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A Unified Approach for Reporting ARM Measurement Uncertainties Technical Report: Updated in 2016

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ARM CLIMATE RESEARCH FACILITY

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Abstract

This report is an updated version of the report by Campos and Sisterson (2015) that includes new instruments that came on line after the original study. Therefore, this report addresses all ARM instruments that are operating or have been operated in the field through 2016. In addition, the "other" category has been investigated more closely with additional information provided by Instrument Mentors and has been eliminated. It has been determined that all instruments previously classified as "other" can be and have been re-classified as "calibration uncertainty" in this report. New suggestions about total measurement error and measurement confidence are also provided in this report for future consideration.

Acknowledgments

For their valuable comments, discussions, and service, we are in debt to the Atmospheric Radiation Measurement (ARM) Climate Research Facility Lead and Associate Instrument Mentors that participated in this study for the years 2012 - 2016. The author's work at Argonne National Laboratory is supported by the ARM Climate Research Facility through DOE contract DE-AC02-06CH11357.

Acronyms and Abbreviations

AOS	Aerosol Observing System
ARM	Atmospheric Radiation Measurement Climate Research Facility
DOE	U.S. Department of Energy
DQO	Data Quality Office
GUM	Guide for Uncertainty Measurements
NIST	National Institute of Standards and Technology
RH	relative humidity
SI	International System of Units
VAP	value-added product
WISG	World Infrared Standard Group
WMO	World Meteorological Organization
WRR	World Radiometric Reference

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1.0 Introduction

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility is observationally based, and quantifying the uncertainty of its measurements is critically important. With over 300 widely differing instruments providing over 2,500 datastreams, concise expression of measurement uncertainty is quite challenging. ARM currently provides data and supporting metadata (information about the data or data quality) to its users through several sources. Because the continued success of the ARM Facility depends on the known quality of its measurements, ARM relies on Instrument Mentors and the ARM Data Quality Office to ensure, assess, and report measurement quality. Therefore, an easily accessible, well-articulated estimate of ARM measurement uncertainty is needed.

This report is a continuation of the work presented by Campos and Sisterson (2015) and provides additional uncertainty information from instruments not available in their report. As before, a total measurement uncertainty has been calculated as a function of the instrument uncertainty (calibration factors), the field uncertainty (environmental factors), and the retrieval uncertainty (algorithm factors). This study will not expand on methods for computing these uncertainties. As before, it will focus on the practical identification, characterization, and inventory of the measurement uncertainties already available to the ARM community through the ARM Instrument Mentors and their ARM instrument handbooks.

This study continues the first steps towards reporting ARM measurement uncertainty as: (1) identifying how the uncertainty of individual ARM measurements is currently expressed, (2) identifying a consistent approach to measurement uncertainty, and then (3) reclassifying ARM instrument measurement uncertainties in a common framework.

2.0 Background

The terms *accuracy* and *precision* are found in multiple studies of measurement uncertainty. This was discussed in detail by Campos and Sisterson (2015) and will not be repeated here. The variety of uncertainty estimation methods available in the ARM measurement uncertainty reports has been classified here using the same methodology as before. This classification assesses our current state of knowledge about the uncertainties with ARM measurements in order to focus later work. The method of classification is slightly revised in this report after further investigation of the *other* category. This category in the original Campos and Sisterson (2105) study was used to indicate an expression of uncertainty that either uses a retrieval or insufficient information to classify by our definitions of *calibration uncertainty, field uncertainty*, *resolution*, and *none* from the information provided. For this study, the *other* data were re-evaluated and found to fall into two categories: 1) a retrieval was used to provide a desired measurement or 2) the additional information provided by the Mentor was sufficient in this study to classify the measurement uncertainty as *calibration uncertainty.* The errors associated with retrieved measurements are included and identified in the Appendix. Therefore, all instrument uncertainties classified as *other* in the Campos and Sisterson (2015) have been reclassified as *calibration uncertainty* in this study.

3.0 Methods

3.1 Data Set

This study initially began in 2012 by building a comprehensive inventory of current ARM uncertainty estimates, based on information provided by each ARM Instrument Mentor for the measurements generated by their ARM instruments. In addition, the instrument handbooks, vendor manuals, electronic mail, and follow-up calls were used to clarify the information provided. The sample size for the Campos and Sisterson (2015) study was the 321 unique instrument primary datastreams available in year 2012. This study includes an additional 96 unique primary measurements from instruments not included in the earlier report, bringing the total to 417 unique datastreams (not including value-added products, or VAPS) available in year 2016.

3.2 Conceptual Model

The same conceptual model used in the Campos and Sisterson (2015) report was used for this study except for the *other* category and estimates of measurement uncertainty are as follows:

- *Field uncertainty (or measurement uncertainty)*, which corresponds to the variability of repeated measurements under field conditions with well-calibrated sensors. This is estimated after minimizing operational contributions of known environmental errors, such as consideration of data-loggers digitization resolution, sample time, cable losses, need for radiation shields or ventilators or aspiration, and other sources of uncertainties described in the manufacturer's specifications that can be mitigated by operational protocols or maintenance.
- *Calibration uncertainty* (or instrument uncertainty), which corresponds to instrument calibration, through the use of well-established calibration references with traceability to the International System of Units (SI) or to consensus references and performed under ideal conditions to constrain known measurement errors.
- *Resolution*, which corresponds to the minimum detectable signal or instrument response. While the minimum detection of a measurement can be traced to a standard reference, there is usually no expression of uncertainty with regard to the actual measurement.
- *None*, which indicates that measurements have largely unknown uncertainty. That is, no reasonable estimates could be provided, because the instrument had not been characterized.

3.2.1 Field Uncertainty

For the uncertainty to be reported as *field (measurement) uncertainty*, the method used to characterize the quantification of uncertainty had to be provided. The information had to include one of the following:

- A measure of the variability of field samples (a function of the statistical mean [needed to compute relative uncertainties {GUM 2008, JCGM 100:2008}] and standard deviation of a number of in-the-field instrument measurements, collected over a defined period of time, under defined environmental conditions) and the results of a calibration of the instrument under ideal conditions.
- The results of a field calibration of the instrument under normal operating conditions.

- Other sources of uncertainties are described in the manufacturer specifications, the results of a calibration of instrument under ideal conditions, data-loggers specification, maintenance, sample time and cable losses, need for radiation shields, engineering judgment, and the scientific literature.

3.2.2 Calibration Uncertainty

For the uncertainty to be reported as based on *calibration uncertainty*, our study required that one of the following had to be available about the calibration reference:

- A traceable standard (i.e., a calibration reference value that is traceable to international references of the appropriate units of the International Systems of Units or traceable to a reference standard developed and maintained by National Institute of Standards and Technology (NIST), World Radiometric Reference (WRR), or World Infrared Standard Group (WISG).
- A consensus procedure (peer-reviewed article describing a method used to obtain a calibration reference).
- Expert judgment, in which the Instrument Mentor or vendor clearly states his/her practice for obtaining a calibration reference. For this study, we considered the vendors and/or Instrument Mentors to be subject-matter experts. Vendors did not always share the details of how they determined the reported uncertainty for their instruments, but there is a body of research literature that has independently addressed instrument measurement error that is consistent with vendor-stated values.

3.2.3 Resolution

For uncertainty to be reported as *resolution*, the method used to determine the instrument's minimum detection level and indicate small changes in measurement had to be provided.

- A traceable standard (i.e., a reference value that is traceable to international references of the appropriate units of the International Systems of Units or traceable to a reference standard developed and maintained by National Institute of Standards and Technology (NIST), World Radiometric Reference (WRR), or World Infrared Standard Group (WISG).
- A consensus procedure (peer-reviewed article describing a method used to obtain a resolution reference).
- Expert judgment, in which the Instrument Mentor or vendor clearly states his/her practice for obtaining a resolution reference. For this study, we considered the vendors and/or Instrument Mentors to be subject-matter experts. Vendors did not always share the details of how they determined the reported uncertainty for their instruments, but there is a body of research literature that has independently addressed instrument measurement error that is consistent with vendor stated values.

3.2.4 None

For uncertainty to be reported as none, there were either no estimates provided or the uncertainty estimates provided are largely unknown. That is, no reasonable estimates could be provided, because the instruments have not been fully characterized.

4.0 Measurement Confidence

The complete statement of a measured value should include an estimate of the level of confidence associated with that value. Properly reporting an experimental result along with its uncertainty allows other people to make judgments about the quality of the experiment, and it facilitates meaningful comparisons with other similar values or a theoretical prediction. Although measurement confidence as reported by Campos and Sisterson (2015) included the other category, the measurement confidence hierarchy was revised here to reflect the elimination of this category and is shown in Table 1. The concept of measurement confidence used here is a simple way to convey that instruments calibrated in the field under conditions in which they are operated are likely to account for more of the measurement total error than instruments calibrated in an idealized setting. Instrument resolution provides an instrument's ability to detect a measurement with certainty, but does not provide the uncertainty of the actual measurement. A more elaborate definition of measurement confidence is provided in Section 7 (Future Work).

