FINAL REPORT

Additional Development of Remote Sensing Techniques for Observing Morphology, Microphysics, and Radiative Properties of Clouds and Tests Using a New, Robust CO₂ Lidar

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SUMMARY

A three-year project with a goal of advancing CO₂ lidar technology and measurement techniques for cloud studies was successfully completed.

An eyesafe, infrared lidar with good sensitivity and improved Doppler accuracy was designed, constructed, and demonstrated. Dual-wavelength operation was achieved. A major leap forward in robustness was demonstrated.

CO₂ lidars were operated as part of two Intensive Operations Periods at the Southern Great Plains CART site. The first used an older lidar and was intended primarily for measurement technique development. The second used the new lidar and was primarily a demonstration and evaluation of its performance.

Progress was demonstrated in the development, evaluation, and application of measurement techniques using CO₂ lidar. The radar/lidar concept for deriving cirrus particle size information was expanded to include retrieval of profiles of ice water content and number concentration. An analysis of the difference in vertical Doppler measured by the two instruments showed useful information on the breadth of the size distribution, but separation of air from particle settling motions would be quite difficult. Path-averaged effective radius of cloud droplets were derived from CO₂ lidar measurements. A comparison with aircraft in situ measurements was encouraging, but experimental limitations prevented any clear conclusions about the accuracy of this new method. A paper presenting the theoretical basis for dual-wavelength CO₂ lidar discrimination of ice and water clouds was finalized and published. The LIRAD method for obtaining cirrus optical parameters was adapted to CO₂ lidar and demonstrated.

A simulation showed that the profile of water cloud microphysical parameters could be obtained with a visible-wavelength lidar and cloud radar.

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I. Background

The Atmospheric Lidar Division (ALD) of the Environmental Technology Laboratory has a long history of atmospheric measurements using CO₂ laser technology. This type of lidar operates in the thermal infrared rather than at a visible or near-visible wavelength like most lidars. Our CO₂ lidars also use coherent detection, enabling Doppler measurements of velocity of the scattering particles. Recognizing the uniqueness of the CO₂ lidar measurements for clouds, we commenced development of measurement techniques partially funded by subcontract from University of Utah under Grant No. DE-FG02-90ER61059. The initial progress was very encouraging and identified the directions this research should proceed. Our proposal to the Atmospheric Radiation Measurements (ARM) Instrument Development Program (IDP) to perform both instrument and measurement technique development was funded as Grant No. DE-AI03-94ER61760. This document reports the research and accomplishments under this grant.

The project can be divided into three parts:

- 1) Design and construction of a bread-board version of a lidar system using new high-pulse-rate, RF-excited CO₂ lasers for more robust operation and for a trial of dual-wavelength sensing techniques.
- 2) Operation of lidar at the Lamont, Oklahoma CART (Cloud and Radiation Testbed) to demonstrate the new lidar's performance and to evaluate cloud-sensing techniques.
- 3) Further development and demonstration of techniques to measure morphology, microphysical parameters, and radiative properties of clouds that are needed for developing and testing cloud models. The techniques in this study centered on measurements by CO₂ or other types of lidar, either alone or simultaneously with other sensors.

This report describes the accomplishments in these three areas.

II. Instrument Development

A. Previous work

The ALD began research into CO₂ lidar technology and applications in 1978. A powerful coherent-detection lidar (0.5-J pulse energy, 20-Hz pulse rate) was designed and constructed to demonstrate this kind of measurement. The system was improved (Post and Cupp, 1989) and the circle of applications widened over the years. These included research on clouds. However, these projects and others revealed some of the limitations of the technology used in the system. The Doppler accuracy, which is 0.3 m s⁻¹ at best, and usually 0.5 - 1.0 m s⁻¹ in practice, is insufficient for measuring vertical motions in clouds and precipitation. The TEA laser and other components were large, maintenance-intensive, and temperamental. For example, the operator must change the gas in the TEA amplifier every few hours of operation. Applications were restricted to intensive research campaigns.

