NEON ALGORITHM THEORETICAL BASIS DOCUMENT (ATBD): SECONDARY PRECIPITATION AND THROUGHFALL (TIPPING BUCKET)

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Change Record

REVISION	DATE	ECO #	DESCRIPTION OF CHANGE
A	06/30/2015	ECO-03108	Initial Release
B	04/27/2018	ECO-05554	Merged throughfall ATBD with secondary precipitation ATBD (this ATBD). Updated document to reflect L1 data product renumbering. Revised *Algorithm Implementation* and *Uncertainty* Sections. Implemented standardized coverage factor of k=2. Moved consistency analyses outline to Future Plans / Modifications Sections. Added information on throughfall position and trough design.
C	04/20/2022	ECO-06809	• Update to reflect change in terminology from relocatable to gradient sites • Revised logo • Added Neon to document title

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1 DESCRIPTION

Contained in this document are details concerning temperature measurements made at all NEON sites. Specifically, the processes necessary to convert "raw" sensor measurements into meaningful scientific units and their associated uncertainties are described.

Across NEON sites two methods will be used to determine bulk precipitation, a double fence inter-comparison reference (DFIR) and a tipping bucket. Core tower sites will use a weighing gauge sensor with a DFIR to determine bulk precipitation, while gradient sites will use a tipping bucket. Precipitation will be measured at core and gradient aquatic sites that are either more than 10km from the tower site or in a different watershed. Core aquatic sites will use a DFIR at sites that support it; otherwise a tipping bucket will be used to measure bulk precipitation. Bulk precipitation measured using a DFIR is known to provide improved results over a tipping bucket. Thus, the DFIR will be considered the "primary" method, while the tipping bucket will be considered the "secondary" method.

NEON will also capture throughfall measurements (i.e., precipitation measurements made by troughs and tipping buckets that are located below canopy) at all sites, except short-stature ecosystems (e.g. grasslands). Both the throughfall collectors and secondary precipitation collectors utilize tipping buckets to quantify the precipitation; however there are a few distinct differences between the two methods. Throughfall collectors are unheated and include collection troughs (and thus a larger collection area), and are located below canopy, while the secondary precipitation collectors do not utilize troughs and are located above canopy.

1.1 Purpose

This document provides the details for secondary precipitation and throughfall measurements. Specifically, this document details the algorithms used for creating NEON L1 DP from L0 DP, and ancillary data as defined in this document (such as calibration data), obtained via instrumental measurements made by Met One 372 (non-heated; NEON P/N: 0308070001) and 379 (heated; NEON P/N: 0308070003) tipping buckets. Regarding secondary precipitation measurements, domains 1, 5, 9, 10, 12, 13, 17, 18, and 19 will use the heated 379 model, while all other domains will use the non-heated 372 model. All throughfall measurements will be made by the Met One 372 (with ancillary trough attachments), regardless of domain. 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

The theoretical background and entire algorithmic process used to derive L1 DP from L0 DP for secondary precipitation and throughfall are described in this document. It is expected that the Met One 372 or 379 tipping bucket will be used to measure secondary precipitation at all gradient tower sites. It is also expected that the Met One 372 and ancillary troughs will be used to measure throughfall at all tower sites, except short-statured ecosystems. It 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.005003	NEON Scientific Data Products Catalog
AD[03]	NEON.DOC.002652	NEON Level 1, Level 2 and Level 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 De-spiking and Time Series Analyses
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.001212	L1P200 Secondary Precipitation Calibration Fixture Manual
AD[12]	NEON.DOC.000927	NEON Calibration and Sensor Uncertainty Values[1]
AD[13]	NEON.DOC.000785	TIS Level 1 Data Products Uncertainty Budget Estimation Plan
AD[14]	NEON.DOC.000751	CVAL Transfer of standard procedure
AD[15]	NEON.DOC.000746	Evaluating Uncertainty (CVAL)
AD[16]	NEON.DOC.001113	Quality Flags and Quality Metrics for TIS Data Products
AD[17]	NEON.DOC.001665	C^3 AQU Secondary Precipitation Gauge

[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

2.3 Acronyms

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

[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.

