TIS Level 1 Data Products Uncertainty Budget Estimation Plan

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1 DESCRIPTION

This document describes the general philosophy and approach to quantify uncertainty of all level 1 (L1), Terrestrial Infrastructure (TIS) data products (DP).

1.1 Purpose

Uncertainty of measurement is inevitable (JCGM 2008; Taylor 1997). It is imperative that uncertainties are identified and quantified in order to determine statistical interpretations about mean quantity and variance structure; both are important when constructing higher-level data products (e.g., L1-L4 DPs) and modeled processes. This document serves as a guideline to identify, evaluate, and quantify sources of uncertainty relating to TIS L1 DPs. Additionally, it provides the necessary tools to generate an uncertainty budget.

1.2 Scope

This plan describes the philosophy and rationale for assuring that estimates of DP uncertainties are traceable to nationally and internationally accepted standards. It is intended that this document be used as a guideline for quantifying uncertainties of in-situ, sensor based measurements and associated L1 DPs throughout NEON's Observatory.

The basis of this overarching philosophy spawns from the *Guide to the Expression of Uncertainty in Measurement* (commonly referred to as the *Guide* or *GUM*; JCGM 2008, ISO 1995). The purpose of the *GUM* is to promote information regarding the quantification of uncertainties and to provide a basis for the international comparison of measurement results (ISO 1995). The National Institute of Standards and Technology (NIST) follows the principles set forth in the *Guide* and also provides further suggestions for correct quantification of measurement uncertainties (Taylor and Kuyatt 1994). The JCGM (2008) *GUM* is as updated version of ISO's (1995) version, and is considered to be the most up to date reference.

For all purposes, the processes by which NEON evaluates and quantifies uncertainties will emulate those proposed by JCGM (2008). This approach will ensure that our DPs are traceable to accepted standards and foster interoperability among observatory networks.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON Observatory Design (NOD) Requirements
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005000	NEON High Level Data Products Management Plan
AD[04]	NEON.DOC.005010	NEON Data Product-Document Framework
AD[05]	NEON.DOC.005004	NEON Level 0 Data Products Catalog
AD[06]	NEON.DOC.005005	NEON Level 1-3 Data Products Catalog
AD[07]	NEON.DOC.005006	NEON Algorithm Theoretical Basis Document Template – Design Specification
AD[08]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[09]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values
AD[10]	NEON.DOC.011081	ATBD QA/QC plausibility tests
AD[11]	NEON.DOC.000902	2D Sonic Anemometer Calibration Procedure (CVAL)
AD[12]	NEON.DOC.000646	NEON Algorithm Theoretical Basis Document – Single Aspirated Air Temperature

2.2 Reference Documents

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

2.3 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.

2.4 Definitions

Table 1 displays definitions of the terms, symbols, and equations reflected within this plan. All definitions were taken from JCGM (2012) with the exception of a few NEON defined terms. A full list of metrology terms and symbols can be found in JCGM (2012).

Table 1: Associated terms and definitions. Metrology definitions are derived from JCGM (2012).

Term	Definition
Accuracy	Closeness of agreement between a measured quantity value and a true quantity value of a measurand
Assembly	*In this document*, an assembly is anything that contributes to the overall uncertainty of the L1 DP. This includes sensor(s), corresponding hardware, Data Acquisition System (DAS), algorithms, calibration procedures, etc.
DAS	Data Acquisition System
DP	Data Product

Drift	Continuous or incremental change over time in indication, due to changes in metrological properties of a measuring instrument
L1	Level-one
Measurand	Quantity intended to be measured. In most cases, the measurand is not measured directly, but is determined from *N* other quantities through a functional relationship.
Metrology	Science of Measurement and its application
Precision	Closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions
Random Error	Component of measurement error that in replicate measurements varies in an unpredictable manner
Resolution	Smallest change in a quantity being measured that causes a perceptible change in the corresponding indication
Sensitivity	Quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured
Systematic Error	Component of measurement error that in replicate measurements remains constant or varies in a predictable manner
TIS	Terrestrial Instrumentation System
Trueness	Closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity
Type A evaluation	Evaluation of a component of measurement uncertainty by statistical analysis of measured quantity values obtained under defined measurement conditions.
Type B evaluation	Evaluation of a component of measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty
Uncertainty	A non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used
Uncertainty Budget	Statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination

Table 2: Variables / symbols with corresponding definitions following JCGM (2008). Mean values are denoted by an over-bar

Variable/Symbol	**Definition**
a	Half-width of a *rectangular distribution* of possible values on of input quantity X_i $$a = (a_+ - a_-)/2$$
a_+	Upper bound of input quantity X_i
a_-	Lower bound of input quantity X_i
$c_i \equiv \frac{\partial f}{\partial x_i}$	Partial derivative (sensitivity coefficient)
f	Functional relationship
k_p	Coverage factor used to calculate expanded uncertainty to a *specified* level of confidence
$s(X_i)$	standard deviation
$s(\bar{X}_i)$	Standard deviation of input mean $\bar{X}_i$.

	Standard uncertainty obtained from Type A evaluation
$t_p(v)$	t-factor for the t -distribution for v degrees of freedom corresponding to a given probability p
$t_p(v_{eff})$	t-factor for the t -distribution for v_{eff} degrees of freedom corresponding to a given probability p, used to calculate expanded uncertainty U_p
$u(x_i)$	Standard uncertainty of input estimate x_i that estimates input quantity X_i. When x_i is determined from arithmetic mean of n independent repeated observations, $u(x_i) = s(\bar{X}_i)$ is a standard uncertainty obtained from a Type A evaluation
$u_c(y)$	Combined standard uncertainty of output estimate y
$u_i(y)$	Component of combined standard uncertainty $u_c(y)$ of output estimate y generated by the standard uncertainty of input estimate x_i $$u_i(y) = \lvert c_i \rvert u(x_i)$$
$u(x_i) / \lvert x_i \rvert$	Relative standard uncertainty of input estimate x_i
$u_c(y)/\lvert y \rvert$	Relative combined standard uncertainty of output y
U_p	Expanded uncertainty of output estimate y that defines an interval $Y = y \pm U_p$ having a high, ***specified*** level of confidence p, equal to coverage factor k_p times the combined standard uncertainty $u_c(y)$ of y $$U_p = k_p u_c(y)$$
v	Degrees of freedom
v_{eff}	Effective degrees of freedom of $u_c(y)$, used to obtain $t_p(v_{eff})$ for calculating expanded uncertainty U_p
x_i	Estimate of input quantity X_i When determined from arithmetic mean of n independent repeated observations, $x_i = \bar{X}_i$
X_i	ith input quantity on which measurand Y depends
y	Estimate of measurand Y, result of a measurement, output estimate
Y	A measurand

Table 3: Lists variables / symbols associated with 2D wind uncertainties

Variable / Symbol	**Definition**
A/D	Analog to Digital converter
A	Accuracy
C	Speed of sound
D	DAS
H	Heater
L	Distance between respective transducer faces
N	Noise
R	Resolution of the digital indication
$T_{x_1}, T_{x_2}, T_{y_1}, T_{y_2}$	Transit times of ultrasonic pulses in the x (zonal) and y (meridional) directions, respectively
V	Zonal (E-W) wind component
U	Meridional (N-S) wind component
S	Wind speed

3 EVALUATING AND EXPRESSING UNCERTAINTIES

This section describes the steps necessary to correctly identify and quantify sources of uncertainty. The methods defined in the subsequent sections are reflected in JCGM's (2008) and NIST's (1994) uncertainty guidelines. All presented steps should be followed in order to ensure that quantified uncertainties are complete and traceable to the aforementioned standards. A running example is provided throughout the subsequent sections to exhibit these methods using NEON's L1 wind speed DP.