Technological advances permitted use of a different type of CO₂ laser, namely RF (radio frequency)-excited lasers, or waveguide lasers as they are often called. A waveguide laser can operate for ~1000 h before a gas change is needed. A lidar using this class of laser features low pulse energy (~1 mJ) but high pulse rates (100-1000 Hz) to achieve adequate sensitivity. The ALD earlier demonstrated such a lidar (Pearson 1993) that used a Q-switched laser with one

multi-pass amplifier stage. The frequency offset of the CW local oscillator laser from the transmitted frequency was controlled using electronic feedback. This system was considerably smaller, had modestly better Doppler accuracy, and was more stable than the TEA laser. However, we quickly recognized the potential for significant additional improvements with a different configuration of the lasers and the use of additional new technology.

B. mini-MOPA description

The objective of the instrument development phase of this project was to design and demonstrate a breadboard version of a CO₂ lidar with potential for eventually engineering into a CART instrument. The term mini-MOPA is our designation for the CART breadboard: "mini" denotes small, and MOPA stands for the master-oscillator power-amplifier laser configuration. The design characteristics of the breadboard system in this project included:

- 1) RF-excited lasers for long gas lifetime.
- 2) Wavelength switching capability for ice/water discrimination and for water vapor DIAL.
- 3) Improved Doppler accuracy.
- 4) Elimination of continual operator intervention and frequent maintenance.

Work accomplished under the project reported here included design, construction, testing, and evaluation of a mini-MOPA CO₂ lidar system.

CO₂ coherent lidars have some distinct differences and advantages compared to more conventional types of lidars. They operate in the thermal infrared (most commonly at 10.59 μm wavelength) instead of at visible or near-visible wavelengths an order of magnitude shorter. In coherent detection, the received backscatter is phase matched and mixed with a local oscillator beam at the detector, whereas the more conventional direct-detection lidars just measure power in the backscattered radiation. A coherent lidar's signal characteristics are, therefore, similar in many respects to those of a radar system, but the signal from the atmosphere depends on optical interactions. For example, a coherent lidar can measure the Doppler shift in the backscattered radiation, so their most common application is measurement of winds and turbulence in the "clear" (free of cloud but not aerosol particles) air. Coherent detection is nearly quantum-limited, giving high detection sensitivity. By virtue of their wavelength and beam expansion by the telescope, all the coherent CO₂ lidars described here are fully eyesafe at the telescope aperture and are classified as Class 1 laser systems outside the lidar container. These systems are impervious to background light, obtaining the same quality of data day and night. They even acquire atmospheric data with little degradation and no equipment damage while staring at the sun's disk! Admittedly, a coherent CO₂ lidar is a fairly complex instrument. However, the kind of information acquired by such a system is unique in several ways from conventional direct-detection lidars operating at wavelengths in or near the visible.

Figure 1 shows a block diagram of the mini-MOPA system. For single-wavelength operation, only one CW laser is needed. The shutters alternate open and shut for dual-wavelength operation. The selected CW laser sends a frequency-stable local oscillator (LO) beam via a beam splitter to the detector. The other beam from the beam splitter traverses the AOM (acousto-optic modulator) assembly, which forms the pulse and offsets the light frequency by 10 MHz to avoid problems with signal at DC and to give the sign of the Doppler shift. (AOM's operate effectively only at frequencies ≥ 40 MHz. However, this would shift the light frequency to the weak edge of

Figure 1 Mini-MOPA Doppler lidar block diagram.

the laser line in the amplifiers and strain the frequency response of the detector. Therefore, an upshift of 54 MHz followed by a downshift of 44 Mhz was used). The two multi-pass amplifiers increase pulse energy to ≈ 1 mJ. After the first 6 passes of the pulse through the gain medium of the first amplifier, the 1/4-wave plate at the top rotates the linear polarization of the beam by 90° , and additional amplification is achieved by 6 more passes in the opposite direction. The pulse traverses the 6 passes in the second amplifier only once. The EOM (electro-optic modulator) and the Faraday isolator prevent all but a small amount of stray energy to propagate from the amplifiers back to the CW lasers. The 1/4-wave plate at the bottom and a polarizing beam splitter to its left use polarization to separate transmit and receive beams. The HgCdTe detector is cooled with liquid nitrogen. The detector output is mixed with the electronic 10 MHz reference frequency from the AOMs to generate in-phase and quadrature signals (I and Q). This configuration fulfilled our expectations for stability, improved Doppler accuracy, and dual-wavelength operation.

