3.6

APPLICATIONS OF DATA FROM THE CLOUD PHYSICS LIDAR

Matthew J. McGill,* Dennis L. Hlavka, and William D. Hart
Goddard Space Flight Center, Greenbelt, Maryland

1. INTRODUCTION

The NASA Cloud Physics Lidar (CPL) is an airborne lidar that has flown on the high-altitude ER-2 aircraft since 2000. The CPL has participated in several major field campaigns. Data from the CPL is being used for satellite validation, for satellite simulations, and for applied science investigations. Science applications of CPL data include analysis of cirrus anvil evolution, modeling of thunderstorm development, improving passive cloud top analyses, development and validation of cloud-aerosol retrieval algorithms, and simulating future satellite instruments. In this presentation we will show an overview of the CPL instrument and measurement capability followed by examples of CPL data for each of the aforementioned applications. Specific emphasis will be placed on demonstrating use of CPL data in non-lidar science applications, thereby underscoring the utility of lidar measurements to the general atmospheric science community.

2. THE CPL INSTRUMENT

The primary objective of the CPL is to provide multi-wavelength measurements of cirrus, subvisual cirrus, and aerosols with high temporal and spatial resolution. The instrument provides information to permit a comprehensive analysis of the radiative and optical properties of optically thin clouds (< optical depth 3). The CPL utilizes state-of-the-art technology with a high repetition rate, low pulse energy laser and photon-counting detection.

The CPL uses a Nd:YVO_4 laser operating at 1064, 532, and 355 nm with a repetition rate of 5 kHz. Use of a low pulse energy, high repetition-rate laser permits photon-counting detection while still maintaining an adequate dynamic range for the measurement. Table 1 lists the primary instrument parameters. Further details of the instrument design can be found in McGill *et al* [2002].

Table 1: CPL instrument parameters

wavelengths and output energy (nominal)	1064 nm, 50 μJ 532 nm, 25 μJ 355 nm, 50 μJ
pulse repetition rate	5 kHz
minimum range resolution	30 m
temporal resolution	1/10 s raw data, 1 s processed data
telescope diameter	20 cm
receiver field of view	100 microradians (full angle)
minimum detectable backscatter (532 nm) (aerosol refers to boundary layer aerosol)	cirrus (daytime): 1.2×10^{-7} $m^{-1}sr^{-1}$ cirrus (nighttime): 5.0×10^{-8} $m^{-1}sr^{-1}$ aerosol (daytime): 3.1×10^{-7} $m^{-1}sr^{-1}$ aerosol (nighttime): 6.8×10^{-8} $m^{-1}sr^{-1}$

3. CPL DATA PRODUCTS

Vertical resolution of the CPL measurements is fixed at 30 m. The CPL laser repetition rate is 5 kHz, but profiles are integrated and saved at 10 Hz. Horizontal resolution is therefore 1/10 second (~20 m at typical ER-2 speed of 200 m/s) for raw data, but data are averaged to 1 second for the final data products.

The CPL fundamentally measures range-resolved profiles of volume 180-degree backscatter coefficients. From the fundamental measurement, various data products are produced, including:

- time-height cross-section images;
- cloud and aerosol layer boundaries;
- optical depth for clouds, aerosol layers, and planetary boundary layer;
- extinction profiles; and
- depolarization ratio (cloud phase).

Data products are produced for each wavelength, except for the depolarization ratio, which is measured only at 1064 nm. Further

---

**Corresponding author address*: Matthew J. McGill, Goddard Space Flight Center, Code 912, Greenbelt, MD 20771;
email: matthew.j.mcgill@nasa.gov

