The Development of a Routine Observational Program with Piloted and Unpiloted Aerospace Vehicles: New Directions for ARM UAV

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1. Program Objectives

The Department of Energy's (DOE) Atmospheric Radiation Measurement – Unmanned Aerial Vehicle (ARM UAV) Program was originally established to develop measurement techniques and instruments suitable for use with a new class of high altitude, long endurance UAVs, and to demonstrate these instruments and measurement techniques in a series of field campaigns designed to support the climate change community with valuable data sets.

The ARM UAV Program was initiated as part of the larger DOE objective of improving the understanding of the role of clouds in global climate change. One component of that objective is addressed by the ARM Program, which emphasizes long-term ground-based measurements of cloud and atmospheric properties. Although the long-term objective of the ARM UAV program was to conduct regular high altitude airborne measurements over the ARM sites, this objective has been hitherto not realized due to platform and instrument constraints. Thus, the ARM UAV program has been flying both piloted and unpiloted aircraft in a series of field experiments or intensive operations periods (IOPs) over the ARM sites and at other locations selected to achieve specific programmatic or scientific goals.

Presently, the ARM UAV Program has reached a mature state **where the original long-term goal of making routine observations can be pursued in coordination with support of IOPs,** both measurement strategies designed to answer questions addressing the largest source of uncertainty in global warming, namely the interaction of clouds with solar and thermal radiation.

Beginning in FY07, the ARM UAV program, being renamed the ARM Aerial Vehicles Program (AAVP), will become part of the ARM Climate Research Facility. This formal designation has changed the focus of the program which will be reflected in the program announcement.

As part of this two-pronged airborne operation program, it is also **imperative for AAVP to support an instrument development program** whereby miniaturized in-situ and remote sensing instruments will be acquired or developed, the small size being critical for the long-term goal of integrating these instruments on UAVs. Any instruments developed under this program should be modular so that they can be easily installed on a variety of platforms.

2. Past Accomplishments

From its inception in 1993 to date, the ARM UAV Program has accomplished 12 major field measurement campaigns. Of those flights, 7 were conducted at the DOE CART site in Oklahoma and another two series at the DOE sites at the North Slope of Alaska (NSA) and at the Tropical Western Pacific (TWP) in Darwin. These flights were generally planned to coincide with IOPs being conducted at the ARM sites to investigate topics such as the impacts of clouds or aerosols on the column radiation budget or better determining cloud properties. Experiments were also conducted at other locations such as Edwards Air Force Base (clear sky flux profiling), Monterey Bay (maritime stratus cloud properties) and Kauai (sub-tropical cirrus cloud properties).

The combination of ground-based measurements from the ARM surface sites, airborne measurements from ARM UAV aircraft and other aircraft, and satellite over flights have provided valuable data sets that have made important contributions to understanding cloud properties and effects. Although the ARM UAV Program has made observations of atmospheric, cloud and radiative properties emphasizing instruments and data collection techniques amenable to UAVs, both UAVs and piloted aircraft have been used depending on the availability and suitability of platforms. However, the instrument payload has always been operated as if installed on a true UAV, with all instruments controlled from the ground. To date, ARM UAV flights have been conducted with General Atomics – Aeronautical Systems (GNAT), “Altus 1” and “Altus 2” UAVs and instrumented Grob “Egrett”, the DOE “Twin Otter” and the Scaled Composites Proteus piloted aircraft.

In the course of the ARM UAV program, a number of notable accomplishments have advanced the state of the art in airborne measurements, demonstrated the utility of UAVs, and collected data sets used to enhance the understanding of the role of clouds in global climate change. Specific accomplishments include the first science flights using a UAV in 1993, the development of a GPS-based system that allows precise vertically stacked flight of a UAV and a piloted aircraft for cloud absorption measurements in 1995, the first use of an unescorted UAV in general use airspace in 1996, a data-taking flight of over 26 hours in duration over the SGP site in 1996, and the development of several compact instruments suitable for UAV applications in the 1990s and 2000s. In terms of unique data contributing to cloud and radiation research, the Proteus aircraft with the ARM UAV Program’s suite of instruments flew 5 missions over the North Slope of Alaska during the Mixed-Phase Arctic Cloud Experiment (M-PACE) in 2004. The project collected critical information on cloud macrophysical and radiative properties that are currently being used to address the important and poorly understood interactions between clouds, the ocean and the atmosphere in the Arctic. More recently during the Tropical Warm Pool International Cloud Experiment (TWP ICE), detailed in-situ cloud observations were made by the Proteus with the goal of examining the radiative impacts of ice clouds generated by tropical convection over their complete life cycle. These measurements are allowing, among other things, an examination of how ice crystals smaller than 50 μm (the numbers of which have not been well measured in past experiments) impact cloud radiative properties.

