High spectral resolution lidar for aerosol characterization and combined lidar+polarimeter retrieval

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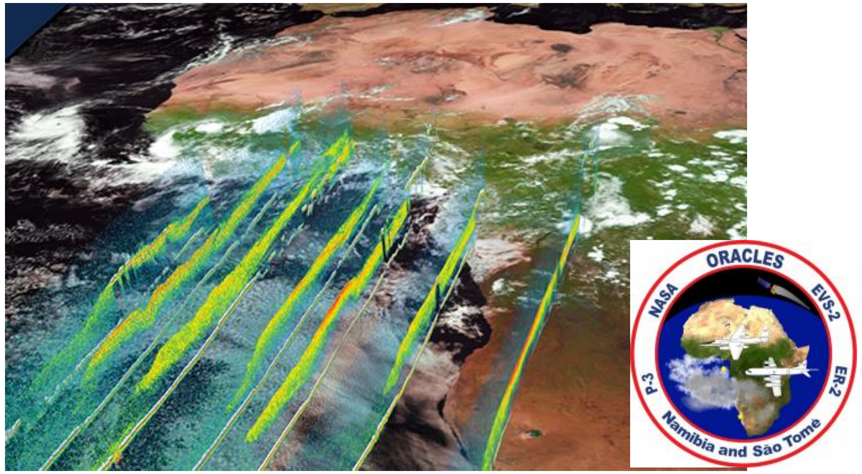
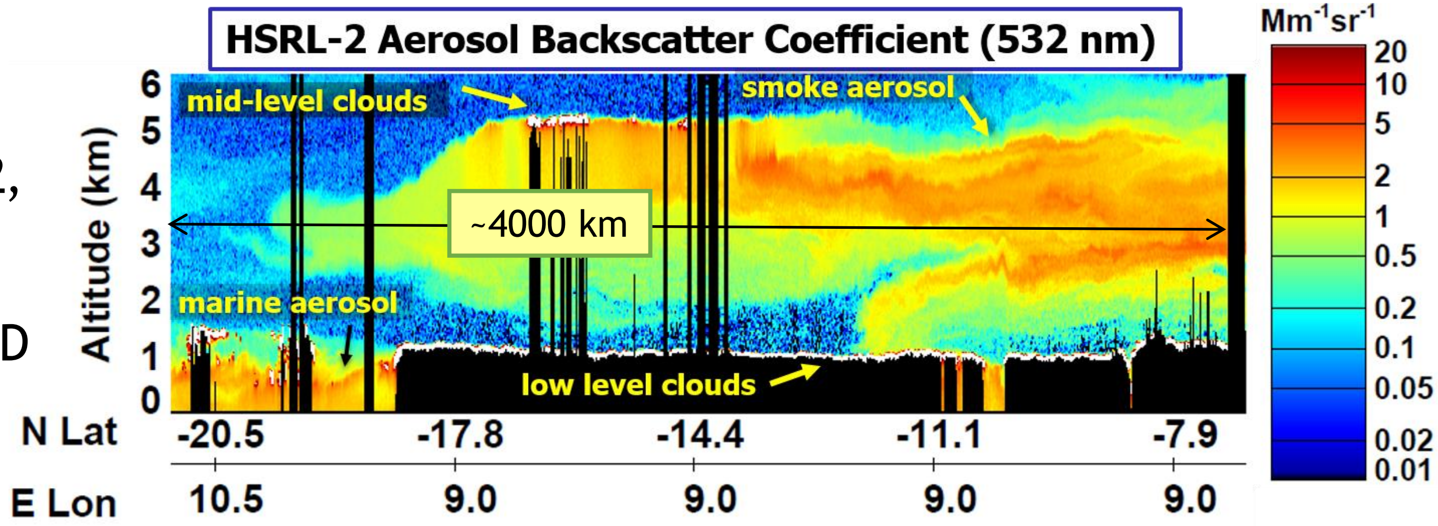
NASA Langley Research Center, HSRL team

NASA Langley HSRL-2

- ACE Decadal Survey satellite prototype
- Nine field missions so far including ORACLES 1,2,3 and CAMP2EX
- Provides satellite calibration and validation
- Provides input to and validation for models



