Airborne High Spectral Resolution Lidar (HSRL) Aerosol Measurements and Comparisons with Transport Models and CALIPSO Measurements

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Airborne HSRL System and Data

**HSRL Technique:**
- Relies on spectral separation of aerosol and molecular backscatter in lidar receiver
- Independently measures aerosol backscatter, extinction, and optical thickness
- Requires no assumptions or additional data to relate backscatter and extinction
- Can be internally calibrated
- Provides **intensive** aerosol parameter to help determine aerosol type

**Data Products**
- Aerosol scattering ratio (aerosol/molecular backscatter) (532 nm) ($\Delta x \sim 1$ km, $\Delta z \sim 60$ m)
- Aerosol backscatter coefficient at 532 nm ($\Delta x \sim 1$ km, $\Delta z \sim 60$ m)
- Aerosol extinction coefficient at 532 nm ($\Delta x \sim 6$ km, $\Delta z \sim 300$ m)
- Aerosol wavelength dependence (532/1064) (i.e. Angstrom exponent for aerosol backscatter) (similar to backscatter color ratio)
- Aerosol extinction/backscatter ratio ("lidar ratio") (532 nm) ($\Delta x \sim 6$ km, $\Delta z \sim 300$ m)
- Aerosol depolarization (532 and 1064 nm) ($\Delta x \sim 1$ km, $\Delta z \sim 60$ m)

**Validation – aerosol extinction**

[AATS14 data from Jens Redemann
HiGEAR data from Tony Clarke]
Field Missions
NASA Langley airborne High Spectral Resolution Lidar (HSRL) Field Campaigns

- **ARCTAS 1 (NASA-DOE-NOAA)**
  - April 1-20, 2008
- **ARCTAS 2 (NASA)**
  - June 25 – July 14, 2008
- **CHAPS (DOE-NASA)**
  - June 3-29, 2007
- **CALIPSO/MODIS/CATZ (NASA)**
  - January 17– Aug 11, 2007
- **CALIPSO Validation (NASA)**
  - June 14 – Aug 10, 2006
- **Caribbean CALIPSO Val. (NASA)**
- **San Joaquin Valley (EPA)**
  - February 8-21, 2007
- **TexAQS II/GoMACCS**
  - Aug 27 – Sep 29, 2006
- **MAXMex/MILAGRO/INTEX-B**
  - DOE-NSF-NASA-Mexico
  - March 1-30, 2006

- **2000-2004:** instrument development and integration
- **Dec 2004:** first test flight on Lear Jet
- **Dec 2005:** first test flight NASA Langley B200 King Air
- **Three field campaigns in each of 2006, 2007, 2008**
Measurements
Aerosol Characterization using HSRL aerosol measurement suite

LaRC Airborne HSRL Measurements over Mexico City, March 13, 2006

- western part of city: high $S_a$, high WVD, low depolarization – urban aerosol
- eastern part of city: low $S_a$, low WVD, high depolarization – dust

**Extinction/AOT (532 nm)**

**Backscatter (532 nm)**

**Depolarization Ratio (1064/532 nm)**

**Depolarization (532 nm)**

**Backscatter $\lambda$ Dependence (1064/532 nm)**
Discrimination of Aerosol Type
Aerosol Classification using HSRL measurements

Aerosol classification is based on HSRL measurements of aerosol intensive parameters

- Extinction/Backscatter Ratio (~absorption)
- Depolarization (~spherical vs. nonspherical – dust/ice)
- Backscatter Color Ratio (~size)
- Depolarization Ratio (1064/532 nm) (~nonspherical/spherical size)

The HSRL measurements of aerosol intensive parameters were used in an objective cluster analysis scheme to discriminate aerosol type. These aerosol types were subjectively related to the aerosol types inferred from AERONET data by Catrall et al. (2005).
Aerosol Characterization using HSRL aerosol measurement suite

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Aerosol Optical Thickness Apportionment

San Joaquin Valley, California
February 2007

CHAPS/CLASIC, Oklahoma
June 2007

MILAGRO, Mexico City
March 2006

CALIPSO Val., Eastern U.S.
Summer 2006, 2007

TexAQS/GoMACCS
Houston
Aug-Sep 2006

Legend:
- Biomass
- Urban
- Urban/Large
- Urban/Biomass
- Dust
- Dust/Large
- Pure Dust

AOT Contribution (552 nm) (%)
Assessment of Chemical Transport Models
Assessments of Model Simulations of Aerosol Extinction Profiles

**WRF-Chem (Δx ~ 3-12 km)**
- WRF-Chem aerosol extinction profiles in very good overall agreement with HSRL
- Performance varies with location: WRF-chem overestimates backscatter and extinction over Gulf and coast - perhaps too much model dust
- Some fine scale layers only crudely represented by model

**STEM (Δx ~ 12-60 km)**
- STEM extinction and AOT typically smaller (~35%) than HSRL
- STEM extinction profiles show less day-to-day variability than HSRL profiles
- STEM extinction profiles have similar gross features as HSRL profiles, but don’t show similar small scale variability

**RAQMS (Δx ~ 80 km)**
- RAQMS profiles have smaller vertically variability than HSRL profiles
- RAQMS shows a tendency to overestimate aerosol extinction above 3-4 km
- RAQMS tends to have long lifetime for aerosols aloft, possibly aerosols from fires in northwestern U.S.

