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# A Unified Approach for Reporting ARM Measurement Uncertainties Technical Report

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ARM
CLIMATE RESEARCH FACILITY

## DISCLAIMER

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# Acronyms and Abbreviations

| | |
|---|---|
| AOS | aerosol observing system |
| ARM | Atmospheric Radiation Measurement |
| DQO | Data Quality Office |
| NIST | National Institute of Standards and Technology |
| RH | relative humidity |
| WISG | World Infrared Standard Group |
| WRR | World Radiometric Reference |

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# 1.0 Introduction

The 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. The ARM Facility currently provides data and supporting metadata (information about the data or data quality) to its users through a number of sources. Because the continued success of the ARM Facility depends on the known quality of its measurements, the Facility relies on instrument mentors and the ARM Data Quality Office (DQO) to ensure, assess, and report measurement quality. Therefore, an easily-accessible, well-articulated estimate of ARM measurement uncertainty is needed.

Note that some of the instrument observations require mathematical algorithms (retrievals) to convert a measured engineering variable into a useful geophysical measurement. While those types of retrieval measurements are identified, this study does not address particular methods for retrieval uncertainty. As well, the ARM Facility also provides engineered data products, or value-added products, based on multiple instrument measurements. This study does not include uncertainty estimates for those data products.

We propose here that a total measurement uncertainty should be calculated as a function of the instrument uncertainty (calibration factors), the field uncertainty (environmental factors), and the retrieval uncertainty (algorithm factors). The study will not expand on methods for computing these uncertainties. Instead, it will focus on the practical identification, characterization, and inventory of the measurement uncertainties already available in the ARM community through the ARM instrument mentors and their ARM instrument handbooks.

As a result, this study will address the first steps towards reporting ARM measurement uncertainty: 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. However, current meteorology guidelines (WMO 2012) consider the term accuracy simply as a qualitative term, and the numerical expression of accuracy to be the uncertainty. Similarly, current metrology practices (GUM 2008) define *accuracy* simply as a concept rather than a numerical value. The reason is that *accuracy* is defined from a comparison between a measured quantity value and its corresponding true quantity value, and this truth is impossible to quantify, i.e., true values are undefined.

True values are often equalized to calibration references or standards. However, recall that each calibration reference possesses an uncertainty itself. As well, instrument calibrations are usually performed in a controlled environment that can be much different from the normal operating environment in the field in which the observations are being made. In fact, there are likely additional known environmental factors that are hard to quantify (such as meteorological conditions changing more rapidly than instrument sampling conditions, or the presence of materials and chemical substances in the atmosphere that potentially interfere with an observation). There are other unknown environmental factors discovered in time that are not accounted for during instrument calibration.

For these reasons, we find the term *accuracy* and *true value* of little practical worth, and this study will avoid the term *accuracy* and *true value* when reporting measurement uncertainties. The term *measurand*—defined as the quantity *intended* to be measured—is used rather than the *true value* of a quantity (GUM 2008).

Ideally, if all sources of measurement errors of an instrument are known individually and can be measured, then the full uncertainty of a measurement can be determined. Rarely are both of these conditions satisfied. As an alternative, instrument measurement comparisons with a calibration reference are typically used to represent the ensemble of all measurement errors. However, to characterize total measurement uncertainty, the calibration must be performed in the instrument's normal operating environment—in the field.

Systematic and random errors are the two sources of error generally considered for measurements, as both types of errors appear in all the stages of a measurement. One can represent these as the mean difference (systematic) and standard deviation (random) from a series of comparisons with the calibration reference. Then, the known systematic errors are used (immediately or during post processing) to correct the result of a measurement, while the random errors (providing dispersion to the measurement values) are used to compute the uncertainty. Sometimes the known systematic errors are not corrected for, but rather incorporated as an uncertainty component. In other words, the known systematic error is simply included in the square root of the sum of the squares of the systematic and random errors.

It is highly desirable to correct individual measurements for systematic errors so that the individual biases are not carried through in the development of engineered data products, retrievals, or data assimilation algorithms. If these random and systematic errors cannot be determined directly, they can be provided from the peer-reviewed literature or even roughly estimated by a subject-matter expert.

There are also unknown systematic errors; those unable to be determined by the calibration, such as sporadic environmental factors. These unknown systematic errors are incorporated implicitly in the measurement uncertainty as the sporadic changes in the standard deviation of the measurement series.

In practice, an important first establishment of uncertainties is done when calibrating an instrument (Figure 1), before deploying it to the field, in order to optimize the instrument performance (by determining and applying a correction factor, from the closeness of agreement between the instrument measurement and the calibration reference values) and *precision* (closeness of agreement between replicate measurements). Then, after applying the *correction factor* to the subsequent measurements, the value of the *calibration precision* is used to represent *calibration uncertainty*. In general, the characterization of uncertainties during calibration is performed under ideal conditions, such as controlled laboratory environments or homogeneous field environments. It is practically impossible to completely address all the sources of uncertainties of the measurement in an operational context. Therefore, one should not expect that a calibration of the instrument will provide the total uncertainty for the operational measurements in the field.