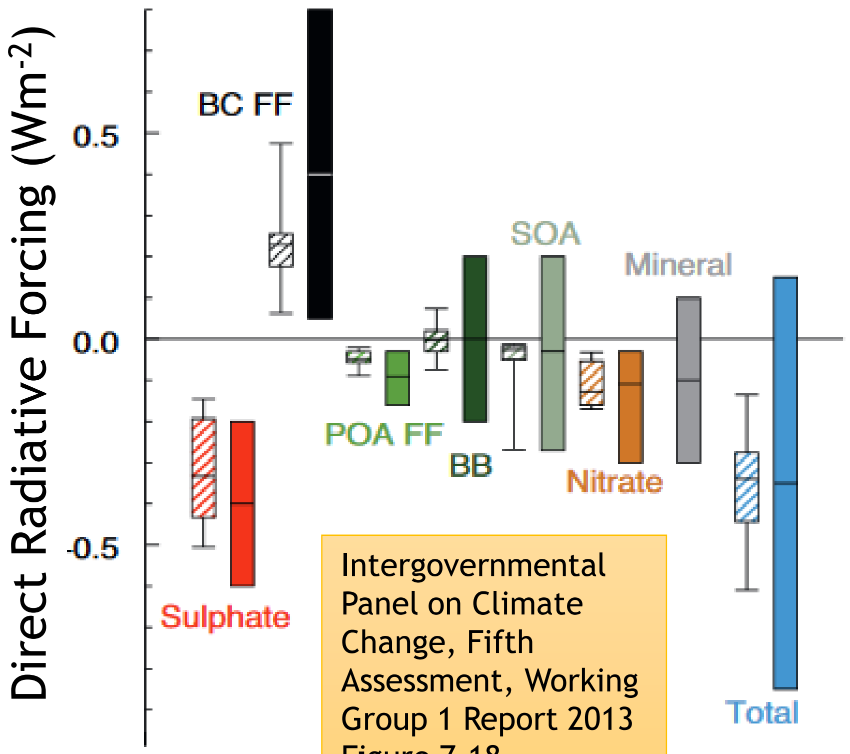
- 3 backscatter wavelengths (355, 532, 1064 nm)
- 2 extinction wavelengths (355, 532 nm)
- 3 depolarization wavelengths (355, 532, 1064 nm)
- Additional products
  - Aerosol optical depth/above cloud AOD
  - Boundary Layer height
  - Qualitative aerosol classification
  - Microphysics retrievals of effective radius, total concentrations (N,S,V)



September 16, 2016

What do we need to know about aerosol?

Amount, size, morphology, composition,



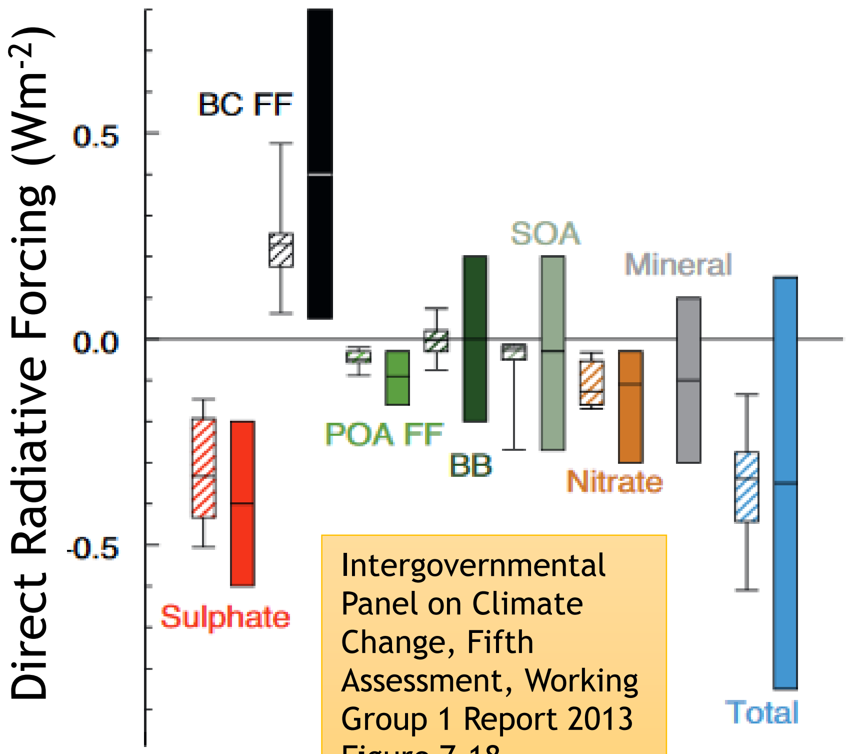
Intergovernmental Panel on Climate Change, Fifth Assessment, Working Group 1 Report 2013 Figure 7.18

Aerosol is a generic category for many different components

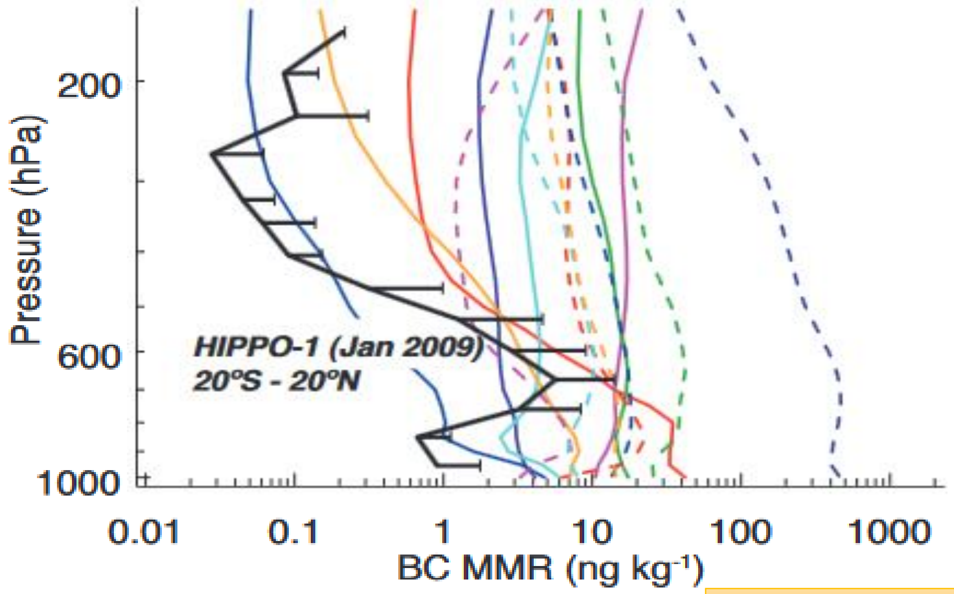
- Aerosols may warm or cool depending on type
- Aerosol-cloud interaction depends on type
- Aerosol transport and lifetime depends on type
- Effects on air quality and health depend on type

