ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD):

BUOY 2D WIND SPEED AND DIRECTION

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A	08/11/2017	ECO-05472	Initial Release
B	10/12/2021	ECO-06635	Account for wind monitor orientation changes on mast position, remove signal despike quality flagging

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1 DESCRIPTION

This document details 2D wind speed and direction measurements made at NEON buoy sites. This ATBD describes the processes necessary to convert “raw” sensor measurements into meaningful scientific units and their associated uncertainties. Wind will primarily be continuously monitored at all NEON core and relocatable sites using a 2D sonic anemometer (RD [03]), but this document focuses on the 2D wind monitor and digital compass situated on buoys at NEON lakes and large river sites.

1.1 Purpose

This document details the algorithms used for creating NEON Level 1 data products for the buoy 2D wind monitor from Level 0 data, and ancillary data as defined in this document (such as calibration data) obtained via instrumental measurements made by the wind monitor and digital compass. It includes a detailed discussion of measurement theory and implementation, appropriate theoretical background, data product provenance, quality assurance and control methods used, approximations and/or assumptions made, and a detailed exposition of uncertainty resulting in a cumulative reported uncertainty for this product.

1.2 Scope

This document describes the theoretical background and entire algorithmic process used to derive Level 1 data from Level 0 data for the buoy 2D wind monitor and digital compass. The 2D wind monitor installed at NEON buoys is model 05108-45 Wind Monitor-HD Alpine, RM Young Company, Traverse City Michigan, USA. The buoy’s digital compass is the Honeywell model HMR 3300, Solid State Electronics Center, Plymouth, MN, USA. This document does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS, ACRONYMS AND VARIABLE NOMENCLATURE

2.1 Applicable Documents

AD[01]	NEON.DOC.000001 NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.002652 NEON Level 1, Level 2 and Level 3 Data Products Catalog
AD[03]	NEON.DOC.011081 ATBD QA/QC Plausibility Tests
AD[04]	NEON.DOC.000746 Calibration Fixture and Sensor Uncertainty Analysis (CVAL)
AD[05]	NEON.DOC.000785 TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[06]	NEON.DOC.000927 NEON Calibration and Sensor Uncertainty Values[1]
AD[07]	NEON.DOC.001113 Quality Flags and Quality Metrics for TIS Data Products
AD[08]	NEON.DOC.003808 NEON Sensor Command, Control and Configuration (C3) Document: Buoy Meteorological Station and Submerged Sensor Assembly
AD[09]	NEON.DOC.002651 NEON Data Product Numbering Convention
AD[10]	NEON.DOC.004613 NEON Preventive Maintenance Procedure: AIS Lake Buoy

[1] Note that CI obtains calibration and sensor values directly from an XML file maintained and updated by CVAL in real time. This report is updated approximately quarterly such that there may be a lag time between the XML and report updates.

2.2 Reference Documents

RD[01]	NEON.DOC.000008 NEON Acronym List
RD[02]	NEON.DOC.000243 NEON Glossary of Terms
RD[03]	NEON.DOC.000780 NEON Algorithm Theoretical Basis Document (ATBD) – 2D Wind Speed and Direction

2.3 External Documents

ED[01]	Wind Monitor-HD Alpine MODEL 05108-45 Instructions, RM Young Company Rev A030513
ED[02]	HMR3200/HMR330 Digital Compass Solutions User's Guide, Honeywell Sensor Products 04-02 Rev. A

2.4 Acronyms

Acronym	Explanation
AIS	Aquatic Instrument System
ATBD	Algorithm Theoretical Basis Document
CI	NEON Cyberinfrastructure
CVAL	NEON Calibration, Validation, and Audit Laboratory
SCI	NEON Science
DAS	Data Acquisition System

DP	Data Product
FDAS	Field Data Acquisition System
GRAPE	Grouped Remote Analog Peripheral Equipment
Hz	Hertz
L0	Level 0
L1	Level 1
QA/QC	Quality assurance and quality control
LHDD	Location Hierarchy Design Document
TIS	Terrestrial Instrument System
API	Application programming interface
FOPS	Field Operations

2.5 Variable Nomenclature

The symbols used to display the various inputs in the ATBD, e.g., calibration coefficients and uncertainty estimates, were chosen so that the equations can be easily interpreted by the reader. However, the symbols provided will not always reflect NEON's internal notation, which is relevant for CI's use, and/or the notation that is used to present variables on NEON's data portal. Therefore, a lookup table is provided in order to distinguish what symbols specific variables can be tied to in the following document.