DP	Data Product
FDAS	Field Data Acquisition System
FIU	Fundamental Instrument Unit
GRAPE	Grouped Remote Analog Peripheral Equipment
Hz	Hertz
L0	Level 0
L1	Level 1
PRT	Platinum resistance thermometer
QA/QC	Quality assurance and quality control

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 Notation	Description
u_{A1}	U_CVALA1	Combined uncertainty of tipping threshold

Note:
Unless otherwise specified the term *precipitation* will be used to collectively represent secondary precipitation and throughfall throughout the remainder of the document.

3 DATA PRODUCT DESCRIPTION

3.1 Variables Reported

The secondary precipitation and throughfall related L1 DPs provided by the algorithms documented in this ATBD are displayed in the accompanying file pre_datapub_NEONDOC002878.txt.

3.2 Input Dependencies

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

Table 1. List of secondary precipitation related L0 DPs that are used to produce L1 DPs via this ATBD.

Description	Sample Frequency	Units	Data Product Number
Tip (reed closure)[1]	NA	NA	NEON.DOM.SITE.DP0.00006.001.01322.HOR.VER.000
Heater[1]	1 Hz	V	NEON.DOM.SITE.DP0.00006.001.01323.HOR.VER.000
Tip (reed closure)[2]	NA	NA	NEON.DOM.SITE.DP0.00006.001.01896.HOR.VER.000

[1]Secondary Precipitation
[2]Throughfall Precipitation

3.3 Product Instances

Secondary precipitation will be measured by tipping buckets at all gradient tower sites, a select few core tower sites, and aquatic sites that are more than 10km from a tower site or in a different watershed; this includes core aquatic sites that do not support the installation of a primary precipitation gauge. Secondary precipitation gauges will be installed at aquatic sites with the inlet at 1.52m above ground level. A metal alter-style wind screen will be used to minimize error for ground-based measurements at aquatic sites.

Throughfall will be measured at all tower sites, except short-stature ecosystems (e.g. grasslands or tundra). The throughfall collectors, i.e., tipping buckets equipped with troughs, will reside below canopy.

3.4 Temporal Resolution and Extent

The L0 DPs for precipitation will be recorded as the number of tips, which will be used to determine one- and thirty minute bulk precipitation values to form respective L1 DPs.

3.5 Spatial Resolution and Extent

The secondary precipitation gauge (i.e., tipping bucket) will be located tower top at all gradient tower sites, a select few core sites, and at 1.52m above ground level at designated aquatic sites. Its spatial resolution will reflect the point in space where the precipitation gauge is located.

The throughfall collector (i.e., tipping bucket & troughs) will be located within the sensor soil plots at NEON tower sites. Its spatial resolution will reflect the point in space where the throughfall collector is located. The sensor is positioned vertically regardless of the slope of the soil surface. On flat ground the sensor collection area is located between 37.5 and 50 cm aboveground. The horizontal distance from the tip of one trough to the tip of the opposite trough is 153 ±1.3 cm.

4 SCIENTIFIC CONTEXT

Precipitation records are fundamental to meteorological and hydrological studies. These data are often used as ancillary data for more detailed investigations. For instance, precipitation records help inform storm surge statistics and abate social, economic, and environmental losses from floods. Together, throughfall and secondary precipitation data help inform interception rates. In turn, evapotranspiration and latent heat fluxes can be better understood and climate conditions can be better modeled.

4.1 Theory of Measurement

Recording precipitation via a tipping bucket is fairly simplistic. Essentially, a collection funnel channels precipitation down to a tipping lever. On each end of the tipping lever is a small bucket that is calibrated to tip for a known volume of water and the number of times that the lever tips is recorded by a reed switch. The volume of a tip is directly related to precipitation depth based on the surface area of the collector, which allows the rate and quantity of precipitation for a given time period to be determined. The greatest difference among tipping bucket models is their housing design. Variations in housing design stem from efforts to minimize measurement uncertainties (e.g., wind errors and splash-out). Additionally, heater elements may be employed when precipitation measurements in freezing areas are desired.