NOTE:
An important and controversial issue regarding the evaluation and expression of uncertainties is the handling of systematic uncertainties. Taylor (1997) states that the only agreed upon theory to handle systematic uncertainties is by identifying and reducing them to a point that their magnitude is substantially less than the required precision. Following this theory, JCGM's (2008) *Guide* promotes the use of *correction factors*, which reduce systematic uncertainties of a system, and thus, assumes that only known, and quantifiable random uncertainties propagate to a combined uncertainty value. While every attempt will be made to correct for known systematic uncertainties, it is highly likely that some systematic uncertainties of NEON's assemblies are currently unknown – and consequently unquantifiable at current date. As time progresses and NEON data are analyzed, a better understanding of assembly specific uncertainties (both random and systematic) may be achieved, therefore making it possible to quantify (or correct) previously unquantifiable uncertainties.

3.1 Identify input quantities

The first and most important step of the procedure is to identify all input quantities, X_i, on which Y(the measurand) depends:

$$Y = f(X_1, X_2, \ldots, X_N) \tag{1}$$

As a simple example, we will consider the measurand to be wind speed. Input quantities of wind speed can be identified by referencing the theory of sonic anemometry:

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

Where S is horizontal wind speed, and V and U are zonal and meridional vector components, respectively. The subscript i represents an instantaneous (1 Hz) datum. Like S, each wind component is a function of input quantities:

$$V_i = f\left(L_x, T_{x_1}, T_{x_2}, N_x\right) = \frac{L_x}{2}\left(\frac{1}{T_{x_1}} - \frac{1}{T_{x_2}}\right)$$

$$U_i = f\left(L_y, T_{y_1}, T_{y_2}, N_y\right) = \frac{L_y}{2}\left(\frac{1}{T_{y_1}} - \frac{1}{T_{y_2}}\right) \quad (3)$$

Where L is the distance between transducer faces along an axis, and T_1 and T_2 are the transit times of ultrasonic pulses along the respective axis. Every measurement is also prone to noise (*N*), thus, we identify it and include it as another source of uncertainty in the relationship.

The functional relationship between Wind speed and its input variables now becomes:

$$Y = f(V, U) = f(L_x, L_y, T_{x_1}, T_{y_1}, T_{x_2}, T_{y_2}, N_x, N_y) \quad (4)$$

The function f should contain every quantity, including all corrections and correction factors, which can contribute uncertainty to the result of the measurement (JCGM 2008). There are no correction factors to be applied to the 2D wind measurements. However, during instances when they are applied, either CVAL or FIU will be responsible for doing so, and will provide and uncertainty value in which these are reflected. Although many sources of uncertainty are identified in this section, our interpretation of *Y* lacks uncertainties that arise from other components of the assembly and internal processing of the 2D anemometer.

3.1.1 Identifying other factors

To ensure that all sources of uncertainty are accounted for, the data flow in which L0 data become L1 data should be kept in mind. It is helpful to create a diagram of an assembly (e.g., Ocheltree and Loescher 2007), identifying the potential sources of uncertainty involved in the measurement (Figure 1).