Symbol	**Internal Notation**	**Description**
A_{0_θ}	CVAL_A0	CVAL sensor-specific calibration coefficient for unit-vector wind direction dead-band identification. Provided by CVAL and stored in CI Data store
A_{1_θ}	CVAL_A1	CVAL sensor-specific calibration coefficient for unit-vector wind direction. Provided by CVAL and stored in CI Data store
A_{1_S}	CVAL_B1	CVAL sensor-specific calibration coefficient for wind speed. Provided by CVAL and stored in CI Data store
u_{A1_θ}	UCVAL_A1$_{\Theta}$	Combined calibration uncertainty of wind direction measurements. Provided by CVAL and stored in CI Data store
u_{A3_θ}	UCVAL_A3$_{\Theta}$	Calibration uncertainty (truth and trueness components, only) of wind direction measurements. Provided by CVAL and stored in CI Data store
u_{A1_S}	UCVAL_A1$_{S}$	Combined calibration uncertainty of wind speed measurements. Provided by CVAL and stored in CI Data store

Symbol	Internal Notation	Description
u_{A3_S}	UCVAL_A3$_s$	Calibration uncertainty (truth and trueness components, only) of wind speed measurements. Provided by CVAL and stored in CI Data store
u_{c1}	Ucompass	Compass uncertainty. Provided by SCI and stored in the CI data store. Note: SCI uses specifications for 0° to ±30° in ED[02]
u_{d1}	Udeclination	Magnetic declination uncertainty. Provided by SCI and stored in the CI data store
u_o	Uorientation	Wind monitor orientation uncertainty. This is based on the uncertainty in the direction the wind monitor faces based on mast orientation and the orientation of the wind monitor atop the mast. Provided by SCI and stored in the CI data store
$\bar{S}$	NA	Uncalibrated wind speed
$\bar{S}_C$	NA	Wind speed calibrated via CVAL coefficient
S_R	NA	RM Young nominal coefficient for converting raw wind speed (Hz) to scalar wind speed (m s^{-1}); provided by SCI and stored in the CI data store
$\bar{S}_T$	NA	Temporally averaged scalar wind speed
θ_o	NA	Wind-monitor offset angle, in degrees, as positioned on mast relative to the compass's direction, such that the mast's 0 degrees reference point corresponds to 0 degrees on the compass when the buoy is oriented to face magnetic North
θ_c	NA	Instantaneous buoy platform compass direction in the same time interval as the buoy's L0 data product, adjusted for magnetic declination, in degrees
θ_c	NA	Instantaneous buoy platform compass direction as the L0 buoy data product, unadjusted for magnetic declination, in degrees
$\bar{\theta}_C$	NA	Unit-vector wind direction calibrated via CVAL coefficient
θ_d	NA	Magnetic declination angle, in degrees. Provided by SCI and stored in the CI data store

Symbol	Internal Notation	Description
θ_U	NA	Compass offset angle, in degrees. Provided by SCI and stored in the CI data store
$\bar{\theta}_w$	NA	Unit-vector mean wind direction, corrected by buoy compass direction (deg)
$\bar{\theta}_w$	NA	Unit-vector mean wind direction, uncorrected for buoy compass direction (deg)
$\bar{\theta}'_w$	NA	Unit-vector mean wind direction, corrected by buoy compass direction (radians)
$\bar{\theta}$	NA	Unit-vector mean wind direction, considered in the same time interval as the buoy's L1 data products
$\bar{\theta}_T$	NA	Unit-vector mean wind direction as an L1 data product, T denotes averaging period
θ_{T,σ^2}	NA	Wind direction variance as an L1 data product, T denotes averaging period
θ_R	NA	RM Young nominal coefficient for converting raw wind direction (V) to polar wind direction (deg); provided by SCI and stored in the CI data store

2.6 Verb Convention

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

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

The buoy 2D wind speed and direction related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file windSpeedDirBuoy_datapub_NEONDOC004406.txt. Statistical summaries 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*.

3.2 Input Dependencies

Table 1 details the buoy compass direction, wind speed, and wind direction related L0 DPs used to produce L1 buoy 2D wind speed and direction DPs in this ATBD.

Table 3-1: List of buoy wind monitor and digital compass L0 DPs that are transformed into L1 wind speed and direction DPs in this ATBD.

Description	**Sample Frequency**	**Units**	**Data Product Number**
wind speed	~4-sec*	m s^{-1}	NEON.DOM.SITE.DP0.20059.001.00340.HOR.VER.000
Unit-vector wind direction	~4-sec*	degree	NEON.DOM.SITE.DP0.20059.001.00380.HOR.VER.00
Unit-vector averaged mean of yaw (heading) angle	~4 sec*	degree	NEON.DOM.SITE.DP0.20059.001.02899.HOR.VER.000

*Data will be reported from the data logger every 4 seconds at 02, 06, 10, 14, 18, 22, 26, 30, 34, 38, and 42 seconds past the minute. If more than 6 seconds pass without data record, the sample data point will not be recorded for a given interval.