Table 1. Hierarchical approach for classification of measurement uncertainty.

Uncertainty class	Method confidence
Field uncertainty	Highest
Calibration uncertainty	Good
Resolution	Fair
None	Lowest

5.0 Results and Discussion

Figure 1 summarizes the distribution of 417 unique primary measurements by uncertainty classification. The results show that uncertainty is provided as *resolution* for 4.32% of the samples (18 measurement types), as *field uncertainty* for 5.27% (22 measurements), as *calibration uncertainty* for 79.38% (331 measurements), and as *none* for 11.03% (46 measurements), because the instruments had not been fully characterized to estimate measurement uncertainty.

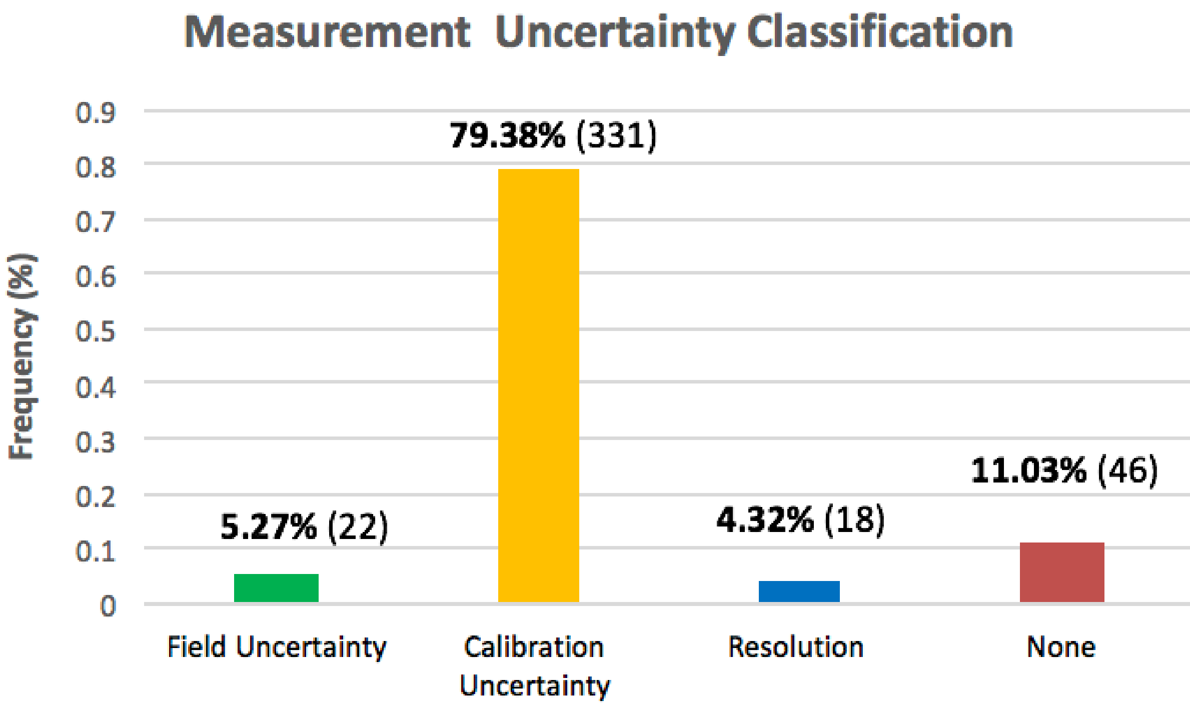

Figure 1. Distribution of instrument uncertainty measurements by uncertainty classification.

While nearly 89% of all measurements provide uncertainty as an assessment of instrument and/or retrieval errors, only 4% had measurement uncertainties performed under field conditions, the highest level of confidence in determining total measurement error.

All but one of the measurements in the *none* category are attributed to the complex ARM cloud and precipitation radar instruments, which, at the time of this study, are all still under evaluation. The spectral width and dual-polarization uncertainty estimates require a number of field calibrations and tests for characterizing each individual radar system. To date, these radars have not been fully characterized, and therefore estimates of the uncertainty cannot be provided at this time. The remaining entry for the *none* category was the Parsivel disdrometer, which will be discussed later in this section.

The Appendix shows the individual ARM instruments, the ARM Instrument Mentors for the instruments at the time of the study, the instrument primary measurements, the primary measurement uncertainty estimates, and our classification of the uncertainty types.

The determination of measurement bias (known systematic error) is particularly important because it is either a positive or negative correction factor to all corresponding measurements, leaving precision to characterize the measurement uncertainty. In addition, because many instruments do not provide geophysical values in their raw datastreams, multiple raw measurements are often needed to be combined in order to retrieve a geophysical value. Thus, it is highly desirable to correct individual raw measurements for bias, so that the individual biases are not carried through in the development of engineered data products or algorithms.

In the majority of the *calibration uncertainty* cases of the Appendix, the Instrument Mentors did not explicitly report systematic errors for their instruments. Systematic errors can depend on a number of factors (calibrating conditions, age of the instrument, etc.), which can yield different correction factor (bias) for each calibration. Therefore, instrument bias (although included in the overall instrument uncertainty) is not reported in the table. However, biases detected from scheduled individual instrument calibrations are determined and applied to the ARM datastreams as appropriate.

Instrument Mentors provided uncertainty expressions for the most important and widely used raw datastreams, but not always for all datastreams from an instrument. The Parsivel disdrometer will provide, in addition to particle size and fall velocity, information about whether the hydrometeor is snow, hail, rain, etc. Details are usually included with the vendor-provided software as measurement output. However, the Mentor did not recommend the use of these parameters as primary ARM datastreams because the vendor classification scheme was not described well enough for the Mentor to have confidence in the results. Therefore, the uncertainty estimates were not included for measurements not recommended by the Instrument Mentor even though they are available for the instrument by the vendor and reported as the *none* category for this particular measurement.

Also, for aerosol measurements, ARM has two Aerosol Observing Systems (AOSs) with almost-identical particle measurement instrumentation but slightly different internal configurations. In this case, two different Instrument Mentors for an identical instrument have reported the characterization of measurement uncertainty differently. A common reason for this difference is how they calibrated their specific instrument. Therefore, our classification of uncertainty type for two identical instrument measurements can be different if the Instrument Mentors used different methods to determine measurement uncertainty.

In many cases, we found a range of variability in the measurement uncertainty as a function of various environmental factors. This is most common for (but not limited to) profiling instrumentation used to characterize the state of the atmosphere from the surface to measurement heights in the troposphere, because measured parameters for vertical profiles can have large gradients, and large changes can occur in the atmospheric parameters during measurement as well as daily, diurnally, seasonally, and annually. Therefore, measurement uncertainty cannot always be expressed as a constant percent or a unique ± value, but rather in terms of environmental relationships (functions). Radiosonde measurements are an example. The relative humidity (RH) sensor experiences extremely high and low values as the sensor ascends through the troposphere. The sensor measurement confidence decreases with low RH values. Therefore, expressions of measurement uncertainty are expressed as a function rather than a constant value.

6.0 Conclusions

The measurement community is moving toward a methodology defining global standard protocols to be used for every instrument that makes atmospheric observations; this will allow universal comparability of atmospheric measurements. Although the measurement community has provided contemporary guidelines for the expression of measurement uncertainty (GUM 2008, WMO 2012 section 1.6), the challenges of implementing these methodologies for the range of instrumentation deployed at the ARM Climate Research Facility are daunting. Therefore, this study should be viewed as only a first step by normalizing the expression of ARM measurement uncertainties in terms of *resolution*, *calibration uncertainty*, and *field uncertainty*, as defined in this study. At the very least, this study allows ARM measurement uncertainties to be uniformly characterized so that they can be used to determine comparability with similar measurements made by others.

This study finds that the best representation (highest confidence based on methods used) of measurement uncertainty for the ARM measurements corresponds to *field uncertainty*, for which estimates are generated by using calibrated instruments and statistics for repeated field readings under normal operating conditions, consistent with GUM (2008). The second and third best representations (*good* and *fair* confidence, respectively) correspond to *calibration uncertainty* and *resolution*, respectively. The minimum acceptable representation (*lowest* confidence) of measurement uncertainty for the ARM measurements corresponds to *none*, for which the estimates consider instrument response time, sampling interval, and minimum detectable signals that cannot be or have not been adequately characterized.

