Cloud and Aerosol Characterization for the ARM Central

Facility: Multiple Remote Sensor Techniques Development

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I. Introduction

Our cooperative research project between the University of Utah and the Wave Propagation Laboratory (WPL) of NOAA designed to investigate how atmospheric remote sensing technology can best be applied to the characterization of the cloudy atmosphere is currently in its second year. Our research program addresses basic atmospheric remote sensing questions, but at the same time is clearly directed toward providing information crucial to the ARM program and for application to the Clouds and Radiation Testbed (CART). The instrumentation that is being brought into play includes a variety of art-of-the-art sensors. Available at NOAA WPL are polarization Doppler K_a-band (0.86 mm) and X-band (3.2 cm) radars, a CO₂ (10.6 μm) Doppler lidar with sequential polarization measurement capabilities, a three-channel (20.6, 31.65 and 90 GHz) microwave radiometer, and variety of visible and infrared radiometers. Instrumentation at the University of Utah Facility for Atmospheric Remote Sensing (FARS) includes a polarization ruby (0.643 μm) lidar, a narrow-beam (0.14°) mid-infrared (9.5-11.5 μm) radiometer coaligned with the lidar, several other radiometers in the visible and infrared spectral regions, and an advanced two-color (1.06 and 0.532 μm), four-channel Polarization Diversity Lidar (PDL) and all-sky video imaging system that have only recently been developed under the ARM IDP.

Our progress to date is summarized below with regard to basic areas of our research program. These areas are the PDL system development, the CLARET II, FIRE IFO II and ASTEX field projects, and analytical and empirical cloud studies.

II. PDL System Development

Although our 50-h PDL dataset of one-color (0.532 μm) zenith observations collected during the FIRE IFO II fortunately contained some spectacular high-resolution cirrus case studies (see below), we learned some valuable lessons on how to significantly improve the performance of this new instrument for future full-scale research. Below, we list the problem areas encountered during the field experiment, and our current solutions to these problems.

i). 1.06 μm Wavelength Operations. No two-channel 1.06 μm data were recorded in the field, although parallel-polarized returns were displayed in real-time. The problem was one of optical component alignment, since unlike the large active areas of PMTs, the silicone avalanche photodiodes have very small active areas that require exact alignment. Our design uses lenses to focus light emerging from the polarizing prism onto the photodiode elements, but the prism holder had become damaged and proved very difficult to align, which has now been corrected.

ii). Telescope Gimbal Mounts. The dual gimbal mounts proved unreliable for maintaining receiver axis alignment with the laser beam, and one of them lost one-axis pointing abilities (in the 1.06 μm channel, which added to our initial difficulties in trying to bring this channel on-line). The mounts were returned for repairs, and we have designed external locks for added pointing stability during scanning operations.

iii) Analog to Digital Boards. The A/D boards worked satisfactorily

for all except the weakest signals, where the 4 mV resolution and lack of software gain control proved to be a problem. Taking advantage of the manufacturers upgrade offer, we have installed higher performance 8-bit digitizer boards that have improved spatial sampling resolution (6 m to currently 1.5 m), 0.2 mV minimum resolution, and programmable gain capabilities.

iv) Daylight Background Problems. The 0.532 μm channels suffered from significant gain reductions caused by too strong DC background levels of sunlight scattered by cirrus clouds. We have redesigned the interference filter holder in the receiver housing to correct for a slight light leak, and have replaced the original filter with narrower bandpass filter. (Due to potential centerline temperature drift effects under adverse environmental conditions, we have allowed for adding filter temperature control if this proves necessary).

We are currently reassembling the unit, and adding full azimuth-over-elevation angle scanning and high-speed variable receiver FOV controls. Remaining additions to complete our unit mainly involve software improvements for real-time displays of zenith and scan data. The current specification of the PDL unit are given in Table 1.

III. CLARET II

The second Cloud Lidar And Radar Exploratory Test (CLARET-II) was conducted at the Erie-1 field site northeast of Boulder, Colorado, during the latter part of the Winter Icing and Storms Project (WISP) from 15 February 1991 to 31 March 1991. The CLARET-II field work was coordinated by the NOAA Wave Propagation Laboratory (WPL) with participation by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) and The Aerospace Corporation. Although CLARET-II was originally planned to occur in May or June of 1991, it became apparent that key instrumentation including aircraft support would not be available then. Therefore, it was decided to muster available WPL systems and conduct the experiment earlier to take advantage of the WISP measurement facilities, including cloud physics aircraft. The accelerated schedule, however, meant that the WPL lidar was able to participate for only a fraction of the six week period. CMDL and the Aerospace Corporation took advantage of the opportunity and joined the latter part of the field activities at Erie-1. Thus, an impressive suite of instruments was assembled on short notice at Erie-1 within the wider context of the data-rich WISP and ARM/IDASS programs.