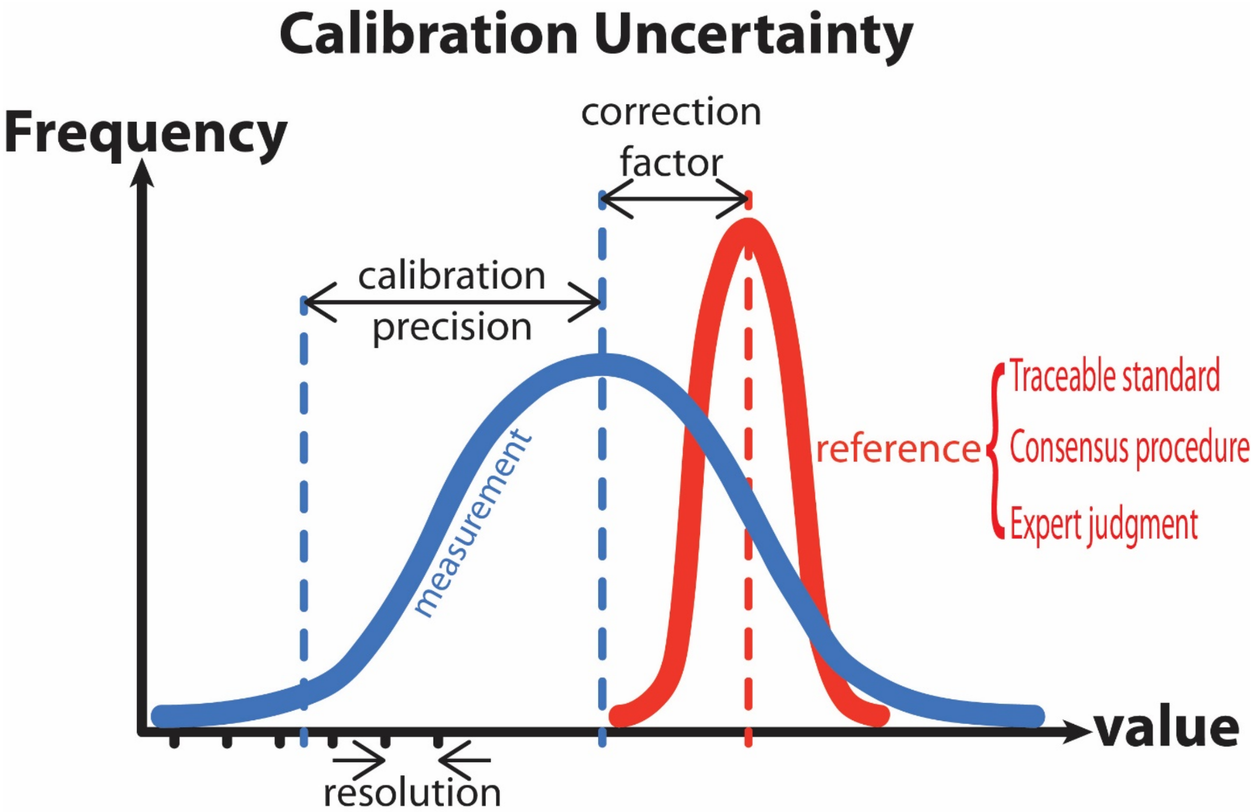



**Figure 1.** Conceptual model for uncertainty classes during calibration. The definitions of calibration uncertainty (precision) and resolution are used here to define ARM measurement uncertainty families. Other categories are not illustrated: field uncertainty, other, and none.

Once the instrument is calibrated, corrected, and returned to its normal operating setting in the field, its measurement uncertainty can change due to other environmental factors not accounted for during instrument calibration, such as sensor operational limitations, instrument maintenance, and the natural variability of the measured quantity. Examples of environmental conditions that affect instrument performance include temperature, humidity, or pressure conditions that are significantly different in the instrument field shelter than those experienced during the calibration. The environmental conditions can also change faster than the instrument sampling conditions, which make the field sample representativeness to differ from the calibration sample representativeness. Other environmental factors include dust collecting on radiometer domes that artificially filter sunlight, as well as atmospheric or chemical contaminates that interfere or interact with the sampling. Additional sources of uncertainties include instrument maintenance and aging, which can affect the sensor response. A change in sensor response can also affect the measurement representativeness, and a change in representativeness in some cases could affect the measurement uncertainty. There are likely other unknown factors that can affect the measurement uncertainty for an instrument under field operational conditions.

In order to determine total measurement uncertainty, assessment of environmental factors is required in the field, where the *field uncertainty* also corresponds to unknown systematic errors and known random errors (Figure 2).

If one could identify and determine *field systematic errors* (e.g., by comparison with a traceable standard, consensus procedure, or expert judgment), then these systematic errors become known, and these should be treated as field correction factors, but not as part of the *field uncertainty* value. However, a measurement reference comparison is generally difficult to implement in the field.

There are known field errors for many measurements that can be mitigated using instrument accessories (e.g., radiation shields and aspirators that reduce sensor heating on thermometers, ventilators that reduce heating and dew formation on radiometers, etc.). As well, many of the largest and most common field errors can be minimized or mitigated partly by following recommended procedures for operating instruments in the field (provided by vendors), or by applying corrections factors (provided from the specialized literature). However, one cannot expect that all measurement errors from environmental factors have been identified and evaluated.

Therefore, for our analysis, we can approximate the field uncertainty as being equal to the field precision, especially if the largest systematic errors have been already minimized prior and during field operations. Also if correction has been applied to the data for known, the remaining unknown systematic errors should be less dominant than the field random errors for a freshly calibrated and well characterized instrument (Figure 2).

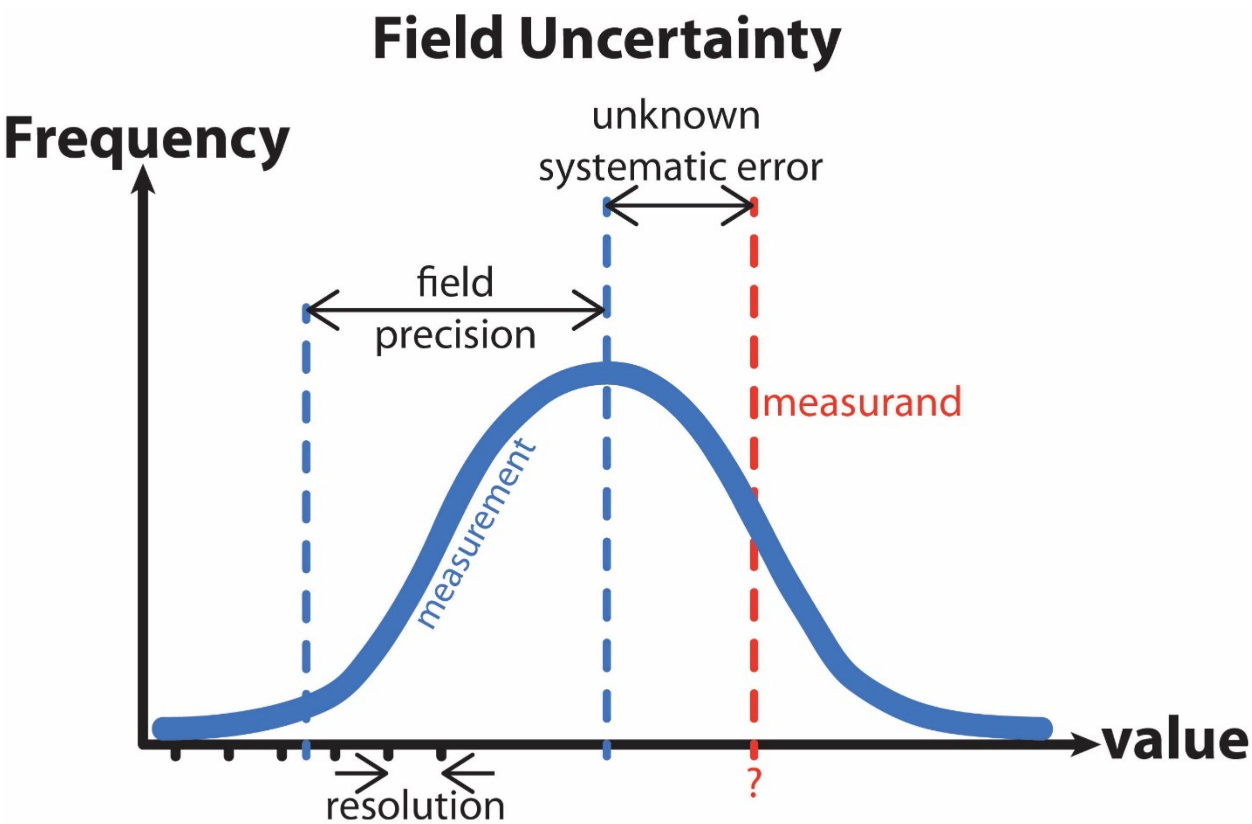



**Figure 2.** Conceptual model for uncertainty classes during field operation.

Thus, after correcting the measurements for known systematic errors, one finds the two most practical options for expressing the uncertainty of a measurement as: 1) the random errors (precision) estimated during comparisons between a measured value and a reference quantity value of the variable (calibration uncertainty) or 2) the reproducibility of the variable, as measured with a well-calibrated instrument operating under field conditions (field uncertainty).