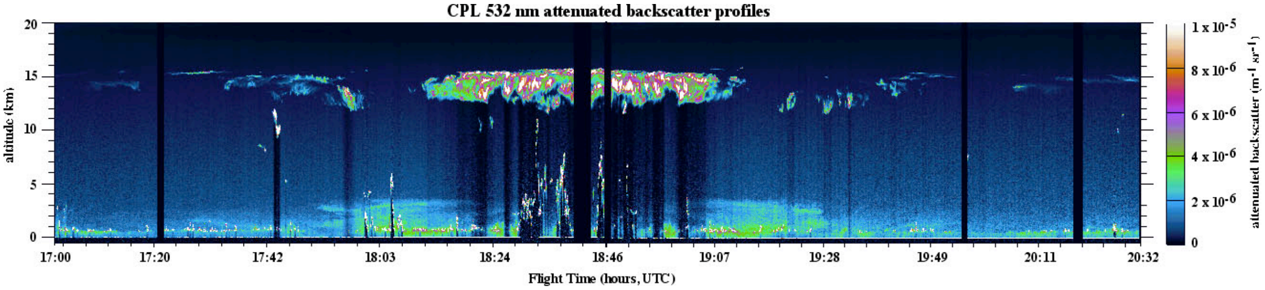

Figure 1: Example of CPL 532 nm attenuated backscatter profiles from July 26, 2002. This image is representative of airborne lidar data, showing cloud height and internal structure (including cirrus, subvisual cirrus, low- and mid-level clouds, and multiple cloud layers) and boundary layer aerosol. In addition, a period of elevated aerosol, known to be Saharan dust, is evident in the middle of the time period.

description of the CPL data products and processing algorithms can be found in McGill *et al* [2003]. The CPL data archive, freely accessible, can be found at http://cpl.gsfc.nasa.gov

A typical time-height cross-section image of CPL data is shown in Figure 1, illustrating the resolution and data quality.

4. APPLICATIONS OF CPL DATA

A primary application of CPL data is validation of satellite instruments. Because the ER-2 aircraft typically flies at 65,000 ft (~20 km), lidar profiling from that platform nearly mimics spaceborne measurements. CPL data is thus useful for satellite validation and for simulating future satellite instruments.

The first deployment for the CPL was the Southern African Regional Science Initiative (SAFARI-2000) field campaign.[Swap *et al*, 1998] The purpose of SAFARI-2000 was to study biomass burning over southern Africa and to perform validation flights for the Moderate Resolution Imaging Spectro-Radiometer (MODIS) instrument on the TERRA satellite. The spatial coverage attainable by the ER-2 permitted studies of aerosol properties across wide regions of the southern African continent.[McGill *et al*, 2003; Schmid *et al*, 2003] The large-scale aerosol mapping provided by the CPL will enhance studies of aerosol transport in this important region.

Two spaceborne lidar missions have benefited from CPL measurements. The Geoscience Laser Altimeter System (GLAS) on the ICESat satellite [Zwally *et al*, 2002] relied on CPL measurements for calibration of the GLAS lidar. During October 2003, the CPL was flown under the GLAS satellite track. The CPL calibration was transferred to the GLAS instrument to permit proper calibration of the GLAS data.

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission [Winker *et al*, 2002] has made extensive use of CPL data for simulating CALIPSO performance and testing algorithms.[Liu et al, 2004a; Liu et al, 2004b] CALIPSO will also utilize CPL for validation once that mission launches in 2005.

Many non-lidar spaceborne instruments also employ CPL data for validation/calibration purposes. The MODIS instruments on the TERRA and Aqua [Parkinson, 2003] satellites have utilized CPL data for validation purposes, as has the Atmospheric Infrared Sounder (AIRS) on the Aqua satellite. The NPOESS Atmospheric Sounder Testbed-Interferometer (NAST-I) instrument, a prototype for future NPOESS instruments, has also used CPL data for validation purposes.[Zhou *et al*, 2004]

Although CPL functions as a stand-alone science instrument for many applications, a real strength of lidar remote sensing arises when the lidar data is combined with data from other sensors. The Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL-FACE) [Jensen *et al*, 2004a] in 2002 was a prime example of the power of data synergy among multiple instruments. CRYSTAL-FACE permitted the first high-altitude combined lidar-radar measurements, an accomplishment that simulated measurements from the future CALIPSO and CloudSat [Stephens *et al*, 2002] missions. The CPL and the new 94 GHz Cloud Radar System (CRS) [Li *et al*, 2004] onboard the ER-2 aircraft acted as proxies for the CALIPSO and CloudSat instruments, respectively. Figure 2 shows an example of the data synergy that results from combining the lidar and radar data. Note in Figure 2 that neither instrument alone senses all cloud or aerosol layers.