Operating parameters for the system as operated at CART are listed in Table 1. More recently, 3 mJ pulse energy simultaneous with transmitter pulse rates of 500 Hz have been achieved. Dual-wavelength operation has also been demonstrated (see below). The system is housed in a 20' standard seatainer. The electrical power required, including environmental control of the seatainer, is 60 amps, 220-volt single phase. The scanner is a two-mirror elevation-over-azimuth mounted on the roof of the seatainer.

Table 1. Mini-MOPA Specifications at CART	
Wavelength	10.59 μm
Pulse energy	0.5 mJ
Pulse rate	100 Hz
Beam divergence	0.140 millirad
Sample interval (I & Q)	15 m
Range resolution	90 m
Averaging time	1 s
Minimum range	180 m
Maximum range recorded	15 km
Velocity range	$\pm 25 \text{ m s}^{-1}$
Velocity accuracy (1-s average)	$0.25 - 1.0 \text{ m s}^{-1}$
Scan	full hemispheric
Angle accuracy	0.1°
Angle precision	0.01°
Telescope diameter	20 cm

C. Mini-MOPA development

Tasks completed as part of this project include:

- 1) Outfitted a seatainer (purchased with other funds) to house the breadboard lidar system
- 2) Design comparison showed the advantage of mini-MOPA configuration
- 3) Designed and specified components for mini-MOPA approach
- 4) Purchase of CW lasers and modification for use in the mini-MOPA
- 5) Design, in-house construction, and laboratory testing of the multi-pass amplifiers
- 6) Purchase of the AOMs and laboratory testing to characterize them
- 7) Purchase of optical tables and numerous miscellaneous optical and electronic parts, including Fresnel prisms for polarization beam splitters
- 8) Modification of a dedicated processor retired from the TEA system to provide real-time data display
- 9) Development of system control electronics and computer software
- 10) Improvement of raw data acquisition software
- 11) Hired contractor to correct deficiencies in scanner inherited from another project

- 12) Development of software for postprocessing of raw data, including noise-whitening filters, important when averaging many pulses when single-pulse signal-to-noise ratio is low
- 13) Whole system testing, evaluation, and optimization

The project began with Kin Pui Chan on a postdoctoral appointment to perform most of the hardware tasks. However, he resigned about 1/3 year into the project to accept permanent employment elsewhere. We attempted to continue with a young staff engineer, but found we were lacking the required expertise. Therefore, almost one year after beginning, we hired another postdoctoral appointee, W. Alan Brewer. The latter found some mechanical flaws while testing Chan's design, so development of the system was unfortunately delayed by about 1 year from the original schedule.

Performance of the lidar in single-wavelength mode was demonstrated and evaluated during spring 1996 at CART. Dual-wavelength operation was installed later and tested in Boulder, along with some other improvements identified as important at CART.

C. Mini-MOPA performance

System performance during the CART evaluation is described first, followed by more recent accomplishments.

As expected, the system is quite robust, which was a great leap forward from the TEA lidar system. After a warm-up period, the mini-MOPA continued to operate well at CART for periods of 4 - 8 hours with no intervention by the operator except to refill the liquid nitrogen dewar for the detector every few hours. We are confident that the few human control and maintenance tasks could be automated by engineering and computer monitoring.

