Investigation of the Potential for Lidar-Plus-Polarimeter Combined Aerosol Retrievals Using Various Instrument Combinations

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Motivation: lidar + polarimeter synergy

Lidar
- vertically resolved measurements

Polarimeter
- multiwavelength, multiangle
- radiances and polarized radiances
- good sensitivity to absorption
- limited information on vertical profile

Lidar + Polarimeter
- optimizes use of both measurement sets to retrieve vertically resolved aerosol properties

- ACCP – synergy of capable polarimeter and HSRL lidar (polar orbit) and polarimeter and elastic backscatter lidar (inclined orbit) to retrieve information on vertical distribution and absorption
- CALIPSO + PARASOL – Complementary measurements that can be combined to be more than the sum of the parts. This methodology also being used to prototype CALIPSO+PARASOL retrieval (still in prelim stage) ⇨maximize output from existing measurements!

Propagating Uncertainties – Why now?

- For ACCP studies, we need *to compare various instrument combinations*.
- *Highlights uncertainties inherent to the measurement configuration.*
- Doing a full retrieval requires additional information (includes constraints, assumptions, smoothing, nudging, tweaks, etc.), different for each measurement system, which complicates comparisons. Uncertainty propagation produces *useful comparisons even for underdetermined systems* with *identical external information*.
- Provides insight on *what can (and can't!) be achieved*.
- The propagation equation [Rodgers 2000] formally separates the measurements from other information (smoothing, assumptions, constraints). For an underdetermined system particularly, this helps *avoid hidden traps and circular reasoning*.
- Not impacted by sources of error like incomplete or incorrect convergence.

The instruments

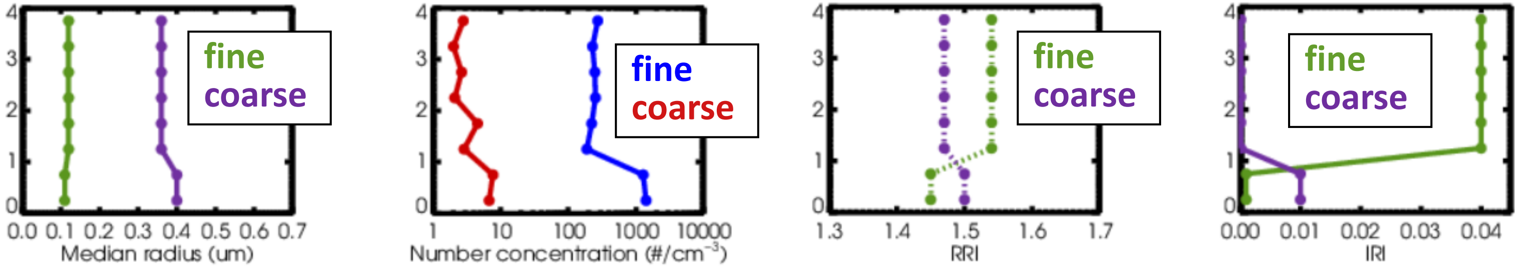
Simulated Polarimeter

- measures three Stokes parameters (I, Q, and U) for 10 viewing angles and 8 wavelengths between 360 and 1650 nm that can be directly used for aerosol retrieval without doing an absorption correction

