FINAL REPORT FOR INTERAGENCY AGREEMENT AI02-05ER63985

Project Title: Characterizing Aerosol Distributions and Optical Properties Using the NASA Langley High Spectral Resolution Lidar

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Project ID: 0011071

Award Register#: ER63985-0011071

Inter Agency Agreement #: AI02-05ER63985

Project Period: 1 January 2005 - 31 December 2011

Date Prepared: 14 February 2013

Table of Contents

Introduction

The objective of this project was to provide vertically and horizontally resolved data on aerosol optical properties to assess and ultimately improve how models represent these aerosol properties and their impacts on atmospheric radiation. The approach was to deploy the NASA Langley Airborne High Spectral Resolution Lidar (HSRL) and other synergistic remote sensors on DOE Atmospheric Science Research (ASR) sponsored airborne field campaigns and synergistic field campaigns sponsored by other agencies to remotely measure aerosol backscattering, extinction, and optical thickness profiles. Synergistic sensors included a nadir-viewing digital camera for context imagery, and, later in the project, the NASA Goddard Institute for Space Studies (GISS) Research Scanning Polarimeter (RSP). The information from the remote sensing instruments was used to map the horizontal and vertical distribution of aerosol properties and type. The retrieved lidar parameters include profiles of aerosol extinction, backscatter, depolarization, and optical depth. Products produced in subsequent analyses included aerosol mixed layer height, aerosol type, and the partition of aerosol optical depth by type. The lidar products provided vertical context for in situ and remote sensing measurements from other airborne and ground-based platforms employed in the field campaigns and was used to assess the predictions of transport models. Also, the measurements provide a data base for future evaluation of techniques to combine active (lidar) and passive (polarimeter) measurements in advanced retrieval schemes to remotely characterize aerosol microphysical properties.

The project was initiated as a 3-year project starting 1 January 2005. It was later awarded continuation funding for another 3 years (i.e., through 31 December 2010) followed by a 1-year no-cost extension (through 31 December 2011). This project supported logistical and flight costs of the NASA sensors on a dedicated aircraft, the subsequent analysis and archival of the data, and the presentation of results in conferences, workshops, and publications. DOE ASR field campaigns supported under this project included

- MAX-Mex /MILAGRO (2006)
- TexAQS 2006/GoMACCS (2006)
- CHAPS (2007)
- RACORO (2009)
- CARE/CalNex (2010)

In addition, data acquired on HSRL airborne field campaigns sponsored by other agencies were used extensively to fulfill the science objectives of this project and the data acquired have been made available to other DOE ASR investigators upon request.

The deliverables for this project were data products from field campaigns, presentations at scientific meetings on the field campaign data and subsequent analyses, and publication of data analyses in scientific journals. This final report is intended as a summary of the activities of the team, listing of data products delivered, presentations made, and publications written. Results and findings can be found in the publications and archived presentations and are not repeated herein. Reporting on this project was done yearly through the DOE RIMS web-based reporting system (https://rimsweb.science.doe.gov/rims/scripts/rims.exe). The report is organized by project year, with a summary of the activities and deliverables for each year.

Year 1 (2005)

The only ASP field mission conducted in 2005 was the MASE mission, which was not an appropriate application for the HSRL. Instead, it was decided that the HSRL would be employed to support MAX-Mex/MILAGRO and, if enough resources were available after that, the TexAQS 2006/GoMACCS field missions. Both of these missions were conducted in 2006. Work done in 2005 by our team was largely devoted to planning and instrument/aircraft preparations for those field missions in 2006. Specific activities included the following.

- Chris Hostetler and Rich Ferrare attended the January 2005 Science Team meeting in Charleston, SC, where they presented their experiment goals and approach to the team and participated in preliminary planning for the MAX-Mex campaign.
- In March, Chris Hostetler traveled to Mexico with a team from DOE and NSF to begin laying the necessary groundwork for the MAX-Mex/MILAGRO mission. The group met with US Embassy personnel to discuss clearances and permits and with SENEAM (the Mexican FAA) to begin discussions of flight operations for the research aircraft. They also traveled to Tampico and Veracruz to evaluate airport options for deploying the research aircraft and site logistics for basing the mission operations center. Veracruz was selected as the deployment base.
- We reevaluated the our options for aircraft to support the Langley remote sensing instruments and switched from a Lear Jet (our proposed aircraft) to a Beech King Air Be-200 as the most suitable aircraft for the upcoming missions. This was based on a variety of factors (optimal flight altitude, aircraft speed, duration on-station, and flight hour cost). The King Air was a better option on the basis of both science and cost, given the objectives of the missions we were considering and the flight scenarios we anticipated. A flight test of the laser system used as the lidar transmitter was conducted in July to ascertain whether the higher vibration levels in the turbo-prop aircraft would impose problems for seeding the laser to operate at a single frequency as required by our measurement technique (the high spectral resolution technique). The laser operated flawlessly, and we proceeded to contact several potential providers of King Air Be-200 aircraft to discuss support for our field missions. We selected the NASA Langley King Air for the missions in August. This was deemed the best option on the basis of availability, cost, and logistical issues associated with the field mission deployments.
- The remaining months of 2005 have been spent configuring the Langley King Air for our instrument payload. This includes the addition and certification of optical ports for the instruments, a power load shed circuit and inverters to deliver power to the instrument, a TCAS system as a laser safety feature (i.e., enabling the laser operator to block the beam when other aircraft fly below the King Air), and fixtures to mount the instruments. NASA Langley has heavily subsidized the costs of the modifications and additions to the aircraft as the same modifications are required to employ our instrument suite for validation of the CALIPSO satellite-based lidar.
- Chris Hostetler and John Hair supported the MILAGRO planning meeting in Boulder in October.
- Chris Hostetler and Rich Ferrare supported the DOE Science Team meeting in Alexandria in November.