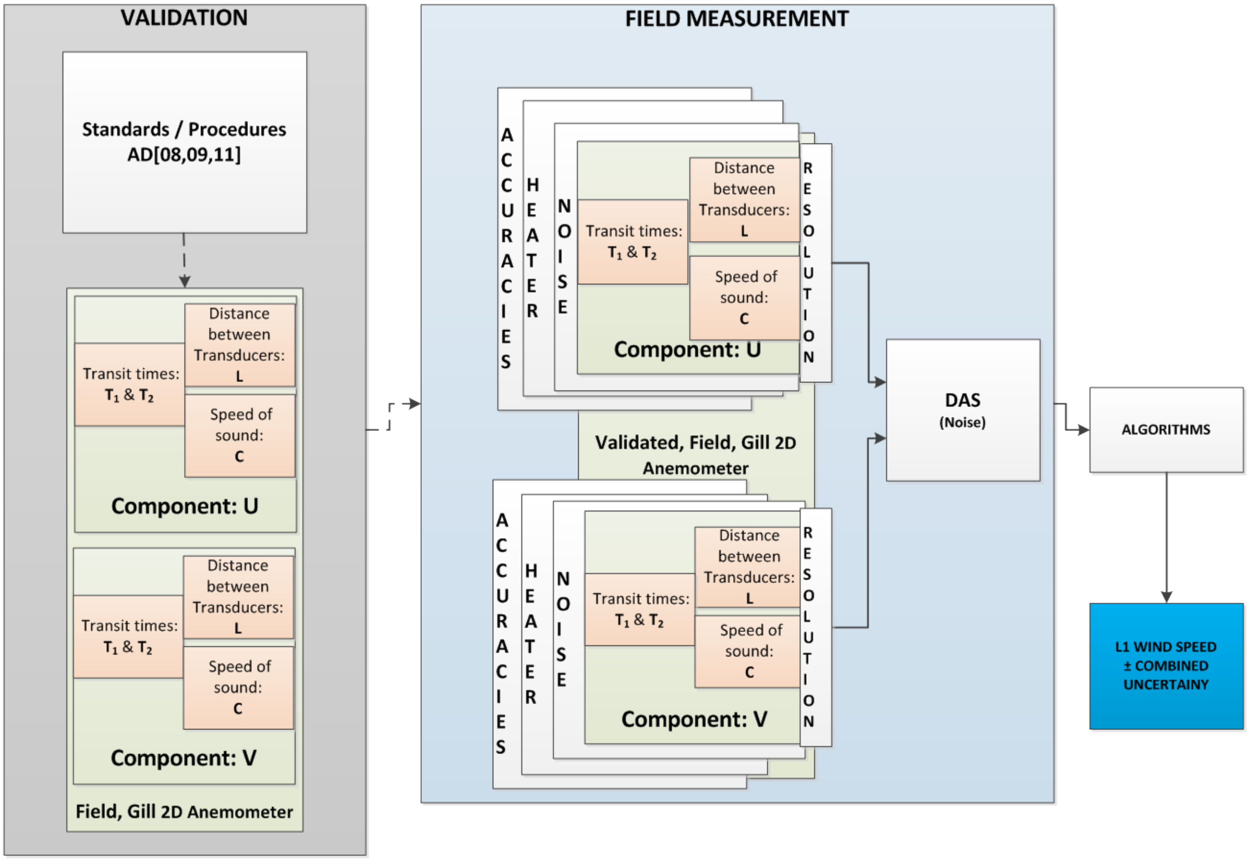

Figure 1: Diagram outlining potential sources of uncertainty associated with 2D wind speed L1 DPs. The salmon colored boxes represent factors relating to the direct measurement of vector velocity based on the theory of sonic anemometry. Standards and procedures of calibration and/or validation will be available through documents provided by CVAL (AD[08,09,11])

Having drawn the diagram, all of the uncertainties associated with this assembly are assumingly identified. It can be stated that Y is a function of the entire assembly:

$$Y = f(V,U) = f(L_x, L_y, T_{x_1}, T_{y_1}, T_{x_2}, T_{y_2}, R_x, R_y, N_x, N_y, H_V, H_U D_V, D_U, A_V, A_U) \quad (5)$$

Where *H* represents the heater, *R* is the resolution of digital indication, *D* is the DAS, and *A* represents the accuracy of vector component magnitude.

NOTE:

Although we acknowledge that human error exists, the extent of its influence is currently unquantifiable. For all purposes, we are assuming human error is negligible to non-existent for all TIS, in-situ assemblies.

3.2 Determine estimated value of input quantities

As proposed by the *Guide,* the second step of evaluating and expressing uncertainty is to determine x_i, the estimated value of X_i. In the case of our wind measurements and those observed by the variety of in-situ sensors, "input quantities" can be thought of as data output from any given sensor. Concerning wind speed, V and U vector components are the only data output from Gill's 2D anemometer, as many of the components of Eq. (5) are processed internally by the 2D anemometer. In other words, each vector component comprises quantities of transit times as well as the distance between transducer heads; the former dynamically changing with wind speed and the latter considered a static quantity. The input quantities of our 1 Hz 2D wind speed datum are 1 Hz U and V vector component data output by the sensor. Here, we provide individual vector component data to represent 1 Hz input quantities:

- $V_i = 7.97\ [m\,s^{-1}]$
- $U_i = 4.65\ [m\,s^{-1}]$

The input quantities of our L1 one-minute, mean, 2D wind speed DP are then the 1 Hz 2D wind speed data. These data are temporally averaged to generate the L1 DP (more explanation is provided in Section 3.5).

NOTE:
Other quantities, e.g., the heater, act *only* as sources of uncertainty – these are discussed in the following section.

3.3 Evaluate standard uncertainties

Evaluation of each standard uncertainty $u(x_i)$ of input estimate x_i is the third step of the process. For estimates obtained from statistical evaluations, corresponding standard uncertainties will be calculated by Type A evaluation, while standard uncertainties associated with estimates obtained by other means should be calculated by Type B evaluations (JCGM 2008).

- Type A evaluation of uncertainty – This type of evaluation is based on statistical analysis. A specific example of a Type A analysis is the assumption that x_i is considered the sample mean of n independent observations X_i obtained under identical measurement conditions. The individual observations, X_i, differ due to random effects, which is reflected by the sample standard deviation:

$$s(X_i) = \left(\frac{1}{(n-1)}\sum_{i=1}^{n}(X_i - \bar{X}_i)^2\right)^{\frac{1}{2}} \tag{6}$$

And the standard uncertainty $u(x_i)$ associated with x_i is the standard deviation of the mean:

$$u(x_i) = s(\bar{X}_i) = \frac{s(X_i)}{\sqrt{n}} \tag{7}$$

NOTE on Type A evaluations:

Such evaluations (i.e., Eq. (6) and (7)) *are only* considered relevant in a controlled environment (i.e., calibration laboratory) where *measured quantity values* are obtained under *defined measurement conditions*. Such an approach is considered invalid when outside of a controlled environment, as there is no *reference quantity value* to compare *measured quantity values* to, and *measurement conditions* cannot be controlled.

- Fitting a curve (polynomial) to data by means of least squares regression is also considered a Type A evaluation (JCGM 2008; Taylor 1997). All sources of individual uncertainties of the resulting equation (i.e., Coefficients, and input data *x*) must be taken into account when deriving the combined uncertainty of the resulting function. An example of fitting a polynomial to the data is provided in Section 3.3.1.

- Type B evaluation of uncertainty – This type of evaluation assumes a distribution of data that is specified by the manufacturer. It can be assumed that the distribution of the data is normal *only* if i) the manufacturer does not hint at or describe other distributions, or ii) scientific judgment can be used to argue otherwise (JCGM 2008). In many cases calibration certificates or manufacturer's specifications infer a *priori* distribution (Taylor and Kuyatt 1994, JCGM 2008). These distributions will most likely be one of the following:
  - Uniform / rectangular (JCGM 2008) - This distribution can be assumed if there is no reason to believe that the value of X_i will fall out of the specified lower a_- and upper a_+ bounds. If there is no knowledge of the possible values of X_i, *it can be stated that it is equally probable for X_i to lie anywhere within the bounds* and the best estimate of X_i is the midpoint of the bounds:

$$x_i = \frac{(a_- + a_+)}{2} \tag{8}$$

It is shown that, for a random variable x_i with a probability density function $P(x_i)$ and mean μ, that variance of any distribution is:

$$u^2(x_i) = \int_{-\infty}^{\infty} P(x_i)(x_i - \mu)^2 \, dx_i \tag{9}$$

Setting the mean equal to 0 we can solve for error distribution:

$$u^2(x_i) = \int_{-\infty}^{\infty} P(x_i){x_i}^2 \, dx_i \tag{10}$$

Given that there is equal chance that the random variable will fall within the designated bounds, the probability function of a uniform distribution is derived as:

$$P(x_i) = \frac{1}{2a} \tag{11}$$

The variance for this distribution is then:

$$\begin{aligned} u^2(x_i) &= \int_{-a}^{a} \frac{1}{2a} {x_i}^2 \, dx_i \\ &= \frac{1}{2a} \int_{-a}^{a} {x_i}^2 \, dx_i \\ &= \frac{1}{2a} \frac{{x_i}^3}{3} \bigg|_{-a}^{a} \\ &= \frac{a^3}{6a} - \left(\frac{-a^3}{6a}\right) \\ &= \frac{a^2}{3} \end{aligned} \tag{12}$$

And the standard uncertainty associated with this distribution is therefore:

$$u(x_i) = \frac{a}{\sqrt{3}} \tag{13}$$

<u>Symmetric trapezoid (JCGM 2008)</u> – It is more realistic to assume that values near the midpoint of the distribution are more likely to occur than those near the lower and upper bounds. When this is the case, a symmetric trapezoid (i.e., isosceles triangle) distribution with a base width $a_+ - a_- = 2a$ and top width $2a\beta$, and $0 \leq \beta \leq 1$, can be assumed. As β approaches 1, the distribution becomes uniform, however, as β approaches 0, the distribution becomes triangular. Using the same steps as above, the error distribution and standard uncertainty of a symmetric trapezoid distribution can be derived.