Simulated Lidars

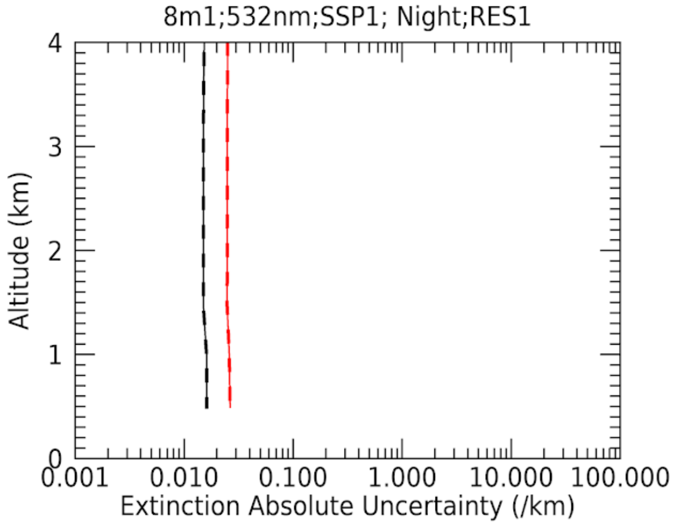
- three lidars are compared here, all provide observations of vertical variability of aerosol
  - BSL: a backscatter lidar (532 nm, 1064 nm) (aka ACCP's Lidar 9'): Measures attenuated backscatter at both channels. Measurements at a given altitude are not independent of components at higher altitude; particulate backscatter and extinction cannot be resolved without simplifying assumptions with systematic error.
  - HSRL: A 2-wavelength lidar with HSRL capability at 532 nm (aka ACCP's Lidar 5'). HSRL provides an additional measurement resulting in calibrated particulate backscatter and extinction resolved at each vertical bin without significant systematic error.
  - mHSRL: A 3-wavelength lidar with HSRL capability at 355 and 532 nm and attenuated backscatter at 1064 nm (aka ACCP's Lidar 6').
- The 3 lidars under consideration also have depolarization measurements at all wavelengths, not addressed in this study.

Inputs



Example 8m1
upper layer, smoke, AOD (550) =0.1, lower layer, pollution, AOD (550)= 0.09

- Aerosol profiles of microphysics (simulated)
  - Bimodal lognormal size distributions + refractive index in two modes
  - Vertical resolution 500 m.
  - Profiles contain two vertically separated aerosol layers of different type; variability within each layer is achieved by randomly varying the mode fraction of fine and coarse mode.
  - Only spherical particles
  - 30 cases were simulated and analyzed (26 shown today), with varying aerosol types, aerosol loading, and layer heights
- Forward model
  - Mie theory (spherical particles) + radiative transfer (Stamnes Applied Op. 2018)
- Measurement uncertainty, including both systematic and random
  - using instrument descriptions for ACCP study instruments



Example extinction uncertainty profiles for multi-wavelength HSRL case 8m1 at night, black=clear, red=cirrus.
Credit: Kathy Powell and Travis Toth

Uncertainty assessment from information content methodology

input: profiles of aerosol microphysics (prescribed)

calculate partial derivs of measurements with respect to aerosol state using forward model

$$\mathbf{J} = \frac{\partial y_i}{\partial x_i}$$

measurements – lidar extinction and backscatter or attenuated backscatter at each vertically resolved level PLUS polarimeter I, Q, and U for each wavelength and view angle

aerosol state – at each vertically resolved level: a bimodal lognormal distribution (6 variables) and fine mode CRI (2 variables; coarse mode assumed known) PLUS 2-9 parameters to define the surface

input: $\mathbf{S}_\varepsilon$ instrument uncertainty as measurement covariance matrices (simulated)

input: $\mathbf{S}_\mathrm{a}$ = prior knowledge of microphysics variable range (chosen conservatively large)

calculate **propagated uncertainty in the state variables** (output) using Rodgers 2000