From this study, the majority (near 89%) of ARM measurement uncertainties are described systematically. The majority of uncertainty estimates using well-established calibration references accounted for 79% of the total sample. This corresponds to the *calibration uncertainty* classification, where the measurement uncertainty is well characterized in an idealized setting for instrument calibration, but the actual variance of the measurement under normal field operation conditions is not necessarily well characterized. *Calibration uncertainty* does not necessarily mean that the total measurement uncertainty is underestimated. In fact, in some instances *calibration uncertainty* might be an overestimate of measurement uncertainty. For this study, *calibration uncertainty* is only an estimate of the measurement uncertainty due to instrument uncertainty.

Approximately 4% of the measurement uncertainty was classified as *resolution.* Although this category assures that the minimum detection limits and the ability to detect changes in measurements could be traced to a reference standard, there was no expression of measurement uncertainty provided for the actual measured values.

Approximately 5% of the measurement uncertainty was classified a *field uncertainty*, representing instruments calibrated in the field under normal operating conditions. While this category provides the highest confidence in measurement uncertainty, there may still be unknown factors that impact total measurement error. Because most of the ARM instruments have been operated for many years, and there has been substantial intercomparison of similar measurements provided by different instruments, any additional error not accounted for calibrating in the field is not likely to be large.

Because the relatively new ARM radars have not all been fully characterized yet, about 10% of the ARM measurements do not have sufficient information to provide estimates of measurement uncertainty for this study, and these fall under the *none* category.

Finally, the quantification of measurement uncertainty is this report may not be representative of the most current values for the individual ARM instruments. This is because instrument characteristics and performance may change over time. While ARM processes its data with the most current calibration information, the measurement uncertainty values can become different than what has been reported in the Appendix of this report. Although beyond the scope of this report, it would be useful to create a dynamic list of information made available to users, similar to what has been provided in the Appendix of this report, which could be updated and tracked as the information changes.

This study is only the initial phase to assess our state of knowledge about uncertainties with ARM measurements, and it sets the groundwork for future activities. Even our study's simple classification will help to determine which ARM measurements have its uncertainty estimation method limited by calibration or field procedures, which will allow calibration improvements that provide higher confidence in the measurement uncertainty values. At the very least, our classification of ARM measurement uncertainty could facilitate a common framework for data exchange across other networks, and usage among the many ARM researchers and stakeholders, including numerical modelers, climatologists, and risk managers.

7.0 Future Work

Properly quantifying and expressing measurement uncertainties poses a significant challenge as well as an opportunity for the near future. While most of the unique, primary measurements fall within the *calibration uncertainty* class in this study, calibrations are usually performed in an idealized environment to constraint other factors that might contribute to total measurement error. Therefore, some calibrations might account for the majority of the total measurement error, while some may not. As a result, measurement confidence needs to be more granular that represented in this study.

Therefore, the next step would be to provide an expanded statement about overall measurement confidence that includes better articulation of the quantification of total measurement error. The confidence rating scheme used in this study is not based on the actual uncertainty values (i.e., on the measured quantities) provided for the measurement, but rather on how the uncertainty values were derived (i.e., on the method of error assessment and determination). Measurement confidence could be on an estimated total measurement error. Therefore, future measurement confidence assessment could be based upon how much of the total measurement error is represented by measured and estimated errors. For example, a revised hierarchical approach for future classification of uncertainty measured could be structured as:

- Highest – All instrument and measurement (including environmental factors) errors are known and accounted for and traceable to a World Meteorological Organization (WMO) standard (or similar) by calibration.
- Good – Instrument and most measurement errors can be quantified and traceable to a WMO (or similar) standard by calibration or standard calibration procedure. Environmental factors might be known, but can only be estimated. However, the environmental factors are likely to be a small fraction of the total error.
- Fair – instrument and most measurement errors are appreciable and but cannot be quantified and are not traceable to a WMO standard. Environmental factors might be known, but can only be estimated, and occasionally could be much larger than the reported instrument errors.
- Low – Instrument and measurement errors are large and can only be characterized by unconventional methods (subject-matter expert), and known environmental errors are likely to be quite large, frequently dominating instrument errors.
- Lowest – Instrument and measurement errors are large and only characterized as a guess and environmental factors contributing to measurement uncertainty are large and unknown.

Also, any discussion of measurement confidence must also include data representativeness. Even a well-calibrated instrument operating within acceptable quantified measurement uncertainty can provide non-representative data. For example, surface flux measurements may only represent a particular crop when the wind is blowing from a specified wind direction. Well-calibrated aerosol instruments may be affected by local emission sources – the measurements are correct, but the intended measurements are usually to provide aerosol background measurements without plumes. The plowing and disking of farmland can create dust locally that makes the local air mass more optically thick – and not due to clouds or fog. For these cases, the measurements are within the stated uncertainty and therefore judged to be good data, but they may not be representative of the desired conditions. Measures could be taken to improve measurement representativeness – develop and implement despiking algorithms, conduct field campaigns that provide additional information, supplementary measurements that are co-located or at a distance location that improve measurement representativeness, etc.

Finally, it would be beneficial to groups combining individual measurements into engineered or value-added products (VAPs) to identify and treat systematic errors as correction factors. Instrument calibrations should be done frequently enough to provide sufficiently large and robust samples under the appropriate conditions to determine correction factors that can be routinely applied to the individual measurements. Applying a correction for individual measurements would reduce the overall measurement uncertainty when combining measurements for atmospheric-data applications such as remote-sensing retrievals, data assimilation of cloud-resolving models, or re-analyses of radiative transfer variables.

8.0 References

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Appendix A

Uncertainty Types for the Individual ARM Instruments through 2016

Table 2. ARM instrument uncertainties reported by instrument lead mentors for instrument systems.

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Lead Mentor: Bartholomew, Mary Jane			
Rain Gauge – Belfort Instruments Model AEPG 600 Weighing Bucket			
Rainfall amount (accumulation)	1	Resolution	± 0.25 mm (0.01 in.)
Rainfall rate	1	Resolution	± 0.25 mm min^{-1} (0.01 in. min^{-1})
Optical Rain Gauge – ORG: Optical Scientific Model 815-DA			
Rainfall amount (accumulation)	1	Calibration Uncertainty	± 5%
Impact Disdrometer – Joss-Walvogel's, Distromet Model RD-80			
Drop diameter	1	Calibration Uncertainty	± 5%
2 Dimensional Video Disdrometer - VDIS - Joanneum Research			
Drop diameter	1	Resolution	0.19 mm
Drop velocity	1	Calibration Uncertainty	Better than ± 4%
Parsivel2, OTT Present Weather Sensor			
Drop diameter	1	Resolution	± 1 size class for diameters up to 2 mm; ± 0.5 size class for diameters > 2mm
Drop velocity	1	None	Unknown and unreliable
Precipitation amount (accumulation)	1	Calibration Uncertainty	± 5% for liquid; ± for solid
Precipitation rate	1	Resolution	Minimum detection, 0.001 mm h^{-1}
Lead Mentors: Biraud, Sebastian			
Carbon Dioxide Flux Measurement System (3-D Sonic Anemometer Gill Solent Windmaster Pro and Licor Inc. LI-7500, Infrared Gas Analyzer			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Turbulence flux of sensible heat	1	Calibration Uncertainty	10 W m^{-2} s^{-1} detection limit, ± 1-3% gain Uncertainty (CO$_2$FLX Handbook p. 3)
Turbulence flux of CH_4	1	Calibration Uncertainty	~ ± 10% for 30-min average
Turbulence flux of CO_2	1	Calibration Uncertainty	0.1 μmol m^{-2} s^{-1} detection limit, ± 1-3% gain Uncertainty (CO$_2$FLX Handbook p. 3)
Turbulence flux of H_2O	1	Calibration Uncertainty	10 W m^{-2} s^{-1} detection limit, ± 1-3% gain Uncertainty (CO$_2$FLX Handbook p. 3)
Picarro G1301 Cavity Ringdown Spectrometer			
CO_2 mixing ratio (with direct measurements of water vapor as input to correction factors to derive dry-air conditions)	1	Field Uncertainty	± 0.06 ppm
CH_4 mixing ratio (with direct measurements of water vapor as input to correction factors to derive dry-air conditions)	1	Field Uncertainty	± 0.28 ppb
Carbon Monoxide Mixing Ratio System, Trace-Level Gas Filter Correlation System Built by Lawrence Berkeley National Laboratory around the Thermo Electron Gas Analyzer Model 48C-TL Instrument			
CO mixing ratio — atmospheric concentration of CO mixing ratio (ppbv dry air) measured in air every 10 min, 60 m above ground level	1	Field Uncertainty	± 10.0 ppb
Flask Samplers for Carbon Cycle Gases and Isotopes (FLASK): Isotopes from Flask Analyses using Mass Spectrometer			
$^{13}CO_2$ isotope ratio: $^{13}C(^{16}O)_2/^{12}C(^{16}O)_2$	1	Field Uncertainty	± 0.03%
Isotopes from Flask Analyses using Mass Spectrometer			
$C^{18}O_2$ isotope ratio: $^{12}C(^{18}O)_2/^{12}C(^{16}O)_2$	1	Field Uncertainty	± 0.03%
Trace Gases from Flask Analyses			
CO_2 concentration (amount per unit volume of CO_2 trace gases)	1	Field Uncertainty	± 0.03 ppm
CH_4	1	Field Uncertainty	± 1.2 ppb
CO	1	Field Uncertainty	± 0.3 ppb
N_2O	1	Field Uncertainty	± 0.4 ppb
Precision Gas System Isotope Analyzer (PGSISO) – Echotech Spectronus FTIR			
CO2	1	Calibration Uncertainty	± 0.1 ppm
Delta 13CO2	1	Calibration Uncertainty	± 0.08 ppm
CH4	1	Calibration Uncertainty	± 0.4 ppb
CO	1	Calibration Uncertainty	± 0.3 ppb