A symmetric trapezoid distribution has a $P(x_i)$ of:

$$P(x_i) = \begin{cases} \dfrac{(a + x_i)}{a^2} & IF \; -a \leq x_i \leq 0 \\ \dfrac{(a - x_i)}{a^2} & IF \;\; 0 \leq x_i \leq a \end{cases} \tag{14}$$

The variance for this distribution is then:

$$u^2(x_i) = \int_{-a}^{0} \frac{(a + x_i)}{a^2} {x_i}^2 \, dx_i + \int_{0}^{a} \frac{(a - x_i)}{a^2} {x_i}^2 \, dx_i$$

$$= \frac{1}{a^2} \int_{-a}^{0} (a + x_i){x_i}^2 \, dx_i + \frac{1}{a^2} \int_{0}^{a} (a - x_i){x_i}^2 \, dx_i$$

$$= \frac{1}{a^2} \int_{-a}^{0} (a + x_i){x_i}^2 \, dx_i + \frac{1}{a^2} \int_{0}^{a} (a - x_i){x_i}^2 \, dx_i$$

$$= \frac{1}{a^2} \left(\left(\frac{{x_i}^3}{3} \right) a + \frac{{x_i}^4}{4} \right) \Bigg|_{-a}^{0} + \frac{1}{a^2} \left(\left(\frac{{x_i}^3}{3} \right) a - \frac{{x_i}^4}{4} \right) \Bigg|_{0}^{a}$$

$$= \left[0 - \left(\left(\frac{-4a^2}{12} \right) + \frac{3a^2}{12} \right) \right] + \left[\left(\left(\frac{4a^2}{12} \right) - \frac{3a^2}{12} \right) - 0 \right]$$

$$= \frac{a^2}{6} \tag{15}$$

The standard uncertainty of this particular distribution is thus:

$$u(x_i) = \frac{a}{\sqrt{6}} \tag{16}$$

In the absence of information regarding symmetry of the distribution, Equation (13) can be used, as it is considered the simplest approximation (JCGM 2008).

NOTE on Type B evaluations:
Information provided by a manufacturer may sometimes be in the form of expanded uncertainty. If this occurs, the expanded uncertainty must be adjusted to a value representing standard uncertainty when relying on Type B evaluations (JCGM 2008; NIST 1994).

NOTE on in-house calibrations:
NEON's Calibration, Validation, and Audit Laboratory (CVAL) will calibrate most of the sensors used throughout NEON's Observatory, thus correcting for known systematic uncertainties and quantifying random uncertainties. For such sensors, CVAL will provide a single combined uncertainty $u_c(x_{CVAL})$. 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 calibration coefficients. If CVAL does not calibrate a specific type of sensor for any reason, they will validate the sensor against the manufacturer's specifications or calibration certificates etc. For more information regarding the manner by which CVAL will calibrate/validate sensors please refer to AD[08]. In the case of non-calibration, CVAL

will not provide a combined uncertainty and the Fundamental Instrument Unit (FIU) of NEON will derive uncertainty from available resources.

An example of an ATBD which makes use of an uncertainty derived by CVAL can be found in AD[12]. To provide an example of a sensor which is validated and not calibrated in-house, standard uncertainties for 2D wind speed are evaluated in the following subsections.

3.3.1 Measurement Accuracy

The raw data output of Gill's 2D anemometers are V and U vectors in units of m s^{-1} and recorded at a frequency of 1 Hz. Quantification of the standard uncertainties associated with each of these components can be achieved via both Type B (information from calibration certificates provided by Gill in Table 4) and Type A (statistical: fitting a curve to the data) evaluations.

Table 4: Accuracy as a function of vector magnitude. ***For simplicity purposes only,*** accuracies displayed here are associated with the magnitude of individual vector components; In reality, however, these values are representative of wind speed accuracy (Murree Sims, Gill Instruments, pers. comm., 2012)

Magnitude (m s^{-1})	Accuracy (± %)
0.01*	1.0
5	1.0
12	2.0
32	3.0
65	4.0
* Starting threshold of Gill's 2D sonic anemometers.	

As displayed in Eq. (3), both wind components are functions of other quantities (*e.g.,* distance between transducer faces). Uncertainties of the input quantities from Eq. (1) and (2) are quantified by Gill Instruments, therefore the information in Table 4 can be thought of as combined uncertainties for all input values of each vector component. Least squares regression can be used with this information to define accuracy as a function of vector magnitude. Here, we aim for optimal regression by fitting a polynomial that results in a coefficient of determination, $r^2 = 1.0$.

$$u(m_{x_i}) = C_4 {x_i}^4 - C_3 {x_i}^3 + C_2 {x_i}^2 - C_1 x_i + C_0 \quad (17)$$

Where,

$u(m_{x_i})$ = Accuracy as a function of the 1 Hz vector component magnitude

x_i = Individual magnitude of the vector component

$C_4 = 5.0E^{-7}$; E denotes scientific notation

$C_3 = 6.0E^{-5}$

$C_2 = 2.3E^{-3}$

$C_1 = 2.0E^{-4}$

$C_0 = 1.0E^{-4}$

Anytime a polynomial is fit to data, the uncertainty of the fit (i.e., coefficients) should be quantified (JCGM 2008). By fitting a polynomial with a resulting $r^2 = 1.0$, *we can assume* that uncertainties of individual coefficients are negligible, however, for completeness, quantifying the uncertainty of the fit is shown. This is completed by taking the partial derivative of Eq. (17):

$$\frac{\partial u(m_{x_i})}{\partial x_i} = 4C_4{x_i}^3 - 3C_3{x_i}^2 + 2C_2x_i - C_1 \quad (18)$$

and multiplying the *derived uncertainty* of the vector component by the absolute value of Eq. (18).

$$u_{x_i}(P) = \left|4C_4{x_i}^3 - 3C_3{x_i}^2 + 2C_2x_i - C_1\right| u(m_{x_i}) \quad (19)$$

Using *the Law of Propagation of Uncertainties*, the combined uncertainty of each vector component now becomes:

$$u_c(x_{m_i}) = \left(u^2(m_{x_i}) + {u_{x_i}}^2(P)\right)^{\frac{1}{2}} \quad (20)$$

Using the above equations, our vector components would have individual standard uncertainties of:

- $u_c(V_{m_i}) = 0.116\, m\, s^{-1}$
    - $u(m_{V_i}) = 0.116\, m\, s^{-1}$
    - $u_V(P_i) = 0.003\, m\, s^{-1}$
- $u_c(U_{m_i}) = 0.043\, m\, s^{-1}$
    - $u(m_{U_i}) = 0.043\, m\, s^{-1}$
    - $u_U(P_i) = 0.001\, m\, s^{-1}$

It is evident here that the uncertainty of fitting a polynomial is orders of magnitude smaller than the uncertainties provided by Gill (2007, 2011), and as stated before, can be considered *negligible*. However, to promote transparency, all quantifiable uncertainties are propagated within this document.

