ALGORITHM THEORETICAL BASIS DOCUMENT: 2D WIND SPEED AND DIRECTION

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1 DESCRIPTION

Contained in this document are details concerning wind measurements made at all NEON sites. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described. Wind will be continuously monitored by NEON at all core and relocatable sites via 2- and 3-dimensional sonic anemometers; this document focuses on 2D sonic anemometers.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 (L1) data products (DPs) for 2D sonic anemometers, and ancillary data as defined in this document (such as calibration data) obtained via instrumental measurements made by the 2D sonic anemometers. It includes a detailed discussion of measurement theory and implementation, appropriate theoretical background, data product provenance, quality assurance and control methods, 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 2D anemometers are describe in this document. The employed anemometers are Gill's Wind Observer II (WOII) and Extreme Weather Wind Observer (EWW0). The WOII has two versions: heated and non-heated; use of either will be site dependent throughout the Observatory. 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.002002	Engineering Master Location Sensor Matrix
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.000782	ATBD QA/QC Data Consistency
AD[09]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[10]	NEON.DOC.000387	2D Wind Sensor Configuration, Command and Control
AD[11]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[12]	NEON.DOC.000784	ATBD Profile Development
AD[13]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values (CVAL)
AD[14]	NEON.DOC.000902	2D Sonic Anemometer Validation Procedure (CVAL)
AD[15]	NEON.DOC.000387	2D Wind C^3 Document
AD[16]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products

2.2 Reference Documents

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

2.3 Acronyms and Variables

Acronym	**Explanation**
$\overline{A}$	Mean, minimum angular distance
A_i	Individual, minimum angular distance
$A_{i,c}$	Individual, corrected, minimum angular distance
A/D	Analog to Digital
ATBD	Algorithm Theoretical Basis Document
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System
DP	Data Product
ENG	NEON Engineering department
EWWO	Gill's Extreme Weather Wind Observer 2D Sonic Anemometer
L0	Level 0
L1	Level 1
LHDD	Location Hierarchy Design Document
S	Wind Speed
U	Meridional (north –south) vector component

UQ	Unquantifiable uncertainty
V	Zonal (east – west) vector component
WOII	Gill's Wind Observer II Sonic Anemometer
Θ	Wind Direction
θ_i	Individual wind direction θ_i
$\theta_{i,c}$	Individual, corrected angle (wind direction) measurement
$\bar{\theta}$	Mean, unit vector wind direction measurement
$\bar{\theta}_c$	Mean, corrected angle (wind direction) θ_i
$\bar{\theta}_T$	Averaged wind direction; T denotes averaging period
θ_{T,σ^2}	Wind direction variance; T denotes averaging period

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 DETAILED DESCRIPTION

3.1 Variables Reported

A suite of L1 data products will be produced by the algorithms displayed within this document. Statistical data associated with wind direction will only be that of variance; *values of minimum and maximum wind directions are misleading and are therefore not included as data products*.

Table 1: List of 2D wind L1 DPs produced in this ATBD. **Note:** The '0XX' in the eighth field of the Data Product ID refers to the vertical location of the sensor. '001' refers to the lowest sensor on the tower infrastructure.

Level 1 Data Product	**Averaging Period**	**Units**	**Data Product ID**
2-minute Mean Wind Speed ($Mean\_S_2$)	2-min.	$m\ s^{-1}$	NEON.DXX.XXX.DP1.00001.001.001.0XX.001
2-minute Minimum Wind Speed (Min_S_2)	2-min.	$m\ s^{-1}$	NEON.DXX.XXX.DP1.00001.001.002.0XX.001
2-minute Maximum Wind Speed (Peak gust) (Max_S_2)	2-min.	$m\ s^{-1}$	NEON.DXX.XXX.DP1.00001.001.003.0XX.001
2-minute Wind Speed Variance ($\sigma^2\_S_2$)	2-min.	$(m\ s^{-1})^2$	NEON.DXX.XXX.DP1.00001.001.004.0XX.001
2-minute QA/QC Wind Speed Summary ($Qsum\_S_2$)	2-min.	text	NEON.DXX.XXX.DP1.00001.001.005.0XX.001
2-minute QA/QC Wind Speed Report ($Qrpt\_S_2$)	2-min.	text	NEON.DXX.XXX.DP1.00001.001.006.0XX.001

30-minute Mean Wind Speed ($Mean\_S_{30}$)	30-min.	m s^{-1}	NEON.DXX.XXX.DP1.00001.001.001.0XX.002
30-minute Minimum Wind Speed (Min_S_{30})	30-min.	m s^{-1}	NEON.DXX.XXX.DP1.00001.001.002.0XX.002
30-minute Maximum Wind Speed (Peak gust) (Max_S_{30})	30-min.	m s^{-1}	NEON.DXX.XXX.DP1.00001.001.003.0XX.002
30-minute Wind Speed Variance ($\sigma^2\_S_{30}$)	30-min.	(m s^{-1})^2	NEON.DXX.XXX.DP1.00001.001.004.0XX.002
30-minute QA/QC Wind Speed Summary ($Qsum\_S_{30}$)	30-min.	text	NEON.DXX.XXX.DP1.00001.001.005.0XX.002
2-minute Wind Direction ($Mean\_\theta_2$)	2-min.	degrees	NEON.DXX.XXX.DP1.00001.001.007.0XX.001
2-minute Wind Direction Variance ($\sigma^2\_\theta_2$)	2-min.	degrees^2	NEON.DXX.XXX.DP1.00001.001.008.0XX.001
2-minute QA/QC Wind Direction Summary ($Qsum\_\theta_2$)	2-min.	Text	NEON.DXX.XXX.DP1.00001.001.009.0XX.001
2-minute QA/QC Wind Direction Report($Qrpt\_\theta_2$)	2-min.	Text	NEON.DXX.XXX.DP1.00001.001.010.0XX.001
30-minute Wind Direction ($Mean\_\theta_{30}$)	30-min.	degrees	NEON.DXX.XXX.DP1.00001.001.007.0XX.002
30-minute Wind Direction Variance ($\sigma^2\_\theta_{30}$)	30-min.	degrees^2	NEON.DXX.XXX.DP1.00001.001.008.0XX.002
30-minute QA/QC Wind Direction Summary ($Qsum\_\theta_{30}$)	30-min.	Text	NEON.DXX.XXX.DP1.00001.001.009.0XX.002

3.2 Input Dependencies

The L0 data used to produce L1 wind DPs are shown in Table 2.

