Performance of the Mini-MOPA, CO_2 Doppler, Cloud Lidar at CART

J. M. Intrieri and W. L. Eberhard
NOAA, Environmental Technology Laboratory
Boulder, Colorado

W. A. Brewer
Cooperative Institute for Research in Environmental Sciences
University of Colorado/NOAA, Environmental Technology Laboratory
Boulder, Colorado

Introduction

The Environmental Technology Laboratory (ETL) mini-Master Oscillator Power Amplifier (MOPA) Doppler lidar was successfully deployed and demonstrated during the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) 1996 Spring Intensive Observation Period (IOP). The project objective was to develop and demonstrate a bread-board version of a CO_2 Doppler lidar (operating in the thermal infrared [IR]) that could eventually be engineered as an automated instrument. Measurements were obtained from 19 April to 4 May, 1996, in three predominant modes: a vertically staring mode to reveal cloud geometry and vertical velocities, a horizontally pointing mode for boundary layer winds, and an aerosol-distribution structure. A variety of engineering test modes were also used to study system calibration and sensitivity issues. In addition, a comparison of clouds detected by the ETL lidar and the Pennsylvania State University (PSU) mm-wave radar is presented to illustrate the advantages of combining instruments of different wavelengths and the pitfalls of relying on only a single instrument for correct cloud information.

IOP Operations

The research task funded by the Instrument Development Program (IDP) proposal included the development of a robust, high Pulse Repetition Frequency (PRF), low-power, CO_2 Doppler lidar system that relies on Radio Frequency (RF) excitation of the continuous wave (CW) laser and optical amplifiers. The system uses a MOPA technique to create the output pulses, which provide frequency-stability for improved velocity accuracy. Table 1 lists specifications and typical characteristics of the system. The mini-MOPA lidar is an improvement over the older CO_2 Doppler lidar system in size, frequency stability, system robustness, and reliability. A detailed description of the mini-MOPA lidar optical configuration and system specifications is given in Brewer et al. (1997).

Table 1. ETL mini-MOPA lidar specifications.

Wavelength	**Tunable between 9.2 to 11.3 m (fully eye-safe)**
Pulse Energy	2 mJ
Pulse Rate	< 200 Hz
Pulse Length	0.3 - 5.0 s
Range and Time Resolution	90 m and 0.2 s (for 100 pulse average)
Minimum/Maximum Range	180 m / 10-15 km
Velocity Accuracy	< 25 cm/s
Scanning Capability	full hemispheric, fixed beam, PPI, RHI, raster, below-horizon
Beam Divergence	140 rad

The lidar successfully operated for over 40 hours during the 1996 Spring IOP and routinely ran for several hour stretches without operator interaction. Operating periods were predominantly determined by coordination with Subsonic Aircraft Contrail and Cloud Effects Special Study (SUCCESS) flights over the experiment area. The range of measurements included the detection of cirrus up to 12 km above ground level (AGL) when staring vertically, and aerosol returns out to 9 km when horizontally scanning. Even the most tenuous clouds observed by the eye were easily detected by the lidar in the vertically staring mode. Evaluation of the system performance indicates better than 25 cm/s velocity precision for 1 s averages.

Data Products and Applications

In addition to utilizing cloud returns to determine geometric boundaries and vertical velocities, additional techniques have been developed using the mini-MOPA lidar backscatter data alone, as well as in combination with other instrument data. These techniques include estimation of ice crystal size (Intrieri et al. 1993), concentration, and ice water content by combining lidar with IR radiometer and mm-wave radar measurements (Eberhard et al. 1994). The adaptation of these concepts to visible-wavelength lidar (like the CART micropulse lidar) and cloud radar for both ice and water clouds appear promising according to our current stage of theoretical development. Water droplet mode radius determination (Eberhard 1993a), and a zenith-enhanced backscatter technique for estimating crystal shape and length (Eberhard 1993b) are other microphysical sensing methods possible with the mini-MOPA lidar.

In its final configuration with the addition of a second wavelength, the mini-MOPA will have the added capability to obtain differential IR absorption lidar (DIAL) measurements and ice/water discrimination. This broadens the applications to clear and cloudy atmospheric studies as well as boundary layer work by coupling the Doppler wind observations with water vapor concentration profiles.

Comparisons with mm-Wave Radar

A comparison of "detected cloud" was made between the Pennsylvania State University (PSU) 3-mm wavelength radar (Clothiaux et al. 1995) and the 10.6-m mini-MOPA lidar to determine the percentage of time these instruments detect similar and dissimilar cloud boundaries. A total of 710 min of simultaneous vertically pointing data were compared spanning 5 days in April 1996. The percentages presented in Table 2 are, of course, biased because the measurements were not specifically obtained for a comparison study. However, it does illustrate that both lidar and radar are necessary in tandem to obtain an accurate cloud data set. Note that because the 3-mm radar can be attenuated in heavily water-laden clouds, there is no way to confirm that the cloud top, as detected by the 3-mm, is "ground-truth" as it is used here. Uttal et al. (1995) describes circumstances under which the 8-mm wavelength radar has detected higher cloud top than the 3-mm wavelength radar.