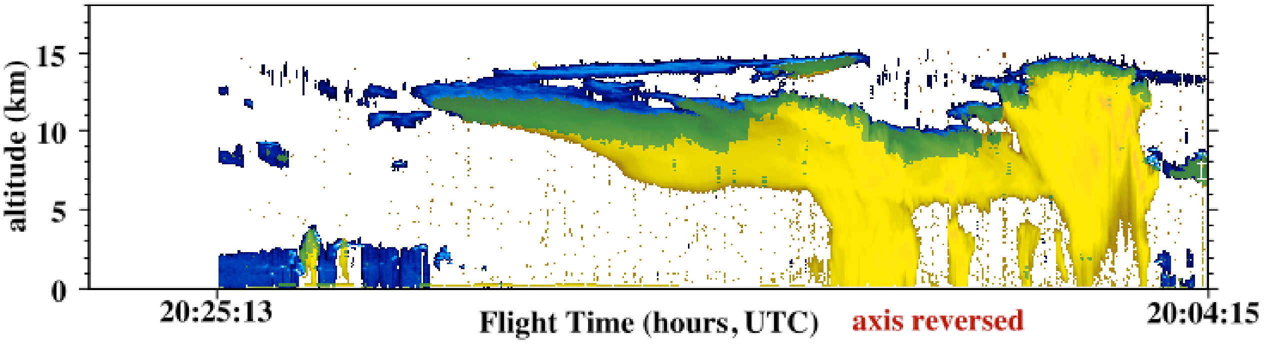

Figure 2: Example of lidar-radar data synergy from CRYSTAL-FACE (July 23, 2002). In this image, areas shaded blue represent cloud/aerosol layers observed only by the lidar, areas shaded yellow were observed only by the radar, and areas shaded green were observed by both the lidar and the radar. This data synergy demonstrates the potential of the future CALIPSO and CloudSat missions. From McGill *et al* (2004).

The lidar is ideal for detecting thin cirrus and aerosol layers, while the radar is ideal for probing optically thick clouds that are impenetrable by the lidar.[McGill *et al*, 2004]

The CRYSTAL-FACE experiment also provided a significant opportunity for combining CPL data products with those from in situ sensors. CPL data from CRYSTAL-FACE has been used to study atmospheric chemistry [Ridley *et al*, 2004], to study tropopause dynamics [Jensen *et al*, 2004b], for improving passive cloud top retrievals [Sherwood *et al*, 2004], to examine convective generation of tropopause cirrus [Garrett *et al*, 2004], and to study particle shapes compared to lidar depolarization ratio [Noel *et al*, 2004].

5. SUMMARY

The CPL instrument provides profiling of cloud and aerosol properties with high spatial and temporal resolution. CPL data finds application in myriad science investigations, many of which are not lidar-centric. The ability of CPL data to contribute to topics as disparate as satellite validation, atmospheric chemistry, and atmospheric dynamics underscores the utility of airborne and spaceborne lidar measurements. As evidenced by results from the CRYSTAL-FACE field campaign, the atmospheric science community is able to make wide-spread use of lidar data.

6. REFERENCES

Garrett, T.J., A.J. Heymsfield, M.J. McGill, D.G. Baumgardner, P.T. Bui, B.A. Ridley, C.R. Webster, and E.M. Weinstock, 2004: "Convective generation of cirrus near the tropopause," *Journal of Geophysical Research*, **109**, doi: 10.1029/2004JD004952.

Jensen, E., D. Starr, and O.B. Toon, 2004a: "Mission investigates tropical cirrus clouds," *EOS Transactions of the AGU*, **84**(5), 45-50.

Jensen, E., L. Pfister, T. Bui, A. Weinheimer, E. Weinstock, J. Smith, D. Baumgardner, and M.J. McGill, 2004b: "Formation of a tropopause cirrus layer observed over Florida during CRYSTAL-FACE," *Journal of Geophysical Research* (*submitted*).

Li, L., G.M. Heymsfield, P.E. Racette, L. Tian, and E. Zenker, 2004: "A 94 Ghz Cloud Radar System on the NASA high-altitude ER-2 Aircraft," *Journal of Atmospheric and Oceanic Technology*, **21**, 1378-1388.

Liu, Z., M. McGill, Y. Hu, C.A. Hostetler, M. Vaughan, and D. Winker, 2004a: "Validating lidar depolarization calibration using solar radiation scattered by ice clouds," *Geoscience Remote Sensing Letters,* **1**, 157-161.

Liu, Z., M.A. Vaughan, D.M. Winker, C.A. Hostetler, L.R. Poole, D. Hlavka, W. Hart, and M. McGill**,** 2004b: "Use of probability distribution functions for discriminating between cloud and aerosol in lidar backscatter data," *Journal of Geophysical Research*, **109**, doi: 10.1029/2004JD004732.

