# RACORO

**R**outine
**A**erial Vehicle Program (AVP)
**C**louds with Low Optical Water Depths (CLOWD)
**O**ptical
**R**adiative
**O**bservations

*RACORO the Raccoon*


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[1] Should logistical issues require it, a minor shift in the proposed one-year period is acceptable.

## ABSTRACT

Our knowledge of boundary layer clouds and cloud processes is insufficient to resolve pressing scientific topics. Many boundary layer clouds have liquid-water paths (LWPs) less than 100 g $m^{-2}$ that are defined here as being "thin" Clouds with Low Optical Water Depths (CLOWD). From the tropics to the Arctic, 50% or more of the liquid-water clouds are believed to have LWPs below this limit, and the Earth's radiative energy balance is particularly sensitive to small changes in their LWPs. It is difficult to retrieve the properties of these clouds accurately because they are tenuous and often broken. This greatly complicates obtaining the routine, long-term statistics needed to address pressing science topics. Our understanding of CLOWD-type clouds can be greatly improved by acquiring in-situ data that has been sorely lacking and is needed to develop and evaluate retrievals.

This proposal will fill this knowledge gap using flights funded by the Atmospheric Radiation Measurement (ARM) Aerial Vehicle Program (AVP) at the Southern Great Plains (SGP). The proposed observation program – Routine AVP CLOWD Optical Radiative Observations (RACORO) – will conduct *long-term, routine* AVP flights in boundary layer (low-altitude), liquid-water clouds at the SGP. The flights, conducted at pre-determined times, will involve sampling whatever boundary layer clouds are present, which should also collect extensive statistics on CLOWD-type clouds given their high frequency of occurrence. The purpose is to obtain *representative statistics* of cloud microphysical properties needed to validate retrieval algorithms and support process studies and model simulations of boundary layer clouds and, in particular, CLOWD-type clouds. These purposes are served by three objectives:

**1. Cloud statistics**. Obtain representative statistics of the cloud optical and microphysical properties, and cloud radiative fluxes for cloud retrieval validations.

**2. Aerosol properties**. Observe the aerosol properties associated with cloud variability, such as aerosol amount, aerosol size distribution, and the number of cloud condensation nuclei.

**3. Meteorological factors**. Facilitate understanding of how meteorological factors influence cloud dynamics, microphysical properties, and aerosol-cloud interactions by also making measurements of properties such as moisture availability and mass flux at cloud base.

These objectives are interrelated and each will be addressed using a prioritized strategy articulated in the text. Extended routine flights over the accessible SGP site will provide the necessary measurements to improve retrieval algorithms, which then can be applied to other ARM Climate Research Facility (ACRF) sites. These objectives are difficult to achieve with a limited set of data, and long-term, routine flights offer the best chance of success. The resulting data will be placed in the ACRF archive and made available to the community.

**Relevance of the Proposed Work to the BER Climate Change Division Long Term Measure of Scientific Advancement**

The observation program proposed herein is directly relevant to the ARM Climate Research Facility (ACRF) mission of studying and monitoring the Earth's system, since clouds and aerosols are essential elements of the Earth's climate. The data obtained and the subsequent knowledge gained can be used to evaluate and improve Global Climate Models (GCMs), which are the primary vehicles for determination by policy makers of acceptable levels of greenhouse gases in the atmosphere. Potential GCM improvements include the parameterization of continental boundary layer clouds, the representation of broken cloudiness and 3D radiative transfer, unresolved sub-grid dynamical processes, and aerosol-cloud interactions.

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## 1. INTRODUCTION & OBJECTIVES

Many boundary layer clouds have liquid-water paths (LWPs) less than 100 g m$^{-2}$ that are defined here as being "thin" Clouds with Low Optical Water Depths (CLOWD). From the tropics to the Arctic, about 50% or more of the liquid-water clouds have LWPs below this limit (Figure 1). The many types of clouds that may fall into this broad classification include stratus decks, cumulus fields, and mixed-phase clouds. Because the Earth's radiative energy balance is particularly sensitive to small perturbations in LWP, small uncertainties in cloud optical properties can easily affect changes in the local radiative energy balance in excess of that for doubled carbon dioxide (Turner et al., 2007). Thus, particularly accurate retrievals of LWP are required to determine their role in climate and evaluate their simulation in climate models.

The accurate retrieval of microphysical and optical properties of liquid water clouds from remote sensors would seem, at first, to be a solved problem, since these clouds are low in the atmosphere (enabling easier *in situ* observation) and are composed of spherical droplets whose scattering is well-described by Mie theory. Nothing could be further from the truth. A recent intercomparison of 18 state-of-the-art retrieval algorithms showed that – for a simple, warm, single-layer stratiform cloud – the retrieved LWPs differed by 50% to 100% (Turner et al., 2007). Furthermore, ARM's primary workhorse for observing LWP is a 2-channel microwave radiometer (MWR), which obtains LWP by inverting the measured microwave sky brightness temperatures. However, this study also showed that applying commonly used algorithms to the same observed brightness temperatures could yield LWP that differ by 50 to 100%.

These differences are unacceptably large, particularly given the importance of these clouds to climate issues that require accurate retrievals for observation, monitoring, and evaluation of model simulations. The prevalence of this type of cloud globally suggests that a dedicated observation program in one location that improves our retrievals would have far reaching benefits to our understanding boundary layer clouds over continents and oceans, the latter of which have an unusually large importance to climate. Topics that would benefit are:

- Model parameterizations of continental boundary layer fair-weather cumulus and stratus do not agree well with observations (Lenderink et al., 2004), partly because they are based on simplified mass-flux cumulus parameterizations that use simplified closure assumptions and overly simplified drizzle representations.

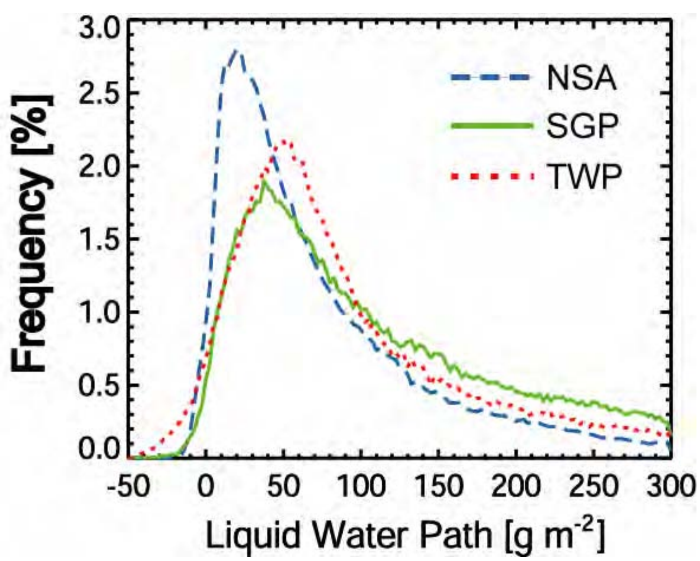


**Figure 1.** Frequency distribution of liquid-water paths (LWP) at three ACRF sites. The locations are the North Slope of Alaska at Barrow (NSA), the Southern Great Plains at Lamont, OK (SGP), and a the Tropical Western Pacific at Nauru Island (TWP). LWP data are for 2004 as retrieved from a microwave radiometer (MWR) when the cloud base was below 3 km. The frequency distributions indicate a preponderance of clouds with LWPs below 100 g m$^{-2}$. The LWP distributions for each site are given as [1$^{st}$ quartile, median, 3$^{rd}$ quartile]:
NSA = [27, 58, 125] g m$^{-2}$
SGP = [54, 126, 309] g m$^{-2}$
TWP = [43, 82, 183] g m$^{-2}$
Figure adapted from Turner et al. (2006).

- Subtropical marine boundary layer (MBL) clouds largely fall within the CLOWD LWP regime. The albedo of MBL clouds are a particular concern for climate since models simulate them poorly (Zhang et al., 2005; Bender et al., 2006; Zhu et al., 2005); yet, their simulation and response to changing environmental conditions is the main source of uncertainty in tropical cloud feedbacks simulated by climate models (Bony and Dufresne, 2005).
- The degree of brokenness in MBL cloud fields has a large impact on the global radiative energy budget because of the large albedo difference between the dark ocean and bright stratocumulus sheets. However, retrieving cloud properties within broken fields is even more complicated than for the simple, stratiform case studied in Turner et al. (2007). Yet, their accurate retrieval are needed for recent investigations into the cause for rapid spatial transitions (termed rift zones or pockets of open cells) from uniform cloud sheets to broad regions of broken cloud (open mesoscale cellular convection), which are thought to result from not-yet-understood aerosol effects on precipitation (Sharon et al. 2006; Stevens et al. 2005).
- CLOWD-type clouds are also intricately linked with atmospheric aerosol. The Intergovernmental Panel on Climate Change (IPCC, 2001) indicates that, of the climate forcings considered, effects of aerosol on clouds has the greatest range of uncertainty. For example, an increase in aerosols (for fixed liquid-water content) causes an increase in droplet concentration and a decrease in droplet size that enhances the cloud's reflection of solar radiation (Twomey, 1974). This process, termed the first indirect effect, is not well understood in boundary layer cumulus due to uncertainties in aerosol properties and changes in LWP. Since the radiative properties of CLOWD-type clouds are so sensitive to small changes in LWP, and aerosol indirect effects are least saturated for thin and developing clouds, these clouds will be particularly sensitive to aerosol effects and uncertainties therein.

## OBJECTIVES

Improving our understanding of CLOWD-type clouds requires data that has been sorely lacking. This proposal will fill this knowledge gap using flights funded by the Atmospheric Radiation Measurement (ARM) Aerial Vehicle Program (AVP) at the Southern Great Plains (SGP). The proposed observation program – Routine AVP CLOWD Optical Radiative Observations (RACORO) – will conduct *long-term, routine* AVP flights in boundary layer (low-altitude), liquid-water clouds at the SGP. The flights, conducted at pre-determined times, will involve sampling whatever boundary layer clouds are present, which should also collect extensive statistics on CLOWD-type clouds given their high frequency of occurrence. The purpose is to obtain *representative statistics* of cloud properties needed to validate retrieval algorithms and support cloud microphysical studies of processes and their model simulations. The three main objectives are:

**1. Cloud statistics**. Obtain representative statistics of the cloud optical and microphysical properties, and cloud radiative fluxes for cloud retrieval validations.

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These objectives are interrelated and each will be addressed using a prioritized strategy articulated later in the text. Extended routine flights over the accessible SGP site will provide the necessary measurements to improve retrieval algorithms, which then can be applied to other ARM Climate Research Facility (ACRF) sites. Our primary objectives would be difficult to accomplish with a limited dataset, which is why long-term, routine flights will be used. The desired representative statistics requires sampling all types of boundary layer clouds (not only the biggest ones); so flight time may be spent between clouds. CLOWD-type clouds will be quite susceptible to aerosol indirect effects (Platnick and Twomey, 1994); so a limited set of aerosol measurements (e.g., CCN) and mass fluxes below and between clouds would provide valuable statistics to interpret these data and evaluate model simulations of the aerosol indirect effect. Together, these observations can help separate the effects of meteorology and aerosols on cloud properties. Thus, our objectives dovetail nicely to make the maximum scientific use of the flight time.

## 2. SCIENCE QUESTIONS

This AVP proposal is for the operations necessary to obtain these aircraft observations and, as such, would not fund scientific investigations using these data. Nevertheless, it is important to indicate the science questions that are motivating this request and articulate their need within the ARM Working Groups (WGs), who we expect will be using these data in PI-level proposals and group investigations. RACORO will serve several crosscutting interests of the CLOWD Working Group (WG) that are shared with major ARM Working Group goals:

1. Determine the radiative forcing of CLOWD clouds at the SGP, which includes evaluations of their 3-D microphysical cloud structure and routine characterization of surface albedo (Radiative Processes WG; RPWG).
2. Ascertain the lower detectability limit of liquid-water contents for ARM radars and other remote sensors, and aid in the development of future radar specifications for improved observations of these clouds (Cloud Properties WG; CPWG).
3. Improve retrieval algorithms of cloud microphysical properties so that the multi-year ACRF datasets may be used to obtain long-term cloud statistics needed (CPWG).
4. Evaluate their impacts on the broadband heating rate profiles (Broadband Heating Rate Profile Project; BBHRP).
5. Quantify aerosol indirect effects in boundary layer clouds (Aerosol Working Group; AWG)
6. Improve model parameterizations of continental boundary layer clouds, whose current treatments have largely been developed using maritime data (Cloud Modeling WG, CMWG)[2].
7. Since these types of clouds are common in the marine environment, these data would benefit the planning and execution of the second ARM Mobile Facility (AMF), which is planned to be a marine-capable AMF.