- Chris Hostetler traveled to Mexico City in early December to brief SENEAM personnel on anticipated flight plans and discuss operational procedures/issues with SENEAM.

Year 2 (2006)

Field Campaigns

In 2006, efforts focused on our participation in the MAX-MEX/MILAGRO and MAX-TEX/TexAQS/GoMACCS field missions. On those missions, we deployed the Langley Airborne High Spectral Resolution Lidar (HSRL) on the Langley NASA King Air. Summary information on those deployments is provided below. We also participated in planning of the Cumulus Humilis Aerosol Processing Study (CHAPS) experiment scheduled for 2007.

MAX-MEX/MILAGRO:

Fifteen science flights amounting to approximately 60 flight hours were conducted from the base of operations in Vera Cruz, Mexico. The objectives included

- Mapping vertical and horizontal distribution of aerosols over Mexico City and the surrounding region
    - Using profiles of extinction, backscatter, and depolarization to characterize the vertical distribution of aerosol optical properties and type
    - Determining relative contribution of various aerosol types to aerosol extinction and optical depth
    - Comparing observations to model transport predictions
    - Providing vertical context for in situ measurements on the G-1 and C-130, remote measurements on the J-31, and ground-based measurements from T0, T1, and T2
    - Comparing aerosol extinction and optical depth measurements with sensors on J-31, G-1, and C-130
- Assessing satellite (MODIS, MISR) retrievals of aerosol optical depth
- Investigating active-passive retrieval techniques of aerosol optical and microphysical properties
    - HSRL + MODIS as a precursor to CALIPSO + MODIS
    - HSRL + RSP as a precursor to CALIPSO + PARASOL

Flights of the King Air were generally coordinated with those of other participating aircraft and satellite overpasses, including

- 5 flights with J-31
- 6 flights with G-1
- 4 flights with C-130
- 5 MISR overpasses
- 9 MODIS overpasses

Preliminary comparisons were made between lidar measurements collected by the HSRL and in situ measurements from the G-1 and C-130 plus remote measurements from the J-31.

MAX-TEX/GoMACCS:

Twenty-two science flights amounting to over 90 flight hours were conducted from the base of operations in Houston, TX. Science objectives included:

- Mapping the vertical and horizontal distribution of aerosols
    - Using profiles of extinction, backscatter, and depolarization to characterize the vertical distribution of aerosol by type (e.g. dust, sulfate, sea salt, etc.)
    - Determining relative contribution of various aerosol types to aerosol extinction and optical depth
    - Characterizing the behavior and variability of the ABL height
    - Evaluating transport model predictions of aerosol distributions and transport in Houston region
    - Providing vertical context for in situ measurements on the P-3 and Twin Otters
    - Providing advance or real-time information to vector other aircraft to locations and altitudes of greatest interest
    - Evaluating the distribution of aerosol backscatter/extinction in the proximity of clouds
- Validating CALIPSO backscatter, extinction, and depolarization measurements
- Investigating use of lidar data in combination with and MODIS and PARASOL to determine vertical distribution of aerosol effective radius, fine mode fraction as a prelude to combined CALIPSO/A-train retrievals
- Investigating the combined use of lidar, photo-polarimeter, and oxygen A-band data to characterize key aerosol optical and microphysical properties

Flights were generally coordinated with those of participating aircraft and satellite overpasses, including:

- 7 flights with NOAA WP-3
- 6 flights with NOAA Twin Otter
- 7 flights with CIRPAS Twin Otter
- 2 flights over the RHB
- 10 CALIPSO validation flights
- 4 MISR LM overpasses
- 14 MODIS overpasses

CHAPS Pre-Mission Planning

In addition to the field mission activities, the team participated in developing the white paper and initial planning for the Cumulus Humilis Aerosol Processing Study (CHAPS) to be conducted by the DOE ASP in June of 2007.

Data Products Delivered

Preliminary HSRL data from the MAX-MEX/MILAGRO campaign were archived on the NASA INTEX-B website by September 1 as per the MAX-MEX/MILAGRO data policy. Data products posted to the archive include

- Aerosol scattering ratio (aerosol/molecular backscatter) (532 nm)

- Aerosol backscatter coefficient at 532 nm
- Aerosol extinction coefficient at 532 nm
- Aerosol extinction/backscatter ratio (532 nm)
- Aerosol wavelength dependence (532/1064) (i.e. Angstrom exponent for aerosol backscatter)
- Aerosol depolarization (532 nm)
- Aerosol depolarization (1064 nm)

Data images from the GoMACCS campaign were archived to the NOAA TexAQS/GoMACCS web site: http://esrl.noaa.gov/csd/2006/. Data were archived on our HSRL data server at NASA Langley and are available upon request by DOE ASP and other scientists.

Several presentations were given on early results from both missions, including presentations at the MILAGRO and DOE ASP Science team meeting. Also, inputs were provided to Steve Schwartz and Jeff Gaffney for the BERAC Review.

