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CLOUD AND AEROSOL CHARACTERIZATION FOR THE ARM

CENTRAL FACILITY: MULTIPLE REMOTE SENSOR

TECHNIQUES DEVELOPMENT

Final Technical Report

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Central Facility: Multiple Remote Sensor Techniques Development

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ABSTRACT

In support of the initial phase of the Instrument Development Program (IDP) of the Atmospheric Radiation Measurement (ARM) program, we have researched the means by which multiple remote sensing techniques could be best applied to characterizing the cloudy atmosphere. This research has directly supported the short-term goal of aiding in the selection of the most appropriate instrumentation for ARM Clouds and Radiation Testbed (CART) sites, but also has more long-term consequences for the application of remote sensing for measuring cloud properties of crucial concern to general circulation and climate models. To accomplish our goals we have,

1. Developed a mobile, state-of-the-art, scanning polarization diversity lidar (PDL) to test a variety of techniques for cloud remote sensing, including simultaneous dual-wavelength and dual-polarization, and high-speed variable field-of-view operations.
2. Successfully participated in field projects using the PDL along with other remote sensors and instrumented aircraft to obtain detailed datasets for the testing of instrument techniques.
3. In collaboration with researchers at the NOAA Wave Propagation Laboratory, used numerical cloud modeling and empirical studies to develop and refine remote sensing approaches for cloud property retrieval.

1. Introduction

Although this research was funded under the Instrument Development Program of ARM, the stated objectives of our research included not only the fabrication of a R&D Polarization Diversity Lidar (PDL) system, but also a thorough examination of the use of multiple remote sensors for the characterization of the cloudy atmosphere. Thus our chief goal was to define the information contents of a variety of remote sensor combinations so that choices could be made in CART instrumentation for determining the three dimensional properties of clouds. Our design of the fully scanable PDL unit reflected this philosophy, in that a combination of laser depolarization, dual-wavelength, and variable field-of-view (FOV) techniques could be evaluated. Our approaches have included participation in major field projects where complimentary remote and in situ research support was available, empirical studies, and remote sensing simulations derived from a sophisticated cloud microphysical model. The Wave Propagation Laboratory (WPL) of NOAA, a subcontractor in our program, has been a partner in these endeavors. The major accomplishments from these aspects of our research program are summarized below.

2. Polarization Diversity Lidar System Development

The current specifications of the PDL system listed in Table 1 in every respect meet or exceed our original estimates. The schematic diagram of Fig. 1 illustrates the main features and advanced capabilities of this versatile instrument, which are all made possible by a high speed 33/486 microcomputer system. The ability to keep track of four channels of polarization data at spatial resolutions down to 1.5 m and at the 10 Hz pulse repetition frequency of the dual-wavelength laser transmitter not only provides for unequalled resolution

Table 1: Specifications of the Two-Color PDL System

<u>Operational</u>	
Wavelength (Nd:YAG)	0.532 + 1.06 μ m (simultaneous)
Peak Energy	0.45 J each color
Maximum PRF	10 Hz
Pulse Width	9 ns
Beamwidths - Transmitter	0.45
Receiver	0.2-3.8 mr, high-speed shutter
Receiver Diameter	30 cm (2 telescopes)
Detectors - Visible	2, Gated PMT's
IR	2, APD's
Maximum Scan Rate	5°s ⁻¹
<u>Data handling</u>	
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
<u>Polarization Properties</u>	
Transmitted	Vert. (Vis) + Horiz. (IR)
Received	Vert. + Horiz. (Vis + IR)

of cloud features in space and time, but also permits rapid scanning and variable FOV operations. In Fig. 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 μ m wavelength. Recent studies of cumulus and altocumulus often 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 μ m) ice crystals.

Figure 1

PDL LIDAR Control & Data Acquisition System

University Of Utah

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.

3. Field Project Participation

Our PDL, which is permanently truck-mounted, and supporting passive remote sensing instruments participated in the November-December 1991 FIRE IFO II field campaign in Coffeyville, KS. Although this project occurred only a little over a year after the inception of our ARM program, we were able to field (a somewhat incomplete) system, and obtained unique high-resolution, two-channel ($0.532\ \mu\text{m}$) datasets from several cloud systems. Examination of the depolarization data collected over the 5-6 December period revealed highly unusual cirrus cloud properties, including spherical scatters between -40° to -50°C , which we concluded was a result of large cloud condensation nuclei of stratospheric volcanic origin, as we reported in Science (Sassen 1992). (A variety of supporting in situ and ground-based data have since supported the hypothesis that tropopause folding activities associated with a subtropical jet stream introduced stratospheric aerosol into the cirrus clouds.) Cloud images such as that shown in Sassen 1992 (see Appendix) amply illustrate how the high resolution multichannel PDL can be used to research fundamental cloud processes.