The occurrence of radar "misses" is divided into two sub-categories: a complete miss and a partial miss. A complete miss is noted when the radar receives no signal during times when the lidar detects cloud return. This most often occurred when high cirrus were present anywhere between ~ 7.5 - 11.0 km AGL and 0.4 to 1.5 km in thickness. The second category differentiates circumstances when a cloud is partially detected by the radar; for example, a lower cloud layer is seen by the radar but not an upper-level cloud. In some instances, a low-level water cloud was not detected by the radar, whereas a higher cloud was. Lidar attenuation most often occurred within 0.4 to 1.0 km of the cloud bottom with typical total cloud thicknesses of 2.0 to 4.0 km as determined by the radar.

In a few situations there is both a missed cloud by the radar and attenuation by the lidar so that the datasets must be combined to accurately depict the cloud scenario. For example, the lidar detects a lower-level water cloud missed by the radar and then attenuates in an upper cloud detected by the radar.

The most sensitive mode of the U.S. Department of Energy-ETL cloud radar is expected to be at least 10 dB more sensitive that the PSU radar, so better coverage is expected

Table 2. ETL lidar and PSU radar comparison of detected clouds during the 1996 Spring IOP.

Date	Julian day	Total min of overlap	Radar and lidar detect similar cloud boundaries	Lidar attenuates within the cloud	Radar partially misses cloud	Radar completely misses cloud
4.19.96	110	35	18	0	0	17
4.20.96	111	271	56	58	13	144
4.21.96	112	139	40	90	8	17
4.24.96	115	38	18	0	0	20
4.27.96	118	227	63	125	17	30
Total (min / %)		710 min	195 min / 27 %	273 min / 38 %	38 min / 5 %	228 min / 32 %

from the CART cloud radar than that reported here. A similar study is needed for CART lidars and radars on detected and missed clouds.

Summary and Future Work

The ETL mini-MOPA lidar was successfully demonstrated and obtained a variety of cloud and boundary layer information during the 1996 Spring IOP at the SGP CART site. Frequency stability, robustness, and low operator-attendance were the key mark attributes of this new system. The addition of a second wavelength is currently under development in order to obtain DIAL measurements of atmospheric water vapor. We also plan to operate the instrument using a CO_2 isotope that will reduce atmospheric CO_2 absorption, thus further extending the range of attainable measurements.

Remote sensing techniques to estimate cloud microphysical parameters have been developed to utilize lidar measurements alone (particle habit, mean droplet size, ice/water discrimination), as well as in combination with other instruments (particle size, shape, and concentration). A cursory comparison of the lidar and the PSU 3-mm radar datasets was made to illustrate the necessity of using a lidar and radar when a complete cloud dataset is sought.

Acknowledgments

This research was supported by the Environmental Sciences Division of the U.S. Department of Energy under grant No. DE-AI03-94ER61760 as part of the Atmospheric Radiation Measurement Program.

References

Brewer, W. A., B. J. Rye, R. M. Hardesty, and W. L. Eberhard, 1997: Preliminary results from a mini-MOPA CO_2 Doppler lidar. Proceedings, Optical Society of America, Santa Fe, New Mexico, 10 - 14 Feb. 1997.

Clothiaux, E. E., M. A. Miller, B. A. Albrecht, J. Verlinde, R. M. Peters, W. J. Syrett, 1995: An evaluation of a 94-GHz radar for remote sensing of cloud properties. *J. Atmos. Oceanic Technol*., **12**, pp. 201-229.

Eberhard, W. L., 1993a: CO_2 lidar technique for observing characteristic drop size in water clouds. IEEE Trans. Geosci. Remote Sens., **31**, pp. 56-63.

Eberhard, W. L., 1993b: Cirrus properties deduced from CO_2 lidar observations of zenith-enhanced backscatter from oriented crystals. FIRE Cirrus Science Results 1993, June 14-17, 1993, Breckenridge, Colorado NASA Conference Publication 3238, pp. 9-12.

Eberhard, W. L., J. M. Intrieri, and G. L. Feingold, 1994: Cirrus radiative and microphysical properties from combined lidar, radar, and infrared radiometer measurements at FIRE II. Eighth Conf. on Atmospheric Radiation, January 23-28, 1994, Nashville, Tennessee, American Meteorological Society, Boston, Massachusetts, pp. 222-224.

Intrieri, J. M., G. L. Stephens, W. L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle sizes using lidar and radar backscatter technique. *J. Appl. Meteor.*, **32**, pp. 1074-1082.

Uttal, T., E. E. Clothiaux, T. P. Ackerman, J. M. Intrieri, and W. L. Eberhard, 1995: Cloud boundary statistics during FIRE II. *J. Atmos. Sci.*, **52**, pp. 4276-4284.