT resistances (R_{T_1}, R_{T_2}, and R_{T_3}). 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:

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

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, it is assumed that the pair-wise differences among the temperature measurements from the three PRTs should not be greater than the combined uncertainty [Eq. (10)] of the two sensors being compared. Currently correlation among the sensors is not accounted for, but may be in the future. Thus, a truth value of 'TRUE' is assigned if if the difference between the two sensor measurements is less than or equal to the combined uncertainty of the two sensors and false otherwise:

$$\mathrm{A} = \begin{vmatrix} \mathrm{True} & \mathrm{if} & \left(\Delta \mathrm{T}_{12} \leq \sqrt{u(T_1)^2 + u(T_2)^2}\right) \\ \mathrm{False} & \mathrm{otherwise} & \end{vmatrix}$$

$$\mathrm{B} = \begin{vmatrix} \mathrm{True} & \mathrm{if} & \left(\Delta \mathrm{T}_{23} \leq \sqrt{u(T_2)^2 + u(T_3)^2}\right) \\ \mathrm{False} & \mathrm{otherwise} & \end{vmatrix} \qquad (3)$$

$$\mathrm{C} = \begin{vmatrix} \mathrm{True} & \mathrm{if} & \left(\Delta \mathrm{T}_{31} \leq \sqrt{u(T_1)^2 + u(T_3)^2}\right) \\ \mathrm{False} & \mathrm{otherwise} & \end{vmatrix}$$

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 triple redundant temperature (TRT):

Table 2. Treatment of temperature sensor data based on results from pair-wise comparisons.

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

Note: An eight bit averaging flag 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 as quality metrics and a quality report that accompany the 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 according to Eq. (4) and (5) to create the L1 DPs listed in the file tat_datapub_NEONDOC002876.txt. However, individual calibrated measurements, i.e. 1 Hz TRT, will be made available upon request.

$$\overline{TRT}_1 = \frac{1}{n}\sum_{i=1}^{n} TRT_i \qquad (4)$$

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

Similarly,

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

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

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

5 ALGORITHM IMPLEMENTATION

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

1. 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 individual, 1 Hz, TRT values from the three PRTs in the TRAATS, as outlined in Section 4.2.
3. QA/QC Plausibility tests will be applied to the TRT data (i.e., **Table 2**) in accordance with AD[06]. The details are provided below.
4. Signal de-spiking will be applied to TRT data (i.e., **Table 2**) 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. Quality metrics, quality flags, and the final quality flag will be produced for one- and thirty-minute averages according to AD[14].

QA/QC Procedure:

1. **Plausibility Tests** AD[06] – All plausibility tests will be determined for the TRT. 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 C³ document (AD[08]). Any L0 DP (i.e., 1 Hz data) that have a heater and flow rate flag applied will not be used in the computation of a L1 DPs. Quality reports will be created for these flags as described in AD[14].

   a. Heater:

$$QF\_H = \begin{cases} 1 \;\; if \quad t_i < t < t_i + (1.5 * Z) \\ 0 \;\; otherwise \end{cases}$$

Where:

t = Current timestamp

t_i = Most recent timestamp that the heater turned on, i.e. state change of H (NEON.DXX.XXX.DP0.00003.001.004.001.00n.001) in AD[08]

Z = Amount of time that the heater stays on for one cycle AD[08]

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.

b. Flow Rate:

The flow rate quality flag (QF_F) indicates whether the sensor is adequately aspirated. If the sensor is not adequately aspirated the quality flag will be set high, i.e. QF_F = 1, and QF_F = 0 otherwise. To determine whether sufficient aspiration is present QF_F incorporates the turbine speed, i.e., S_T, as well as the wind speed measurement from the corresponding tower level. Wind speed is needed to account for wind based biases induced in the turbine measurement when wind speeds are > 12 m/s. However, the tower top 3D wind sensor will not accompany the initial deployment of TRAAT sensor. Thus, initially horizontal wind speed will be determined from the 2D wind measurements on the boom below the tower top level, i.e., data products NEON.DOM.SITE.DP0.00001.001.01306.HOR.VER.000 and NEON.DOM.SITE.DP0.00001.001.01307.HOR.VER.000 according to Eq. (3) in AD[17]. Yet, once the 3D sonic anemometers have been deployed on the tower top, horizontal wind speed will be determined via data products NEON.DOM.SITE.DP0.XXXXX.001.XXXXX.HOR.VER.000 and NEON.DOM.SITE.DP0.XXXXX.001.XXXXX.HOR.VER.000 according to AD[16]. Once the corresponding wind speed, i.e., W_s, has been determined the QF_F will be set accordingly:

$$QF\_F = \left| \begin{array}{l} 1 \;\; if \;\; \frac{1}{n}\sum_{i=1}^{n} \mathrm{S}_{T\,i} < 650\ RPM\ and\ W_s < 12\ \mathrm{m/s} \\ \\ 0 \;\; otherwise \end{array} \right.$$