What do we need to know about aerosol?

Amount, size, morphology, composition, and location, location, location



Intergovernmental Panel on Climate Change, Fifth Assessment, Working Group 1 Report 2013 Figure 7.18



IPCC5 Figure 7.15

Large diversity in current models' ability to reproduce vertical profile shape

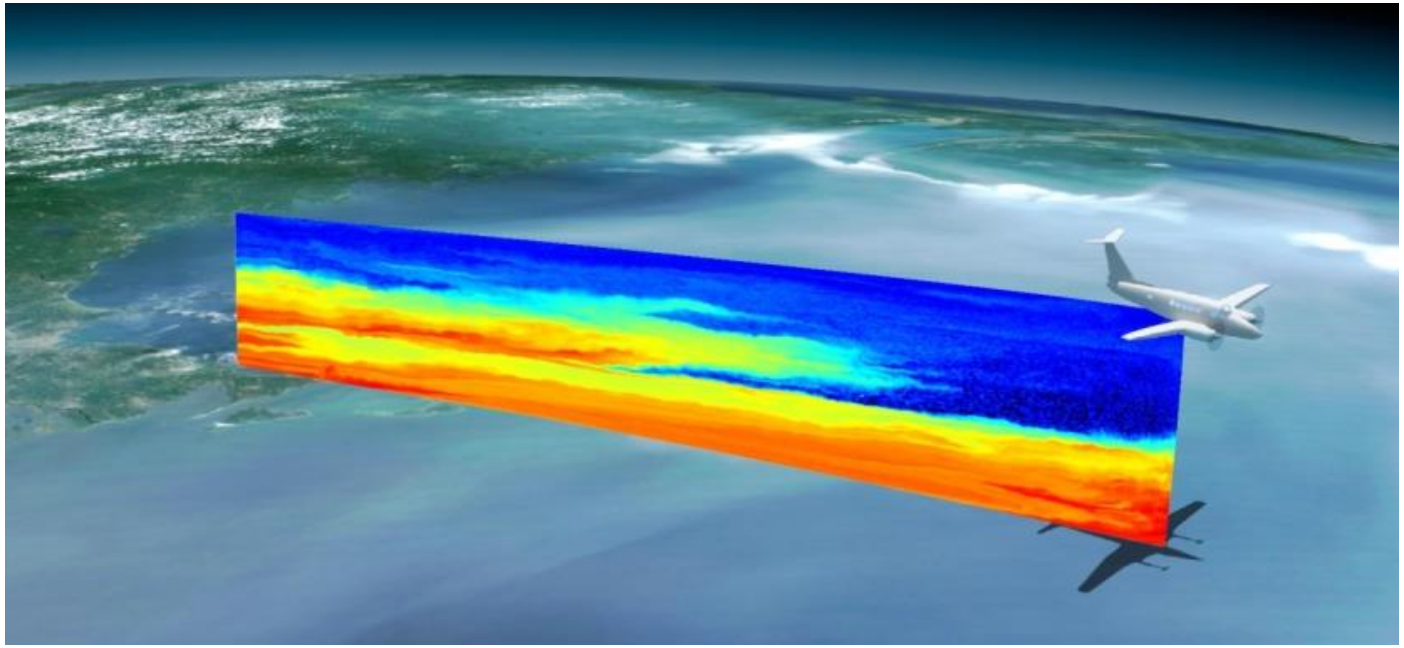
Aerosol is a generic category for many different components

- Aerosols may warm or cool depending on type *and altitude*
- Aerosol-cloud interaction depends on type *and altitude*
- Aerosol transport and lifetime depends on type *and altitude*
- Effects on air quality and health depend on type *and altitude*

Why lidar?

Compared to passive aerosol sensors, lidar ...