Standard, Met One tipping buckets, which are used to produce the secondary precipitation data product, (models 379 and 372) have a collection area (i.e., surface area) of 324.29 cm^2 (**Figure 1**). Alternatively, the Met One 372 tipping buckets used to collect throughfall have been slightly modified to increase their collection area. Throughfall collectors are equipped with troughs that extend laterally outward from the tipping bucket (**Figure 2**). Multiple throughfall collectors are located throughout a single NEON site enabling the spatial variability of throughfall to be captured (e.g. Helvey and Patric 1965, Puckett 1991, Holwerda et al. 2006). The modified collection area needs to be taken into account in order to accurately relate a tip to a given depth, which will be discussed in more detail below.

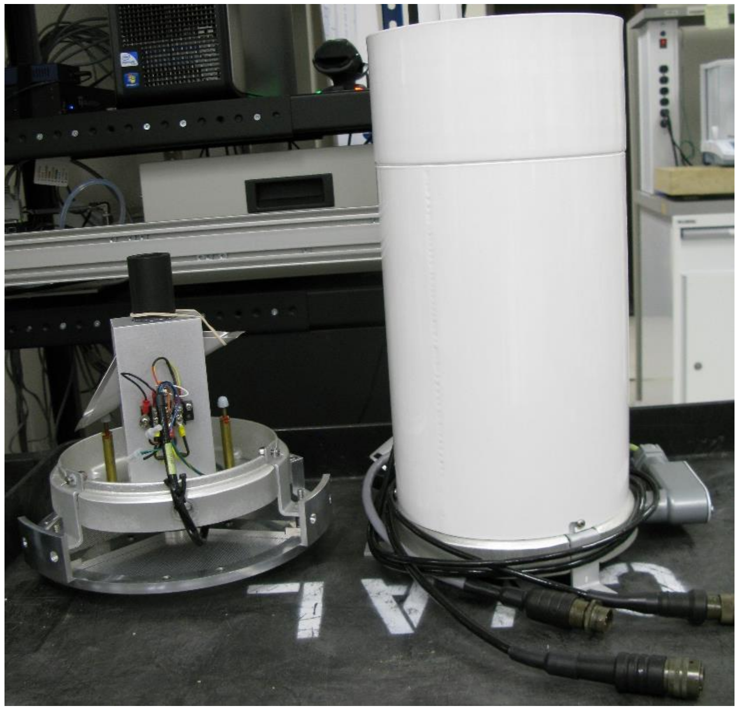

Figure 1. Image of a non-heated Met One tipping bucket sensor. The internal tipping mechanism can be seen on the left and the complete unit with shroud and funnel shown on the right.

Figure 2. Image of a modified Met One tipping bucket sensor to collect throughfall in the field.

4.2 Theory of Algorithm

L0 DPs simply represent the number of tips recorded by the tipping bucket. To quantify precipitation *recorded* by the tipping bucket, an individual tip is multiplied by the tipping threshold. The tipping threshold is based on the nominal Met One collection area of 324.29 cm^2. Thus, Eq. (1) will be used to produce the secondary precipitation data product. Alternatively, Eq. (1) needs to be slightly modified for throughfall since the troughs increase the collection area. The total exposed trough surface area (horizontal effective area) is 2514 cm^2 (± 1%) for throughfall collectors. This is based on a trough installation angle of 10^o, a width of 10 cm, a length of 63.82 cm, and 4 troughs per throughfall collector. Thus, Eq. (2) needs to be used to convert tips from the throughfall collector to depth of precipitation.

$$P_i = (T_i * T_H) \tag{1}$$

Where:

P_i = Recorded precipitation for individual tip (mm)

T_i = Individual tip; $T_i \in \{0,1\}$

T_H = Tipping threshold (sensor specific and provided by CVAL) (mm)

$$P_{T\,i} = \left(T_i * T_H * \frac{A_B}{A_T}\right) \tag{2}$$

Where:

$P_{T\,i}$ = Recorded throughfall precipitation for individual tip (mm)

T_i = Individual tip; $T_i \in \{0,1\}$

A_B = 32429, the surface area of tipping bucket (mm^2)

A_T = 251400, the surface area of throughfall collector, ± 1% (mm^2)

T_H = Tipping threshold (sensor specific and provided by CVAL) (mm)

