NEON ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD) – PRIMARY PRECIPITATION (DFIR)

PREPARED BY	ORGANIZATION	DATE
Derek Smith	FIU	11/03/2015
Josh Roberti	FIU	04/29/2014

APPROVALS	ORGANIZATION	APPROVAL DATE
Kate Thibault	SCI	04/20/2022

RELEASED BY	ORGANIZATION	RELEASE DATE
Tanisha Waters	CM	04/20/2022

See configuration management system for approval history.

The National Ecological Observatory Network is a project solely funded by the National Science Foundation and managed under cooperative agreement by Battelle. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	09/13/2017	ECO-04989	Initial Release
B	04/20/2022	ECO-06809	• Update to reflect change in terminology from relocatable to gradient sites • Updated logo

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1 DESCRIPTION

1.1 Purpose

Across NEON sites two methods will be used to determine bulk precipitation. Bulk precipitation measurements at core sites consist of a weighing gauge surrounded by a double fence inter-comparison reference (DFIR). While bulk precipitation measurements at gradient sites is determined using a tipping bucket. Bulk precipitation measured using a DFIR and a weighing gauge is known to provide improved results over tipping bucket measurements. Thus, the weighing gauge surrounded by the DFIR is considered the "primary" method, while the tipping bucket is referred to as the "secondary" method. This document will provide the details for primary precipitation, which consists of a DFIR, alter shield, and weighing gauge. Specifically, this document details the algorithms used to create NEON Level 1 data products (DPs) from Level 0 DPs obtained via instrumental measurements made by Belfort AEPG II 600M weighing gauges. Additionally, ancillary data/inputs such as calibration data are defined in this document. Domains 1, 5, 9, 10, 12, 13, 17, 18, and 19 will use the heated version (P/N: CG07180010 and NEON P/N: 0303440002), while all other domains will use the non-heated version (DGD P/N: CG07180000 and NEON P/N: 0303440001). A detailed discussion of measurement theory and implementation is provided. In addition, 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 is provided.

1.2 Scope

The theoretical background and entire algorithmic process used to derive Level 1 data from Level 0 data for primary precipitation are described in this document. It is expected that the AEPG II 600M weighing gauge will be used to measure precipitation at all core tower sites. This document does not provide computational implementation details, except for cases where these stem directly from algorithmic choices explained here.

2 RELATED DOCUMENTS AND ACRONYMS

2.1 Applicable Documents

AD[01]	NEON.DOC.000001	NEON Observatory Design
AD[02]	NEON.DOC.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.005004	NEON Level 1-3 Data Products Catalog
AD[04]	NEON.DOC.005005	NEON Level 0 Data Products Catalog
AD[05]	NEON.DOC.000782	ATBD QA/QC Data Consistency
AD[06]	NEON.DOC.011081	ATBD QA/QC plausibility tests
AD[07]	NEON.DOC.000783	ATBD QA/QC Time Series Signal Despiking for TIS Level 1 Data Products
AD[08]	NEON.DOC.000897	C^3 Primary Precipitation Gauge
AD[09]	NEON.DOC.000898	ATBD Primary Precipitation Gauge
AD[10]	NEON.DOC.000367	C^3 Secondary Precipitation Gauge
AD[11]	NEON.DOC. 003289	Primary Precipitation Sensor L1P100 – CVAL Standard Operating Procedure
AD[12]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values
AD[13]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[14]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[15]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products
AD[16]	NEON.DOC.001213	Primary Precipitation Calibration Fixture Manual

2.2 Reference Documents

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

2.3 Acronyms

Acronym	Explanation
ATBD	Algorithm Theoretical Basis Document
CVAL	NEON Calibration, Validation, and Audit Laboratory
DFIR	Double Fence Intercomparison Reference
DGD	Data generating device
DP	Data Product
L0	Level 0
L1	Level 1

2.4 Variable Nomenclature

The symbols used to display the various inputs in the ATBD, e.g., calibration coefficients and uncertainty estimates, were chosen so that the equations can be easily interpreted by the reader. However, the symbols provided will not always reflect NEON's internal notation, which is relevant for CI's use, 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/Portal Notation	Description
A_k	CVALA1	CVAL Strain gauge calibration coefficient
B_k	CVALA2	CVAL Strain gauge calibration coefficient
f_{0_k}	CVALF0	CVAL Strain gauge calibration coefficient for an empty collector
u_{A1}	U_CVALA1	Combined, relative calibration uncertainty of a strain gauge reading (%)
$V_{eff_{A1}}$	U_CVALD1	Effective degrees of freedom relating to u_{A1} (unitless)

2.5 Verb Convention

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

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

The primary precipitation related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying data publication file (pre_datapub_NEONDOC002878).

3.2 Input Dependencies

Table 1 details the primary precipitation related L0 DPs used to produce L1 DPs in this ATBD.

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

Data product	Sample Frequency	Units	Data Product ID
Strain Gauge Frequency 1 (f_1)	0.1 Hz	Hz	NEON.DOM.SITE.DP0.00006.001.01900.HOR.VER.101
Strain Gauge Frequency 2 (f_2)	0.1 Hz	Hz	NEON.DOM.SITE.DP0.00006.001.01900.HOR.VER.102
Strain Gauge Frequency 3 (f_3)	0.1 Hz	Hz	NEON.DOM.SITE.DP0.00006.001.01900.HOR.VER.103
Strain Gauge Stability 1 (S_1)	0.1 Hz	NA	NEON.DOM.SITE.DP0.00006.001.01897.HOR.VER.101
Strain Gauge Stability 2 (S_2)	0.1 Hz	NA	NEON.DOM.SITE.DP0.00006.001.01897.HOR.VER.102
Strain Gauge Stability 3 (S_3)	0.1 Hz	NA	NEON.DOM.SITE.DP0.00006.001.01897.HOR.VER.103
Inlet Temperature*	0.1 Hz	°C	NEON.DOM.SITE.DP0.00006.001.01905.HOR.VER.000
Internal Temperature*	0.1 Hz	°C	NEON.DOM.SITE.DP0.00006.001.01906.HOR.VER.000
Heater Flag (i.e., orificeHeaterFlag)*	0.1 Hz	NA	NEON.DOM.SITE.DP0.00006.001.02000.HOR.VER.000

Note: * Signifies that these data products pertain to heated models only

3.3 Product Instances

Primary precipitation will be measured by a weighing gauge surrounded by a small double fence intercomparison reference (DFIR) at all core tower sites.