Table 2: List of L0 DPs from 2D anemometer used to produce L1 wind DPs

Data Product	**Sample Frequency**	**Units**	**Data Product ID**
U component	1 Hz	m s^{-1}	NEON.DXX.XXX.DP0.00001.001.001.001.XXX.001
V component	1 Hz	m s^{-1}	NEON.DXX.XXX.DP0.00001.001.002.001.XXX.001

3.3 Product Instances

Multiple 2D anemometers will be deployed at tower sites. These will be located on each boom arm below the top of the tower.

3.4 Temporal Resolution

Two- and thirty-minute averages of wind speed and direction will be calculated to form L1 DPs.

3.5 Spatial Resolution and Extent

Each 2D anemometer will represent the point at which it is placed on the tower infrastructure. Ultimately, wind speed and direction profiles will be developed for each tower site from the array of 2D anemometers on the tower (see AD[05] for detail on sensor placement for a specific core site, and AD[12] for description of the algorithms used for deriving this profile).

4 SCIENTIFIC CONTEXT

Wind plays an important role in atmospheric and environmental sciences. A function of differential heating of Earth's surface and subsequent pressure gradients, horizontal and vertical winds are responsible for advection of atmospheric pollutants, moisture, heat and momentum (Stull 1988). As such, horizontal and vertical winds will be measured throughout the NEON Observatory. This document details the processes by which mean horizontal wind is derived.

4.1 Theory of Measurement

Two-dimensional sonic anemometry relies on two pairs of transducers that measure wind velocity along orthogonal axes. Sound pulses are simultaneously emitted from each transducer. The times taken for ultrasonic pulses to travel along their respective axis to the far transducer head are compared between one another (Gill 2005) - for example, T_1 is compared with T_2 (Figure 1). This process is completed for the east – west and north-south axes independently. Wind velocities (i.e. zonal and meridional vector components) can then be calculated from the differences in flight times across each axis (Brock and Richardson 2001; Gill 2005). Wind velocity along each axis is computed with:

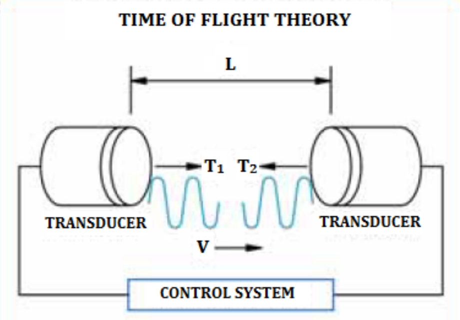

Figure 1. Ultrasonic anemometer theory (Gill 2007).

$$U_i = \frac{L_U}{2}\left(\frac{1}{T_{1_i}} - \frac{1}{T_{2_i}}\right) \tag{1}$$

And

$$V_i = \frac{L_V}{2}\left(\frac{1}{T_{1_i}} - \frac{1}{T_{2_i}}\right) \tag{2}$$

Where:

T_{1_i} & T_{2_i} = Individual (1 Hz) transit times of ultrasonic pulses
L = Distance between transducer faces
U_i = Individual meridional (N-S) velocity (Figure 2).
V_i = Individual zonal (E-W) velocity (Figure 2).

Gill's 2D anemometers have an internal Analog to Digital (A/D) converter. Thus, NEON's Data Acquisition System (DAS) will acquire vector magnitudes in digital form.

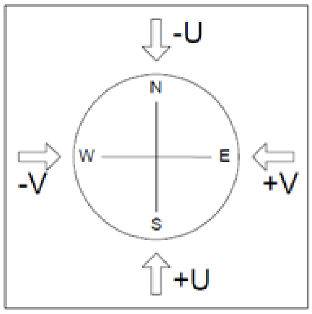

Figure 2. Gill's (2007,2011) coordinate system

4.2 Theory of Algorithms

The following sections describe the theory and implementation of algorithms for 2D sonic anemometer measurements.

4.2.1 Wind Speed

The magnitude of the horizontal wind speed, S_i, will be calculated for each 1 Hz, Level 0 datum, in accordance with the Pythagorean Theorem:

$$S_i = \left(U_i^2 + V_i^2\right)^{\frac{1}{2}} \tag{3}$$

After the vector components are converted to horizontal wind speed, two-minute ($\bar{S}_2$) and thirty-minute ($\bar{S}_{30}$) averages of horizontal wind speed will be determined accordingly to create L1 SAAT DPs:

$$\bar{S}_2 = \frac{1}{n}\sum_{i=1}^{n} S_i. \tag{4}$$

where, for each two-minute average, *n* is the number of measurements in the averaging period T, which is defined as 0 ≤ T < 120 seconds.

and

$$\bar{S}_{30} = \frac{1}{n}\sum_{i=1}^{n} S_i. \tag{5}$$

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.

4.2.2 Wind Direction

Individual wind direction, θ_i, will be calculated for each Level 0 datum independent of wind speed magnitude.

$$\theta_i = \tan^{-1}\left(\frac{V_i}{U_i}\right), \tag{6}$$

Gill's (2007, 2011) coordinate system is rotated 90° relative to a normal, polar coordinate system (Figure 3A). Additionally, all of Gill's 2D anemometers will be positioned upside down throughout the NEON Observatory (refer to AD[10]), thus the zonal plane is essentially flipped (Figure 3B). To account for both modifications, the coordinate system must be rotated 180° to ensure the data correspond to a normal, polar coordinate system (Figure 3C) and resulting values are representative of the correct quadrant (*e.g.,* sin and cosine of resulting angle will be positive for wind directions between 0° and 90°).