Bulk precipitation will then be determined every one- and thirty-minutes according to Eq. (3) and (4) to create the L1 DPs listed in file pre_datapub_NEONDOC002878.txt.

$$P_{B_1} = \sum_{i=1}^{n} P_i \ or \ P_{T\,i} \tag{3}$$

where, n represents the number of tips observed, P_i is a secondary precipitation measurement and $P_{T\,i}$ is a throughfall precipitation measurement obtained during the 60-second period [0, 60), and P_{B_1} is the one-minute bulk precipitation value.

and

$$P_{B_{30}} = \sum_{i=1}^{n} P_i \ or \ P_{T\,i} \tag{4}$$

where, n represents the number of tips observed, P_i is a secondary precipitation measurement and $P_{T\,i}$ is a throughfall precipitation measurement obtained during the 1800-second period [0, 1800), and $P_{B_{30}}$ is the thirty-minute bulk precipitation value.

Note:

The beginning of the first period in a series shall be the nearest whole minute less than or equal to the first timestamp in the series. If no precipitation occurs over a time interval, the resulting L1 DP will be zero. In addition, data are only output from the sensor when the bucket tips. Therefore, under the current design it is not possible to distinguish the difference between periods of no rain and missing data. However, verification methods to test sensor functionality may be explored in the future.

5 ALGORITHM IMPLEMENTATION

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

1. One- and thirty-minute values for bulk precipitation will be calculated using Eq. (3) and (4).
2. QA/QC Plausibility tests will be applied to the data stream in accordance with AD[06], details are provided below.
3. Quality metrics, quality flags, and the final quality flag will be produced for one- and thirty-minute averages according to AD[16].

<u>**QA/QC Procedure**</u>:

1. **Plausibility Tests** AD[06] – With the exception of the Range Test, plausibility tests will not be completed for bulk precipitation. The range test will be run on the bulk precipitation outputs, i.e., the one- and thirty-minute bulk precipitation values. In addition, the one- and thirty-minute bulk precipitation DPs will have separate maximum values for the range test, which will be provided by FIU and maintained in the CI data store. The minimum for the range test will not be computed for bulk secondary precipitation.

2. **Sensor Flags** – The heated tipping buckets, Model 379, has two heaters. One heater is located at the base to prevent the buildup of ice around tipping bucket mechanism. The second heater is located under the collection funnel to melt solid precipitation and prevent the funnel from icing up. Heater flags will be applied to represent the states of the heaters. These heater flags are derived from current measurements of the heater relay that are converted into voltage using a scale factor of 4.6A/V.

$$QF\_H = \left| \begin{array}{l} 3 \;\; if \;\; H > V_3 \text{ ; Both heaters are active} \\ 2 \;\; if \;\; V_3 \geq H > V_2 \text{ ; The funnel heater is active} \\ 1 \;\; if \;\; V_2 \geq H > V_1 \text{ ; The base heater is active} \\ 0 \;\; if \;\; H \leq V_1 \text{ ; The heaters are inactive} \end{array} \right.$$

Where:

H	= Heater voltage (V)
V_1	= 0.05 Maximum voltage when the heaters are inactive (V)
V_2	= 0.06 Maximum voltage when the base heater is operational (V)
V_3	= 0.26 Maximum voltage when the funnel heater is operational (V)

3. **Signal De-spiking and Time Series Analysis** – Currently, there is no plan to run signal de-spiking and time series analysis for secondary precipitation. However, signal de-spiking and time series analysis may be explored in the future.

4. **Quality Flags (QFs) and Quality Metrics (QMs)** AD[16] – If a L1 DP has failed the ***range*** test a L1 DP will not be created and that time stamp will be flagged by the range QF. α and β QFs and QMs will not be determined for secondary precipitation and accordingly no final quality flag will be determined. The only QMs generated will be for the heater test, which are listed in the datapub_NEONDOC000816_1min.csv and datapub_NEONDOC000816_30min.csv files. Ancillary information needed for the algorithm and other information maintained in the CI data store is shown in **Table 3**.

Table 2. Flags associated with secondary precipitation measurements.

