Algorithm Theoretical Basis Document
Barometric Pressure

PREPARED BY	ORGANIZATION	DATE
Derek Smith	FIU	02 Jul 2013
Josh Roberti	FIU	02 Jul 2013

APPROVALS (Name)	ORGANIZATION	APPROVAL DATE

RELEASED BY (Name)	ORGANIZATION	RELEASE DATE

Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	Jan 2013		Initial Release

TABLE OF CONTENTS

1 DESCRIPTION

1.1 Purpose

This document details the algorithms used for creating NEON L1 DP from L0 DP for tower-based measurements of barometric pressure, and ancillary data (such as calibration data), obtained via instrumental measurements made by the Vaisala BAROCAP® Digital Barometer PTB330. 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 for creating the NEON L1 data product for barometric pressure, NEON.DXX.XXX.DP1.00004.001, from input data. It does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON OBSERVATORY DESIGN
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005004	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.005005	NEON Level 0 Data Products Catalog
AD[05]	NEON.DOC.005505	NEON CVAL Technical and Operating Requirements
AD[06]	NEON.DOC.000735	Atmospheric Pressure Calibration Fixture
AD[07]	NEON.DOC.000782	ATBD QA/QC Data Consistency
AD[08]	NEON.DOC.011081	ATBD QA/QC plausibility tests
AD[09]	NEON.DOC.000783	ATBD De-spiking and time series analyses
AD[11]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[12]	NEON.DOC.000646	NEON Algorithm Theoretical Basis Document: SAATs
AD[13]	NEON.DOC.000746	Evaluating Uncertainty(CVAL)
AD[14]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values
AD[15]	NEON.DOC.000735	CVAL Barometric Pressure Calibration Fixture
AD[16]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products

2.2 Reference Documents

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

2.3 Acronyms

Acronym	**Explanation**
AGL	Above Ground Level
ASL	Above Sea Level
ATBD	Algorithm Theoretical Basis Document
CVAL	NEON Calibration, Validation, and Audit Laboratory
DAS	Data Acquisition System
DP	Data Product
L0	Level 0
L1	Level 1
LR	Lapse Rate
N/A	Not Applicable
UQ*	Unquantifiable

2.4 Verb Convention

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

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

Table 1 details the barometric pressure related L1 DPs provided by the algorithms disclosed in this ATBD.

Table 1: List of barometric pressure barometric pressure related L1 DPs that are produced in this ATBD.

Data product	Averaging Period	Units	Data stream ID
1-minute Mean Station Pressure (Mean_P_{s1})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.001.001.001
1-minute Minimum Station Pressure (Min_P_{s1})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.002.001.001
1-minute Maximum Station Pressure (Max_P_{s1})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.003.001.001
1-minute Variance Station Pressure ($\sigma^2\_P_{s1}$)	1-min	kPa^2	NEON.DXX.XXX.DP1.00004.001.004.001.001
1-minute QA/QC Summary Station Pressure ($Qsum\_P_{s1}$)	1-min	N/A	NEON.DXX.XXX.DP1.00004.001.005.001.001
1-minute QA/QC Report Station Pressure ($Qrpt\_P_{s1}$)	1-min	N/A	NEON.DXX.XXX.DP1.00004.001.006.001.001
30-minute Mean Station Pressure (Mean_P_{s30})	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.001.001.002
30-minute Minimum Station Pressure (Min_P_{s30})	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.002.001.002
30-minute Maximum Station Pressure (Max_P_{s30})	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.003.001.002
30-minute Variance Station Pressure ($\sigma^2\_P_{s30}$)	30-min	kPa^2	NEON.DXX.XXX.DP1.00004.001.004.001.002
30-minute QA/QC Summary Station Pressure ($Qsum\_P_{s30}$)	30-min	N/A	NEON.DXX.XXX.DP1.00004.001.005.001.002
1-minute Mean Reduced Pressure (Mean_P_{01})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.006.001.001
1-minute Minimum Reduced Pressure (Min_P_{01})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.007.001.001
1-minute Maximum Reduced Pressure (Max_P_{01})	1-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.008.001.001
1-minute Variance Reduced	1-min	kPa^2	NEON.DXX.XXX.DP1.00004.001.009.001.001

Pressure ($\sigma^2\_P_{01}$)			
1-minute QA/QC Summary Reduced Pressure ($Qsum\_P_{01}$)	1-min	Text	NEON.DXX.XXX.DP1.00004.001.010.001.001
1-minute QA/QC Report Reduced Pressure ($Qrpt\_P_{01}$)	1-min	Text	NEON.DXX.XXX.DP1.00004.001.011.001.001
30-minute Mean Reduced Pressure ($Mean\_P_{030}$)	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.006.001.002
30-minute Minimum Reduced Pressure (Min_P_{030})	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.007.001.002
30-minute Maximum Reduced Pressure (Max_P_{030})	30-min	*kPa*	NEON.DXX.XXX.DP1.00004.001.008.001.002
30-minute Variance Reduced Pressure ($\sigma^2\_P_{030}$)	30-min	kPa^2	NEON.DXX.XXX.DP1.00004.001.009.001.002
30-minute QA/QC Summary Reduced Pressure ($Qsum\_P_{030}$)	30-min	N/A	NEON.DXX.XXX.DP1.00004.001.010.001.002

3.2 Input Dependencies

Table 2 details the barometric pressure related L0 DPs used in this ATBD. Please note that the L1 SAAT DP from the *closest SAATS assembly to the barometer's location* must be used in order to calculate reduced pressure; this will be site-specific.

Table 2: List of barometric pressure related L0 DPs that are transformed into L1 DPs in this ATBD.

Data product	**Sample Frequency**	**Units**	**Data stream ID**
Atmospheric Pressure (P_s)	0.1 Hz	*kPa*	NEON.DXX.XXX.DP0.00004.001.001.001.001.001
Station Temperature (T_s)	NA	$^{\circ}C$	NEON.DXX.XXX.DP1.00002.001.001.00X.00X

3.3 Product Instances

Barometric pressure will be recorded at all core and relocatable sites through a Vaisala BAROCAP® Digital PTB330 Class A barometer.