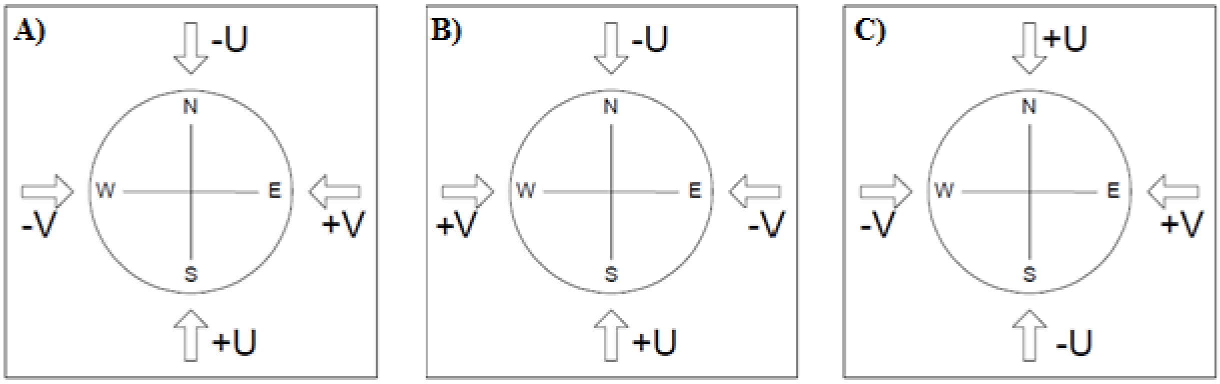

Figure 3. A) Coordinate system of an upright sonic anemometer (Gill 2007, 2011); B) coordinate system of Gill's 2D sonic anemometer oriented upside-down - it is important to note that the zonal plane is flipped because one of the transducer arms must be aligned.

A quadrant correction must applied to account for this 180° rotation:

$$\theta_{i,c} = \begin{cases} (2\pi - \theta_i) & \text{If} \quad V_i < 0 \; \& \; U_i < 0 \\ |\theta_i| & \text{If} \quad V_i \geq 0 \; \& \; U_i < 0 \\ (\pi - \theta_i) & \text{If} \quad V_i \geq 0 \; \& \; U_i \geq 0 \\ (\pi + |\theta_i|) & \text{If} \quad V_i < 0 \; \& \; U_i \geq 0 \end{cases}$$

Where, $\theta_{i,c}$ is the individual, corrected angle given in radians.

Calculating mean and linear variance of wind direction is complicated by the fact that wind direction is a periodic variable with a discontinuity at 2π. For periods in which observations are i) dispersed across the discontinuity (2π) or ii) vary more than 180°, direct calculation of the arithmetic mean and variance are misleading. Consequently an alternative approach is required for an exact solution. Here we follow an analytical two-pass method; this is a simple formulation with a theoretical basis, thoroughly reviewed (*e.g.,* Yamartino 1984; Mori 1986; Weber 1997; Farrugia *et al*. 2009).

In the first pass the components of the average unit-distance vector over an observation period with sample size *n* are calculated

$$\bar{X} = \frac{1}{n}\sum_{i=x}^{n} \sin(\theta_{i,c}) \qquad (7)$$

$$\bar{Y} = \frac{1}{n}\sum_{i=x}^{n} \cos(\theta_{i,c}) \qquad (8)$$

where, for each two-minute average, *n* represents the number of measurements in the averaging period T, which is defined as 0 ≤ T < 120 seconds. Similarly, for each thirty-minute average, *n* represents 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.

Note: The average *unit vector* components $\bar{X}$ and $\bar{Y}$ differ from the *average wind vector* components in that they *are not weighted* by the wind magnitude of the individual, corresponding wind speed, S_i.

Next, the *unit-vector mean wind direction* is derived (e.g., Yamartino 1984):

$$\bar{\theta} = tan^{-1}\left(\frac{\bar{X}}{\bar{Y}}\right) \qquad (9)$$

where $\bar{\theta}$ is mean unit vector wind direction in radians.

Quadrant adjustments must also be made because the arc-tangent is limited to a range of 180°:

$$\bar{\theta}_c = \left| \begin{array}{cl} \theta & \text{If} \quad \bar{X} \geq 0 \,\&\, \bar{Y} \geq 0 \\ (\pi + \theta) & \text{If} \quad \bar{X} \geq 0 \,\&\, \bar{Y} < 0 \\ (\pi + \theta) & \text{If} \quad \bar{X} < 0 \,\&\, \bar{Y} \geq 0 \\ (2\pi + \theta) & \text{If} \quad \bar{X} < 0 \,\&\, \bar{Y} < 0 \end{array} \right.$$

Where $\bar{\theta}_c$ is the mean, corrected angle given in radians.

Note: To avoid the need for quadrant corrections, it is recommended the ATAN2 function, an alternative version of the arctangent be used in place of Eq. (9). Quadrant corrections can be disregarded if the ATAN2 function is used.

In the second pass, the *minimum angular distance* (A_i) between subsequent observations is calculated (Batschelet, 1981)

$$A_i = \left|\cos^{-1}\left(cos\left(\theta_{i,c} - \bar{\theta}_c\right)\right)\right| \tag{10}$$

Subsequently the sign of the minimum angular distance is determined (Farrugia *et al*. 2009):

$$A_{i,c} = \left| \begin{array}{lll} A_i & \text{if} & \bar{\theta}_c \leq \theta_{i,c} < (\bar{\theta}_c + \pi) \\ -A_i & \text{if} & (\bar{\theta}_c - \pi) < \theta_{i,c} < \bar{\theta}_c \end{array} \right.$$

Where, $A_{i,c}$ is the individual, corrected, minimum angular distance between subsequent measurements.

Next, the average over all $A_{i,c}$ can be calculated *with an expected value of zero for symmetric angular distributions*:

$$\bar{A}_T = \frac{1}{n}\sum_{i=1}^{n} A_{i,c} \tag{11}$$

Where, for each two-minute average, *n* is the number of measurements in the averaging period T, which is defined as 0 ≤ T < 120 seconds. OR for each thirty-minute average, *n* is the number of measurements in the averaging period T defined as 0 ≤ n < 1800 seconds. Again, 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.