3.4 Temporal Resolution and Extent

The L0 DPs for primary precipitation will be recorded by three strain gauges, which will be used to determine 5- and 30-minute bulk precipitation values to form the L1 DPs.

3.5 Spatial Resolution and Extent

The primary precipitation gauge (i.e., weighing gauge housed in a small DFIR) will be located at all core tower sites. The distance of the primary precipitation gauge from the tower will depend on the local terrain and therefore will be site specific. The opening of the precipitation gauge is 200 mm^2. Thus, the spatial resolution of the gauge will reflect a surface area of 200 mm^2 at the point in space where the precipitation gauge is located.

4 SCIENTIFIC CONTEXT

Precipitation records are fundamental to an array of ecological studies. As such, precipitation data is often used as ancillary data for more detailed investigations. Furthermore, precipitation records help inform storm surge statistics and abate social, economic, and environmental losses from floods.

4.1 Theory of Measurement

The measurement of precipitation is relatively straight forward; however it can easily become biased by wind. Wind generally leads to the undercatch of precipitation and is the main factor that induces uncertainty in the measurement. The presence of solid precipitation only compounds this problem and windy conditions can result in 20-50% undercatch (Rasmussen, R. et al., 2012). Therefore, in order to reduce uncertainty in the measurement, NEON has chosen to follow the site selection guidelines of the U.S. Climate Reference Network (USCRN) for the installation of precipitation gauges (CRN, 2002). Additionally, NEON has chosen to incorporate the small DFIR configuration into their primary precipitation design in order to minimize the effects of wind on the measurement. Precipitation itself is determined via a weighing gauge. Essentially, the weighing gauge, with a known surface area, monitors the change in weight of the collector over time, which is directly equated to an accumulation in precipitation.

The weighing gauge is housed within a polyethylene resin shell that serves to protect the sensor components as well as reduce wind effects. In climates where freezing temperatures are expected, heaters will be installed in the housing inlet of the sensor. The heaters serve two main purposes. First, heaters reduce the potential of the gauge becoming encased in ice. Secondly, heaters melt solid precipitation to provide precipitation estimates when solid precipitation is present. The precipitation measurement consists of three strain gauges that monitor the weight of a collector. A strain gauge consists of a metal wire that has known resonation characteristics. Therefore, when a known current is applied to a strain gauge it causes the wire to resonate at a known frequency. This frequency is proportional to the square of the tension in the wire (Bakkehøi, S. et al., 1985). A range of calibration weights are then used to develop a relationship between strain gauge frequency and weight for the gauge. This in turn allows the frequency output from the strain gauges to be used to calculate a corresponding depth measurement.

4.2 Theory of Algorithm

First, for each observation, the three strain gauge frequencies need to be converted into a depth measurement. The three strain gauge frequencies and their corresponding stability information (i.e., S_1, S_2, and S_3) are also needed for this conversion. The stability of a strain gauge will correspond to "P" only when it has stabilized, "S" when it is searching for stability or "F" if there is a gauge failure. This information is converted on site to a binary format where P = 1, S = 0, and F = -1. Accordingly, 1 (i.e., P) signifies that the strain gauge has passed a stability test, while 0 (i.e., S) represents that the strain gauge has not yet stabilized, and -1 (i.e., F) if there is a strain gauge failure which can indicate a broken wire or temperature thermistor see AD[08] for more details (Belfort Instrument Company, 2014). Only stabilized strain gauge frequency measurements will be converted to depth.

Bulk precipitation will be reported at 5- and 30-minute intervals. Precipitation at 5-minute intervals is determined from a single set of averaged strain gauge measurements. Since raw frequency data (i.e., L0 data) are recorded continuously at a rate of 0.1 Hz (i.e., once every 10 seconds), multiple observations will exist for each time interval. Thus, using a procedure similar to the USCRN, 1-minute averages of each strain gauge's depth measurements will be reported at 5-minute intervals (i.e., the average of 6 10-second samples) (Leeper et al. 2015). This averaging period may be altered in the future if it is found to improve sensor performance. Alternatively, precipitation at 30-minute intervals will be derived as the sum of the 5-minute bulk precipitation results over the 30 minute interval. In order to determine 5-minute bulk precipitation, 1-minute averages for each strain gauge first need to be determined accordingly.

First, frequencies for strain gauges over the 1-minute averaging interval (i.e., the last minute in a 5-minute interval) that correspond with stable measurement (i.e., S = 1) are selected. In the event that stability information is missing for the current time stamp, precipitation will not be determined for that interval and the null quality flag shall be set to 1 for the 5-minute bulk precipitation value. Alternatively, the null 30-minute null quality flag will be set to 1 in the event that no 5-minute bulk precipitation values exist over the 30-minute interval.

$$f_{k,i} \ when \ \mathrm{S}_{k,i} = 1 \tag{1}$$

f = is a 0.1-Hz frequency measurement taken during the 60-second averaging period when the measurements were stable (Hz)
S = Strain gauge stability
k = 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i = Running index

For the 1-minute interval n = 6 if all frequencies are stable. Frequencies that are unstable (i.e., S = 0 or -1) shall be set to NULL (i.e., $f_{k,i} = \boldsymbol{NULL}$).