3.3 Product Instances

2D wind monitors and digital compasses will be deployed at all NEON buoy sites in lakes and non-wadeable streams. A single wind speed monitor shall be located off the buoy mast. The digital compass shall be located in the upper instrument canister (MET canister) attached near the center of the buoy. Canister rotation may affect the digital compass' pitch and roll measurements, but should not influence the yaw (compass heading) direction needed to correct wind direction measurements. The buoy's Preventive Maintenance document (AD [10]) outlines steps for FOPS to ensure appropriate correction to heading, pitch, and roll based on canister orientation.

3.4 Temporal Resolution and Extent

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 wind monitor will represent wind speed and direction at the point which it is placed on the buoy mast.

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 Observatory. This document details the processes to determine mean horizontal wind speed and direction from a buoy with a digital compass.

4.1 Theory of Measurement

The wind monitor measures wind speed and direction using a propeller and vane. The wind monitor mounting atop the buoy's mast consistently aligns its vane towards the north facing direction such that the wind direction readings will always be offset by the same radial distance relative to the buoy platform (AD [08]). Since the buoy is not fixed and may rotate, the wind monitor's direction readings must be corrected via the buoy's compass readings to represent true wind direction.

The wind monitor's vane measures the direction by transmitting vane position using a 10K ohm precision conductive plastic potentiometer (ED[01]). A regulated excitation voltage constantly applied to the potentiometer yields an analog voltage output signal directly proportional to azimuth angle. A 5° dead band region occurs when the potentiometer wiper is in the 355° to 0° region. This owes to the region that the potentiometer voltage must go from the maximum to minimum voltage. When the potentiometer wiper is in this region, the output signal may show varying or unpredictable values. This will be accounted for by flagging data that occurs in the dead band zone.

The wind monitor's propeller induces an AC signal within a stationary coil from a six pole magnet mounted on the rotating propeller shaft. Three complete AC sine wave cycles represent one propeller revolution (ED[01]). A calibration formula converts propeller revolution frequencies to wind speed. Individual calibrations may improve the ± 0.3 m/s standard accuracy. The wind monitor's calibration relating wind speed to propeller rotations is internally applied to report a wind speed in meters per second.

The digital compass is fixed within buoy's MET canister. The MET canister may inadvertently rotate during maintenance activities, which would affect the pitch and roll measurements. The buoy preventive maintenance procedures (AD [10]) have field technicians manually enter in pitch and roll offsets to correct compass data. These procedures should aid L0 data accuracy. However in high wave action circumstances, compass tilt could influence compass heading as much as 3° or 4° for tilts up to 60° (ED[02]). Tilt and roll presently are not reported as data products. The digital compass data must also take into account the magnetic declination at each site. Since declination varies across space, and to a lesser degree time, the buoy's compass direction must be periodically corrected to true north throughout the NEON operations. Magnetic declination is updated on an annual basis.

4.2 Theory of Algorithm

The buoy reports three measurements relevant to wind speed and direction, including wind speed, wind direction and buoy compass direction. Unless specified, the term 'direction' may apply to both the wind and compass directions, since direction measurements use the same averaging techniques.

Sampling intervals of the L0 wind and compass data vary due to constraints in the buoy's datalogger resources, but wind direction, wind speed, and compass direction all share the same timestamps. Sampling intervals will begin at 2 seconds after each minute, and follow 4 second intervals until 42 seconds after the minute. Wind speed and direction output from the data logger represent 4 second, mean values. The buoy's data logger calculates mean horizontal wind speed as a simple arithmetic average, and averages direction data as unit vector means across these short time intervals.

NEON reports the buoy's L1 wind speed and direction as temporal averages. Multiple wind speed and wind direction averaging algorithms exist, but the buoy data will follow averaging techniques reported by DACT, VEEP, and ARES payloads (on-board computer systems) installed on NOAA buoy systems. In these systems, average wind speed is computed as an arithmetic average, while wind direction is calculated as a unit-vector average.

4.2.1 Wind Speed

Level 0 wind speed, $\bar{S}$, output by the sensor at approximately 4 second intervals, shall follow the simple arithmetic averaging technique to convert into L1 wind speed data $\bar{S}_T$, where *T* represents the L1 data product's temporal averaging period. Before this happens, however, the nominal calibration factor applied to the wind speed data will be removed and a sensor-specific calibration coefficient, provided by CVAL, will be applied (Eq. 1).

$$\bar{S}_C \quad = \left(\frac{\bar{S}}{S_R}\right) * A_{\mathbf{1}_S} \tag{1}$$

The simple arithmetic average follows RD [03] and may be computed as follows (Eq. 2):

$$\bar{S}_T = \frac{1}{n}\sum_{\mathbf{1}}^{n} \bar{S}_C \tag{2}$$

where *n* is the number of wind speed measurements output by the buoy during the averaging period.