If the angular distribution is skewed $\bar{A}_T$ is exactly the difference between the arithmetic mean wind direction and the unit-vector mean wind direction from Eq.(9). The arithmetic mean is defined such that it minimizes the sample variance. With respect to the arithmetic mean, $A_{i,c}$ are thus overestimated by $\overline{A}$; this discrepancy is compensated to yield the arithmetic mean and variance:

$$\bar{\theta}_T = \bar{\theta}_c + \bar{A}_T \tag{12}$$

$$\theta_{T_{\sigma^2}} = \left(n^{-1}\sum_i (A_{i,c})^2 - (\bar{A}_T)^2\right) \tag{13}$$

Finally the resulting angles are converted from radians to angular degree:

$$\bar{\theta}_T = \bar{\theta}_T \frac{180}{\pi} \tag{14}$$

$$\theta_{T_{\sigma^2}} = \theta_{T_{\sigma^2}} \frac{180}{\pi} \tag{15}$$

Where the subscript *T* represents either 2 (two-minute average) or 30 (thirty-minute average)

5 ALGORITHM IMPLEMENTATION

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

1. Incoming, 1 Hz U and V wind components will be stored as level 0 data
2. WIND SPEED:
    a. The L0 vector data will be converted to horizontal wind speed via Eq.(3).
    b. QA/QC Plausibility tests will be applied to each scalar wind speed datum in accordance with AD[06]. The details are provided in Section 5.1.
    c. Signal de-spiking and time series analysis will be applied to the data stream in accordance with AD[07].
    d. Average (two and thirty-minute), horizontal wind speeds will be calculated using Eq. (4) and (5)
        i. A post-averaging check will take place on two and thirty-minute *wind speed* averages (see Section 5.1)
    e. Descriptive statistics, i.e., minimum, maximum, and variance, of wind speed will be determined for both two- and thirty-minute averages.
    f. QA/QC consistency tests will be applied to two and thirty-minute averages in accordance with AD[08].
    g. QA/QC Summary (Qsum) will be produced for two- and thirty-minute averages according to AD[16].

3. WIND DIRECTION:
    a. The L0 U and V data will be converted to wind direction (radians) via Eq. (6).
    b. Limited QA/QC Plausibility tests will be applied to each wind direction datum in accordance with AD[06]; details are provided in Section 5.1.
    c. Time series analysis will be applied to the data stream in accordance with AD[07]. Signal de-spiking will not be applied to wind direction
    d. Two and thirty-minute average, unit vector wind directions will be calculated using equations (7) through (15).
    e. Variance of wind direction will be calculated for both two- and thirty-minute averages
    f. QA/QC consistency analysis will be applied to two- and thirty-minute averages in accordance with AD[08].
    g. QA/QC Summary (Qsum) will be produced for two- and thirty-minute averages according to AD[16].

5.1 QA/QC Procedure

1. Plausibility tests AD [06] – All plausibility tests with the exception of the sigma and step test will be determined for wind speed and direction. Unless otherwise noted all plausibility tests will be applied to the sensor's converted L0 DPs and associated quality flags (QFs) will be generated for each test. Test parameters will be provided by FIU and maintained in the CI data store.
    a) Range Test – Wind flows become distorted if subject to interference (i.e. tower) upstream of the anemometer (Dyer 1980; WMO 2008). In the *likely* event that wind passes through the tower infrastructure and onto the anemometer, a flag, $QF_{\theta,}$ should be applied to both speed and direction data to note that wind flow has been distorted prior to measurement. Site Specific wind direction ranges ± 10 degrees of the tower's width (i.e. those where a potential flow distortion can occur) will be provided by FIU and maintained in the CI data store. *L1 data will still be computed when accompanied by this flag*.
        a. *Wind Direction* – It is impractical to assign minimum and maximum thresholds for wind direction, as it is constricted to 0 – 360°. However, if wind speed falls below the WMO's (2008) threshold (see 'ii' above), L1 wind direction may or may not be calculated as a numeric value (please refer to 'notes' in Section 5.5).

5.2 Post-averaging Check

To verify the plausibility of reporting wind direction as a numeric value, the following post-averaging check must be implemented.

The Office of the Federal Coordinator for Meteorology (OFCM) (2005) notes that wind directions derived from calm winds (specifically – wind speeds ≤ 6 kts (~3.0 m s^{-1})) are unreliable. The World Meteorological Organization (WMO) (2008) also acknowledges this relationship, but states a lower threshold – wind speeds ≤ 0.5 m s^{-1}. To insure international traceability, we will abide by the standard set forth by the WMO (2008). Thus, two and thirty-minute averaged wind speed data will undergo a post-averaging check to determine if their value is ≤ 0.5 m s^{-1}. In the event that the average wind speed is ≤ 0.5 m s^{-1}, *wind direction* for the same averaging period shall be flagged (QF_c), and presented in non-numeric form as not available (e.g., *CALM*).

5.3 Sensor Test

Gill's 2D anemometers produce error codes that accompany raw U and V vector measurements. These codes will result in the generation of a flag. For example, if the 2D anemometer displays an error code of '10' (refer to AD[15]), the sensor is informing the user that inaccurate data are likely being output because of a system gain max. In any case, data accompanied by error codes will be denoted by and error flag:

$$QF_E = \left|\begin{array}{l} 1 \ \text{If raw datum is accompanied by error code.} \\ \\ 0 \ \ otherwise \end{array}\right.$$

5.4 Signal De-spiking and Time Series Analysis

Signal de-spiking will not be conducted with wind speed or direction, however, time-series analyses will be conducted with both.

5.5 Consistency Analysis

A QA/QC flag for data consistency will be applied according to the consistency analysis outlined in AD[08], and a pass/fail flag will be generated to reflect this activity. For 2D wind consistency analysis, L1 wind speed and direction data from a given anemometer will first be compared to the neighboring anemometer located above it on the tower infrastructure. If a statistical relationship between the two wind speed or direction measurements falls within defined limits provided by FIU (and maintained in the CI data store), then the sensor will pass the consistency analysis. Alternatively, a wind speed or direction difference outside the defined limits will result in a failed test. In this event of a failed test, the anemometer will then be compared to the neighboring anemometer located below it; if this too results in a failed test then the wind speed or direction data will fail the consistency analysis and be flagged as such. If the data fail the first test but pass the second, then they will pass the consistency analysis. This structure helps to ensures that non-functional sensors (e.g. sensors that are faulty or down for service) do not bias the test, since a resulting failed test will allow the sensor to be compared to the one below it. Accordingly, the 2D anemometer located on the bottom of the tower will only be compared to the neighboring anemometer located above it. The uppermost 2D anemometer will be compared to the anemometer below it and the 3D anemometer above it.

Note: Although this consistency analysis may be applicable for regions with homogeneous terrain, such an approach may not be applicable to regions of heterogeneous terrain and those where anemometers are located above and below a canopy.

5.6 Quality Flags (QFs) and Quality Metrics (QMs) AD[16]

If a datum has the following flag it will not be used to create a L1 DP: $\underline{QF_E}$. α and β QFs and QMs will be determined for the following flags QF_δ, QF_N, QF_G, QF_Θ, QF_E. All L1 DPs will have an associated final quality flag, QF_{NEON}, and quality summary, Qsum, as detailed in AD[16]. Flags that may be associated with wind direction and wind speed measurements, as well as information maintained in the CI data store can be found below in Tables 3 and 4.