Next the stable frequency measurements are converted to depth through Eq. (2) (Campbell Scientific, 2011).

$$D_{k,i} = \left(A_k\left(f_{D_{k,i}} - f_{0\,k}\right) + B_k\left(f_{D_{k,i}} - f_{0\,k}\right)^2\right) * 10 \tag{2}$$

Where:

D	= Individual precipitation depth for a given strain gauge (mm)
A	= Strain gauge specific calibration coefficient provided by CVAL (mm*sec)
B	= Strain gauge specific calibration coefficient provided by CVAL (mm*sec^2)
f_D	= Stable strain gauge frequencies over the 1-minute interval (Hz)
f_0	= Frequency with an empty collector at calibration, strain gauge specific and provided by CVAL (Hz)
i	= Running index
k	= 1,2, or 3 (i.e., the number of strain gauges in the precipitation sensor)

Next the depth measurement are averaged over the 1-minute interval accordingly,

$$\overline{D_k} = \frac{1}{n}\sum_{i=1}^{n} D_{k,i} \tag{3}$$

Where:

$\overline{D}$	= Is the 1-minute average depth for a given strain gauge (mm)
D	= is a 0.1-Hz depth measurement taken during the 60-second averaging period when the measurements were stable (mm)
k	= 1,2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i	= Running index

In the event that 2 or more strain gauges are unstable for the entire averaging period then no depth information will be reported for that time interval (i.e., $\overline{D}_{1,2,3} = \boldsymbol{NULL}$) and consequently precipitation will not be determined for that 5-minue interval and the $unstableQF$ will be set according to Eq. (18).

A single precipitation depth is determined at a given time interval using the three 1-minute depth averages ($\overline{D}_1$,$\overline{D}_2$, $\overline{D}_3$), which are obtained from the strain gauge frequencies (f_1,f_2, f_3). Here we use a modified version of USCRN's precipitation algorithm (Leeper et al. 2015) to determine bulk precipitation at 5-minute intervals. Bulk precipitation is determined on a rolling 1-hour window and incorporates 2-hours of previous depth measurements. The algorithm determines the depth change between strain gauge depth measurements and then weights each strain gauge based on its noise characteristics over the three hour period. Thus, three hours of depth measurements (i.e., a maximum of 36 per strain gauge) are needed to calculate bulk precipitation for the most recent hour. The most recent hour contains the depths to be processed, while the first 2-hours of depth data are used to in calculating sensor noise.

Once the strain gauge frequencies are converted to depth and 1-minute depth averages at 5-minute intervals are determined according to Eq. (3), the change in depth between 5-minute intervals is determined according to Eq. (4). If depth data is missing for two or more strain gauges from the preceding time stamp then the depth from two intervals back will be used in Eq. (4) (i.e., $D_{k,i-2}$ will be used in place of $D_{k,i-1}$). If $D_{k,i-2}$ is missing for two or more strain gauges as well, then precipitation will not be determined for that interval (i.e., precipitation set to ***NULL***) and the priorDeltaQF will be set according to Eq. (19).

$$deltaD_{k,i} = \overline{D}_{k,i} - \overline{D}_{k,i-1} \tag{4}$$

Where:

$deltaD$	= Depth change between 5-minute depth measurements for a given strain gauge (mm)
$\overline{D}$	= 1-minute average of precipitation depth for each strain gauge at 5-minute intervals (mm)
k	= 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i	= Running index

Next the wire weights are determined as the inverse delta variance accordingly;

$$deltaVarD_k = \frac{n-1}{\sum_{i=1}^{n}(deltaD_{k,i} - \overline{deltaD_k})^2} \tag{5}$$

Where:

$deltaVarD$	= Inverse delta variance for an individual strain gauge
$\overline{deltaD}$	= Average depth change for an individual strain gauge over a 3 hour period
$deltaD$	= Depth change between 5-minute depth measurements (mm)
k	= 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
n	= Sample size of depth measurements for an individual strain gauge over a 3-hour window. Nominal size is 36 for 5-minute averages
i	= Running index

Next we check to see if any of the depths for a given strain gauge were unreasonably low (i.e., < -10) over the three hour period, which may indicate a broken wire according to the USCRN and $lowDepthQF$ will be set according to Eq. (20). Strain gauges that are unreasonably low will be excluded from further calculations through the following logic,

$$deltaVarD_k = \left| \begin{array}{l} 0 \;\; if \;\; any(\overline{D}_{k,i}) < \text{lowRange} \\ \\ deltaVarD_k \;\; otherwise \end{array} \right. \tag{6}$$

Where:

lowRange = -10 the threshold for an unreasonably low strain gauge value

Thus, for a given strain gauge, if any of the recorded depths over the 3-hour period are less than -10 then the delta variance is set to zero, which excludes that strain gauge from any subsequent calculations.

USCRN uses the following logic to exclude a strain gauge's measurements if the absolute value of any of its calculated deltas is too extreme over the current hour being processed (i.e., 12 deltas if all of the measurements were captured) and $exDeltaQF$ will be set according to Eq. (21). Large deltas may exist for a variety of reasons (e.g., broken wires, gauge emptying, wind pumping, etc.).

$$deltaVarD_k = \begin{cases} 0 \ \ if\ over\ the\ past\ hour\ any\left(\left|deltaD_{k,i}\right|\right) > \text{highRange} \\ deltaVarD_k \ \ otherwise \end{cases} \quad (7)$$

Where:

highRange = 25 the threshold for an unreasonably large delta between strain gauge measurements

t = represents the index for the deltaD measurements over current hour of measurements being processed

Next if data from two or more strain gauges is missing then precipitation will not be calculated and $missingWireInfoQF$ will be set according to Eq. (22). This is determined as follows,

$$missingData_k = \begin{cases} 1 \ \ if\ \ deltaVarD_k = 0 \\ 0\ otherwise \end{cases} \quad (8)$$

$$deltaVarD_k = \begin{cases} \boldsymbol{NULL} \ \ if\ \ \sum_{k=1}^{3} missingData_k \geq 2 \\ deltaVarD_k \ \ otherwise \end{cases} \quad (9)$$

Following these checks we determine the final strain gauge weights by scaling them to 1 accordingly,

$$SGWeight_k = \frac{deltaVarD_k}{\sum_{i=1}^{3} deltaVarD_i} \quad (10)$$

Where:

$SGWeight$ = final weight for a given strain gauge
$deltaVarD$ = Inverse delta variance for an individual strain gauge
k = 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i = Running index

The weighted 5-minute bulk precipitation for the last hour of data can then be computed as follows,

$$depth_i = \sum_{k=1}^{3} (SGWeight_k * deltaD_{k,i}) \quad (11)$$

Where:

$depth$ = Precipitation depth over a 5-minute interval (mm)
$SGWeight$ = final weight for a given strain gauge
$deltaD$ = Depth change between 5-minute depth measurements (mm)
k = 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i = Running index over the last hour of collected precipitation data (maximum number of points = 12)

Next we adopt a couple of USCRN tests that assess the validity of the measurements. First we assess the maximum difference in depth change among the strain gauges. If the difference in the depth change among the strain gauge measurements is too large, precipitation for that time interval is set to 0 and $gaugeNoiseQF$ is set according to Eq. (23). Otherwise the calculated precipitation is carried through.

$$depth_i = \left| \begin{array}{l} 0 \;\; if \;\; \max(deltaD_{k,i}) - \min(deltaD_{k,i}) > deltaThreshold \\ \\ Result\ from\ Eq.(11)\ otherwise \end{array} \right. \quad (12)$$

Where:

$deltaD$ = Result from Eq. (4)
k = 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i = Running index over the last hour of collected precipitation data (maximum number of points = 12)
$deltaThreshold$ = 0.5

Next we assess whether any of the depth changes were less than zero for a given strain gauge. If any of the differences between subsequent measurements for any of the strain gauges was less than zero, precipitation is set to zero for that observation and $wireNoiseQF$ is set according to Eq. (24). Otherwise the calculated precipitation is carried through.

$$depth_i = \begin{cases} 0 \ \ if \ \ \text{any}(deltaD_{k,i}) < 0 \\ Result\ from\ Eq.(11)\ otherwise \end{cases} \tag{13}$$

Where:

$deltaD_{k,i}$ = Result from Eq. (4)

The depth results from Eq. (13) must then be rounded to the hundredth decimal place, with values ≥ 5 rounded up. Next, the detection limit of the sensor is assessed. Assessments from CVAL show that the current rain gauge has a repeatability and accuracy of 0.02 mm. Therefore, depth changes between measurement intervals less than this cannot be resolved, and after precipitation depths are rounded the depths result from Eq. (13) are treated as follows;

$$depthFive_i = \begin{cases} 0\ if\ roundedDepth_i < dectectionLimitThreshold \\ roundedDepth_i\ otherwise \end{cases} \tag{14}$$

Where:

$depthFive$ = Final precipitation depth for a five-minute interval (mm)
$roundedDepth_i$ = Depth from Eq. (13) rounded using rules above (mm)
$dectectionLimitThreshold$ = 0.02 (mm) i.e., detection limit of the sensor between subsequent measurements
i = Running index over the last hour of collected precipitation data (maximum number of points = 12)

Note: In the event that a different sensor is used and/or the detection limit changes this threshold will need to be revised.

Lastly we check to ensure that the gauge was not overflowing during the measurement interval and $overflowQF$ is set according to Eq. (25),

$$depthFive_i = \begin{cases} \boldsymbol{NULL}\ \ if\ any(\overline{D}_{k,i}) \geq maxDepth \\ Result\ from\ Eq.(14)\ otherwise \end{cases} \tag{15}$$

Where:

$depthFive$	= Final precipitation depth for a five-minute interval (mm)
$maxDepth$	= 1100 (mm)
$\overline{D}$	= 1-minute depth average for each strain gauge (mm)
k	= 1, 2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
i	= Running index over the last hour of collected precipitation data (maximum number of points = 12)

Bulk precipitation for the two 30-minute intervals over the last hour is then determined accordingly,

$$depthThirty = \sum_{i=1}^{n} depthFive_i \tag{16}$$

Where:

$depthThirty$	= Final precipitation depth over a 30-minute interval (mm)
$depthFive$	= Precipitation depth over a 5-minute interval taken during the 30-minute interval (mm)
i	= Running index over the 30-minute interval
n	= Total number of 5-minute depths in a 30-minute- interval (maximum of 6)

5 ALGORITHM IMPLEMENTATION

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

1. One-minute depth averages will be determined at 5-minute intervals according to Eq. (1)-(3).
2. Bulk precipitation will be determined at 5- and 30-minute intervals according to Eq. (4)-(16).
3. Number of points used to compute the 30-minute bulk precipitation value shall be determined. Nominally, 6 5-minute bulk precipitation values shall be used to create the 30-minute value.
4. QA/QC tests will be applied to the data stream according to the QA/QC Procedure section below andin accordance with AD[06].
5. Quality flags will be produced for 5-minute precipitation values according to AD[15].

QA/QC Procedure:

1. **Plausibility Tests** AD[06] – Initially only the null test will be run for primary precipitation. However, additional plausibility analyses may be explored in the future. As stated in section 4.2, in the event that stability information is missing for the current time stamp, precipitation will not be determined for that interval and the null quality flag shall be set to 1 for the 5-minute bulk precipitation value. Alternatively, the null 30-minute null quality flag will be set to 1 in the event that no 5-minute bulk precipitation values exist over the 30-minute interval.

