Multiwavelength Lidar at CCNY

Ben Herman, Marco Vargas, Barry Gross, Fred Moshary and Sam Ahmed
City College of New York

- Instrumentation Development
- Numerical Processing
  - Validation Efforts
    - NASA Langley
    - Earlinet
    - UMBC
  - Sunphotometer+Single Channel Lidar
- Multiwavelength Lidar Processing
  - Iterative Lidar Processing
  - Inversion error assessment
  - Graphical
  - Bayesian

Lidar Instrumentation

- Transmitter: Coherent Infinity Nd:YAG
  - 355, 532, 1064 nm 300mJ 50Hz
- Receiver: 20” F3.5 Dobsonian, Hamamatsu PMTs
- Data Acquisition: 2 Channel Licel Transient Recorder, Gage 14 bit A/D

Other Instruments

- CIMEL Robotic Sunphotometer
- AERONET, GSFC
- YES Inc. TS440 All Sky Camera
- GPS-MET Station

Validation (1)

Excellent Agreement Between CCNY and Langley Processing Of Langley Lidar Data
Validation (2) UMBC-CCNY

CCNY Processing

Validation (3)

CCNY Data Processed by both CCNY and Earlinet.

Earlinet used a slightly nonlinear S ratio which is on the order of 10

Fusion of Aeronet

CIMEL + Lidar (532nm)

Processed Lidar Signals from CCNY 532nm
Lidar using Lidar Ratios 10 < S < 100

532nm OD ~ .32 at 2:30PM

Boundary Layer

June 8, 2004

Small clouds

Sharpest contrast at 1064nm

532 nm 1064 nm
Aerosol Extinction
Daytime

Multi-wavelength Lidar Efforts

– Iterative Lidar Processing

Using multiwavelength data to estimate range dependant single channel S-ratios for lidar processing

– Inversion error assessment (how to estimate errors for three channel lidar)
  • Graphical
  • Bayesian

Iterative Multiwavelength Lidar Inversion for inhomogeneous atmospheres

• Significant errors occur when homogeneous aerosol assumptions Saer=Constant are used.
• Raman Lidar is by far the most powerful tool to probe the inhomogeneous aerosol ratio but such systems are complex (especially daytime operation)
• Multiwavelength Optical Data Retrievals (such as those from Fernald Back-Integration) provide some information on the underlying distribution (and compatible S ratios) which could be used for improvement

Iterative Multiwavelength Algorithm

<table>
<thead>
<tr>
<th>Initial / New Scattering Ratios</th>
<th>Lidar Single Channel (FERNALD) Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ S_d(x_j) ]</td>
<td>[ j_i R \lambda \beta \rho(G) ]</td>
</tr>
</tbody>
</table>

Determine new S ratios from pre-generated interpolation of S ratio look-up tables

\[ \hat{R}(\lambda) = S_{d_i}(k_{i_j}) \]

Perform inversion (LUT)/registration of Backscatter data (Angstrom Coefficient)

\[ k_{i_j}(R, \lambda_j) \Rightarrow \hat{R}(\lambda) \]
**Night Measurements 355-532nm**

Return Insensitive to S Ratio and BC

**Solution Scatter**

Angstrom Coefficient Scatter
Substantially less than
From Fernauld Solution with
Uncertain S ratios

**Conclusions**

- Processing of synthetic data shows algorithm is convergent for
  Junge models (two-wavelength) models (not shown)
- Processing of real data (2-wavelength) seems feasible if uncertainty
  in backscatter ratio BC error can be kept below < 20% when can
  occur if the PBL is sharply defined.
- Processing of synthetic data shows algorithm is not generally
  convergent for log-normal models (three-wavelength) but converges
  for a large set of log-normal parameters determined from a
  monotonicity condition
- Methods to increase regions of stability using spatial averaging
  methods are being examined.
- Comparisons with CCNY Raman Lidar Needed