Again, calibration uncertainty is often performed under ideal conditions and simply provides an estimate of the instrument's contribution to measurement uncertainty, by comparing its measurements with a reference. However, frequent instrument calibration is important because it can be used to assess additional sources of instrument uncertainties such as the inherent issues of time response, temperature response, spectral response, and aging. In other words, systematic and random errors may not be constant for the lifetime of the instrument.

Field uncertainty, on the other hand, is a more dynamic value that depends on the natural variability of the measured variable under a range of complex meteorological conditions during the sampling period, as well as the field performance of the instrument. Assessment of field uncertainty is becoming the current practice in metrology, and it is usually expressed numerically by measures of imprecision (such as a function proportional to standard deviation). Instrument response time and sampling period, as well as the temporal change in environmental conditions, measurement setup and maintenance, can affect the representativeness of a measurement in the field. A change in measurement representativeness also affects measurement uncertainty. A more complete uncertainty estimate than provided only by instrument calibration requires many environmentally-representative measurements by a well-calibrated instrument running in the normal operating environment. The resulting mean and standard deviation of these representative measurements can be used to define measurement field uncertainty. By this definition, measurement field uncertainty represents the most complete estimate of measurement uncertainty during field operations, even though the individual error terms are not necessarily known. The challenge for reporting measurement *field uncertainty* is in defining the environmentally representative conditions because the atmospheric conditions being sampled vary over a considerable range of temporal and spatial scales. Therefore, the uncertainty in a measured quantity can be different over different measurement intervals.

The most complete representation of total measurement uncertainty would be expressed in our study as *field uncertainty* for well-calibrated sensors, in accordance with the internationally accepted protocols for computing Expanded Uncertainty (GUM 2008). Ideally, all instruments would produce measurements that could be traced back to international prototypes (Newell 2014) of the units in the International Systems of Units (http://www.bipm.org/en/si/). This traceability can be achieved using comparisons with standards maintained by the National Institute of Standards and Technology (NIST; http://www.nist.gov), and by the World Radiometric Reference (WRR; http://www.pmodwrc.ch/pmod.php?topic=wrc), or by internationally accepted consensus reference, e.g., the World Infrared Standard Group (WISG; http://www.pmodwrc.ch/pmod.php?topic=irc),. Although this is a desirable goal, it is a particularly difficult challenge for the wide range of remote and in situ instruments commonly used for atmospheric measurements by researchers, as well as the ARM Climate Research Facility.

To further complicate the issue of measurement uncertainty, some ARM instruments require implicit assumptions (a retrieval algorithm) to generate a meaningful or useful observation. For these instruments, the uncertainty of the retrieval must also be determined. There is often no traceable reference standard for retrievals. However, retrievals are usually vetted through the peer review process for publications, and therefore retrieval uncertainties can be estimated.

We then need to classify the variety of uncertainty estimation methods available in the ARM measurement uncertainty reports. One reason is that this classification will assess our state of knowledge about the uncertainties with ARM measurements in order to focus later work. Another reason is that the classification will help to determine which ARM measurements have their uncertainty dominated by limitations in calibration or field procedures, and this will allow better operational protocols for quality assurance. Finally, the classification will facilitate data exchange and usage among the many ARM stakeholders, including numerical modelers, climatologists, and risk managers. The details on how we proceed with this first classification of ARM measurement uncertainty follow.

# 3.0 Methods

## 3.1 Data Set

This study 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 at that time. We asked each mentor to prepare a PowerPoint slide that characterized their instrument's uncertainty. We had 100% participation from the instrument mentors. We used instrument mentor handbooks, vendor manuals, electronic mail, and follow-up calls to clarify the information provided in the instrument mentor slides.

In order to objectively assess the state of affairs, we deliberately did not share our uncertainty background information (given earlier in section 2) nor our conceptual model for uncertainty classification (given later in section 3.2). We took the mentors' characterizations of instrument uncertainty, which resulted in a rich, yet dissonant collection of uncertainty methods, and harmonized these uncertainty assessments using a single framework: our conceptual model (section 3.2, below). Then, we shared the classification results and report drafts with each mentor for feedback and comment.

Although the ARM Facility uses over well 300 instruments systems and provides well over 2500 individual measurements for all ARM fixed sites and mobile facilities, identical instruments and measurements are typically duplicated. For this study, we provide information for particular raw datastreams (measurements) from unique instruments and not the retrieved values. Our sample size was the 321 unique datastreams available in year 2012. This does not include all current ARM instruments, because several new instruments have been implemented since 2012.

## 3.2 Conceptual Model

The large number of ARM measurements opens many possibilities for classifying uncertainties. As a strategy, we classified each estimate of measurement uncertainty as follows:

- *Calibration uncertainty* (or instrument uncertainty), which corresponds to instrument calibration, use of well-established calibration references, and performance under ideal conditions to constrain known measurement errors.

- *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.

- *Resolution*, which corresponds to the minimum detectable signal or instrument response.

- *None*, which indicates that measurements have unknown uncertainty. That is, no estimates could be provided, because the instrument had not been characterized.

- *Other*, which indicates 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.

Our classification method, conceptually modeled in Figures 1 and 2, is actually a hierarchical approach towards a more confident measurement uncertainty (Table 1). This confidence rating scheme is not based on the actual uncertainty values (i.e., on the quantities) provided for the measurement, but rather based on how the uncertainty values were derived (i.e., on the method).

By our classification definitions, the *none* category is at the lowest end of measurement confidence because the uncertainty is completely unknown. The resolution category follows, as it well characterizes instrument detection limits, but it does not address errors for the reported measurements that are within the detection range. Furthermore, we are not able to discern if a *resolution* value corresponds to an over estimate or under estimate of the true measurement uncertainty. Therefore, confidence, as a characterization method of measurement uncertainty, is relatively low for the *resolution* category. The *other* category identifies measurement errors, but it does not provide sufficient information to determine how these errors were specifically estimated (it is not clear if errors contributing to the measurement uncertainty were obtained by generally accepted methods). We are not able to discern if the *other* value is best represented as *calibration uncertainty* or *field uncertainty*. However, our confidence on uncertainty estimation methods in the *other* category is better than with methods in the *resolution* category, because an instrument authority (mentor or vendor) has made an effort to assess instrument errors for the *other* category. The *calibration uncertainty* category gives the most complete assessment for instrument errors in a controlled setting, but reproducibility of results of measurements in the instrument's operating environment (in the field) is not known. Thus, our confidence on the uncertainty estimation method is higher if the uncertainty estimate is classified as *calibration uncertainty* than if it is classified in the *other* category. The *field uncertainty* category is at the highest end of our uncertainty method confidence because its uncertainty value gives the most complete consideration of measurement errors and reproducibility in normal field conditions.