3.3.2 Noise

It is reported by Gill (2007, 2010) that each measurement is accompanied by 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. The value provided by Gill is actually an additional, random uncertainty, most likely arising from effects such as measurement noise and/or the internal conversion from analog to digital signal.

3.3.3 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 resides outside these bounds, we can assume uniform distribution (JCGM 2008) and an uncertainty of:

$$u(R) = \frac{0.01\text{ms}^{-1}}{\sqrt{3}} = 0.00578\ \text{m s}^{-1} \tag{21}$$

In the event that a sensor is calibrated in-house, uncertainties arising from resolution of the digital indication will be reflected in the uncertainty value provided by CVAL (please refer to Note on in-house calibrations in Section 3.3).

3.3.4 Heaters

Two models of Gill's sonic anemometers are equipped with heaters. To avoid ice buildup, these heaters turn on 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 the transducer heads will cause small thermals around each transducer, thus altering the neighboring temperature and causing uncertainty of the wind measurement. Since NEON *will not* calibrate these sensors or monitor the current draw of the heaters, we cannot confidently quantify the uncertainty induced by heating at current time.

However, we have been assured by Gill Instruments that heating of the 2D anemometer causes *negligible* uncertainty to the sonic wind measurement.

NOTE:
Heaters, as well as other components of the assembly *may* cause large systematic uncertainties in the measurement. Although the magnitude of these uncertainties may not be quantifiable at the time the sensor and its assembly are deployed, it *may be possible* that analysis of NEON data will help identify and correct for previously unquantifiable systematic uncertainties.

3.3.5 Data Acquisition System (DAS)

Most sensors used throughout the NEON Observatory output data in analog form. For sensors outputting data in this form, NEON's data acquisition system (DAS) will add uncertainty (noise) to the raw measurement. The magnitude of this noise is a function of the 'raw' measurement's *magnitude*. CVAL will provide a relative uncertainty value $u_r(x_{DAS})$ representing the uncertainty of the measurement as a function of noise; further information can be found in AD [08, 09]. *For each raw measurement*, this value must be converted from a percentage to appropriate measurement units prior to its propagation. This is completed in two steps. First, the uncertainty is converted from relative to standard:

$$u\left(x_{i_{DAS}}\right) = \left(u_r(x_{DAS}) * x_i\right) + \ \mathrm{O}_{DAS} \quad [\text{V}] \text{ or } [\Omega] \tag{22}$$

Where $u\left(x_{i_{DAS}}\right)$ represents the standard uncertainty of an individual (1 Hz) measurement, x_i, and O_{DAS} is the offset of the DAS. The offset accounts for readings of 0.00 [V] or [Ω] depending on the analog signal. Second, the standard uncertainty is multiplied by the absolute value of the partial derivative comprising calibration/conversion coefficients. This is completed to convert from analog units to measurement units:

$$u_{x_i}(y) = \left|\frac{\partial y}{\partial x_i}\right| u\left(x_{i_{DAS}}\right) \quad [SI\ units] \tag{23}$$

Where, $u_{x_i}(y)$ is the partial uncertainty of the resulting measurand y, as a function of the individual measurement x_i, and $\frac{\partial y}{\partial x_i}$ is the partial derivative (sensitivity coefficient) of the appropriate conversion equation.

NOTE:
Gill's 2D anemometers have an internal Analog to Digital converter (A/D) and output data in digital form, and thus, uncertainty related to NEON's data acquisition system (DAS) can be considered negligible. It is proposed that measurement noise and/or the *internal* A/D completed by Gill's 2D anemometers result in the ± 0.01 m s^{-1} uncertainty displayed in Section 3.3.2.

3.3.7 Algorithms (finite-precision)

When data are converted from L0 to L1 data products via algorithms, additional, yet trivial uncertainties may arise. These uncertainties are likely the result of finite-precision arithmetic (*i.e.,* round-off errors and / or 'ill-conditioned' algorithms; JCGM 2008). Since it is common practice *not* to round-off individual values of estimated measurands and uncertainties during calculations, uncertainties arising from finite-precision arithmetic can considered negligible to non-existent; unless otherwise stated, such uncertainties can be disregarded.

3.3.8 Drift

We acknowledge that drift is an inherent characteristic of any sensor. Drift may occur gradually or abruptly, is considered generally unpredictable, and can only be corrected via calibration (Brock and Richardson 2001). Drift will be explicitly quantified for each type of sensor during annual in-house calibrations/validations completed by CVAL (Please refer to AD[08] for more information).

3.4 Evaluate Correlations

In the event that input quantities x_i are correlated in some fashion, the correlations must be taken into account (JCGM 2008). To determine if input quantities (i.e., x_i , x_j) are correlated, the correlation coefficient, *r*, should be calculated:

$$r\left(x_i, x_j\right) = \frac{u(x_i, x_j)}{u(x_i)u(x_j)} \tag{24}$$

where $-1 \leq r(x_i, x_j) \leq 1$ is the correlation coefficient and $r(x_i, x_j) = r(x_j, x_i)$. If input quantities are correlated the combined uncertainty of the terms must reflect this correlation (Please refer to Section 3.6 for further information).

For 2D wind, we can assume that the input variables V and U are uncorrelated. It is possible, however, that in some instances an increase of wind speed may increase the magnitude of each vector component concurrently (*i.e.,* wind direction at a ~45° relative to a specific quadrant with varying wind speed). In most cases a magnitude increase of one component should not result in an increase in the other. Moreover, a decrease in component magnitude should not cause a magnitude increase in the other component.

NOTE:
Although we accept that correlated data may exist, we are assuming that all data are *independent* and *uncorrelated* for *all of NEON's TIS sensors*.