Table 3. Flags associated with 2D wind measurements.

Tests	Flags
Delta (δ)	QF_δ
Null	QF_N
Gap	QF_G
Distorted flow	QF_θ
Sensor Test AD[15]	QF_E
Consistency Analysis	QF_V
Calm winds	QF_c
Final quality flag	QF_{NEON}

Table 4. Information maintained in the CI data store for biological temperature.

Tests/Values	CI Data Store Contents
Sigma (σ)	Time segments and threshold values
Delta (δ)	Time segment and threshold values
Step	Threshold values
Null	Test limit
Gap	Test limit
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[13]
Sensor Test	AD[15]
Consistency Analysis	Test limits
Final Quality Flag	AD[16]

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 L1 mean DPs. It is a reflection of the information described in AD[11], and is explicitly described for the 2D wind assembly in the following sections.

6.1 Uncertainty of wind measurements

Uncertainty of the 2D wind assembly is discussed in this section. Sources of uncertainties include those arising from vector component measurements, measurement noise, heater, resolution of the digital indication, and orientation to True North (Figure 4).

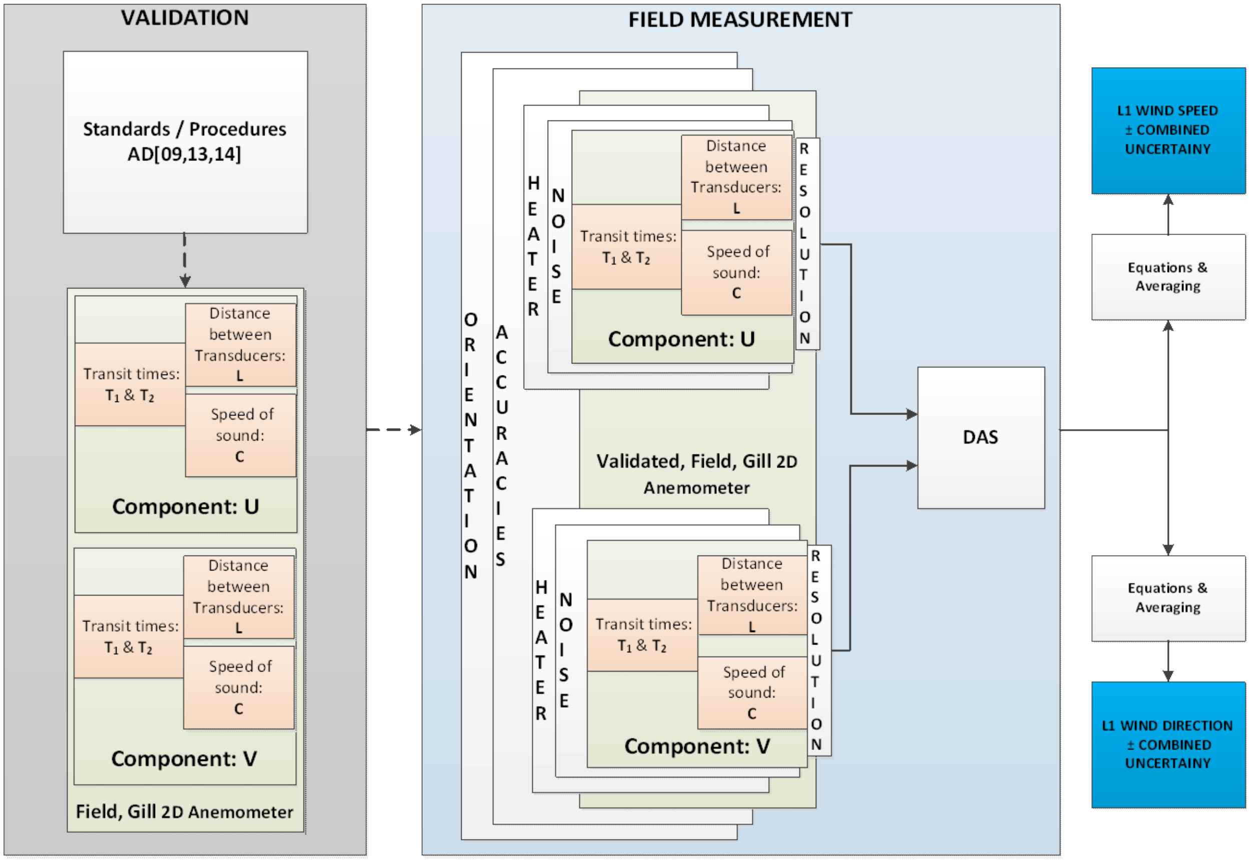

Figure 4. Diagram outlining potential sources of uncertainty associated with 2D wind L1 DPs. The Salmon colored boxes represent the direct measurement of vector velocity based on the theory of sonic anemometry. For more information regarding the validation procedure, please refer to AD[09, 13, 14].

6.1.1 Validation

Uncertainties associated with the *calibration* process propagate into combined, standard uncertainty and is provided by CVAL. However, CVAL will be *validating* (not *calibrating*) Gill's 2D anemometers, and therefore no value will be supplied by CVAL. Uncertainties must therefore be derived through a combination of manufacturer's specifications and scientific judgment; for further justification please refer to AD[11].

6.1.2 Accuracy

Gill does not provide accuracy values for individual vector components, but supplies them for horizontal wind speed (Table 5) and direction (±2° = 0.0349 radians). Despite the fact that Gill provides values of accuracy for horizontal, scalar wind speed and direction, our L0 data are in vector component form. Additionally, other uncertainties arise within the 2D wind assembly that will affect the overall uncertainty of wind speed and direction. Therefore, we must back-calculate individual vector component uncertainties as well as uncertainties relating to the sensor's assembly. This allows proper quantification all individual sources of uncertainty relating specifically to NEON L1 wind DPs.

Table 5. Relationship between wind speed and accuracy. It should be noted that these accuracies are related to horizontal wind speed and *not individual vector component magnitude* (Murree Sims, personal communication, Gill Instruments, 2012).