**Table 1.** Hierarchical approach for uncertainty estimation methods.

| Uncertainty class | Method confidence |
|---|---|
| Field uncertainty | Highest |
| Calibration uncertainty | Good |
| Other | Fair |
| Resolution | Low |
| None | Lowest |

In summary, our hierarchy of uncertainty types is such that

$$None < Resolution < Other < Calibration\ uncertainty < Field\ uncertainty. \quad (1)$$

Figure 3 presents four examples of the strategy used in this study. The Uncertainty Type column in Figure 3 indicates the higher-order uncertainty type reported by the instrument mentor. Particular values of the Uncertainty Estimate column in Figure 3 also depend on instrument sampling periods. Further details on the *calibration uncertainty*, *field uncertainty*, and *other* categories are given in the next subsection.

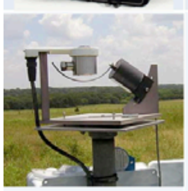
| | Instrument | Measurement | Uncertainty Estimate | Uncertainty Type |
|---|---|---|---|---|
|  | Flask Samplers for Carbon Cycle Gases and Isotopes **(FLASK)** | Isotope Ratio: $C^{13}(O^{16})_2$ / $C^{12}(O^{16})_2$ | ± 0.03% | Field uncertainty: the variability of field samples, estimated when the field samples are brought into the lab. Calibration is done previously using a consensus procedure. |
|  | Multifilter Rotating Shadowband Radiometer **(MFRSR)** | Clear Skies total horizontal irradiance | ± 2.1 % | Calibration uncertainty: Calibration reference from consensus procedure, using traceable standards (NIST) and consensus procedure (Langley plots). |
|  | C-band Scanning Precipitation Radar **(C-SAPR)** | Absolute Reflectivity | 4 dB | Other: Combination of calibration of various components, literature review, and expert opinion. Calibration is highly idealized, assumes no atmospheric losses, a known target in the far field, the return is from the target only, and no multi-path to the target. |
|   | Rain Gauge – Belfort Model AEPG 600 Weighing Bucket | Rainfall amount (accumulation) | ± 0.25mm (0.01 inches) | Resolution (minimum detectable signal) |

**Figure 3.** Examples of four classes of ARM measurement uncertainties. Uncertainty type column indicates the higher-order uncertainty type reported by the instrument mentor.

### 3.2.1 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 NIST, WRR, or 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 providing a well-defined calibration reference.

### 3.2.2 Field Uncertainty

For the uncertainty to be reported as *field 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, section 7.2) 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 described in the manufacturer specification, the results of a calibration of instrument under ideal conditions, data loggers specification, maintenance, sample time and cable losses, need for radiation shields, and engineering judgement.

### 3.2.3 Other

For the uncertainty to be reported as *other*, information about the calibration reference was insufficient to assign the category as *field uncertainty*, *calibration uncertainty*, *resolution*, or *none*. In addition, some instruments require the use of an algorithm to retrieve a geophysical value from the instrument measurement. That is the case of many remote-sensing estimates. Even if a procedure from a peer-reviewed article is used to assess retrieval errors, the retrieval uncertainty was classified as *other* in this case, partially because of non-robust calibration references and to indicate that others might use different retrieval error estimates to provide the desired measurement uncertainty. Therefore, the class *other* corresponds to uncertainty estimates that have one of the following characteristics:

- Use of a retrieval to obtain a desired measurement.

- Calibration references are *unknown* (e.g., instrument vendor or mentor does not detail the practice used for obtaining a calibration reference).

- Calibration references are *non-robust* (e.g., a mix of several theoretical and/or empirical error contributions, or retrievals).
- Calibration references are *unresolved* (e.g., the combination of *resolution*, *calibration uncertainty*, and/or *field uncertainty* values does not fit uniquely into our uncertainty categories).

# 4.0 Results

Appendix A shows the individual ARM Instruments, the ARM instrument mentors for the instruments at the time of the study, the instrument measurements, the measurement uncertainty estimates, and our classification of the higher-order 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 datastream, 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 in Appendix A, the 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 applied to the data as appropriate.

Mentors provided uncertainty expressions for the most important and widely used raw datastreams, but not always for all datastreams from an instrument. For example, a 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 mentors did not recommend the use of these parameters as primary ARM datastreams because the vendor classification scheme was not described well enough for the mentors to have confidence in the results. Therefore, we did not include uncertainty estimates for measurements not recommended by the mentors even though they are available for the instrument by the vendor.

Also, for aerosol measurements, the ARM Facility has two aerosol observing systems (AOSs) with almost-identical particle measurement instrumentation but slightly different internal configurations. In this case, two different mentors for an identical instrument have reported the characterization of measurement uncertainty differently. A common reason for this difference is on how they calibrated their specific instrument. Therefore, our classification of uncertainty type for two identical instrument measurements will be different if the 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 is 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 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.

Figure 4 summarizes the distribution of instrument uncertainty measurements by uncertainty classification. The results show that uncertainty is provided as *resolution* for nearly 4% of the samples (12 measurement types), as *field uncertainty* for about 3% (10 measurements), as *calibration uncertainty* for nearly 40% (127 measurements), as *none* for almost 15% (47 measurements, because the instruments had not been fully characterized to estimate measurement uncertainty), and as *other* for nearly 39% (125 measurements). For the measurement uncertainties classified as *other*, 44 measurement types had *non-robust* calibration references, 14 measurements had *unresolved* calibration references, and 67 had *unknown* calibration references.