2. **Sensor Specific Tests**

i. unstableQF – The unstable quality flag indicates when precipitation could not be calculated for a time period because two or more of the strain gauge measurements were unstable during the measurement period.

$$unstable_k = \begin{cases} 1 \;\; if \;\; result\ from\ Eq.(3) = \text{NULL} \\ 0 \; otherwise \end{cases} \tag{17}$$

$$unstableQF = \begin{cases} 1 \;\; if \;\; \sum_{k=1}^{3} unstable_k \geq 2 \\ 0 \;\; otherwise \end{cases} \tag{18}$$

ii. priorDepthQF – The prior depth quality flag indicates when precipitation could not be calculated for a time period because the two previous depth measurements were missing for two or more of the strain gauges.

$$priorDepthQF = \begin{vmatrix} 1\ when\ Eq.(4)\ can\ not\ be\ computed\ for > 2\ straingauges \\ \\ 0\ \ otherwise \end{vmatrix} \tag{19}$$

iii. lowDepthQF – The low depth quality flag indicates when precipitation could not be calculated for one or more of the strain gauges because the depth measurement was unreasonably low (i.e., < -10), which may indicate a broken strain gauge.

$$lowDepthQF = \begin{vmatrix} 1\ when\ if\ statement\ of\ Eq.(6) = TRUE \\ \\ 0\ \ otherwise \end{vmatrix} \tag{20}$$

iv. exDeltaQF – The extreme delta quality flag indicates when precipitation could not be calculated for one or more of the strain gauges because the difference between the current and previous depth measurements for a given strain gauge was too extreme large. This is an indication of an erroneous measurement that may arise for a number of reasons, e.g., broken wire, gauge emptying, and wind pumping.

$$exDeltaQF = \begin{vmatrix} 1\ when\ if\ statement\ of\ Eq.(7) = TRUE \\ \\ 0\ \ otherwise \end{vmatrix} \tag{21}$$

v. missingWireInfoQF – The missing wire information flag indicates when precipitation could not be calculated for a time period because two or more of the strain gauges had invalid measurements.

$$missingWireInfoQF = \begin{vmatrix} 1\ when\ if\ statement\ of\ Eq.(9) = TRUE \\ \\ 0\ \ otherwise \end{vmatrix} \tag{22}$$

vi. gaugeNoiseQF – The gauge noise quality flag indicates when precipitation was set to zero for a time period because the difference among the individual strain gauge measurements was too large for the given time interval.

$$gaugeNoiseQF = \begin{cases} 1 \; when \; if \; statement \; of \; Eq.(12) = TRUE \\ 0 \; otherwise \end{cases} \quad (23)$$

vii. wireNoiseQF – The wire noise quality flag indicates when precipitation was set to zero for a time period because one or more of the strain gauges depth change was negative over the time interval.

$$wireNoiseQF = \begin{cases} 1 \; when \; if \; statement \; of \; Eq.(13) = TRUE \\ 0 \; otherwise \end{cases} \quad (24)$$

viii. overflowQF – The overflow quality flag indicates when precipitation could not be calculated (i.e., set to *NULL*) for a time period because the gauge was overflowing.

$$overflowQF = \begin{cases} 1 \; when \; if \; statement \; of \; Eq.(15) = TRUE \\ 0 \; otherwise \end{cases} \quad (25)$$

ix. heaterErrorQF – The heater error quality flag indicates whether a heating error occurred during five-minute bulk precipitation. This is realized by comparing the inlet temperature (where the heaters are located) to the internal sensor temperature (assumed to represent ambient temperatures) when conditions exist that should result in heater operation. If the inlet temperature is less than the internal temperature then the heaterErrorQF shall be set high. Additionally, if the heater status at the five minute mark indicates heaters are enabled but the temperature is above the heater set point then the heaterErrorQF shall be set to 1. See **Figure 1** for details.

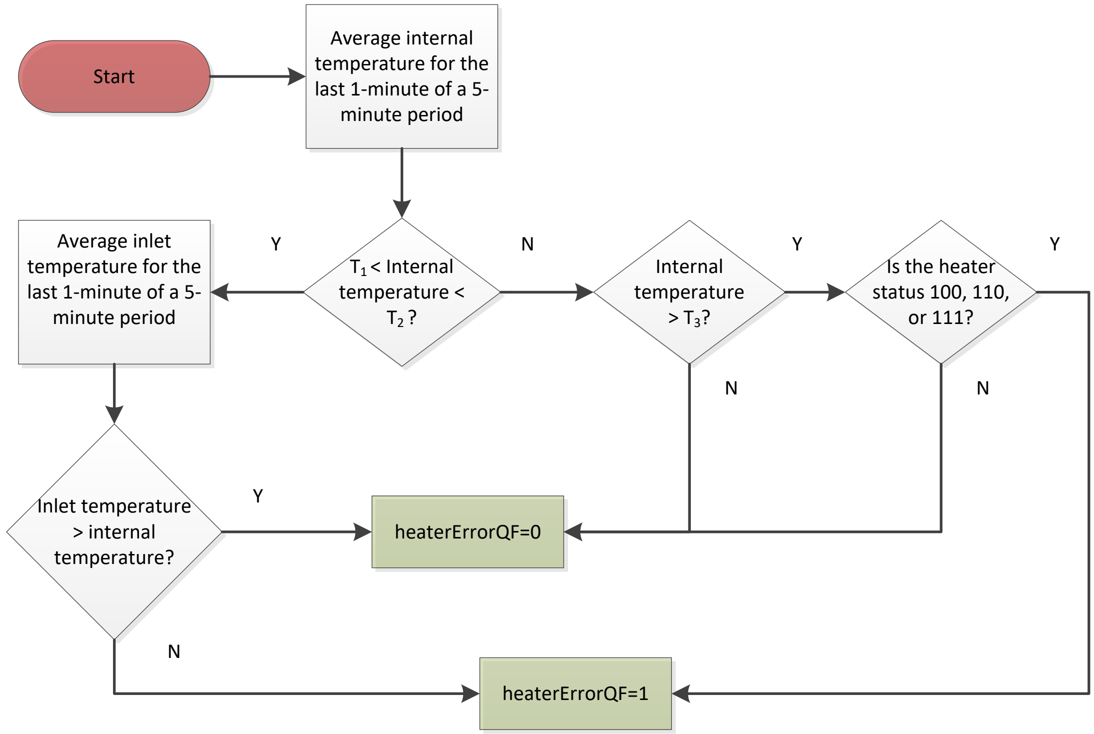

Figure 1. Heater error flag logic, temperature thresholds of T_1 = -6 °C, T_2 = 2 °C, and T_3 = 6 °C.