- provides high resolution vertical profiles
- provides indicators of size, shape, composition
- works at night
- works equally well over bright surfaces
- works between broken clouds and near clouds



Combined lidar + polarimeter retrieval

Lidar
- vertically resolved measurements
- multi-wavelength backscatter and extinction coefficients
- good accuracy for size distribution
- less accuracy for absorption

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

Lidar + Polarimeter
- vertically resolved profiles of size distribution, concentrations, and absorption

The combination of lidar + polarimeter measurements optimizes the information about the vertical profile of absorption properties

Role of combined retrieval in ACCP

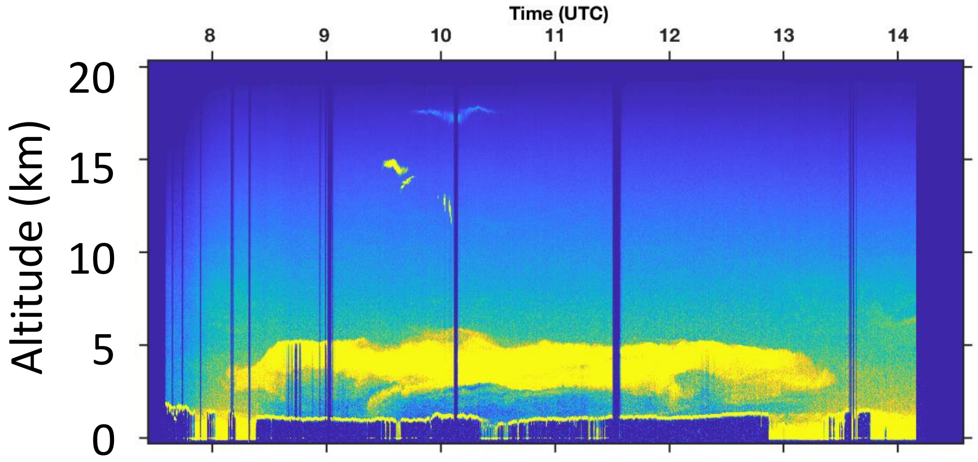
- Retrieval of ACCP geophysical variables
  - SATM includes *layer resolved* aerosol size distribution and absorption
  - Requires *combined retrieval* of polarimeter (sensitive to absorption) and lidar (vertically resolved)
- Assessment of measurement capabilities
  - Our retrieval architecture is adaptable to other instruments
  - Information content analysis allow quantitative assessment of ACCP candidate configurations
  - HSRL2 + RSP field campaign data allows us to compare performance against down-selected data (simulating less capable architectures)

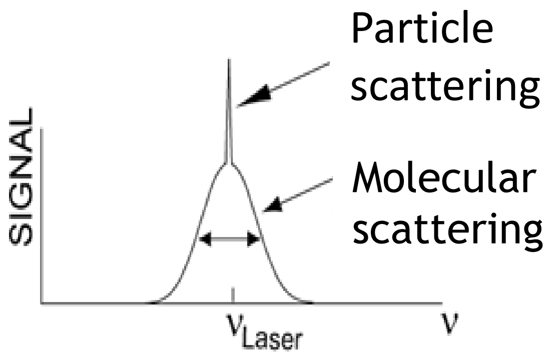
High Spectral Resolution Lidar
= independent measures of extinction and backscatter

2 unknowns

β=> backscatter, α=> extinction

$$P_a(r)r^2 = [\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^r [\alpha_m(r') + \alpha_a(r')]dr'\right\}$$





High Spectral Resolution Lidar
= independent measures of extinction and backscatter

2 unknowns — β=> backscatter, α=> extinction — 2 equations

$$P_a(r)r^2 = [\beta_m(r) + \beta_a(r)]\exp\left\{-2\int_0^r [\alpha_m(r') + \alpha_a(r')]dr'\right\}$$