Tests
Range
Heater Flag

Table 3. Information maintained in the CI data store for the secondary precipitation.

Tests/Values	**CI Data Store Contents**
Range	Maximum value
Uncertainty	AD[12]

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 secondary precipitation measurements as well as L1 bulk secondary precipitation data products. It is a reflection of the information described in AD[13], and is explicitly described for the secondary precipitation assembly in the following sections.

6.1 Uncertainty of Precipitation Measurements (using tipping buckets)

Uncertainty of the tipping bucket assembly (including throughfall) is discussed in this section. Sources of identifiable uncertainties include those arising from the sensor, calibration procedure, and those introduced by i) heating the sensor's inlet (i.e., evaporative losses), ii) heavy precipitation events (i.e., undercatchment and splash-out), iii) wind, iv) wetting, and v) representativeness (Nemec 1969; Humphrey *et al.* 1997; Brock and Richardson 2001; WMO 2008). Nearly every type of uncertainty results in an underestimation of precipitation; however, there are specific instances when overestimations can occur. All types of identified uncertainties are detailed in the following sections.

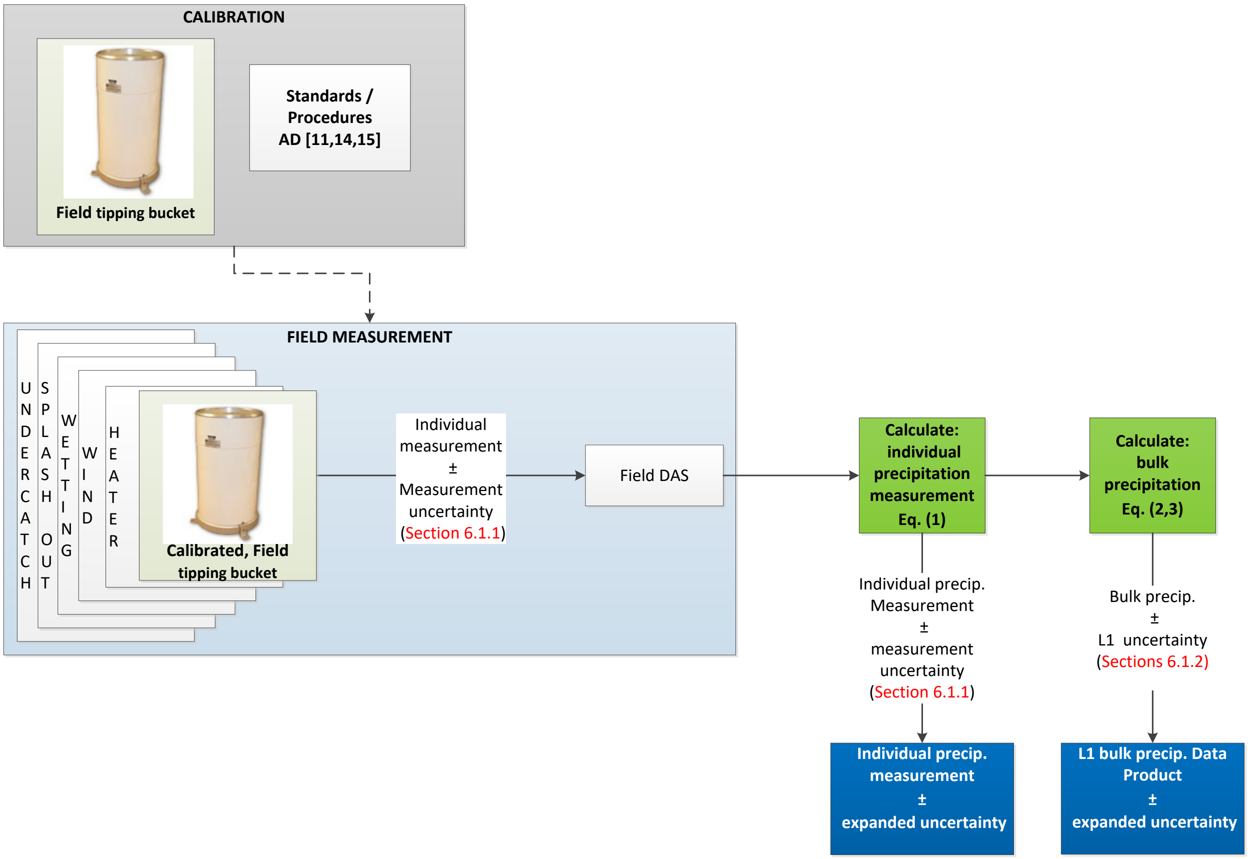

Figure 3. Displays the data flow and associated uncertainties of individual precipitation measurements and L1 bulk precipitation DPs. For more information regarding the methods by which the tipping bucket is calibrated, please refer to AD[11,14,15].

6.1.1 Measurement Uncertainty

The following subsections present the uncertainties associated with an individual bucket tip. It is important to note that, at this time, the only uncertainties NEON is able to quantify are those associated with the calibration process. Additionally, these uncertainties assume that any observed bucket tips are the result of an actual precipitation event. In other words, the uncertainty of whether or not a tip is due to natural phenomena other than precipitation is not quantified by NEON at this time.

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:

$$u_c(y) = \left(\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \right)^{\frac{1}{2}} \tag{5}$$

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 by summing the *quantifiable* input uncertainties in quadrature. The calculation of these *quantifiable* input uncertainties is discussed below.

6.1.1.1 Calibration

Uncertainties associated with tipping buckets and their calibration processes are combined into an individual, relative uncertainty u_{A1} by CVAL. This value represents i) the variation of an individual sensor from the mean of a sensor population, and ii) uncertainty of the calibration procedure. It is a relative value that will be provided by CVAL (AD[12]), stored in the CI data store, and applied to the tipping threshold as determined during calibration in CVAL.