3.4 Temporal Resolution and Extent

Barometric pressure will be recorded at a rate of 0.1 Hz for L0 DPs, and these L0 DPs will be used to calculate the L1 DPs, one- and thirty-minute averages of station and reduced pressure.

3.5 Spatial Resolution and Extent

The pressure sensor will be located on the tower infrastructure at a site specific installation height (h) above ground level (AGL). Therefore, barometric (station) pressure will represent the point in space at which the barometer is located on the tower.

4 SCIENTIFIC CONTEXT

Barometric pressure, or static atmospheric pressure, is a vital measurement for NEON. Barometric pressure is significant in influencing weather conditions as well as aqueous chemistry (e.g. the amount of gas that can dissolve in solution). Recording static atmospheric pressure will allow atmospheric gas mixing ratios to be converted into mass quantities. Barometric pressure will be recorded over NEON's entire operational range and the accuracy and precision requirements can be found in Dynamic Object-Oriented Requirements System.

4.1 Theory of Measurement

Simply stated, barometric pressure is the weight exerted on a given location by the atmosphere above it, per unit area. Barometric pressure has long been determined using mercury barometers, which relate the weight of the atmosphere to the weight of a column of mercury. While mercury barometers are common for many historical applications, digital, aneroid barometers are becoming much more prevalent. This is mainly attributed to their ruggedness and ability to be automated while still maintaining high accuracy and stability (Van der Meulen 1992).

Aneroid barometers operate on the principal of converting pressure proportionally to electrical voltage through the use of transducers (i.e. silicon diaphragm), microprocessors, and sensors. In the Vaisala BAROCAP® barometer, pressure is determined from changes in the capacitance of a silicon crystal sensor. CVAL's calibration process to meet NEON's accuracy and precision requirements can be found in AD[06].

4.2 Theory of Algorithm

Pressure will be presented as both station pressure, p_s, and pressure reduced to sea level, p_0. Station pressure will first be determined applying calibration coefficients, supplied by CVAL, to the "raw" sensor output as follows:

$$p_{s_i} = C_{A2}{p_i}^2 + C_{A1}p_i + C_{A0} \tag{1}$$

Where:

p_{s_i} = Individual (0.1 Hz) station pressure (kPa)
C_{A2} = Calibration coefficients provided by CVAL (kPa^{-1})
C_{A1} = Calibration coefficients provided by CVAL (unitless)
C_{A0} = Calibration coefficients provided by CVAL (kPa)
p_i = Individual (0.1 Hz) pressure output from sensor (kPa)

Due to the effects that temperature and altitude have on pressure, readings are often normalized to sea level so that they are analogous among locations. The WMO (2008) presents Eq. (2), which is used to adjust station pressure to sea level pressure. Although other algorithms exist, the algorithm provided by the WMO (2008) is considered the standard method:

$$p_0 = p_s * e^{\left(\frac{Z_\Phi * \frac{g_0}{R_d}}{\overline{T_v}}\right)} = p_s * e^{\left(\frac{Z_\Phi * \frac{g_0}{R_d}}{T_s + \frac{\alpha * Z_\Phi}{2} + e_v * C_h}\right)} \tag{2}$$

Where:

Z_Φ: Geopotential Height of barometer (gpm) Above Sea Level (ASL)
g_0: Standard acceleration of gravity = 9.80665 (m s^{-2})
R_d: Gas constant of dry air = 287.05 (J kg^{-1}·K^{-1})
$\overline{T_v}$: Mean virtual temperature (K)
α: Standard Atmospheric Lapse Rate of temperature = 0.0065 (K m^{-1})
p_0: Pressure reduced to sea level (kPa)
p_s: Station pressure (kPa)
T_s : Station temperature (K)
e_v: Vapor pressure (kPa)
C_h: Lapse rate of vapor pressure = 1.2 (K kPa^{-1}; Rao 1957, 1958)

By rearranging the equation, some uncertainties can be reduced. First, the dry air constant can be moved to the denominator of the exponential equation. Second, according to Wallace and Hobbs (2006), the calculation of Z_Φ is:

$$Z_\Phi \equiv \frac{\Phi_{(z)}}{g_0} = \int_0^z g dz \tag{3}$$

Where:

Z_Φ: Barometer's geopotential Height (gpm)
$\Phi_{(z)}$: Geopotential (m^2 s^{-2}) at station height
z: Barometer's geometric height (m ASL)
g: Local gravity as a function of elevation and latitude of the station (m s^{-2})

Therefore, we substitute geometric station height and local gravity for geopotential height and standard gravity, as these former metrics will be measured at each NEON tower site. The calculation for local gravity is displayed below (Jursa 1985):

$$g = 9.780356(1 + 0.0052885 \sin^2\theta - 0.0000059 \sin^2\theta) - Xz \tag{4}$$

Where:

θ = latitude of site (radians)
X = 0.003086 (m s^{-2} km^{-1})

z = height of barometer (km ASL).