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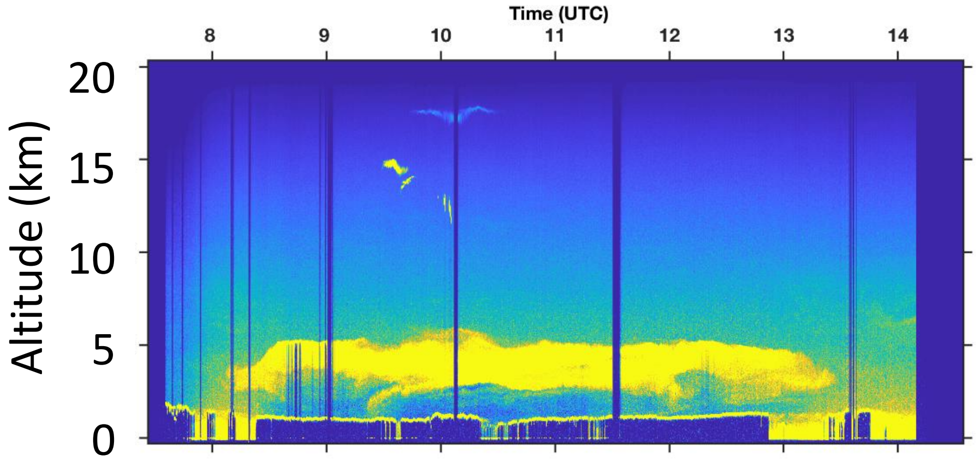
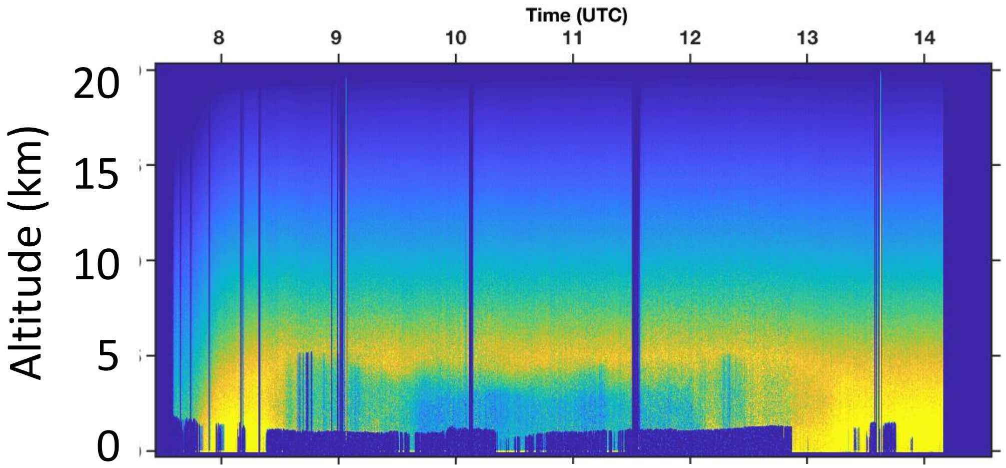
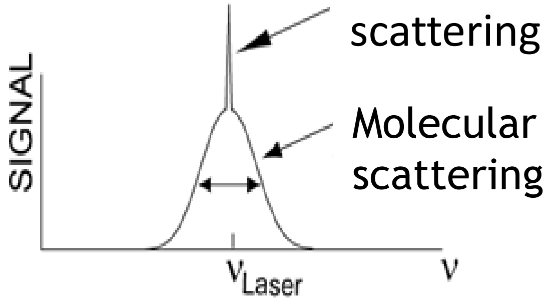
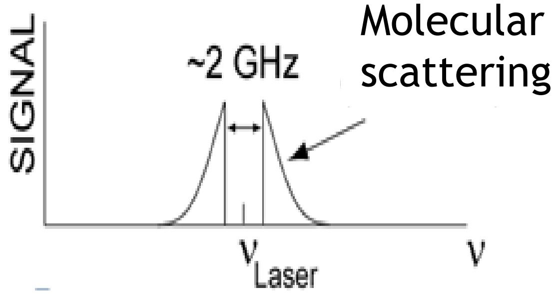