3.5 Calculate the result of the measurement

As proposed by the *Guide,* the fifth step of evaluating and expressing uncertainty is to determine y, the estimated value of the measurand Y, from the functional relationship using estimate input quantities (JCGM 2008).

$$y = \bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i = \frac{1}{n}\sum_{i=1}^{n} f(\, X_{1,i}\,,\, X_{2,i}, \ldots,\, X_{N,i}\,) \qquad (25)$$

Where, y is considered the arithmetic mean of n independent observations.

NOTE:
Equation (25) represents the manner by which a mean quantity is derived for a Type A uncertainty evaluation. Consequently, a standard uncertainty is then derived via Eq. (6) and (7) representing the deviation of repetitive measurements under *specified measurement conditions*. Such a process will be completed in-house by our CVAL laboratory. On the contrary, although NEON's L1 TIS DPs will be derived via temporal averaging (similar form of Eq. (25)), the resulting measurand comprises uncertainties of the *entire assembly* (refer to Sections 3.3.1 through 3.3.7), and is made under *unspecified measurement conditions*, thus, it does not serve as a basis by which a standard uncertainty shall be derived.

A brief example is provided here using our 2D wind speed L1 DPs. First, individual wind speeds, S_i, are computed via Eq. (2):

$$S_i = \left(V_i^2 + U_i^2\right)^{\frac{1}{2}} = (7.97^2 + 4.65^2)^{\frac{1}{2}} = 9.2273 \quad [m\, s^{-1}] \qquad (26)$$

Next, a L1 one-minute, mean 2D wind speed will be calculated via temporal averaging:

$$S = \frac{1}{n}\sum_{i=1}^{n} S_i. \tag{27}$$

Where, for each minute average, *n* is the number of measurements over time and the averaging period is defined as 0 ≤ n < 60 seconds OR for each thirty-minute average, *n* is the number of measurements over time and averaging periods are defined as 0 ≤ n < 1800 seconds.

For simplicity and conciseness, we assume that the individual wind speed datum represents our temporal average, and thus:

$$\bar{S} = 9.23\, m\, s^{-1} \tag{28}$$

Where $\bar{S}$ is the L1, one-minute, mean 2D wind speed.

NOTE:
Since the digital resolution of Gill's 2D anemometers is 0.01 m s^{-1}, we round the final value to the hundredth decimal place. For simplification purposes we will assume that the result from Eq. (28) is the mean wind speed during a one-minute period.

3.6 Calculate the combined uncertainty

Per NEON requirement and to ensure traceability, all L1 data products must be accompanied by a value of combined standard uncertainty. JCGM (2008) notes two important guidelines for the evaluation of combined uncertainty:

- It is *unnecessary to classify* components with commonly used terms such as 'random ±' or 'systematic +,-'. If an uncertainty is asymmetrically distributed (i.e. systematic - always positive or always negative), *a correction factor will be applied to the uncertainty.*
- *All standard uncertainties should be treated equally* regardless of the manner in which they were evaluated (i.e., Type A or B).

JCGM (2008) derives the combined standard uncertainty as:

$$u_c(y) = \left(\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i)u(x_j)r(x_i,x_j)\right)^{\frac{1}{2}} \tag{29}$$

Where:

- f — Function representing sources of uncertainties that can be quantified
- $u(x_{i,j})$ — Individual standard uncertainties
- $\frac{\partial f}{\partial x_{i,j}} = \left.\frac{\partial f}{\partial X_{i,j}}\right|_{x_1,x_2,\ldots,x_n}$ — Partial derivatives (also known as sensitivity coefficients (c_i))
- $r(x_i, x_j)$ — Correlation coefficient where $-1 < r(x_i,x_j) < 1$.

In the event that the standard uncertainties are uncorrelated ($r(x_i, x_j) \approx 0$) and independent from one another, Eq. (29) becomes:

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \right)^{\frac{1}{2}} \tag{30}$$

If input quantities are correlated to the point that $r = +1$ (i.e., 100% positive correlation), Eq. (29) becomes:

$$u_c(y) = \sum_{i=1}^{N} \frac{\partial f}{\partial x_i} u(x_i) \tag{31}$$

which is simply the *linear sum of individual uncertainties*; this should not be confused with the *Law of Propagation of Uncertainty*, (Eq (30)), although it has similar form (JCGM 2008).

NOTE on correlated data:
As mentioned in Section 3.4, and stated again here to reflect importance – Although we accept that correlated data may exist, we are assuming that all data are independent and uncorrelated at this time (unless otherwise specified).

NOTE on data QA/QC:
In the event that data are flagged for quality reasons, L1 DPs and uncertainty values *may or may not be calculated*. This subject is further explained within sensor specific ATBDs. To provide an example, individual wind speed and direction measurements will be flagged in the event that flow distortion occurs (i.e., wind flows through tower infrastructure) upstream of the 2D sonic anemometer. Despite being flagged, such data will be used to compute L1 DPs and the end-user will be made aware of the flagging.

The standard uncertainties listed in Sections 3.3.1 through 3.3.7 are inherent in each individual (1 Hz) vector component datum. As such, the combined uncertainty of such measurements must be derived before a combined uncertainty for 1 Hz wind speed and one-minute, mean wind speed can be derived.

Following Eq. (30), the combined uncertainties for each individual vector component datum are respectively:

$$u_c(V_i) = \left({u_c}^2(V_{m_i}) + u^2(R) + u^2(N) \right)^{\frac{1}{2}}$$

$$u_c(V_i) = (0.116^2 + 0.00578^2 + 0.01^2)^{\frac{1}{2}} = \pm\, 0.117 \;\; [m\, s^{-1}] \tag{32}$$

$$u_c(U_i) = \left(u_c{}^2\left(U_{m_i}\right) + u^2(R) + u^2(N)\right)^{\frac{1}{2}}$$
$$u_c(U_i) = (0.043^2 + 0.00578^2 + 0.01^2)^{\frac{1}{2}} = \pm\, 0.045 \;\; [m\, s^{-1}] \quad (33)$$

The partial derivative of wind speed with respect to each vector component must be computed:

$$\frac{\partial S_i}{\partial V_i} = \frac{V_i}{\left(U_i{}^2 + V_i{}^2\right)^{\frac{1}{2}}} \quad (34)$$

$$\frac{\partial S_i}{\partial U_i} = \frac{U_i}{\left(U_i{}^2 + V_i{}^2\right)^{\frac{1}{2}}} \quad (35)$$

The partial uncertainties of wind speed with respect to each vector component are then derived by multiplying the absolute value of the appropriate partial derivative by the appropriate uncertainty value:

$$u_V(S_i) = \left|\frac{\partial S_i}{\partial V_i}\right| u_c(V_i) = \left|\frac{7.97}{(7.97^2 + 4.65^2)^{\frac{1}{2}}}\right| 0.117 = 0.101 \; [m\, s^{-1}] \quad (36)$$

$$u_U(S_i) = \left|\frac{\partial S_i}{\partial U_i}\right| u_c(U_i) = \left|\frac{4.65}{(7.97^2 + 4.65^2)^{\frac{1}{2}}}\right| 0.045 = 0.023 \;\; [m\, s^{-1}] \quad (37)$$