Thus, it is shown:

$$Z_{\Phi} * g_0 \equiv \frac{\Phi_{(z)}}{g_0} * \; g_0 \equiv \; \Phi_{(z)} \equiv z * g \tag{5}$$

And, Eq. (2) becomes:

$$p_0 = p_s * e^{\left(\frac{Z_{\Phi} * g_0}{R_d\left(T_s + \frac{\alpha * Z}{2} + \; e_v * C_h\right)}\right)} = p_s * e^{\left(\frac{z * g}{R_d\left(T_s + \frac{\alpha * Z}{2} + \; e_v * C_h\right)}\right)} \tag{6}$$

Vapor pressure, e_v, which is a function of dew point, is simply the pressure that atmospheric water vapor exerts on the atmosphere (Wallace and Hobbs 2006). Values of e_v are rarely > 3 kPa in mid-latitude regions, but can occasionally reach slightly higher values in the Subtropics and Tropics where concentrations of atmospheric water vapor is high. It is not necessary to use near real-time values of e_v if the station of interest does not reside in a warm / humid climate, and a mean value will suffice (WMO 1964). Vapor pressure can be derived from monthly dew point averages from nearby stations (<10 km, if possible) at similar altitudes (± 200 m, if possible) to NEON's towers:

$$\bar{e_v} = \frac{6.11 * 10^{\left(\frac{7.5 * \overline{T_d}}{237.7 + \; \overline{T_d}}\right)}}{10} \tag{7}$$

Where:

$\bar{e_v}$: Monthly mean vapor pressure at nearby station (kPa)

$\overline{T_d}$: Monthly mean dew point at nearby station in (°C)

The final equation for reduction of station pressure will be:

$$p_{0_i} = p_{s_i} * e^{\left(\frac{z * g}{R_d\left(\overline{T_s} + \frac{\alpha * Z}{2} + \overline{e_v} * C_h\right)}\right)} \tag{8}$$

<u>Notes</u>:

- NEON site specific elevations will be determined by FCC, and captured and maintained in the CI data store.
- The L1 mean SAAT DP from the boom level below the barometer will be used as station temperature ($\overline{T_s}$). If the temperature measurement is unavailable for the time period, then the L1 mean SAAT DP from the level above the barometer will be used as station temperature. Furthermore, the one-or thirty-minute average of SAAT with a time stamp that most closely

coincides with the time stamp of the barometric pressure measurement will be used for station temperature. However, temperature averages must first be converted from °C to K (i.e., $T_s = T_{1/30} + 273.15$) before either can be used.

- Monthly dew point data for nearby stations will be provided by FIU and stored in the CI data store.

Once station pressure is adjusted to sea level via Eq. (8), one- and thirty-minute averages of station (p_s) and reduced (p_0) pressure will be determined to create the L1 DPs as follows:

$$\overline{p_{s/o_1}} = \frac{1}{n}\sum_{i=1}^{n} p_{s/o_i} \qquad (9)$$

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

and,

$$\overline{p_{s/o\ 30}} = \frac{1}{n}\sum_{i=1}^{n} p_{s/o_i} \qquad (10)$$

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

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

5 ALGORITHM IMPLEMENTATION

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

Unadjusted Barometric Pressure (p_s)

1. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[08]. The details are provided below.
2. Signal de-spiking and time series analysis will be applied to the data stream in accordance with AD[09].
3. One- and thirty-minute pressure averages will be calculated using Eq. (9) and (10).
4. Descriptive statistics, i.e. minimum, maximum, and variance, will be determined for both one- and thirty-minute averages.
5. QA/QC Summary (Q_{sum}) will be produced for one-and thirty-minute averages according to AD[16].

Reduced Pressure (p_0)

1. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[08]. The details are provided below.
2. Signal de-spiking and time series analysis will be applied to the data stream in accordance with AD[09].
3. Barometric pressure will be converted to p_0 using Eq. (8).
4. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[08]. The details are provided below.
5. Signal de-spiking and time series analysis will be applied to the data stream in accordance with AD[09].
6. One- and thirty-minute pressure averages will be calculated using Eq. (9) and (10).
7. Descriptive statistics, i.e. minimum, maximum, and variance, will be determined for both one- and thirty-minute averages.
8. QA/QC Summary (Q_{sum}) will be produced for one-and thirty-minute averages according to AD[16].

QA/QC Procedure:

1. **Plausibility Tests** AD[08] – All plausibility tests will be determined for the net radiometer. Test parameters will be provided by FIU and maintained in the CI data store. All plausibility tests will be applied to the sensor's converted L0 DPs and associated quality flags (QFs) will be generated for each test.

2. **Signal De-spiking and Time Series Analysis** – Time segments and threshold values for the automated despiking QA/QC routine will be specified by FIU and maintained in the CI data store. QFs from the despiking analysis will be applied according to AD[09].

3. **Consistency Analysis** – Currently, there is no plan to run consistency analysis on the L1 DP for barometric pressure. However, time series consistency analysis may be explored in the future.

4. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[16] – If a datum has one of the following flags it will not be used to create a L1 DP, QF_R, and QF_D. α and β QFs and QMs will be determined for the following flags QF_R, QF_σ, QF_δ, QF_S, QF_N, QF_G ,and QF_D. All L1 DPs will have an associated final quality flag, QF_{NEON}, and quality summary, Qsum, as detailed in AD[16]. Flags that may be associated with barometric pressure measurements, as well as information maintained in the CI data store can be found below in Tables 3 and 4.

Table 3. Flags associated with SAATS measurements.

Tests	**Flags**
Range	QF_R
Sigma (σ)	QF_σ
Delta (δ)	QF_δ
Step	QF_S

Null	QF_N
Gap	QF_G
Signal Despiking and Time Series Analysis	QF_D QF_o QF_I
Final quality flag	QF_{NEON}

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

Tests/Values	**CI Data Store Contents**
Range	Minimum and maximum values
Sigma (σ)	Time segments and threshold values
Delta (δ)	Time segment and threshold values
Step	Threshold values
Null	Test limit
Gap	Test limit
Signal Despiking and Time Series Analysis	Time segments and threshold values
Calibration	CVAL sensor specific calibration coefficients
Uncertainty	AD[14]
Final Quality Flag	AD[16]

6 UNCERTAINTY

Uncertainty of measurement is inevitable (JCGM 2008, 2012; Taylor 1997). It is crucial that uncertainties are identified and quantified to determine statistical interpretations about mean quantity and variance structure; both are important when constructing higher level data products (e.g., L1 DP) and modeled processes. This portion of the document serves to identify, evaluate, and quantify sources of uncertainty relating to L1 mean pressure DPs. It is a reflection of the information described in AD[11], and is explicitly described for the barometric assembly in the following sections.