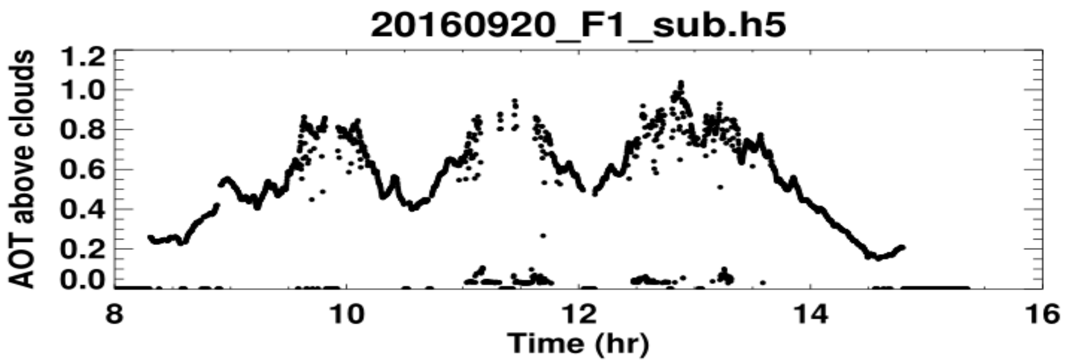


Aerosol extinction

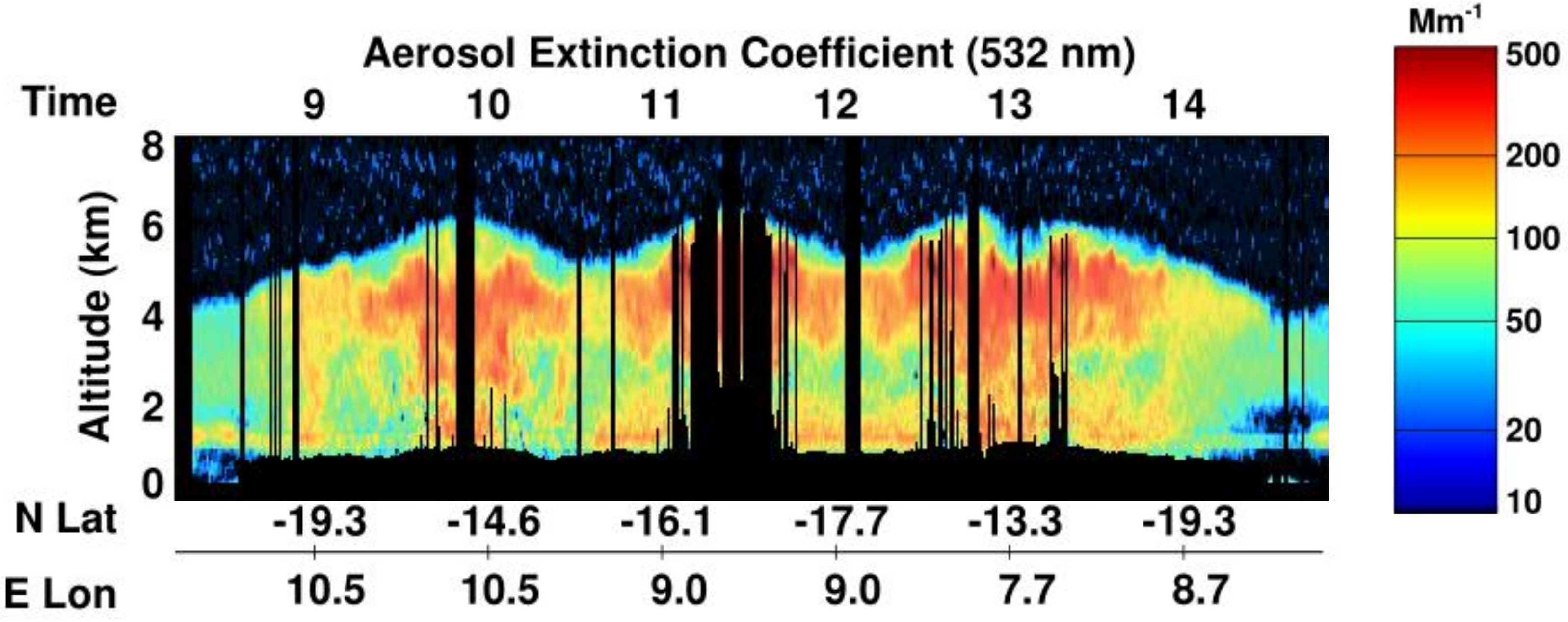
HSRL "molecular" channel or "attenuation" channel:

1 unknown

$$P_m(r)r^2 = [\beta_m(r)]\exp\left\{-2\int_0^r [\alpha_m(r') + \alpha_a(r')]dr'\right\}$$