McGill, M.J., D.L. Hlavka, W.D. Hart, V.S. Scott, J.D. Spinhirne, and B. Schmid, 2002: "The Cloud Physics Lidar: instrument description and initial measurement results," *Applied Optics*, **41**, 3725-3734.

McGill, M.J., D.L. Hlavka, W.D. Hart, E.J. Welton, and J.R. Campbell, 2003: "Airborne lidar measurements of aerosol optical properties during SAFARI-2000," *Journal of Geophysical Research*, **108**, doi: 10.1029/2002JD002370.

McGill, M.J., L. Li, W.D. Hart, G.M. Heymsfield, D.L. Hlavka, P.E. Racette, L. Tian, M.A. Vaughan, and D.M. Winker, 2004: "Combined lidar-radar remote sensing: initial results from CRYSTAL-FACE," *Journal of Geophysical Research*, **109**, doi: 10.1029/2003JD004030.

Noel, V., D. Winker, M. McGill, and P. Lawson, 2004: "Classification of particle shapes from lidar depolarization ratios in convective ice clouds compared to in situ observations during CRYSTAL-FACE," *Journal of Geophysical Research* (accepted, *in press*).

Parkinson, C.L., 2003: "Aqua: An Earth-observing satellite mission to examine water and other climate variables," *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 173-183.

Ridley, B., L. Ott, K. Pickering, L. Emmons, D. Montzka, A. Weinheimer, D. Knapp, F. Grahek, L. Li, G. Heymsfield, M. McGill, P. Kucera, M.J. Mahoney, and G. Brasseur, 2004: "Florida thunderstorms: a faucet of reactive nitrogen to the upper troposphere," *Journal of Geophysical Research* (*submitted*).

Schmid, B., J. Redemann, P.B. Russell, P.V. Hobbs, D.L. Hlavka, M. McGill, W. Hart, B.N. Holben, E.J. Welton, J. Campbell, O. Torres, R. Kahn, D. Diner, M. Helmlinger, D.A. Chu, C. Robles-Gonzalez, and D. de Leeuw, 2003: "Coordinated airborne, spaceborne, and ground-based measurements of massive, thick aerosol layers during the dry season in Southern Africa," *Journal of Geophysical Research*, **108**, doi: 10.1029/2002JD002297.

Sherwood, S.C., J-H. Chae, P. Minnis and M. McGill, 2004: "Underestimation of deep convective cloud tops by thermal imagery," *Geophysical Research Letters,* **31**, doi: 10.1029/2004GL019699.

Stephens, G.L., D.G. Vane, R.J. Boain, G.G. Mace, K. Sassen, Z. Wang, A.J. Illingworth, E.J. O'Connor, W.B. Rossow, S.L. Durden, S.D. Miller, R.T. Austin, A. Benedetti, C. Mitrescu, and the CloudSat Science Team, 2002: "The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation," *Bulletin of the American Meteorological Society*, **83**, 1771-1790.

Swap, B., J. Privette, M. King, D. Starr, T. Suttles, H. Annegarn, M. Scholes and C.O. Justice, 1998: "SAFARI 2000: a southern African regional science initiative," *EOS Earth Observer*, **10**(6), 25-28.

Winker, D.M., J. Pelon and M.P. McCormick, 2002: "The CALIPSO Mission: spaceborne lidar for observation of aerosols and clouds," in *Proceedings of SPIE*, Vol. 4893 (U. Singh, T. Itabe, Z. Liu eds.), 1-11, Hangzhou, China, 24-25 October 2002.

Zhou, D., J. Murray, X. Liu, A. Larar, W. Smith, J. Li, and H-L. Huang, 2004: "Atmospheric and cloud parameter retrieval using IR spectral data," in *Proceedings of the International Radiation Symposium*, Busan, Korea, 23-28 August 2004.

Zwally, H.J., B. Schutz, W. Abdalati, J. Abshire, C. Bentley, A. Brenner, J. Bufton, J. Dezio, D. Hancock, D. Harding, T. Herring, B. Minster, K. Quinn, S. Palm, J. Spinhirne, and R. Tomas, 2002: ICESat's laser measurements of polar ice, atmosphere, ocean, and land," *Journal of Geodynamics*, **34**, 405-445.