Resulting values then propagate into a combined uncertainty for the 1 Hz wind speed datum:

$$u_c(S_i) \; = \left(u_V{}^2(S_i) + u_U{}^2(S_i)\right)^{\frac{1}{2}} \quad (38)$$
$$u_c(S_i) = (0.101^2 \; + 0.023^2)^{\frac{1}{2}} = \pm\, 0.10358 \;\; [m\, s^{-1}]$$

The resulting value is multiplied by the partial derivative of the L1 DP. Since the DP is a temporal average, the partial derivative is simply:

$$\frac{\partial \bar{S}}{\partial S_i} = \frac{1}{n} \quad (39)$$

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):

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

Finally, the combined uncertainty of the L1 mean DP is calculated via quadrature. For simplicity, we assume that all 60, 1 Hz wind speed measurements are of the same magnitude, and thus, the L1 one-minute mean 2D wind speed is then:

$$u_c(\bar{S}) = \left(\sum_{i=1}^{n} {u_{S_i}}^2(\bar{S})\right)^{\frac{1}{2}} = \ 0.01337 \approx 0.01 \quad [m\, s^{-1}] \tag{41}$$

NOTE:
When *displaying* resulting values of combined and expanded uncertainties, significant figures should always be truncated (rounded) to mirror the significant figures of the reported measurand. Since the digital resolution of Gill's 2D anemometers is 0.01 m s^{-1}, we round the final values to the hundredth decimal place:

3.7 Calculate the expanded uncertainty

Expanded uncertainty defines an interval about the resulting measurement which encompasses a larger, or *expanded*, fraction of the distribution of values that could be attributed to the measurand (JCGM 2008). In other words, it is the combined uncertainty broadened to a larger level of confidence. It is given by:

$$U_p = k_p u_c(y) \tag{42}$$

where k is the coverage factor at a specified level of confidence p. If $u_c(y)$ is the sum of two or more individual standard uncertainties (which is usually the case) k_p should be calculated as a function of *effective degrees of freedom* via the Welch-Satterthwaite formula:

$$v_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N} \frac{u_i^4(y)}{v_i}} \tag{43}$$

where v_i is the *degrees of freedom* from a specific input quantity x_i. For Type A evaluations, v_i is simply $n-1$. For Type B evaluations, degrees of freedom is approximated by:

$$v_i \approx \frac{1}{2}\left[\frac{\Delta u(x_i)}{u(x_i)}\right]^{\frac{1}{2}} \tag{44}$$

CAVEAT:
The *Guide* (JCGM 2008) acknowledges that Eq. (44) is *subjective* in nature since it is a reflection of available information (e.g., calibration certificates) and one's scientific judgment. To standardize the manner that Type B evaluations are reflected, a conservative approach is taken and an estimate of 100

will be used for associated degrees of freedom. Like other expanded uncertainties, those provided by NEON should be considered subjective in nature because many will be partial functions of Type B evaluations. *Combined uncertainty* is not accompanied by this caveat, because it is the universally accepted method of expressing uncertainty and considered objective in nature.

All expanded uncertainties at NEON will pertain to a 95% confidence level unless otherwise stated and will be represented by U_{95}. Equation (42) is transformed to represent an expanded uncertainty at 95% confidence:

$$U_{95} = k_{95} u_c(y) \tag{45}$$

Where k_{95} is the coverage factor obtained with the aid of Table 5 as a function of the resulting degrees of freedom (v_{eff}) from Eq. (43).

Table 5: Excerpt from JCGM (2008) defining coverage factors, k, associated with specified levels of confidence and degrees of freedom. NEON's expanded uncertainties will be provided at 95% confidence (highlighted column).

Degrees of freedom ν	Fraction p in percent					
	68,27[a)]	90	95	95,45[a)]	99	99,73[a)]
1	1,84	6,31	12,71	13,97	63,66	235,80
2	1,32	2,92	4,30	4,53	9,92	19,21
3	1,20	2,35	3,18	3,31	5,84	9,22
4	1,14	2,13	2,78	2,87	4,60	6,62
5	1,11	2,02	2,57	2,65	4,03	5,51
6	1,09	1,94	2,45	2,52	3,71	4,90
7	1,08	1,89	2,36	2,43	3,50	4,53
8	1,07	1,86	2,31	2,37	3,36	4,28
9	1,06	1,83	2,26	2,32	3,25	4,09
10	1,05	1,81	2,23	2,28	3,17	3,96
11	1,05	1,80	2,20	2,25	3,11	3,85
12	1,04	1,78	2,18	2,23	3,05	3,76
13	1,04	1,77	2,16	2,21	3,01	3,69
14	1,04	1,76	2,14	2,20	2,98	3,64
15	1,03	1,75	2,13	2,18	2,95	3,59
16	1,03	1,75	2,12	2,17	2,92	3,54
17	1,03	1,74	2,11	2,16	2,90	3,51
18	1,03	1,73	2,10	2,15	2,88	3,48
19	1,03	1,73	2,09	2,14	2,86	3,45
20	1,03	1,72	2,09	2,13	2,85	3,42
25	1,02	1,71	2,06	2,11	2,79	3,33
30	1,02	1,70	2,04	2,09	2,75	3,27
35	1,01	1,70	2,03	2,07	2,72	3,23
40	1,01	1,68	2,02	2,06	2,70	3,20
45	1,01	1,68	2,01	2,06	2,69	3,18
50	1,01	1,68	2,01	2,05	2,68	3,16
100	1,005	1,660	1,984	2,025	2,626	3,077
∞	1,000	1,645	1,960	2,000	2,576	3,000

a) For a quantity z described by a normal distribution with expectation μ_z and standard deviation σ, the interval $\mu_z \pm k\sigma$ encompasses p = 68,27 percent, 95,45 percent and 99,73 percent of the distribution for k = 1, 2 and 3, respectively.