6.1 Uncertainty of Atmospheric Pressure Measurements

Here the propagation of uncertainty for barometric pressure is discussed. Sources of uncertainties include those arising from the calibration procedures, and those inherent in the barometer's performance. Additional uncertainties include those of other variables when calculating reduced pressure (Figure 1)

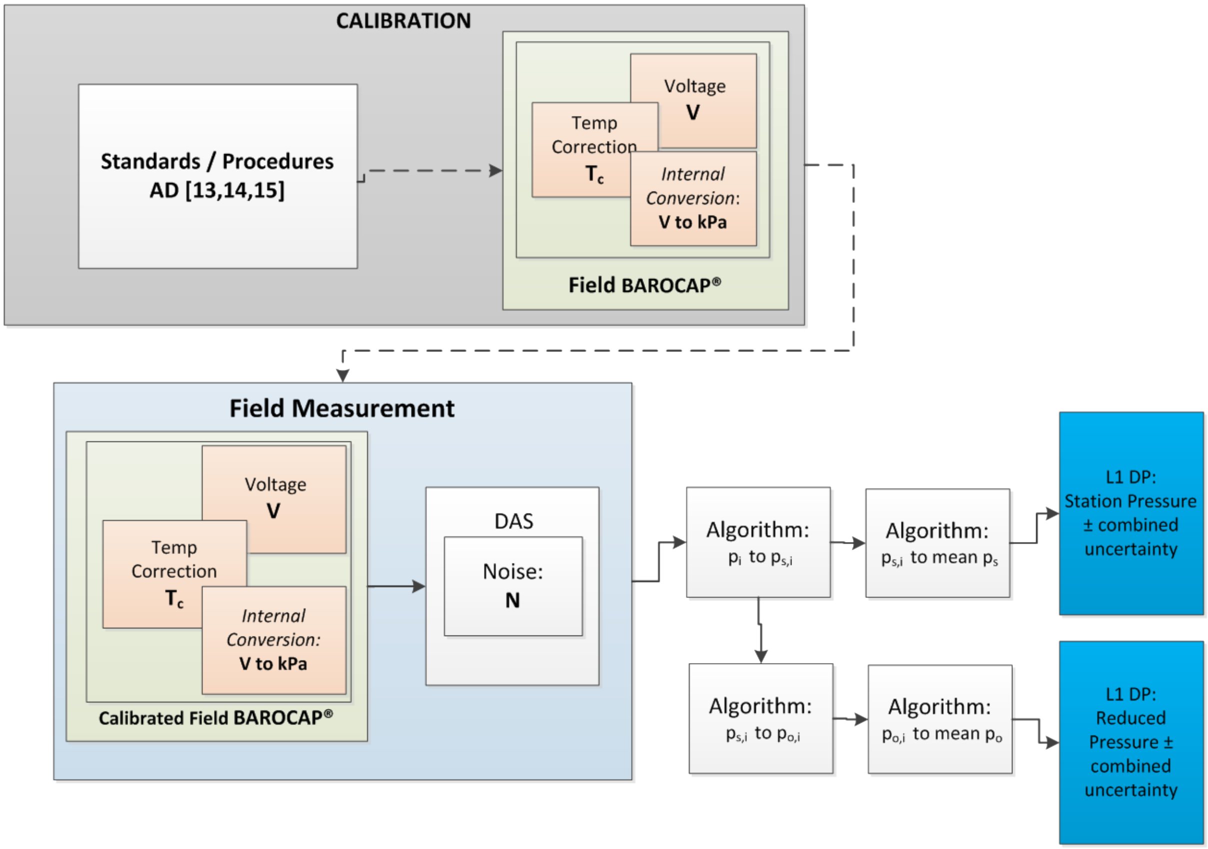

Figure 1: Displays the sources of uncertainty and data flow for L1 Station and reduced pressure DPs. The salmon colored boxes represent the measurement of pressure based on the theory of aneroid barometry. For more information regarding the calibration procedure, please refer to AD [13,14,15].

6.1.1 Calibration

Uncertainties associated with the barometer and its calibration processes are combined into an individual, standard uncertainty $u_c(P_{CVAL})$ by CVAL. It represents i) the variation of an individual sensor from the mean of a sensor population, ii) uncertainty of the calibration procedures and iii) uncertainty of coefficients used to convert raw pressure readings to calibrated station pressure (refer to Eq. (1)). It is a constant value that will be provided by CVAL (AD[14]), stored in the CI data store, and applied to all barometric pressure measurements (that is, it does not vary with any specific sensor, DAS component, etc.).

6.1.2 DAS

This barometer has an internal A/D converter and outputs data in digital form. Because of this, DAS noise (uncertainty) can be considered negligible.

6.2 Combined Uncertainty – Station Pressure

Because CVAL's uncertainty is the sole uncertainty that associated with station pressure, the combined uncertainty for each 1 Hz station pressure datum is simply:

$$u_c(p_{s_i}) = u(P_{CVAL}) \quad [kPa] \tag{11}$$

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:

$$\frac{\partial \overline{p_s}}{\partial p_{s_i}} = \frac{1}{n} \tag{12}$$

Where n represents the number of valid observations made during the averaging period. The absolute value of Eq. (12) is then multiplied by Eq. (11):

$$u_{p_{s_i}}(\overline{p_s}) = \left|\frac{1}{n}\right| u_c(p_{s_i}) \quad [kPa] \tag{13}$$

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

$$u_c(\overline{p_s}) = \left(\sum_{i=1}^{n} u_{p_{s_i}}{}^2(\overline{p_s})\right)^{\frac{1}{2}} \quad [kPa] \tag{14}$$

<u>Note</u>: In some applications the environmental variation of pressure may be of equal or greater interest than the measurement uncertainty). While we acknowledge that many approaches exist to quantify environmental variation, listing each method would be lengthy. To promote conciseness we present one method, a simple approach, which describes the variation of the *L1 mean DP* as a function of standard deviation:

$$u(\overline{p_s}) = \left(\frac{s^2(p_{s_i})}{n}\right)^{\frac{1}{2}} \quad [kPa] \tag{15}$$

Where, $s^2(p_{s_i})$ is the variance DP (NEON.DXX.XXX.DP1.00004.001.004.001.00X) and n are the number of observations used to generate the DP. It should be noted that such an equation *assumes* the data are normally distributed.