**Graphical Inversion & Error Assessment**

- For three optical backscatter measurements,
  regularization methods are unstable unless refractive
  index is assumed
- Even assuming refractive index, graphical methods
  using optical data ratios is very simple and does not
  have the instabilities of nonlinear inversion or the time
  overhead of statistical linearized inversion
- If optical data ratios are used, correct definition of
  confidence bounds are needed since optical data ratios
  due not satisfy the standard gaussian and independence
  assumptions.
- Correct determination of confidence bounds allows inter-
  comparison of information content for different optical
  data sets.
Results

- Assuming Gaussian Independent statistics gives rise to incorrect confidence bounds
- The addition of a single raman extinction measurement provides significant inversion improvement but a second raman extinction measurement has no additional value if refractive index is assumed
- Index of Refraction retrieval is possible using graphical methods but loses its simplicity so a direct Bayesian approach will be explored

Bayesian Parameter Retrieval Error Distributions

- Standard inversion error assessment adds measurement noise around a single optical data vector which can lead to bias
- A semi-analytic Bayesian approach to determine the parameter space conditional PDF is developed to eliminate the bias.
- Statistical regularization approaches using GCVD and positivity regularization along with an averaging of regularized solutions seem to provide a stable PSD inversion and strong refractive index constraint but are very time consuming
- Shape constrained profiles (Log-Normal) satisfy all regularization conditions by definition so inverting with shape constraints should be strongly correlated to regularization results

Information content by Graphical Approach

Ratio measurements only depend on size parameters

\[
R_i = \frac{\Delta \rho_{455}}{\Delta \rho_{532}} \quad R_i = \frac{\Delta \rho_{532}}{\Delta \rho_{355}}
\]

Proper definition requires construction of appropriate Probability Distribution Function for Ratio Random variables as well as taking into account Statistical dependence.

Graphical Assessment of Raman Extinction Measurements to elastic backscatter from NdYAG system

Given refractive index, the above graphs show that one extinction channel improves retrieval but the second extinction channel offers no improvement.

Results

• Assuming Gaussian Independent statistics gives rise to incorrect confidence bounds
• The addition of a single raman extinction measurement provides significant inversion improvement but a second raman extinction measurement has no additional value if refractive index is assumed
• Index of Refraction retrieval is possible using graphical methods but loses its simplicity so a direct Bayesian approach will be explored
Inversion Comparison

Forward Monte Carlo: Underestimates error, biasing it towards the initial signal.
Reverse Monte Carlo: Agrees extremely well with a semi-analytic Bayesian Approach.

Bayesian approach to assess effects of extinction channels

Retrieval of PSD possible but refractive index not retrievable
Retrieval of PSD possible slightly improved as well as imaginary component

Intercomparisons (assuming known refractive index)

<table>
<thead>
<tr>
<th>PSD Distribution Parameter</th>
<th>Bayesian Log-Normal % error</th>
<th>Regularization NASA-GSFC (Veselovskii et al) % error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_n$</td>
<td>4.75</td>
<td>6.9 (over)</td>
</tr>
<tr>
<td>$r_{eff}$</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$c_{m0}$</td>
<td>4.8</td>
<td>2.8 (under)</td>
</tr>
<tr>
<td>$c_s$</td>
<td>8.9</td>
<td>3.6 (under)</td>
</tr>
</tbody>
</table>

Results-Future Work

- Semianalytic Bayesian formulations have been developed for any number of optical data ratios (where the optical data is assumed gaussian and uncorrelated).
- The formalism is applied to a sequence of optical data sets including $3I/2$ (PSD only), $3I/4 + 4I$ (PSD + Imag only), $3I/2 + 2I$ (PSD + reffindex).
- Results are quantitatively consistent to statistical regularization approach but overestimates the surface and volume moments.
- The regularization approach on the other hand seems to overestimate the number density moment.
- Comparisons of Bayesian moment errors to regularization moment errors are ongoing.