Wind Speed (m s^{-1})	Accuracy (± %)
0.01[A]	1.0
5	1.0
12	2.0
32	3.0
65	4.0
70[B]	4.0

[A] Starting threshold of Gill's 2D anemometers. It is assumed here that the accuracy of measurement is ± 1 %
[B] Only applicable with the EWWO

Least squares regression can be used with the information in the above table to define accuracy as a function of wind speed. Accuracy of horizontal wind speeds ≥ 0.01 and ≤ 5.00 m s^{-1}, as well as those ≥ 65 m s^{-1}, will be directly calculated with the aid of Table 5 (shown below in respective order):

$$u_c(S_i) = S_i * 0.01 \quad [m\,s^{-1}] \tag{16}$$

$$u_c(S_i) = S_i * 0.04 \quad [m\,s^{-1}] \tag{17}$$

However, horizontal wind with magnitudes ≥ 5.01 and ≤ 64.99 m s^{-1} are computed via linear interpolation. Here, we apply separate linear fits to interpolate the accuracy data between:

A. 5.01 to 11.99 m s^{-1}

$$u_c(S_i) = C_{A1}S_i - C_{A0} \quad [m\, s^{-1}] \tag{18}$$

B. 12.00 to 31.99 m s^{-1}

$$u_c(S_i) = C_{B1}S_i - C_{B0} \quad [m\, s^{-1}] \tag{19}$$

C. 32.00 to 64.99 m s^{-1}

$$u_c(S_i) = C_{C1}S_i - C_{C0} \quad [m\, s^{-1}] \tag{20}$$

Where:

$u_c(S_i)$ = Combined uncertainty (i.e., accuracy; Gill 2007, 2011) of individual wind speed S
S_i = individual (1 Hz) wind speed as calculated with Eq. (3).
C_{A1} = 0.0271
C_{A0} = 0.0857
C_{B1} = 0.036
C_{B0} = 0.192
C_{C1} = 0.0497
C_{C0} = 0.6303

Whenever a function is fit to data, the uncertainty of the function (i.e., the coefficients) should be quantified (JCGM 2008; Taylor 1997). However, since we are interpolating between two points to obtain uncertainty (i.e., a linear fit with resulting r^2 values = 1.0), we can assume that uncertainties of the coefficients are negligible.

From here, the individual vector component uncertainties can be derived with the aid of the wind speed and direction accuracy information provided by Gill (2007, 2011). To accomplish this, the partial derivatives with respect to each vector component must be derived from Eq. (3) and (6).

$$\frac{\partial S_i}{\partial V_i} = \frac{V_i}{\left({U_i}^2+{V_i}^2\right)^{\frac{1}{2}}} \tag{21}$$

$$\frac{\partial S_i}{\partial U_i} = \frac{U_i}{\left({U_i}^2+{V_i}^2\right)^{\frac{1}{2}}} \tag{22}$$

$$\frac{\partial\theta}{\partial V_i} = \frac{U_i}{{V_i}^2 + {U_i}^2} \tag{23}$$

$$\frac{\partial\theta}{\partial U_i} = \frac{-V_i}{{V_i}^2 + {U_i}^2} \tag{24}$$

The individual uncertainties propagate into separate combined uncertainties representing wind speed and direction:

$${u_c}^2(S_i) = \left(\frac{V_i}{\left({U_i}^2 + {V_i}^2\right)^{\frac{1}{2}}}\right)^2 u^2(V_i) + \left(\frac{U_i}{\left({U_i}^2 + {V_i}^2\right)^{\frac{1}{2}}}\right)^2 u^2(U_i) \quad [m\, s^{-1}] \tag{25}$$

$${u_c}^2(\theta) = \left(\frac{U_i}{{V_i}^2 + {U_i}^2}\right)^2 u^2(V_i) + \left(\frac{-V_i}{{V_i}^2 + {U_i}^2}\right)^2 u^2(U_i) \quad [rad] \tag{26}$$

We can now solve for the uncertainties (accuracies) of individual U and V vector component measurements by rearranging the above equations:

$$u^2(V_i) = \frac{{u_c}^2(S_i) \ * \ \left({V_i}^2 + {U_i}^2\right) - \ {U_i}^2 * u^2(U_i)}{{V_i}^2} \quad [m\, s^{-1}] \tag{27}$$

$$u^2(U_i) = \frac{{u_c}^2(\theta) \ * \ \left({V_i}^2 + {U_i}^2\right)^2 - \ {U_i}^2 * u^2(V_i)}{-{V_i}^2} \quad [m\, s^{-1}] \tag{28}$$

Rearranging once more, we can solve for the uncertainty of the V component.

$$u^2(V_i) = \frac{{u_c}^2(S_i) \ * \ \left({V_i}^2 + {U_i}^2\right) - \ {U_i}^2 * \left(\dfrac{{u_c}^2(\theta) \ * \ \left({V_i}^2 + {U_i}^2\right)^2 - \ {U_i}^2 * u^2(V_i)}{-{V_i}^2}\right)}{{V_i}^2} \quad [m\, s^{-1}] \tag{29}$$

Once $u^2(V_i)$ is calculated, its resulting value can be plugged into Eq. (28) and $u^2(U_i)$ can be computed.

Notes:

- ${u_c}^2(\theta)$ must be in radians when calculating individual component uncertainties
- Unlike ${u_c}^2(S_i)$, which is a function of the magnitude of wind speed and therefore dynamic in nature, ${u_c}^2(\theta)$ is a static value. Thus, the subscript i is not displayed.

6.1.3 Resolution of the digital indication

As noted by Gill (2007, 2011), their 2D anemometers have a digital resolution of 0.01 m s^{-1}. Given that it is reasonable to assume the value of the measurand lies with equal probability between the bounds of this resolution and it is unlikely that it resided outside these bounds, we can assume uniform distribution (ISO1995) and an uncertainty of:

$$u(R) = \frac{0.01\mathrm{m\,s}^{-1}}{\sqrt{3}} = \pm\, 0.0058 \quad [m\,s^{-1}] \tag{30}$$

6.1.4 DAS

Gill 2D anemometers have an internal Analog to Digital (A/D) converter and outputs data in digital form. Therefore, no data conversions occur within the DAS. Thus, uncertainty related to the DAS can be considered negligible

6.1.5 Noise

It is reported by Gill (2007, 2010) that each measurement is accompanied within an *offset* of ± 0.01 m s^{-1}. However, Gill's usage of the term 'offset' is incorrect, as an offset typically denotes a systematic uncertainty or bias. The value provided by Gill is actually a random uncertainty, most likely arising from effects such as measurement noise and the internal A/D conversion.