Where, *n* is the number of observations captured in a 30 second interval. It is necessary to average the turbine speed over a thirty second period due to the resolution of the sensor, which is digitized to intervals of 30 RPM. W_s is determined as the 1Hz wind speed that corresponds to the last 1Hz turbine measurement in a 30 second average, where the one second period is defined as ∈ [0.000000, 1.000000) seconds. For a given flow rate flag, its status will be applied to the corresponding 30 second interval of 1 Hz temperature measurements that were captured during its computation, where a 30 second period is defined as ∈ [0.000000, 30.000000) seconds.

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

4. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[14] **–** If a datum has failed one of the following tests it will not be used to create a L1 DP, ***range***, ***persistence***, ***step***, ***heater***, and ***flow***. α and β QFs and QMs will be determined for all of the external flags, **Table 3**. In addition, L1 DPs will have a quality report and quality metrics associated with each flag listed in **Table 3** as well as a final quality flag, as detailed in AD[14]. Ancillary information needed for the algorithm and other information maintained in the CI data store is shown in **Table 4**.

Table 3. Flags associated with TRAATS measurements.

Tests
Range
Persistence
Step
Null
Gap
Signal De-spiking
Sensor Tests AD[09]
Averaging Flag
Alpha
Beta
Final quality flag

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

Tests/Values	CI Data Store Contents
Range	Minimum and maximum values
Persistence	Window size, threshold values and maximum time length
Step	Threshold values
Null	Test limit
Gap	Test limit
Signal De-spiking	Time segments and threshold values
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[13]
Sensor Test	heater and flow thresholds
Consistency Analysis	Test limits
Final Quality Flag	AD[14]