An example of vertically staring data acquired between about 2000 and 2020 UTC on 19 April 1996 is shown in Fig. 2. The lidar parameters were as in Table 1, and this graph was produced while in the field. The top frame in Fig. 2 gives the raw intensity in dB, which includes the power of the local oscillator which was at 0 dB. The bottom frame is velocity in m s^{-1} , with positive values downward, and black regions with speckled colors where no signal from the atmosphere was detected. A cirrus layer was present between 8 and 9 km AGL. The vertical velocities there were small, and the velocity scale in Fig. 2 is too coarse to reveal their details. Strong aerosol backscatter extends from the surface to 4 km AGL. Very diffuse aerosol was detected between 4 and nearly 5 km, more easily seen in the velocity data than this intensity display. Convection in the mixed layer is clearly evident in the lower frame from the surface to about 2.5 km height. The weak vertical motions accompanied by aerosol backscatter reveal the location of the residual layer from previous days' convection. The lidar is excellent for revealing both the vertical structure of scatterers and the dynamics of the troposphere in these layers.

The data in Fig. 3 are for nearly an hour on a different day (April 20) where 5-s averages were used. The vertical axis is height MSL, and the horizontal axis is time (UTC). The top frame shows the intensity from a complex event of cirrus clouds. The intensity is expressed as wideband signal-to-noise ratio (SNR) in dB. (The wideband SNR is the average for a single-pulse. The numerator is the integral of the spectrum of atmospheric backscatter, and the denominator is the integral of the local oscillator noise over the entire 10-MHz receiver bandwidth). The bottom frame is velocity (downward motions positive). The intensity shows the detailed structure common for this type of cloud. The vertical velocity measurements indicate

Figure 2 Vertically staring mini-MOPA data for 20 min showing aerosol returns (0-4 km) and cirrus (8-9 km). The top frame displays raw intensity in dB, and the bottom shows velocity in m/s.

Mini-MOPA

wb SNR (dB)

20 APR 1996

Mini-MOPA
RMFM_RMDC

Vertical Velocity (m/s)

20 APR 1996

Figure 3. Mini-MOPA measurement of cirrus cloud: Signal-to-noise ratio (wideband) in top frame, and vertical Doppler velocity (downward motion positive) in bottom frame.

good fidelity where cloud was detected. The regions of upward and downward motion are consistent with expectations. Doppler velocities were downward where fall streaks are clear in the intensity structure. Upward motion tends to occur near cloud tops where nucleation may be occurring. The upward motion at about 1916 and 7.4 km MSL is in a region of high intensity, where lifting is apparently creating rather dense cloud. Doppler estimates were obtained below about 6 km MSL where aerosol particles provide signal too weak to appear on the scale chosen for the intensity, but strong enough to provide coarse ($\approx 0.5 \text{ m s}^{-1}$ accuracy) Doppler estimates. Other wind (e.g., profile of the horizontal wind using the VAD technique) and turbulence measurements were made with good success but are not shown here. One important outcome is that the vertical velocity and turbulence measurements by the mini-MOPA lidar are accurate enough to be of great value in atmospheric research.

The Doppler accuracy (more technically, the precision) depends on SNR, pulse length (which affects spectral width of the signal), number of pulses averaged, and the receiver bandwidth. Figure 4 shows the observed Doppler accuracy as a function of SNR for mini-MOPA measurements in the boundary layer compared to the Cramer-Rao Lower Bound (CRLB). The CRLB is a theoretical limit that no processing algorithm can exceed. The Doppler accuracy was determined from horizontally staring data where a distribution of SNR is obtained as a function of range because of the drop-off in raw backscatter. A long time series of velocity was obtained at each range gate. Spectral analysis on each time series allowed us to separate the true atmospheric variations from the random instrumental uncertainty, which is plotted in Fig. 4. When SNR was high at CART, a velocity accuracy of 0.25 m s^{-1} standard deviation was achieved for 1-s averages and (Fig. 4) 0.15 m s^{-1} for 5-s averages. Doppler accuracy can be improved at the cost of range resolution by lengthening the pulse, which increases the pulse energy and narrows the signal spectrum. More importantly, the recent increases in transmitter power and pulse rate provide better Doppler accuracy than listed in Table 1 while maintaining the temporal and spatial resolution.