Year 3 (2007)

Field Campaigns

Efforts for this year focused on our participation in the Cumulus Humilis Aerosol Processing Study (CHAPS) experiment conducted in Oklahoma over the period from June 3 through June 29, 2007. The main objective of CHAPS was to investigate the effects of anthropogenic aerosols on fair weather cumulus clouds and the effects of these clouds on aerosols that pass through them. The primary aircraft platforms for the mission were the DOE G-1, deploying in situ sensors, and the NASA Langley King Air B200, deploying remote sensors. Our team was responsible for the King Air platform and the instruments deployed on that platform: the Langley Airborne High Spectral Resolution Lidar (HSRL) (the primary instrument) and a digital camera. Over the course of the mission, we conducted 20 science flights (66 flight hours) with the King Air. Portions of at least eight B200 flights were coordinated with the G-1 flights so that the HSRL and G-1 measurements were coincident and co-located. Some King Air flights were also designed to provide aerosol and cloud data for use by investigators from the DOE ARM Cloud and Land Surface Interaction Campaign (CLASIC) campaign, which was conducted simultaneously with CHAPS. Twelve of the King Air flights included segments over the DOE ARM SGP CRF, and four flights were coordinated with the CIRPAS Twin Otter aircraft deployed during CLASIC. The combination of HSRL measurements and digital camera images, along with the in situ data collected by the G-1 and CIRPAS Twin Otter aircraft, provide a unique dataset to examine the variability of aerosols near clouds. Eight of the King Air flights were also coordinated with overpasses of the CALIPSO and CloudSat satellites in order to acquire HSRL data for validation of the CALIOP lidar. The G-1 and CLASIC aircraft were also coordinated with the CALIPSO overpasses on some of these validation flights; the in situ measurements will be used to provide a detailed characterization of aerosol and cloud properties to assess the satellite aerosol and cloud retrievals.

The team also participated in two other experiments in 2007: the EPA San Joaquin Valley Experiment and the CALIPSO and Twilight Zone (CATZ) experiment. The San Joaquin Valley

experiment involved a series of HSRL flights across the San Joaquin Valley in California to determine the extent to which MODIS satellite radiometer data can be used to estimate PM2.5 at ground level. The CATZ experiment involved HSRL flights and ground-based sun photometer measurements along CALIPSO orbit tracks and focused on validating satellite and sun-photometer retrievals of aerosols and investigation of aerosol and cloud optical properties in broken cloud fields (i.e., the so-called "twilight zone" between aerosols and clouds). While not funded by ASP, the data from these and similar experiments are being used in statistical analyses of aerosol and cloud optical properties relevant to our science objectives in the ASP program and can be made available to other ASP investigators upon request.

Data Products Delivered

Preliminary HSRL data products and data images from the CHAPS campaign were archived on the ARM IOP archive site (iopshare.archive.arm.gov/var/ftp/clasicchaps/incoming/kingair/). HSRL data products posted to the archive include

- Aerosol scattering ratio (ratio of aerosol/molecular backscatter) (532 nm)
- Aerosol backscatter coefficient at 532 and 1064 nm
- Aerosol extinction coefficient at 532 and 1064 nm
- Aerosol extinction-to-backscatter ratio (532 nm)
- Aerosol backscatter wavelength dependence (532/1064)
- Aerosol depolarization at 532 and 1064 nm
- Aerosol depolarization (1064 nm)
- Aerosol optical depth at 532 nm

Conference Proceedings and Workshop Presentations

1. "Airborne High Spectral Resolution Lidar aerosol measurements during MILAGRO and TexAQS/GoMACCS", R. Ferrare, C.A. Hostetler, J.W. Hair, A.L. Cook, D.B. Harper, S. Burton, A. Clarke, P.B. Russell, J. Redemann, Ninth Conference on Atmospheric Chemistry, American Meteorological Society Annual Meeting, San Antonio, TX, January, 2007.
2. "Airborne High Spectral Resolution Lidar Aerosol Measurements", R. Ferrare, C.A. Hostetler, J.W. Hair, A.L. Cook, D.B. Harper, Third Symposium on Lidar Atmospheric Applications, American Meteorological Society Annual Meeting, San Antonio, TX, January, 2007.
3. "Airborne High Spectral Resolution Lidar aerosol measurements during INTEX-B/MILAGRO", R. Ferrare, C.A. Hostetler, J.W. Hair, A.L. Cook, D.B. Harper, S. Burton, A. Clarke, P.B. Russell, J. Redemann, INTEX-B Workshop, Virginia Beach, VA, March 2007.
4. "Airborne High Spectral Resolution Lidar Aerosol Measurements", C.A. Hostetler, R. Ferrare, J.W. Hair, A.L. Cook, D.B. Harper, EarthCARE Workshop, ESA/ESTEC Noordwijk, The Netherlands, May 2007.
5. "Airborne High Spectral Resolution Lidar Aerosol Measurements", J.W. Hair, R. Ferrare, C.A. Hostetler, A.L. Cook, D.B. Harper, S. Burton, A. Clarke, P.B. Russell, J. Redemann, L. Kleinman, MILAGRO Workshop, Mexico City, Mexico, May 2007.
6. "Airborne High Spectral Resolution Lidar Measurements of Atmospheric Aerosols", R. Ferrare, C. A. Hostetler, J.W. Hair, A.L. Cook, D.B. Harper, S. Burton, L. Kleinman, A.

Clarke, P. Russell, J. Redemann, J. Livingston, J. Szykman, J. Al-Saadi, (Invited) AGU Joint Assembly Meeting, Acapulco, Mexico, May 2007.

7. "High Spectral Resolution Lidar for Measurements of Atmospheric Aerosols", R. Ferrare, C.A. Hostetler, J.W. Hair, A.L. Cook, D.B. Harper, Yoram J. Kaufman Memorial Symposium, Greenbelt, MD, May, 2007.
8. "Aerosol Classification during TEXAQS using HSRL measurements", R. Ferrare, C. Hostetler, J. Hair, A. Cook, D. Harper, S. Burton, C. Kittaka, R. Bradley Pierce, L. Kleinman, TexAQS II/GoMACCS Principal Findings Data Analysis Workshop, Austin TX, May 2007.
9. "Preliminary Raman lidar and HSRL measurements of aerosols during CLASIC/CHAPS", R. Ferrare, C. Hostetler, J. Hair, A. Cook, D. Harper, M. Obland, M. Wusk, M. Clayton, R. Rogers, S. Burton, D. Turner, DOR ARM Aerosol/Radiative Properties Working Group Meeting, Madison, WI, Sept. 17-19, 2007.
10. Ferrare, R. A.; Hostetler, C. A.; Hair, J. W.; Cook, A. L.; Harper, D. B.; Burton, S. P.; Obland, M. D.; Rogers, R. R.; Kleinman, L.; Clarke, A.; Chin, M.; Carmichael, G.; Emmons, L. K.; Pierce, R. B.; and Kittaka, C.: Airborne High Spectral Resolution Lidar Aerosol Measurements and Comparisons With Transport Models. Presented at 2007 AGU Fall Meeting, December 10-14, 2007, San Francisco, California.