3. **Ancillary Sensor Information –** The orifice heater flag (i.e., orificeHeaterFlag) will be summarized as QMs over the entire 5-minute and 30-minute intervals for a L1 DP. Alternatively, strain gauge stability flag (strainGaugeStability) will be summarized as QMs over the one minute averaging period (Eq. (3)) and included only with the 5-minute L1 DP. This ancillary information along with the quality flags are shown below in Table 5 and will be included in the quality summary.

4. **Signal De-spiking** – Currently, there is no plan to run signal de-spiking and time series analysis for primary precipitation L1 Dps. However, signal de-spiking and time series analysis may be explored in the future.

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

6. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[15] – QFs listed in Table 5-1 will accompany each 5-minute precipitation L1 DP. While, QFs listed in Table 5-2 will accompany each 30-minute precipitation L1 DP. Quality metrics will only be determined for the ancillary sensor information as discussed in bullet 3 above. The stability L0 DPs results will be converted into quality metrics for each state (i.e., stable= 1, unstable = 0, and sensor failure = -1) for each of the three strain gauges over the 1-minute averaging period that was used in Eq. (3) and be output only with 5-

minute bulk precipitation values. An additional QM per strain gauge will be created to represent the percent of measurements that were missing (i.e., NA). Thus, in total there will be twelve stability QMs created, i.e., four per strain gauge, e.g., for strain gauge 1, wire1StabilityPassQM, wire1StabilitySearchQM, wire1StabilityFailQM, and wire1StabilityNAQM. Alternatively, inlet heater quality metrics will summarize the inletHeaterQF over the entire 5-minute and 30-minute intervals. There are three inlet heater quality metrics that correspond to the number of heaters that were operational during that period and a forth that corresponds to the percent of measurements that had no heater information (i.e., missing). Accordingly, inletHeaters1QM corresponds to the percent of inletHeaterQF=100, inletHeaters2QM to the percent of inletHeaterQF=110, inletHeaters3QM to the percent of inletHeaterQF=111 over the measurement period, and inletHeaterNAQM is the percent of missing heater data over the measurement period.

The final quality flag will be determined according to Eq. (26) for 5-minute precipitation values. Similarly, the final quality flag for a 30-minute precipitation DP will be set to 1 if any of the corresponding 5-minute precipitation DPs had a final quality flag of 1.

$$finalQF = \left| \begin{array}{l} 1\ if\ any(QF^{*}\ in\ Table\ 5-1 = 1) \\ \\ 0\ otherwise \end{array} \right. \qquad (26)$$

The WireNoiseQF is not included in the calculation of the finalQF because initial analyses revealed it was frequently triggered due to sensor noise in the absence of precipitation events.

Table 2. Quality metrics/flags associated with primary precipitation measurements for 5-minute bulk precipitation.

Quality Metric (QM)/ Quality Flag (QF)
wire1StabilityPassQM
wire1StabilitySearchQM
wire1StabilityFailQM
wire1StabilityNAQM
wire2StabilityPassQM
wire2StabilitySearchQM
wire2StabilityFailQM
wire2StabilityNAQM
wire3StabilityPassQM
wire3StabilitySearchQM
wire3StabilityFailQM
wire3StabilityNAQM
inletHeaters1QM

inletHeaters2QM
inletHeaters3QM
inletHeatersNAQM
priorDepthQF*
unstableQF *
lowDepthQF*
exDeltaQF*
missingWireInfoQF*
gaugeNoiseQF*
wireNoiseQF
overflowQF*
heaterErrorQF*
nullQF*
finalQF

Table 3. Quality metrics/flags associated with primary precipitation measurements for 30-minute bulk precipitation.

Quality Metric (QM)/ Quality Flag (QF)
inletHeaters1QM
inletHeaters2QM
inletHeaters3QM
inletHeatersNAQM
nullQF
finalQF

Table 4. Information maintained in the CI data store for the primary precipitation.

Tests/Values	CI Data Store Contents	Type
lowRange	-10	Constant
highRange	25	Constant
deltaThreshold	0.5	Constant
detectionLimitThreshold	0.02	Constant
maxDepth	1100	Threshold
T_1	-6	Threshold
T_2	2	Threshold
T_3	6	Threshold

6 UNCERTAINTY

Uncertainty of measurement is inevitable; therefore, measurements should be accompanied by a statement of their uncertainty for completeness (JCGM 2008; Taylor 1997). To do so, it is imperative to identify all sources of measurement uncertainty related to the quantity being measured. Quantifying the uncertainty of TIS measurements will provide a measure of the reliability and applicability of individual measurements and TIS data products. This portion of the document serves to identify, evaluate, and quantify sources of uncertainty relating to individual, calibrated primary precipitation measurements as well as L1 bulk primary precipitation data products. It is a reflection of the information described in AD[13], and is explicitly described for the primary precipitation assembly in the following sections.

6.1 Uncertainty of Precipitation Measurements (using the DFIR)

Uncertainty of the DFIR assembly is discussed in this section. Sources of identifiable uncertainties include those arising from the sensor, calibration procedure, evaporation, wind, wetting, and representativeness (Nemec 1969; Humphrey *et al.* 1997; Brock and Richardson 2001; WMO 2008). The DFIR setup (i.e., NEON's primary precipitation assembly) provides more accurate precipitation than other measurement techniques such as a tipping bucket (Rasmussen 2012). All types of identified uncertainties are detailed in the following sections. It is important to note that precipitation uncertainties provided by NEON assume the occurrence of precipitation. In other words, precipitation uncertainty estimates are null when precipitation is not occurring.