6.3 Expanded Uncertainty – Station Pressure

The expanded uncertainty for L1 station pressure DPs can be derived with the following equations:

$$V_{eff_{p_{s_i}}} = \frac{{u_c}^4(p_{s_i})}{\frac{{u_c}^4(p_{s_i})}{Veff_{P_{CVAL}}}} = Veff_{P_{CVAL}} \tag{16}$$

Where $Veff_{P_{CVAL}}$ is a function of the number of tests conducted by CVAL during calibration – its value will be stored in the CI data store.

Second, the effective degrees of freedom must be calculated for our L1 mean station pressure DP:

$$V_{eff_{\overline{p_s}}} = \frac{{u_c}^4(\overline{p_s})}{\sum_{i=1}^{n}\left(\frac{(u_c(p_{s_i})/n)^4}{V_{eff_{p_{s_i}}}}\right)} \tag{17}$$

Then, the expanded uncertainty is calculated:

$$U_{95}(\overline{p_s}) = k_{95} * u_c(\overline{p_s}) \quad [kPa] \tag{18}$$

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

- Table 5 from AD[11]
- $V_{eff_{\overline{p_s}}}$

6.4 Reduction Pressure (Sea Level Pressure)

The L0 pressure data will be reduced to sea level via Eq. (8), a slightly altered version of WMO's (2008) standard method (displayed again for reference):

$$p_0 = p_s * e^{\left(\frac{z*g}{R_d\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v} * C_h\right)}\right)} \tag{19}$$

This equation comprises a great deal of uncertainty because it assumes the measurand is being observed in a "standard atmosphere." Additionally, atmospheric constants (i.e., R_d and α) are subject to their own uncertainties (Henrion and Fischhoff 1986). All individual uncertainties comprising the combined uncertainty of reduced pressure are derived in the sections below.

6.4.1 Station Pressure

The partial derivative of Eq. (19) with respect to p_s must be calculated in order to identify the sensitivity coefficient of station pressure:

$$\frac{\partial p_{o_i}}{\partial p_{s_i}} = e^{\left(\frac{z*g}{R_d\left(\overline{T_s}+\frac{\alpha*z}{2}+\overline{e_v}*C_h\right)}\right)} \tag{20}$$

The absolute value of this sensitivity coefficient will be multiplied by the combined uncertainty of station pressure to derive the partial uncertainty of reduced pressure as a function of station pressure:

$$u_{p_{s_i}}\left(p_{0_i}\right) = \left|e^{\left(\frac{z*g}{R_d\left(\overline{T_s}+\frac{\alpha*z}{2}+\overline{e_v}*C_h\right)}\right)}\right| * u_c\left(p_{s_i}\right) \quad [kPa] \tag{21}$$

6.4.2 Elevation of Barometer

The barometer's elevation Above Sea Level (ASL) is the second source of uncertainty that propagates into the combined uncertainty of reduced pressure. This uncertainty will be will be provided by Field Deployment and maintained in the CI data store.

The sensitivity coefficient with respect to the barometer's elevation ASL is then derived:

$$\frac{\partial p_{o_i}}{\partial z} = \frac{4*g*p_s*(\overline{T_s}+\overline{e_v}*C_h)*e^{\left(\frac{2*g}{\alpha*R}-\frac{4*g*(\overline{T_s}+\overline{e_v}*C_h)}{\alpha*R_d(\alpha*z+2(\overline{T_s}+\overline{e_v}*C_h))}\right)}}{\left(\alpha*z+2(\overline{T_s}+\overline{e_v}*C_h)\right)^2*R_d} \tag{22}$$

The partial uncertainty of reduced pressure as a function of the barometer's elevation ASL is then:

$$u_z\left(p_{o_i}\right) = \left|\frac{4*g*p_s*(\overline{T_s}+\overline{e_v}*C_h)*e^{\left(\frac{2*g}{\alpha*R}-\frac{4*g*(\overline{T_s}+\overline{e_v}*C_h)}{\alpha*R_d(\alpha*z+2(\overline{T_s}+\overline{e_v}*C_h))}\right)}}{\left(\alpha*z+2(\overline{T_s}+\overline{e_v}*C_h)\right)^2*R_d}\right| * u(z) \quad [kPa] \tag{23}$$

6.4.3 Acceleration of Gravity

As displayed in Eq. (4), local gravity is a function of station elevation ASL and latitude. Given the current technology of GPS, it is reasonable to assume that the uncertainty of the station's latitude is negligible. Because of this and that uncertainty of station elevation is quantified (refer to the previous section), it can be argued that the acceleration of local gravity can be considered negligible. The argument can be further strengthened because Eq. (19) uses local gravity as opposed to standard gravity (Eq. (2)).

6.4.4 Dry Air Constant

A minor pitfall associated with using the dry air constant within any equation is that it assumes the atmosphere is free of water vapor. It can be said that the use of the dry air constant could cause asymmetric (systematic) uncertainty within an equation because it always assumes a completely dry atmosphere. However, in the case of reducing station pressure, this 'systematic' uncertainty is corrected through the use of virtual temperature, which accounts for atmospheric moisture via vapor pressure. In theory, the pressure of a region can be expressed as:

$$p = \rho R_d T_v = \rho R_m T \tag{24}$$

where ρ is the density of the air, R_m is the moist air constant, and T is temperature.

The dry air constant, R_d, is the gas constant for 1 kg of dry air. It is a function of the *universal gas constant* $R*$ (8.3145 J K^{-1} mol^{-1}) and the apparent molecular weight of dry air M_d (28.97 g)

$$R_d = 1000\frac{8.3145}{28.97} = 287.05\, J\, K^{-1}\, kg^{-1} \tag{25}$$

Since it is a constant, it is considered a true value. However, we know from JCGM (2008) that a true value can never be measured, and universal constants will always comprise a level of uncertainty (Henrion and Fischhoff 1986). However, magnitude of this uncertainty is most likely minimal, especially compared to those of the other variables comprising Eq. (19). Thus, we can assume that the dry air constant comprises negligible uncertainty.