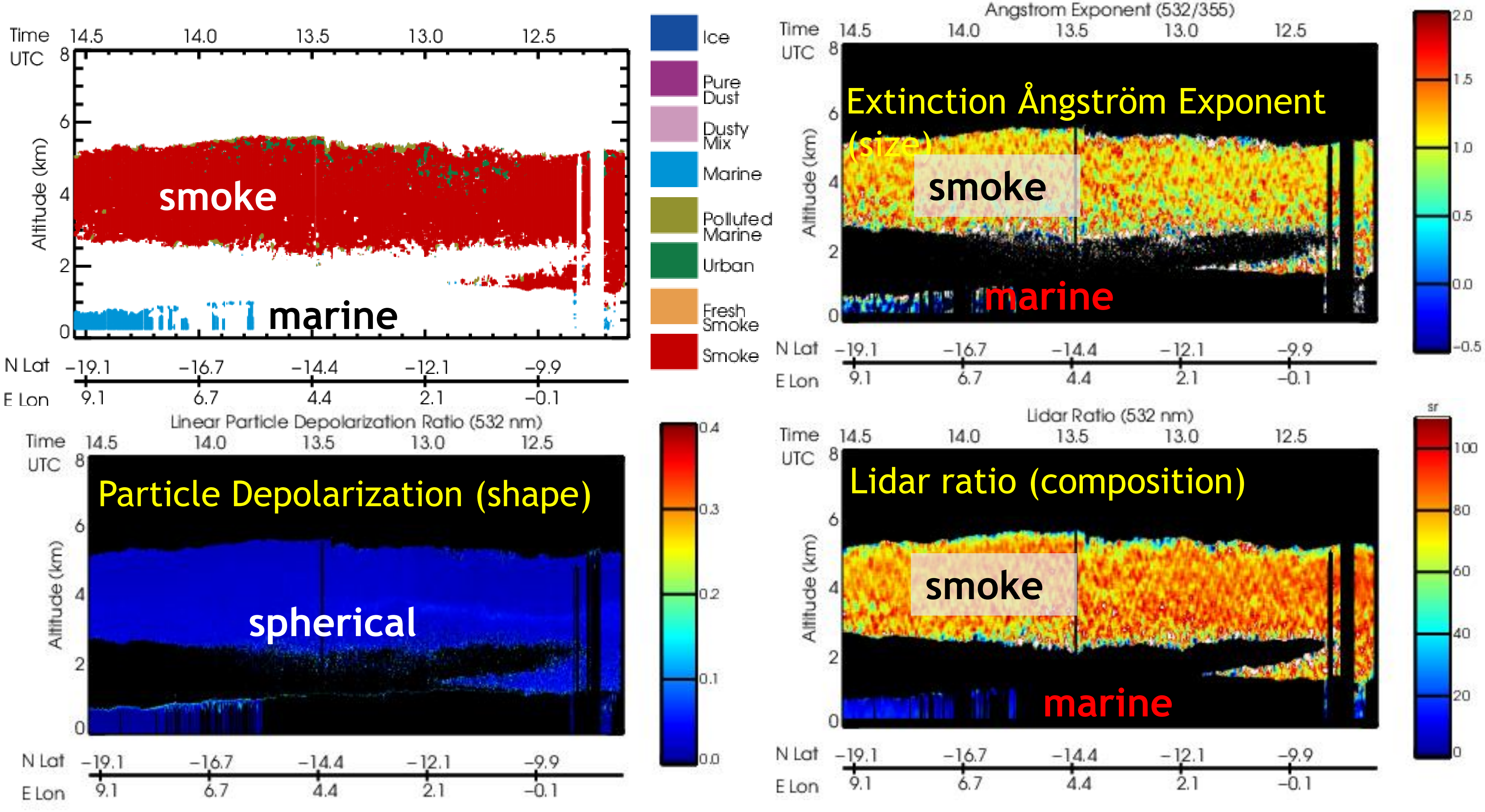


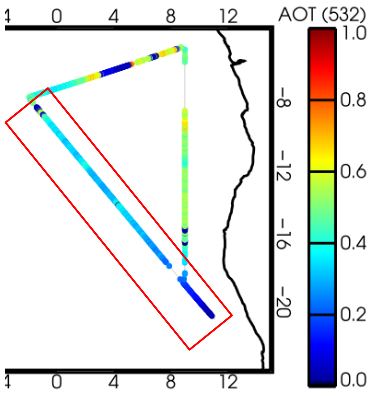
- The filtered channel provides direct measure of AOT and extinction
- Extinction measurement does not require modeled lidar ratio or constraint
- Little loss of accuracy from attenuation
- No need for layer detection



Aerosol intensive parameters: size, shape, and composition

ORACLES September 12, 2016

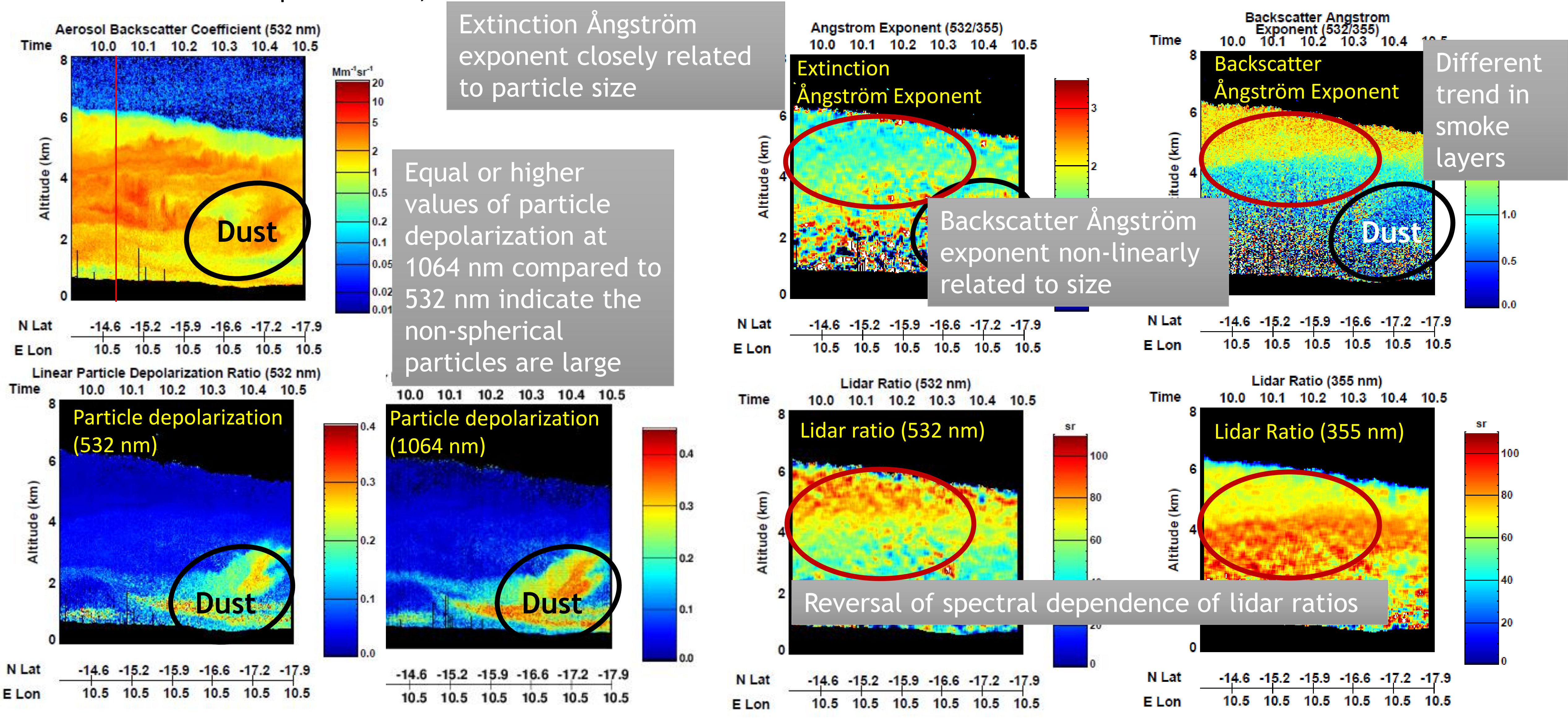




See also: Burton et al. 2012 AMT *Aerosol Classification of Airborne High Spectral Resolution Lidar Measurements – Methodology and Examples*