6.1.6 Heaters

Two models of Gill's sonic anemometers (EWWO and WOII: *version 2*) are equipped with heaters. These heaters warm the transducer heads if the ambient temperature drops below a certain threshold. The principles of sonic anemometry rely on the speed of sound, which is a function of temperature. It is hypothesized that heating of the transducer heads will cause small thermals around each transducer head, thus altering the neighboring temperature and causing uncertainty of the measurement. Due to the fact that NEON *will not* calibrate these sensors in-house or monitor the current draw of the heaters, we cannot confidently determine the uncertainty introduced by the heaters. We have been assured by Murree Sims (Gill Instruments, pers. comm. 2012) that heating will cause negligible uncertainty. This is an example of an uncertainty that can be identified, but cannot be quantified *at this time*. Given the reassurance from the manufacturer, L1 Wind DPs will still be computed during instances when the heater is on.

6.1.7 Orientation

The 2D anemometer's orientation relative to true north is considered a source of uncertainty. As part of NEON's 2D wind requirements, the N-S axis of all 2D anemometers shall be oriented within ± 1° of true north. Similarly to the resolution of the digital indication, we assume that the probability of the N-S axis residing within the ± 1° bounds is uniform, and the resulting uncertainty is thus:

$$u(O) = \frac{1^\circ}{\sqrt{3}} = 0.57735^\circ \ = 0.010077 \quad [\,rad] \tag{31}$$

6.1.8 Distorted Flow

As mentioned in Section 5.1, wind flows become distorted if subject to interference (e.g., tower) upstream of the anemometer (Dyer 1980; WMO 2008). Distorted flow introduces uncertainty that is a function of the i) obstructions upstream of the anemometer ii) magnitude of wind speed, and iii) characteristics of the wind (i.e., laminar vs. turbulent flow independent of upstream obstacles). Although previous researchers (e.g., Dyer 1980) have quantified the uncertainty associated with distorted flow, the obstructions upstream of our 2D anemometers differ from those utilized by previous researchers. Thus, it may be inappropriate to solely use their results as metrics to quantify the uncertainty introduced by distorted flow. However, as NEON data are analyzed, this topic will be further investigated and hopefully quantified. At current date, this is an uncertainty that can be identified, but not fully quantified; therefore, as mentioned in Section 5.1, the data will be flagged during instances of distorted flow.

6.2 Combined Uncertainty

The combined uncertainties of individual vector component measurements are given below:

$$u_c(V_i) = \left(u^2(V_i) + u^2(R) + u^2(N)\right)^{\frac{1}{2}} \quad [m\,s^{-1}] \tag{32}$$

$$u_c(U_i) = \left(u^2(U_i) + u^2(R) + u^2(N)\right)^{\frac{1}{2}} \quad [m\,s^{-1}] \tag{33}$$

Where, $u^2(N)$ is the measurement noise noted by Gill (2007, 2011; refer to Section 6.1.5). Resulting values are multiplied by appropriate partial derivatives to produce the partial uncertainties of wind speed and direction as functions of the V and U vector components.

The partial uncertainties of horizontal wind speed with respect to each vector component are:

$$u_V(S_i) = \left|\frac{\partial S_i}{\partial V_i}\right| u_c(V_i) \tag{34}$$

$$u_U(S_i) = \left|\frac{\partial S_i}{\partial U_i}\right| u_c(U_i) \tag{35}$$

And the partial uncertainties of wind direction with respect to each vector component are:

$$u_V(\theta_i) = \left|\frac{\partial \theta_i}{\partial V_i}\right| u_c(V_i) \tag{36}$$

$$u_U(\theta_i) = \left|\frac{\partial \theta_i}{\partial U_i}\right| u_c(U_i) \tag{37}$$

6.2.1 Wind Speed

Deriving a combined uncertainty for our L1 mean wind speed DPs can be completed in two steps. Firstly, the combined uncertainty of *individual*, valid (i.e., *those that are not flagged and omitted*) observations made during the averaging period is calculated.

$$u_c(S_i) = \left(u_V{}^2(S_i) + u_U{}^2(S_i)\right)^{\frac{1}{2}} \quad [m\, s^{-1}] \tag{38}$$

The resulting value is multiplied by the partial derivative of the L1 DP. Since the DP is a temporal average, the partial derivative with respect to an individual measurement is simply:

$$\frac{\partial \bar{S}}{\partial S_i} = \frac{1}{n} \tag{39}$$

Where n represents the number of valid observations made during the averaging period. The absolute value of Eq. (39) is then multiplied by Eq. (38):

$$u_{S_i}(\bar{S}) = \left|\frac{\partial \bar{S}}{\partial S_i}\right| u_c(S_i) \quad [m\, s^{-1}] \tag{40}$$

Finally, the combined uncertainty of the L1 mean DP is calculated via quadrature:

$$u_c(\bar{S}) = \left(\sum_{i=1}^{n} u_{S_i}{}^2(\bar{S})\right)^{\frac{1}{2}} \quad [m\, s^{-1}] \tag{41}$$

6.2.2 Wind Direction

The combined uncertainty of the L1 mean wind direction data products is computed in similar fashion. Firstly, the combined uncertainty of *individual*, valid (i.e., *those that are not flagged and omitted*) observations made during the averaging period is calculated.

$$u_c(\theta_i) = \left(u_V{}^2(\theta_i) + u_U{}^2(\theta_i) + u^2(O)\right)^{\frac{1}{2}} \quad [rad] \tag{42}$$

The resulting value is multiplied by the partial derivative of the L1 DP. Since the DP is a temporal average, the partial derivative with respect to an individual measurement is simply:

$$\frac{\partial\bar{\theta}}{\partial\theta_i} = \frac{1}{n} \tag{43}$$

Where n represents the number of valid observations made during the averaging period. The absolute value of Eq. (43) is then multiplied by Eq. (42):

$$u_{\theta_i}(\bar{\theta}) = \left|\frac{\partial\bar{\theta}}{\partial\theta_i}\right| u_c(\theta_i) \quad [rad] \tag{44}$$

Finally, the combined uncertainty of the L1 mean DP is calculated via quadrature:

$$u_c(\bar{\theta}) = \left(\sum_{i=1}^{n} {u_{\theta_i}}^2(\bar{\theta})\right)^{\frac{1}{2}} \quad [rad] \tag{45}$$

Note:

In the event that wind direction is presented as a non-numeric value (refer to Section 5.2), then combined and expanded uncertainty of wind direction will not be calculated.

