# Cloud and Aerosol Characterization for the Atmospheric Radiation Measurement Central Facility: Multiple Remote Sensor Techniques Development

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Determining the means to characterize the microphysical and radiative properties of the cloudy atmosphere from a Cloud and Radiation Testbed (CART) site has been the central theme of this Atmospheric Radiation Measurement (ARM) Instrument Development Program (IDP) research project. Previous studies have clearly indicated that only a varied combination of remote sensing instruments can provide this sort of information on an extended basis. However, the makeup of the remote sensor ensemble appropriate for a CART site obviously depends on the specific scientific research objectives at a particular locale, as well as logistical (e.g., instrument reliability and safety) concerns.

We have taken an approach that specifies two levels of instrument observational capabilities. Using a basic combination of remote sensors, the first level provides for the measurement of the three-dimensional distribution of clouds and aerosols, including their boundaries, type, and phase. In addition to this fundamental characterization of the state of the cloudy atmosphere, the second level addresses more specific measurement categories, such as effective cloud particle size, to help provide fundamental radiative cloud quantities. Although the latter measurements are currently more feasible to obtain from comprehensive remote and in situ field campaigns, we intend to develop, test, and verify these multiple remote sensor techniques so that they can be applied to increasing the information content of CART operations (though, we hope, relatively minor component or system additions and improved data analysis algorithms).

To accomplish this process, the University of Utah and the National Oceanic and Atmospheric Administration's (NOAA) Wave Propagation Laboratory (WPL) (see companion papers) participated in major field projects to obtain detailed cloud datasets, along with complementary cloud modeling and empirical studies. We describe our progress to date in our main research areas below.

## Polarization Diversity Lidar (PDL) Development

As reviewed at the start of the ARM Program (Sassen 1991), polarization lidar techniques have unique cloud-sensing capabilities, particularly with regard to the unambiguous discrimination of cloud phase and accurate determination of cloud boundaries. Various polarization techniques had not been systematically evaluated in the field, but such evaluations could now be facilitated by modern lidar designs based on high-speed microcomputers for system control and multistream data handling (Sassen 1991).

The design of the state-of-the-art PDL system accommodates the testing of these hybrid techniques, which include simultaneous two-color linear depolarization, variable field-of-view (FOV), and rapid scanning operations. The current PDL specifications are listed in Table 1, which, along with the schematic system diagram of Figure 1, illustrates the main features and advanced capabilities of this versatile instrument. A 33/486 microcomputer system tracks four polarization data channels at spatial resolutions down to 1.5 m and at the 10-Hz pulse repetition frequency (PRF) of the dual-wavelength laser transmitter. This capability not only provides for unequalled resolution of cloud features in space and time, but also permits rapid scanning and variable FOV operations.

**Table 1.** Specifications of the two-color PDL system.

| | |
|---|---|
| Operational: | |
| Wavelength (Nd:YAG) | 0.532 + 1.06 μm (simultaneous) |
| Peak Energy | 0.45 J each color |
| Maximum PRF | 10 Hz |
| Pulse Width | 9 ns |
| Beamwidths - Transmitter | 0.45 mr |
| Receiver | 0.2-3.8 mr, high-speed shutter |
| Receiver Diameter | 30 cm (2 telescopes) |
| Detectors - Visible | 2, Gated PMTs |
| IR | 2, APDs |
| Maximum Scan Rate | $5°s^{-1}$ |
| Data Handling: | |
| Number of Channels | 4 (simultaneous) |
| Sample Width (resolution) | 1.5 m maximum |
| Range Gates | 8 k maximum |
| Pulses Averaged | 1 - 10+ |
| Maximum Throughput | 164 k samples/second |
| Digitizer Resolution | 8 bits |
| Storage | 8 mm video tape |
| Polarization Properties: | |
| Transmitter | Vert. (Vis) + Horiz. (IR) |
| Receiver | Vert. + Horiz. (Vis + IR) |

In Figure 2, we provide high-resolution dual-wavelength displays of a cirrus cloud recently probed at our Facility for Atmospheric Remote Sensing (FARS) on the University of Utah campus. Although little difference in returned laser power as a function of wavelength is apparent (aside from signal noise effects), the cirrus depolarization data are unusual in that much lower linear depolarization ratios (δ) occur in the upper cirrus layer (at left at ~9.4 km) at the 1.06 μm wavelength. Recent studies of cumulus and altocumulus show wavelength-dependencies in backscattering resulting from small-particle effects, so it is possible that the upper cirrus layer was composed of quite small (~1 μm) ice crystals.