Publications

Publication of results from the MAXMex/MILAGRO and MAXTex/TexAQS-2/GoMACCS experiments are in work. The following publication contains HSRL data from the MAXTex/TexAQS-2/GoMACCS.

1. Liu, Z., A. Omar, M. Vaughan, J. Hair, C. Kittaka, Y. Hu, K. Powell, C. Trepte, D. Winker, C. Hostetler, R. Ferrare, R. Pierce, CALIPSO Lidar Observations of the Optical Properties of Saharan Dust: A Case Study of Long Range Transport, submitted to JGR-Atmospheres, 2007.
2. Ferrare, R. A., C. Hostetler, J. Hair, A. Cook, D. Harper, and S. Burton, 2007: Planetary Boundary Layer (PBL) Heights derived from NASA Langley Airborne High Spectral Resolution Lidar (HSRL) data acquired during the Texas Air Quality Study (TexAQS)/Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS): A Report to the Texas Environmental Research Consortium, August 30, 2007.

Year 4 (2008)

Field Campaigns

No ASP-sponsored field mission was conducted this year as anticipated in our proposal. Efforts since our last report have instead focused on analysis of the data acquired on past ASP campaigns as well as the use of data acquired on campaigns funded by NASA and the EPA in analyses of interest to the ASP. In particular, the efforts included the following:

- Processing and archival of the data acquired on the ASP-sponsored Cumulus Humilis Aerosol Processing Study (CHAPS) field campaign.
- Reprocessing of all Airborne HSRL data acquired to date to remove processing artifacts and improve calibration. The reprocessed data sets included data from the following ASP-funded field missions: MAXMex/MILAGRO, MAXTex/TexAQS, and CHAPS. The data were re-archived on a password-protected FTP site along with images of data plots to provide access to interested ASP scientists. (Data acquired on NASA-sponsored field missions are also available to interested ASP scientists.)
- Submission of a report to the Texas Commission on Air Quality on mixed layer heights determined from the HSRL on the MAXTex/TexAQS field campaign.
- Participation in the development of a paper summarizing the objectives and initial results from CHAPS (first author Larry Berg, PNNL).
- Comparative assessment of HSRL aerosol observations with those from in situ and remote sensors on other platforms from ASP-funded missions. An AGU poster was given on instrument intercomparisons from MAXMex/MILAGRO and a journal article on these comparisons is in preparation.
- Analysis of all HSRL data acquired to date to infer aerosol type along the lidar curtain (i.e., vertically and horizontally resolved maps of aerosol type) and partition observed aerosol optical depth by type for every lidar profile. Results have been summarized in numerous presentations and a paper on the aerosol typing analysis is in progress.
- Analyses of HSRL data from CHAPS and NASA-funded flights to examine systematic variation in aerosol optical properties as a function of distance from clouds in broken cloud fields. A publication on this analysis for some NASA-funded flights was accepted for publication in JGR-Atmospheres. Work is ongoing on further analysis of CHAPS-specific observations. This analysis also includes the use of data from the ground-based lidar at the CART site.
- Assessment of aerosol predictions from transport models using vertically and horizontally resolved HSRL data from MAXMex/MILAGRO and MAXTex/TexAQS.

The team also participated in two major NASA-sponsored field deployments: the Arctic Research on the Troposphere from Aircraft and Satellite (ARCTAS), phases 1 (April) and 2 (June-July). For phase 1 of ARCTAS, operations of the HSRL on the Langley King Air were based in Barrow, Alaska. The objectives included the study of arctic haze aerosol and satellite validation. ARCTAS-1 was concurrent with the DOE ARM-sponsored ISDAC field campaign for which ARM had instrumented the Canadian Convair 580 for studies of Arctic clouds over the Barrow site. During our deployment of the HSRL in Barrow, we collaborated closely with our DOE ARM colleagues and flew coordinated patterns with the ISDAC aircraft on numerous occasions to characterize aerosol above and between clouds sampled by the Convair 580. ASP also sponsored some of the instruments and investigators that participated in this mission. The analyzed data have been archived and Rich Ferrare presented some initial results and coordinated further analysis plans with other investigators at the ISDAC Workshop in November. Flights were also coordinated with the NASA DC-8, the NASA P3, and the NOAA P3 to acquire coincident measurements of arctic haze aerosol. For ARCTAS-2, the HSRL was deployed to Yellowknife, Alaska for measurements of boreal forest fire smoke. On this mission, flights were coordinated with the NASA P3 and NASA DC-8. While not funded by ASP, the data from these

experiments are being used in analyses of aerosol and cloud optical properties relevant to our science objectives in the ASP program and can be made available to other ASP investigators upon request.