We can calculate the expanded uncertainty of our L1 one-minute, mean, 2D wind speed DP is computed in a number of steps. First, the effective degrees of freedom of $u_c(V_{m_i})$ and $u_c(U_{m_i})$ should be calculated:

$$v_{eff_{V_{m_i}}} = \frac{u_c{}^4(V_{m_i})}{\frac{u^4(m_{V_i})}{v_{effm_{V_i}}} + \frac{u_v{}^4(P_i)}{v_{v_i}}} = \frac{0.116^{\ 4}}{\frac{0.116^4}{100} + \frac{0.003^4}{4}} = 100 \tag{46}$$

$$v_{eff_{U_{m_i}}} = \frac{u_c^4(U_{m_i})}{\frac{u^4(m_{U_i})}{v_{effm_{U_i}}} + \frac{u_U{}^4(P_i)}{v_{U_i}}} = \frac{0.043^{\ 4}}{\frac{0.043^4}{100} + \frac{0.001^{\ 4}}{4}} = 100 \tag{47}$$

NOTE:
Uncertainty values $u(m_{V_i})$ and $u(m_{U_i})$ spawn from Type B analyses ($v_{eff} = 100$), while $u_V(P_i)$ and $u_U(P_i)$ result from a Type A uncertainty evaluation of fitting a polynomial to the data ($v_i = n - 1$). Since our polynomial was fit using available accuracy data (i.e., 5 points) from Gill Instruments we are assuming $5 - 1 = 4$ degrees of freedom.

These effective degrees of freedom are then included in the calculation of effective degrees of freedom for each vector:

$$v_{eff_{V_i}} = \frac{u_c{}^4(V_i)}{\frac{u_c{}^4(V_{m_i})}{v_{eff_{V_{m_i}}}} + \frac{u^4(R)}{v_{eff_R}} + \frac{u^4(N)}{v_{eff_N}}} = \frac{0.117^4}{\frac{0.116^4}{100} + \frac{0.00578^4}{100} + \frac{0.01^4}{100}} = 103.49 \tag{48}$$

And

$$v_{eff_{U_i}} = \frac{u_c{}^4(U_i)}{\frac{u_c{}^4(U_m)}{v_{effm_{U_i}}} + \frac{u^4(R)}{v_{eff_R}} + \frac{u^4(N)}{v_{eff_N}}} = \frac{0.045^4}{\frac{0.043^4}{100} + \frac{0.00578^4}{100} + \frac{0.01^4}{100}} = 119.56 \tag{49}$$

Uncertainty values $u(R)$ and $u(N)$ are considered Type B because they are derived by the manufacturer, and as such, their corresponding effective degrees of freedom are 100.

The resulting values from Eq. (48) and (49) are then used to compute the effective degrees of freedom for the 1 Hz wind speed datum:

$$v_{eff_{S_i}} = \frac{u_c^4(S_i)}{\frac{u_V{}^4(S_i)}{v_{eff_{V_i}}} + \frac{u_U{}^4(S_i)}{v_{eff_{U_i}}}} = \frac{0.10358^4}{\frac{0.101^4}{103.49} + \frac{0.023^4}{119.56}} = 114.21 \tag{50}$$

Finally, the effective degrees of freedom for our L1 one-minute, mean, wind speed DP are calculated:

$$V_{eff_{\bar{S}}} = \frac{u_c{}^4(\bar{S})}{\sum_{i=1}^{n}\left(\frac{(u_c(S_i)/n)^4}{V_{eff_{S_i}}}\right)} = 6848.25 \tag{51}$$

Finally, the expanded uncertainty is provided at 95% confidence:

$$U_{95}(\bar{S}) = k_{95} * u_c(\bar{S}) = 1.96 * .01337 = .0262 \approx .03 \; [m\, s^{-1}] \quad (52)$$

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

- Table 5
- $V_{eff_{\bar{S}}}$

3.8 Report Uncertainty

When reporting uncertainty, JCGM (2008) recommends the estimated value, *y*, and its uncertainty (either combined or expanded) be displayed together.

$$Y = y \pm u_c(y) \; [units] \;\; OR \;\; Y = y \pm U_{95} \; [units] \quad (53)$$

On NEON's data portal, all TIS L1 mean DPs will be displayed with a combined and an expanded uncertainty. Effective degrees of freedom and the *coverage* factor (*k*) of each computed L1 DP will not be displayed, but will be available by request.

3.7.1 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.

NOTE:
In the event that the final combined uncertainty of a DP is the function of other combined uncertainties, such as with wind speed, the order of uncertainty propagation will be denoted by color shading from lightest to darkest.

Table 6: Example uncertainty budget for NEON's L1 mean, 2D wind speed DPs

Source of uncertainty	Standard uncertainty component u(X$_i$)	Type of eval.	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	$u_c(\bar{S})$	A,B[1]	Eq. (41)	N/A	N/A	Eq. (51)
1 Hz Wind Speed	$u_c(S_i)$	A,B[1]	Eq. (38)	Eq. (39)	Eq. (40)	Eq. (50)
1 Hz U component	$u_c(U_i)$	A,B[1]	Eq. (33)	Eq. (35)	Eq. (37)	Eq. (49)
Combined accuracy U	$u_c(U_{m_i})$	A,B[1]	Eq. (20)	1	Eq. (20)	Eq. (47)
Accuracy U comp.	$u(m_{U\,i})$	B[1]	Eq. (17)	1	Eq. (17)	100
Poly Fit U comp.	$u_U(P_i)$	A	Eq. (17)	Eq. (18)	Eq. (19)	4
Dig. Ind. Resolution	$u(R)$	B[1]	Eq. (21)	1	Eq. (21)	100
Measurement noise	$u(N)$	B[1]	0.01	1	0.01	100
1 Hz V component	$u_c(V_i)$	A,B[1]	Eq. (32)	Eq. (34)	Eq. (36)	Eq. (48)
Combined accuracy V	$u_c(V_{m_i})$	A,B[1]	Eq. (20)	1	Eq. (20)	Eq. (46)
Accuracy V comp.	$u(m_{V\,i})$	B[1]	Eq. (17)	1	Eq. (17)	100
Poly Fit V comp.	$u_v(P_i)$	A	Eq. (17)	Eq. (18)	Eq. (19)	4
Dig. Ind. Resolution	$u(R)$	B[1]	Eq. (21)	1	Eq. (21)	100
Measurement noise	$u(N)$	B[1]	0.01	1	0.01	100

k_{95}: $v_{eff\,\bar{S}}$ & Table 5

$U_{95}(\bar{S})$: Eq. (52)

[1]Gill Instruments (2007, 2011)

4 UNCERTAINTY AND ATBD DOCUMENTS

Documentation of the evaluation and quantification of uncertainties will be included in the *Uncertainty Estimation* section of each ATBD. At a bare minimum, this section of the ATBD will display:

- Identifiable sources of uncertainty
- Brief statement(s) justifying whether a specific uncertainty can be quantified
    - If quantifiable – the origin of individual standard (or relative) uncertainties
- Type(s) of evaluation
- Algorithm(s) used to compute combined and expanded uncertainties for L1 data product(s)
- Algorithm(s) used to compute degrees of freedom (effective) for quantifiable uncertainties
- Uncertainty budget

Extensive explanations are displayed in this Plan because it serves as a reference. Lengthy explanations regarding the evaluation and expression of uncertainty will most likely not appear within individual ATBDs. However, there may be instances when additional explanations may be needed to justify or explain complex topics.

5 REFERENCES

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