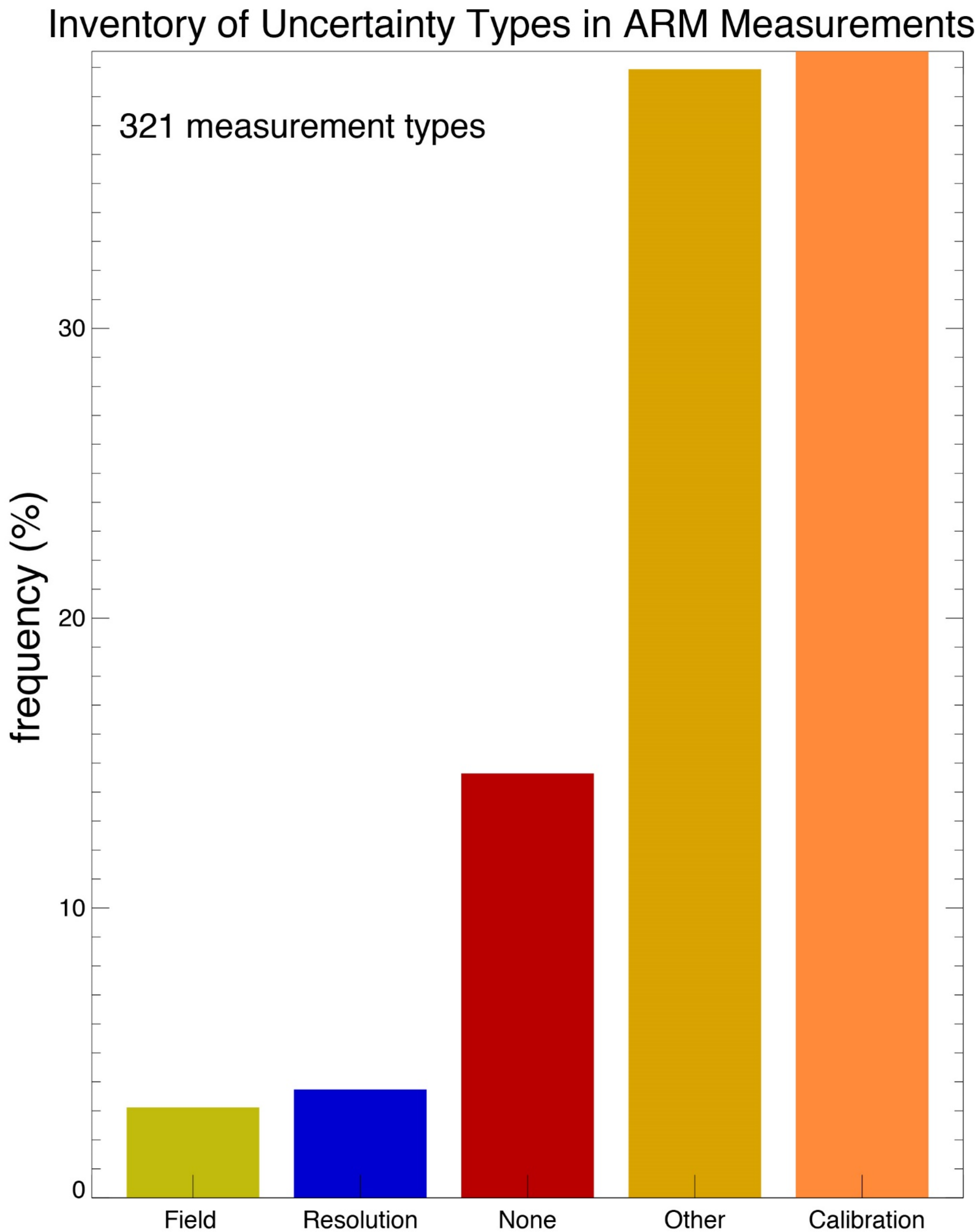



**Figure 4.** Distribution of instrument uncertainty measurements by uncertainty classification.

While over 78% of all measurements provide uncertainty as an assessment of instrument and/or retrieval errors, usually as instrument calibration in an idealized environment (*calibration* and *other*), only 40% had well-established calibration references (*calibration uncertainty*). Generally speaking, we could characterize the *other* category as an incomplete description of instrument calibrations as provided by the mentor. Therefore, further investigation and successful resolution of instrument-specific issues, identified as *other*, would improve the counts for instrument uncertainties classified as *calibration uncertainty*.

Most of the measurements in the *none* category are attributed to instruments that were relatively new at the time. For example, with the ARM cloud and precipitation radars, the spectral width and dual-polarization uncertainty estimates would 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. They represent the bulk of the *none* category.

# 5.0 Discussion and 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), the challenges of implementing these methodologies for the range of instrumentation deployed at the ARM Climate Research Facility are daunting. Therefore, this study is only a first step in 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 characterized so that they can be used to determine comparability with similar measurements made by others.

The 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 *other*, respectively. The minimum acceptable representation (*low* confidence) of measurement uncertainty for the ARM measurements corresponds to *resolution*, for which the estimates consider instrument response time, sampling interval, and minimum detectable signals.

This study classifies a representative sample of ARM measurement uncertainties according to the higher-order uncertainty type reported by instrument mentors. Near 3% of the ARM measurement uncertainties analyzed here fall under the *field uncertainty* category, and roughly 4% fall under the *resolution* category.

From our study, the majority (nearly 85%) of ARM measurement uncertainties are described systematically and do not fall in the *none* category. We found uncertainty estimates using well-established calibration references for nearly 40% 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 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.

Because the relatively new ARM radars have not all been yet fully characterized, about 14% 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.

Field estimates of measurement uncertainty are dynamic in time and space, and they also have dependencies on multiple environmental factors and instrument sampling periods. Examples are the range variability in measurement uncertainty of relative humidity measurements from radiosonde launches and the time variability in measurement uncertainty of hourly temperature measurements from surface sensors.

On several occasions, we approached instrument mentors for more information about calibration references for their specific instruments. Most of the mentors relied upon vendor information. This was often insufficient for this study, because vendors did not always document how the expression for uncertainty was determined. This problem is exacerbated by vendor proprietary software issues regarding data pre-processing done by the instrument. Further interactions among instrument vendors and mentors are needed to reduce the number of *other* and *none* uncertainties. In addition, some instrument measurements required the use of algorithms to provide useful information. Instrument mentors did not always provide the calibration references of algorithm uncertainty estimates. Resolution of instrument-specific issues identified as *other* would allow these cases to be classified as *calibration uncertainty*.

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 the ARM Facility 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.

# 6.0 Future Work

Properly quantifying and expressing measurement uncertainties poses a significant challenge as well as an opportunity for the near future. In the short term, it would be advantageous to resolve the issues that caused measurement uncertainties to be classified as *other*. Most of this category (67 measurement types with unknown calibration references) was attributed to incomplete description of calibration methodology. Nearly all of the measurement uncertainties in the *other* category could likely be re-classified as *calibration uncertainty*. The use of *calibration uncertainty* uncertainties are common practice for data assimilation in numerical modeling, which is an important target for ARM-Facility-related science. However, this re-classification (from *other* into *calibration uncertainty*) would involve more extensive interactions with mentors and vendors.

For all measurements in the *calibration uncertainty* class, it is highly desirable 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 reanalyses of radiative transfer variables.

Most (97%) of the ARM measurements to date have not yet been characterized in terms of *field uncertainty*. This is not a problem that is unique to ARM measurements, by any means. What is unique is that the long-term measurement records by the ARM Facility provide an opportunity to investigate the interactions among various environmental factors and the *field uncertainty*. This characterization (in terms of *field uncertainty*) is not easy and would take considerable effort (resources) in the long term. However, such steps would be needed to address the guidelines of higher metrology standards of the expression of uncertainty, consistent with GUM (2008), and provide the most complete description of measurement uncertainty. This is not a trivial task. However, because the ARM Facility has provided continuous measurements for nearly two decades, it is feasible that *field uncertainty* studies for all measurements will be undertaken. It is suggested that a subset of ARM instruments could be targeted to determine methods for assessing field measurement uncertainty.