Data Products Delivered

Final HSRL data products and data images from the CHAPS campaign were archived on the ARM IOP archive site (iopshare.archive.arm.gov/var/ftp/clasicchaps/incoming/kingair/). HSRL data products posted to the archive include

- Aerosol scattering ratio (ratio of aerosol/molecular backscatter) (532 nm)
- Aerosol backscatter coefficient at 532 and 1064 nm
- Aerosol extinction coefficient at 532 and 1064 nm
- Aerosol extinction-to-backscatter ratio (532 nm)
- Aerosol backscatter wavelength dependence (532/1064)
- Aerosol depolarization at 532 and 1064 nm
- Aerosol depolarization (1064 nm)
- Aerosol optical depth at 532 nm

Conference Proceedings and Workshop Presentations

1. Hostetler, C. A.; Ferrare, R. A.; Hair, J. W.; Obland, M. D.; Cook, A. L.; Harper, D. B.; Rogers, R. R.; Burton, S. P.; Clayton, M. F., and Su, W.: Airborne High Spectral Resolution Lidar (HSRL) Aerosol Measurements during Several Recent Field Experiments. Presented at 2008 DOE ASP Science Team Meeting, February 25-27, 2008, Annapolis, Maryland.
2. Ferrare, R. A.; Hostetler, C. A.; Hair, J. W.; Cook, A. L.; Harper, D. B.; Obland, M. D.; Rogers, R. R.; Burton, S. P.; Clayton, M. F.; and Turner, D.: Airborne and Ground-based Lidar Measurements of Aerosols and Clouds During Cloud Land Surface Interaction Campaign (CLASIC)/Cumulus Humilis Aerosol Processing Study (CHAPS). Presented at 18th DOE ARM Science Team Meeting, March 10-February 14, 2008, Norfolk, Virginia.
3. Ferrare, R. A.; Burton, S.; Hostetler, C. A.; Hair, J. W.; Obland, M. D.; Rogers, R. R.; Cook, A. L.; Harper, D. B.; Remer, L. A.; and Kittaka, C.: Using Airborne High Spectral Resolution Lidar Data to Evaluate Combined Active/Passive Retrievals of Aerosol Extinction Profiles. Presented at MODIS/VIIRS Science Team Meeting, May 14-16, 2008, Linthicum, Maryland.
4. Burton, S.; Ferrare, R. A.; Kittaka, C.; Hostetler, C. A.; Hair, J. W.; Obland, M. D.; Rogers, R. R.; Cook, A. L.; and Harper, D. B.: Using Airborne High Spectral Resolution Lidar Data to Evaluate Combined Active Plus Passive Retrievals of Aerosol Extinction Profiles. Presented at 24th International Laser Radar Conference, June 23-27, 2008, Boulder, Colorado.
5. Obland, M. D.; Hostetler, C. A.; Ferrare, R. A.; Hair, J. W.; Rogers, R. R.; Burton, S. P.; Cook, A. L.; and Harper, D. B.: Aerosol Profile Measurements From the NASA Langley Research Center Airborne High Spectral Resolution Lidar. Presented at 24th International Laser Radar Conference, June 23-27, 2008, Boulder, Colorado.
6. Rogers, R. R.; Hair, J. W.; Hostetler, C. A.; Ferrare, R. A.; Cook, A. L.; Harper, D. B.; Obland, M. D.; Burton, S.; Clarke, A.; Shinozuka, Y.; Mcnaughton, C. S.; Redemann, J.;

Russell, P.; and Livingston, J.: Evaluation of NASA/LaRC Airborne High Spectral Resolution Lidar Aerosol Extinction Measurements. Presented at 24th International Laser Radar Conference, June 23-27, 2008, Boulder, Colorado.

7. Fast, J., W. Shaw, R. Ferrare, C. Hostetler, J. Hair, Simulations of Multi-Scale Circulations and Boundary Layer Structure and their Effect on Particulate Layering Over and Downwind of the Central Mexican Plateau, 13 Conference on Mountain Meteorology, Whistler, B.C., August, 2008.
8. Ferrare, R. A.; Hostetler, C. A.; Hair, J. W.; Obland, M. D.; Rogers, R. R.; Burton, S. P.; Harper, D. B.; and Cook, A. L.: Aerosol Observations from the NASA Langley Airborne High Spectral Resolution Lidar. Presented at European Fleet For Airborne Research Expert Working Group Meeting on Active Remote Sensing, Sept. 4-5, 2008, Paris, France.
9. Ferrare, R. et al., Airborne High Spectral Resolution Lidar (HSRL) Aerosol Measurements and Comparisons with Transport Models and CALIPSO Measurements, AEROCOM Meeting, October 2008.
10. Hostetler, C. et al, Observations from the NASA Langley Airborne High Spectral Resolution Lidar and Plans for Active-Passive Aerosol-Cloud Retrievals, DOE ARM Instrumentation Workshop, October 2008.
11. Ferrare et al., HSRL Aerosol/Cloud Measurements during ARCTAS/ISDAC, ISDAC Workshop, Landsdowne, VA, November, 2008.
12. Burton et al., Evaluation of Combined Active-Passive Aerosol Extinction Profile Retrieval Using Airborne High Spectral Resolution Lidar, American Geophysics Union (AGU) Fall Meeting, San Francisco, Dec. 15-19, 2008.

Publications

1. Hair, J. W., C. A. Hostetler, A.L. Cook, D.B. Harper, R. A. Ferrare, T. L. Mack, W. Welch, L.R. Isquierdo, F. E. Hovis, Airborne high spectral resolution lidar for profiling Aerosol Optical Properties, submitted to Appl. Optics, 2008.
2. Su, W., G.L. Schuster, N. Loeb, R. A Ferrare, C.A. Hostetler, J.W. Hair, M. Obland, Aerosol and Cloud Interaction Observed from High Spectral Resolution Lidar Data, accepted by J. Geophys. Res., 2008.

