AEROSOL PROFILE MEASUREMENTS FROM THE NASA LANGLEY RESEARCH CENTER AIRBORNE HIGH SPECTRAL RESOLUTION LIDAR

Michael D. Obland [1], Chris A. Hostetler[1], Richard A. Ferrare[1], John W. Hair[1], Raymond R. Rogers[2], Sharon P. Burton[2], Anthony L. Cook[1], David B. Harper[1]

[1]*NASA Langley Research Center, 100 NASA Road, M/S 401A, Hampton, VA, USA, Michael.D.Obland@nasa.gov*
[2]*SSAI/NASA Langley Research Center, 100 NASA Road, M/S 401A, Hampton, VA, USA*

ABSTRACT

Since achieving first light in December of 2005, the NASA Langley Research Center (LaRC) Airborne High Spectral Resolution Lidar (HSRL) has been involved in seven field campaigns, accumulating over 450 hours of science data across more than 120 flights. Data from the instrument have been used in a variety of studies including validation and comparison with the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite mission, aerosol property retrievals combining passive and active instrument measurements, aerosol type identification, aerosol-cloud interactions, and cloud top and planetary boundary layer (PBL) height determinations. Measurements and lessons learned from the HSRL are leading towards next-generation HSRL instrument designs that will enable even further studies of aerosol intensive and extensive parameters and the effects of aerosols on the climate system. This paper will highlight several of the areas in which the NASA Airborne HSRL is making contributions to climate science.

1. INTRODUCTION

The NASA Langley Research Center (LaRC) Airborne High Spectral Resolution Lidar (HSRL) was conceived with the purpose of making accurate, calibrated measurements of cloud and aerosol properties in support of atmospheric composition, climate, and air quality studies as well as playing a primary validation/calibration role for the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite [1].

Unlike normal backscatter lidar techniques, which typically require the aerosol extinction to backscatter ratio, S_a, to be assumed or derived from additional data [2, 3] for the retrieval of aerosol backscatter and extinction profiles, the HSRL technique differentiates between the Doppler-broadened molecular scattering and the negligibly broadened aerosol scattering to directly measure aerosol extinction and backscatter [4-7]. Avoiding the need to assume a value of S for aerosols, S_a, removes a potential source of error, since S_a can vary widely based on HSRL measurements (~10 < S_a < ~90). Also, by making a direct measurement of S_a, the HSRL provides important information on aerosol type since S depends on particle composition, size distribution, and shape.

Beyond measuring backscatter and extinction at 532 nm, the NASA Airborne HSRL also functions as a standard backscatter lidar at 1064 nm, enabling the calculation of the backscatter color ratio or wavelength dependence, β_{1064}/β_{532}. In addition, depolarization is measured at both wavelengths, enabling discrimination of spherical vs. nonspherical aerosol/cloud particles. Optical depth is found by integrating the extinction profiles. Automatic internal calibration of the polarization channels gain ratio, aerosol and molecular backscatter channels gain ratio, and autonomous boresighting of the transmitter/receiver alignment increase the accuracy of the data products. The vertically resolved intensive (which depend only on the nature or type of the particles and not on their quantity or concentration) and extensive (which depend on the concentration and type of aerosol/cloud particles) aerosol parameters measured by the HSRL are listed in Table 1. Table 2 lists key system parameters.

Table 1. HSRL measurement capabilities. Typical horizontal and vertical resolutions are given, which can be varied as needed.

Parameter	Wavelength [nm]	Vert. Res. [m]	Horiz. Res. [km]
Intensive Parameters			
S_a	532	300	6
Depolarization Ratio	532, 1064	30	1
Wavelength Dependence (β_{1064}/β_{532})	NA	30	1
Extensive Parameters			
Backscatter, β	532, 1064	30	1
Extinction, α	532	300	6
Optical Depth	532	NA	6

Table 2. HSRL system properties.

Transmitter	
Repetition Rate	200 Hz
532 nm energy	2.5 mJ
1064 nm energy	1 mJ
Optical Receiver	
Telescope	0.4 m diameter
532 etalon FWHM	40 pm
1064 IF FWHM	1 nm
Detection Electronics	
532 nm	PMT, analog detection
1064 nm	APD with analog detection