3. Research Objectives

The focus of the former ARM UAV program, and now the ARM Aerial Vehicle Program (AAVP) is being expanded so that the concept of making routine observations of cloud properties is moved into an operation phase while continuing participation in IOPs, Both data collection strategies will contribute to the understanding of clouds, aerosols, radiation and the climate system. For both routine and continuous observations, measurements of cloud, atmospheric, aerosol and radiative properties will be made with in-situ and remote sensing instruments on both piloted and unpiloted platforms depending on operational constraints including platform availability and suitability. Because a long-term goal of the AAVP program remains the acquisition of routine, long-term observations using UAVs including those flying at altitudes above the tropopause at up to 70,000 feet, the AAVP will continue to support the development of miniaturized instruments for remote sensing and in-situ observations of cloud, aerosol and radiative properties. Hence, the AAVP will support three types of activities as summarized below:

1) Routine observations of cloud, aerosol and radiative properties
2) Participation in IOPs designed to contribute to our fundamental understanding of cloud properties and effects.
3) Foster an instrument development program whereby miniaturized in-situ and remote sensing instruments will be purchased or developed, the small size of the instruments ultimately allowing them to be used on UAV platforms.

3.1 Routine Observations of Cloud, Aerosol and Radiative Properties

The AAVP will move towards implementing the concept of making routine airborne observations of cloud properties into an operation phase. This is consistent with ARM's operational strategy which emphasizes long-term ground-based measurements of cloud and atmospheric properties. Considerable synergy would be gained by having both sets of operations on a more routine basis, permitting statistical studies of airborne in-situ and remote sensing data. Current studies of airborne data concentrate mainly on case studies and to some degree statistical analysis of a limited data sets. Science questions that could be addressed with more routine airborne observations are listed in Section 4. Measurements in regions that can't be well sampled remotely with either the ARM fixed sites or the ARM Mobile Facility (AMF), such as over the Arctic Ocean or over oceans removed from land sites would be especially useful in extending the range of science questions that the ARM program can address.

The ARM program is currently making routine twice-weekly observations of aerosols over the SGP site. This is making large contributions to the understanding of the vertical distributions of the concentrations, size distributions, compositions and single-scattering radiative properties of aerosols and their variability. The technology and instruments now exist to conduct similar observations for warm cloud microphysical properties. It is hope that the development of higher flying compact platforms and miniaturization of instruments will eventually allow similar observations for mixed-phase and ice clouds, and that active remote sensors, such as radar and lidar, can be included in the payload.

It is envisioned that the feasibility of conducting such a routine observational program will start with a piloted aircraft and set of instruments capable of measuring the properties of warm rain clouds over the SGP site. These observations will then be extended to other ARM sites and to more remote oceanic locations as permitted by the availability of platforms and instruments as well as ARM's science needs. Making the cloud observations will be more complex than the aerosol observations that the ARM program is currently making as the flight profiles will be more complex. Clouds must be targeted to some degree, but a certain amount of random sampling is still required to get a representative sample that is not biased by, for example, larger and thicker clouds. The acquisition of such a unique set of routine cloud data would allow statistical studies of cloud properties that may be more representative than analysis of current IOP data. For example, there are currently few observations available to evaluate retrievals for clouds with low liquid water paths, clouds that can have a yet to be determined important contribution to the energy cycle. Routine observations of clouds by aircraft could provide not only unique data on the vertical distributions of liquid in low liquid water path clouds, but also help evaluate and develop retrievals for such clouds.

Although the initial routine observations will likely be made by piloted aircraft, the long-term goal is the acquisition of such observations using fleets of UAVs to give statistically significant measures of cloud properties at multiple locations. The acquisition of long-term records of routine cloud observations with aircraft would be a significant breakthrough in the aircraft observational strategy because it would allow us to better understand cloud feedbacks and the variability of cloud properties. Cloud properties exhibit incredible variability and an understanding of why cloud properties vary and how clouds feed back on the atmosphere's water and energy balance represent critically unanswered science questions. In addition, extending the database of cloud properties that are currently being remotely sensed at the fixed ARM sites to more locations using aircraft would enhance our understanding of clouds and cloud feedbacks in many more regions, these regional datasets being critical for ultimately evaluating the performance of large-scale models. A statistical analysis of cloud properties and their dependence on other atmospheric variables could also be addressed.