The primary goal of CLARET-II was to examine non-precipitating layer clouds with remote sensors of different wavelengths, and to use those measurements to infer the microphysical composition of the clouds and assess their radiative effects. The participating NOAA WPL instrumentation included X-band and K_a-band Doppler radars, the CO₂ Doppler lidar, the three-channel steerable microwave radiometer, and various visible and infrared radiometers.

Table 1: Current Specifications of the University of Utah Two-Color Polarization Diversity Lidar (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 mr
Receiver	0.2-3.8 mr, high-speed shutter
Receiver Diameter	30 cm (2 telescopes)
Detectors - Visible	2, Gated PMT's
IR	2, SAPD's
Maximum Scan Rate	3.5°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)

* Additional Equipment

- a. All-sky video imager with time-lapse VCR
 - b. PRT-5 narrow-beam (0.14°) mid-IR (9.5-11.5 μ m) radiometer †
 - c. Camcorder camera †
- († aligned parallel to transmitter on lidar table)

IV. FIRE IFO II

Preliminary indications are that the November-December 1991 FIRE IFO II field campaign at Coffeyville, KS, was an outstanding success that should result in significant improvements in our understanding of cirrus clouds and their radiative properties, and so will help clarify their role in global climate. Although some problems were encountered in the essentially untested systems, the core instrumentation from the University of Utah and NOAA WPL performed well and collected uniquely detailed observations of the cirrus cloud properties. Our combined observations provides an excellent dataset for our multiple remote sensor intercomparison research, and will significantly contribute to the Project FIRE goals by characterizing the cirrus when our measurements are made available to co-researchers.

The WPL K_a-band Doppler radar recorded a total of 142-h of data over a 17 day period during FIRE II, before a major failure of the new antenna unit

occurred. Parameters measured were radar reflectivity, Doppler velocity, Doppler spectral width, and circular depolarization ratio. Sequences of scans were performed that allowed a long time history of the cloud reflectivity and vertical velocity structure to be observed with a vertical resolution of just 37 m. The precision of the in-cloud vertical motion measurements obtained with this radar was typically about 5 cm/s. Such precision is necessary in order to observe the weak vertical motions typical of cirrus clouds. Detailed in-cloud wind profiles were also obtained. However, during radar data acquisition there seems to have been an error introduced into our depolarization data because of a small angular displacement of the quarter wave plate, a key component of the new offset Cassegrain antenna which was used for the first time during FIRE II.

The WPL CO₂ lidar was attended for 180-h during FIRE II and achieved excellent coverage of cirrus events. The lidar was used to measure backscatter intensity and velocities to reveal important cloud parameters, including cloud boundaries and wind profiles within and below the cloud. Data were acquired to describe the profile of cirrus cloud emissivity and also to identify the presence of horizontally oriented, pristine ice crystals that affect radiative transfer differently than randomly oriented particles. Unfortunately, although the lidar-derived horizontal wind profiles are of good quality, difficulties with the lidar frequency stability reduced the accuracy of the vertical velocity measurements. Nevertheless, useful cloud vertical velocity information will be retrieved from the lidar data.

As summarized previously, the problems encountered in bringing on-line the University of Utah PDL unit permitted only 50-h of one-color polarization data to be collected, but this high spatial resolution (1 to 10 Hz shot data recording) dataset contains some remarkable cirrus cloud case studies, which are already indicating some unexpected findings. Particularly significant are the cirrus cloud systems studied over the 4-6 December 1991 period, which were characterized by moist subtropical flow and strong jet streams. These cirrus displayed some quite unusual properties, including PDL depolarization evidence for highly supercooled liquid cirrus uncinus cell heads (between -40° to 50°C) and extremely high ice crystal concentrations (100-300 liter⁻¹ according to supporting in situ U.N.D. Citation data). Since this period corresponded to a sudden influx of Mt. Pinatubo volcanic debris in the lower stratosphere and upper troposphere, we are investigating the hypothesis that the unusual cirrus properties were due to the cloud microphysical effects of the decaying volcanic aerosols. In a note submitted to Science, we have pointed out the possible climatic effects of this volcano/cloud feedback mechanism (Sassen 1992). Clearly, additional comprehensive studies involving various FIRE IFO II co-investigators is needed, and this effort has already begun.

V. ASTEX

NOAA WPL FY-1992 plans call for full participation in ASTEX on Porto Santo Island in the eastern Atlantic Ocean with a new high pulse rate Doppler lidar, the 8 mm wavelength cloud radar, and a 3 channel microwave radiometer. Participation on a research vessel with a two-channel microwave radiometer, a 915 MHz wind profiler/RASS, and a surface flux package will also be possible

because of additional support from the DOE/ARM program. A late request for additional funding for the Russian research vessel Kurchatov has caused us to change our plans for the installation of remote sensors on this ship. However, arrangements have been made for the Malcolm Baldrige, a NOAA research vessel, to be the shipboard platform for these remote sensors. All systems are currently being prepared for shipping and for operation on Porto Santo Island in June. Special efforts are being made to protect the instruments from the harsh marine environment that most of them have never experienced before. Three motor generator sets have been procured to convert 50 Hz island power to 60 Hz power required by our instruments. Finally, a meeting was recently held with all ASTEX participants to finalize the ASTEX Implementation Plan.