[Graphs showing HSRL vs. WRF-Chem, HSRL vs. STEM, HSRL vs. RAQMS, MILAGRO, GoMACCS]
Aerosol Classification: Comparison to WRF-Chem

- In the vicinity of Mexico City, WRF-CHEM compositions qualitatively agree with aerosol types inferred from HSRL measurements
  - High concentrations of NO₃, SO₄, EC -> urban
  - High concentrations of dust (other inorganics, OIN, in the model) -> mix of dust and urban
- Outside of Mexico City, dust and urban pollutants mix together
PBL Height
Long range transport of aerosols depends on whether aerosols injected above PBL

HSRL data used to determine:
• PBL height
• Upper and lower limits of the backscatter transition (i.e. entrainment) zone
• Fraction of aerosol optical thickness within PBL

- PBL heights over water significantly lower than PBL heights over land
- Large fraction (40-50%) of AOT above PBL during MILAGRO, GoMACCS, CHAPS
- Most (80-90%) of AOT within PBL during San Joaquin Valley Mission
- HSRL PBL heights now routinely requested by other investigators
CALIPPSO Validation
Preliminary CALIOP Level-2 Profile Product Assessments Using HSRL Data

- Have logged over 57 underflights of CALIPSO with Airborne HSRL under a variety of conditions and locations
- Objectives
  - Validate Calibration
  - Validate Level-2 extinction and backscatter products
  - Expand database of measured extinction-to-backscatter ratio ($S_a$) values used in CALIOP retrievals
  - Assess sampling issues
The poor correlation for Sa would indicate that extinction and backscatter will have better correlation for R² = 0.07 (or 0.27 without the circled points) backscatter values, which is not the case.

Nighttime – CALIPSO bsc still biased low (as is the calibration).
HSRL – CALIOP 532 nm Level-2 Aerosol Product Comparison, Daytime

These correspond to bsc532>0.006 values!

Daytime only data – CALIPSO backscatter biased low. Correlation very poor
Combined Active/Passive Retrievals
Assessment of AOT-Constrained CALIOP Retrievals Using HSRL Data

Objectives

- Improve CALIOP retrievals of aerosol backscattering and extinction using satellite (e.g. MODIS, PARASOL) measurements of aerosol optical thickness (AOT) to constrain the atmospheric transmission and so derive a mean value of the lidar ratio (Sa) through the layer (constrained retrieval)

Methodology

HSRL data are used to:
- Examine vertical variability of lidar ratio
- Evaluate satellite retrievals of AOT
- Provide high S/N, well calibrated backscatter data as a proxy for CALIPSO data to test constrained retrievals (Ferrare/LaRC; Remer,Martins/GSFC)
- Provide direct measurements of aerosol extinction to evaluate constrained retrieval results (Ferrare/LaRC; Remer,Martins/GSFC)
Assessment of AOT-Constrained CALIOP Retrievals Using HSRL Data

- Examined results from 20 flights where AOT > 0.2
- Horizontal resolution 80 km to increase S/N
- Extinction profiles derived from CALIPSO backscatter profiles constrained by MODIS AOT show better agreement with HSRL profiles than extinction profiles from standard CALIPSO product
Future Plans
ACE: Aerosol/Cloud/Ecosystems Mission

Aerosol/Cloud/Ecosystems Mission (ACE)
Launch: 2013-2016
Mission Size: Large

- Climate
  - Affect of aerosols on clouds and precipitation
  - Cloud-climate feedback
  - Ocean-aerosol-cloud feedback
  - CO₂ uptake in ocean

- Air Quality
  - Better information on aerosol type and distribution to improve forecast models

- Instruments:
  - Aerosol/cloud lidar
  - Cloud radar
  - Multiangle, multiwavelength polarimeter
  - Multi-band cross track UV/Visible spectrometer
ACE Lidar: LaRC Multi-wavelength HSRL Concept

- Single-beam $3\beta+2\alpha$ HSRL (airborne version is under development)
  - Backscatter at 3 wavelengths ($3\beta$): 355, 532, 1064 nm
  - Extinction at 2 wavelengths ($2\alpha$): 355, 532 nm
  - Depolarization at 355, 532, and 1064

- $3\beta+2\alpha$ HSRL provides layer-wise information on aerosol concentration (surface and volume), size (effective radius), composition and absorption (refractive index, single scatter albedo) (Müller et al., 1999, 2000, 2001; Veselovskii et al., 2002, 2004)

- Vertically resolved information of this kind is required for understanding the effects of aerosols on clouds and air quality and building better physics into models. For instance
  - Altitude resolved information needed to assess and improve predictive capability of chemical transport models: source estimates, injection altitudes, removal mechanisms, etc.
  - In broken cloud fields, need information on aerosol size and composition at cloud altitude; correlate aerosol sources, size, and composition to changes in cloud albedo and precipitation.
  - Determine vertical profile of absorbing layers (e.g., above cloud layers where they induce warming)

- Anticipate $3\beta+2\alpha$ and multiwavelength depolarization data extremely powerful in combined lidar-polarimeter retrieval
Evolution of Aerosol Lidar Capability

- Aerosol layer heights
- Qualitative vertical distribution (backscatter profile)
- Aerosol type vs. altitude
- Extinction profile from backscatter
- Extinction profile with column constraint
- Fine-coarse mode fraction vs. altitude
- Extinction profile
- Complex refractive index vs. altitude
- Aerosol size vs. altitude
- SSA vs. altitude
- Concentration vs. altitude

Further enhanced by addition of passive sensors (e.g. multiangle polarimeter).
Questions for AEROCOM modelers

How can these ACE lidar measurements be useful for modeling of aerosol direct/indirect effects?

Can we quantitatively simulate the benefits of these measurements? How?

What can we measure from this ACE lidar that can be used to critically evaluate the models?

What are the kinds of things that we will need verification and validation of? For example, models have converged on AOT in part because of the observations of MODIS and MISR. Where would new observations help the models converge (vertical distribution, SSA, microphysics)?
Thank You