3.2 Participation in IOPs

Although the ARM program has embraced the philosophy of making long-term continuous ground-based measurements of cloud and atmospheric properties at fixed and mobile facilities around the world, these measurements need to be supplemented with focused sets of airborne and other observations. These more limited time period observation are used to evaluate remote sensing retrievals, to provide forcing data sets for model simulations, and to provide specialized data designed to contribute to the understanding of cloud and radiative effects. The IOPs in which these observations are collected can either be at the location of the fixed sites, the mobile sites, or at any other location around the globe. It is recognized that such aircraft measurements during IOPs will continue to be an important component of ARM's research on the role of clouds in global climate change because there are some questions that cannot be answered using remote sensing data from ground-based or satellite instruments alone.

When an IOP is endorsed by the ACRF because of its importance in meeting ARM's science goals, the AAVP will search for the best platform and combination of instruments available to meet the science goals of the project. Both piloted and unpiloted platforms may be used for this purpose, depending on the location, FAA regulations and instrument requirements. The relative balance between participation in IOPs against the collection of more routine cloud observations will be determined by the ARM Science Team, the ACRF, the AAVP team and the AAVP Chief Scientist.

Examples of past IOPs include the following: the 1995 ARM Enhanced Shortwave Experiment (ARESE) where the absorption of solar radiation by the clear and cloudy atmosphere was studied using two aircraft flying in tightly stacked formation providing solar flux measurements above and below cloud; the Spring 2000 Cloud IOP where a dataset suitable for the determination of the three dimensional distribution of cloudiness and cloud properties over the SGP was generated; the 2002 SGP IOP aimed at improving the understanding of both water and ice advection into a column and solar and thermal fluxes over a column, for the purposes of improving single column model (SCM) simulations and enhancing the understanding of mid-latitude cirrus; the 2003 aerosol IOP where airborne measurements of aerosol absorption, scattering, and extinction were taken to characterize the routine ARM aerosol measurements taken at the SGP and to help resolve differences between measurements and models of diffuse irradiance at the surface; the 2004 M-PACE experiment aimed at enhancing the understanding of Arctic mixed-phase clouds and improving our ability to simulate them with models covering a variety of scales; the 2005 ALIVE campaign where measurements with a Jetstream were combined with four flights of the ARM Cessna 206; and the 2006 TWP-ICE experiment aimed at examining the impact of convection on its environment and the linkages between the characteristics of convection and the resulting cirrus characteristics.

It is envisioned that future IOPs will examine similar science issues aimed at enhancing our understanding of the role of clouds in the climate system. It is also possible that future IOPs be conducted in coordination with the routine cloud observations described in Section 3.1. As an example of this, the CIRPAS Twin Otter was the primary platform for the 2003 Aerosol IOP, but the routine twice-weekly observations of aerosol properties over the SGP made by the Cessna 172 were integrated into the experiment plan.

3.3 Support of Instrument development Program

Either routine observations or IOP observations made by the AAVP will rely on the continued integration of state-of-the-art instrumentation onto aircraft platforms. Ideally, these instruments should be miniaturized so that they can be used on whatever sized platform is deemed appropriate for the measurement needs of an IOP or routine set of observations. Further, all instruments to be developed or purchased through this activity should be modular so that the AAVP will continue to have the flexibility to use the platform identified as most appropriate for the measurement needs of a particular IOP or routine observation activity. Ideally, instruments should be able to be used on both slower and lower flying platforms and faster and higher flying platforms, and should be simple to operate so that they can be used on both piloted and unpiloted platforms.

Although substantial progress has been made in the development of miniaturized instruments capable of measuring aerosol and warm cloud properties in-situ and solar and thermal radiative fluxes, instrument development is still needed before miniaturized instruments capable of measuring in-situ cloud properties in mixed- and ice-phase clouds and using active remote sensing techniques to retrieve cloud properties are available. Some projected measurement needs of the program are summarized in Section 3.4.