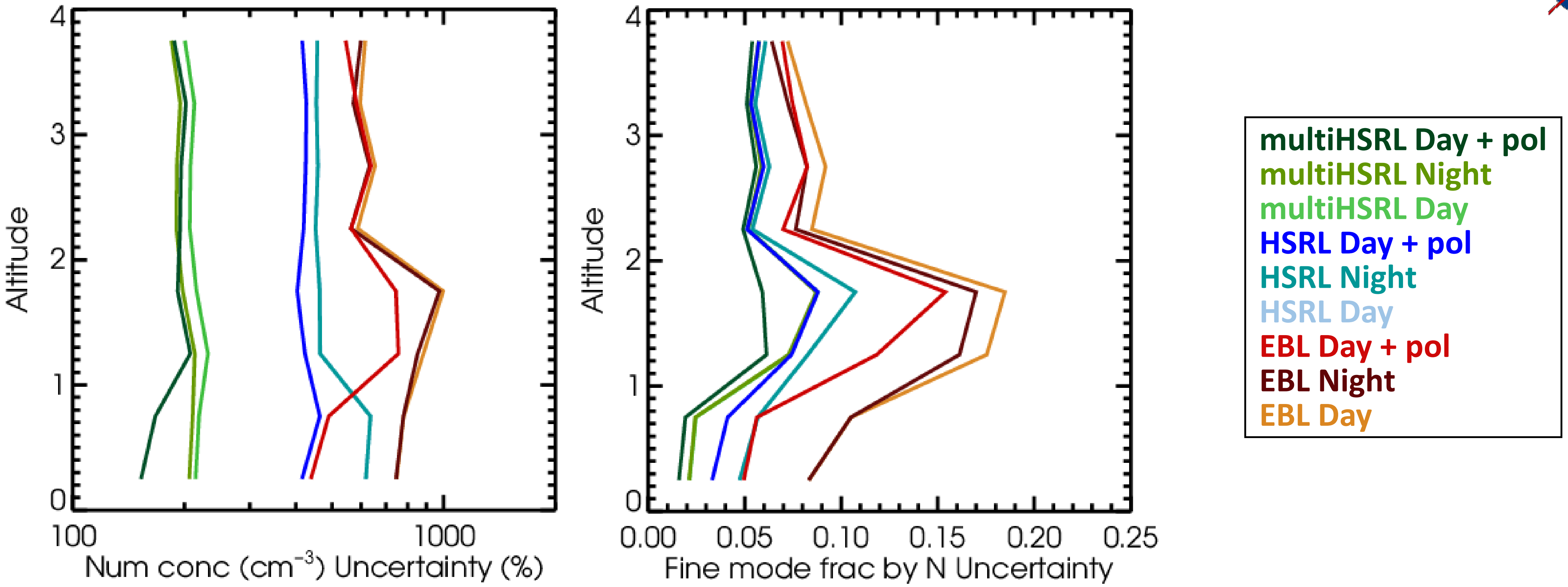
$$\hat{\mathbf{S}} = (\mathbf{J}^T \mathbf{S}_\varepsilon^{-1} \mathbf{J} + \mathbf{S}_a^{-1})^{-1}$$

calculate **propagated uncertainty in additional quantities of interest** (output) (e.g. SSA)

$$\sigma_z = \sqrt{\sum_i \sum_j \hat{S}_{ij} \frac{\partial z}{\partial x_i} \frac{\partial z}{\partial x_j}}$$

builds on Burton, et al. ***AMT*** *2016: Information content and sensitivity of the 3β + 2α lidar measurement system for aerosol microphysical retrievals.*