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

Wind direction is typically indicated as degrees from true north in the clockwise direction; e.g., 90^{o} indicates a wind blowing from the east and 180^{o} a wind blowing from the south, etc. In addition, 0^{o} represents no (measurable) wind whereas 360^{o} indicates a northerly wind (RD [03]). Wind and compass direction L0 data from the buoy are output simultaneously. Wind direction L0 data represents intervals as unit-vector averaged measurements, while compass L0 data are instantaneous readings. Prior to correcting the wind monitor's L0 direction data with buoy compass data, a number of data corrections must take place. First, the nominal calibration factor applied to the unit-vector wind data will be removed and a sensor-specific calibration coefficient, derived by CVAL, will be applied (Eq. 3).

$$\bar{\theta}_C = \left(\frac{\bar{\theta}_w}{\theta_R}\right) * A_{16} \tag{3}$$

The raw L0 wind direction data must be flagged when wind directions fall in the instrument's 355^{o} to 360^{o} dead zone (see Section 5.1). Next, the wind direction measurements will be corrected to account for the buoy's orientation while accounting for offsets relating to the compass, wind monitor orientation, and magnetic declination. The algorithm will then follow an analytical two-pass method (*e.g.,* Yamartino 1984; Mori 1986; Weber 1997; Farrugia *et al*. 2009) per RD [03] to generate temporally averaged wind direction data products.

Digital compass data must first account for magnetic declination specific to each site and date. Declination is the angle between true north and magnetic north. Since magnetic declination changes unpredictably albeit slowly across time due to Earth's fluctuating magnetic fields, each individual buoy's magnetic declination should be annually updated based on its coordinates. The site-specific (buoy) magnetic declination, θ_d, in decimal degrees shall be provided by SCI and stored in the CI data store. Magnetic declination may be retrieved from the NOAA api (https://ngdc.noaa.gov/geomag-web/) and shall be updated annually by SCI. The compass offset, θ_o, represents the discrepancy between the digital compass reading and a manual compass reading at any time the buoy canister is serviced/moved/installed. The concurrent compass directions submitted by Field Science to Aquatics must then be entered with the corresponding date in the Thresholds database as a calculated compass offset. The offset is calculated by subtracting the digital compass reading from the manual (true) compass reading. Instantaneous buoy compass direction must then be converted from unadjusted digital compass measurements, θ_c , to magnetic-declination/offset-adjusted digital compass measurements, θ_c (Eq. 4):

$$\theta_c = [\theta_c + \theta_d + \theta_O] \text{ modulo } 360° \tag{4}$$

The buoy wind direction data may then be summed with the magnetic-declination-adjusted digital compass data. The correction is similar to the boom-arm correction for terrestrial tower sites (e.g. RD [03]), except the digital compass direction changes with time as the buoy moves, whereas the boom arm correction is fixed. However, the wind monitor's orientation atop the buoy mast is susceptible to inconsistent install orientation. Therefore, as the wind monitor's installed orientation may change periodically during field maintenance/refresh, a record of wind monitor changes shall be submitted by Field Science to AIS. AIS staff must then update the wind monitor azimuth offset in the Named Location Database. Note that an uncertainty term, u_o , corresponds to the uncertainty associated with this orientation offset. The wind direction measurements corrected by buoy compass data, $\bar{\theta}_w$, is calculated by summing the uncorrected but calibrated wind direction measurements, $\bar{\theta}_C$, the declination-adjusted compass measurements, θ_c , and the wind-monitor on-mast offset from the Named Location Database, θ_o (Eq. 5):

$$\bar{\theta}_w = [\bar{\theta}_C + \theta_c + \theta_O] \text{ modulo } 360° \tag{5}$$

where $\bar{\theta}_w$ is the actual wind direction given in degrees at the same temporal instance as the L0 compass data.

Note that wind direction is calculated independently of wind speed.

Unit-vector mean wind direction must be converted from degrees ($\bar{\theta}_w$) to radians ($\bar{\theta}'_w$), according to the *meteorological coordinate system* for computational convenience in the following steps (Eq. 6):

$$\bar{\theta}'_w = \frac{\pi}{180°}\bar{\theta}_w \tag{6}$$

Once the unit-vector mean wind direction has been converted to radians, the buoy's 2D wind direction may follow the same steps as the 2D Wind Speed and Direction ATBD (RD [03])

Calculating the mean and variance of 2D 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 is 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 that has been thoroughly reviewed (*e.g.,* Yamartino 1984; Mori 1986; Weber 1997; Farrugia *et al*. 2009).