$$u(T_H) = u_{A1} * \; T_H \tag{6}$$

Where,

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

6.1.1.2 DAS

Noise from the DAS is considered negligible because the tipping buckets quantify precipitation via reed closure and data are output in binary form.

6.1.1.3 Evaporative Losses

Exposure to direct sunlight or use of heaters (see below paragraph) can cause the sensor's funnel and buckets to be warmer than the ambient environment. If this occurs for prolonged periods before or during precipitation events evaporative losses can occur, amplifying measurement uncertainty. This is especially true at the onset of precipitation (Brock and Richardson 2001), and during *light* precipitation events (WMO 2008). Additionally, because of the relatively large tipping threshold (0.5 mm) of Met

One's 372 and 379 tipping buckets, *light* precipitation events (i.e., <0.5 mm/hr) may go completely undetected.

As mentioned in Section 1.1, Met One's heated tipping bucket (model 379) will be used at a handful of NEON's domains. Through use of the two heaters (one to heat the base, the other to heat the funnel), freezing and frozen precipitation can be melted, thus allowing quantification of precipitation when temperatures are near or below freezing. Although beneficial, use of the heaters can cause precipitation loss due to evaporation (Brock and Richardson 2001). In the attempt to quantify this uncertainty, the heaters' voltage output will be monitored. As NEON's bulk precipitation data are analyzed it is NEON's goal to quantify measurement uncertainty as a direct result of evaporative losses induced by the heater. However, at current time, we cannot confidently quantify the extent of this uncertainty.

6.1.1.4 Undercatchment (improper bucket repositioning)

Undercatchment refers to the process by which the two buckets of the gauge cannot reposition themselves fast enough to collect incoming precipitation after a single tip has occurred (Humphreys *et al.* 1997). This process is common during heavy rain events and can result in underestimations of bulk precipitation amounts by 10% to 30% for rainfall intensities > 25 mm h^{-1} (Marselek 1981; Alena *et al.* 1990). Humphreys *et al.* (1997) show that for tipping buckets with tipping thresholds of 1.0 mm, undercatchment does not become problematic until rainfall rates are > 50 mm h^{-1}. Thus it can be stated that undercatchment is a function of the tipping threshold and frequency of tips. Tipping buckets with larger tip thresholds (e.g., 0.5 to 1.0 mm) will result in fewer tips during heavy rain events than those with smaller tipping thresholds, (e.g., 0.1 to 0.2 mm). Since Met One's tipping bucket threshold is 0.5 mm, undercatchment will result in a smaller uncertainty than those sensors with small tipping thresholds. This type of uncertainty will be indirectly quantified during CVAL's calibration (see AD[11]).