Additionally, it is likely that these data would foster community interest from other agency programs, such as the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Program for satellite studies and calibration.

[2] An ARM Large-Eddy Simulation (LES) Test bed is being proposed (Zhu et al., 2006) that targets boundary layer fair-weather cumulus and stratus. They plan to address shallow cumulus models that do not match observations well because they are based on simplified mass-flux cumulus parameterizations that use simplified closure assumptions and overly simplified drizzle representations.

Several specific science questions would uniquely benefit from these year-long, routine RACORO observations:

1. Do cloud property retrievals exhibit a diurnal cycle in their accuracies?
2. Can radiative transfer calculations using the observed cloud fields attain agreement/closure with the observed surface radiative fluxes?
3. Which probability distribution functions (PDFs) of small-scale cloud property variations are needed to achieve surface radiative closure, and can high-resolution climate models simulate their seasonal variations?
4. What is the role of aerosol loading in varying the microphysical and macrophysical properties of boundary layer cloud fields, and can the large sampling statistics from a year-long project isolate differences associated with different aerosol types and cloud types?
5. Can parcel models represent the aerosol activation observed in real clouds, and is aerosol compositional complexity required to achieve closure on drop number concentration?
6. What are the linkages between aerosol, cloud dynamics/microphysics, and the initiation of drizzle in warm, shallow clouds?
7. How well do boundary layer models simulate the statistics of clouds and aerosol-cloud interactions?

## 3. APPROACH & EXPERIMENTAL METHODS

We propose that RACORO be flown at the SGP ACRF and target boundary layer, liquid-water clouds for several reasons:

1. The SGP is easily accessible and has ample personnel to support a long-term field program,
2. The extensive complement of state-of-the-art surface ACRF measurements enables validation studies for a broad range of retrieval algorithms,
3. Boundary layer clouds are common at the SGP year around (see Figures 2 and 3) and about half of them are CLOWD-type clouds (Figure 1), so there is a high probability of encountering clouds of interest;
4. Low-altitude clouds are more easily accessible by aircraft and, therefore, cheaper to sample than higher altitude clouds; and
5. Instrumentation for aircraft *in situ* observations of liquid-water clouds has been developed for decades and measurements needed should be sufficiently tested for routine observations.

Thus, prospects are favorable to maximize the frequency of cloud samples needed to obtain representative statistics needed for retrieval validation and studies of cloud microphysical and cloud-aerosol interactions. The next three subsections explain considerations that are used to design our flight patterns and instrument complement, which include retrieval validation, anticipated cloud sampling, and flight strategy. Clouds are not present all the time; so the last section discusses how the go/no-go decision is made for flying.

### 3.1 Surface-Based Cloud Property Retrieval Validation

A major emphasis for RACORO is to obtain *in situ* cloud statistical properties needed to validate surface remote sensing algorithms. The cloud properties of interest here are the LWP, effective radius (Reff), optical depth, and their vertical profiles, which can be retrieved from surface measurements made at the SGP using a wide variety of retrieval techniques. (A summary of typical retrieval approaches is given in Appendix A and in Turner et al. [2007].)

Comparing remotely sensed cloud properties with *in situ* observations is difficult due to the temporal and spatial differences in the volumes observed by the surface sensor and aircraft. The clouds of interest for RACORO are often broken or tenuous, which presents an added challenge. The best way to approach this problem is to evaluate the remote sensing methods using statistical ensembles of *in situ* observations, generated from large numbers of co-located observations. Considerations for the validation of different cloud variables are discussed here.

- ***Liquid-Water Path.*** *In situ* liquid-water content (LWC) observations are useful for evaluating radar-retrieved estimates of the LWC, although they can be hampered by small sampling volume observed by the aircraft. However, LWP (the vertical integral of LWC) is the most important cloud parameter from a radiative energy point of view and, in addition to the small sampling cross section, obtaining a good estimate of LWP from aircraft is challenging because: the aircraft must make several horizontal passes in cloud at multiple heights to estimate the vertical integral of LWC to get LWP, and significant variations in cloud height (cloud base and/or top) can occur during these transects. Spiral flight patterns improve the accuracy of airborne LWP measurements, but significant horizontal variability in LWC that can still adversely affect the LWP derived.
- ***Effective Radius.*** The solar radiative field is more sensitive to changes in the LWP than Reff (e.g., Sengupta et al. 2003), but accurate retrievals of Reff are also needed to effectively model the atmospheric radiative transfer (Slingo 1989) and interpret cloud-aerosol interactions (e.g., the first indirect effect). Retrievals provide either range-resolved estimates of Reff (e.g., radar-MWR methods) or column-averaged Reff, while aircraft measurements provide an estimate of Reff from size-resolved cloud droplet number density measured at a specific height. As for LWC and LWP, aircraft observations can be compared fairly directly to range-resolved retrievals of Reff, but sampling issues may result in significant differences for the column-averaged Reff, which are best addressed using a large statistical set[3].
- ***Nighttime Validation.*** *In situ* cloud observations used for validations are typically made during daytime, but nighttime data are also needed. For example, a cloud retrieval algorithm by Turner (2007) uses Atmospheric Emitted Radiance Interferometer (AERI) measurements from 8-13 µm and 3-5 µm. In the daytime, the thermal emission observed in the 3-5-µm channel is largely dominated by solar scattering; thus, the retrieval accuracy may have a diurnal variation. Similarly, although we expect that radar and MWR methods do not have diurnal biases (e.g., from heating), this hypothesis has not been directly evaluated using daytime and nighttime data.
- ***3D & broken cloud fields.*** Cloud field horizontal inhomogeneities can impact the accuracy of a remote sensing retrieval method due to partially filled fields-of-view, and 3-D scattering effects. Therefore, it is critical that statistically significant *in situ* data sets be collected for retrieval validations of broken cloud fields (e.g., cumulus) as well as the stratiform clouds (which are assumed to be relatively homogeneous).
- ***Multi-layered clouds.*** Many remote sensing methods are designed to retrieve cloud properties for a single-layered cloud. Therefore, *in situ* data are also needed in multi-layer cloud conditions to evaluate the accuracy of the retrieved liquid-water properties of the lower-level cloud (especially the relatively common case of cirrus overlying boundary layer cloud).

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[3] The procedure for deriving column-averaged Reff from in situ observations is similar to that for determining LWP; however, the variability in Reff is significantly smaller than the variability in LWP and, thus, the vertical integral of Reff from in situ observations is less uncertain than for LWP. Nonetheless, a large ensemble of data also will be needed to evaluate the retrievals of Reff for column-averaged cases.

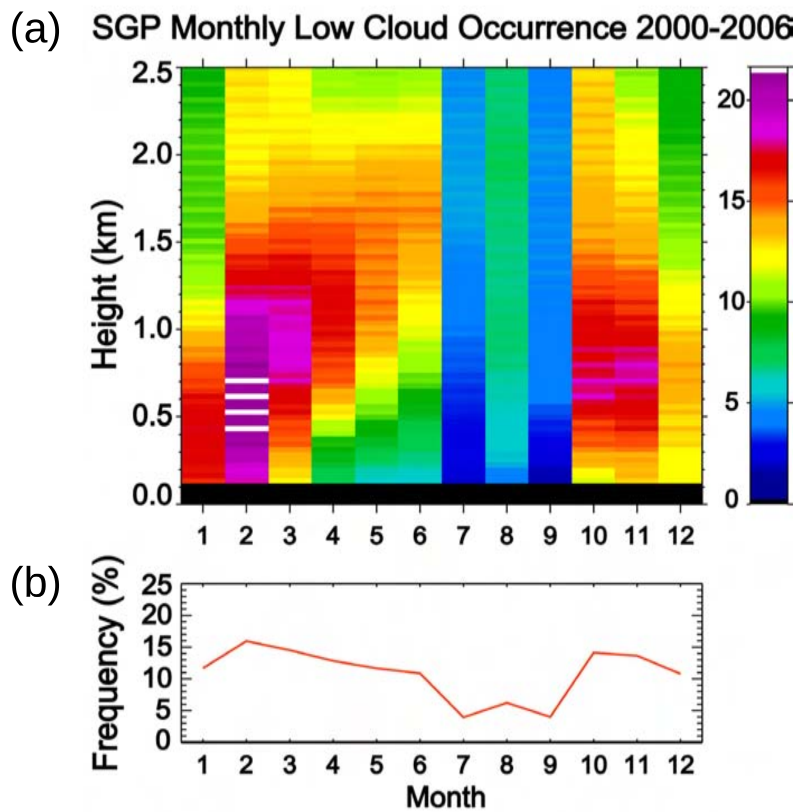


**Figure 2**. Seasonal frequency of SGP low-clouds. The heights of clouds below 2.5 km are determined using ARSCL data from 2000 to 2006. The monthly frequencies are normalized in an absolute sense to enable equal comparisons across the plot (i.e., combined the data into height bins per month and normalized each by the total number of observations per bin x100). Months are included only when the radar and lidar functioned for more than 20 days. Since cloud frequency also has a pronounced diurnal cycle (Fig. 3), the diurnally averaged monthly frequencies are reduced by hours when cloud frequency is lower. (a) A seasonal cycle in cloud base height is evident, increasing from January to June with mean daily frequencies between 15 and 25%. The pattern is less clear in July and August, possibly because of convective activity in the region. (b) Simplified line representation of (a) where monthly values are averaged from 0 to 2.5 km.

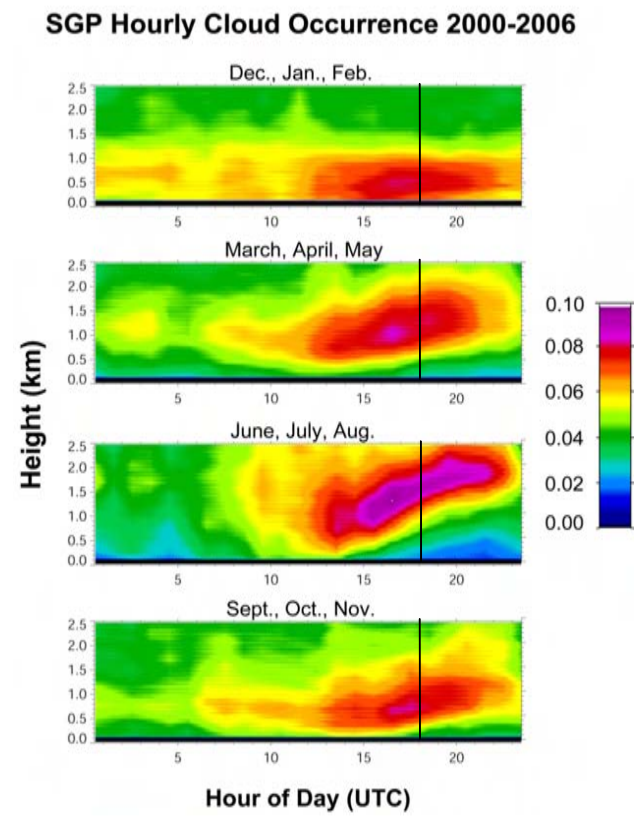


**Figure 3.** Diurnal cycles of SGP low-clouds per season. The ARSCL data used from 2000-2006 is explained in Fig. 2. The relative diurnal cloud occurrence per season is presented, where each season is normalized by the total number of cloudy points *per panel*. (Thus, the color bar only indicates the time of most likely cover per season, and like-colors do not imply the same quantity as for other seasons in this figure or for Fig. 2.) Generally speaking, the SGP daytime is from about 1200 to 2400 UTC, and solar noon is about 18 UTC (vertical reference lines). Regardless of season, the cloud frequencies tend to have maxima during daytime, although their magnitudes and altitudes have different seasonal characteristics. Individual years tend to have patterns similar to these averages, but the frequency magnitudes can show pronounced interannual differences per season.