6 UNCERTAINTY

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

6.1 Uncertainty of Temperature Measurements

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

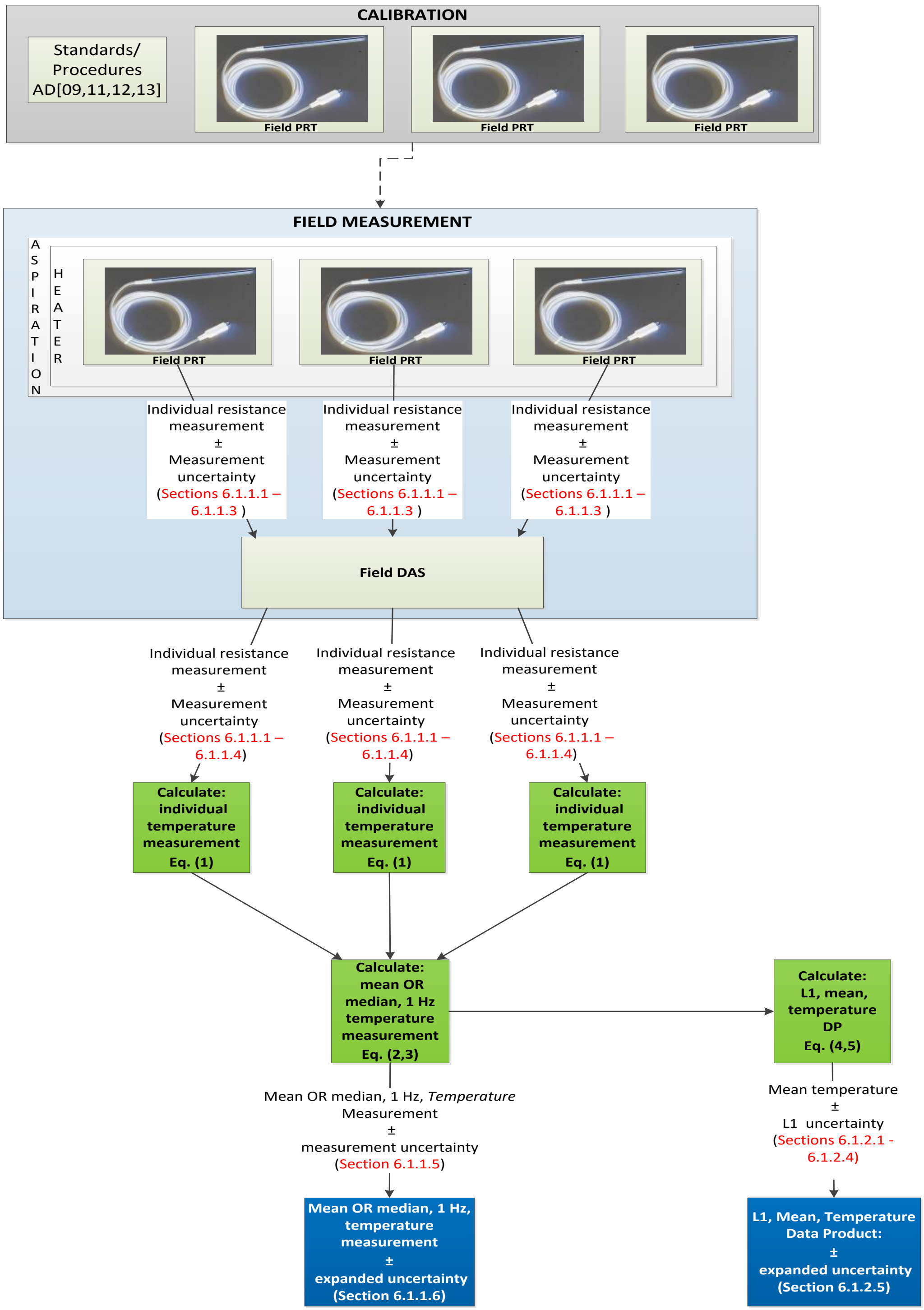

Figure 2. Displays the data flow and associated uncertainties of individual TRT measurements and L1 mean TRT DPs. A detailed explanation of the PRT calibration procedures, please refer to AD[09,11,12].

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with *individual temperature 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* temperature measurement. These uncertainties should not be confused with those presented in Section 6.1.2. We urge the reader to refer to AD[11] for further details concerning the discrepancies between quantification of measurement uncertainties and L1 uncertainties.

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

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

$$u_c(y) = \left(\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)\right)^{\frac{1}{2}} \quad (6)$$

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. For temperature measurements, the sources of uncertainty are depicted in **Figure 2**. The calculation of these input uncertainties is discussed below.

6.1.1.1 Calibration

Uncertainties associated with the PRT calibration process propagate into a standard, combined measurement uncertainty. This combined uncertainty, u_{A1}, represents i) the repeatability and reproducibility of the sensor and the lab DAS and ii) uncertainty of the calibration procedures and coefficients including uncertainty in the standard (truth) (refer to Eq. (1)). It is a constant value that will be provided by CVAL (AD[15]), stored in the CI data store, and applied to all *individual temperature measurements* (that is, it does not vary with any specific sensor, DAS component, location, etc.). A detailed summary of the calibration procedures and corresponding uncertainty estimates can be found in AD[09,11,12].

6.1.1.2 Heater

Throughout the 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 (refer to AD[08] for specifics). 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 cause measurement bias.

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.

6.1.1.3 Aspiration

The WMO (2006) argues that aspirated shields, i.e., those that utilize fan-forced air, result in more accurate temperature measurements than naturally ventilated (passive) shields. However, this is assuming that aspiration within the shield is of a magnitude that minimizes the effects of incoming solar radiation. 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 slows or ceases.

Met One (1997) states that their 076B aspirated shield reduces temperature biases to $< 0.05\ °F\ (0.028\ °C)$ at 1120 W m^{-2} of incoming solar radiation; this is also assuming that aspiration within the shield is approximately $500\ F^3\ min^{-1} (0.236\ m^3\ s^{-1})$. Unfortunately, the latter is the only uncertainty metric that Met One (1997) supplies. The company does not supply uncertainty estimates as functions of varying magnitudes of insolation or aspiration. Thus, their statement can be thought of as a worst case uncertainty, *applicable only when the aspiration within the shield is maintained at* $\sim 0.236\ m^3\ s^{-1}$. It is unclear how large these temperature biases could be if the aspiration within the shield slows or ceases.