6.4.5 Station Temperature

The uncertainty of the L1 mean SAAT DP will be calculated via the algorithms discussed in AD[12]. This uncertainty should represent the same temporal averaging period as the resulting L1 pressure DP. In other words, when calculating the *one-minute* L1 mean station pressure DP, the corresponding *one-minute* L1 mean SAAT DP should be used.

The sensitivity coefficient of Eq. (19) with respect to $\overline{T_s}$ is:

$$\frac{\partial p_{o_i}}{\partial \overline{T}_s} = \frac{-g * p_s * z * e^{\left(\frac{g * z}{R_d\left(\overline{T}_s + \frac{\alpha * z}{2} + \overline{e_v} * C_h\right)}\right)}}{\left(\overline{T}_s \; + \; \frac{\alpha * z}{2} \; + \; \overline{e_v} \; * \; C_h\right)^2 * R_d} \tag{26}$$

The partial uncertainty of reduced pressure as a function of station temperature is then:

$$u_{\overline{T}_s}\left(p_{o_i}\right) = \left|\frac{-g * p_s * z * e^{\left(\frac{g * z}{R_d\left(\overline{T}_s + \frac{\alpha * z}{2} + \overline{e_v} * C_h\right)}\right)}}{\left(\overline{T}_s \; + \; \frac{\alpha * z}{2} \; + \; \overline{e_v} \; * \; C_h\right)^2 * R_d}\right| * u_c\left(\overline{T}_s\right) \quad [kPa] \tag{27}$$

6.4.6 Lapse Rate of Temperature

As mentioned before, the standard atmospheric lapse rate is 0.0065°K km^{-1} (WMO 2008). Although this can be considered a “constant,” it holds a great deal of uncertainty because it is somewhat fictitious in nature. Atmospheric lapse rates (LR) can vary between 0.005 °K km^{-1} (moist adiabatic lapse rate) and 0.010 °K km^{-1} (dry adiabatic lapse rate), and can occasionally reach extremes on either side (Wallace and Hobbs 2006). To account for these variations we take a fairly conservative approach and assume this lapse rate is reliable to ~80%, and derive a value that reflects 20% uncertainty:

$$u(\alpha) = \alpha * 0.20 = \; 0.0065 * 0.20 = \pm\, 0.0013 \quad [K \; km^{-1}] \tag{28}$$

And the partial derivative of Eq. (19) with respect to α is:

$$\frac{\partial p_{o_i}}{\partial \alpha} = \frac{-2g * p_s * z^2 * e^{\left(\frac{2g * z}{R_d\left(\alpha * z + \; 2\left(\overline{T}_s + \overline{e_v} * C_h\right)\right)}\right)}}{\left(\alpha * z + \; 2\left(\overline{T}_s + \overline{e_v} \; * \; C_h\right)\right)^2 * R_d} \tag{29}$$

The partial uncertainty of reduced pressure as a function of temperature’s lapse rate is then:

$$u_\alpha\left(p_{o_i}\right) = \left|\frac{-2g * p_s * z^2 * e^{\left(\frac{2g * z}{R_d\left(\alpha * z + \; 2\left(\overline{T}_s + \overline{e_v} * C_h\right)\right)}\right)}}{\left(\alpha * z + \; 2\left(\overline{T}_s + \overline{e_v} \; * \; C_h\right)\right)^2 * R_d}\right| * u(\alpha) \quad [kPa] \tag{30}$$

6.4.7 Vapor Pressure

Atmospheric vapor pressure is a function of dew point and other atmospheric constants. It can be argued that the uncertainty of vapor pressure should be relatively large because our current approach derives vapor pressure from monthly dewpoint averages of nearby stations. This is especially true at mountainous sites, as the effects of complex terrain, specifically orographic lift, promote a highly dynamic environment where these sites are sporadically enshroud in clouds; thus, dewpoints in these regions fluctuate dynamically. However, at most sites, dewpoint is far less dynamic in nature. Additionally, a non-linear relationship exists between dewpoint and vapor pressure. Because of this, the variance of dewpoint will always be greater than that of vapor pressure. Here, we take a conservative approach and assign dewpoint an uncertainty of:

$$u(\overline{T_d}) = \pm 6 \quad [^{\circ}\mathrm{C}] \tag{31}$$

This represents the uncertainty we have when utilizing a monthly mean value from a nearby station as a representation of dewpoint values at a NEON tower. To show how significantly this uncertainty affects that of vapor pressure, the partial derivative of Eq. (7) with respect to dewpoint must be derived:

$$\frac{\partial \overline{e_v}}{\partial \overline{T_d}} = \frac{7.93135E^{10} * e^{\left(\frac{-4104.93}{237.7+\ \overline{T_d}}\right)}}{(237.7 +\ \overline{T_d})^2} \tag{32}$$

Where, E denotes scientific notation; and the uncertainty of dewpoint (Eq.(31)) must be multiplied by the absolute value of Eq. (32):

$$u_c(\overline{e_v}) = \left| \frac{7.93135E^{10} * e^{\left(\frac{-4104.93}{237.7+\ \overline{T_d}}\right)}}{(237.7 +\ \overline{T_d})^2} \right| * u(\overline{T_d}) \quad [kPa] \tag{33}$$

This combined uncertainty of vapor pressure then propagates into the combined uncertainty of reduced pressure via the following equations:

$$\frac{\partial p_{o_i}}{\partial \overline{e_v}} = \frac{-p_s * g * C_h * z * e^{\left(\frac{z*g}{R_d\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)}\right)}}{\left(\overline{T_s}\ + \frac{\alpha * z}{2}\ +\ \overline{e_v} * C_h\right)^2 * R_d} \tag{34}$$

And,

$$u_{\overline{e_v}}(p_{o_i}) = \left| \frac{p_s * g * C_h * z * e^{\left(\frac{z*g}{R_d\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)}\right)}}{\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)^2 * R_d} \right| * u(\overline{e_v}) \quad [kPa] \tag{35}$$

Overall, the impact of vapor pressure is quite small when compared to other variables in the reduced pressure equation (WMO 1964).