In the first pass, the components of the average distance vector over an observation period with sample size *n* are calculated (Eqs. 7 & 8):

$$\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} \sin(\bar{\theta}'_w) \tag{7}$$

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} \cos(\bar{\theta}'_w) \tag{8}$$

where, for each two-minute average, *n* represents the number of measurements in the averaging period [0, 120) seconds. Similarly, for each thirty-minute average, *n* represents the number of measurements in the averaging period [0, 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 *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

Next, the *unit-vector mean wind direction* is derived (e.g., Yamartino 1984) using the atan2 function (Eq. 9):

$$\bar{\theta} = \begin{cases} 2\pi & \text{if } \bar{X} > 0 \;\&\; \bar{Y} = 0, \\ [2\pi + \operatorname{atan2}(\bar{Y}, \bar{X})] \bmod (2\pi) & \text{otherwise.} \end{cases} \tag{9}$$

Again, care must be taken when assigning arguments to the atan2 function as discussed above.

Alternatively, the arc tangent function can be used with the appropriate corrections (Eq. 10):

$$\bar{\theta} = \begin{cases} \left[2\pi + \tan^{-1}\left(\frac{\bar{Y}}{\bar{X}}\right)\right] \text{ modulo } 2\pi & \text{if } \bar{X} \neq 0 \\ \frac{\pi}{2} & \text{if } \bar{Y} > 0 \;\&\; \bar{X} = 0 \\ \frac{3\pi}{2} & \text{if } \bar{Y} < 0 \;\&\; \bar{X} = 0 \\ 0 & \text{if } \bar{X} = \bar{Y} = 0 \end{cases} \tag{10}$$

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

In the second pass, the *minimum angular distance* (A_i) between an observation $\overline{\theta}'_w$ and the mean is calculated (Batschelet, 1981) (Eq. 11):

$$A_i = \left|\cos^{-1}\left(\cos\left(\overline{\theta}'_w - \bar{\theta}\right)\right)\right|. \tag{11}$$

Subsequently the sign of the minimum angular distance is determined (Farrugia *et al*. 2009) (Eq. 12):

$$A_{i,c} = \begin{cases} A_i & \text{if} \quad \bar{\theta} \leq \overline{\theta}'_w < (\bar{\theta} + \pi), \\ -A_i & \text{if} \quad (\bar{\theta} - \pi) < \overline{\theta}'_w < \bar{\theta}, \end{cases} \tag{12}$$

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* (Eq. 13):

$$\bar{A}_T = \frac{1}{n}\sum_{i=1}^{n} A_{i,c}. \tag{13}$$

Where, for each two-minute average, *n* is the number of measurements in the averaging period, [0,60) seconds. For each thirty-minute average, *n* is the number of measurements in the averaging period [0, 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.

The arithmetic mean is defined such that it minimizes the sample variance. 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. With respect to the arithmetic mean, $A_{i,c}$ are thus overestimated by $\bar{A}_T$; this discrepancy is compensated for to yield the arithmetic mean and variance (Eq. 14):

$$\bar{\theta}'_T = [\bar{\theta} + \bar{A}_T] \text{ modulo } (2\pi) \tag{14}$$

The sample variance of wind direction is calculated as follows (Yamartino, 1984) (Eq. 15):

$$s^2(\bar{\theta}'_T) = \left(n^{-1}\sum_i (A_{i,c})^2 - (\bar{A}_T)^2\right). \tag{15}$$

Finally the resulting angles are converted from radians to angular degree to create the L1 wind-direction DPs listed in windSpeedDirBuoy_datapub_NEONDOC004406.txt (Eqs. 16 and 17):

$$\bar{\theta}_T = \bar{\theta}'_T \cdot \frac{180}{\pi} \tag{16}$$

and

$$s^2(\bar{\theta}_T) = s^2(\bar{\theta}'_T) \cdot \frac{180}{\pi} \tag{17}$$

where the subscript *T* represents either 1 (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. Signal de-spiking shall not be conducted for wind speed or direction.
2. QA/QC plausibility tests will be applied to the unit-vector mean wind direction, unit-vector mean compass direction, and arithmetic mean data streams in accordance with AD [03]. The details are provided in Section 5.1.
3. WIND SPEED:
    a. QA/QC plausibility tests will be applied to each L0 arithmetic wind speed datum in accordance with AD [03]. The details are provided in Section 5.1.
    b. Average (one and thirty-minute), horizontal wind speeds will be calculated using Eq. (1)
    c. Descriptive statistics, i.e., minimum, maximum, and variance of wind speed will be determined for both two- and thirty-minute averages.
    d. Quality metrics, quality flags, and the final quality flag will be produced for two- and thirty-minute averages according to AD [07].
4. BUOY COMPASS DIRECTION:
    a. QA/QC Plausibility tests will be applied to each uncorrected buoy compass direction datum (θ_c) in accordance with AD [03]; details are provided in Section 5.1.
5. WIND DIRECTION:

a. The L0 unit-vector mean wind direction will be removed when the wind vane direction fails the sensor test for the dead-band region (see Section 5.1). The L1 time-averaged periods should include flags for sensor test failure.
b. The L0 unit-vector mean wind direction will be corrected by buoy orientation and digital compass offset via Eq. (4), corrected by magnetic declination and wind monitor offset via Eq (5), and converted to radians in Eq. (6).
c. QA/QC Plausibility tests will be applied to each buoy compass direction datum in accordance with AD [03]; details are provided in Section 5.1.
d. Two- and thirty-minute average, unit-vector wind directions will be calculated using equations (7) through (16).
e. Variance of wind direction will also be calculated in the aforementioned unit-vector wind direction averaging steps.
f. Quality metrics, quality flags, and the final quality flag will be produced for two- and thirty-minute averages according to AD [07].

5.1 QA/QC Procedure

1. **Plausibility tests AD [03]** - All plausibility will be determined for the wind speed, wind direction, and compass direction, and associated quality flags (QFs) will be generated for each test. The test parameters will be provided by SCI and maintained in the CI data store. Wind speed and direction components failing any plausibility test will not be used to generate the L1 mean data product.
2. **Signal De-spiking AD [05]** - Signal de-spiking will not be conducted with wind speed or direction.
3. **Calm Winds RD[03]**
   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}, which is used as the threshold from the 2D sonic anemometer data collected on NEON tower sites (RD[03]).

   The RM Young monitor automatically reports a wind direction of 0° when the wind speed reading is 0 m s^{-1}. To stay consistent with the framework set forth for NEON's towered sites, the calm wind flag will be applied to calibrated wind speeds ($\bar{S}_C$) that fall below the threshold from the 2D sonic anemometer data of ≤ 0.5 m s^{-1}. The following logic should be applied for calm wind flagging:

$$Q_{c} = \begin{cases} 1 & \text{if } \bar{\theta}_w = 0^{\circ} \ \mathbf{O} \ \bar{S}_C \le 0.5 \text{ m s}^{-1} \\ 0 & \text{otherwise.} \end{cases} \quad (18)$$

4. **Dead band AD [08]**

The RM Young wind monitor's raw L0 wind direction must be flagged when the vane's potentiometer wiper falls within a 5° dead band region. This dead-band region falls in the 355° to 360° direction. Initial testing by CVAL also revealed that within the dead-band, the sensor is sometimes prone to outputting readings ~12°. As such, any L0 wind direction that fall within this dead-band shall be flagged, and excluded from further processing

$$Q_{d} = \begin{cases} 1 & \text{if } \frac{\bar{\theta}_C}{A_{1_\theta}} > 0.986 \ \mathbf{O} \ \frac{\bar{\theta}_C}{A_{1_\theta}} = (A_{0_\theta} \pm 0.005) \\ 0 & \text{otherwise.} \end{cases} \quad (18)$$

5. **Quality Flags (QFs) and Quality Metrics (QMs) AD [07]**

If a wind speed, wind direction, or compass datum has failed one of the following tests it will not be used to create a L1 DP: ***range**, and **persistence***. Additionally, any *wind direction* datum that has failed the ***dead band*** test or *wind speed* datum that has failed the **spike** test will not be used to create the respective L1 DPs. α and β QFs and QMs for wind speed and wind direction will be determined using the flags in Table 5-1. Unless otherwise noted, the flags indicated in Table 5-1 are applied to both wind speed, wind direction, and the buoy's compass. In addition, L1 DPs will have a QA/QC report and quality metrics associated with each flag listed in Table 5-1 as well as a final quality flag, as detailed in AD [16]. Ancillary information needed for the algorithm and other information maintained in the CI data store is shown in Table 5-2.

Note: Individual quality flags and metrics of the compass will propagate to the α and β QMs of wind direction.

Table 5-1: Flags associated with RM Young wind monitor measurements.

Flags
Range
Persistence
Step
De-spiking
Null
Gap

Flags
Calm winds (wind direction only)
Dead band (wind direction only)
Valid calibration
Alpha
Beta
Final quality flag

Table 5-2: Information maintained in the CI data store for RM Young wind monitor

Tests/Values	CI Data Store Contents
Dead Band	CVAL sensor specific coefficient
Range	Minimum and maximum values
Persistence	Window size, threshold values and maximum time length
Step	Threshold values
Signal De-spiking	Time segments and threshold values
Null	Test limit
Gap	Test limit
Calibration	CVAL sensor specific calibration coefficients
Valid Calibration	CVAL sensor specific valid calibration date range
Uncertainty	AD [06]
Final Quality Flag	AD [07]

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 [05], 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. The section is broken down into two topics. The first informs the sources of *measurement* uncertainty, i.e., those associated with *individual measurements*. The second details uncertainties associated with temporally averaged data products.