Year 5 (2009)

Field Campaigns

Our major focus in 2009 was our participation in the DOE ASP RACORO campaign. The primary aircraft for RACORO was the DOE-sponsored CIRPAS Twin Otter, which was outfitted with a variety of in situ cloud and aerosol instruments. The Twin Otter made routine flights in the vicinity of the ARM Central Facility from January through June 2009. Our team was responsible for the deployment of remote sensors on the B200 for an intensive operations period in June 2009. The B200 flew mainly coordinated patterns with the Twin Otter in the vicinity of the ACRF Central facility, providing remote sensing measurements of aerosol and cloud optical properties from the HSRL and the Research Scanning Polarimeter (RSP). Occasionally flights were conducted further from the Central Facility to sample under better meteorological

conditions or to fly coordinated patterns with the A-Train satellite sensors. Over the course of the mission, we conducted 19 science flights, amounting to 64 flight hours, with an additional 9 hours in transits to and from the B200 home base in Hampton, Virginia. Of these flights, 15 were coordinated with the Twin Otter and 16 included overpasses of the Central Facility. Preliminary HSRL data from these flights have been processed and are available for use by DOE researchers. Also, the team has supported preliminary science analysis of results and reported those results at DOE ARM Cloud Properties and Aerosol Working Group Meetings held in Boulder, Colorado during September, 2009.

Other efforts were focused on analysis and reporting of the data acquired on past DOE campaigns as well as the use of data acquired on campaigns funded by NASA and the EPA in analyses of interest to the ASR. In particular, the efforts included the following:

- Publication of a paper on the HSRL instrument, featuring initial results from MaxMEX/MILAGRO [*Hair et al.*, 2008]. HSRL data from MaxMEX was used for the cover illustration on this issue of Applied Optics.
- Investigation of the variation of aerosol parameters within the PBL associated with humidification, using relative humidity (RH) derived from ARM Raman lidar. Aerosol extinction, lidar ratio and backscatter wavelength dependence increase with RH and aerosol depolarization decreases with RH, consistent with particles becoming more spherical and fine particles becoming more dominant as RH increases.
- Analyses of data acquired by the HSRL during the NASA ARCTAS mission that was conducted coincidently with the DOE ISDAC mission over/near the DOE NSA ACRF during April 2008. The HSRL and Convair data were used to examine smoke from Siberian forest fires as well as to examine relationships between the HSRL measurements and cloud condensation nuclei (CCN) concentrations.
- Updated the analysis of all HSRL data acquired to date to infer aerosol type along the lidar curtain (i.e., vertically and horizontally resolved maps of aerosol type) and partition observed aerosol optical depth by type for every lidar profile; began comparison between aerosol typing and in situ measurements acquired during ARCTAS/ISDAC.
- Conducted comparison with GEOS-5 model reanalysis, finding good correspondence in variation of aerosol type with altitude, and general good agreement between average HSRL measurements and GEOS-5 simulations of aerosol extinction, but GEOS-5 dust fractions are generally higher than HSRL estimates (using aerosol depolarization measurements) and the difference increases with altitude.
- Rich Ferrare served as reviewer and a review panel member on the NNSA lab proposal on climate modeling (May, 2009).

Data Products Delivered

Preliminary HSRL data products and data images from the RACORO campaign were archived on a Langley FTP site (URL and login information available upon request). HSRL data products posted to the archive include

- Aerosol scattering ratio (ratio of aerosol/molecular backscatter) (532 nm)
- Aerosol backscatter coefficient at 532 and 1064 nm
- Aerosol extinction coefficient at 532 and 1064 nm
- Aerosol extinction-to-backscatter ratio (532 nm)

- Aerosol backscatter wavelength dependence (532/1064)
- Aerosol depolarization at 532 and 1064 nm
- Aerosol optical depth at 532 nm

Conference Proceedings and Workshop Presentations

1. Ovchinnikov et al., Real and Apparent Changes in Aerosol Optical Properties Near Cumulus Clouds: A Modeling Case Study and Implications for Passive and Active Remote Sensing, PIERS 2009, Moscow, Russia.
2. Kassianov et al., 3D Radiative Effects of Clouds in Aerosol Retrieval: Can we Remove Them?, SPIE 2009 Europe Remote Sensing Meeting.
3. R. A. Ferrare et al. Lidar observations of aerosols near clouds, AMS special symposium on Aerosol-Cloud-Climate, Phoenix, AZ, 2009.
4. Ferrare et al., HSRL Aerosol/Cloud Measurements during ARCTAS/ISDAC, DOE Aerosol and Cloud Modeling Working Group Meeting, October, 2009.
5. Ferrare et al. Overview of NASA B-200 King Air ARCTAS Operations and Science, NOAA ARCPAC Workshop, Boulder, CO., March, 2009.
6. Ferrare et al. Arctic Aerosol Properties Derived from Remote Sensing Measurements on the NASA B200 King Air Aircraft, POLARCAT Workshop, New Hampshire, June 2009.
7. deFoy et al. "Transport and transformation of biomass burning plumes during the MILAGRO field campaign with High Spectral Resolution Lidar measurements and WRF-Flexpart simulations.", Fall AGU, 2009.

Publications

1. Berg, L.K., C.M. Berkowitz, J.A. Ogren, C.A. Hostetler, R.A. Ferrare, M.K. Dubey, E. Andrews, R.L. Coulter, J.W. Hair, J.M. Hubbe, Y.N. Lee, C. Mazzoleni, J. Olfert, and S.R. Springston, 2009: Overview of the Cumulus Humilis Aerosol Processing Study. *Bull. Amer. Meteor. Soc.*, **90**, 1653–1667.
2. Rogers, R. R., J. Hair, C. Hostetler, R. A. Ferrare, M. D. Obland, A. L. Cook, D. B. Harper, S. P. Burton, Y. Shinozuka, C. McNaughton, A. D. Clarke, J. Redemann, P. B. Russell, J. M. Livingston, L. Kleinman, 2009: NASA LaRC Airborne High Spectral Resolution Lidar Aerosol Measurements During MILAGRO: Observations and Validation, *Atmos. Chem. Phys.* **9**, 4811-4826.