Measurement	No.	Uncertainty Type	Uncertainty Estimate
N2O	1	Calibration Uncertainty	± 0.08 ppb
NSA Ameriflux Measurement Components (AMC) – Lawrence Berkeley National Laboratory			
Soil Volumetric Water Content (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.1 cm^3/ cm^3
Temperature (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.5ºC
SGP Ameriflux Measurement Components (AMC) – Lawrence Berkeley National Laboratory			
Soil Volumetric Water Content (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.03 to 0.1 cm^3/ cm^3
Temperature (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.5ºC
OLI Ameriflux Measurement Components (AMC) – Lawrence Berkeley National Laboratory			
Soil Volumetric Water Content (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.01 to 0.1 cm^3/ cm^3
Temperature (Campbell Scientific CS665)	1	Calibration Uncertainty	± 0.5ºC
Precision Gas System (PGS) – Lawrence Berkeley National Laboratory			
CO2 (Picarro G2301)	1	Calibration Uncertainty	± 0.03 ppm
CH4 (Picarro G2301)	1	Calibration Uncertainty	± 0.3 ppb
ENA Aerosol Observation System Green House Gas (AOSGHG) – Lawrence Berkeley National Laboratory			
CO2 (Picarro G2301)	1	Calibration Uncertainty	± 0.05 ppm
CH4 (Picarro G2301)	1	Calibration Uncertainty	± 0.2 ppb
OLI Aerosol Observation System Green House Gas (AOSGHG) – Lawrence Berkeley National Laboratory			
CO2 (Picarro G2301)	1	Calibration Uncertainty	± 0.1 ppm
CH4 (Picarro G2301)	1	Calibration Uncertainty	± 0.2 ppb
Lead Mentor: Cadeddu, Maria			
Microwave Radiometer (MWR) - Radiometrics Corporation			
23.8- and 31.4-GHz sky brightness temperature	1	Calibration Uncertainty	± 0.3 K
Precipitable water vapor (water vapor path) - Retrieved	1	Calibration Uncertainty	± 0.5-0.7 mm
Liquid water path - Retrieved	1	Calibration Uncertainty	± 0.02-0.03 mm
Microwave Radiometer – 3 Channel (MWR3C) - Radiometrics Corporation			
23.834- and 30-GHz sky brightness temperature	1	Calibration Uncertainty	± 0.5-0.6 K

Measurement	No.	Uncertainty Type	Uncertainty Estimate
89-GHz sky brightness temperature	1	Calibration Uncertainty	± 1.5 K
Precipitable water vapor (water vapor path) - Retrieved	1	Calibration Uncertainty	± 0.5-0.7 mm
Liquid water path - Retrieved	1	Calibration Uncertainty	± 0.01-0.02 mm
90- and 150-GHz sky brightness temperature	1	Calibration Uncertainty	± 1.5 K
G-band (183-GHz) Vapor Radiometer (GVR) - ProSensing, Inc.			
Brightness temperature (183.3 ± 1, 3, 7, 14 GHz)	1	Calibration Uncertainty	± 1.5-2 K
Precipitable water vapor (PWV; water vapor path) - Retrieved	1	Calibration Uncertainty	3-4% (PWV < 10 mm) to ~ ± 10% (PWV > 10 mm)
Liquid water path - Retrieved	1	Calibration Uncertainty	± 0.010-0.015 mm
G-band (183 GHz) Vapor Radiometer Profiler (GVRP) - Radiometrics Corporation			
Brightness temperatures at 15 channels, 170-183.3 GHz	1	Calibration Uncertainty	± 1.5 K
Microwave Radiometer Profiler (MWRP) - Radiometrics Corporation			
Brightness temperature, 20-30 GHz	1	Calibration Uncertainty	± 0.5 K
Brightness temperature, 50-60 GHz	1	Calibration Uncertainty	± 1.5 K
Precipitable water vapor (water vapor path) - Retrieved	1	Calibration Uncertainty	± 0.5-0.7 mm
Liquid water path - Retrieved	1	Calibration Uncertainty	± 0.025-0.030 mm
Air temperature profile	1	Calibration Uncertainty	± 1-2 K (at height 0-2 km) to ± 3-4 K (at height 10 km)
Vapor density profile	1	Calibration Uncertainty	± 0.5-1 g m^{-3} (at height 0-1 km) to 0.01-0.05 g m^{-3} (at height 10 km)
Lead Mentor: Cherry, Jessica			
Total Precipitation Sensor (TPS or “Hotplate”) – Yankee Environmental Systems			
Precipitation liquid equivalent rate	1	Calibration Uncertainty	± 30%
Lead Mentor: Collins, Don			
Humidified Tandem Differential Mobility Analyzer (HTDMA) – Texas A&M University			
Size-dependent particle concentration in 90 size bins for diameters 13-750 nm	6	Calibration Uncertainty	For particle size: ± 15% for 20-nm particles, ± 3% for 100-nm particles, ± 10% for 500-nm particles; for particle concentration: ± 20% for 20-nm particles, ± 5% for 100-nm particles, ± 20% for 500-nm particles

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Hygroscopic growth-dependent particle concentration in 75 size bins for hygroscopic growth factors ~0.85-2.3, from sequential measurements of particles with dry diameters = 13, 25, 50, 100, 200, 400, 600 nm	6	Calibration Uncertainty	Uncertainty in measured hygroscopic growth (x-axis of distributions) and in measured concentration (y-axis of distributions): each ~ ± 10% for 13-nm particles, ± 2% for 100-nm particles, ± 10% for 600-nm particles
Aerodynamic Particle Sizer (APS) - Texas A&M University			
Size-dependent particle concentration in 51 size bins for diameter range 500-20,000 nm (0.5-20 mm)	6	Calibration Uncertainty	For particle size: ± 20% for 500-nm particles, ± 10% for 1,000-nm particles, ± 10% for 5,000-nm particles; for particle concentration: ± 10% for 500-nm particles, ± 10% for 1,000-nm particles, ± 20% for 5,000-nm particles
Lead Mentor: Cook, David			
Soil Water and Temperature System (SWATS) - Campbell Scientific, Inc., Model 229L Matric Potential Sensor			
Reference temperature	1	Calibration Uncertainty	± 0.5ºC
Soil temperature	1	Calibration Uncertainty	± 0.5ºC
Temperature difference	1	Calibration Uncertainty	± 0.5ºC
Soil-water potential	1	Calibration Uncertainty	± 4-20 kPa
Water content	1	Calibration Uncertainty	± 0.05 m^3 m^{-3}
Energy Balance Bowen Ratio (EBBR) System - REBS			
Sensible heat flux	1	Calibration Uncertainty	± 10%
Latent heat flux	1	Calibration Uncertainty	± 10%
Net radiation	1	Calibration Uncertainty	± 5%
Soil surface heat flux	1	Calibration Uncertainty	± 6%
Air temperature	1	Calibration Uncertainty	± 1%
Relative humidity	1	Calibration Uncertainty	± 3%
Atmospheric pressure	1	Calibration Uncertainty	± 2%
Soil heat flow	1	Calibration Uncertainty	± 3%
Soil moisture	1	Calibration Uncertainty	± 5%