### 3.2 Cloud Sampling Considerations

The routine sampling proposed study is somewhat different from prior aircraft field deployments and requires careful thought as to the sampling methods and strategies. Aircraft fly thin two-dimensional lines (essentially one-dimensional) through the atmosphere. This can be likened to cheese wire cutting cheese[4] – although the wire occupies very little volume of the atmosphere, it can be very effective if used correctly. Moreover, the combination of aircraft measurements and surface based remote sensing is a powerful combination, with the latter providing the context for the *in situ* measurements (e.g., cloud base, cloud top, column integrated liquid water amount). We discuss sampling issues below before introducing the general flight plans Section 3.3.

- ***Cloud Field Sampling.*** Earlier field experiments tended to focus on individual clouds. This is feasible for a large, well-defined cloud, which has a significant thickness and is amenable to multiple aircraft penetrations. However, in practice, tracking individual clouds is difficult since they grow at different rates and their final growth state is unpredictable. An alternative approach is statistical sampling, where predetermined flight plans are generated with the goal of maximal sampling of the cloud field. This approach is much better aligned with the goals of this project – namely, sampling of both small and large clouds without prejudice.
- ***Extended Sampling Periods.*** The timing and even the occurrence of clouds are not very predictable, which can be problematic for a typical one-month field experiment. Therefore, conducting cloud sampling over an extended period of time (as proposed here) has the benefit of improving the representativeness of the data, and also increases the probability of sampling uncommon events. Uncommon events may not be of great interest with respect to the mean conditions, but they can offer opportunities for focused research efforts that elucidate processes. Long sampling periods also provide the opportunity to sample and differentiate between multiple conditions (e.g., frontal vs. local convection, stratiform vs. convective, updrafts vs. downdrafts, and seasonal effects that include meteorological and land surface changes).
- ***Flight Leg Length.*** Cloud probes typically have small cross sections and the total sample volume is determined by the length of sampling (duration or distance); so, the leg length must be increased to improve the statistical significance of the sample. This establishes a requirement for the spatial/volume scale and geometry of measurement in order for the data to be useful (Hallett, 2003). Cloud size and the size of large boundary layer eddies are strong determinants; so, on a given leg, it is desirable to capture several large eddies in order to observe a number of clouds and their updraft statistics. Assuming that a large eddy is approximately a few hundred meters, the flight legs should be tens of kilometers long.
- ***Aircraft and Probe Speed.*** Implicit in these considerations, the speed of the aircraft and the probe sampling frequency must be appropriately paired to satisfy the measurement requirements for a given cloud type. For example, an aircraft flying at 100 m $s^{-1}$ with probes sampling at 1 Hz would restrict the sampling to clouds larger than a few 100 m (horizontal dimension). However, with probes sampling at 10 Hz, it would produce a sample (N=5) for only a 50 m cloud; further, should the aircraft also be slowed to 50 m $s^{-1}$, it would double the useful sample size for the 50 m cloud (N=10). RACORO is designed to sample small and large clouds in a statistically significant manner, which suggests either slower moving platforms or faster probes or both. Many probes do not have the flexibility in their sampling rate (particularly those that are suitable for routine use in a year-long program) so slower aircraft would be advantageous (e.g., 50 m $sec^{-1}$).

[4] Cheese wire is a long, thin wire with wooden handles at each end, used to cut large rounds or wedges of cheese.

- ***Representative Statistics & Parameter Variability.*** The parameters of interest here have large ranges of temporal/spatial variabilities that will likely depend on cloud type and meteorology. Cloud parameters (e.g., LWC) may vary on spatial scales of meters while aerosol parameters (e.g., number concentration) may vary at scales of tens of kilometers (except near strong sources and sinks). Since we will achieve stable/representative statistics more quickly when events can be observed frequently and/or when the field changes slowly, we may obtain stable statistics for some parameter and not for others. The outcome may depend on the parameter, meteorology and season (e.g., Figures 2, and 3). Thus, we will examine these statistics carefully and, where possible, consider modifications to the flight strategy. (The evaluation of the statistics is discussed more in Section 5.)

### 3.3 General Flight Plan & Measurement Strategy

Pre-determined flight tracks will be flown 2 to 3 times a week for one year during RACORO. We plan to fly at pre-selected flight times when low-level clouds are present, and fly through whatever clouds are there. Thus, we seek to obtain a dataset that is representative of low clouds over the SGP, which is different from typical intensive operations periods (IOPs) that would bias the dataset sampling towards a specific cloud condition. Although a motivation of RACORO is a focus on clouds with low liquid-water amounts (CLOWD), the microphysical properties of both optically thin and thick clouds will be measured. CLOWD-type clouds will almost certainly constitute a significant fraction of clouds measured since retrievals suggest that about 50% of the liquid clouds at the SGP have LWPs less than 100 g $m^{-2}$ (Turner, 2007).

We will institute guidelines that maximize the scientific utility of the data obtained by the predetermined flight tracks. They will describe the orientation, vertical spacing, and length of the flight legs, and stipulate when deviations from the preset legs are allowed. The purpose of the guidelines is to minimize operator input that could bias the sample towards specific cloud conditions (e.g., either low or high optical water depths). Also, repeating the same horizontal pattern at successive heights has the benefits of simplicity for the pilot, and the revisits provides consistency in the overflown surface properties (surface albedo and soil moisture fluxes).

A final set of rules will be determined before the commencement of the program, after an aircraft operator has been established and details worked out with air traffic control (ATC). Nevertheless, it is important to emphasize that, due to the novel nature of these flights: ***the strategy will be revisited throughout the project and adjusted if necessary to maximize the utility of the data.***

The rules and guidelines are discussed in Appendix B, and are summarized below.

- ***Flight patterns***: Several potential flight pattern examples are provided in Appendix B. They will use long, straight legs in simple configurations to minimize in-flight pilot decisions and possible sampling biases. Each leg will be about 50 km long to capture multiple large eddies and remain within the vicinity of the SGP Central Facility (CF) (if not over it). For sampling reasons, the legs will tend to be flown parallel and perpendicular to the wind. The vertical columns will be sampled in a stepwise manner and, at the end, a downward spiral over the CF will be used to sample the column above the remote sensors. Stipulations are discussed for deviating from these guidelines[5] in Appendix B.

[5] There needs to be some flexibility in the sampling approach for the days approved for flights. It is better to obtain some cloud measurements that are less than optimal than none because sampling requirements are too strict. Nevertheless, days that contain sub-optimal sampling should be flagged as such.

- ***Flight Times:*** The year is partitioned into four seasons and, for each season, flight departures are predetermined following a schedule designed to sample, per week, different aspects of the diurnal cycle. They include: (1) morning, which climatologically has maximum cloud occurrence, (2) noon, for optimal solar retrieval validations and coincidence with EOS satellite overpasses, and (3) late afternoon and nighttime sampling. The flight schedule rolls back during the season to minimize schedule conflicts with pilot rest cycles.
- ***Go/No-go & Delay Decisions***: Provisions are provided within the decision making structure to delay or cancel flights in the event of severe weather or icing conditions, or if the low-cloud cover is less than about 10%. The command structure for the go/no-go decision-making is discussed further in Section 7, *Project Management & Personnel*, and resource needs are described in Section 11, *ACRF Resources Required.*

## 4. AVP MEASUREMENTS

The RACORO instrument suite is designed for routine observations of boundary layer liquid-water cloud properties. Gathering good statistics is a major goal; so the aircraft payload must be kept as simple as possible to enable the cost effectiveness needed for routine observations. This means that probes must have a track record of reliability, require minimal maintenance and have relatively routine processing by automated means. We emphasize probes with small weight and low power consumption to enable using a smaller and cheaper aircraft for the observations. Newer probes that would otherwise be desirable may not be included in the payload because they require more attention than is possible in a long-term, routine observational program. However, all probes require maintenance and calibration; so the necessary personnel and resources for ensuring data quality and archiving the data are required (discussed further in Section 10).

The boundary layer clouds to be sampled include stratus and fair-weather cumulus. They are often broken or tenuous and, because they can have a large horizontal variability, their properties can vary rapidly. Thus, following the above constraints, we prefer: (1) slow aircraft speeds, (2) fast instrument response times, and (3) if possible, large particle sampling volumes. Tradeoffs are inevitable when balancing the high instrument sampling rates needed with their cost and the ultimate utility/quality of the measurements. This is true for all three categories of measurements that we are proposing – cloud microphysical, radiative fluxes, and aerosols. Instruments that measure exactly what we need might not exist in a form that fit our reliability and cost constraints for long-term observations. The solution adopted for RACORO is, when possible, to deploy a *pair* of robust instruments: a slower measurement of the property with the desired accuracy and, to guide its interpretation when conditions are highly variable, deploy a faster measurement of a subset or analogous property.

The aircraft instrument complement is designed especially for observing cloud optical radiative properties and the associated cloud microphysics of thin and broken clouds. Ancillary measurements of properties that may influence the cloud state are considered but only when: (1) their intakes/mounts, payload, and power can be accommodated after satisfying the primary (critical) measurements, (2) they are deemed essential for cloud process interpretation, and (3) are reliable and require minimal upkeep (*i.e.*, routine processing).

A candidate list of measurements for RACORO is discussed next by measurement category and the science priorities addressed. Details of the measurement specifications and priority rankings needed by AVP to cost this proposal are provided in Appendix C. They are separated by measurement category in Tables C1 to C5, and a net priority ranking across categories is given in Table C6. These rankings are an essential part of our planning, as they dictate our allocation of instrument resources to meet our objectives. The instrument rankings generally follow the order of the objectives given in the introduction, while tradeoffs are considered between item cost and its incremental scientific benefit.

The type of aircraft that AVP will use is currently unknown, as are its potential operation costs (e.g., required number of pilots and engines). Operation costs will largely dictate the funding available for instruments, as well as payload capability (weight and power). The rankings are to ensure that measurements for the most important science objectives are included first, even though all of the measurements listed have a strong scientific rationale. If this proposal is successful, we would hope to be involved in the discussions about the tradeoffs between measurement need, platform size, and cost. Our instrument priorities follow this order: (1) reliability, (2) small instrument size (for cost-effective routine flights), and (3) fast response.

### 4.1 Cloud Microphysical Properties, Atmospheric & Aircraft State

For cloud microphysics, the key measurements are cloud droplet size distributions (including drizzle sizes), bulk cloud liquid water contents (LWC) and identification of mixed-phase clouds. The size distributions of cloud droplets will be measured by a forward scattering spectrometer probe (FSSP) that sizes particles from 3 and 50 μm. Because of the small horizontal scales of some clouds that will be sampled, ideally the FSSP will be a fast-response FSSP, which also provides particle interarrival times and information about the spatial evolution of the size distribution at the smallest scales. A one-dimensional cloud probe (1DC) will measure the size distributions of drizzle-sized drops between 50 and 640 μm. If space and weight constraints permit, we will include a 2-D cloud probe that detects larger size drops up to about 1.2 mm. The 1DC and 2DC measure the occultation of laser light on an array of photodiodes and provides good information about the concentrations of spherical particles in liquid clouds. A measurement of bulk LWC is required for redundancy, to check that probe calibrations have not drifted during the experiment and to ensure consistency with the LWC derived from the size distributions. The Gerber probe or King liquid water probe are viable instruments; the choice may depend on probe availability and power requirements. If possible, redundant measurements of integrated LWC should be made. The FSSP and 1DC fit into standard pods that are installed beneath the wings of aircraft used for cloud physics research. If power and weight requirements permit, a Rosemount icing detector (RICE) should be added to the payload, which gives an unambiguous detection of the supercooled water by measuring changes in the vibrational frequency of a wire caused by the riming of supercooled water as it freezes. We note that a more comprehensive suite of microphysical probes might be desirable, but may not be viable for these low-cost, routine cloud observations. This may include measurements of bulk light extinction at multiple wavelengths, asymmetry parameters, and larger precipitation sized particles.