Year 6 (2010)

Field Campaigns

This year our major focus was our participation in two closely related field experiments: the DOE ASP-sponsored Carbonaceous Aerosol and Radiative Effects Study (CARES) based in Sacramento, CA, and the NOAA-sponsored CalNex mission based in Ontario, CA. Our team was responsible for the deployment of remote sensors on the Langley B200 aircraft on these two experiments. The instruments were the NASA Langley Airborne High Spectral Resolution Lidar

(HSRL) and the NASA Goddard Institute for Space Studies (GISS) Research Scanning Polarimeter (RSP). For the NOAA CalNex experiment, the B200 flew a total of 8 science flights (29.5 flight hours) primarily over the LA basin and the lower San Joaquin Valley. Flights were coordinated with participating aircraft: 6 flights with the CIRPAS Twin Otter and 3 with the NOAA P3. Also 6 flights were coincident with overpasses of the MODIS and/or MISR satellite spectro-radiometers. For the DOE CARES mission, the B200 flew 28 science flights (68 flight hours) in the northern California, with a focus on the Sacramento region and to a lesser extent the northern San Joaquin Valley. Flights were primarily coordinated with the DOE G1 aircraft (19 G1-B200 coordinated flights total); however, 6 flights were also coordinated with the NOAA Twin Otter and 2 flights with the NOAA P3. In addition, an overpass of the NOAA R/V Atlantis was conducted and 11 of the flights were coincident with overpasses of MODIS and/or MISR. Preliminary HSRL data from these flights have been processed and are available for use by DOE researchers.

Other efforts were focused on analysis and reporting of the data acquired on past ASR campaigns as well as the use of data acquired on campaigns funded by NASA and the EPA in analyses of interest to the ASP. In particular, the efforts included the following:

- Analysis of all HSRL data acquired to date to infer aerosol type along the lidar curtain (i.e., vertically and horizontally resolved maps of aerosol type) and partition observed aerosol optical depth by type for every lidar profile. Results have been summarized in numerous presentations and a paper on the aerosol typing analysis is in progress.
- Analysis of past HSRL data sets to produce boundary layer heights for the MILAGRO, TexMax, CHAPS, and San Joaquin Valley field experiments. These data are being made available to modelers to assess accuracy of transport model predictions.
- Worked with Jerome Fast (PNNL) in comparison of lidar-derived aerosol distribution and properties with aerosol predictions from WRF-Chem.
- Worked with Larry Berg (PNNL) in use of G-1 data to look at RH variability near clouds for the CHAPS field mission.
- Worked with Ben deFoy (St. Louis University) in the use of HSRL measurements to assess Flexpart aerosol results.
- Worked with Evgueni Kassianov (PNNL) in his use to evaluate aerosol optical depth from reflectance ratios during CHAPS
- Reprocessing of all Airborne HSRL data acquired to date to remove processing artifacts and improve calibration.
- Participation in the development of two field mission proposals to ASR.
- Participation in production of publications and presentations listed below.

Data Products Delivered

Preliminary HSRL data products and data images from the RACORO campaign were archived on a Langley FTP site (url and login information available upon request). HSRL data products posted to the archive include

- Aerosol scattering ratio (ratio of aerosol/molecular backscatter) (532 nm)
- Aerosol backscatter coefficient at 532 and 1064 nm
- Aerosol extinction coefficient at 532 and 1064 nm

- Aerosol extinction-to-backscatter ratio (532 nm)
- Aerosol backscatter wavelength dependence (532/1064)
- Aerosol depolarization at 532 and 1064 nm
- Aerosol depolarization (1064 nm)
- Aerosol optical depth at 532 nm

Conference Proceedings and Workshop Presentations

1. Hostetler et al. "Airborne High Spectral Resolution Lidar and Research Scanning Polarimeter Measurements During RACORO", DOE ASR Meeting, Spring 2010
2. Ferrare et al. "Airborne HSRL Aerosol, Ice, and Cloud Observations During ARCTAS/ISDAC", Spring, 2010
3. Fast et al., "The Effect of Thermally-Driven Flows on Anthropogenic and Biogenic Aerosols along the Sierra Nevada Mountains", 14th Conference on Mountain Meteorology, 2010.