Since it began taking scientific measurements in December of 2005, the NASA Airborne HSRL has accumulated over 450 hours of atmospheric data while operating nearly flawlessly on more than 120 flights that have taken place across the continental United States as well as Mexico and the eastern Caribbean Sea. Flying on board the NASA King Air B200 aircraft, the instrument participated in its first field campaign in March of 2006 with the Megacity Initiative: Local and Global Research Observations (MILAGRO) deployment. Subsequent campaigns have included the CALIPSO/CloudSat Validation Experiment (CC-VEX) throughout the spring and summer of 2006, the Texas Air Quality Study (TEXAQS)/Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS) in the fall of 2006, air quality flights for the Environmental Protection Agency (EPA) in the San Joaquin Valley of California, the Cumulus Humilis Aerosol Processing Study/Cloud and Land Surface Interaction Campaign (CHAPS/CLASIC) in June of 2007, flights in support of the CALIPSO and Twilight Zone (CATZ) campaign in the summer of 2007, and low-latitude CALIPSO validation measurements in the eastern Caribbean during January of 2008. Missions planned for the remainder of 2008 include the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) campaigns in Barrow, Alaska, during April and Yellowknife, Canada, during June-July.

Data from the HSRL have been used in a number of studies beyond CALIPSO validation and are available via FTP to other interested research groups. The remainder of this paper provides brief descriptions of several current and future areas of study.

2. CURRENT AREAS OF STUDY

2.1 CALIPSO Validation and Comparisons

The NASA LaRC Airborne HSRL has flown nearly 50 flights in support of CALIPSO validation and comparison. Flights have included two dedicated campaigns (CC-VEX in 2006 and eastern Caribbean flights in 2008) as well as many flights of opportunity during other field campaigns. The NASA King Air aircraft range typically allows HSRL measurements to be taken along a CALIPSO ground track for 1-3 hours, with the satellite overpass point nominally in the center of the King Air ground track. These underflights have been conducted both at night and during daytime, and provide an independent validation of several CALIOP Level-1 and Level-2 data products.

2.2 Coordinated Observations

A primary goal of flight planning during the field campaigns in which the NASA HSRL participates has been to coordinate observations, to the maximum extent possible, with available ground-based, airborne, and spaceborne sensors. These measurements, coordinated in time and location, enable instrument intercomparison, studies of combined passive/active instrument retrievals of aerosol measurements, and opportunities to combine complementary data sets to better address particular research problems. Figure 1 shows a preliminary comparison between HSRL aerosol extinction profiles with those derived from the 14 channel NASA Ames Airborne Tracking Sunphotometer (AATS-14, operating at 519 nm), and the Hawaii Group for Environment and Atmospheric Research (HiGEAR) in situ aerosol scattering (nephelometer, operating at 550 nm) and absorption

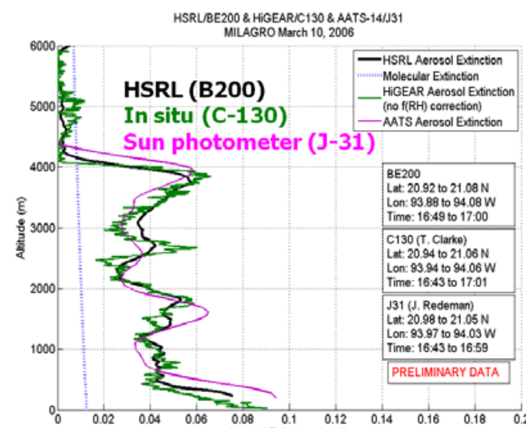

Figure 1. Comparison of extinction profiles measured by the Airborne HSRL (black), the NASA Ames Airborne Tracking Sun Photometer (AATS-14) (magenta), and the Hawaii Group for Environmental Aerosol Research (HiGEAR) in situ instrumentation (scattering + absorption, green) during the MILAGRO campaign.

(Particle Soot Absorption Photometer-PSAP, operating at 530 nm) measurements acquired during the MILAGRO campaign. AATS14 was deployed on the J-31 aircraft and the in situ instruments were deployed on the NCAR C-130. These aircraft performed spirals while the NASA King Air flew directly overhead.

Several other intercomparison studies are underway between the NASA HSRL and satellite instruments and other aircraft or surface instruments (see, for example, [8, 9]).

2.3 Aerosol Type Identification

The data products produced by the NASA HSRL can be combined in a number of ways to produce PDF's of aerosol characteristics, which can then be used through cluster analysis to infer aerosol type. One example of aerosol type identification is shown in figure 2. HSRL measurements were obtained during a CALIPSO validation flight and show variations in aerosol type near the Florida coastline. On the left (northern) side of the color plots, higher values of S_a and backscatter wavelength dependence, and lower values of depolarization, suggest smaller, more spherically shaped particles (e.g., sulfate drops) more typically associated with urban/industrial pollution. Lower S_a and higher depolarization values over the right (southern) part of the plots suggest higher concentrations of dust [10-13]. Back trajectories revealed this to be Saharan dust.