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 References

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# Appendix A

# Uncertainty Types for ARM Facility Instruments Used in 2012 and Analyzed for This Study

**Table A.1** ARM Instrument Uncertainties Reported by Instrument Mentors for Instrument Systems.

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Mentor: Gary Hodges | | | |
| *Yankee Environmental Systems, Inc., Multifilter Rotating Shadowband Radiometer (MFRSR)* | | | |
| 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 | ± 4.3% |
| Spectral irradiance at 500 nm | 1 | Calibration uncertainty | ± 4.1% |
| Spectral irradiance at 615 nm | 1 | Calibration uncertainty | ± 4.0% |
| Spectral irradiance at 673 nm | 1 | Calibration uncertainty | ± 4.0% |
| Spectral irradiance at 870 nm | 1 | Calibration uncertainty | ± 4.0% |
| Spectral irradiance at 940 nm | 1 | Calibration uncertainty | ± 4.0% |
| Aerosol optical depths | 1 | Calibration uncertainty | ± 0.005 + 0.01 $m^{-1}$ |
| Mentor: Daniel Hartsock | | | |
| *Campbell Scientific, Inc., Model 229L Matric Potential Sensor, Soil Water and Temperature System (SWATS)* | | | |
| 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 $m^3$ $m^{-3}$ |
| Mentor: Mike Ritsche | | | |
| *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% |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| *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;<br>± (1.2 + 0.012 x reading)% for -40 to -20ºC;<br>± (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 |
| 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.* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| 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 | Other | ± 10% for 10 m to 20 km |
| *Chilled Mirror Hygrometer, Technical Services Laboratory Model 1088* | | | |
| Temperature | 1 | Other | ± 0.5ºF (-58 to 122ºF), ± 1º in rest of range |
| Dew point | 1 | Other | ± 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 | Other | ± 0.2ºC |
| Frost point | 1 | Other | ± 0.2ºC |
| *Datalogger, Campbell Scientific Model CR10/10X* | | | |
| Voltage measurements | 1 | Other | ± 0.1%, full scale range |
| Excitation accuracy | 1 | Other | ± 5 mV (-25 to 50ºC) |
| Resistance measurement | 1 | Other | ± 0.02%, full scale input |
| *Datalogger, Campbell Scientific Model CR23X* | | | |
| Voltage measurements | 1 | Other | ± 0.075%, full scale range |
| Excitation accuracy | 1 | Other | ± 5 mV (-25 to 50ºC) |
| Resistance measurement | 1 | Other | ± 0.02%, full scale input |
| *Datalogger, Campbell Scientific Model CR3000* | | | |
| Voltage measurement | 1 | Other | ± 0.09, full scale range (-40 to 85ºC) |
| Voltage output (Vx) | 1 | Other | ± 0.09% + 0.5 mV (-40 to 85ºC) |
| Resistance output (Ix) | 1 | Other | ± 0.15% + 0.5 µA (-40 to 85ºC) |
| Resistance measurement | 1 | Other | ± 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* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Temperature | 1 | Calibration uncertainty | ± 0.2ºC |
| Mentor: David Cook | | | |
| *Energy Balance Bowen Ratio (EBBR) System* | | | |
| 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% |
| Soil temperature | 1 | Calibration uncertainty | ± 1% |
| *Surface Energy Balance System (SEBS)* | | | |
| 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 | Other | ± 7% |
| *Facility-Specific Multi-Level Meteorological Instrumentation (TWR): SGP Tower* | | | |
| Air temperature | 1 | Other | ± 1% |
| Relative humidity | 1 | Other | ± 3% |
| Vapor pressure | 1 | Other | ± 3% |
| *Eddy Covariance Flux System (ECOR)* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| 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) |
| Mentors: Sebastian Biraud, Marc Fischer | | | |
| *Carbon Dioxide Flux Measurement System (3-D Sonic Anemometer Gill Solent Windmaster Pro and Licor Inc. LI-7500, Infrared Gas Analyzer* | | | |
| 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 | Other | ~ ± 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) |
| Mentor: Maria Cadeddu | | | |
| *Radiometrics Corporation, Microwave Radiometer (MWR)* | | | |
| 23.8- and 31.4-GHz sky brightness temperature | 1 | Calibration uncertainty | ± 0.3 K |
| Precipitable water vapor (water vapor path) | 1 | Other | ± 0.5-0.7 mm |
| Liquid water path | 1 | Other | ± 0.02-0.03 mm |
| *Radiometrics Corporation, Microwave Radiometer – 3 Channel (MWR3C)* | | | |
| 23.834- and 30-GHz sky brightness temperature | 1 | Calibration uncertainty | ± 0.5-0.6 K |
| 89-GHz sky brightness temperature | 1 | Calibration uncertainty | ± 1.5 K |
| Precipitable water vapor (water vapor path) | 1 | Other | ± 0.5-0.7 mm |
| Liquid water path | 1 | Other | ± 0.01-0.02 mm |
| 90- and 150-GHz sky brightness temperature | 1 | Calibration uncertainty | ± 1.5 K |
| *ProSensing, Inc., G-band (183-GHz) Vapor Radiometer (GVR)* | | | |
| Brightness temperature (183.3 ± 1, 3, 7, 14 GHz) | 1 | Calibration uncertainty | ± 1.5-2 K |
| Precipitable water vapor (PWV; water vapor path) | 1 | Other | 3-4% (PWV < 10 mm) to ~ ± 10% (PWV > 10 mm) |
| Liquid water path | 1 | Other | ± 0.010-0.015 mm |
| *Radiometrics Corporation, G-band (183 GHz) Vapor Radiometer Profiler (GVRP)* | | | |
| Brightness temperatures at 15 channels, 170-183.3 GHz | 1 | Calibration uncertainty | ± 1.5 K |
| *Radiometrics Corporation, Microwave Radiometer Profiler (MWRP)* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| 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) | 1 | Other | ± 0.5-0.7 mm |
| Liquid water path | 1 | Other | ± 0.025-0.030 mm |
| Air temperature profile | 1 | Other | ± 1-2 K (at height 0-2 km) to ± 3-4 K (at height 10 km) |
| Vapor density profile | 1 | Other | ± 0.5-1 g $m^{-3}$ (at height 0-1 km) to 0.01-0.05 g $m^{-3}$ (at height 10 km) |
| Mentor: Mary Jane Bartholomew | | | |
| *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 | Other | ± 5% |
| *Impact Disdrometer – Joss-Walvogel's, Distromet Model RD-80* | | | |
| Drop diameter | 1 | Other | ± 5% |
| *2 Dimensional Video Disdrometer - VDIS - Joanneum Research* | | | |
| Drop diameter | 1 | Resolution | 0.19 mm |
| Drop velocity | 1 | Other | 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 | Not reported |