While developing future instruments for the AAVP potential platforms on which the instruments might ultimately be integrated should be considered. There are principally three different types of aircraft platforms that could be used for such measurements. The first class of platform would be a small low-flying platform with a relatively simple payload of either aerosol or warm rain cloud microphysics instruments. An example of this type of platform might be a Cessna 172 or 206, similar to the type of platforms that have been used to collect twice-weekly routine observations of aerosols over the SGP. A second class of platform would be a larger platform that would have more flexibility to fly larger and different payloads depending on the mission needs, but would still be cheap enough to use for routine observations. A twin engine aircraft with a higher ceiling than the Cessna would probably suffice for this type of activity. A third type of platform would be a more capable plane with more flexibility of where it could fly, including locations where icing might be encountered and altitudes high enough to sample t tropical cirrus either in-situ or remotely from above. This platform should be capable of integrating a more complete payload of instrumentation and likely would be more expensive so that only limited time-period IOPs could be conducted. Examples of this type of platform would include the Scaled Composites Proteus, the General Atomics Altus-II aircraft, or the NASA WB-57 or ER-2 aircraft. **It is emphasized that the AAVP does not envision supporting the development of UAV or aircraft platforms, but merely aims to use the most suitable available platform for its measurement needs.**

3.4 Measurement Needs

The ARM Science Team and the AAVP Chief Scientist will play a critical role in identifying instrument priorities and in determining the order in which new instruments should be acquired. As part of the instrument program, it is important to identify both the long-term and short-term measurement needs of the program. Below some of the instrument development needs foreseen by the ARM –UAV program are listed (existing instruments are listed in Appendix A). Only general classes of instruments, rather than specific makes and models, are identified:

1) Aerosol measurements: light scattering, backscattering, and absorption of aerosols at multiple wavelengths; relative humidity dependence of light scattering; aerosol size distributions and compositions; cloud condensation nucleus concentrations at multiple supersaturations; ice nuclei concentrations and compositions; Angstrom coefficients; extinction to backscatter ratios.

2) In-situ cloud microphysics measurement needs: accurate measurements of concentrations of ice crystals smaller than 50 to 100 μm; size and shape distributions of ice crystals from 1 μm to 1 cm; high-resolution ice crystal images; bulk measures of ice cloud extinction and bulk water content; direct measurements of asymmetry parameter and scattering phase function; bulk measures of liquid water content; size distributions of cloud droplets and raindrops, covering the size range 1 μm to 1 cm; high spatial resolution observations (10s of meters) of the interface between ice and water in mixed-phase clouds; fast response cloud particle probe for measuring spacing between cloud drops.
3) A cloud radar whose capabilities at a minimum should include: operating at 94 GHz or another frequency capable of retrieving cloud information; provide Doppler velocity and radar reflectivity with a Nyquist velocity of approximately 20 m s^{-1}; capable of operating unattended for long periods of times; sensitivities of -35 dBZ at 2 km and -40 dBZ at 1 km; 30-45 m horizontal resolution and 100 m vertical resolution.
4) Upward and downward looking lidars: preferably polarized and dual wavelength; measuring backscatter and extinction; provided data quality needed to retrieve cloud and aerosol macrophysical and microphysical properties such as optical depth above and below the aircraft, cloud boundaries, cloud thicknesses, cloud phase and particle sizes.
5) Passive remote sensing instruments including the following: hemispheric field of view broadband radiances at solar and infrared wavelengths, zenith and nadir mounted, preferably on a stabilized platform to improve data quality and reduce processing time; scanning high-resolution interferometers; infrared thermometers; scanning narrow-field-of-view spectrometers operating at solar, near-infrared and infrared wavelengths that emulate similar satellite instruments; and a sub-millimeter imaging radiometer.
6) Measurements of atmospheric state parameters: accurate and fast response measurements of temperature and dew-point inside and outside of cloud; pressure and altitude; fast response measurements of vertical and horizontal velocity at aircraft position.

In summary, the list of instruments above gives examples of instruments required by the AAVP in the coming years. This list should not be regarded as complete and all instruments listed above will likely not be developed or acquired by the Program.

4. Research Questions

The research agenda for the AAVP will be established by selection of research proposals submitted to the ARM Climate Resources Facility (ACRF) board. This will include proposals for both routine observations and conducting IOPs. The Chief Scientist, will work in conjunction with the AAVP Team and ARM scientists to accomplish the objectives in the proposals endorsed by the ACRF. Some examples of research questions that might be addressed by the program are listed below, concentrating mainly on questions that could be addressed by acquisition of more routine cloud observations.