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with *individual observations*. It is important to note that the uncertainties presented in the following subsections are *measurement uncertainties*, that is, they reflect the uncertainty of an *individual* measurement. These uncertainties should not be confused with those presented in Section 6.1.2. We urge the reader to refer to AD [05] for further details concerning the discrepancies between quantification of measurement uncertainties and L1 uncertainties.

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

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

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial}{\partial x_i}\right)^2 u^2(x_i)\right)^{\frac{1}{2}} \tag{19}$$

where

$\frac{\partial}{\partial x_i}$ = partial derivative of *y* with respect to x_i

$u(x_i)$ = combined standard uncertainty of x_i.

Thus, the uncertainty of the measurand can be found be summing the input uncertainties in quadrature. The calculation of these input uncertainties is discussed below.

6.1.1.1 Calibration

Uncertainties associated with the calibration process propagate into separate, combined measurement uncertainty estimates. Each combined uncertainty, u_{A1_θ}, and u_{A1_S} represents i) the repeatability and reproducibility of the sensor and the lab DAS and ii) uncertainty of the calibration procedures and coefficients including uncertainty in the standard (truth) (refer to Eq. (1)). Both are constant values that will be provided by CVAL (AD [15]), stored in the CI data store, and applied to all individual wind direction and wind speed measurements, respectively (that is, it does not vary with any specific sensor, DAS component, location, etc.).

6.1.2 DAS

The RM Young anemometers are connected to CR1000 dataloggers. These dataloggers have an internal Analog to Digital (A/D) converter and output data in digital form. No A/D data conversions occur within the DAS. Thus, uncertainty related to the DAS can be considered negligible. However, A/D conversion uncertainty may be accounted for in the CR1000 dataloggers, at similarly small magnitudes as the DAS used in other NEON sensor systems. Future plans in Section 7 address quantifying dataloggers A/D conversion uncertainty.

6.1.3 Orientation

The 2D anemometer's orientation relative to true north is considered a source of uncertainty. This source of uncertainty is accounted for by correcting the wind direction measurements by compass measurements as noted in Eq. (4). The uncertainty associated with the compass measurements, u_{c1}, and the declination correction, u_{d1}, will be provided by SCI and stored in the CI data store.

6.1.3.1 Combined Measurement Uncertainty

The combined measurement uncertainties of individual wind speed measurements, $u_c(S_i)$, is simply equal to u_{A1_S}.

The combined measurement uncertainty of individual wind direction measurements, $u_c(\theta_i)$, is computed by summing the individual, uncertainties from CVAL, the compass, the declination correction, and the orientation of the monitor atop the mast in quadrature (Eq. 20):

$$u_c(\theta_i) = \left({u_{A1_\theta}}^2 + {u_{c1}}^2 + {u_{d1}}^2 + {u_o}^2\right)^{\frac{1}{2}} \tag{20}$$

6.1.3.2 Expanded Measurement Uncertainty

The expanded measurement uncertainty is calculated as:

$$U_9\ (y_i) = k_9\ \ * u_c(y_i) \tag{21}$$

Where:

$U_9\ (y_i)$ = expanded measurement uncertainty at 95% confidence
k_9 = 2; coverage factor for 95% confidence (unitless)

6.1.4 Uncertainty of L1 Mean Data Products

The following subsections discuss uncertainties associated with L1 mean data products. As stated previously, it is important to note the differences between the *measurement uncertainties* presented in Section 6.1.1 and the uncertainties presented in the following subsections. The uncertainties presented in the following subsections reflect the uncertainty of a time-averaged mean value, that is, they reflect the uncertainty of a distribution of measurements collected under non-controlled conditions (i.e., those found in the field), as well as any uncertainties, in the form of *Truth* and *Trueness*, related to the accuracy of the field assembly.

6.1.4.1 Repeatability (natural variation)

To determine the validity of the L1 mean DPs, its uncertainty must be calculated. The distribution of the individual measurements is used as a metric to quantify this uncertainty. Specifically, the *estimated standard error of the mean (natural variation)* is computed. This value reflects the repeatability of wind speed and direction measurements for the specified time period:

$$u_N\ \ (\bar{y}) = \frac{s(y_i)}{\sqrt{n}} \tag{22}$$

where $s(y_i)$ is the experimental standard deviation of the respective wind observations (speed or direction) during the averaging period, and n is the number of observations made over the same time period.

6.1.4.2 Calibration

The uncertainty detailed here is similar to that described in Section 6.1.1.1. However, the relevant uncertainty for the mean DPs, u_{A3_θ}, and u_{A3_S} do not consider i) individual sensor repeatability, or ii) the variation of sensors' responses over a population of sensors (reproducibility). This component of uncertainty estimates the uncertainty due to the accuracy of the instrumentation in the form of *Truth* and *Trueness*, a quantity which is not captured by the standard error of the mean. These are constant values that will be provided by CVAL (AD [15]) and stored in the CI data store. Please refer to AD [05] for further justification regarding evaluation and quantification of this combined uncertainty.