| Precipitation amount (accumulation) | 1 | Other | ± 5% for liquid; ± for solid |
| Precipitation rate | 1 | Resolution | Minimum detection, 0.001 mm $h^{-1}$ |
| Mentor: Laurie Gregory | | | |
| *Cimel Sunphotometer (CSPHOT)* | | | |
| 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% |
| Mentor: Donna Holdridge | | | |
| *Balloon-borne Sounding System (SONDE) - Vaisala RS92 Radiosonde* | | | |
| Temperature | 1 | Other | ± 0.5ºC |
| Relative humidity (with respect to liquid water) | 1 | Other | ± 5% at 0-100% |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Pressure | 1 | Other | ± hPa at 1080-100 hPa; ± 0.6 hPa at 100-3 hPa |
| Wind speed | 1 | Other | ± 0.15 m $s^{-1}$ |
| Wind direction | 1 | Other | ± 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 |
| Mentor: Victor Morris | | | |
| *Infrared Thermometer (IRT) – Heitronics KT19.85 II Infrared Radiation Pyrometer* | | | |
| Sky brightness temperature (Tsky) | 1 | Other | 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 | Other | 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 | Other | ± 0.1 $(10000 \times sr \times km)^{-1}$ |
| *Total Sky Imager (TSI) – Yankee Environmental Systems, Model TSI-660* | | | |
| Cloud fraction | 1 | Calibration uncertainty | < ± 10% |
| Mentor: Jessica Cherry | | | |
| *Total Precipitation Sensor (TPS or "Hotplate") – Yankee Environmental Systems* | | | |
| Precipitation liquid equivalent rate | 1 | Calibration uncertainty | ± 30% |
| Mentor: Anne Jefferson | | | |
| *Radiance Research, Particle Soot Absorption Photometer (PSAP)* | | | |
| 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 |
| *Continuous Light Absorption Photometer (CLAP), National Oceanic and Atmospheric Administration Design* | | | |
| Aerosol absorption coefficient (for 1-min averaged data) | 1 | Other | 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 |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| *Droplet Measurement Technologies Model 3010, Cloud Condensation Nuclei Particle Counter (CCN)* | | | |
| Supersaturation | 1 | Other | ± 0.05% |
| Particle number concentration | 1 | None | Not reported |
| *TSI Model 3563, Nephelometer* | | | |
| 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 |
| *TSI Model 3010, Condensation Particle Counter (CPC)* | | | |
| Aerosol particle number concentration | 1 | Other | ± 10% |
| Mentor: Richard Coulter | | | |
| *Micro Pulse Lidar (MPL)* | | | |
| Detected signal | 1 | Resolution | 1 photon per microsecond |
| Height | 1 | Resolution | 0.5 × range gate (15, 30, 75 m) |
| *Radar Wind Profilers (RWPs, 1290 and 915 MHz)* | | | |
| Wind speed | 1 | Other | < ± 1 $m s^{-1}$ |
| Wind direction | 1 | Other | < ± 10 deg |
| Height | 1 | Other | ~ ± 6m + 0.5 × range gate |
| Radial wind speed | 1 | Other | < ± 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)* | | | |
| Wind speed | 1 | Other | < ± 0.6 $m s^{-1}$ |
| Wind direction | 1 | Other | < ± 4 deg |
| Height | 1 | Other | 0.5 × range gate |
| Radial wind speed | 1 | Other | < ± 0.25 $m s^{-1}$ |
| Sodar signal | 1 | Resolution | -15 dB |
| Mentor: Jonathan Gero | | | |
| *Atmospheric Emitted Radiance Interferometer (AERI)* | | | |
| Atmospheric emitted spectral radiance (in watts per square meter per steradian per wavenumber) | 1 | Calibration uncertainty | < ± 1% |
| Mentor: Rob Newsom | | | |
| *Raman Lidar (RL)* | | | |
| Water vapor mixing ratio | 1 | Calibration uncertainty | < ± 4% for heights < ± 5 km (nighttime); < ± 5% for heights < ± 4 km (daytime) |
| *Doppler Lidar (DL)* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| 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) |
| Mentors: Margaret Torn, Sebastien Biraud, Marc Fischer, Joe Berry | | | |
| *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 |
| Mentor: Peter Kiedron | | | |
| *Rotating Shadowband Spectrometer* | | | |
| Direct normal solar spectral irradiance (W $m^{-2}$ $nm^{-1}$) | 1 | Other | ± 5% |
| Total horizontal solar spectral irradiance (W $m^{-2}$ $nm^{-1}$) | 1 | Other | ± 5% |
| Diffuse horizontal solar spectral irradiance (W $m^{-2}$ $nm^{-1}$) | 1 | Other | ± 5% |
| Mentor: Don Collins | | | |
| *Humidified Tandem Differential Mobility Analyzer (HTDMA)* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| 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 |
| 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)* | | | |
| 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 |
| Mentor: Stephen Springston — Systems Lead: Chongai Kuang | | | |
| *Condensation Particle Counter (CPC) Model 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% |
| Mentor: Stephen Springston — Systems Lead: Gunnar Senum | | | |
| *Ultra-High Sensitivity Aerosol Spectrometer (UHSAS) Model DMT* | | | |
| Concentration of particles 0.06-1 µm (counts per second) | 1 | Other | 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% |
| Mentor: Stephen Springston — Systems Lead: Chongai Kuang | | | |
| *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% |
| Mentor: Stephen Springston — Systems Lead: Art Sedlacek | | | |
| *Particle Soot Absorption Photometer (PSAP) Model Radiance* | | | |
| Particle absorbance, 60-s averaging time | 1 | Other | 0.2 M $m^{-1}$ for 2 $\sigma$ at 60 s |
| Mentor: Stephen Springston — Systems Lead: Gunnar Senum | | | |
| *Ambient Nephelometer (Neph) Model TSI 3563* | | | |
| Particle light scattering coefficient | 1 | Other | ± 0.25 M $m^{-1}$ for 2 $\sigma$ at 5 min |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Mentor: Stephen Springston — Systems Lead: Art Sedlacek | | | |
| *Single Particle Soot Photometer (SP2) Model DMT* | | | |
| Individual particle incandescence | 1 | Other | ± 30% |
| Mentor: Stephen Springston — Systems Lead: Manvdendra Dubey | | | |
| *Photo Acoustic Soot Spectrometer (PASS-3)* | | | |
| Particle absorption | 3 | Other | 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 | Other | 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) |
| Mentor: Stephen Springston — Systems Lead: Art Sedlacek | | | |
| *Aethalometer (Magee Science)* | | | |
| Particle absorbance | 1 | Resolution | ± 100 ng $m^{-3}$ for 5-min sampling periods |
| Mentor: Stephen Springston — Systems Leads: Fan Mei, Bill Behrens | | | |