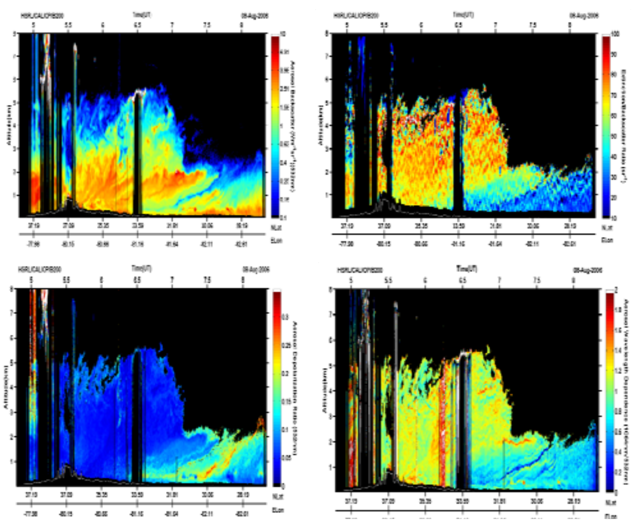

Figure 2. HSRL measurements from August 8th, 2006, illustrating how different measured parameters can be used to infer aerosol types. Top left: aerosol backscatter ratio at 532 nm. Top right: aerosol extinction to backscatter ratio. Bottom left: depolarization ratio. Bottom right: backscatter wavelength dependence.

2.4 Aerosol-Cloud Studies

The high signal-to-noise ratio and high spatial resolution of the Airborne HSRL data product enable unique studies of aerosols between and above clouds. Preliminary studies are underway to use data acquired over broken cloud systems to study the variability of aerosol optical properties as a function of distance from clouds and assessing potential biases in aerosol optical depth from passive satellite sensors due to side scatter from clouds. Imagery to aid in these studies is provided by a simple nadir-viewing digital camera flown as part of the payload on all Airborne HSRL flights. These imagery provides spatial context for the lidar profiles and will be used in future studies to composite averages of HSRL observables as a function of distance from cloud edges in broken cloud systems.

2.5 Cloud Top and PBL Height Determination

Algorithms have been developed that use HSRL data to determine cloud top and PBL heights [14]. The PBL height is derived by identifying the sharp gradients in 532 nm aerosol backscatter signal located at the top of the boundary layer, using an automated technique based on [15]. The algorithm has been applied to HSRL data during the MILAGRO, GoMACCS, SJV, and CHAPS campaigns, and has been successful even though the terrain and overlying aerosol layers complicate many of the analyzed scenes.

3. FUTURE INSTRUMENT DEVELOPMENT

Design and construction of the next-generation NASA LaRC Airborne HSRL is already underway. This instrument will have all of the capabilities of the current HSRL, but will add the capability to measure aerosol backscatter and extinction at 355 nm, allowing for an independent measurement of S_a in the ultraviolet wavelength regime. Combinations of backscatter measurements at three wavelengths (355, 532, and 1064 nm) and extinction at two wavelengths (355 and 532 nm) will further delineate aerosol characteristics between differing types, allowing for unprecedented studies of range-resolved aerosol typing. The next-generation HSRL will also add ultraviolet wavelength channels that will provide differential absorption lidar (DIAL) measurements of atmospheric ozone. This next-generation instrument will be configured for flight on the NASA ER-2 aircraft, enabling long-duration flights at altitudes above 60,000 feet.

4. CONCLUSION

The NASA Airborne High Spectral Resolution Lidar has been consistently building a well-calibrated database of aerosol spatial distribution and optical properties from numerous field campaigns in the United States, Mexico, and the eastern Caribbean. Hundreds of hours of lidar data have been collected and archived and are currently being used in a number of studies, including CALIPSO validation and comparison, combined passive and active instrument retrievals, aerosol type identification, aerosol-cloud studies, and cloud top and PBL height determinations. A next-generation version of the instrument will incorporate even greater capabilities. The HSRL data along with spatially and temporally coincident digital camera images are available via FTP to research groups interested in collaborative studies.

5. ACKNOWLEDGEMENTS

The authors would like to thank the NASA Langley flight crew, maintenance, and support personnel for making the King Air flights possible. We also thank the Department of Energy (DOE) Atmospheric Science Program, the NASA HQ Science Mission Directorate Radiation Sciences Program, and the NASA CALIPSO project for funding this HSRL-related research. Michael Obland appears courtesy of the NASA Postdoctoral Program, administered by Oak Ridge Associated Universities through a contract with NASA.