Atmospheric state parameters are required to provide the context for interpreting the cloud microphysical and radiative properties. We explicitly mention all properties of interest, recognizing that some are a subset of other measurements (e.g., many are a subset of those needed to measure turbulence). Measurements of air temperature, atmospheric humidity, static pressure, updraft velocity, and turbulence are needed with a cycle time of 10 Hz or more. Global Positioning System (GPS) altitude, latitude, and longitude are required to assess where the observations are obtained for comparison with ground-based remote sensing data. True air speed is needed to determine the cloud probe sample volume to deduce particle size distributions. Flight-level wind speed and direction are useful to interpret comparisons with the ground-based remote sensing observations. Finally, in order to determine the tilt and solar zenith angles needed for the radiometric observations (discussed next section), aircraft position (GPS altitude, latitude, and longitude) and aircraft attitude (pitch and roll) and heading are needed.

### 4.2 Radiometric Quantities

Given the objectives of RACORO, measurements of the downwelling and upwelling shortwave (SW) and longwave (LW) irradiances are needed to relate the cloud microphysical measurements to their effects on radiation. These types of broadband radiometer instruments have been successfully flown previously (e.g., in the ARM UAV program). However, previous aircraft campaigns have shown that particular care is needed when measuring the downwelling SW irradiance. Non-level flight can have a significant impact on it because, when the sun is not completely blocked by overhead cloud, the downwelling SW has a prominent directional component that is very sensitive to the aircraft-sun orientation (attitude). The other irradiances (upwelling SW, and downwelling and upwelling LW) are more diffuse in nature and are less influenced by moderate aircraft pitch and roll.

Stabilized platforms, such as that used in ARESE, greatly decreases the measurement uncertainties due to pitch and roll. However, they are unlikely for RACORO because they are heavy (payload weight), and can be unreliable. These complications are incompatible with long-term routine observations, which require small and cheap aircraft with (largely) turnkey instrument operation. Thus, we propose a measurement methodology that circumvents using a stabilized platform, by complementing the measurement accuracy of the standard broadband radiometers with fast-response radiometers for data reduction and interpretation.

Previous attempts to correct SW irradiances for aircraft tilt have had limited success primarily because only the direct component of the total SW should have a tilt correction applied (the diffuse SW component being far less affected); thus, *a priori* knowledge is required of the partitioning of the total downwelling SW between the direct and diffuse components. For this reason, we recommend that a fast-response, total and diffuse radiometer be added to measure downwelling SW, such as Delta-T Devices model SPN-1[(6)]. These data can be used to infer the ratio of the direct over total SW that, in turn, can determine the portion of the tilt correction that should be applied to the total downwelling SW measurement. For accuracy, the total SW from an unshaded pyranometer is best. So we do not recommend substituting the upward facing pyranometer with an SPN-1; rather, it should be added as a complement.

The cloud fields might vary quickly, which may pose a problem for slower response pyranometers and pyrgeometers. Because of the long flight legs used for our sampling, this variability would be averaged out and still provide a very useful measure of average cloud albedo (above cloud) and transmittance (below cloud). Uplooking and downlooking MFR heads (narrowband spectral) are needed to map the surface albedo being overflown. If these heads are operated in rapid-sample mode, they could also provide valuable information on the variability of the SW radiation field being viewed by the pyranometers and when it changes faster than the pyranometer can respond. The same approach may be used for the pyrgeometers where a rapid-sampling IRT (infrared thermometer) is mounted facing the same direction. Although the IRT is

[6] The SPN-1 radiometer uses an array of seven, miniature thermopile detectors to infer the total and diffuse SW at a fast rate (< 200 ms). It separately determines the total and diffuse SW (and, by subtraction, the direct SW), regardless of azimuthal orientation of the instrument, by using a proprietary shading pattern that does not involve moving parts, shade rings or motorized tracking.

a narrow band and narrow field-of-view (NFOV) instrument, its rapid response can indicate when the infrared field viewed by the broadband, hemispheric pyrgeometer is relatively constant for periods sufficiently long to be recorded by its e-folding response time.

Finally, ARM research has shown that inversions using surface radiance spectra can obtain valuable information about cloud properties in broken fields (e.g., Marshak et al., 2004; Chiu et al., 2006). These methods use two or three radiances in narrow wavelength bands where differential surface properties (albedos) can be exploited to retrieve the cloud properties. This approach may offer a means of retrieving integrated cloud property information above the aircraft in the presence of broken clouds. Zenith radiance measurements on aircraft may be even more successful than from the surface, since the upwelling flux can be characterized better. Studies suggest that this could yield a horizontal mapping of the cloud optical depth above the aircraft to within 3% to 15%, respectively, for stratiform and cumuliform clouds (Barker et al., 2002). Thus, we recommend including an upwardlooking (multiple wavelengths) NFOV instrument to measure the zenith radiance, and, for its interpretation, a downward looking measurement of the upwelling irradiance (2π sr FOV) spectra.

### 4.3 Aerosol Properties

The objective of aerosol measurements in RACORO is to allow a statistically robust evaluation of the relationship between below-cloud aerosols and cloud microphysical and radiative properties. The highest priority is given to measurement of aerosol size distribution in the diameter range from 20-500 nm, which has been shown to be the most important aerosol property for diagnosing the concentration of cloud condensation nuclei (CCN) concentrations (Feingold, 2003). A scanning electrical mobility spectrometer (SEMS, also called Scanning Mobility Particle Spectrometer, SMPS) is well suited to making this measurement, and NOAA has routinely operated such an instrument on a Cessna 206 since mid-2006. A condensation particle counter (CPC) will measure the total aerosol number concentration (CN), which would also greatly aid interpreting the slower cycling SEMS. The SEMS cannot distinguish aerosol changes on sub-minute time scales, but a fast total particle counter (CPC) could identify when the aerosol was changing rapidly and impact the size distribution measurements.

However, many earlier studies (Bigg, 1986; Chuang et al., 2000; Covert et al., 1998; Roberts et al., 2006; Snider and Brenguier, 2000; Wood et al., 2000) have also found that CCN concentrations are often over-predicted based on measured aerosol size distributions and inferred chemical composition. Even with size-resolved chemistry, direct measurements of CCN are important especially in regions near local sources since the aerosols are often highly externally mixed (Medina et al., 2007). Thus, an instrument for routine measurement of CCN would be highly desirable.

A suitable CCN instrument is not commercially available – however, a prototype miniature CCN counter has been developed (Roberts, 2006). It is based on the streamwise CCN counter (Roberts and Nenes, 2005), developed by the Dr. Roberts at Scripps Institution of Oceanography and commercialized by Droplet Meas-

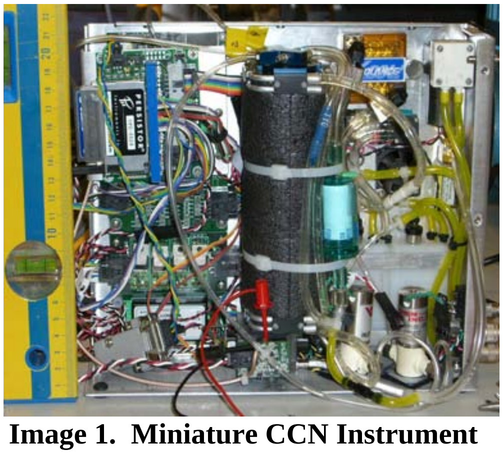

**Image 1. Miniature CCN Instrument**

| | |
|---|---|
| Dimensions | 21 x 20 x 7 cm |
| Weight | 1.8 kg (without case) |
| Power | 40 W (peak) |

See Appendix D for details. Image courtesy Dr. Greg Roberts.

urement Technologies (DMT)[7]. However, continuous airborne CCN measurements do not exist because the small aircraft needed for routine observations (e.g., RACORO) cannot accommodate the size and weight of the commercial instrument. Dr. Roberts has since developed a miniaturized prototype for turnkey operation (Image 1), by optimizing the CCN chamber design to reduce its size considerably – without compromising performance. Additional information on the miniaturized CCN counter and its performance is given in Appendix D. If the miniaturized version becomes available in time, it would be a valuable addition to the payload, offering the first routine aircraft measurements of CCN. It would also demonstrate how AVP can incorporate cutting-edge technologies as soon as they are available. Dr. Roberts has expressed an interest working on this project (see *Letter of Support* in Section 12).

Finally, a measure of particle sizes greater than 500 nm and smaller than 3 μm diameter (the lowest limit of an FSSP) would be useful since these particles affect the precipitation process (e.g. Johnson 1982) and if they exist in high enough concentrations (a few per $cm^{-3}$) they could also modulate the super saturation and therefore the number of activated droplets (e.g., Ghan et al. 1998). Optical particle counters (OPCs) that measure in this range would be an important complement to the proposed aerosol package and allow us to better address aerosol-precipitation questions.

## 5. SAMPLING EVALUATION

In addition to the QC performed by AVP personnel, the RACORO investigator team will be responsible for monitoring the data collected for QA to determine that the flight strategy and instruments are functioning well enough to address the proposed science and, if not, to course adjust. To take this a step further, we plan to meet approximately at the half-way point to discuss the data in detail, preferably to take a preliminary foray at using the collected data to address a focused science question, *i.e.* a much more quantitative assessment. There is no better QA than actually attempting to use the data for a focused scientific purpose. Only through such a focused study can we verify that we are getting the type of data that we would like and, if not, to evaluate appropriate adjustments to the measurement strategy (prior to this point, we may lack the statistics to assess whether an adjustment is needed). The difference between the standard monitoring and the 6-month review is the level of scrutiny, which is applied before the end of the experiment to improve the chance of obtaining the most useful dataset possible. This is not something that can be done well within a normal one-month IOP framework but it is essential for long-term efforts[8]. This effort could lead to fine tuning in several areas; examples are:

- **Flight plans:** Determine that our sampling strategy is lacking for a subset of the cloud types and modify it accordingly;

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[7] The commercial DMT CCN instrument (http://www.dropletmeasurement.com) has been thoroughly characterized (Lance et al., 2006). It was first flown (Roberts et al., 2006) in 2004 during the Cloud Indirect Forcing Experiment (CIFEX) and has since been successfully deployed in dozens of international airborne and ground-based campaigns. Instrument features include: supersaturation is a function of flow rate and temperature gradient, continuous flow allows fast sampling (1 Hz), and the cylindrical geometry reduces size and minimizes buoyancy effects. A single column generates CCN spectra by modifying the flow rate and/or temperature gradient to measure CCN between 0.07 and 2% supersaturation.

[8] A halfway check has been used in past long-term ACRF observation programs and has proven to be invaluable. For example, halfway checks were components of the project planning for the Nauru Island Effects Study (NIES) and the current NSA Radiometer IOP. For, NIES it showed that Nauru had switched from the convectively suppressed to active regime and that power problems had adversely affected the early data quality; this meant that the IOP needed to be extended to gather sufficient data. For the NSA Radiometer IOP, it was included with the explicit purpose to investigate the data thus far and, depending on results, refine the radiometer heater/fan setups.

- **Instrumentation:** Decide that a different instrument is needed to measure a variable, or assess that, for unforeseen reasons, the needed accuracy cannot be attained in practice. If the latter, the instrument could even be replaced by another to focus on a different objective;
- **Achievement of sampling objectives:** Determine whether more data would be needed and whether we should pursue an extension (e.g., if operational obstacles existed at the beginning) or, conversely, that the program can be completed early[9].

For the sampling objectives, considerations regarding sampling variable cloud fields were outlined in Section 3.2 and how they may affect the sampling statistics (e.g., Hallett, 2003). We would investigate the statistical sampling confidence (e.g., 90% interval) of the different variables of interest for different cloud classes and/or meteorological states. Should we determine that we are significantly ahead or behind our objectives, a plan modification may be made to best use the remaining time.

## 6. SUMMARY OF EXPECTED FINAL PRODUCTS

The anticipated final products are a statistically representative dataset of cloud *in situ* microphysical, radiative, and aerosol properties, for use in cloud retrieval validations and cloud microphysical studies. AVP will process these data and place them in the archive. The data used for real-time flight assessment and for the mid-way point evaluation and final report would be made available to the community (see webpage discussion in next section) so that users may efficiently cull the data for cases of interest. In addition, supported by individual PI science funding, several manuscripts are anticipated that would either be based on or use these data; the topics are suggested by the science questions given in Section 2.