Publications

1. Molina, L. T., Madronich, S., Gaffney, J. S., Apel, E., de Foy, B., Fast, J., Ferrare, R., Herndon, S., Jimenez, J. L., Lamb, B., Osornio-Vargas, A. R., Russell, P., Schauer, J. J., Stevens, P. S., Volkamer, R., and Zavala, M.: An overview of the MILAGRO 2006 Campaign: Mexico City emissions and their transport and transformation, Atmos. Chem. Phys., 10, 8697-8760, doi:10.5194/acp-10-8697-2010, 2010.
2. Parrish, Allen, Bates, Estes, Fehsenfeld, Feingold, Ferrare, Hardesty, Meagher, Nielsen-Gammon, Pierce, Ryerson, Seinfeld, Williams, Overview of the Second Texas Air Quality Study (TexAQS II) and the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS), JGR, 114, D00F13, doi:10.1029/2009JD011842.
3. Kassianov, E., M. Ovchinnikov, L.K. Berg, S.A. McFarlane, C. Flynn, R. Ferrare, C. Hostetler, M. Alexandrov, Retrieval of Aerosol Optical Depth in Vicinity of Broken Clouds from Reflectance Ratios: Case Study, submitted to Journal Atmospheric Measurement Techniques, 2010.
4. Lewis, J., DeYoung, R., R. Ferrare, D. A. Chu, Comparison of Summer and Winter California Central Valley Aerosol Distributions from Lidar and MODIS Measurements, Atm. Environ., 2010.
5. Burton, S.P., R.A. Ferrare, C.A. Hostetler, J.W. Hair, C. Kittaka, M.A. Vaughan, M.D. Obland, R.R. Rogers, A.L. Cook, D.B. Harper and L.A. Remer, 2010: Using Airborne High Spectral Resolution Lidar Data to Evaluate Combined Active Plus Passive Retrievals of Aerosol Extinction Profiles, *J. Geophys. Res.*, **115**, D00H15, doi:10.1029/2009JD012130.
6. Kassianov, E., M. Ovchinnikov, L.K. Berg, S.A. McFarlane, C. Flynn, R. Ferrare, C. Hostetler, M. Alexandrov, 2010: Retrieval of Aerosol Optical Depth in Vicinity of Broken Clouds from Reflectance Ratios: Case Study, submitted to *Journal Atmospheric Measurement Techniques*.
7. Warneke C., Froyd K.D., Brioude J., Bahreini R., Brock C.A., Cozic J., de Gouw J.A., Fahey D.W., Ferrare R., Holloway J.S., Middlebrook A.M., Miller L., Montzka S., Schwarz, J.P., Sodemann H., Spackman J.R., Stohl, A., 2010: An important contribution to springtime Arctic aerosol from biomass burning in Russia, *Geophys. Res. Lett.*, **37**, L01801, doi:10.1029/2009GL041816.

Year 7 (2011)

No-Cost Extension

Year 7 was a no-cost extension on our project to conduct analysis of data acquired on recent DOE-funded missions, including CHAPS, ARCTAS/ISDAC, and RACORO. For example:

- Refined the classification of aerosol types and updated the analysis of all HSRL data acquired to date to infer aerosol type along the lidar curtain (i.e., vertically and horizontally resolved maps of aerosol type). A paper on the aerosol typing analysis is in progress.
- Calculated preliminary planetary boundary layer heights and entrainment zone depths for recent missions ARCTAS and RACORO.
- Continued analyses of HSRL data from CHAPS and NASA-funded flights to examine systematic variation in aerosol optical properties as a function of distance from clouds in broken cloud fields. Analyses have focused on the use of B200 camera images in conjunction with HSRL data to determine proximity to clouds. This analysis also includes the use of data from the ground-based lidar at the CART site.

Conference Proceedings and Workshop Presentations

1. M. Obland, A. Swanson, R. Ferrare, S. Burton, J. Hair, C. Hostetler, R. Rogers, J. Fast, L. Berg, M. Pekour, W. Shaw, R. Zaveri, C. Haman, A. Cook, and D. Harper, "Variability of aerosol properties and Planetary Boundary Layer heights from airborne High Spectral Resolution Lidar, ground-based measurements, and the WRF model during CalNex and CARES", 2011 Fall AGU Conference, San Francisco, CA, 5-9 Dec 2011.
2. B. Cairns, C. Emde, A. Wasilewski, K. Knobelspiesse, M. A. Alexandrov, I. Geogdzhayev, M. I. Mishchenko, 2011: Partial cloud fraction effects on aerosol retrievals using polarized reflectance observations", invited talk 2011 Fall AGU Conference, San Francisco, CA, 5-9 Dec 2011.

Publications

1. Bierwirth, E., M. Wendisch, E. Jäkel, A. Ehrlich, K. S. Schmidt, H. Stark, P. Pilewskie, M. Esselborn, G. P. Gobbi, R. Ferrare, T. Müller, A. Clarke (2010), A new method to retrieve the aerosol layer absorption coefficient from airborne flux density and actinic radiation measurements, J. Geophys. Res., 115, D14211, doi:10.1029/2009JD013636
2. de Foy, B.,S.P. Burton, R.A. Ferrare, C.A. Hostetler, J.W. Hair,C. Wiedinmyer, L. T. Molina, Aerosol Plume Transport and Transformation in High Spectral Resolution Lidar measurements and WRF-Flexpart simulations during the MILAGRO Field Campaign, Atmos. Chem. Phys., 11, 3543-3563, 2011.
3. Brock, C., J. Cozic, R. Bahreini, K. D. Froyd, A. M. Middlebrook, A. McComiskey, J. Brioude, O. R. Cooper, A. Stohl, K. C. Aikin, J. A. de Gouw, D. W. Fahey, R. A. Ferrare, R.-S. Gao, W. Gore, J. S. Holloway, G. Hübler, A. Jefferson, D. A. Lack, S. Lance,

R. H. Moore, D. M. Murphy, A. Nenes, P. C. Novelli, J. B. Nowak, J. A. Ogren, J. Peischl, R. B. Pierce, P. Pilewskie, P. K. Quinn, T. B. Ryerson, K. S. Schmidt, J. P. Schwarz, H. Sodemann, J. R. Spackman, H. Stark, D. S. Thomson, T. Thornberry, P. Veres, L. A. Watts, C. Warneke, and A. G. Wollny, Characteristics, sources, and transport of aerosols measured in spring 2008 during the aerosol, radiation, and cloud processes affecting Arctic Climate (ARCPAC) Project, Atmos. Chem. Phys., 11, 2423-2453, 2011.

4. Burton, S. P., Ferrare, R. A., Hostetler, C. A., Hair, J. W., Rogers, R. R., Obland, M. D., Butler, C. F., Cook, A. L., Harper, D. B., and Froyd, K. D.: Aerosol classification using airborne High Spectral Resolution Lidar measurements – methodology and examples, Atmos. Meas. Tech. Discuss., 4, 5631-5688, doi:10.5194/amtd-4-5631-2011.