| *Aerosol Chemical Speciation Monitor (ACSM) Model Aerodyne* | | | |
| Particle mass and concentration | 1 | Calibration uncertainty | ± 10% |
| Mentor: Stephen Springston — Systems Lead: Yin-Nan Lee | | | |
| *Particle-into-Liquid Sampler-Ion Chromatograph-Total Organic Carbon (PILS-IC-TOC, assembled from components)* | | | |
| 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) |
| Mentor: Stephen Springston — Systems Lead: Gunnar Senum | | | |
| *Hygroscopic Tandem Differential Mobility Analyzer (HTDMA), Model BMI* | | | |
| Particle size | 1 | Calibration uncertainty | Greater of ± 7% or ± 100 × (number concentration/number concentration)$^{-2}$ |
| Relative humidity | 1 | Other | ± 10% |
| *Humidigraph, Wet Nephelometer, Model RH Control, TSI 3563* | | | |
| Particle total scatter | 1 | Other | ± 0.25 M $m^{-1}$ (2 σ for 5-min sampling periods) |
| Relative humidity | 1 | Other | ± 10% |
| *Cloud Condensation Nuclei Counter (Models DMT CCN-100 for AMF2-AOS and ENA-AOS; DMT CCN-200 for MAOS A)* | | | |
| Nuclei counts per cubic centimeter | 1 | Other | The greater of ± 7% or ± 100 × (number concentration/number concentration)$^{-2}$ |
| Cloud condensation saturation | 1 | Other | ± 6% |
| Mentor: Stephen Springston — Systems Lead: Yin-Nan Lee | | | |
| *Proton Transfer Reaction Mass Spectrometer (Ionicon Hi-Res PTRMS)* | | | |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Benzene, toluene, xylenes, isoprene, methylvinyl ketone/methacrolein, pinene, sesquiterpenes, formic acid, acetic acid, methanol, acetonitrile, and species requested by users | 11 | Other | ± 20% for surface measurements at 1-min sampling periods |
| Mentor: Stephen Springston — Systems Lead: Stephen Springston | | | |
| *Off-axis ICOS for CO (Model Los Gatos $CO/N_2O/H_2O$)* | | | |
| Carbon monoxide concentration | 1 | Other | Greater of ± 2 ppbv or ± 5% for 1-s sampling periods |
| *Ozone Analyzer (Model TEI 49i)* | | | |
| Ozone concentration | 1 | Other | Greater of ± 2 ppbv or ± 5% for 4-s sampling periods |
| *Oxides of Nitrogen Analyzer ($NO/NO_2/NO_y$, model AQD Ground $NO_x$)* | | | |
| NO, $NO_2$, and $NO_y$ concentrations | 3 | Other | NO: greater of ± 0.01 ppbv (2 $\sigma$) or ± 5%; $NO_2$: greater of ± 0.03 ppbv (2 $\sigma$) or ± 5%; $NO_y$: greater of ± 0.05 ppbv (2 $\sigma$) or ± 5%, all at 15-s sampling periods |
| *Sulfur Dioxide Analyzer (TEI 43i-TLE)* | | | |
| $SO_2$ concentration | 1 | Other | Greater of ± 0.5 ppbv (2 $\sigma$ for 10-s sampling period) or ± 10% |
| *Meteorology Sensors (Vaisala WXT520)* | | | |
| Wind speed, wind direction, temperature, barometric pressure, RH, and rainfall accumulation | 6 | Other | 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 |
| Mentor: Connor Flynn | | | |
| *High Spectral Resolution Lidar (HSRL)* | | | |
| Particulate backscatter profile | 3 | Other | ± 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 | Other | ± 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 | Other | 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 |
| *Atmospheric Sounder Spectrometer for Infrared Spectral Technology (ASSIST)* | | | |
| Infrared spectral zenith radiance from channel A, wavelength 670-1400 $cm^{-1}$ | 1 | Other | Noise channel A < ± 0.2 mW $(m^2\ sr\ cm^{-1})^{-1}$ |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Infrared spectral zenith radiance from channel B, wavelength 2000-2600 $cm^{-1}$ | 1 | Other | Noise channel B < ± 0.015 mW $(m^2\ sr\ cm^{-1})^{-1}$ |
| *Shortwave Spectroradiometer (SWS)* | | | |
| 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)* | | | |
| 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 | Other | ± 10% or more |
| *Shortwave Array Spectroradiometer-Hemispheric (SASHE)* | | | |
| Hemispheric spectral radiances for two channels, 350-1000 nm and 970-1700 nm (same two spectroradiometers as SASZE) | 2 | Calibration uncertainty | ±1% to ±5% |
| Mentors: Kevin Widener, Nitin Bharadwaj | | | |
| *C-Band ARM Precipitation Radar (CSAPR)* | | | |
| Absolute reflectivity, Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity, Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity, Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity, Doppler velocity | 2 | Other | 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 |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| *Ka ARM Zenith Radar (KAZR)* | | | |
| Absolute reflectivity; Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity; Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity; Doppler velocity | 2 | Other | 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)* | | | |
| Absolute reflectivity; Doppler velocity | 2 | Other | 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])* | | | |
| Absolute reflectivity; Doppler velocity | 2 | Other | 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 |
| Mentors: Manajit Sengupta, Ibrahim Reda, Aron Habte, Mark Kutchenreiter, Peter Gotseff, Afshin Andreas, Mike Dooraghi | | | |
| *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 | Calibration 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 | Calibration 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 | Calibration uncertainty | + 4.0% to -(4% + 20 W $m^{-2}$) for zenith < 80 deg; |

| Measurement | No. | Uncertainty Type | Uncertainty Estimate |
|---|---|---|---|
| Downwelling longwave (atmospheric) irradiance (flux) for PIR model radiometer, with SIRS and SKYRAD making the measurement in the same manner | 2 | Calibration uncertainty | ± (5.0% +4 W $m^{-2}$) |
| *Solar and Infrared Radiation Station (SIRS), and Ground Radiometers on Stand for Upwelling Radiation (GNDRAD)* | | | |
| Upwelling longwave (atmospheric) irradiance (flux) for PIR model radiometer | 1 | Calibration uncertainty | ± (5.0% +4 W $m^{-2}$) |
| Upwelliing shortwave (reflected shortwave) irradiance (flux) for PSP model radiometer, with SIRS and GNDRAD making the measurement in the same manner | 2 | Calibration uncertainty | ± 3.0% or 10 W $m^{-2}$ |
| Upwelling longwave (reflected/emitted longwave) irradiance (flux) for PIR model radiometer, with SIRS and GNDRAD making the measurement in the same manner | 2 | Calibration uncertainty | ± 2% or 2 W $m^{-2}$ |

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