Finally, we would keep an open willingness to participate with other interested groups during this observation period, provided that it would not compromise our strategy for unbiased sampling. For one example, the introduction mentioned a newly proposed ARM Large-Eddy Simulation (LES) Test bed (Zhu et al., 2006) would routinely test the ability of current high-resolution models to simulate boundary layer fair-weather cumulus and stratus. Should those efforts be developed, they would make a natural and immediate bridge between RACORO and model validation. These and other ARM Working Group efforts should be involved to the extent possible during these observations to attain the maximum value of the resources.

## 7. PROJECT MANAGEMENT & EXECUTION

Several mechanisms will be used for the successful, long-term execution of the project, as listed below. We also anticipate that there may be useful lessons learned from the upcoming AVP RISCAM flights. The management strategy is discussed here and the associated resources needed are discussed in Section 10. The background of the RACORO steering committee (PI team) covers the most important aspects of the RACORO operations and observations, which include aircraft sampling of aerosol and cloud microphysics, aerosol-cloud interactions, and surface and satellite remote sensing. Summaries of the team member backgrounds, their RACORO roles, and their vitae are given in Section 11.

**a) RACORO Operations Command Structure.** Our expectation is that AVP personnel will take the lead in conducting the flights and quality controlling the data. We expect that AVP will have a meteorologist on contract to provide flight-planning information that will assist with go/no-go decision-making. A subset of the RACORO Steering Committee will consti

[9] The sampling could be completed early if flights have been extremely successful and we have met our objectives or, should there be a fiscal emergency (such as that brought about by a continuing resolution), determine an early stop point that would preserve/satisfy at least some of the objectives.

tute an "Executive Board" who will provide the requisite guidance and feedback on operations. We anticipate that the Executive Board will visit the SGP at the start of operations to review and discuss practical issues for the execution of operations. ACRF instrumentation suggested for the go/no-go decision is discussed in Section 10.

**b) RACORO Steering Committee Involvement.** The Executive Board will confer with the steering committee and AVP personnel regarding operations and execution through regular telecons and meetings. The telecons will be held frequently at the start of the program so that a group consensus is developed for the go/no-go decision making process. It will also be important to iterate on the proposed flight strategy based on pilot feedback on the difficulties (or not) in performing the desired flight patterns (e.g., flying parallel and perpendicular to the wind in a cloud field). Other practical matters will also be addressed such as any impacts of flight control issues or, perhaps, patterns in the cloud occurrence (spatial and temporal) that were not anticipated. The telecons will start at a weekly interval for the first month, and taper off to a less intensive but regular interval every two weeks. The beginning of a new season will be marked with weekly telecons for the first two weeks to ensure that the flight adaptations for the diurnal timing are appropriate. Meeting updates will be coordinated with ARM WG meetings and the ARM Science Team. This structure will serve as interim coordination in addition to the halfway check described in Section 5.

**c) RACORO Web Information Site.** Program management will be conducted partly through postings on a shared Media Wiki Website (http://www.mediawiki.org/wiki/MediaWiki) that is password locked and viewable only to AVP and RACORO team members and other select officials. This will offer a more centralized organizational complement to e-mail communications. With password access, all team members will be able to routinely post and organize, on a routine basis, information needed for operations. ACRF operations (likely the XDC) will be responsible for posting all supporting data in a way that is easily useable by the team; items include: weather maps, TSI still images of the times flown (beginning and end), satellite images, and surface wind speed and direction. AVP operations will be responsible for archiving all flight information such as flight paths flown, QC assessment plots, and a running count of the observation hours achieved per diurnal hour (see Section 3.3). Once these data are sufficiently vetted, they can be made viewable (but not changeable) to the outside community. In fact, the posting board can be partitioned between sections that are always viewable to everyone and those that are only for private operational use by the operations team.

**d) Reviews and Reporting.** The importance of having a mid-year review was discussed in Section 5. AVP and RACORO steering committee members will participate in this evaluation and in one at the end of the program. In preparation for each, AVP operations will provide a mid-term and final report to the steering committee that summarizes each flight and provides overview data plots.

## 8. RELEVANCY TO LONG TERM GOALS OF THE DOE OFFICE OF BER

The observation program proposed herein is directly relevant to the ARM Climate Research Facility (ACRF) mission of studying and monitoring the Earth's system, since clouds and aerosols are essential elements of the Earth's climate. The data obtained and the subsequent knowledge gained can be used to evaluate and improve Global Climate Models (GCMs), which are the primary vehicles for determination by policy makers of acceptable levels of greenhouse gases in the atmosphere. Potential GCM improvements include the parameterization of continental boundary layer clouds, the representation of broken cloudiness and 3D radiative transfer, unresolved sub-grid dynamical processes, and aerosol-cloud interactions.

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## 10. ACRF RESOURCES REQUIRED

Some of the ACRF resource needs were introduced in Section 7. They are discussed here along with other ACRF resources: a) AVP Operations, b) Real-time data access, c) RACORO Web support, d) AVP Quality Control, e) Reporting and Steering Committee Travel, f) AVP Instrumentation, and g) SGP Instrumentation.

### a) AVP Operations

Naturally, the campaign will require AVP to provide an aircraft and the appropriate personnel at the SGP, reduction of the aircraft data, transmission of the data collected, and subsequent storage in the ACRF archive. As discussed in Section 7, our expectation is that AVP personnel will take the lead in conducting the flights and that, to do so, they will have a meteorologist on contract to provide flight planning information that will assist with go/no-go decision making.

### b) Real-time data access

To assist AVP flight go/no-go decision making, real-time access to satellite data and SGP surface instruments might be needed. (The final decision as to its need and the end point of where it would be used is up to AVP operations personnel, but we list it here for completeness.) The data that we foresee to be most useful are GOES satellite imagery (which can be available with only a 15 minute lag), and the following SGP instruments: (1) the TSI (Total Sky Imager), (2) MMCR, (3) one of the laser sensors (MPL, Raman lidar, or ceilometer) to detect thin clouds the MMCR might miss, and (4) the MWR (for LWP estimates). For the TSI, much of the background work has already been done by Dr. C. Long (already operational for the TWP sites)[10], and an Engineering Change Request (ECR) is pending to extend the same capability at the remaining ACRF sites.

### c) RACORO Web support

The steering committee plans to interface with AVP operations and assist in program management, in part, through postings on a shared Wiki Website (Media Wiki) that is password locked and viewable only to team members and other select officials. ACRF assistance would be needed to initiate the website and provide templates as needed that team members could use to post content (e.g., plots of results). ACRF operations (likely the XDC) needs to post supporting data there in a timely manner (possibly automated) and in a form that is easily useable by the team; items include weather maps, TSI still images of the times flown (beginning and end), satellite images, and surface wind speed and direction. AVP operations will be responsible for posting flight information such as flight paths flown, QC assessment plots, and a running count of the observation hours achieved per diurnal hour.

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[10] Dr. C. Long already makes TSI images available real-time; the ARM "most recent sky image" is available every 5 minutes from the web for the TWP sites (e.g., see http://198.129.82.242/~tsi/darwin/recent.html). Only a small amount of effort is necessary for the access to become operational at the SGP, and an ECR is currently pending to do the same at all the remaining ACRF sites (SGP, NSA, and AMF). The effort necessary to do the same for the other instruments (MMCR, laser sensor, and MWR) is not known to us at this time. However, we are aware that the MPL had a configuration by Dr. C. Flynn that enabled a real-time feed, and that Dr. K. Widener was able to make MMCR data to be available in "really soon time" during TWP-ICE (e.g., http://engineering.arm.gov/~widener/drw_mmcr/drw_mmcr_recent.jpg). If possible, same real-time data feed for these other instruments would be helpful for RACORO; however, given the longer period for RACORO than TWP-ICE, we realize that different logistical issues might arise that precludes this.

**d) AVP Quality Control**

We request that AVP conduct quality control (QC) checks on all measurements provided. In the operations of typical, short-term aircraft field campaigns, each instrument has a PI who knows the instrument and is responsible for its QC and for providing the data to a central archive. Similarly, in ACRF, each instrument has a mentor who is versed in the instrument operations and is responsible for monitoring its data quality and provides information support to users. Since AVP is so new, we do not yet know whether a similar mentor structure will be used but, regardless, it is vital that personnel who have experience with the instruments and their operation on the aircraft perform QC and serve as a contact for investigators who may have questions about their operation.

**e) Reporting and Steering Committee Involvement**

AVP operations will provide a mid-term and final report to the steering committee that summarizes each flight and provides overview data plots. We anticipate that AVP will shoulder much of the operational load but, beyond the designing RACORO, the steering committee will be responsible for:

- Guiding the experiment throughout the one-year period and perform specific functions identified in Section 7 that include: (1) Regular data quality control analysis and telecons to discuss if data quality and flight strategy meets the science objectives, and (2) Punctuate these running checks by participating in a mid-year check, where the net quality/utility of the data collection is assessed. These functions will insure quality assured data delivered to the archive.
- We also anticipate that there will be a need for one or more PIs to travel to the SGP to interact with pilots, technicians and operations personnel, especially in the beginning of the campaign.

Most of the Steering Committee involvement will not require monetary support from AVP – they have contributed to the ARM program for years, and most have at least some continued support for their activities as a Translator, Site Scientist, or Associate Chief Scientist. However, about $40K would be needed for the PI involvement associated with the aforementioned activities and quality control. Should separate travel be required for these activities, we request that AVP pay for travel that is solely associated with assurance of project operations and data quality.

**f) AVP Instrumentation**

The prioritized aircraft instrument complement is provided in Section 4.0. Additional support is requested only for the mini-CCN instrument, which exists in prototype form but it is yet not ready for field deployment (see Section 4.3 and Appendix D).

- The current prototype of the CCN instrument requires about $50K of instrument development funding for Dr. Roberts (Scripps Institution of Oceanography, UCSD) to complete a field-ready instrument. Additional funding would be needed if FAA certification of the instrument is required, or if AVP desires to acquire ownership of a mini-CCN counter.
- Because the mini-CCN counter is not a proven, commercial instrument, the RACORO team recommends that Dr. Roberts be asked to serve as the instrument mentor (see letter of support). As such, he would be responsible for processing the CCN data, its quality

control, and its final delivery. We estimate the mentorship duties at $40K, which includes travel and time for instrument install/uninstall, one scheduled maintenance trip, one unscheduled, and time for data processing and archiving.

We recognize that all formal negotiations and actual budgets would be taken care of by the AVP office.

**g) SGP Instrumentation**

No additional surface instrumentation will be required at the SGP. The principal investigators of the ARM program have utilized the various remote sensors at the SGP ACRF in a multitude of retrieval algorithms. It is our hope to evaluate as many of these retrieval algorithms as possible with this unique RACORO dataset. Thus, the following instruments are critical to this effort:

MMCR
WACR
AERI (rapid-sample mode)
MWR
MFRSR
Shortwave spectrometer
MPL
Raman lidar
Radiosondes
Shortwave broadband radiometers (pyranometers)
Longwave broadband radiometers (pyrgeometers)
TSI
Disdrometer

The following instruments are considered important for this effort, as they provide ancillary data to understand the retrieved data or atmospheric conditions:

VCEIL
Surface aerosol properties
CIMEL
NIMFR
MWRP
915 MHz wind profiler

## 11. BIOGRAPHICAL SKETCHES

- **Dr. Vogelmann** is co-chair of the ARM CLOWD Working Group, a member of the ARM Cloud Radiative Processes Steering Committee, and a member of the Chief Scientist Team for the ARM Program. His research involves satellite and surface-based observations of clouds and aerosols and their impacts on climate. Dr. Vogelmann will be the lead PI for RACORO and serve as the point of contact for the project. He will plan and coordinate operations with steering committee members, as well as subsequent analyses of the data.
- **Dr. McFarquhar** is the Chief Scientist for the DOE Aerial Vehicles Program and the former chair of the ARM Cloud Properties Working Group. His research expertise is in conducting and analyzing cloud and aerosol aircraft measurements to enhance our understanding of cloud microphysical processes and improve their parameterizations in climate models. Dr. McFarquhar will participate in the planning and analyses of the RACORO data, particularly through these strengths, and will also serve as a liaison to AVP officials.
- **Dr. Ogren** directs NOAA's aerosol monitoring program and serves on the European Supersites for Atmospheric Aerosol Research (EUSAAR) scientific advisory committee. He is the instrument mentor for the ARM Aerosol Observing Systems (AOS), and also for the ARM In-situ Aerosol Profiling (IAP) aircraft program that successfully conducted routine aircraft observations of aerosol properties at the SGP for seven years, averaging an impressive two flights per week. Dr. Ogren will contribute his AOS and IAP experiences to the planning and operation of RACORO, as well as his expertise in analyzing and interpreting aerosol data.
- **Dr. Turner** is the founder and co-chair of the ARM CLOWD Working Group and has made significant contributions to assessing the accuracy of retrieval algorithms for thin liquid water clouds. He has developed a significantly improved MWR retrieval product (MWRRET), unique algorithms that retrieve cloud microphysical properties from AERI measurements, and has also played a pivotal role in establishing the liquid-water profiling capability for the ARM Raman lidar. Dr. Turner will contribute to RACORO his experience with field programs and his surface remote sensing expertise using the MWR, AERI, and Raman lidar.
- **Dr. Comstock** is the translator of the ARM CLOWD Working Group where she facilitates the development of ARM Value Added Products (VAPs), and she is also the chair of the ARM Cloud Properties Working Group – Ice Clouds Focus Group. She has extensive experience in the modeling and remote sensing of clouds, particularly using laser-based instrumentation. Dr. Comstock will participate in the planning and analyses of the RACORO data, particularly through her strengths interpreting active remote sensor data and retrievals.
- **Dr. Feingold** conducts research at the interface between modeling and measurements of aerosol-cloud interactions at large-eddy scales. He is a member of international committees such as the International Commission on Clouds and Precipitation (ICCP), the WMO/IUGG International Aerosol-Precipitation Science Assessment Group, and the Climate Change Science Program Assessment Group. Dr. Feingold will participate in RACORO, particularly through his strengths in assessing cloud-aerosol interactions in observations and models.
- **Dr. Long** is the site scientist for the ARM Program’s Tropical Western Pacific Region, and is the translator for the Radiative Processes Working Group where he facilitates the development of ARM Value Added Products (VAPs). His research expertise includes radiometry and developing novel methods that extract the maximum scientific benefit long-term radiometer datasets. Dr. Long will participate in the planning and analyses of the RACORO data, particularly through his strengths in aircraft and surface radiometry.

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28 May 2007

Dr. Andrew Vogelmann
Brookhaven National Laboratory
Atmospheric Sciences Division, Bldg 490D
Upton, NY 11973

Dear Dr. Vogelmann,

I would like to express my interest in your ACRF Proposal for RACORO and, in particular, my potential involvement with the deployment of the mini-CCN instrument for routine airborne observations.

As described in the proposal text (Appendix D), the prototype CCN instrument has been completed and successfully tested. Producing a field version of the prototype will require repackaging and testing, which would take approximately six months of effort and be completed well ahead of the first RACORO flights in 2009.

I realize that, should your proposal be successful, that AVP would be responsible for choosing and acquiring the necessary instrumentation. Should they be interested in pursuing this venture, it would offer the potential of making the first routine, long-term airborne CCN measurements, which opens up exciting avenues of research of mutual interest.

Best wishes in your proposal and would I look forward to working with you on this project.

Sincerely,

Gregory C Roberts

Dr. Gregory C. Roberts

# APPENDIX A

## OVERVIEW OF CLOUD PROPERTY SURFACE REMOTE SENSING

The following methods can use surface-based measurements to retrieve some or all of the cloud properties of interest (LWP, Reff, optical depth, LWC).

- **Microwave emission.** The LWP can be retrieved from the cloud's emission of microwave energy measured by a MWR using various approaches (e.g., Turner et al. 2006). However, the frequencies commonly used by MWRs do not have the desired sensitivity for low LWPs, and are not sensitive to particle size.
- **Solar transmission.** The optical depth of an overcast, stratiform cloud can be determined from diffuse solar fluxes (Min and Harrison 1996; Barnard and Long, 2004). Since optical depth contains information on LWP and Reff, an estimate of LWP (e.g., from the MWR) yields a determination of Reff.
- **Infrared emission.** Cloud microphysical information is contained in high-resolution infrared spectra of atmospheric windows such as that between 8 to 12 μm. Using a temperature profile, narrow field-of-view infrared radiances from the Atmospheric Emitted Radiance Interferometer (AERI) can be inverted to obtain optical depth, Reff, and LWP, but are limited cases below 60 g $m^{-2}$ (Turner and Holz, 2005).
- **Lidar probing.** Lidar actively probes clouds by emitting a laser pulse and measuring the time and magnitude of the backscattered return signal. This can provide crucial information on the vertical distribution of cloud liquid water content (LWC; the mass of liquid water in a volume of air). However, lidars are typically limited to cloud optical depths less than about three, above which the return signal is fully attenuated.
- **Cloud radar probing.** Millimeter Cloud Radars (MMCRs) respond to the $6^{th}$ power of the cloud's drop size distribution, which is not directly related to the $3^{rd}$ power needed for LWP estimates. However, cloud radars can retrieve profiles of LWC and Reff if an assumption is make of the profile number density (e.g., Frisch et al. 1995).
- **Multiple instruments.** Limitations of the information content available from specific wavelength regions can be circumvented by simultaneously using wavelengths that have complementary sensitivities, therefore providing additional retrieval constraints. For example Austin and Stephens (2001) combine MMCR reflectivities and MFRSR cloud optical depths to improve retrievals of LWC profiles and Reff, and Turner (2007) combines AERI and MWR measurements to retrieve LWP for the entire dynamic range with an especially improved accuracy for LWP < 60 g $m^{-2}$.

The suite of surface radiometric measurements at the SGP ACRF site would enable the validation studies of these and other types of retrieval methods during RACORO.

# APPENDIX B

## FLIGHT PLANNING

Discussed in this appendix are general guidelines for flight patterns that may be used to achieve our sampling objectives. The actual rules would be determined before the program, after an aircraft operator has been established and details worked out with air traffic control (ATC). Due to the novel nature of these flights:

> ***The strategy will be revisited throughout the project and adjusted if necessary to maximize the utility of the data.***

### a) Flight Pattern Considerations & Rules

Because the flights would be in cloud, the pilot will be following Instrument Flight Rules (IFR) that are more structured than when the skies are clear and the pilot may use the predominately "*see-and-avoid*" Visual Flight Rules (VFR). Thus, the pilots will need to deal with navigation, IFR flight rules, ATC, as well as potential turbulence, limited visibility, and wind shifts (with time and/or altitude). For these reasons, we pursue the simplest patterns necessary to accomplish our goals.

- ***Flight patterns will use long, straight legs in simple configurations*** to minimize in-flight pilot decisions and possible sampling biases. Each leg will be about 50 km long in order to capture multiple large eddies in a leg, and still remain close to the sample volumes of the SGP Central Facility (CF) remote sensing instrumentation. The variation of cloud microphysical properties sampled in cloud can depend considerably on the orientation of the leg flown relative to the ambient wind. Our patterns are designed to fly parallel or perpendicular to the wind[11] to simplify later analyses of the cloud microphysical data. The most recent SGP sounding will be used to orient the legs relative to wind direction at the lifting condensation level (and possibly real-time MMCR and/or lidar data). To enable the best comparisons of the aircraft data with the time series of surface retrievals (obtained as the clouds advect over the CF), a leg will be started downwind of the SGP CF and flown into the wind until crossing over the CF. Examples of three flight patterns that generally satisfy these criteria are illustrated in Figure B1.
- ***Deviations from Pre-determined Legs*** will be considered only when a shift would significantly increase the cloud sample without biasing it[12]. For example, if a line of clouds is oriented perpendicular to the wind, moving the perpendicular legs a few kilometers could result in flying in a line of clouds rather than between them. Since some cloud types such as fair weather cumuli sometimes have only 10% cover, some flexibility is desirable. However, allowing flight deviations will remove the random nature of the sampling, and may bias the observations towards optically thicker clouds that are more easily identified. We envision allowing pilot discretion to deviate from predetermined straight legs by up to 5 km if he/she

[11] Note: not all legs will be parallel or perpendicular to the wind throughout the entire flight due to changes in wind direction with time and altitude, but this strategy will simplify the resulting data analysis as much as possible.
[12] There needs to be some flexibility in the sampling approach for the days approved for flights. It is better to obtain some cloud measurements that are less than optimal than none because sampling requirements are too strict. Nevertheless, days that contain sub-optimal sampling should be flagged as such.

feels that a significant increase in cloud observations would be realized, without a bias towards thicker, thinner or clouds that are more versus less developed. All legs will occur along long, straight lines to prevent varying pitch and roll that would adversely affect the radiative observations.

- ***Statistical sampling of cloud fields will be conducted at multiple vertical levels***[13]. A complete circuit will be flown below cloud base; the altitude is then increased (by about

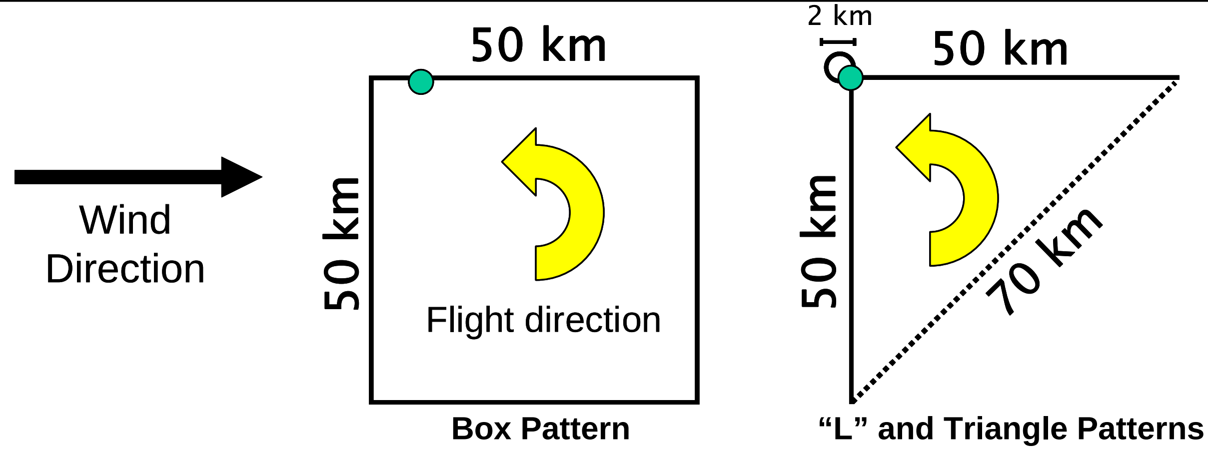


**FIGURE B1. THREE SAMPLE FLIGHT PATTERNS.** Shown are a Box, "L," and Triangle flight patterns. The green circle (●) indicates the SGP Central Facility (CF).

- The Box pattern uses 50-km legs and aims to acquire cloud statistics only in the cross-wind and along-wind directions. It allows the pilot to more easily fine-tune the placement of the legs that do not pass over the CF. For example, if the clouds are organized into streets, the pilot can slightly shorten or lengthen a leg so that the next leg runs directly down the cloudy part of the street.
- The "L" pattern modifies this concept by using only two, orthogonal 50-km legs. Upon reaching one of the two "L" end points, they climb to a new altitude while completing a 180° turn and set a level leg at a new height before retracing the pattern. Overall, this pattern increases the number of CF overpasses possible during flight (needed for surface retrieval validation) but compromises some sampling during the 180° turns.
- The Triangle pattern adds the hypotenuse to the "L" pattern (dotted line). Although it is potentially harder to interpret the cloud microphysical data for legs that are arbitrarily oriented with the wind, it provides a sample of the cloud population that is independent of any potential cloud organization relative to the wind direction.

At an air speed of 80 m $s^{-1}$, the Box Pattern would take about 2.78 hrs to complete 4 square circuits at different cloud altitudes. The Triangle Pattern would take slightly less time to complete four circuits (2.36 hrs), and the time difference would roughly accommodate an extra downward spiral over the CF (1,500 m at 1 m $s^{-1}$). Contingent on the types of cloud fields experienced during a given day, each of these patterns may provide sampling advantages relative to each other.