6.1.1 Measurement Uncertainty

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

NEON calculates measurement uncertainties according to recommendations of the Joint Committee for Guides in Metrology (JCGM) 2008. In essence, if a measurand *y* is a function of *n* input quantities $x_i\ (i = 1, \ldots, n),\ i.e., y = f(x_1, x_2, \ldots, x_n)$, the combined measurement uncertainty of *y*, assuming the inputs are independent, can be calculated as follows:

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \right)^{\frac{1}{2}} \quad (27)$$

where

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

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

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

6.1.1.1 Calibration

An individual (bulk), primary precipitation measurement is a combination of three, calibrated strain gauge measurements. NEON's CVAL applies unique calibration coefficients to each strain gauge (Eq. (2) but provides a measurement uncertainty estimate that collectively accounts for all three gauges. In other words, the estimate represents an individual depth reading (Eq. (11), with the assumption that all three gauges are stable and equally weighted (RD[16]). The measurement uncertainty is a relative value that will be provided by CVAL (AD[12]), stored in the CI data store, and applied to a bulk precipitation measurement.

$$u(depth_i) = u_{A1} * \ depth_i \qquad (28)$$

Where,

u_{A1} = relative uncertainty of bulk precipitation measurement (%)
$u(depth_i)$ = standard uncertainty of bulk precipitation measurement (mm)

6.1.1.2 DAS

The weighing gauge quantifies precipitation in units of Hz captured through the serial port of the DAS. Because of this, the signal, although analog, can be treated as a digital signal and uncertainties introduced by the DAS can be considered negligible.

6.1.1.3 Evaporative Losses

Use of heaters can cause a weighing gauge's inlet to be warmer than the ambient environment thus causing a chimney effect (Rasmussen 2012). If this occurs for prolonged periods before or during precipitation events, evaporative losses can occur, amplifying measurement uncertainty (Brock and Richardson 2001; WMO 2008).

Although beneficial, use of the heaters can cause precipitation loss due to evaporation (Brock and Richardson 2001). At current time we cannot confidently quantify the extent of this uncertainty. However, the inlet temperature of the precipitation gauge will be monitored, and as NEON's primary precipitation data are analyzed, measurement uncertainty introduced by evaporative losses will hopefully be quantified.

6.1.1.4 Wind

The measurement of precipitation is particularly sensitive to wind (WMO 2008). Laminar and turbulent flows can result in a reduction of catch at the inlets of precipitation gauges, thus resulting in underestimations of precipitation measurements. Brock and Richardson (2001) note that catch reductions can be up to 20% with winds ranging from 5 to 10 m s^{-1} and nearly 80% for winds >10 m s^{-1} during light rainfall and most snowfall events. Wind speeds near the weighing gauge can be reduced and catch reduction can be mitigated by shielding the precipitation gauge with shields such as fencing (WMO 2008). Such is the case for the NEON's primary precipitation assembly, which comprises an alter shield, and two fences around the weighing gauge. As NEON precipitation data are collected and analyzed, wind induced uncertainties may become quantifiable through the aid of co-located, in-situ wind measurements.

6.1.1.5 Wetting

Wetting is a term used to describe a buildup of precipitation at the inlet of a precipitation sensor (Groisman and Legates 1994). In most cases such precipitation would evaporate before falling *into* the weighing gauge and would not be quantified, thus causing an underestimation of precipitation due to *wetting loss.* Such losses are small (Sevruk 1982), and given the magnitude of other uncertainties (i.e., wind induced), we are considering wetting losses to be negligible.

6.1.1.6 Representativeness

It is argued that any type of precipitation gauge is unrepresentative of precipitation over large areas – caution should be executed when spatially interpolating and extrapolating precipitation measurements. It is considered poor sampling when one precipitation gauge is used to represent precipitation characteristics of a larger surrounding area (e.g., 200 km^2); this is especially true during thunderstorms (Rinehart 2004; WMO 2008). Passing of a localized rainstorm can grossly overestimate (if directly over the gauge) or underestimate (if storm misses gauge completely) precipitation characteristics for a mesoscale sized region (Brock and Richardson 2001). With the aid of radar imagery, representativeness can be better understood.

6.1.1.7 Combined Measurement Uncertainty

The only quantifiable uncertainty for precipitation is that provided by CVAL. Because of this, the combined uncertainty is simply equal to $u(depth_i)$.

The measurement uncertainty estimate of bulk precipitation is only applicable to bulk precipitation measurements where all three strain gauges were used to calculate bulk precipitation. For instances where only two gauges were used, the end-user should be aware that the provided uncertainty estimate may be an underestimate when the following flags are present: lowDepthQF, exDeltaQF, and wireNoiseQF.

6.1.1.8 Expanded Measurement Uncertainty

The expanded uncertainty is calculated as:

$$U_{95}(depth_i) = k_{95} * u(depth_i) \quad (29)$$

Where:

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

6.1.2 Uncertainty of Bulk Precipitation

The following subsections discuss uncertainties associated with temporally aggregated, L1, bulk precipitation data products. As stated previously, it is important to note that precipitation uncertainties provided by NEON assume the occurrence of precipitation.

6.1.2.1 Combined Uncertainty

A relative uncertainty value, u_{A1}, will be provided by CVAL (AD[12]), and stored in the CI data store. It will be converted to units of *mm* to provide a standard, combined uncertainty value for bulk precipitation:

$$u(depth) = u_{A1} * \sum_{i=1}^{n} depth_i \quad (30)$$

Where,

u_{A1} = relative uncertainty of individual tip (%)

Note:
The combined uncertainty estimate of the five-minute bulk precipitation estimate will equal that of the combined *measurement* uncertainty, i.e., there is no summation of bulk precipitation measurements. Because the thirty-minute bulk precipitation data product is a function of multiple five-minute bulk precipitation measurements, the uncertainties of each five-minute bulk precipitation measurements are additive (Eq. (30)).

6.1.2.2 Expanded Uncertainty

The expanded uncertainty is calculated as:

$$U_{95}(depth) = k_{95} * u(depth) \quad (31)$$

Where:

$U_{95}(depth)$ = expanded uncertainty at 95% confidence (mm)
k_{95} = 2; coverage factor for 95% confidence (unitless)

6.1.2.3 Communicated Precision

The repeatability of the weighing gauge is significant to a thousandth of a mm. As such, the communicated precision of L1, bulk, primary precipitation data will be 0.001 mm.

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. 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 5. Uncertainty budget for individual precipitation measurements.