6.1.1.5 Splash-out

Splash-out occurs when large raindrops hit the collection area and because of impact, fragment, causing portions of the drops to "splash-out" of the funnel or troughs; this causes an underestimation of precipitation (Brock and Richardson 2001). Proper quantification of splash-out and related uncertainty are most likely beyond the limits of measurements made throughout the NEON Observatory. For one to confidently acknowledge the presence of large raindrops, a sensor capable of measuring drop size distribution (e.g., a disdrometer) must be used. It is possible that future installation of dual polarization radars will aid in the recognition of drop size distribution (Rinehart 2004), thus making it possible to quantify potential splash-out. Until then we cannot confidently quantify the extent of splash-out and its effect on precipitation measurements made by tipping buckets.

6.1.1.6 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 tipping buckets funnel, 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 tipping bucket can be reduced and catch reduction can be partially mitigated by shielding the rain gauge with buffers such as fencing (WMO 2008). Unfortunately, NEON's tipping buckets will be located on tower-tops, rendering the use of fencing implausible. We currently cannot quantify the extent of wind related uncertainties. However, as bulk precipitation data are collected and analyzed these uncertainties may become quantifiable through the aid of wind measurements from the nearby CSAT3 anemometer and radar imagery.

6.1.1.7 Wetting

Wetting can have two different meanings depending on the precipitation measuring assembly. For all types of precipitation gauges, including weighing and tipping assemblies, *wetting* is commonly 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.

Regarding tipping bucket assemblies only, the term *wetting* is also sometimes used to describe the event when precipitation does not completely empty out of the bucket during the previous tip; this is likely the result of contaminants (e.g., hygroscopic particles) within the precipitation, and can cause overestimation of precipitation (WMO 2008). It is hypothesized that this type of wetting is more likely to occur in coastal and dessert regions, as hygroscopic particles are more prevalent in these areas. With the aid of data collected by our dust analyzers, uncertainties due to wetting may be better estimated.

6.1.1.8 Representativeness

It is argued that any type of precipitation gauge (e.g., weighing gauge, tipping bucket, optical 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 surrounding, larger 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.

The uncertainty of representativeness for throughfall measurements can be alleviated by extending collection troughs outward from the tipping buckets, and also placing multiple assemblies (i.e., tipping bucket and troughs) at various locations in micro- or meso-scale area (e.g. Helvey and Patric 1965, Puckett 1991, Holwerda et al. 2006). Both approaches are used throughout the NEON Observatory.

6.1.1.9 Combined Measurement Uncertainty

Secondary Precipitation:

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

$$u_c(P_i) = u(T_H) \tag{7}$$

Throughfall Precipitation:

The combined uncertainty for throughfall precipitation is defined in the below equations. First, the partial derivatives and partial uncertainties of those terms with quantifiable uncertainties must be derived:

$$\frac{\partial P_{T\,i}}{\partial T_H} = \frac{A_B}{A_T} \tag{8}$$

$$u_{T_H}\left(P_{T\,i}\right) = u(T_H)\left|\frac{\partial P_{T\,i}}{\partial T_H}\right| \tag{9}$$

$$\frac{\partial P_{T\,i}}{\partial A_T} = \frac{-A_B * T_H}{{A_T}^2} \tag{10}$$

$$u_{A_T}\left(P_{T\,i}\right) = u(A_T)\left|\frac{\partial P_{T\,i}}{\partial A_T}\right| \tag{11}$$

Where,

$\frac{\partial P_{T\,i}}{\partial T_H}$	= Partial derivative of individual, throughfall precipitation measurement with respect to the tipping threshold (unitless)
$u_{T_H}\left(P_{T\,i}\right)$	= Partial uncertainty of individual, throughfall precipitation measurement with as a function of the tipping threshold (mm)

$\frac{\partial P_{T\,i}}{\partial A_T}$ = Partial derivative of individual, throughfall precipitation measurement with respect to the surface area of throughfall collector ($\frac{-1}{mm}$)