Studies involving both passively ventilated and fan-forced (aspirated) shields show that temperature errors are a function of both 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 natural 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.

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. As stated previously, the magnitudes of these errors are currently unknown. In the future it may be possible to derive sufficient aspiration, i.e., those that minimize temperature bias, 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, it also may be possible that aspiration should be ≥ 4.0 m s^{-1} to minimize temperature biases during periods when insolation is ≥ 800 W m^2.

As a conservative approach we assume that temperatures measured when aspiration is << $0.236\, m^3\, s^{-1}$ are accompanied by an unquantifiable systematic uncertainty. During these instances data will be flagged and will not be used to calculate L1 DPs. At current date, NEON will not correct for the temperature bias described by Met One (1997). We encourage the end-user to use scientific judgment when applying this 0.028 ℃ temperature bias, and caution that this bias may be unrepresentative of actual biases over a range of incoming solar radiation and aspiration rates.

6.1.1.4 Field DAS

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

$$u_{FDAS}\left(R_{T_{k,i}}\right) = \left(u_{R1} * R_{T_{k,i}}\right) + O_R \tag{7}$$

Where:

$u_{FDAS}\left(R_{T_{k,i}}\right)$ = standard uncertainty of the resistance measurement introduced by the Field DAS (Ω); computed for each PRT sensor, k

$R_{T_{k,i}}$ = *individual,* raw, resistance measurement (Ω); computed for each PRT sensor, k

u_{R1} = combined, relative Field DAS uncertainty for resistance measurements provided by CVAL (unitless)

O_R = offset imposed by the FDAS for resistance readings, provided by CVAL (Ω)

$$\frac{\partial T_{k,i}}{\partial R_{T_{k,i}}} = (2 * C_{k,2} * R_{T_{k,i}}) + C_{k,1} \tag{8}$$

$$u_{FDAS_{R_T}}(T_{k,i}) = \left|\frac{\partial T_{k,i}}{\partial R_{T_{k,i}}}\right| u_{FDAS}(R_{T_{k,i}}) \tag{9}$$

Where:

$C_{k,2}$ = calibration coefficients for k^{th} PRT provided by CVAL (°C/Ω^2)

$C_{k,1}$ = calibration coefficient for k^{th} PRT provided by CVAL (°C/Ω)

$u_{FDAS_{R_T}}(T_{k,i})$ = converted, combined, standard uncertainty introduced by the Field DAS (°C); computed for each PRT sensor, k

6.1.1.5 Combined Measurement Uncertainty

The calculation of measurement uncertainty for 1 Hz data (TRT_i) will be contingent on the results of the pair-wise differencing tests (**Table 2**). Ultimately, two scenarios can arise; to avoid ambiguity, each scenario is detailed below:

SCENARIO 1

If QF_A = 0, 3, 5 or 6:

$$u_c(T_{k,i}) = \left(u_{A1}^2 + u_{FDAS_{R_T}}^2(T_{k,i})\right)^{\frac{1}{2}} \tag{10}$$

Where $T_{k,i}$, is a 1 Hz temperature measurement from PRT k, $k \in S$. $S \subseteq \{1,2,3\}$ identifies the PRT sensors used to calculate TRT_i according to **Table 2**. The resulting value is multiplied by the partial derivative of the appropriate equation from **Table 2** with respect to $T_{k,i}$:

$$\frac{\partial TRT_i}{\partial T_{k,i}} = \frac{1}{\#S} \tag{11}$$

Where $\#S$ represents the number of sensors used to calculate TRT_i (e.g., if QF_A =3, #*S*=2). The absolute value of Eq. (11) is then multiplied by Eq. (10):

$$u_{T_{k,i}}(TRT_i) = \left|\frac{\partial TRT_i}{\partial T_{k,i}}\right| u_c(T_{k,i}) \tag{12}$$

Following Eq. (6), the combined uncertainty for this scenario is simply:

$$u_c(TRT_i) = \left(\sum_{k \in S} u_{T_{k,i}}^2(TRT_i)\right)^{\frac{1}{2}} \tag{13}$$

SCENARIO 2

If QF_A = 1, 2, 4 or 7:

In this case, the median of the three PRT readings is used for the TRT value.

$$u_c(T_{M,i}) = \left(u_{A1}^2 + u_{FDAS_{R_T}}^2(T_{M,i})\right)^{\frac{1}{2}} \tag{14}$$