1. Scaling Issues: Satellite observations are currently used to extend ground-based remote sensing observations to longer time and spatial scales. Satellite observations are also assessed through comparison against ground-based remote sensing observations. In addition to needing aircraft in-situ and remote sensing measurements to evaluate ground-based remote sensing retrievals, such measurements, especially at resolutions higher than those possible with satellites, offer a critical missing link for determining how atmospheric cloud and radiative properties vary over multiple scales. Although such observations exist for specific times and specific geographical regions, especially over land, such observations are needed more routinely and in a variety of locations where such observations do not exist (e.g., oceanic regions, Arctic regions, convective regions especially in the Tropics). Past experience has shown that scaling trends valid for one regime do not necessarily extend to another.

2. Statistics of Cloud and Radiative Properties at Multiple Levels and Locations: The use of long time series of cloud properties from the ARM ground sites have allowed scientists to determine previously undetected relationships that were not determined from IOP data sets alone (e.g., precipitating clouds exhibit stronger variability than non-precipitating clouds implying that separate parameterizations of sub-grid variability are required for each). With the availability of such data at a number of such locations, including those previously under sampled, long time series or databases of atmospheric quantities can be derived. Since there may be substantial differences in atmospheric properties between regions, this larger database may help determine relationships between cloud properties, aerosol properties and meteorological forcings in different geographic regions and hence help in the development of new cloud parameterizations for large-scale models. Vertical profiles of in-situ microphysics in a variety of locations and meteorological regimes are crucial for evaluating the results of ground-based and satellite remote sensing schemes. Aircraft in-situ observations are needed to measure quantities such as the frequency of occurrence of smaller crystals that cannot be accurately measured from ground-based or satellite remote sensing, and hence must be inferred from these retrievals.

3. Observations of Complete Life Cycles of Clouds: Routine aircraft observations may help track the life cycle of cloud systems that are currently sampled only over a limited number of times from ground-based or satellite remote sensing techniques. Because of the limited endurance of some aircraft platforms and limited numbers of flight hours during IOPs, it has been difficult to obtain measurements of clouds at all stages in their evolution: growth, maturation, and dissipation. With the ultimate development and use of longer-duration platforms and with the acquisition of more routine cloud observations, it may be possible to observe clouds over their complete life cycle so that the data can be analyzed in a statistically meaningful way. This may also give information on physical processes that can be used in parameterization development. Observations over the complete life cycle of deep convection and the generated cirrus would be especially useful.

4. Evaluation of Numerical Models using Data from a wider Range of Conditions than Previously Possible: In typical field experiment or IOP, a number of representative cases are sampled and must be used to illustrate a particular phenomena or class of cloud. However, since clouds exhibit considerable variability it is difficult to identify typical behavior, or even to determine how synoptic and local conditions affect the evolution of systems. Hence, numerical models are frequently used to fill in the phase space of plausible scenarios to predict atmospheric behavior, with the models only well validated for one or two specific conditions. If cloud observations are obtained on a more routine basis, a larger database of observations on how conditions affect the time evolution of systems would be obtained and hence could be used to evaluate the numerical models.

5. Atmospheric statistics in currently sparse data regimes may contribute to our understanding of weather and climate processes. Although satellites and the ARM ground-based sites have improved the availability of data used to enhance our understanding of cloud processes and for initializing and evaluating model simulations, these data are frequently missing at critical locations or critical regimes in the phase space of possible atmospheric parameters (e.g., low densities of observations over the oceans). To illustrate how observations in data sparse regimes could be useful, we envision that routine observations of cloud, radiative, and oceanic properties for transects across the Pacific Ocean from Peru to Darwin might enhance our understanding of ENSO (El Nino Southern Oscillation), a precursor for understanding Earth's climate. A statistical analysis of the variation of cloud and radiative properties as a function of longitude and sea surface temperature, which are not currently available, might help us better assess how clouds might feed back on future climatic states.