Maximum range depends partly on the aerosol particles in the air. During the CART tests the maximum range horizontally for 1-s averages was typically 7 km, but varied from about 2 km immediately after a steady rain to about 11 km on a dry day with wind-blown dust. Cirrus clouds were detected overhead as high as 12 km, and the lidar detected all clouds that could be seen by eye. The sensitivity of mini-MOPA is quite satisfactory for cloud and boundary-layer measurements.

Since the CART demonstration, pulse energy has been increased to 3 mJ at a higher pulse rate of 500 Hz. (Unfortunately, the current data system is restricted to about 200 Hz recording rate, so we plan to obtain a faster data system and perform real time averaging). We have also been able to reduce the reflections of the acoustic energy in the AOMs and eliminate the contamination seen in Fig. 2 at 1.1 km range.

Dual-wavelength operation has recently been achieved. The system was configured for its first attempt to measure water vapor using the DIAL (differential absorption of light) method. The on-line and off-line wavelengths were $10.247 \text{ }\mu\text{m}$ (on-line) and $10.261 \text{ }\mu\text{m}$ (off-line), switching every $1/4 \text{ s}$. Pulse energies were about 0.1 mJ (which can easily be increased to about 1 mJ), and the pulse rate was 160 Hz. The system stared at 11° elevation angle. The 15-m data samples were fit over a 600-m interval centered on 900-m range. Each data point in Fig. 5 was

mini-MOPA

500 pulse, 90 m gates, 600 ns (fwhm)

Figure 4 Precision of 5-s average velocity estimates as a function of SNR. The lower curve is the theoretical limit, and the squares are results calculated from an hour-long, horizontally-pointing time series.

Figure 5. Water vapor concentration measurement by CO_2 DIAL compared with in situ data nearby.

obtained from a 5-min average, so the effective SNR was very high. The DIAL result is very encouraging. Dual-wavelength operation has been successfully demonstrated. Combined Doppler and water vapor measurements, and an attempt to profile ammonia, are planned for the near future.

III. Field Campaigns at CART

We operated CO₂ lidars during two field campaigns at the Oklahoma CART site. The first was the Remote Cloud Sensing (RCS) Intensive Operations Period (IOP) in spring 1994. Because the mini-MOPA lidar was not ready yet, we used the TEA system to obtain data for evaluating some of the techniques described below for obtaining cloud parameters. The second campaign was in 1996 with the mini-MOPA system in conjunction with the ARM IOP in support of SUCCESS (Subsonic Aircraft: Contrail and Cloud Effects Special Study).

A. Remote Cloud Sensing Intensive Operations Period

With the delays due to personnel changes and other problems, it became apparent that the mini-MOPA lidar would not be ready in time for this IOP. We decided in consultation with our project monitor to operate the older TEA CO₂ lidar to obtain data for technique evaluation and to support the remote cloud sensing science.

The lidar, housed in its semi-trailer, was transported from Boulder to the SGP CART site. The lidar was on site for 14 days (17-30 April 1994) with a crew of 3-4 persons, including W. Eberhard (principal investigator), Janet Intrieri (meteorologist), Kathleen Healy (computer specialist), and (some of the time) Ron Willis or MJ Post for some engineering tasks. After solving some problems that arose during shipping, data were acquired for a total of about 38 h. The lidar was calibrated with a sandpaper calibration target that we constructed at the site. Data were obtained during cirrus, middle cloud, and low stratus regimes. These measurements were coordinated with those of cloud radars and other lidars participating in the IOP. Coordination was also achieved with flights of an instrumented aircraft, which provided in situ data for comparison with our measurements and retrievals.

M. Platt of CSIRO in Australia had constructed a narrow-field infrared radiometer with high sensitivity under the IDP. We desired data like this in conjunction with our cloud measurements. He agreed it would be beneficial if we operated his instrument at the IOP, so he loaned it to us. It worked well after we solved a problem with its power supply, which was designed to use U.S. as well as Australian electrical power, but had never been tested here. About 36 h of data were acquired.