The last remaining problem we have encountered is that of shipping the remote sensors to Porto Santo Island. Initial quotes for shipping far exceed our earlier estimates. We are continuing to obtain additional quotes, and these are expected to be lower than the initial quotes, but may still exceed our budgeted amount by more than \$60 K. We will continue to search for additional funding from other agencies and within NOAA to make up the difference as we look for more economical shipping alternatives.

Our scientific objectives for ASTEX remain largely unchanged. The new high pulse rate lidar promises to have much better frequency stability, and therefore better velocity accuracy, than the one used in FIRE II. With the WPL cloud radar, the new lidar and the multi-channel microwave radiometer operating together on Porto Santo Island, we plan to document cloud properties such as cloud boundaries, sub-cloud base and in-cloud turbulent and mean velocity structure, mean drop radius and liquid water content. Such measurements are crucial in addressing the primary ASTEX goal, which is to identify the relative importance of the various mechanisms proposed for stratocumulus transition and breakup. Such mechanisms are currently not accounted for in GCMs, and improved understanding of them is a necessary step for the physics of these important cloud processes to be correctly modeled.

VI. Analytical and Empirical Cloud Studies

It is clear that the combined CLARET, FIRE, and upcoming ASTEX field activities employing the NOAA WPL and the University of Utah PDL remote sensing capabilities are providing us with a wealth of data pertinent to the characterization of the cloudy atmosphere. Crucial next steps are to perform empirical and computer-based analytical studies to evaluate the remote sensing techniques with indicated potential, and validate the relationships derived from remote sensing measurements for the cloud parameters of interest. Our theoretical approaches are based on the application of sophisticated cloud growth models, and Mie and approximate scattering theory solutions for spherical cloud droplets and nonspherical ice crystals, respectively.

The numerical simulation of realistic cloud signals from lidar, radar and passive remote sensors is a very important component of the development and validation of cloud-sensing techniques using these instruments. A unique approach we are emphasizing is the use of a sophisticated cloud model to

simulate the growth of water and mixed phase clouds. We have already assessed the dependence of polarization lidar returns on basic microphysical and thermodynamic variables (Sassen et al. 1992). Cloud contents that evolve with height in updrafts are converted into Mie scattering parameters to calculate cloud droplet single and double backscattering, and attenuation coefficients. The lidar equation includes forward multiple scattering attenuation corrections based on diffraction theory for droplets and ice crystals, whose relative scattering contributions are treated empirically. Lidar depolarization is computed from droplet and crystal single scattering, and an analytical treatment of droplet double scattering. Results from pure water clouds reveal the expected increases in linear depolarization ratios (δ values) with increasing field-of-view and distance-to-cloud, but also indicate that depolarization depends primarily on cloud liquid water content, a strong function of cloud temperature. Ice crystals in mixed phase clouds modulate liquid water contents through water vapor competition effects, thereby affecting multiple scattering δ values as functions of crystal size and concentration. Comparisons with field data demonstrate that this modeling approach is a valuable supplement to polarization lidar cloud measurements (Sassen 1991); we are also using this approach as the basis for developing autonomous lidar cloud detection algorithms (Sassen and Zhao 1992).

Currently, we are converting the microphysical model results into lidar and radar backscattering profiles at several wavelengths to understand how cloud characterization algorithms can be derived from multiple remote sensor observations of cloud boundaries. To simulate the radar returns we have developed a conjugate gradient-fast Fourier transform method to treat ice particles of any shape, and have already derived some useful relations between ice mass content and K_a -band radar reflectivity factor (Liao and Sassen 1992). Similarly, the capability for computing scattering from arbitrarily shaped particles using the discrete-dipole method is being developed at NOAA WPL, and other approaches are being examined (Palmer et al. 1992).

Our growing field program datasets are already providing the basis for empirically-based improvements in defining cloud information content using the multiple remote sensor approach. Various combinations of CO_2 lidar and radar data, along with infrared and microwave radiometer measurements are being used to compute ice water content, characteristic ice crystal sizes and concentrations, and cloud optical thickness. Preliminary studies with CLARET data are very promising (Eberhard 1991, 1992a,b; Eberhard and Post 1991; Intrieri et al., 1992; Palmer et al., 1992), and the more comprehensive and higher quality FIRE dataset is being used to perform similar calculations of these radiatively important cloud parameters.

VII. Significant Project Accomplishments

We are particularly pleased by our successful participation in the CLARET II and FIRE IFO II field projects. In demonstrating just some of the advanced research capabilities of the PDL system during the FIRE campaign, we appear to have discovered a mechanism for climatic perturbations following major volcanic eruptions, which involves alternations in cirrus cloud properties due to the fallout of volcanic aerosols. Significant progress has

also already been made in our multiple remote sensor analytical and empirical cloud studies to back up our measurement database.

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