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Soil temperature	1	Calibration Uncertainty	± 1%
Surface Energy Balance System (SEBS) - REBS			
Net radiation	1	Calibration Uncertainty	± 3%
Surface soil heat flux	1	Calibration Uncertainty	± 6%
From soil heat flow	1	Calibration Uncertainty	± 3%
From soil moisture	1	Calibration Uncertainty	± 5%
From soil temperature	1	Calibration Uncertainty	± 1%
Surface energy balance	1	Calibration Uncertainty	± 7%
Facility-Specific Multi-Level Meteorological Instrumentation (TWR): SGP Tower			
Air temperature	1	Calibration Uncertainty	± 1%
Relative humidity	1	Calibration Uncertainty	± 3%
Vapor pressure	1	Calibration Uncertainty	± 3%
Eddy Covariance Flux System (ECOR) – Argonne National Laboratory			
Turbulence flux of momentum	1	Calibration Uncertainty	± 5% (ECOR Handbook p. 4)
Turbulence flux of sensible heat	1	Calibration Uncertainty	± 6% (ECOR Handbook p. 4)
Turbulence flux of latent heat	1	Calibration Uncertainty	± 5% (ECOR Handbook p. 4)
Soil Temperature and Moisture Profiles (STAMP) – Stevens Water Monitoring Inc.			
Soil specific water content	1	Calibration Uncertainty	± 3%
Plant water availability	1	Calibration Uncertainty	± 1% mm
Total plant water availability	1	Calibration Uncertainty	± 1% mm
Soil temperature	1	Calibration Uncertainty	± 0.3ºC
Loam soil water content	1	Calibration Uncertainty	± 3%
Soil conductivity	1	Calibration Uncertainty	± 2% Siemens/m
Real dielectric permittivity	1	Calibration Uncertainty	± 1.5% (unitless)

Measurement	**No.**	**Uncertainty Type**	**Uncertainty Estimate**
Precipitation – Texas Electronics Inc.	1	Calibration Uncertainty	± 1% mm
Lead Mentor: Coulter, Richard			
Micro Pulse Lidar (MPL) – Sigma pace Corporation			
Detected signal	1	Resolution	1 photon per microsecond
Height	1	Resolution	0.5 × range gate (15, 30, 75 m)
Radar Wind Profilers (RWPs)- 1290 MHZ (Radian) and 915 MHz (DeTect, Inc.)			
Wind speed	1	Calibration Uncertainty	< ± 1 m s^{-1}
Wind direction	1	Calibration Uncertainty	< ± 10 deg
Height	1	Calibration Uncertainty	~ ± 6m + 0.5 × range gate
Radial wind speed	1	Calibration Uncertainty	< ± 0.5 m s^{-1}
Radar signal	1	Resolution	-25 to -20 dB (Range reflects the variance in the number of instrument systems.)
Scintec Sodars (SODAR)- Scintec			
Wind speed	1	Calibration Uncertainty	< ± 0.6 m s^{-1}
Wind direction	1	Calibration Uncertainty	< ± 4 deg
Height	1	Calibration Uncertainty	0.5 × range gate
Radial wind speed	1	Calibration Uncertainty	< ± 0.25 m s^{-1}
Sodar signal	1	Resolution	-15 dB
Roll Pitch Yaw (RPY) Stable Table – Sarnicola Systems			
Roll	1	Resolution	± 0.00025ºC
Pitch	1	Resolution	± 0.00025ºC
Roll Pitch Heave (RPH) Stable Table – Sarnicola Systems			
Roll	1	Resolution	± 0.005ºC
Pitch	1	Resolution	± 0.005ºC
Lead Mentor: Dexheimer, Darielle			
TBS Liquid Water Tethersonde - Anasphere			
Frequency of vibrating wire (Anasphere Supercooled Liquid Water Content Sonde)	1	Calibration Uncertainty	± 0.021 hz
TBS Met Tethersondes			
Pressure (Anasphere Tethersonde - Intersema MS55400C)	1	Calibration Uncertainty	± 3 mb for 300-1000mb and temp of -40 to 85ºC

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Relative Humidity (Anasphere Tethersonde - Honeywell HIH-4000)	1	Calibration Uncertainty	± 3.5% at -40 to 100ºC
Temperature (Anasphere Tethersonde - Honeywell 202CAK-H01)	1	Calibration Uncertainty	± 0.5ºC
TBS Ground Station			
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.5ºC at -40ºC
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.4ºC at -20ºC
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.3ºC at 0ºC
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.2ºC at 20ºC
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.3ºC at 40ºC
Temperature (Campbell Scientific HMP45C Sensor)	1	Calibration Uncertainty	± 0.4ºC at 60ºC
Wind speed (OTECH - Calibrated NRG#40	1	Calibration Uncertainty	± 1.48%
Wind direction (LSM303D)	1	Calibration Uncertainty	± 3º
Longitude/latitude/altitude (GlobaTop PA6H)	1	Calibration Uncertainty	± 3m
TBS Wetness Sensors			
Dielectric constant of wetness sensor's upper plate (Campbell Scientific Leaf Wetness Sensor (LWS)	1	Resolution	± 0.6mV
Lead Mentor: Dubey, Manvendra			
Photo Acoustic Soot Spectrometer (PASS-3)- DMT			
Particle absorption	3	Calibration Uncertainty	5-min sample under same measurement conditions: ± 0.9 M m^{-1} (405 nm); ± 1.6 M m^{-1} (532 nm); ± 0.6 M m^{-1} (781 nm)
Particle scattering	3	Calibration Uncertainty	5-min sample under same measurement conditions: ± 0.6 M m^{-1} (405nm); ± 0.3 M m^{-1} (532 nm); ± 0.4 M m^{-1} (781 nm)
Lead Mentor: Flynn, Connor			
Atmospheric Sounder Spectrometer for Infrared Spectral Technology (ASSIST) - LR Tech, Inc.			
Infrared spectral zenith radiance from channel A, wavelength 670-1400 cm^{-1}	1	Calibration Uncertainty	Noise channel A < ± 0.2 mW (m^2 sr $cm^{-1})^{-1}$
Infrared spectral zenith radiance from channel B, wavelength 2000-2600 cm^{-1}	1	Calibration Uncertainty	Noise channel B < ± 0.015 mW (m^2 sr $cm^{-1})^{-1}$

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Shortwave Spectroradiometer (SWS) – Pacific Northwest National Laboratory			
Absolute spectral radiance of the zenith above the instrument in units of W m^{-2} nm^{-1} sr^{-1}; 256 channels in the Si detector (wavelengths of 300-1100 nm, sampling periods of 75-100 ms); 256 channels for the InGaAs detector (wavelengths of 900-2200 nm, sampling periods of 150-250 ms)	2	Calibration Uncertainty	For both detectors: ± 2% at 400 nm; ± 1% at 500-900 nm; ± 2-3% at 900-1700 nm; ± 5% at 1700-2100 nm (upper theoretical limits based on calibration source)
Shortwave Array Spectroradiometer-Zenith (SASZE) – Pacific Northwest National Laboratory			
Zenith sky shortwave (spectral) radiance over the spectral range from near infrared to ultraviolet for spectroradiometer detectors in the visible (350-1000 nm) and near-infrared (970-1700 nm)	2	Calibration Uncertainty	± 10% or more
Shortwave Array Spectroradiometer-Hemispheric (SASHE) – Pacific Northwest National Laboratory			
Hemispheric spectral radiances for two channels, 350-1000 nm and 970-1700 nm (same two spectroradiometers as SASZE)	2	Calibration Uncertainty	±1% to ±5%
Lead Mentor: Gero, Jonathan			
Atmospheric Emitted Radiance Interferometer (AERI) – University of Wisconsin			
Atmospheric emitted spectral radiance (in watts per square meter per steradian per wavenumber)	1	Calibration Uncertainty	< ± 1%
Lead Mentor: Goldsmith, John			
High Spectral Resolution Lidar (HSRL) – University of Wisconsin			
Particulate backscatter profile	3	Calibration Uncertainty	± 6 x 10^{-3} sr $(M\ m)^{-1}$ at 30 m x 30-s sampling intervals; ± 4 x 10^{-3} sr $(M\ m)^{-1}$ at 60 m x 60-s sampling intervals; ± 3 x 10^{-3} sr $(M\ m)^{-1}$ at 120 m x 120-s sampling intervals
Particulate extinction profile	3	Calibration Uncertainty	± 60 M m^{-1} at 30 m x 30-s sampling intervals; ± 15 M m^{-1} at 60 m x 60-s sampling intervals; ± 4 M m^{-1} at 120 m x 120-s sampling intervals
Particulate depolarization ratio	3	Calibration Uncertainty	8% at 30 m x 30-s sampling intervals; 5% at 60 m x 60-s sampling intervals; 3% at 120 m x 120-s sampling intervals
Lead Mentor: Gregory, Laurie			
Cimel Sunphotometer (CSPHOT) - CIMEL Electronique			
Aerosol optical depth	1	Calibration Uncertainty	± 0.01-0.02 (wavelength dependent, due to calibration Uncertainty for the field instruments)
Sky radiance	1	Calibration Uncertainty	± 5%