6.3 Expanded Uncertainty

Before computing the expanded uncertainties of the L1 mean data products, the effective degrees of freedom for each 1 Hz vector component measurement must be computed:

$$V_{eff_{V_i}} = \frac{{u_c}^4(V_i)}{\frac{u^4(V_i)}{Veff_V} + \frac{u^4(R)}{Veff_R} + \frac{u^4(N)}{Veff_N}} \tag{46}$$

$$V_{eff_{U_i}} = \frac{{u_c}^4(U_i)}{\frac{u^4(U_i)}{Veff_U} + \frac{u^4(R)}{Veff_R} + \frac{u^4(N)}{Veff_N}} \tag{47}$$

Where $Veff_V$, $Veff_U$, $Veff_R$ and $Veff_N$ are products of Type B evaluations, i.e., their corresponding uncertainty values are derived by the manufacturer, Gill Instruments. Thus, their values will be 100 (please refer to AD[11] for further justification). The expanded uncertainties of the L1 wind DPs can now be computed.

6.3.1 Wind Speed

The effective degrees of freedom of an individual (1 Hz) wind speed measurement are derived:

$$V_{eff_{S_i}} = \frac{u_c^4(S_i)}{\frac{u_V{}^4(S_i)}{V_{eff_{V_i}}} + \frac{u_U{}^4(S_{L1})}{V_{eff_{U_i}}}} \tag{48}$$

Next, the effective degrees of freedom are derived for the L1 mean wind speed DP:

$$V_{eff_{\bar{S}}} = \frac{u_c{}^4(\bar{S})}{\sum_{i=1}^{n}\left(\frac{(u_c(S_i)/n)^4}{V_{eff_{S_i}}}\right)} \tag{49}$$

Finally, the expanded uncertainty is calculated:

$$U_{95}(\bar{S}) = k_{95} * u_c(\bar{S}) \quad [m\ s^{-1}] \tag{50}$$

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

- Table 5 from AD[11]
- $V_{eff_{\bar{S}}}$

6.3.2 Wind Direction

The effective degrees of freedom of individual wind direction measurements are derived:

$$V_{eff_{\theta_i}} = \frac{u_c^4(\theta_i)}{\frac{u_V{}^4(\theta_i)}{V_{eff_{V_i}}} + \frac{u_U{}^4(\theta_i)}{V_{eff_{U_i}}} + \frac{u^4(O)}{V_{eff_O}}} \tag{51}$$

Where V_{eff_O} is a product of a Type B analysis and its value will be 100 (refer to AD[11]).

Next, the effective degrees of freedom are derived for the L1 mean wind direction DP:

$$V_{eff_{\bar{\theta}}} = \frac{u_c{}^4(\bar{\theta})}{\sum_{i=1}^{n}\left(\frac{(u_c(\theta_i)/n)^4}{V_{eff_{\theta_i}}}\right)} \tag{52}$$

Finally, the expanded uncertainty is calculated:

$$U_{95}(\bar{\theta}) = k_{95} * u_c(\bar{\theta}) \quad [rad] \tag{53}$$

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

- Table 5 from AD[11]
- $V_{eff_{\bar{\theta}}}$

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

Source of uncertainty	**Standard uncertainty component $u(x_i)$**	**Value of standard uncertainty [m s^{-1}]**	$c_i \equiv \frac{\partial f}{\partial x_i}$	$u_i(Y) \equiv \lvert c_i \rvert u(x_i)$ **[m s^{-1}]**	**Degrees of Freedom**
L1 Wind Speed DP	$u_c(\bar{S})$	Eq. (41)	--	--	Eq. (49)
1 Hz Wind Speed	$u_c(S_i)$	Eq. (38)	Eq. (39)	Eq. (40)	Eq. (48)
1 Hz V component	$u_c(V_i)$	Eq. (32)	Eq. (21)	Eq. (34)	Eq. (46)
"Accuracy"	$u(V_i)$	Eq. (29)*	1	Eq. (29)	100
Dig. Ind. Resolution	$u(R)$	Eq. (30)	1	Eq. (30)	100
Measurement noise	$u(N)$	0.01	1	0.01	100
1 Hz U component	$u_c(U_i)$	Eq. (33)	Eq. (22)	Eq. (35)	Eq. (47)
"Accuracy"	$u(V_i)$	Eq. (28)*	1	Eq. (28)	100
Dig. Ind. Resolution	$u(R)$	Eq. (30)	1	Eq. (30)	100
Measurement noise	$u(N)$	0.01	1	0.01	100
L1 Wind Direction DP	$u_c(\bar{\theta})$	Eq. (45) [rad]	--	--	Eq. (52)
1 Hz Wind Direction	$u_c(\theta_i)$	Eq. (42) [rad]	Eq. (43)	Eq. (44) [rad]	Eq. (51)
1 Hz V component	$u_c(V_i)$	Eq. (32)	Eq. (23)	Eq. (36)	Eq. (46)
"Accuracy"	$u(V_i)$	Eq. (29)*	1	Eq. (29)	100
Dig. Ind. Resolution	$u(R)$	Eq. (30)	1	Eq. (30)	100
Measurement noise	$u(N)$	0.01	1	0.01	100
1 Hz U component	$u_c(U_i)$	Eq. (33)	Eq. (24)	Eq. (37)	Eq. (47)
"Accuracy"	$u(V_i)$	Eq. (28)*	1	Eq. (28)	100
Dig. Ind. Resolution	$u(R)$	Eq. (30)	1	Eq. (30)	100
Measurement noise	$u(N)$	0.01	1	0.01	100

k_{95}: $v_{eff_{\bar{S}}}$ & Table 5 of AD[11]
$U_{95}(\bar{S})$: Eq. (50)
k_{95}: $v_{eff_{\bar{\theta}}}$ & Table 5 of AD[11]
$U_{95}(\bar{\theta})$: Eq. (53)

*Square root must be computed prior to multiplying by partial derivative

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream and included in the QA/QC summary DP (*Qsum_s*$_1$, *Qsum_s*$_{30}$, *Qsum_Θ*$_1$, and *Qsum_Θ*$_{30}$) that summarizes any flagged data that went into the computation of the L1 DP.

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