B. SUCCESS Intensive Operations Period

The mini-MOPA lidar was transported from Boulder to the SGP CART site. The seatainer enclosure was mounted on a flatbed semitrailer for transport and setup. The system was on site for 16 days (19 April - 4 May 1996) and made atmospheric measurements for a total of about 40 h. Considerable additional work was performed in optimizing and evaluating the system, arranging for special joint measurements with other investigators, etc. The crew of 3 consisted of A. Brewer, C. Locker (technician), and either W. Eberhard or J. Intrieri. A sandpaper target was again constructed and used for calibration. See Section IIC for examples of data.

IV. Technique development

The wavelength of CO₂ lidar is an order of magnitude longer than that of most lidars, so the scattering size parameters are that much smaller. The refractive indexes of water and ice are also quite different than for wavelengths within and near the visible. CO₂ lidar therefore provides a different slant on the information available from cloud measurements, and even unique analysis products. Progress was made in development of these techniques, and introduction of new ones, in this project. In this section we describe our accomplishments for each technique individually.

1) *Path-averaged mean radius or effective radius of drops*

The special backscattering and extinction behavior of CO₂ lidar from cloud droplets is the basis for this method. Eberhard (1993) showed that the backscatter-to-extinction ratio S is a good indicator of the mean or effective radius of a cloud drop size distribution. When the lidar probes an optically thick cloud, the average value of S over the penetration depth can be obtained by integrating the measured, calibrated backscatter.

We obtained a data set during the RSC IOP for testing this technique. We measured low altitude water clouds and applied our algorithm to obtain the result in Fig. 6. Unfortunately, unstable performance of the laser and variation of the signal from aerosol below the cloud demonstrated unsteady sensitivity of the lidar during this period, placing significant uncertainty on the drop size retrieval.

During this case, a Citation aircraft carrying an FSSP probe measured cloud droplet size distributions during passes nearby at various altitudes in the cloud or ascents and descents through the cloud. Although general agreement was encouraging, we were unable to conclusively evaluate the accuracy of this method from these data. The aircraft attempted to fly just above the CART site, but its GPS data showed it was typically 0.5 - 1 km away in the crosswind direction at closest approach, which was the typical scale size of cloud variations measured by both the lidar and the aircraft. Therefore, at best a statistical comparison could be made. The size distributions measured by the FSSP in the bottom part of the cloud were also suspect. The drops were of a size poorly measured by the optical technique used by the FSSP, and the shape of the size distribution changed with height in a strange way, even after reprocessing by the scientists in charge of the FSSP. Therefore, we could not be confident of the accuracy of the FSSP data in the part of the cloud penetrated by the lidar.

Because of the uncertainties in the lidar calibration and the reference FSSP measurements, no clear conclusions could be drawn about the accuracy of the lidar method. However, the shape of the height profile of backscatter measured by the lidar and that calculated from the FSSP data were highly consistent. Absolute calibration of the lidar aside, this shows good agreement between the lidar and aircraft measurements. It also supports the theory of the lidar drop size retrieval method as far as the experimental uncertainties will allow.

2) *Profile of mean radius and number density of drops*

This method, which would rely on two CO₂ lidar wavelengths, was just an idea at the time the proposal was written. We examined the information content in the backscatter and extinction at two wavelengths, but determined that severe ambiguity would be inherent in any

Figure 6. Effective radius of cloud drops averaged over the penetration depth of a CO₂ lidar into a stratus cloud using the extinction-to-backscatter method unique to this type of lidar.

retrievals. Although profiles of mean radius and number density of drops would be an extremely valuable observational technique, two wavelengths producible by CO₂ lidar isn't the answer.