$u_{A_T}(P_{T\,i})$ = Partial uncertainty of individual, throughfall precipitation measurement with as a function of the throughfall collection area (mm)

$u(A_T)$ = uncertainty of the throughfall collection area (mm); defined as:

$$u(A_T) = A_T * 0.01 \tag{12}$$

The combined uncertainty of an individual throughfall measurement is calculated as:

$$u_c(P_{T\,i}) = \left(u_{T_H}(P_{T\,i})^2 + u_{A_T}(P_{T\,i})^2\right)^{\frac{1}{2}} \tag{13}$$

6.1.1.10 Expanded Measurement Uncertainty

The expanded uncertainty is calculated as:

$$U_{95}(X_i) = k_{95} * u(X_i) \tag{14}$$

Where:

X_i = individual precipitation or throughfall measurement (mm)

$U_{95}(X_i)$ = 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, i.e., L1 bulk precipitation (secondary and throughfall) data products. As stated previously, it is important to note that at this time, the uncertainties provided by NEON for precipitation measurements assume the occurrence of an actual precipitation event.

6.1.2.1 Combined Uncertainty

A relative uncertainty value, u_{A1}, will be provided by CVAL (AD[13]), and stored in the CI data store. It will be converted to units of *mm* to provide a standard, combined uncertainty values for bulk secondary precipitation and throughfall.

Bulk secondary precipitation:

$$u_c(P_B) = u_{A1} * \sum_{i=1}^{n} P_i \tag{15}$$

Bulk throughfall precipitation:

$$u_c(P_{T\,B}) = \left(\sum_{i=1}^{n} u_c(P_{T\,i})^2\right)^{\frac{1}{2}} \tag{16}$$

6.1.2.2 Expanded Uncertainty

The expanded uncertainty is calculated as:

$$U_{95}(X_B) = k_{95} * u(X_B) \tag{17}$$

Where:

X_B	= bulk, secondary precipitation or throughfall data product (mm)
$U_{95}(X_B)$	= expanded uncertainty at 95% confidence (mm)
k_{95}	= 2; coverage factor for 95% confidence (unitless)

6.1.2.3 Communicated Precision

The tipping threshold (sensitivity) of the tipping bucket is 0.01 in (0.254 mm). As such, the communicated precision of L1, bulk, secondary precipitation and throughfall 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 4. Uncertainty budget for individual precipitation measurements.

Source of measurement uncertainty	**measurement uncertainty component $u(x_i)$**	**measurement uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ **(mm)**
Secondary precip.	$u_c(P_i)$	Eq. (7)	n/a	n/a
Throughfall precip.	$u_c(P_{T\,i})$	Eq. (13)	n/a	n/a
Calibration	$u(T_H)$	Eq. (6)	Eq. (8)	Eq. (9)
Surface Area	$u(A_T)$	Eq. (12)	Eq. (10)	Eq. (11)

Table 5. Uncertainty budget for bulk precipitation measurements.

Source of uncertainty	**uncertainty component $u(x_i)$**	**uncertainty value**	$\frac{\partial f}{\partial x_i}$	$u_{x_i}(Y) \equiv \left\lvert\frac{\partial f}{\partial x_i}\right\rvert u(x_i)$ **(mm)**
Bulk, secondary precip.	$u_c(P_B)$	Eq. (15)	n/a	n/a
Bulk, throughfall precip.	$u_c(P_{T\,B})$	Eq. (16)	n/a	n/a
Calibration	$u(T_H)$	Eq. (6)	Eq. (8)	Eq. (9)
Surface Area	$u(A_T)$	Eq. (12)	Eq. (10)	Eq. (11)

7 FUTURE PLANS AND MODIFICATIONS

Future system flags may be incorporated into the data stream.

A calibration curve *may* be applied to secondary precipitation measurements (L0 DP) and L1 secondary bulk precipitation (L1 DP). If so, the algorithm(s) will be added to this document and applied by CI.

Details concerning the evaluation and quantification of Sensor and Field DAS drift will be added to the uncertainty section.

QA/QC tests may be expanded to include consistency analyses among similar measurement streams.

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