Example uncertainty profiles for aerosol “state” variables

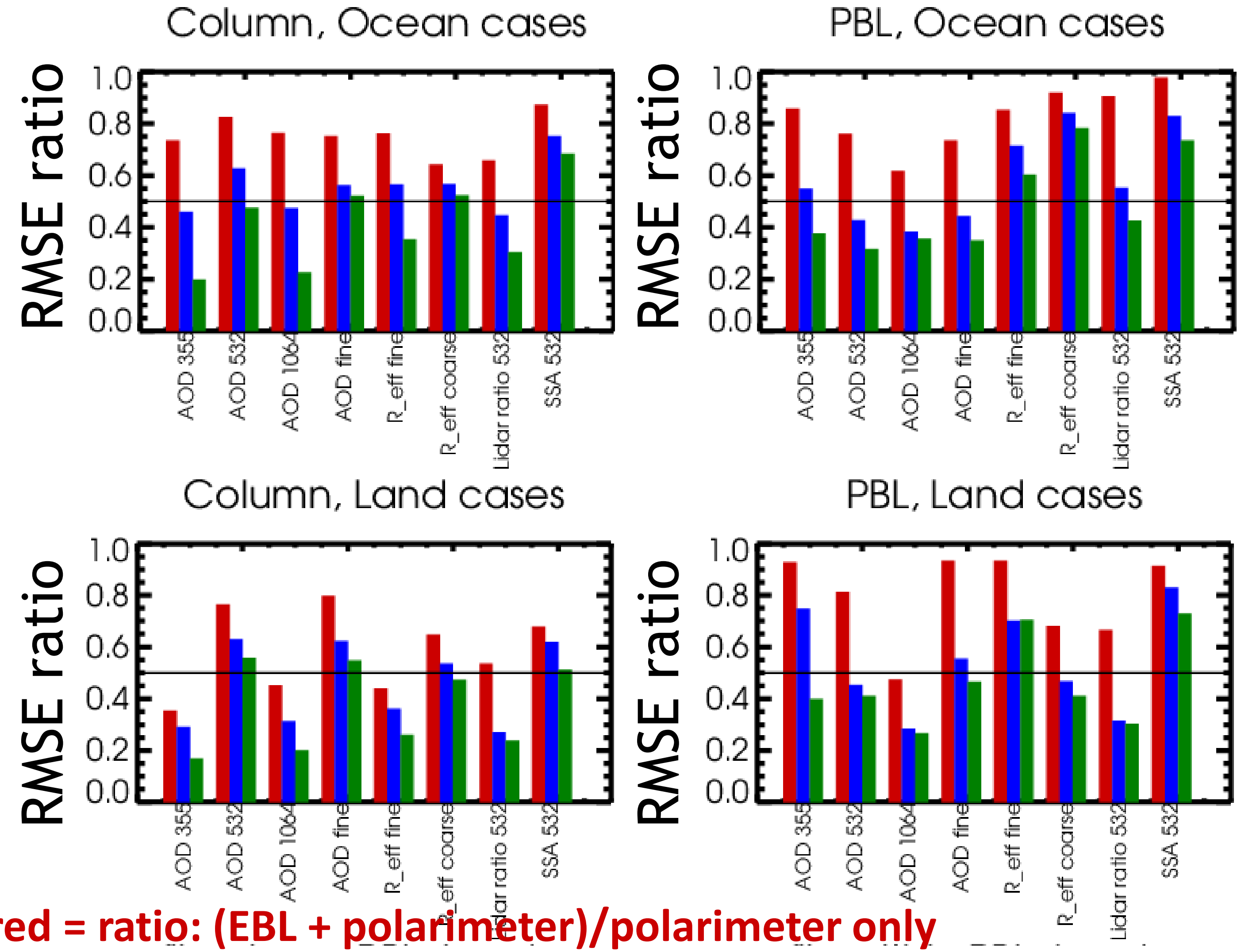


- Adding polarimeter improves over lidar alone
- Multiwavelength HSRL (with and without pol) has the smallest uncertainties in state variables, followed by single wavelength HSRL, followed by elastic backscatter lidar.

Simulated example 8m1:
500-m vertical, 50 m horizontal resolution with two aerosol layers over land

- smoke from 1 to 4 km with AOT 0.1
- urban pollution 0 to 1 km with AOT 0.09

Column and PBL-integrated quantities



red = ratio: (EBL + polarimeter)/polarimeter only

blue = ratio: (HSRL + polarimeter)/polarimeter only

green = ratio: (mHSRL + polarimeter)/polarimeter only

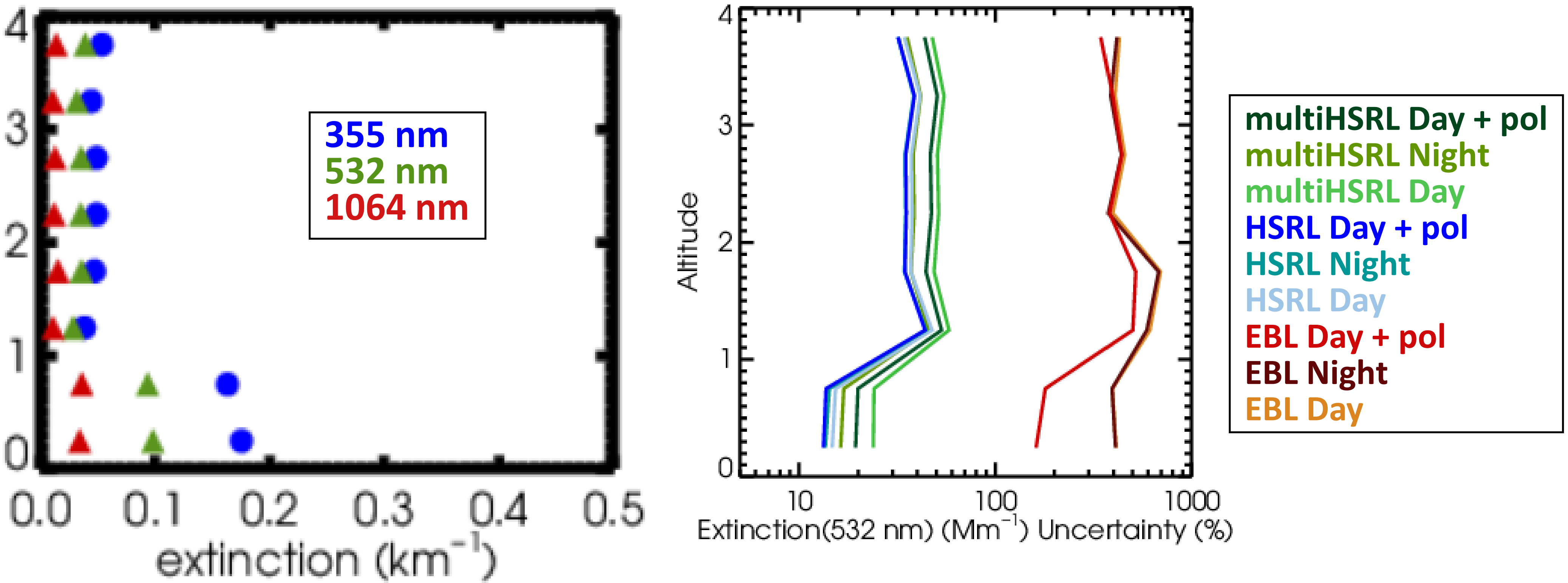
Quantities shown:

AOD 355, 532, 1064 nm
Fine mode AOD (532 nm)
Effective radius (fine)
Effective radius (coarse)
Layer-avg Lidar ratio (532)
Single Scatt Albedo (532)

bars show means of 26 cases

- Combining with lidar reduces uncertainty from polarimeter alone
- More improvement over land
- Some quantities' uncertainties reduced by half or more when combined with HSRL:
  - column and PBL-layer AOD at multiple wavelengths
  - column fine mode effective radius
  - column and PBL effective lidar ratios
  - fine mode AOD for the PBL layer

Extinction profile uncertainties



- HSRL and multi HSRL (with and without pol) have the smallest uncertainties in extinction
- Adding polarimeter improves uncertainties compared to elastic backscatter lidar alone

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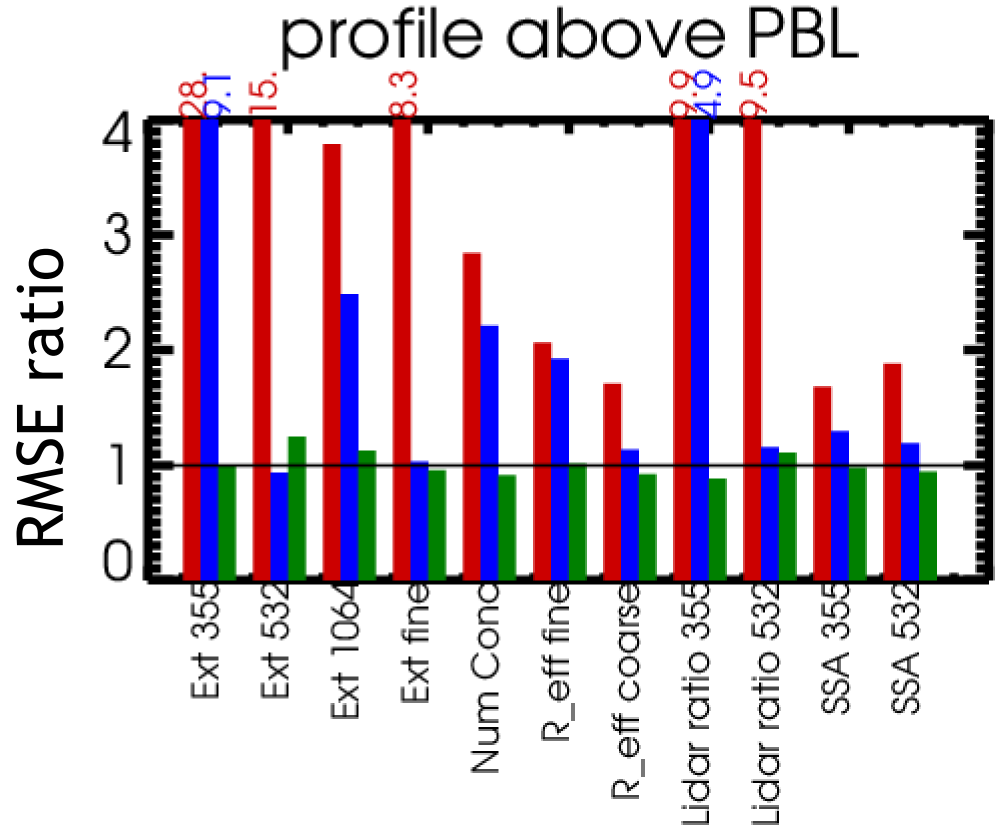
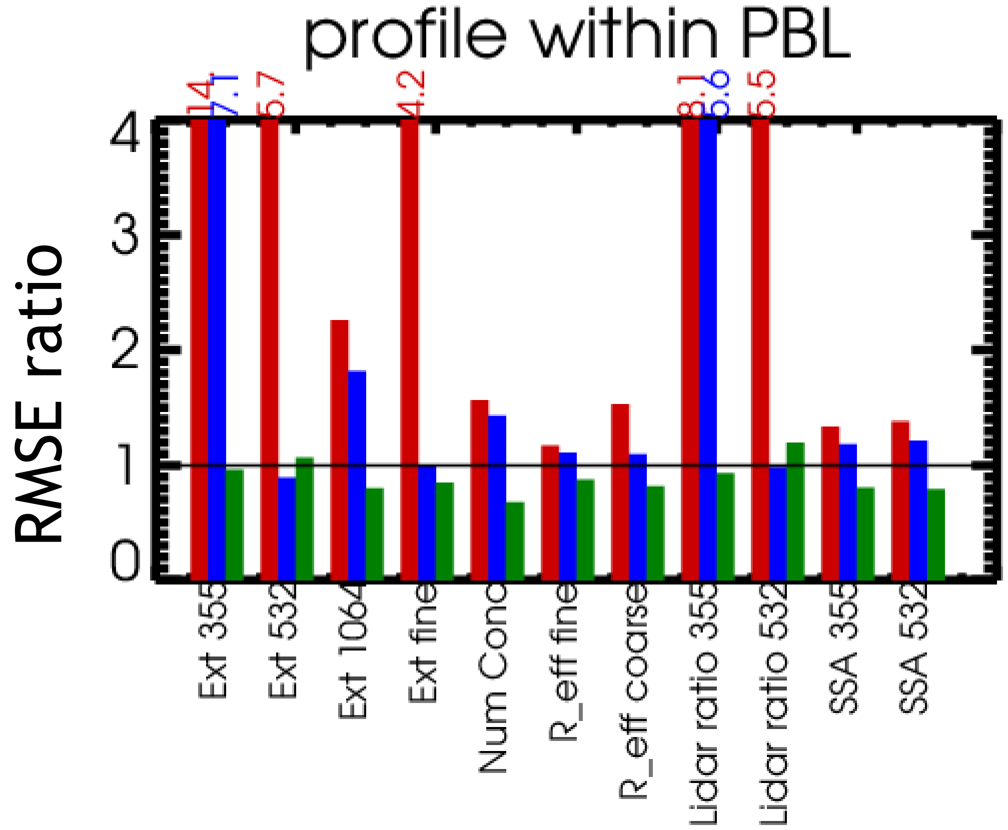
Comparison charts for Profile Quantities





- Multiwavelength HSRL alone outperforms other combinations for many quantities
- Combined retrieval uncertainty < mHSRL alone for most quantities in lower profile

denominator = multiHSRL Night
EBL Day + pol / multiHSRL Night
HSRL Day + pol /multiHSRL Night
multiHSRL Day + pol / multiHSRL Night

bars show means of 26 cases

Conclusions

- Propagated uncertainties are derived from information content analysis (ICA) for aerosol optical and microphysical variables
- Useful for direct assessment of how measurements constrain the retrieval variables, well suited to comparing different systems for ACCP
- Combined polarimeter and lidar reduces the uncertainties compared to polarimeter alone or lidar alone
- Smallest uncertainties for HSRL and multiwavelength HSRL
- Compared to polarimeter alone, adding HSRL reduces uncertainty by half for some AOD wavelengths, fine mode AOD, and column fine mode effective radius
- Greatest reduction in uncertainties in col/PBL quantities over land
- For profile quantities, adding polarimeter reduces uncertainties compared to multi-wavelength HSRL alone, e.g. SSA profile and Number concentration profile