6. Critically needed data for assessing sub-grid variability in a grid box representative of a climate model. As well as there being little data available for evaluating model simulations the data are also not available for assessing sub-grid variability in a typical GCM grid box. For the ARM ground-based sites, the question always arises as to whether the variation of quantities in time (measured by such sites) can be representative of the variation of such quantities in space (i.e., the sub-grid variability over a 100 km square grid box). More routine profiles with aircraft, especially airborne remote sensing observations, would give the statistics needed to address sub-grid variability. In addition, if such data were available at multiple locations, sub-grid variability could be assessed for a variety of cloud types, formation mechanisms and geographic regimes.

7. Long routine transects of aircraft helpful for parameterization development. How do cloud properties vary as functions of sea surface temperature? In typical experiments, such questions might be answered using 100 hours of data obtained during a specific month of a particular year. How representative are such observations? This is unknown, but we do now that our confidence in relationships derived from observations increases with larger datasets. The use of multiple observations over a series of years could help address these observations (i.e., profiles over the warm pool). In addition, a larger database could be established for examining how cloud and radiative properties vary depending on aerosol concentrations and degrees of pollution.

8. Tropospheric/stratospheric Exchange: Few measurements at very high altitudes, especially in the Tropics, are available. In order to adequately understand the climate problem, in-situ observations in this region would be of critical importance (e.g., what are the properties of thin tropopause cirrus, how much water vapor and trace chemical species are transported into the stratosphere and what does this rate of transport depend on, etc.). Measurements of atmospheric properties at the tropopause, especially in the

Tropics, have been difficult to make because of its high altitude and the paucity of airstrips large enough to handle conventional research aircraft. If long-endurance, higher flying aircraft were ultimately deployed they could vastly improve the available database to examine tropospheric/stratospheric exchange.

9. Aerosol/cloud interactions and indirect effects: In order to asses the indirect effects of aerosols on radiation through the modification of cloud properties, the most difficult observational problem is to separate aerosol effects on clouds from the natural variability in cloud properties that exist from variations in synoptic-scale forcings and thermodynamic conditions. The acquisition of more routine observations in clouds both affected and unaffected by aerosols would give a larger data base to explore the multi-dimensional phase space of how both varying aerosols and varying meteorology impact clouds and radiation, and to stratify how varying aerosol concentrations affect cloud properties in varying meteorological conditions and in varying locations around the world. Both in-situ and remote sensing data can play a critical role in such analysis.

10. Indirect effects in ice clouds: Very little is known about how anthropogenic aerosols affect the typical sizes and concentrations of cloud particles in cirrus. There are little data available to investigate such issues, especially in the Tropics, because of the high heights and remote locations of these clouds (again UAVs are ideally suited for such observations). A greater fundamental understanding of the basic mechanisms by which aerosols affect the production of ice crystals is required. A larger database of observations (chemical, radiative, in-situ microphysics) in a variety of meteorological and climatic regimes is required to address these issues.

Appendix A: Existing ARM UAV Instruments Previously Purchased by DOE

Instrument	**Description**	**Source/Supplier**
Cloud Aerosol and Precipitation Spectrometer (CAPS)	Measures cloud particle size distributions and liquid water content; mounted on canard hard point; uses PMS canister	Droplet Measurement Technologies
Model 2014M Transducer (MADT)	Differential and Static Pressure	Rosemount
CR-2 Frost Point Hygrometer	Relative humidity; Sterling engine cooled (-105^{o}C)	Buck Research
Dew Point Sensor Model 1011C	Relative humidity; thermo-electric cooled (-50^{o}C)	Buck Research
C-MIGITS II	INS/GPS altitude reference platform	BEI Systron Donnor
C-MIGITS III	INS/GPS altitude reference platform	BEI Systron Donnor
Video Ice Particle Sampler	Video images of ice particles	NCAR
Cloud Integrating Nephelometer	Bulk measures of cloud extinction and asymmetry parameter	Gerber Scientific
Nevzorov Probe	Liquid water content/total water content	Sky Tech. Research
Stable radiometer platform	Mounts CG-4, CM-22*	Sonoma Design Group
SphereOptics-Hoffman SMS-500	Laboratory calibration for radioemters	SphereOptics-Hoffman
IRT	Infrared Thermometer	Heitronics
Cloud Particle Imager (CPI)	High resolution images of ice crystals	Stratton Park Engineering Company Inc.
BAT Turbulence Probe	Wind speed and direction, turbulence	NOAA/ARA
Sandia Laser Hygrometer	Relative humidity	MayComm Instruments, LLC

*Needs repair; currently not functional