The PDL unit, which is permanently truck-mounted, and supporting passive remote-sensing instruments participated in the November-December 1991 First ISCCP[a] Regional Experiment (FIRE) intensive field observation (IFO) II field campaign in Coffeyville, Kansas. Here the unique high-resolution multichannel PDL data were used to research fundamental cloud processes.

For example, the depolarization data collected over the 5-6 December period revealed highly unusual cirrus cloud properties, including spherical scatterers between -40° to -50°C, which we concluded was a result of large cloud condensation nuclei of stratospheric volcanic origin, as reported in Sassen (1992). (A variety of supporting in situ and ground-based data have since supported the

(a) International Satellite Cloud Climatology Project.

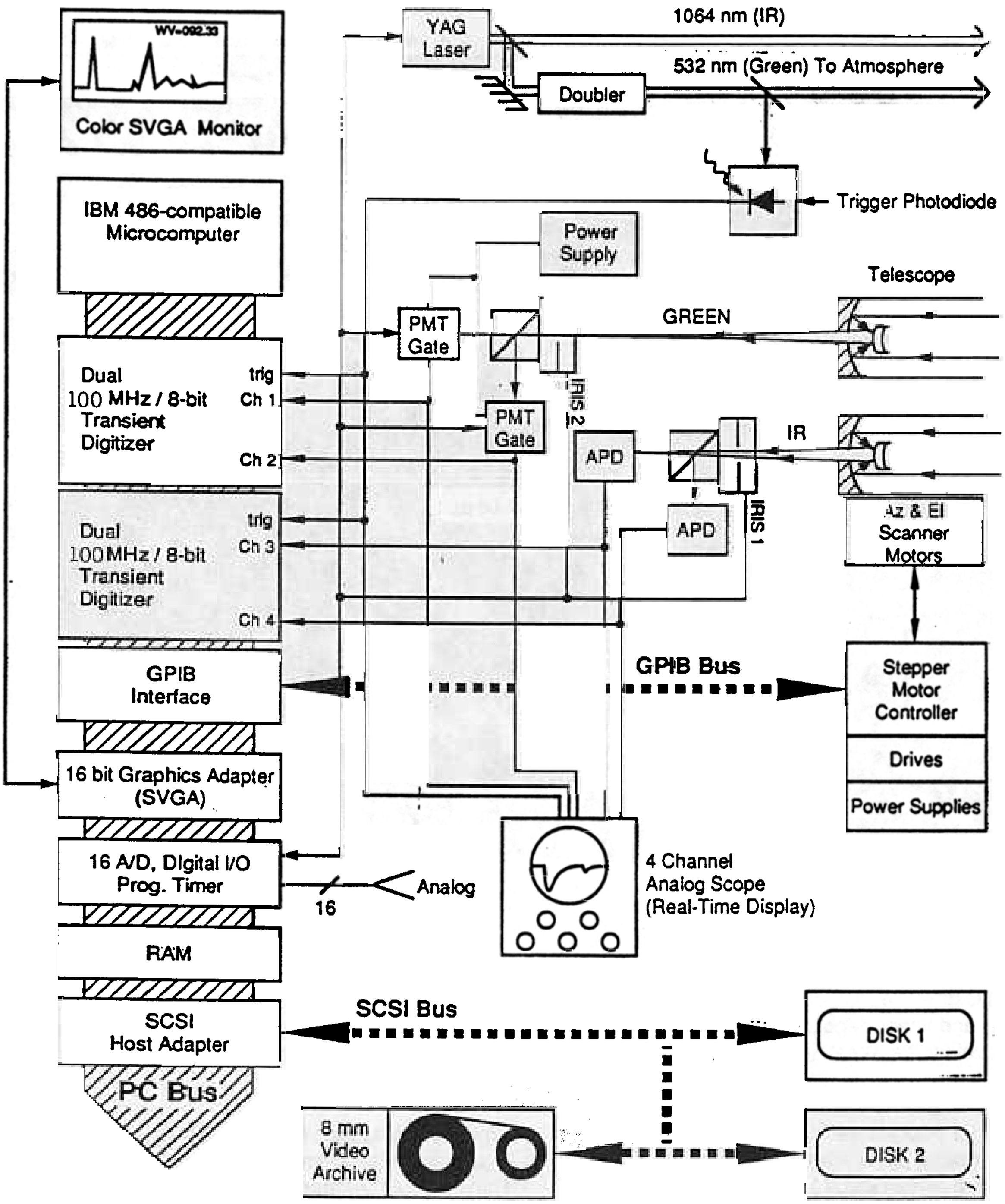


**Figure 1.** PDL LIDAR control and data acquisition system.

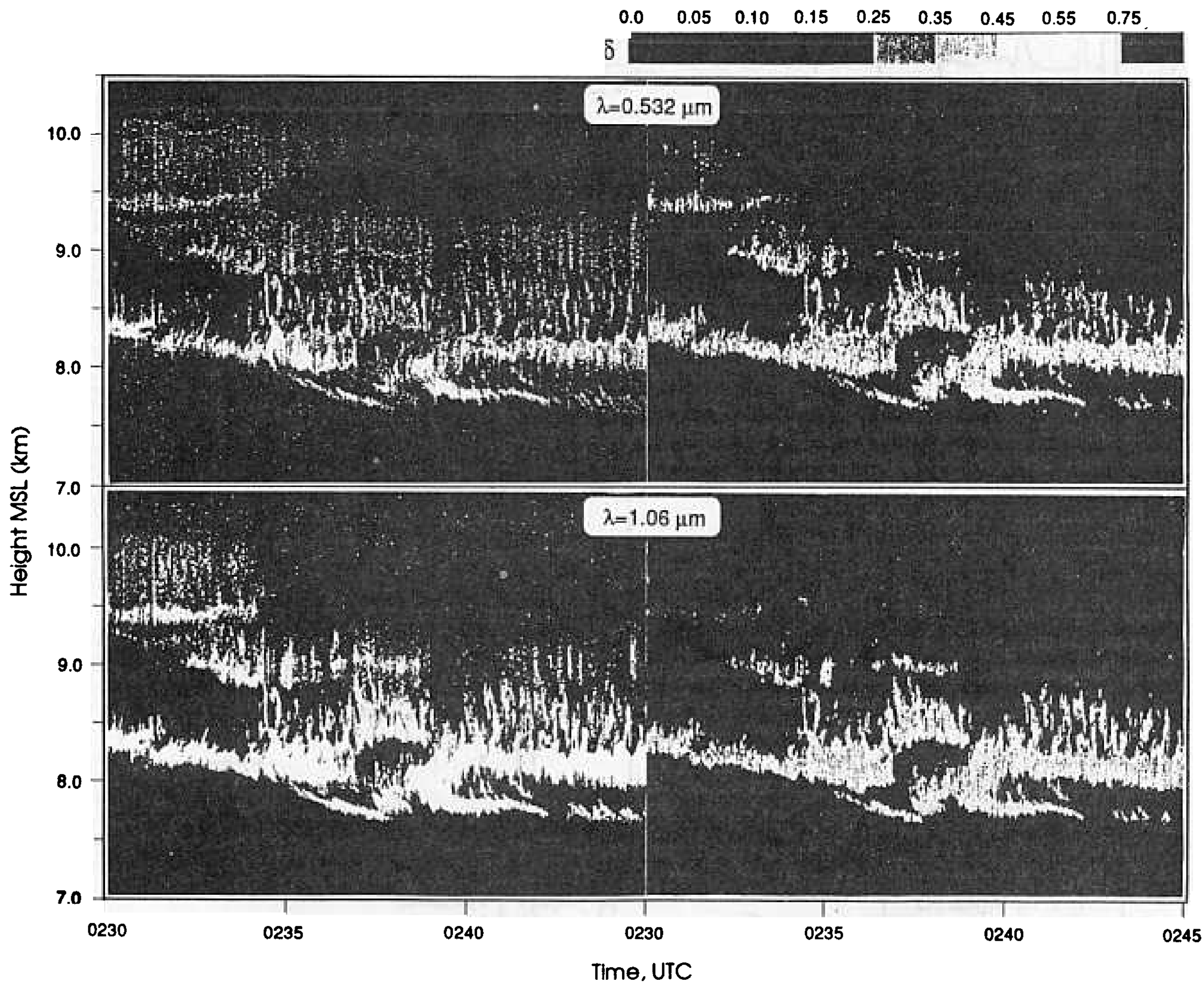


**Figure 2.** Height-time PDL displays of cirrus clouds sampled from FARS on 9 April 1993, showing the log of returned energy (left) and linear depolarization ratios (right, note δ scale at top right), at both the 0.532 μm (top) and 1.06 μm (bottom) wavelengths. Weak noisy signals are removed before δ values are calculated.