3) *CO₂ dual-wavelength discrimination of ice & water*

Revisions were made to a theoretical paper introducing this method, and it was published (Eberhard 1995). The refractive index of ice and water change differently with wavelength from about the 10.5 to the 11.4 μm part of the spectrum accessible by CO₂ lidar. The ratio of backscatter at two sufficiently separated wavelengths is significantly greater from ice particles than from water drops. The ratio depends little on scatterer size for most clouds and precipitation.

We had proposed a field demonstration of this method, but the unfortunate delays mentioned above prevented us from configuring the laser with the rare ¹³C¹⁶O₂ isotope preferred for this measurement. Testing of the method is still planned.

4) *Cirrus particle size microphysics from radar & CO₂ lidar*

The wavelengths of radar and CO₂ lidar are vastly different. Radar backscatter from ice particles is principally in the Rayleigh regime and scales as ND^6 , where N is the particle concentration, and D is a characteristic diameter. CO₂ lidar backscatter scales as ND^2 . A method was developed earlier (Intrieri et al., 1993) to retrieve vertical profiles of the effective radius of the cirrus particle size distribution from the ratio of calibrated radar and lidar backscatter.

Under this project, this method was extended to retrieve profiles of ice water content and particle concentration (Eberhard, Intrieri, and Feingold 1994; Intrieri, Eberhard, and Feingold, 1994). An analysis of the effect of measurement and calibration errors showed more margin of error allowable in the radar backscatter than in the lidar backscatter. Also, the accuracy of the effective radius was found to be least sensitive to measurement errors and particle concentration to be most sensitive of the three parameters. A comparison between the two remote sensing methods developed in ETL and aircraft measurements was reported in Matrosov et al. (1995).

5) *Emissivity and optical depth of cirrus from CO₂ LIRAD*

We adapted for the first time the LIRAD technique from the usual visible-wavelength lidar implementation to the CO₂ lidar. In this method, the radiance measured by a narrow-field infrared radiometer and the vertical profile of lidar backscatter are combined to infer the emissivity and optical depth of a cirrus cloud. Software was written and debugged to apply this technique. It incorporates some features not published before. One feature is proper averaging to match a series of lidar pulses with infrared radiometer data averaged for an appreciable time (~ min). Another feature is a new closure technique in which a theoretical relationship between the absorption cross section and the lidar extinction cross section is assumed, an approach more valid for CO₂ lidar than for shortwave lidars. CO₂ LIRAD processing of cirrus data was presented by Eberhard and Intrieri (1995A, 1995B).

6) *Doppler vertical motions in cirrus*

A theoretical analysis of differential velocities measured by Doppler lidar and radar confirmed that some useful information is available. The breadth of the cirrus size distribution can be obtained, but ambiguity would occur in some situations. Separation of air and particle

vertical motions with differential Doppler lidar and radar appears too difficult to be dependable.

7) *Extend radar/CO₂ lidar techniques to shortwave lidar*

The concept of extending the lidar/radar method to shortwave lidar was considered. One result was an analytical demonstration that the profile of microphysical parameters of a non-precipitating water cloud can be obtained over the penetration depth of a visible-wavelength lidar (Eberhard et al., 1997). The profile of calibrated radar backscatter is used as in method (4). However, the lidar data are processed for the profile of extinction cross-section using the familiar Klett technique. (Multiple scatter is not significant for very narrow-field lidars like ARM's MPL). No calibration of the lidar is needed, but linear detection is required. The ratio of radar backscatter and lidar extinction provides a profile of drop effective or mean radius, liquid water content, and concentration. Figure 7 shows the results of a simulation on a complex cloud generated by an LES model.

V. Publications and Presentations

The following publications and presentations at science meetings were funded at least partially under this project. Also, the publications designated by * in the reference list were funded under this project.

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VI. References

(See Sec. VI for the meaning of *)

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Figure 7. Ratio of retrieved to “actual” r_{eff} obtained in a simulation of the lidar backscatter and radar reflectivity method based on data generated from an LES model with detailed microphysics. Cloud top height was about 700 m. The r_{eff} increased generally from 1 to 5 μm over the height penetrated by the lidar, and was typically 11 μm near cloud top.

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