6.1.5 Wind Speed

6.1.5.1 Combined Uncertainty

The uncertainty of our L1 mean wind speed DPs is calculated as follows:

$$u_c(\bar{S}) = \left(u_{A3_S}{}^2 + u_N^2 \quad (\bar{S})\right)^{\frac{1}{2}} \tag{23}$$

6.1.5.2 Expanded Uncertainty

The expanded uncertainty for wind speed may then be calculated using Equation (21).

6.1.6 Wind Direction

6.1.6.1 Combined Uncertainty

The uncertainty of our L1 mean wind direction DPs is calculated as follows:

$$u_c(\bar{\theta}) = \left(u_{A3_\theta}{}^2 + u_N^2 \quad (\bar{\theta}) + u_{c1}{}^2 + u_{d1}{}^2 + u_o \quad {}^2\right)^{\frac{1}{2}} \tag{24}$$

6.1.6.2 Expanded Uncertainty

The expanded uncertainty for wind direction may then be calculated using Equation (21).

6.1.6.3 Communicated Precision

The RM Young wind vane reports at precisions of 0.1 m s^{-1} and 0.01°, for wind speed and wind direction, respectively As such, the communicated precision of the L1 mean data products will be limited to these precisions.

6.2 Uncertainty Budget

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

Table 6-1: Uncertainty budget for an individual wind measurement. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of measurement uncertainty	**Measurement uncertainty component** $\boldsymbol{u(x_i)}$	**Measurement uncertainty value**	$\boldsymbol{\frac{\partial}{\partial x_i}}$	$\boldsymbol{u_{x_i}(Y) \equiv \left\lvert\frac{\partial}{\partial x_i}\right\rvert u(x_i)}$
Wind Speed	$u_c(S_i)$	--	n/a	--
Sensor/calibration	u_{A1_S}	--	1	u_{B1}
Wind Direction	$u_c(\theta_i)$	--	--	--
Sensor/calibration	u_{A1_θ}	--	1	u_{A1}
Compass	u_{c1}	--	1	u_{c1}
Declination	u_{d1}	--	1	u_{d1}

Table 6-2: Uncertainty budget for L1 wind data products. Shaded rows denote the order of uncertainty propagation (from lightest to darkest).

Source of measurement uncertainty	**Measurement uncertainty component** $\boldsymbol{u(x_i)}$	**Measurement uncertainty value**	$\boldsymbol{\frac{\partial}{\partial x_i}}$	$\boldsymbol{u_{x_i}(Y) \equiv \left\lvert\frac{\partial}{\partial x_i}\right\rvert u(x_i)}$
Wind Speed	$u_c(\overline{S})$	--	n/a	--
Sensor/calibration	u_{A3_S}	--	1	u_{B3}
Nat. variation	$u_N \quad (\overline{S})$	--	1	$u_N \quad (\overline{S})$
Wind Direction	$u_c(\overline{\theta})$	--	--	--
Sensor/calibration	u_{A3_θ}	--	1	u_{A3}
Nat. variation	$u_N \quad (\overline{\theta})$	--	1	$u_N \quad (\overline{\theta})$
Compass	u_{c1}	--	1	u_{c1}
Declination	u_{d1}	--	1	u_{d1}

7 FUTURE PLANS AND MODIFICATIONS

Compass heading tilt compensation. The digital compass's heading may vary by 3° or 4° when tilted by as much as 60°. If buoy pitch and roll may be reported by the digital compass, this may improve the compass heading accuracy, and in turn the wind direction accuracy.

Vector-mean direction averaging uncertainty. The buoy's internal Campbell Scientific datalogger has the capability to calculate L0 4-second mean compass and wind direction standard deviation per the

Yarmartino (1984) algorithm. Accounting for this uncertainty would allow buoy wind data to fully comply with the EPA's guidelines for straight-line Gaussian dispersion models.

Datalogger analog to digital conversion uncertainty. Uncertainty associated with the Cambpell Scientific data logger's analog to digital (A/D) converter should be integrated into the 2D wind monitor's uncertainty estimates. This uncertainty should be similar to the GRAPE DAS.

Edit wind speed algorithm to remove despike component. During the NEON.DOC.004738 Rev A time period, the wind speed algorithm performed despiking and quality flagging. During the Rev B period, NEON has adjusted buoy wind direction spike test parameters such that spikes should not be detected in any published data. Future work shall edit the buoy wind speed algorithm to exclude the spike test.

8 BIBLIOGRAPHY

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