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Lead Mentor: Hodges, Gary			
Multifilter Rotating Shadowband Radiometer (MFRSR) - Yankee Environmental Systems, Inc.			
Clear skies total horizontal irradiance	1	Calibration Uncertainty	± 2.1%
Clear skies direct normal irradiance	1	Calibration Uncertainty	± 2.3%
Clear skies diffuse horizontal irradiance	1	Calibration Uncertainty	± 5.2%
Spectral irradiance at 415 nm	1	Calibration Uncertainty	± 5.0%
Spectral irradiance at 500 nm	1	Calibration Uncertainty	± 5.0%
Spectral irradiance at 615 nm	1	Calibration Uncertainty	± 5.0%
Spectral irradiance at 673 nm	1	Calibration Uncertainty	± 5.0%
Spectral irradiance at 870 nm	1	Calibration Uncertainty	± 5.0%
Spectral irradiance at 940 nm	1	Calibration Uncertainty	± 5.0%
Aerosol optical depths	1	Calibration Uncertainty	± 0.005 + 0.01 m^{-1}
Narrow Field of View Zenith Radiometer (NFOV 2 channel) – Pacific Northwest National Laboratory			
Clear sky spectral radiance at 673 nm	1	Calibration Uncertainty	± 5.0%
Clear sky spectral radiance at 870 nm	1	Calibration Uncertainty	± 5.0%
Normal Incidence Multifilter Radiometer (NIMFR) – Pacific Northwest National Laboratory			
Clear sky direct normal irradiance	1	Calibration Uncertainty	± 2.3%
Spectral radiance at 415 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 500 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 615 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 673 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 870 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 940 nm	1	Calibration Uncertainty	± 5.0%
Aerosol optical depths	1	Calibration Uncertainty	± 0.005 + 0.01 m^{-1}
Multifilter Radiometer (MFR) – Pacific Northwest National Laboratory			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Clear skies diffuse horizontal irradiance	1	Calibration Uncertainty	± 5.2%
Spectral radiance at 415 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 500 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 615 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 673 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 870 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 870 nm	1	Calibration Uncertainty	± 5.0%
Spectral radiance at 940 nm	1	Calibration Uncertainty	± 5.0%
Aerosol optical depths	1	Calibration Uncertainty	± 0.005 + 0.01 m^{-1}
Clear skies total horizontal irradiance (Yankee Environmental)	1	Calibration Uncertainty	± 2.1%
Clear skies direct normal	1	Calibration Uncertainty	± 2.3%
Lead Mentor: Holdridge, Donna			
Balloon-borne Sounding System (SONDE) - Vaisala RS92 Radiosonde			
Temperature	1	Calibration Uncertainty	± 0.5ºC
Relative humidity (with respect to liquid water)	1	Calibration Uncertainty	± 5% at 0-100%
Pressure	1	Calibration Uncertainty	± hPa at 1080-100 hPa; ± 0.6 hPa at 100-3 hPa
Wind speed	1	Calibration Uncertainty	± 0.15 m s^{-1}
Wind direction	1	Calibration Uncertainty	± 2 deg
Vaisala Ground Check Set (GC25) temperature (probe installed on the GC25 ground check set, used to correct temperature readings on the RS92 radiosonde; has its own manufacturer Uncertainty)	1	Calibration Uncertainty	± 0.1ºC
Combined RS92 and GC25 - Temperature = $(\text{RS92Uncertainty}^2 + \text{GC25Uncertainty}^2)^{-2}$	1	Calibration Uncertainty	± 0.5ºC
Automatic Weather Station (MAWS)			
Barometric pressure (Vaisala PTB330 Pressure Sensor - Class A Sensor)	1	Calibration Uncertainty	± 0.15 hPa for -40 to +60ºC for 500 to 1100 hPa

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Temperature (Vaisala HMP155 Temperature and Relative Humidity Probe, for RS485 output)	1	Calibration Uncertainty	± (0.176 - 0.0028 x temperature ºC) for -80 to + 20ºC; +/- (0.07 + 0.0025 x temperature ºC) for +20 to + 60ºC)
Relative humidity (Vaisala HMP155 T and RH Probe)	1	Calibration Uncertainty	± 1.0 % RH (40 to 97% RH) for +20ºC
Wind speed (Vaisala WMT700 Ultrasonic Sensor)	1	Calibration Uncertainty	± 0.1 m/s or 2% of reading, whichever is greater
Wind direction (Vaisala WMT700 Ultrasonic Sensor)	1	Calibration Uncertainty	± 2ºC
Automatic Weather Station (MAWS datalogger)			
Voltage (Vaisala QML201 Data Logger)	1	Calibration Uncertainty	± +/- 5.0V range: <0.06 % of reading +/- 100 microV; +/- 2.5 V range: <0.04 % of reading +/- 50 microV; +/- 250 milliV: <0.06 % of reading +/- 6 mircoV; +/- 25 milliV range: <0.06 % of reading +/- 5 microV
Lead Mentor: Jefferson, Anne			
(NOAA) Particle Soot Absorption Photometer (PSAP) - Radiance Research			
Aerosol absorption coefficient (for 1-min averaged data)	1	Calibration Uncertainty	Uncertainty (M m^{-1}) for absorption coefficient (M m^{-1}) = ± 0.5 for 1; ± 0.6 for 5; ± 1.0 for 10; ± 1.7 for 20; ± 4.2 for 50
(NOAA) Continuous Light Absorption Photometer (CLAP) - National Oceanic and Atmospheric Administration			
Aerosol absorption coefficient (for 1-min averaged data)	1	Calibration Uncertainty	Uncertainty (M m^{-1}) for absorption coefficient (M m^{-1}) = ± 0.5 for 1; ± 0.6 for 5; ± 1.0 for 10; ± 1.7 for 20; ± 4.2 for 50
(NOAA) Cloud Condensation Nuclei Particle Counter (CCN) - Droplet Measurement Technologies			
Supersaturation	1	Calibration Uncertainty	± 0.05%
Particle number concentration	1	Calibration Uncertainty	± 5 % particles cm^{-3} of the reported total number concentration
(NOAA) Nephelometer - TSI 3563			
Aerosol total scattering (scattering coefficient at 550 nm for 1-min averaging time)	1	Calibration Uncertainty	Uncertainty (M m^{-1}) for scattering coefficient (M m^{-1}): Uncertainty (M m^{-1}) = ± 1.33 for 1; ± 1.92 for 10; ± 1.70 for 20; ± 5.23 for 50; ± 9.58 for 100
(NOAA) Condensation Particle Counter (CPC) - TSI 3010			
Aerosol particle number concentration	1	Calibration Uncertainty	± 10%
(NOAA) Impactor - National Oceanic and Atmospheric Administration			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Aerodynamic cut size diameter of 1.0 micron corresponds to 0.8 micron geometric cut size. (Custom built jet-plate style impactor - heated)	1	Calibration Uncertainty	±7% to ±12%
Lead Mentor: Kuang, Chongai			
Condensation Particle Counter (CPC) TSI 3772			
Concentration of particles with diameter > 10 nm	1	Calibration Uncertainty	± 14%
Ultra-Fine Condensation Particle Counter (UCPC) Model TSI 3776			
Concentration of particles with diameter > 2.5 nm (cm^{-3})	1	Calibration Uncertainty	± 10%
Scanning Mobility Particle Sizer (SMPS) Model TSI 3080/3772			
Number size distribution of particles with diameter 10-500 nm, expressed as dN/dlogDp (N = particle number concentration in cm^{-3}; Dp = particle diameter in nm), for 5-min measurement period	1	Calibration Uncertainty	± 15%
Nano Scanning Mobility Particle (Nano SMSP– TSI 3910			
Particle mobility diameter (10 to 420 nm)	1	Calibration Uncertainty	± 1%
Particle number size distribution (13 channels)	1	Calibration Uncertainty	± 20%
Lead Mentor: Kyrouac, Jenni			
T/RH Probes Vaisala HMP45D			
Temperature	1	Calibration Uncertainty	± 0.2ºC at 20ºC
Relative humidity	1	Calibration Uncertainty	± 2% for 0-90%; ± 3% for 90-100%
T/RH Probes Vaisala HMP155			
Temperature	1	Calibration Uncertainty	± (0.1 + 0.00167 x temp)ºC
Relative humidity	1	Calibration Uncertainty	± (1.4 + 0.032 x reading)% for -60 to -40ºC; ± (1.2 + 0.012 x reading)% for -40 to -20ºC; ± (1.0 + 0.008 x reading)% for -20 to +40ºC
T/RH Probes Vaisala HMT 337			
Temperature	1	Calibration Uncertainty	± 0.2ºC at 20ºC
Relative humidity	1	Calibration Uncertainty	± (1.5 + 0.015 x reading) for -40 to +180ºC
T/RH Probes Vaisala HMP 233			
Temperature	1	Calibration Uncertainty	± 0.1ºC at 20ºC