REFERENCES

[1] Hair, J., C. Hostetler, R. Ferrare, A. Cook, D. Harper, The NASA Langley High Spectral Resolution Lidar for Measurements of Aerosols and Clouds, in: *Reviewed and Revised Papers Presented at the 23rd International Laser Radar Conference*, C. Nagasawa and N. Sugimoto, Eds., 411-414, 2006.

[2] Klett, J.D., Stable analytical inversion solution for processing lidar returns, *Appl. Opt*., **20**, pp. 211-220, 1981.

[3] Fernald, F.G., Analysis of atmospheric lidar observations: some comments, *Appl. Opt.*, **23**, pp. 652-653, 1984.

[4] Shipley, S.T., D.H. Tracy, E.W. Eloranta, J.T. Trauger, J.T. Sroga, F.L. Roesler and J.A. Weinman, A High Spectral Resolution Lidar to Measure Optical Scattering Properties of Atmospheric Aerosols, Part I: Instrumentation and Theory, *Appl. Opt*., **23**, pp. 3716-3724, 1983.

[5] Grund, C.J. and E.W. Eloranta, The University of Wisconsin High Spectral Resolution Lidar, *Opt. Eng*., **30**, pp. 6-12, 1991.

[6] She, C. Y., R. J. Alvarez II, L. M. Caldwell, and D. A. Krueger, High-spectral-resolution Rayleigh-Mie lidar Measurement of Aerosol and Atmospheric Profiles, *Opt. Lett.* **17**, pp. 541-543, 1992.

[7] Hair, J. W., L. M. Caldwell, D. A. Krueger, and C. Y. She, High-spectral-resolution lidar with iodine-vapor filters: measurement of atmospheric-state and aerosol profiles, *Appl. Opt.*, **40**, pp. 5280-5294, 2001.

[8] Burton, S. P., R. A. Ferrare, C. Kittaka, C. A. Hostetler, J. W. Hair, M. D. Obland, R. R. Rogers, A. L. Cook, D. B. Harper, Using Airborne High Spectral Resolution Lidar Data to Evaluate Combined Active Plus Passive Retrievals of Aerosol Extinction Profiles, *Presented at the 24th International Laser Radar Conference*, 2008.

[9] Rogers, R. R., R. A. Ferrare, C. A. Hostetler, J. W. Hair, A. L. Cook, D. B. Harper, M. D. Obland, S. P. Burton, A. Clarke, Y. Shinozuka, J. Redemann, P. Russell, J. Livingston, Evaluation of NASA/LaRC Airborne High Spectral Resolution Lidar Aerosol Extinction Measurements, *Presented at the 24th International Laser Radar Conference*, 2008.

[10] Browell, E. V., et al., Large-scale air mass characteristics observed over the remote tropical Pacific Ocean during March-April 1999: Results from PEM Tropics B Field Experiment, *J. Geophys. Res*., **106**, pp. 32,481-32,501, 2001.

[11] Sugimoto N., I. Matsui, A. Shimizu, I. Uno, K. Asai, T. Endoh, and T. Nakajima, Observation of dust and anthropogenic aerosol plumes in the Northwest Pacific with a two-wavelength polarization lidar on board the research vessel Mirai, *Geophys. Res. Lett*., **29** (19), 1901, doi:10.1029/2002GL015112, 2002.

[12] Cattrall, C., J. Reagan, K.Thome, O. Dubovik, Variability of aerosol and spectral lidar and backscatter and extinction ratios of key aerosol types derived from selected Aerosol Robotic Network locations, *J. Geophys. Res*., **110**, D10S11, doi:10.1029/2004JD005124, 2005.

[13] Murayama T., D. Müller, K. Wada, A. Shimizu, M. Sekiguchi, T. Tsukamoto, Characterization of Asian dust and Siberian smoke with multi-wavelength Raman lidar over Tokyo, Japan in spring 2003, *Geophys. Res. Lett*., **31**, L23103, doi:10.1029/2004GL021105, 2004**.**

[14] Burton, S.P., R.A. Ferrare, C.A. Hostetler, J.W. Hair, A.L. Cook, D. B. Harper, M. D. Obland, and R. R. Rogers, Planetary Boundary Layer (PBL) Heights Derived From NASA Langley Airborne High Spectral Resolution Lidar (HSRL) Data Acquired During TexAQS/GoMACCS, CHAPS, and MILAGRO, *Presented at the Fall Meeting of the American Geophysical Union (AGU)*, 2007.

[15] Brooks, I.M., Finding Boundary Layer Top: Application of Wavelet Covariance Transform to Lidar Backscatter Profiles, *J. Atmos Ocean. Tech*., **20**, pp. 1092-1105, 2003.