6.4.8 Lapse Rate of Vapor Pressure

The lapse rate of vapor pressure is adapted by the WMO (1964) and incorporated into the sea level reduction equation. It is based on seasonal variation of vapor pressure within the lower atmosphere (Rao 1958). Like that of temperature, the lapse rate of vapor pressure can be considered to hold a great deal of uncertainty. This is especially true over large elevation ranges. Here we take a similar, conservative approach to that of quantifying the uncertainty of temperature lapse rate and use of relative uncertainty of 20%:

$$u(C_h) = C_h * 0.20 = 1.2 * 0.20 = \pm 0.24 \quad [K\ kPa^{-1}] \tag{36}$$

Its associated sensitivity coefficient is:

$$\frac{\partial p_{o_i}}{\partial C_h} = \frac{-p_s * g * e_v * z * e^{\left(\frac{z*g}{R_d\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)}\right)}}{\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)^2 * R_d} \tag{37}$$

And its propagating term is:

$$u_{C_h}(p_{o_i}) = \left| \frac{-p_s * g * e_v * z * e^{\left(\frac{z*g}{R_d\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)}\right)}}{\left(\overline{T_s} + \frac{\alpha*z}{2} + \overline{e_v}*C_h\right)^2 * R_d} \right| * u(C_h) \quad [kPa] \tag{38}$$

6.5 Combined Uncertainty – Reduced Pressure

The combined uncertainty of L1 reduced pressure DPs can be derived in a few steps. First, the combined uncertainty of *individual*, valid (i.e., *those that are not flagged and omitted*) reduced pressure measurands computed during the averaging period is calculated.

$$u_c\left(p_{0_i}\right) = \left(u_{p_s}{}^2\left(p_{0_i}\right) + u_z{}^2\left(p_{0_i}\right) + u_{\overline{T_s}}{}^2\left(p_{0_i}\right) + u_\alpha{}^2\left(p_{0_i}\right) + u_{\overline{e_v}}{}^2\left(p_{0_i}\right) + u_{C_h}{}^2\left(p_{0_i}\right)\right)^{\frac{1}{2}} \quad [kPa] \tag{39}$$

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:

$$\frac{\partial \overline{p_o}}{\partial p_{o_i}} = \frac{1}{n} \tag{40}$$

Where n represents the number of valid observations made during the averaging period. The absolute value of Eq. (40) is then multiplied by Eq. (39):

$$u_{p_{o_i}}\left(\overline{p_o}\right) = \left|\frac{1}{n}\right| u_c\left(p_{o_i}\right) \quad [kPa] \tag{41}$$

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

$$u_c\left(\overline{p_o}\right) = \left(\sum_{i=1}^{n} u_{p_{o_i}}{}^2\left(\overline{p_o}\right)\right)^{\frac{1}{2}} \quad [kPa] \tag{42}$$

<u>**Note**</u>**:** For reasons noted in Section 6.2, the natural variation of the mean is presented:

$$u\left(\overline{p_o}\right) = \left(\frac{s^2\left(p_{o_i}\right)}{n}\right)^{\frac{1}{2}} \quad [kPa] \tag{43}$$

Where, $s^2\left(p_{o_i}\right)$ is the variance DP (NEON.DXX.XXX.DP1.00004.001.009.0XX.00X) and n are the number of observations used to generate the DP.

6.6 Expanded Uncertainty – Reduced Pressure

Computing an expanded uncertainty for reduced pressure is completed with the following steps. First, the effective degrees of freedom for each individual reduced pressure datum must be calculated:

$$V_{eff\,p_{o_i}} = \frac{u_c{}^4\left(p_{o_i}\right)}{\frac{u_{P_{s_i}}{}^4\left(p_{o_i}\right)}{Veff_{P_{s_i}}} + \frac{u_z{}^4\left(p_{o_i}\right)}{Veff_z} + \frac{u_{\overline{T_s}}{}^4\left(p_{o_i}\right)}{Veff_{\overline{T_s}}} + \frac{u_\alpha{}^4\left(p_{o_i}\right)}{Veff_\alpha} + \frac{u_{\overline{e_v}}{}^4\left(p_{o_i}\right)}{Veff_{\overline{e_v}}} + \frac{u_{C_h}{}^4\left(p_{o_i}\right)}{Veff_{C_h}}} \tag{44}$$

Where $Veff_{P_{s_i}}$ is derived in Eq. (16); $Veff_{\overline{T_s}}$ represents the effective degrees of freedom for the L1 mean SAAT DP (refer to AD[12] for the equations necessary to compute its value); $Veff_z$, $Veff_\alpha$, $Veff_{\overline{e_v}}$, and $Veff_{C_h}$ are considered results of Type B evaluations and their values will all be 100 (please refer to

AD[11] for further justification). It should be noted that the effective degrees of freedom of vapor pressure's lapse rate, $Veff_{\bar{e_v}}$, is solely a function of $Veff_{\overline{T_d}}$, the effective degrees of freedom of dewpoint. Given this, and that both are considered to result from Type B evaluations, a separate calculation computing $Veff_{\bar{e_v}}$ is not needed, as $Veff_{\bar{e_v}} \equiv \; Veff_{\overline{T_d}}$

Second, the effective degrees of freedom must be calculated for our L1 mean reduced pressure DP:

$$V_{eff_{\overline{p_o}}} = \frac{{u_c}^4(\overline{p_o})}{\sum_{i=1}^{n}\left(\frac{(u_c(p_{o_i})/n)^4}{V_{eff_{p_{o_i}}}}\right)} \tag{45}$$

Finally, the expanded uncertainty is calculated:

$$U_{95}(\overline{p_o}) = k_{95} * u_c(\overline{p_o}) \quad [kPa] \tag{46}$$

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

- Table 5 from AD[11]
- $V_{eff}(\overline{p_o})$

6.7 Uncertainty Budget

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

Table 3: Uncertainty budget for L1 station and sea level DPs. Shaded rows denote propagation (from lightest to darkest) of uncertainties.