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Relative humidity	1	Calibration Uncertainty	± 2% at 0-90%; ± 3% at 90-100%
T/RH Probes Rotronic MP100H			
Temperature	1	Calibration Uncertainty	±0.2°C at 20-25ºC
Relative humidity	1	Calibration Uncertainty	±1.5% at 0-100%
R.M. Young Wind Monitor Models 05103/05106			
Wind speed	1	Calibration Uncertainty	± 2% for 2.5 m s^{-1} to 30 m s^{-1}
Wind direction	1	Calibration Uncertainty	± 3º
Vaisala WS425/425 F/G 2-d Ultrasonic			
Wind speed	1	Calibration Uncertainty	± 0.135 m s^{-1} or ± 3% of reading, whichever is greater
Wind direction	1	Calibration Uncertainty	± 2º for wind speeds > 1.0 m s^{-1}
Barometer Vaisala PTB 201			
Pressure	1	Calibration Uncertainty	± 0.3 hPa
Barometer Vaisala PTB 220			
Pressure	1	Calibration Uncertainty	± 0.15 hPa
Barometer Vaisala PTB 330			
Pressure	1	Calibration Uncertainty	± 0.10 hPa
Tipping Bucket Rain Gauge, Heated, Novalynx Model 2600-250 12 in.			
Rainfall accumulation	1	Resolution	± 0.254 mm; unknown during heavy winds or snow
Tipping Bucket Rain Gauge, RIMCO 7499 Series			
Rainfall accumulation	1	Calibration Uncertainty	± 1% up to 250 mm h^{-1} rain rate; 0 to -7% for 250-500 mm h^{-1} rain rate
Optical Rain Gauge (ORG), Optical Scientific Model 815			
Rainfall accumulation	1	Calibration Uncertainty	± 5% of accumulation
Present Weather Detector, Vaisala PWD-22			
Rain rate	1	Resolution	± 0.05 mm h^{-1} or less for 10-min sample time
Visibility	1	Calibration Uncertainty	± 10% for 10 m to 20 km
Chilled Mirror Hygrometer, Technical Services Laboratory Model 1088			

Measurement	**No.**	**Uncertainty Type**	**Uncertainty Estimate**
Temperature	1	Calibration Uncertainty	± 0.5ºF (-58 to 122ºF), ± 1º in rest of range
Dew point	1	Calibration Uncertainty	± 2ºF root mean square error (RMSE) (30-86ºF); ± 3ºF RMSE (-10 to 30ºF); ± 4ºF RMSE (-30 to -10ºF)
Chilled Mirror Hygrometer, General Eastern Hygro M4/E4			
Dew point	1	Calibration Uncertainty	± 0.2ºC
Frost point	1	Calibration Uncertainty	± 0.2ºC
Datalogger, Campbell Scientific Model CR10/10X			
Voltage measurements	1	Calibration Uncertainty	± 0.1%, full scale range
Excitation accuracy	1	Calibration Uncertainty	± 5 mV (-25 to 50ºC)
Resistance measurement	1	Calibration Uncertainty	± 0.02%, full scale input
Datalogger, Campbell Scientific Model CR23X			
Voltage measurements	1	Calibration Uncertainty	± 0.075%, full scale range
Excitation accuracy	1	Calibration Uncertainty	± 5 mV (-25 to 50ºC)
Resistance measurement	1	Calibration Uncertainty	± 0.02%, full scale input
Datalogger, Campbell Scientific Model CR3000			
Voltage measurement	1	Calibration Uncertainty	± 0.09, full scale range (-40 to 85ºC)
Voltage output (Vx)	1	Calibration Uncertainty	± 0.09% + 0.5 mV (-40 to 85ºC)
Resistance output (Ix)	1	Calibration Uncertainty	± 0.15% + 0.5 µA (-40 to 85ºC)
Resistance measurement	1	Calibration Uncertainty	± 0.03% + offset/Vx or Ix) (-40 to 85ºC)
Solar Shields, Gill Non-Aspirated Model			
Temperature	1	Calibration Uncertainty	± 0.2ºC for winds > 6 m s^{-1} (assume aspirated shield error); ± 0.4ºC for wind speed 3 m s^{-1}; ± 0.7ºC for wind speed 2 m s^{-1}; ± 1.5ºC for wind speed 1 m s^{-1}
Solar Shields, Gill Aspirated Model			
Temperature	1	Calibration Uncertainty	± 0.2ºC
Lead Mentor: Michalsky, Joe			
Rotating Shadowband Spectrometer – Yankee Environmental Systems, Inc.			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Direct normal solar spectral irradiance (W m^{-2} nm^{-1})	1	Calibration Uncertainty	± 5%
Total horizontal solar spectral irradiance (W m^{-2} nm^{-1})	1	Calibration Uncertainty	± 5%
Diffuse horizontal solar spectral irradiance (W m^{-2} nm^{-1})	1	Calibration Uncertainty	± 5%
Lead Mentor: Morris, Victor			
Infrared Thermometer (IRT) – Heitronics KT19.85 II Infrared Radiation Pyrometer			
Sky brightness temperature (Tsky)	1	Calibration Uncertainty	Greater value of ±0.5 K + 0.007(Tsky –Tref) or Tsky resolution = ±1.20 K; where Tref : internal reference temperature
Ground surface temperature (Tgnd)	1	Calibration Uncertainty	Greater value of ±0.5 K + 0.007(Tgnd – Tref) or Tgnd resolution = ±0.10 K; where Tref : internal reference temperature
Laser Ceilometer (VCEIL) - Vaisala CL31 Ceilometer			
Cloud base height	1	Calibration Uncertainty	± 10 m
Vertical visibility	1	Calibration Uncertainty	± 10 m
Backscatter profile, range and sensitivity normalized	1	Calibration Uncertainty	± 0.1 $(10000 \times sr \times km)^{-1}$
Total Sky Imager (TSI) – Yankee Environmental Systems, Model TSI-660			
Fractional sky coverage - visible	1	Calibration Uncertainty	< ± 10%
Infra-Red Sky Imager (IRSI)			
Fractional sky coverage - infrared	1	Calibration Uncertainty	± 0.5%
Fractional sky coverage - visible	1	Calibration Uncertainty	< ± 2.0%
Lead Mentor: Newsom, Rob			
Raman Lidar (RL) – Continuum and ORCA Photonics			
Water vapor mixing ratio	1	Calibration Uncertainty	< ± 4% for heights < ± 5 km (nighttime); < ± 5% for heights < ± 4 km (daytime)
Doppler Lidar (DL) – Halo			
Radial velocities	1	Field Uncertainty	< ± 10 cm s^{-1} at high SNR (for SNR > 0.05 or -13 dB); generally < ± 20 cm s^{-1} in atmospheric boundary layer (height < ~ 2 km)
Lead Mentor: Reynolds, Mike			
Portable Radiation Package (PRP) – Remote Measurement & Research, Co.			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
GPS longitude, latitude position (Garman Model GPS17X)	1	Calibration Uncertainty	± 10m
Tilt compensation from pitch and angle roll (Precision Navigation, Inc., Model TCM2.5).	1	Calibration Uncertainty	± 0.2º for 1 minute mean
Longwave and shortwave irradiance computed from PSP and PIR sensors	1	Calibration Uncertainty	<1 W m^{-2}
Global (total) and diffuse radiation (Delta - T Devices Ltd. Model SPN-1	1	Resolution	± 0.6 W m^{-2}
Total horizontal direct and diffuse irradiances measured at 415, 500, 615, 673, 870, 940 nm (Yankee Environmental Systems, Inc.	6	Calibration Uncertainty	± 1 mv Uncertainty
Lead Mentor: Sedlacek, Art			
Particle Soot Absorption Photometer (PSAP) Model Radiance			
Particle absorbance, 60-s averaging time	1	Calibration Uncertainty	0.2 M m^{-1} for 2 σ at 60 s
Aethalometer (AETH) - Magee Science			
Particle absorbance	1	Resolution	± 100 ng m^{-3} for 5-min sampling periods
Cavity Attenuated Phase Shift Extinction Monitor (CAPS-PMEX) – Aerodyne Research, Inc.			
Total extinction	1	Calibration Uncertainty	<5%
Lead Mentors: Sengupta, Manajit			
Solar and Infrared Radiation Station (SIRS), and Sky Radiometers on Stand for Downwelling Radiation (SKYRAD)			
Direct normal (beam) irradiance (flux) for NIP model radiometer, with SIRS and SKYRAD making the measurement in the same manner	2	Field Uncertainty	± 3.0% (> 700 W m^{-2})
Diffuse horizontal (sky) irradiance (flux) for 8-48 model radiometer, with SIRS and SKYRAD making the measurement in the same manner	2	Field Uncertainty	+ 4.0% to -(4% + 2 W m^{-2})
Downwelling shortwave (global) irradiance (flux) for PSP model radiometer, with SIRS and SKYRAD making the measurement in the same manner	2	Field Uncertainty	+ 4.0% to -(4% + 20 W m^{-2}) for zenith < 80 deg;
Downwelling longwave (atmospheric) irradiance (flux) for PIR model radiometer, with SIRS and SKYRAD making the measurement in the same manner	2	Field Uncertainty	± (5.0% +4 W m^{-2})
Solar and Infrared Radiation Station (SIRS), and Ground Radiometers on Stand for Upwelling Radiation (GNDRAD)			
Upwelling shortwave (reflected shortwave) irradiance (flux) for PSP model radiometer, with SIRS and GNDRAD making the measurement in the same manner	2	Field Uncertainty	± 3.0% or 10 W m^{-2}