hypothesis that tropopause folding activities associated with a subtropical jet stream introduced stratospheric aerosol into the cirrus clouds.)

NOAA WPL instrumentation participated not only in this field campaign but in two other cloud/radiation field experiments as well: CLARET II (Cloud Lidar And Radar Exploratory Test), and ASTEX (Atlantic Stratocumulus Transition Experiment). In all three experiments, our measurements were augmented by many other instruments including in situ cloud microphysics data from aircraft, surface radiation instruments, radiosondes, radar wind profilers, surface meteorological stations, and infrared radiometers and spectrometers. These experiments have provided an excellent opportunity for gathering data and comparing retrieved parameters with other methods to meet our ARM objectives.

## Cloud Modeling and Empirical Studies

We have applied a sophisticated adiabatic cloud growth model, developed previously to study cirrus cloud particle nucleation processes, to simulate remote sensor returns from water, mixed water and ice, and ice phase clouds. This approach not only holds promise for interpretating field data, but also is requisite to evaluating the information contents of various remote sensing techniques.

The model uses detailed microphysical and dynamical equations to generate cloud contents that evolve with height in updrafts, beginning with a specified size distribution of dry cloud condensation nuclei (CCN). These vertically-resolved cloud contents represent a significant advantage over using height-invariant cloud compositions based on limited in situ data, although for some simulation purposes, the use of empirical temperature-dependent cirrus cloud contents are currently justified. We have improved the model so that cloud particle size distributions generated during diffusional growth are now converted to backscatter and extinction coefficients, and returned signal profiles for essentially any lidar or radar system, using subroutines that select Mie or Rayleigh theory for spherical or small (relative to the incident wavelength) nonspherical particles, or approximations based on geometrical optics ray tracing, conjugate gradient-fast Fourier transform, or empirical methods for ice crystals.

These numerical methods have been used to simulate polarization diversity lidar returns (with a first-order multiple scattering approximation) from water and mixed-phase clouds (Sassen et al. 1992), to develop an autonomous liquid cloud base detection algorithm for analyzing a winter mountain storm polarization lidar dataset (Sassen and Zhao 1993), and to obtain water and ice cloud mass content relationships using radar reflectivity factors (Liao and Sassen, in press). We have also initiated numerical studies aimed at evaluating the special PDL data-gathering capabilities such as the dual-wavelength and variable FOV techniques.

## Future Plans

We will continue to apply cloud modeling and empirical analysis methods to evaluate the multiple remote sensor approach for characterizing the cloudy atmosphere. Recommendations for CART instrumentation to satisfy this objective will include an appropriate combination of microwave radar and lidar polarization techniques, preferably on a single scannable platform to obtain the three-dimensional cloud distribution. We look forward to taking full advantage of CART facilities through PDL participation in focused intensive observation period studies of important cloud properties.

## Publications

Liao, L., and K. Sassen. In press. Investigation of relationships between $K_a$-band radar reflectivity and ice and liquid water contents. *Atmos. Res.*

Sassen, K. 1991. The polarization lidar technique for cloud research: A review and current assessment. *Bull. Am. Met. Soc.* **72**:1848-1866.

Sassen, K. 1992. Evidence for liquid-phase cirrus cloud formation from volcanic aerosols: Climate implications. *Science* **257**:516-519.

Sassen, K., H. Zhao, and G. C. Dodd. 1992. Simulated polarization diversity lidar returns from water and precipitating mixed phase clouds. *Appl. Opt.* **31**:2914-2923.

Sassen, K., and H. Zhao. 1993. Supercooled liquid water clouds in Utah winter mountain storms: Cloud seeding implications of a remote sensing dataset. *J. Appl. Meteorol.* **32**:1548-1558.