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

6.1.1.6 Expanded Measurement Uncertainty

Regardless of which scenario the individual temperature measurement qualifies as, the expanded measurement uncertainty is calculated as:

$$U_{95}(TRT_i) = k_{95} \; * u_c(TRT_i) \tag{15}$$

Where:

$U_{95}(TRT_i)$	= expanded measurement uncertainty at 95% confidence (°C)
k_{95}	= 2; coverage factor for 95% confidence (unitless)

6.1.2 Uncertainty of L1 Mean Temperature Data Product

The following subsections discuss uncertainties associated with L1 mean temperature 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 *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 the temperature measurements for the specified time period:

$$u_{NAT}(\overline{TRT}) = \frac{s(TRT_i)}{\sqrt{n}} \quad [°\mathrm{C}] \tag{16}$$

where $s(TRT_i)$ is the experimental standard deviation of 1 Hz temperature observations for the specified averaging period, and n is the number of observations made over the same time period.

6.1.2.2 Calibration

The uncertainty detailed here is similar to that described in Section 6.1.1.1. However, the relevant uncertainty for the mean DPs, u_{A3}, does not consider i) individual sensor repeatability, or ii) the variation of sensors' responses over a population of sensors (reproducibility). This component of uncertainty estimates the uncertainty due to the accuracy of the instrumentation in the form of *Truth* and *Trueness*, a quantity which is not captured by the standard error of the mean. It is a constant value that will be provided by CVAL (AD [13]) and stored in the CI data store. Please refer to AD[10] for further justification regarding evaluation and quantification of this combined uncertainty.

6.1.2.3 Field DAS

Since the L1 mean temperature DP is a function of the individual temperature measurements, any measurement bias introduced by the Field DAS will be reflected in the L1 mean data product. Here, the individual raw measurement(s) that maximizes the combined uncertainty of an individual measurement (Eq. (13) or (14)) is used in the calculation of the L1 mean DP uncertainty. Uncertainty components due to random effects, whether a function of the environment or the measurement assembly, are quantified via the natural variation of the mean (see Section 6.1.2.1). For more information regarding the justification of this approach, please see AD[10].

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

$$u_{FDAS(TT)}\left(R_{T_{k,MAX}}\right) = \left(u_{R3} * R_{T_{k,MAX}}\right) + O_R \tag{17}$$

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

$$MAX = \{i: u_c(TRT_i) = \max[u_c(TRT_1), \dots, u_c(TRT_n)]\}. \tag{18}$$

Also,

$u_{FDAS(TT)}\left(R_{T_{k,MAX}}\right)$ = Field DAS *Truth* and *Trueness* uncertainty of $R_{T_{k,MAX}}$ (Ω)

$R_{T_{k,MAX}}$ = individual, raw, resistance measurement from sensor *k* observed at MAX index (Ω)

u_{R3} = relative, combined, Field DAS *Truth* and *Trueness* for resistance measurements, provided by CVAL (unitless)

O_R = offset imposed by the FDAS for resistance measurements, provided by CVAL (Ω)

Thus, analogous to Eq. (9),

$$u_{FDAS(TT)}\left(T_{k,MAX}\right) = \left|\frac{\partial T_k}{\partial R_{T_k}}\right|_{R_{T_{k,MAX}}} u_{FDAS(TT)}\left(R_{T_{k,MAX}}\right), \tag{19}$$

where:

$\left|\frac{\partial T_k}{\partial R_{T_k}}\right|_{R_{T_{k,MAX}}}$ = partial derivative of T_k with respect to R_{T_k} (Eq. (8)) evaluated at $R_{T_{k,MAX}}$ (°C/Ω)

$u_{FDAS(TT)}\left(T_{k,MAX}\right)$ = Field DAS *Truth* and *Trueness* uncertainty of $T_{k,MAX}$ (°C)

6.1.2.4 Combined Uncertainty

The combined uncertainty depends upon the method used to calculate TRT_i.