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Upwelling longwave (reflected/emitted longwave) irradiance (flux) for PIR model radiometer, with SIRS and GNDRAD making the measurement in the same manner	2	Field Uncertainty	± 2% or 2 W m^{-2}
Lead Mentor: Senum, Gunnar			
Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) Model DMT			
Concentration of particles 0.06-1 µm (counts per second)	1	Calibration Uncertainty	The larger of (1) ± 3% per absolute (1.53 reflective Index); or (2) ± 100 x square root of number of particles divided by number of particles; or (3) ± 3%
Hygroscopic Tandem Differential Mobility Analyzer (HTDMA) - Brechtel			
Particle size	1	Calibration Uncertainty	Greater of ± 7% or ± 100 × (number concentration/number concentration)$^{-2}$
Relative humidity	1	Calibration Uncertainty	± 10%
Humidigraph, Wet Nephelometer RH Control - TSI 3563			
Particle total scatter	1	Calibration Uncertainty	± 0.25 M m^{-1} (2 σ for 5-min sampling periods)
Relative humidity	1	Calibration Uncertainty	± 10%
Cloud Condensation Nuclei Counter - CCN-100 and CCN-200 (DMT)			
Nuclei counts per cubic centimeter	1	Calibration Uncertainty	The greater of ± 7% or ± 100 × (number concentration/number concentration)$^{-2}$
Cloud condensation saturation	1	Calibration Uncertainty	± 6%
(BNL) Impactor – 1 micron (Brechtel 8003) and 10 micron (Brechtel and 8006)			
50% cut-out diameter for 1 micron particles	1	Calibration Uncertainty	10%-15%
50% cut-out diameter for 10 micron particles	1	Calibration Uncertainty	10%-15%
Lead Mentor: Springston, Stephen			
Off-axis ICOS for CO ($CO/N_2O/H_2O$) - Los Gatos			
Carbon monoxide concentration	1	Calibration Uncertainty	Greater of ± 2 ppbv or ± 5% for 1-s sampling periods
Ozone Analyzer - TEI 49i			
Ozone concentration	1	Calibration Uncertainty	Greater of ± 2 ppbv or ± 5% for 4-s sampling periods
Oxides of Nitrogen Analyzer ($NO/NO_2/NO_y$ - Air Quality Design Ground NO_x			

Measurement	No.	Uncertainty Type	Uncertainty Estimate
NO, NO_2, and NO_y concentrations	3	Calibration Uncertainty	NO: greater of ± 0.01 ppbv (2 σ) or ± 5%; NO_2: greater of ± 0.03 ppbv (2 σ) or ± 5%; NO_y: greater of ± 0.05 ppbv (2 σ) or ± 5%, all at 15-s sampling periods
Sulfur Dioxide Analyzer - TEI 43i-TLE			
SO_2 concentration	1	Calibration Uncertainty	Greater of ± 0.5 ppbv (2 σ for 10-s sampling period) or ± 10%
Meteorology Sensors - Vaisala WXT520			
Wind speed, wind direction, temperature, barometric pressure, RH, and rainfall accumulation	6	Calibration Uncertainty	Wind speed: greater of ± 0.3 m s^{-1} or ± 3%; temperature: ± 0.2 to ± 0.7ºC at -50 to 60ºC; pressure: 0.5 hPa at 0-30ºC, ± 1 hPa at -52 to 60ºC; RH: ±3% at 0-90% RH, ±5% at 90-100% RH; rainfall accumulation = ± 5% (weather dependent); wind direction = ± 3% at resolution of 1 deg
Single Particle Soot Photometer (SP2) Model DMT			
Individual particle incandescence	1	Calibration Uncertainty	± 30%
Ambient Nephelometer (Neph) Model TSI 3563			
Particle light scattering coefficient	1	Calibration Uncertainty	± 0.25 M m^{-1} for 2 σ at 5 min
Lead Mentor: Stuefer, Martin			
Multi-Angle Snowflake Camera (MASC) – Fallgatter Technologies			
Camera images of snowflakes	1	N/A	
Snowflake fall speeds	1	Calibration Uncertainty	± 10%
CFH - DMT			
Frost point temperature (EN-SCI Environmental Science Cryogenic frost point hygrometer)	1	Calibration Uncertainty	± 0.2K
Lead Mentor: Walton, Scott			
SeaNav – iXSea Inc., HYDRINS			
Position accuracy real time with GPS	1	Calibration Uncertainty	± 0.3 m s^{-1}
Position accuracy port-processed with GPS	1	Calibration Uncertainty	± 0.25 m s^{-1}
Heading accuracy	1	Calibration Uncertainty	± 0.01 degree secant latitude
Roll and pitch dynamic accuracy	2	Calibration Uncertainty	0.01 deg
Heave accuracy	1	Calibration Uncertainty	The smaller of the two: 2.5 cm or 2.5%

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Lead Mentor: Watson, Tom			
Aerosol Chemical Speciation Monitor (ACSM) - Aerodyne			
Particle mass and concentration	1	Calibration Uncertainty	± 10%
Particle-into-Liquid Sampler-Ion Chromatograph-Total Organic Carbon (PILS-IC-TOC) - Brookhaven National Laboratory			
Concentrations (μg m^{-3}) of NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, oxalate, Br^-, and PO_4^{3-} or total organic carbon (TOC)	11	Calibration Uncertainty	± 15% (for sampling periods of 15 min for ions; 5 min for TOC)
Proton Transfer Reaction Mass Spectrometer (PTRMS) - Ionicon Hi-Res			
Benzene, toluene, xylenes, isoprene, methylvinyl ketone/methacrolein, pinene, sesquiterpenes, formic acid, acetic acid, methanol, acetonitrile, and species requested by users	11	Calibration Uncertainty	± 20% for surface measurements at 1-min sampling periods
Lead Mentors: Widener, Kevin; Bharadwaj, Nitin			
C-Band ARM Precipitation Radar (CSAPR) – Advanced Radar Corporation (CSAPR1) and Baron Services (CSAPR2)			
Absolute reflectivity, Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 4 dB; Doppler velocity = ± 1.0 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width to be determined (TBD); dual-polarization parameters TBD
X-Band Scanning ARM Precipitation Radar (XSAPR) – Radtec Engineering (XSAPR1) and Barons Services (XSAPR2)			
Absolute reflectivity, Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity= 4 dB; Doppler velocity= ± 1.0 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
X-Band Scanning ARM Cloud Radar (XSACR) – Prosensing Inc.			
Absolute reflectivity, Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 3 dB; Doppler velocity = ± 1.0 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
Ka-Band Scanning ARM Cloud Radar (KASACR) – Prosensing Inc.			
Absolute reflectivity, Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 3 dB; Doppler velocity = ± 0.1 m s^{-1}

Measurement	No.	Uncertainty Type	Uncertainty Estimate
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
Ka ARM Zenith Radar (KAZR) – Prosensing Inc.			
Absolute reflectivity; Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 4 dB; Doppler velocity = ± 0.1 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
Scanning ARM Cloud Radar, tuned to W-Band, 95GHz (WSACR) – Prosensing Inc.			
Absolute reflectivity; Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 3 dB; Doppler velocity = ± 0.1 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
W-Band (95 GHz) ARM Cloud Radar (WACR) — Prosensing Inc.			
Absolute reflectivity; Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 4 dB; Doppler velocity = ± 0.1 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
W-Band (95 GHz) ARM Cloud Radar, mounted to scan (SWACR) – Prosensing Inc.			
Absolute reflectivity; Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity = 3 dB; Doppler velocity = ± 0.1 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD
Marine W-Band (95 GHz) ARM Cloud Radar (MWACR [SWACR on stabilized platform]) – Prosensing Inc.			
Absolute reflectivity; Doppler velocity	2	Calibration Uncertainty	Absolute reflectivity= 3 dB; Doppler velocity = ± 0.1 m s^{-1}
Spectral width and dual-polarization parameters (differential reflectivity, correlation coefficient, differential phase, specific differential phase)	5	None	Spectral width TBD; dual-polarization parameters TBD

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