NOAA WPL participated in three cloud/radiation field experiments in association with this project. They were CLARET II (Cloud Lidar And RadarExploratory Test), FIRE II (First ISCCP [International Satellite Cloud Climatology Program] Regional Experiment), and ASTEX (Atlantic Stratocumulus Transition Experiment). Table 2 provides some specific information. Funding from this project was important in bringing about WPL participation, but additional resources from NOAA base, the NOAA Climate and Global Change Program, FAA, and other DOE grants were also essential. All three of these experiments were augmented by many other instruments operated by WPL or other institutions, including in situ cloud microphysics measurements by aircraft, surface radiation instruments, radiosondes, radar wind profilers, surface meteorological stations,

and infrared radiometers and spectrometers. These experiments provided an excellent opportunity for data gathering and comparison of retrieved parameters with other methods to meet the objectives of this ARM project.

4. 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 interpreting 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 (Sassen 1991; Sassen et al. 1992), although for some simulation purposes the use of empirical temperature-dependent cirrus cloud contents are currently justified (Liao and

Table 2: NOAA WPL Multiple Remote Sensor Experiments

Location	<u>CLARET II</u> Erie, Colorado	<u>FIRE II</u> Coffeyville, Kansas	<u>ASTEX</u> Porto Santo, Madeira Islands
Begin Date	14 Feb 1991	19 Nov 1991	1 June 1992
End Date	31 Mar 1991	7 Dec 1991	28 June 1992
Cloud emphasis	Supercooled Water, Cirrus	Cirrus	Marine Stratocumulus
Instrument hours:			
CO ₂ lidar	22	180	67
8-mm radar	81	142	600
μ wave radiometer	1048	continuous	continuous

Sassen 1993). 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. For ice particles approximations based on geometrical optics ray tracing, conjugate gradient-fast Fourier transform, or empirical methods are used.

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 to analyze 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 1993). We have also recently initiated numerical studies aimed at evaluating the special PDL data gathering capabilities such as the dual-wavelength and variable FOV techniques. We show for illustration in Fig. 3 PDL lidar returned signal simulations (at $0.532 \mu\text{m}$ wavelength) from two simple cirrus cloud models (consisting of populations of 20 and $200 \mu\text{m}$ radius ice spheres yielding empirically-based backscatter and extinction coefficients of $0.036 \text{ km}^{-1}\text{sr}^{-1}$ and 0.387 km^{-1} , respectively) when the receiver FOV_r is varied from 0.25 to 4.0 mrad (see Table 1). Also inserted in Fig. 3 are the forward-scattering correction factors η from the lidar equation (derived from diffraction theory), which affect the lidar returns by modulating optical attenuation according to lidar design and particle size. These obviously simple simulations clearly show the potential of the high-speed (10Hz) variable FOV technique for inferring a measure of particle size. The combined application of this and other techniques, as illustrated

Figure 3. Simulated variable FOV PDL lidar signals from a 4-km deep idealized cirrus cloud composed of 20 μm (top) and 200 μm (bottom) equivalent ice spheres. Results show promise for particle sizing using the variable FOV method.

below, will lead to the development of improved methods for effective particle sizing, an important parameter in the radiative transfer equation.

For example, novel techniques have been developed by WPL in this project for retrieving information on cirrus particle size distributions from combined optical and microwave backscatter measurements. Analytical studies were used to develop algorithms for converting the ratio of backscattering at radar and CO₂ lidar wavelengths to obtain vertical profiles of the effective radius, ice mass content, and number density of the cirrus size distribution. Comparison of the effective radius from this method agreed well with an in situ aircraft measurement at CLARET II (Intrieri et al. 1993). Encouragingly, sensitivity studies show only a modest dependence on the width of the size distribution. In a parallel effort, the radar backscatter combined with radiometric measurements at 10.5 μm gave the column average of mean or effective radius, number density, and ice content (Matrosov et al., 1992). An attempt has also been made to add Doppler measurements of particle fall speed so as to derived vertical profiles of these parameters (Matrosov et al., 1993). Finally, another cirrus parameter, the vertical flux of ice, can be estimated using Doppler radar data (see Fig. 4). The ice content was estimated from the radar reflectivity, but refinements could be made by including lidar or infrared radiometer data. The vertical transport of ice is important for understanding the hydrological cycle and the distribution of water vapor in the upper troposphere.