SCENARIO 1

If QF_A = 0, 3, 5 or 6:

$$u_c(T_{k,MAX}) = \left(u_{A3}^2 + u_{FDAS(TT)}^2(T_{k,MAX})\right)^{\frac{1}{2}} \tag{20}$$

Where $T_{k,MAX}$ is an individual temperature measurement from PRT *k* observed at the MAX index. The resulting value is multiplied by the partial derivative of the appropriate equation from **Table 2** with respect to T_k :

$$u_{T_{k,MAX}}(TRT_{MAX}) = \frac{1}{\#S} u_c(T_{k,MAX}) \tag{21}$$

The combined uncertainty for this scenario is simply:

$$u_c(\overline{TRT}) = \left(u_{NAT}^2(\overline{TRT}) + \sum_{k \in S} u_{T_{k,MAX}}^2(TRT_{MAX})\right)^{\frac{1}{2}} \tag{22}$$

SCENARIO 2

If QF_A = 1, 2, 4 or 7:

Because only *one* temperature measurement (i.e., the median) is used, the resulting combined uncertainty is simply:

$$u_c(\overline{TRT}) = \left(u_{NAT}^2(\overline{TRT}) + u_{A3}^2 + u_{FDAS(TT)}^2(T_{M,MAX})\right)^{\frac{1}{2}} \tag{23}$$

Where, $T_{M,MAX}$ is the *median* temperature measurement of the three (i.e., $T_{1,MAX}, T_{2,MAX}, T_{3,MAX}$) instantaneous, individual , temperature measurements corresponding to the MAX index, and is derived using Eq. (17) through (19).

6.1.2.5 Expanded Uncertainty

Regardless of which scenario the temperature DP qualifies as, the expanded uncertainty is calculated as:

$$U_{95}(\overline{TRT}) = k_{95} * u_c(\overline{TRT}) \tag{24}$$

where:

$U_{95}(\overline{TRT})$ = expanded measurement uncertainty at 95% confidence (°C)

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

6.2 Uncertainty Budget

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

Table 5. Uncertainty budget for an individual TRAAT measurement. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of measurement uncertainty	**Measurement uncertainty component $u(x_i)$**	**Measurement uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ **[°C]**
SCENARIO 1: 1 Hz TRT	$u_c(TRT_i)$	Eq. (13) [°C]	n/a	n/a
1 Hz temp.	$u_c(T_{k,i})$	Eq. (10) [°C]	Eq. (11)	Eq. (12)
Sensor/calibration	u_{A1}	AD[13] [°C]	1	AD[13]
FDAS	$u_{FDAS}(R_{T_{k,i}})$	Eq. (7) [Ω]	Eq. (8)	Eq. (9)
SCENARIO 2: 1 Hz TRT	$u_c(TRT_i)$	Eq. (14) [°C]	n/a	n/a
1 Hz temp.	$u_c(T_{M,i})$	Eq. (14) [°C]	1	Eq. (14)
Sensor/calibration	u_{A1}	AD[13] [°C]	1	AD[13]
FDAS	$u_{FDAS}(R_{T_{M,i}})$	Eq. (7) [Ω]	Eq. (8)	Eq. (9)

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

Source of uncertainty	**Uncertainty component $u(x_i)$**	**Uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\|\frac{\partial f}{\partial x_i}\right\| u(x_i)$ **[°C]**
SCENARIO 1: L1 mean TRT DP	$u_c(\overline{TRT})$	Eq. (22) [°C]	n/a	n/a
Natural variation	$u_{NAT}(\overline{TRT})$	Eq. (16) [°C]	1	Eq. (16)
Ind. PRT obs.	$u_c(T_{k,MAX})$	Eq. (20) [°C]	Eq. (11)	Eq. (21)
Sensor(TT)	u_{A3}	AD[13] [°C]	1	AD[13]
FDAS (TT)	$u_{FDAS(TT)}\left(R_{T_{k,MAX}}\right)$	Eq. (17) [Ω]	Eq. (8)	Eq. (19)
SCENARIO 2: L1 mean TRT DP	$u_c(\overline{TRT})$	Eq. (23) [°C]	n/a	n/a
Natural variation	$u_{NAT}(\overline{TRT})$	Eq. (16) [°C]	1	Eq. (16)
Sensor(TT)	u_{A3}	AD[13] [°C]	1	AD[13]
FDAS (TT)	$u_{FDAS(TT)}\left(R_{T_{M,MAX}}\right)$	Eq. (17) [Ω]	Eq. (8)	Eq. (19)

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream. Additionally, individual calibrated and QA/QCd measurements with their respective uncertainties may become a common data output.

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

QA/QC tests may be expanded to include consistency analyses among similar measurement streams. 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, i.e., meanTRT_1 and meanTRT_30) 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.

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