[13] We will not attempt repeated penetrations through the same cloud because of the likely small vertical extent of clouds with low optical depths, their potential modification by aircraft, and their movement and evolution between legs make it difficult to identify and to fly repeated penetrations through the same cloud. Statistical sampling of cloud fields at multiple levels has worked during previous field campaigns such as the Indian Ocean Experiment (INDOEX) and the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS).

300 m), and the flight circuit is repeated (about 4 times) until one is completed above cloud. The altitude changes will be done as quickly as possible at the beginning of each circuit at a point far from the CF. At the end of the flight, a spiral descent will be flown in the volume above the CF. The circuits will continue until the flight time is used up or until two full circuits are flown above all cloud tops. Because clouds rise to different heights, parts of the circuits will inevitably be above some cloud but not necessarily above all. The circuit below cloud base will sample ambient aerosols and the vertical mass flux, and these routine measurements below and just above cloud base will significantly extend the data set beyond that previously obtained, enabling investigations of the cloud-aerosol interactions under a wide variety of aerosol and meteorological conditions.

- ***Spiral descents over the CF for comparison with ground-based remote sensing retrievals.*** The spiral descents from cloud top to cloud base will be performed regardless of cloud type so that statistics are not biased towards thicker clouds. We hope that, over the course of the experiment, spirals through thinner wispy clouds will yield information about their vertical profile. To minimize effects due to horizontal variability (that will likely be present), the spirals will be executed with as tight of a turning radius as permissible by the operator. The aircraft descent rate will be approximately 1 m $s^{-1}$ (or faster if dictated by the remaining flight time).

## b) Flight Times

Flight operations will be conducted three days a week with no flights allowed on consecutive days. The optimal flight days will be worked out in coordination with the aircraft operator and Vance ATC.

The year will be partitioned into four 3-month seasons. For each season (starting January 1, April 1, July 1 and October 1), flights systematically start at different times to acquire cloud statistics that span the pre-sunrise to post-sunset hours of the diurnal cycle. The boundary layer cloud climatology (Figure 3) shows that, independent of season, the frequency maxima occur during early morning daylight hours, which would ease flight operations (should our flight period follow climatology). However, a significant number of afternoon clouds exist, which are important to sample since different dynamics likely drive their formation. In addition to these considerations, emphasis will be placed on take-offs: (1) at high solar elevation angles, for evaluation of solar retrievals, (2) nighttime flights in benign conditions, for validation of the Raman lidar LWC and AERI Reff retrievals, and (3) flights coincident with EOS satellite overpasses (around 1030 and 1330 local), so that EOS observations may be used to assess horizontal cloud variability and, when possible, provide data for their validation.

Exact flight timetables will be determined later. An example that uses the above considerations is given in Table B1 for a season beginning 1 January. Flights start at 8 AM and, for the next four weeks, progress forward one hour per week to sample the morning cloud frequency maximum. The next month emphasizes mid-day flights that will have high solar zenith angles and may coincide with EOS A-Train overpasses (1330). The last month conducts afternoon and nighttime flights. A gradual progression in take-off times should minimize conflicts with crew rest cycles and permit the use of a single crew for the flight operations[14].

[14] A possible exception occurs towards the end of the season when switching from evening to early morning flights. Extra rest days would be needed if the night flights were executed at the end of the week and, therefore, conflict with the next week's early morning schedule.

Some seasonal dependence will be included in the flight-start planning. For example, in the summer, we may emphasize morning flights since a greater fraction of small cumulus occurs during that time.

**TABLE B1**
**Example Season #1: 12 Weeks Starting 1 January**

| Week Number | Month Number | Week Departure Time | Comment |
|---|---|---|---|
| 1 | **Month 1** | 8 AM | Progress 1 hr each week to capture the cloud frequency maximum in the early morning |
| 2 | | 9 AM | |
| 3 | | 10 AM | |
| 4 | | 11 AM | |
| 5 | **Month 2** | Noon | High solar zenith angle, which is between Terra and A-Train overpasses (1030, 1330) |
| 6 | | Noon | |
| 7 | | Noon | |
| 8 | | Noon | |
| 9 | **Month 3** | 3 PM | Later afternoon statistics |
| 10 | | 3 PM | |
| 11 | | 9 PM | Nighttime statistics (evening and morning) |
| 12 | | 6 AM | |

**<u>c) Go/No-go & Delay Decisions</u>**

Every effort will be made to follow a predetermined flight schedule, but the nature of clouds makes it impossible to follow a preset schedule every day. Predetermined flights will not be flown if clouds are not present or if weather conditions preclude the safe operation of the aircraft (*e.g.*, possible icing or severe weather). Flight cancellation due to severe weather will be made by the AVP operations team and aircraft operator, based on DOE and other safety procedures. Based on the climatology at Ponca City, we anticipate that icing conditions will preclude flights in low-level clouds only about 14 days a year (C. Greenwood, 2007, personal communication).

However, input will be needed to decide when to cancel a flight due to the absence of cloud. Because we are stressing routine observations and representative statistics during RACORO, we will fly unless the cloud coverage is less than 10%, since low cloud-cover conditions may provide representative statistics for clouds that have LWP and optical depths. The command structure for the go/no-go decision-making is discussed in Section 7, *Project Management & Personnel*, and resource needs are described in Section 11, *ACRF Resources Required.* The decision to cancel will be made on the day of flight about approximately 3 to 4 hours before take-off. Substantial take-off delays will not be permitted due to the cost of keeping a pilot available for the day. If a flight is cancelled, it will be rescheduled for the following day. If a rescheduled flight cannot be flown, the flight will be dropped from the rotation and the next regularly scheduled flight will be executed.

# APPENDIX C

## AVP Measurement Requirements and Suggested Instruments[15]

**Tables C1 to C5 –** Specifications and Priorities per Category. Ranked using three tiers: Critical, Important, or Useful.
**Table C6 –** Net Summary of Instrument Rankings

**Table C1. Cloud Microphysics[16]**

| Property | Range | Accuracy & Resolution | Frequency (ν) | Priority | Suggested Instrument | Comment |
|---|---|---|---|---|---|---|
| Cloud drop size distribution (incl. drizzle) | 3.0 μm to 1.2 mm | | | | | |
| | 3.0 to 50 μm | 10% < 20 μm<br>5% > 20 μm | 10 Hz | Critical | Forward scattering spectrometer probe (FSSP) | If reliable, 10 Hz is preferable (e.g., fast FSSP); however averaging over longer time periods still may be necessary. |
| | 50 to 640 μm | 5% | 10 Hz | Critical | One-dimensional cloud probe (1DC) | |
| | 125 μm to 1.2 mm | 5% | 0.1 Hz | Important | Two-dimensional cloud probe (2DC) with 50 μm spacing | Consider tradeoff with platform size |
| Cloud liquid-water content | 0.005 to 3.0 g $m^{-3}$ | 5% | 20 Hz | Critical | King and/or Gerber Probes | Redundancy preferred (Useful) |
| Flag presence of mixed-phase cloud | NA | NA | 1 Hz | Important | Rosemount icing detector (RICE) | If power and weight requirements permit |

[15] The recommended instruments are examples and do not restrict the AVP to only the instruments listed.

[16] Most of the instruments listed in this table fit into standard pods that are installed beneath the wings of aircraft used for cloud physics research. The maximum number of pods on a plane does not have a predetermined limit. It depends on the plane, and the way that the pods are mounted on the plane. For example, the CIRPAS Twin Otter has a "pod multiplier", which enables attaching three pods to a single pod attach point. However, the extent to which such payload could be accommodated by AVP depends on aircraft limitations, and the cost of the instruments and of their data processing during the campaign.

If pod-space is limited, we note that a DMT CAPS probe, in one package, could replace both the FSSP and the 2D probe and provide a hot-wire detector for LWC. We chose for now the FSSP and 2D-C because they have a longer period of proven operational quality and their performance characteristics are well understood, having been studied over years. Also, experience with one CAPS probe found it to use a substantial amount of power. However, all three instruments (CAPS, 2D-C, FSSP) are planned for use in the 2008 AVP campaigns for Indirect and Semi-Direct Aerosol Campaign (ISDAC), and Routine In Situ Cloud and Aerosol Measurements (RISCAM). Contingent on the performance of the CAPS to the other instruments, the instrument choice may be revisited.

**Table C2. Radiometric Quantities**

| Property[17] | Ranges | Accuracy | Resolution | ν | Priority | Suggested Instrument | Comment |
|---|---|---|---|---|---|---|---|
| **Irradiances (2π sr FOV)** | | | | | | | |
| ↑↓ SW BB[18] (Total) | 0.285 to 2.8 μm<br>0 to 1400 W m$^{-2}$ | 5 W/m2 | 0 to 8 W m$^{-2}$ | 1 Hz (1/e)[19] | ↑ Critical<br>↓ Critical | Epply PSP[20] | ↑ SW approach avoids using a stabilized platform because of its weight and dependability. |
| ↑↓ SW BB (Total & Diffuse) | 0.4 to 2.7 μm<br>0 to 1400 W m$^{-2}$ | T = ±8%<br>D = ±10 W m$^{-2}$ | 0.60 W m$^{-2}$ | 5 Hz (0.2 s) | ↑ Critical<br>↓ Useful | SPN-1[21] | Fast-response SW to interpret the slower pyranometer and partition the direct and diffuse fields. |
| ↑↓ LW BB | 3.5 to 50 μm<br>0 to 700 W m$^{-2}$ | 15 W/m2 | 0.04 W m$^{-2}$ | 0.5 Hz (1/e) | ↑ Important<br>↓ Useful | Epply PIR | Pyrgeometer interpretation assisted by fast-response pyrometer. |
| ↑↓ SW NB (Spectral) | 5 to 6 bands from 300 to 900 nm @ 0 to 100 W m$^{-2}$ | ±5 % | 1 %<br>Widths each 10 to 30 nm | 10 Hz | ↑ Important<br>↓ Important | MFR Head | Surface albedo mapping, assisted by the ↓↑ SW direct-diffuse partitioning (e.g., SPN-1). Prefer MFR Head in rapid sample mode. |
| **Radiances** | | | | | | | |
| ↑↓ LW NB | 9.6-11.5 μm<br>2.0° FOV<br>213 to 350 K | ±0.5 K | ±1.85 K | 5 Hz (0.2 s) | ↑ Important<br>↓ Useful | IRT (Infrared Thermometer): Heitronics | Fast-response, narrowband pyrometer to interpret slower pyrgeometers |
| ↑↓ SW NB (Spectral) | 400 to 900 nm<br>↑NB 1° FOV<br>↓NB 2π FOV | ±5 % | 1 %<br>≤ 10 nm | 3.7 Hz (0.27 s) | ↑ Important<br>↓ Useful | NIMFR or ASD FieldSpec Handheld Pro[22] | Broken cloud analysis/retrievals. Full spectral coverage not necessary. Optimal λ centers include 0.67, 0.87, and 1.6 μm.[23] |

[17] The direction of the radiometer indicated by ↑=uplooking, and ↓=downlooking.
[18] Broadband=BB, Narrowband=NB
[19] In a constant radiative field, approximately 5x(1/e) is needed for a stabilized measurement.
[20] Response time of Epply PSP preferred over the Zipp & Zonen
[21] SPN-1 specifications at http://www.delta-t.co.uk/products.html?product2006111306455.
[22] Measurement by a NIMFR (Normal Incidence Multi-Filter Radiometer, without the tracker), or high-resolution spectra out to 1075 nm from an ASD FieldSpec Handheld Pro with replaceable foreoptics available for 1° and 2π FOVs (specifications at http://www.asdi.com/products_specifications-FSHH-FSHHP.asp).
[23] Other ASD instruments include the 1.6-μm channel but, although desirable, the channel is not covered by the specified wavelength because of the extra cost.