Also during this project, large strides were made on a method to measure the effective radius of cloud drop size distributions using CO₂ lidar. It has been suggested that the mode radius could be obtained using a wavelength of 9.5 μm , but our work (Eberhard, 1993) showed that the effective radius could be more dependably determined at a longer wavelength. By integrating the extinction-reduced backscatter over the lidar pulse penetration depth, the lidar obtains

Figure 4. Vertical ice mass flux measured during the November 26, 1991, case study at FIRE II, computed from WPL radar reflectivity and Doppler measurements. The vertical profiles have been normalized to equal cloud thickness and to equal maximum flux to better reveal similarities in the profiles.

the extinction-to-backscatter ratio, and a somewhat different relationship is valid for effective radius (averaged over the lidar penetration depth). First attempts at using this method yielded effective radii on the sides of small cumulus clouds that were within expected values and had the proper height dependence. This technique might be particularly useful for studying the effect of anthropogenic aerosol particles on the drop size distribution in stratus and stratocumulus clouds.

5. Recommendations for CART Instrumentation

In view of our collaborative research efforts, we are encouraged to recommend a combination of appropriate lidar, radar, and infrared and microwave radiometers for deployment at CART sites to determine the structure, microphysical characteristics, and radiative properties of clouds. Pulsed lidar and radar methods can together provide nearly complete coverage of cloud layers and heights, and when coordinated scanning operations are conducted, the three-dimensional distribution of cloud coverage is obtained. Our highest priority recommendation involves a scanning platform consisting of the University of Massachusetts dual 3.2 and 8.6 mm wavelength CART radar with a coaligned visible or near-infrared (10 Hz or higher PRF) polarization lidar. Simultaneous polarization lidar (for cloud phase discrimination) and millimeter wave radar observations provide synergistic cloud sensing capabilities that contain much more complete information on cloud structure and distribution than either instrument can provide alone. However, we recommend that an independent scanning "weather" (5 or 10 cm) radar be relied on during periods of moderate-to-heavy precipitation, because of the attenuation effects at shorter wavelengths. Whether or not the combined scanning lidar/radar platform proves feasible, we would also like to point out that a depolarization channel can be rather easily

added to a nitrogen/water vapor Raman lidar to obtain zenith cloud phase discrimination in addition to water vapor profiles. (A high priority to future IDP activities should be to develop the technologies needed for day-time water vapor profiles extending up to cirrus cloud altitudes.)

Since we are now more confident that those cloud microphysical properties of importance for studying cloud evolution and radiative effects can be satisfactorily retrieved using combined passive and active remote sensing data, a kernel of supporting sensors is also recommended. These include microwave multichannel radiometers for liquid and water vapor depth column integrations, all-sky video imagers, infrared window radiometers (broadband and spectrally-resolved), and CO₂ lidars. Although midinfrared lidars can not obtain cloud phase information due to the strong absorption of water and ice at the usual CO₂ laser wavelengths (Eberhard 1992), these lasers offer certain advantages for deriving aerosol, water, and ice cloud contents as part of multiple remote sensor studies. Moreover, WPL has developed and tested (at ASTEX) a new type of CO₂ laser transmitter that is smaller and more robust than current systems, and so is better suited for "turnkey" CART operations. This concludes our CART instrumentation recommendations for characterizing the vertical distribution of clouds, and with further techniques development, for retrieving radiatively important cloud microphysical data.

6. Reviewed Publications Resulting From ARM Support

Eberhard, W.L., 1992: Ice cloud depolarization of backscatter for CO₂ and other infrared lidars. *Appl. Opt.*, 31, 6485-6490.

Eberhard, W.L., 1993: CO₂ lidar technique for observing characteristic drop size in water clouds. *IEEE Trans. Geosci. Remote Sensing*, (in press).

Intrieri, J.M., G.L. Stephens, W.L. Eberhard and T. Uttal, 1993: Method for

- determining cirrus cloud particle sizes using lidar and radar backscatter. *J. Appl. Meteorol.*, 32, 1074-1082.
- Liao, L. and K. Sassen, 1993: Investigation of relationships between K_a-band radar reflectivity and ice and water cloud mass content. *Atmos. Research*, (in press).
- Matrosov, S.Y., T. Uttal, J.B. Snider and R.A. Kropfli, 1992: Estimation of ice cloud parameters from ground-based infrared radiometer and radar measurements. *J. Geophys. Res.*, 97, 11567-11574.
- Matrosov, S.Y., B.W. Orr, R.A. Kropfli and J.B. Snider, 1993: Retrieval of vertical profiles of cirrus cloud microstructure parameters from Doppler radar and IR radiometer measurements. *J. Atmos. Sci.*, (submitted).
- Sassen, K., 1991: The polarization lidar technique for cloud research: A review and current assessment. *Bull. Amer. Meteor. Soc.*, 72, 1848-1866.
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- 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. Meteor.*, 32, 1548-1558.
7. Graduate Student Training
- i. Hongjie Zhao, "Model Simulation of Polarization Lidar Returns from Realistic Clouds", Master of Science Degree approved May 1991.
 - ii. Liang Liao, "Ka-band Radar Research Applications for Ice and Water Clouds", Ph.D. Dissertation approved November 1993.

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