Source of uncertainty	**Standard uncertainty component u(X$_i$)**	**Type of eval.**	**Value of standard uncertainty [kPa]**	$c_i \equiv \frac{\partial f}{\partial x_i}$	$u_i(Y) \equiv \lvert c_i \rvert u(x_i)$ **[kPa]**	**Degrees of Freedom**
L1 station pres. DP	$u_c(\overline{p_s})$	AD[14]	Eq. (14)	N/A	N/A	Eq. (17)
0.1 Hz station pres.	$u_c(p_{s_i})$	AD[14]	Eq. (11)	Eq. (12)	Eq. (13)	Eq. (16)
Sensor/calibration	$u_c(P_{CVAL})$	AD[14]	AD[14]	1	AD[14]	AD[14]
L1 reduce pres. DP	$u_c(\overline{p_o})$	A,B*	Eq. (42)	N/A	N/A	Eq. (45)
0.1 Hz reduce pres.	$u_c(p_{o_i})$	A	Eq. (39)	Eq. (40)	Eq. (41)	Eq. (44)

0.1 Hz station pres.	$u_c(p_{s_i})$	AD[14]	Eq. (11)	Eq. (20)	Eq. (21)	Eq. (16)
Elevation	$u(z)$	AD[TBD]	AD[TBD] [m]	Eq. (22)	Eq. (23)	100
Temperature	$u_c(\overline{T_s})$	AD[12]	AD[12] [K]	Eq. (26)	Eq. (27)	AD[12]
Temp. lapse rate	$u(\alpha)$	B*	Eq. (28) [K km^{-1}]	Eq. (29)	Eq. (30)	100
Vapor pres. (VP)	$u_c(\overline{e_v})$	B*	Eq. (33)	Eq. (34)	Eq. (35)	100
Dewpoint	$u(\overline{T_d})$	B*	Eq. (31) [$^{\circ}$C]	Eq. (32)	Eq. (33)	100
VP lapse rate	$u(C_h)$	B*	Eq. (36) [K kPa^{-1}]	Eq. (37)	Eq. (38)	100

k_{95} of station pressure: $v_{eff_{\overline{p_s}}}$ & Table 5 of AD[11]

$U_{95}(\overline{p_s})$: Eq. (18)

k_{95} of reduced pressure: $v_{eff_{\overline{p_o}}}$ & Table 5 of AD[11]

$U_{95}(\overline{p_o})$: Eq. (46)

*Based on scientific judgment

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream and included in the QA/QC summary DP ($Qsum_{1min}$ and $Qsum_{30min}$) that summarizes any flagged data that went into the computation of the L1 DP.

In the future, if station humidity measurements become available at NEON towers, in-situ measurement of atmospheric vapor pressure may be determined. Thus, in-situ vapor pressure values can be used in place of monthly, mean values from nearby stations in Eq. (8). If this occurs, the uncertainty in Section 6.2.7 should be recalculated to reflect those methods associated with quantifying other in-situ based measurements such as station pressure and temperature.

8 BIBLIOGRAPHY

Brock, F. V., and S. J. Richardson (2001) Meteorological Measurement Systems. Oxford University Press. pp. 290.

Bureau International des Poids et Meaures (BIPM) (1901) General conference on weights and measures, 70.

Henrion, M., and B. Fischhoff (1986), Assessing uncertainty in physical constants, Am. J. Phys., 54, 791-798, doi :10.1119/1.14447.

Joint Committee for Guides in Metrology (JCGM) (2008) Evaluation of measurement data – Guide to the expression of uncertainty in measurement. pp. 120.

JCGM (2012) International vocabulary of metrology – Basic and general concepts and associated terms (VIM). 3rd Edition. pp. 92

Jursa, A. S., (1985) Handbook of Geophysics and the Space Environment, 4th ed., Air Force Geophysics Laboratory, pp. 14-17.

Met One Instruments, Inc. (1997) Fan Aspirated Radiation Shield: Specification Sheet. Rev. 076B, pp. 2. *(K:\FIU\TIS Assemblies\3. Aspirated Air Temp-single\Manuals)*

Rao, K.N. (1957) Regression of Vapour Pressure with Height, Latitude and Longitude. Bombay.

Rao, K.N. (1958) Contribution of the humidity term in the formula for reduction of pressure to sea level. Bombay.

Taylor, J. R. (1997) An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements. University Science Books, Mill Valley, California. 2nd Ed. pp. 327.

Vaisala (2008) Vaisala BAROCAP digital barometer PTB330. *Vaisala Oyj*, pp. 139.

Vaisala (2009) Vaisala PTB330 Digital Barometer for Professional Meteorology, Aviation, and Industrial Users: *Technical Information*. Ref. B210708EN-B. pp.2
(P:\FIU\TIS Assemblies\9. Barometric Pressure\Manuals)

Van der Meulen, J.P. (1992) The WMO automatic digital barometer intercomparison. *WMO*, WMO Technical Document 474, pp. 106.

Wallace, J. M., and P. V. Hobbs (2006) Atmospheric Science: An Introduction Survey. Academic Press. 2nd Ed. pp. 483.

World Meteorological Organization (WMO) (1964) Note on the Standardization of Pressure Reduction Methods in the International Network of Synoptic Stations. WMO Technical Note No. 61, WMO-No. 154.TP.74, Geneva.

WMO (2008) Measurement of Atmospheric Pressure. *Guide to Meteorological Instruments and Methods of Observation*. 8th Ed. pp. 1.3-1 – 1.3-25.

9 CHANGELOG