Source of measurement uncertainty	**measurement uncertainty component** $u(x_i)$	**measurement uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\|\frac{\partial f}{\partial x_i}\right\| u(x_i)$ **(mm)**
Precipitation measurement	$u(depth_i)$	Eq. (28)	n/a	n/a

Table 6. Uncertainty budget for bulk precipitation measurements.

Source of uncertainty	**uncertainty component** $u(x_i)$	**uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\|\frac{\partial f}{\partial x_i}\right\| u(x_i)$ **(mm)**
Bulk precipitation	$u(depth)$	Eq. (30)	n/a	n/a

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream. Additionally, hydraulic oil and at some sites antifreeze will be added to the gauges, which may cause biases in the measurements. Quantifying these biases and accounting for them in the algorithm may be explored in the future.

The frequency of the strain gauge is not just a function of weight exerted upon it, but also temperature. This is due to the physical characteristics of metal and how they will change over temperature (Lamb, H. H. and J. Swenson, 2005). Thus, to account for this temperature dependence Eq. (2) can be modified to Eq. (32). However, this temperature bias is very small, accounting for drift that is 0.001% of full scale per °C (Bakkehøi, S. et al., 1985). Since, Eq. (2) is the generally accepted form for determining depth from frequency it will initially be used to determine the depth from frequency. However, this temperature bias and the use of Eq. (32) may be explored in the future if temperature is found to have notable effect the strain gauge measurements.

$$D_{k,i} = A_k\left(f_{D_{k,i}} - f_{0\,n}\right) + B_k(f_{D_{k,i}} - f_{0\,k})^2 * \left(1 - C(T_0 - T_A)\right) \quad (32)$$

Where:

$D_{k,i}$ = Individual precipitation depth for each strain gauge (mm)
i = Running index
k = 1,2, or 3 (i.e., the number of strain gauges in the precipitation sensor)
A_k = Strain gauge specific calibration coefficient provided by CVAL (mm*sec)
B_k = Strain gauge specific calibration coefficient provided by CVAL (mm*sec^2)
$f_{D_{k,i}}$ = 1-minute average of strain gauge frequency (Hz)
$f_{0\,k}$ = Frequency with an empty collector at calibration, strain gauge specific (Hz)
C = Coefficient of linear expansion for the stain gauge wire (mm/°C)
T_0 = Temperature at calibration (°C)
T_A = Internal temperature of the collector at the time of observation (°C)

8 BIBLIOGRAPHY

Baker, C. B., Buckner, R., Collins, W., and M. Phillips. (2005) Calculation of USCRN precipitation from Geonor weighing precipitation gauge. NOAA Tech. Note NCDC No. USCRN-05-1. [Online]. Available: http://www1.ncdc.noaa.gov/pub/data/uscrn/documentation/program/technotes/TN05001GeonorAlgorithm.pdf [December, 2013].

Bakkehøi, S., Øien, K., and E.J. Førland. (1985) An automatic precipitation gauge based on vibrating-wire strain gauges. Nordic Hydrology. **16**, 193-202, DOI: 10.2166/nh.1985.015.

Belfort. (2014) Universal all environment precipitation gauge model APEG II 1200 instruction manual MK III. Belfort instrument Company. pp. 55, Manual Number 90008-3

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

Campbell Scientific. (2011) Geonor T-200B series precipitation gauge. Rev. 10.7 [Online]. Available: http://s.campbellsci.com/documents/ca/manuals/geonort-200b_man.pdf [December, 2013].

Collins, W. G., Baker, C. B., and T. Wilson. (2005) The new precipitation algorithm for the three-wire Geonor gauge of the U.S. climate reference network – objectives, description and performance. AMS 13th Symposium on Meteorological Observations and Instrumentation. [Online]. Available: https://ams.confex.com/ams/pdfpapers/93695.pdf [December, 2013].

CRN. (2002) Climate reference network site information handbook. NOAA/NESDIS CRN Series X030. [Online]. Available: http://www1.ncdc.noaa.gov/pub/data/uscrn/documentation/program/X030FullDocumentD0.pdf [December, 2013].

Groisman, P. Y., and Legates, D. R. (1994). The accuracy of United States precipitation data. Bulletin of the American Meteorological Society., **75**, 215-227.

Humphrey M. D., Istok J. D., Lee J. Y., Hevesi J. A., and Flint A. L. (1997) A new method for automated

dynamic calibration of tipping-bucket rain gauges. *J. Atmos. Ocean Tech.*, **14**, 1513 - 1519

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

Joint Committee for Guides in Metrology. (2012) International vocabulary of metrology – Basic and general concepts and associated terms (VIM). 3rd Edition. pp. 92

Lamb, H. H. and J. Swenson. (2005) Measurement errors using a Geonor weighing gauge with a Campbell Scientific datalogger. AMS 16th Conference on Climate Variability and Change. [Online]. Available: https://ams.confex.com/ams/Annual2005/techprogram/paper_84196.htm [December, 2013].

Leeper, R.D., Palecki, M.A., and E. Davis. (2015) Methods to calculate precipitation from weighing-bucket gauges with redundant depth measurements. American Meteorological Society. **32**, 1179-1190, DOI: 10.1175/JTECH-D-14-00185.1.

Rasmussen, R., Baker, B., Kochendorfer, J., Meyers, T., Landolt, S., Fischer, A.P., Black, J., Theriault, J.M., Kucera, P., Gochis, D., Smith, C., Nitu, R., Hall, M., Ikeda, K., and E. Gutmann. 2012. How well are we measuring snow? The NOAA/FAA/NCAR winter precipitation test bed. Bull. Amer. Meteor. Soc., **93**, 811-829, DOI: 10.1175/BAMS-D-11-00052.1.

Sevruk, B. (1982) Methods of correction for systematic error in point precipitation measurement for operational use. Operational Hydrology Report 21. World Meteorological Organization. pp. 91.

World Meteorological Organization (WMO) (2008) Guide to meteorological instruments and methods of observations: Chapter 6 - Measurement of precipitation. pp. 23