**Table C3. Aerosol Properties**

| Property | Range | Accuracy | Frequency (ν) | Priority | Suggested Instrument | Comment |
|---|---|---|---|---|---|---|
| Aerosol size distribution | 20-500 nm | ±10% | 0.02 Hz | Critical | Scanning Electrical Mobility Spectrometer (SEMS) | Also called a Scanning Mobility Particle Spectrometer (SMPS) |
| Total aerosol number concentration (CN) | 0 to $10^4$ $cm^{-3}$ | ±10% | 1 Hz | Critical | Condensation Particle Counter (CPC) | Fast sensor, required for evaluation of slower SEMS data |
| Cloud condensation nuclei concentration (CCN) | 0 to $10^4$ $cm^{-3}$ | ±10% | 1 Hz | Important[24] | Not commercially available | Prototype mini-CCN instrument completed by G. Roberts. |
| Large aerosol size distribution | 0.5 to 3.0 μm | Estimated ±10% | 1 Hz | Important | Optical Particle Counter (OPC) | Assists aerosol-precipitation studies |

**Table C4. Aircraft State**

| Property | Ranges | Accuracy | Resolution | ν | Priority | Suggested Instrument | Comment |
|---|---|---|---|---|---|---|---|
| True aircraft speed | 0.0 to ~100 m $s^{-1}$ | 1.0 m $s^{-1}$ | 1% | 1 Hz | Critical | TBD | Essential for particle cloud and aerosol data reduction |
| Geopositioning | | | | 50 Hz | Critical | TBD | Essential for radiometer data reduction and surface validations |
| Latitude, Longitude | 30 to 40 °N, 90 to 105 °W | 1.8 E-5° (20 m) | 9.0 E-6° (10 m) | | | | |
| Geometric altitude | 0 to 3,000 m | 10 m | 1 m | | | | |
| True Heading | ±180° | 0.05° | 0.01° | | | | |
| Pitch, Roll | ±90°, ±90° | 0.05° | 0.01° | | | | |

[24] Would be ranked "critical" if a suitable commercial instrument existed. See Section 4.3 and Appendix D for the prototype developed by Dr. Roberts.

**Table C5. Atmospheric State**

| Property | Range | Accuracy & Resolution | Frequency | Priority | Suggested Instrument | Comment |
|---|---|---|---|---|---|---|
| Water vapor concentration | 0.0 to 30 g $kg^{-1}$ | 1% | 50 Hz | Critical | TDL Hygrometer | Optical measurement required |
| Air temperature | -40 C to 40°C | 0.1°C | 50 Hz | Critical | TBD | |
| Air pressure (static) | 0 to 1080 mb | 0.5 mb<br>0.003 mb | 50 Hz | Critical | TBD | |
| Updraft velocity | -10 to 10 m $s^{-1}$ | 0.10 m $s^{-1}$ | 50 Hz | Critical | Fast gust probe | |
| Turbulence | 0.0 to 100 $cm^2$ $s^{-3}$ | 0.10 $cm^2$ $s^{-3}$ | 50 Hz | Important | Fast gust probe | |
| Horizontal wind speed and direction at cloud level | 0 to 60 m $s^{-1}$<br>0 to 360° | 2 m $s^{-1}$<br>5 degrees | 1 Hz | Useful | TBD | Aids comparison with ground-based retrievals |
| Video of clouds flown | NA | NA | Standard video rate | Useful | TBD | Only if can be automated and cheap |

## Table C6. Net Summary of Instrument Rankings

Net ranking of the instrument priorities based on current assessments in Tables C1 to C5. The rankings are partitioned into three tiers that correspond, respectively, to Critical, Important and Useful. The final instrument suite selection will be based on rankings plus factors pertaining to the aircraft and other constraints that are unknown until AVP has selected a platform.

### TIER 1 - CRITICAL

**ALL CRITICAL INSTRUMENTS ARE NEEDED. NO PRIORITIZATION POSSIBLE.**

| CATEGORY (Table) | ITEM NUMBER | OBSERVATION |
|---|---|---|
| Cloud Microphysics (C1) | 1 | Liquid-water content (LWC) |
| | 2 | Cloud drop size distribution from 3 to 640 μm (diameter) |
| Radiation (C2) | 3 | Uplooking hemispheric SW (pyranometer) |
| | 4 | Uplooking total/diffuse SW (SPN-1) |
| | 5 | Downlooking hemispheric SW (pyranometer) |
| Aerosol Instruments (C3) | 6 | Aerosol size distribution from 0.02-0.5 μm (diameter) |
| | 7 | Total CN [fast instrument also assists aerosol size measurement] |
| Aircraft state (C4) | 8 | True aircraft speed |
| | 9 | Aircraft geopositioning data (lat/long/alt/heading/pitch & roll) |
| Atmospheric state (C5) | 10 | Temperature, water vapor concentrations, pressure |
| | 11 | Updraft velocity |

(Continued)

## TABLE C6 (continued)

### TIER 2 – IMPORTANT

| Tier Ranking | Observation | Category | Overall Category Ranking |
|---|---|---|---|
| 1 | CCN[25] | Aerosol | 1 |
| 2 | Turbulence | Atmospheric State | 1 |
| 3 | Drizzle drop size distribution (2DC)[26] | Cloud property | 1 |
| 4 | Surface albedo (↑↓ SW NB, spectral, rapid sample) | Radiation | 1 |
| 5 | Uplooking hemispheric LW (pyrgeometer) | Radiation | 2 |
| 6 | Uplooking spectral NFOV SW (fast, 1º FOV) | Radiation | 3 |
| 7 | Uplooking NFOV IR (IRT) | Radiation | 4 |
| 8 | Flagging of mixed-phase clouds | Cloud property | 2 |
| 9 | Large aerosol size distribution (0.5 to 3 μm) | Aerosol | 2 |

### TIER 3 – USEFUL

| Tier Ranking | Observation | Category | Overall Category Ranking |
|---|---|---|---|
| 1 | Downlooking hemispheric LW (pyrgeometer) | Radiation | 5 |
| 2 | Fast downlooking IR (IRT) | Radiation | 6 |
| 3 | Horizontal wind speed and direction at cloud level | Atmospheric State | 2 |
| 4 | Downlooking spectral NFOV SW (fast, $2\pi$ FOV) | Radiation | 7 |
| 5 | Fast downlooking SW (SPN-1, cloud albedo) | Radiation | 8 |
| 6 | Video of what flown | Atmospheric State | 3 |
| 7 | Redundant (bulk) LWC | Cloud property | 3 |

[25] Would be ranked "critical" if a suitable commercial instrument existed. See Section 4.3 and Appendix D for the prototype developed by Dr. Roberts.
[26] 125 μm to 1.2 mm diameter

## APPENDIX D

### Miniature CCN Instrumentation for AVP (G. Roberts)

The streamwise CCN counter [*Roberts and Nenes*, 2005], developed by the Dr. Roberts at Scripps Institution of Oceanography and commercialized by Droplet Measurement Technology (http://www.dropletmeasurement.com), has significantly improved the quality of CCN measurements on the ground as well as on airborne platforms. Image D1 shows the five-year evolution of the streamwise CCN instruments. The first prototypes were flown on the CIRPAS Twin Otter during CRYSTAL/FACE in July 2002 [*VanReken et al.*, 2003]. The streamwise DMT CCN instrument (Droplet Measurement Technologies, Boulder, CO), has been thoroughly characterized [*Lance et al.*, 2006] and was first flown during CIFEX [*Roberts et al.*, 2006]. It since has been successfully deployed in dozens of international airborne and ground-based

**Table D1.** Comparison of the commercial CCN instrument and the miniature CCN instrument.

| Instrument | Commercial CCN (DMT) | Miniature CCN |
|---|---|---|
| Dimensions (cm) | 80 x 48 x 34 | 21 x 20 x 7 |
| Weight (kg) | 28 | 1.8 (without case) |
| Power (W) | 420 (peak) | 40 (peak) |

**Image D1.** Development of streamwise CCN instrument. Version and year given below.


| 1st Prototype 2001 | 2nd Prototype 2002 | DMT Version 2004 | Mini-CCN 2006 |
|---|---|---|---|

experiments. Within three years, the streamwise CCN instrument has become the *de facto* standard because it is the only successful commercially available instrument of its type. The salient features of this instrument include: supersaturation is a function of flow rate and temperature gradient; continuous flow allows fast sampling (1 Hz); and simple cylindrical geometry reduces size and minimizes buoyancy effects. The use of a single column will generate CCN spectra by modifying the flow rate and/or temperature gradient to measure CCN between 0.07 and 2% supersaturation.

However, due to the size and weight of the current commercial instrument, airborne CCN measurements have been limited to larger aircraft. To address this limitation, theory and model simulations have been developed by Dr. Roberts to optimize its design and define operating limits of the CCN chamber. These calculations ensure proper performance and reduce the overall size of the instrument – making the instrument far easier for field deployment and compatible with various aircraft, including small lightweight unmanned aerial vehicles. Dr. Roberts has developed a miniaturized version that has been reduced to 20 cm x 25 cm x 7 cm and weighs less than 2 kg (compared to the commercial version of 45 x 26 x 80 cm at 24 kg; Table D1) – without compromising performance. The miniature prototype instrument has been calibrated and its performance validated by the sharp activation curves in Figure D1.

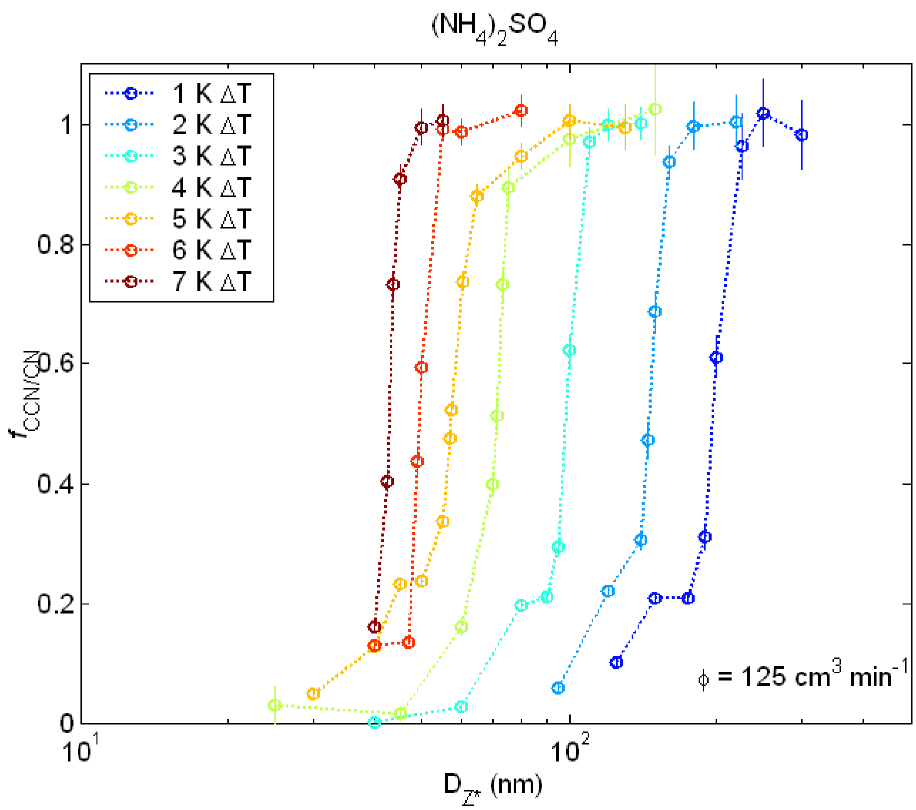


**Figure D1.** Calibration curves for the prototype miniature CCN. The activation curves show the fraction of CCN to total aerosol concentrations for particles of known composition and size. The x-axis is the size of the calibration particles and the y-axis is the fraction that activated into droplets. Each curve is for a different supersaturation. The sharpness of the change as a function of particle size indicates good performance of the instrument.

CCN instruments have been deployed since their conception to measure the number of particles that grow in a controlled supersaturation (e.g., Twomey, 1963). However, these measurements have been plagued for decades by a myriad of challenges such as sampling resolution, frequent user intervention, instrument failure, and calibration discrepancies. Consequently, CCN and aerosol observations have been generally associated with intensive field campaigns lasting several weeks. However, since the commercialization of the streamwise CCN instrument in 2004, it is already being used to make continuous measurements at several ground-based stations (e.g., Southern Great Plains, Oklahoma; Pt. Barrow, Alaska). There are no continuous airborne CCN measurements because the aircraft used for routine observations (as proposed for the RACORO project) are small and cannot accommodate the large commercial CCN instrument. However, the mini-CCN instrument described here offers the potential of obtaining routine aircraft CCN measurements for the first time.

### ***Appendix D References***


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