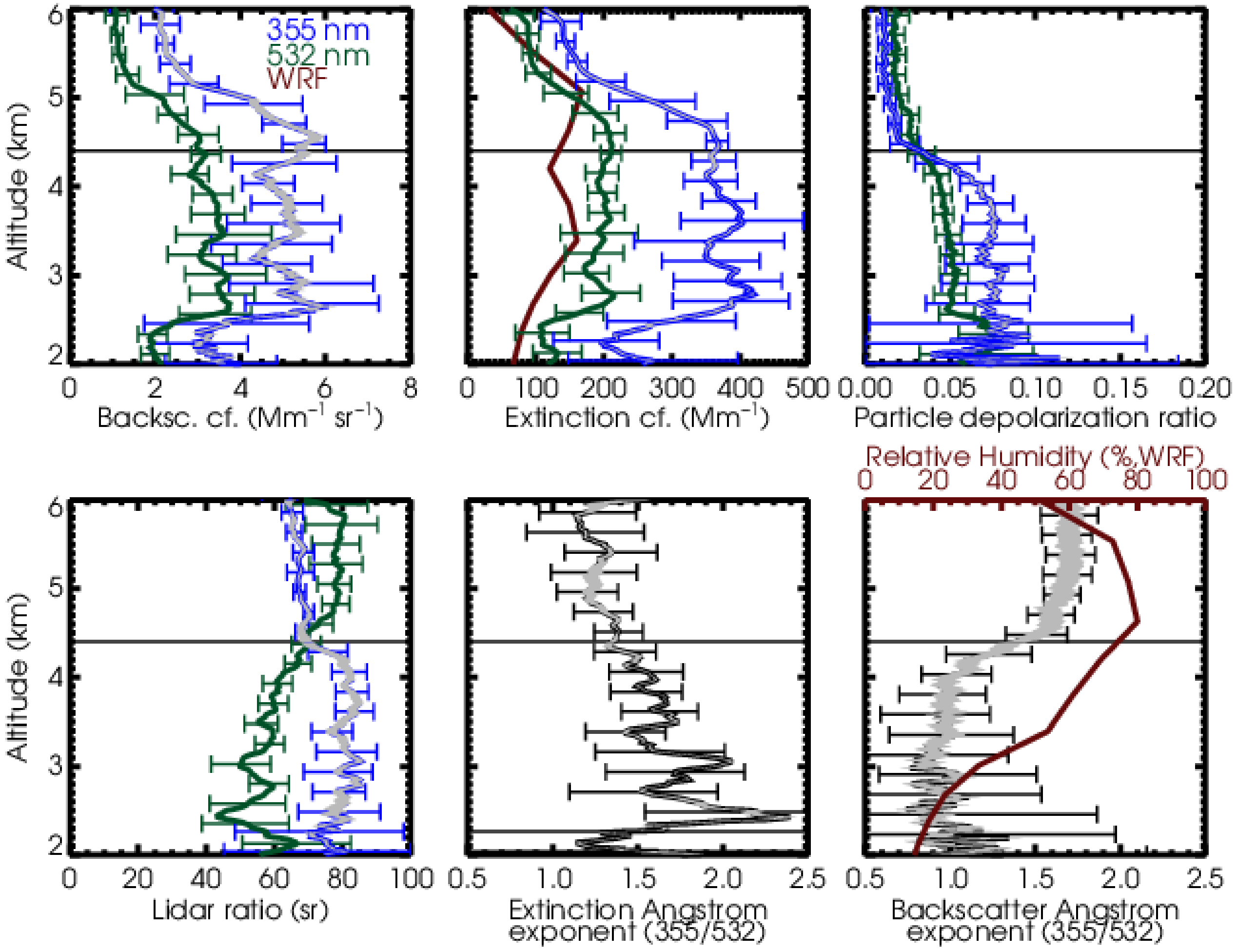
Aerosol intensive parameters, part 2

ORACLES September 20, 2016



Vertical variability on September 20, 2016

ORACLES 2016 September 20 9:54-10:06 UT



Below vs. above 4.4 km:

- Some smoke depolarization
- Lidar ratio spectral ratio reverses
- Extinction Ångström exponent increases, suggesting smaller particles
- Backscatter Ångström exponent decreases
- Less relative humidity

Burton et al. 2018, Calibration of a high spectral resolution lidar using a Michelson interferometer, with data examples from ORACLES, *Applied Optics*, 2018

Is it "young" smoke?

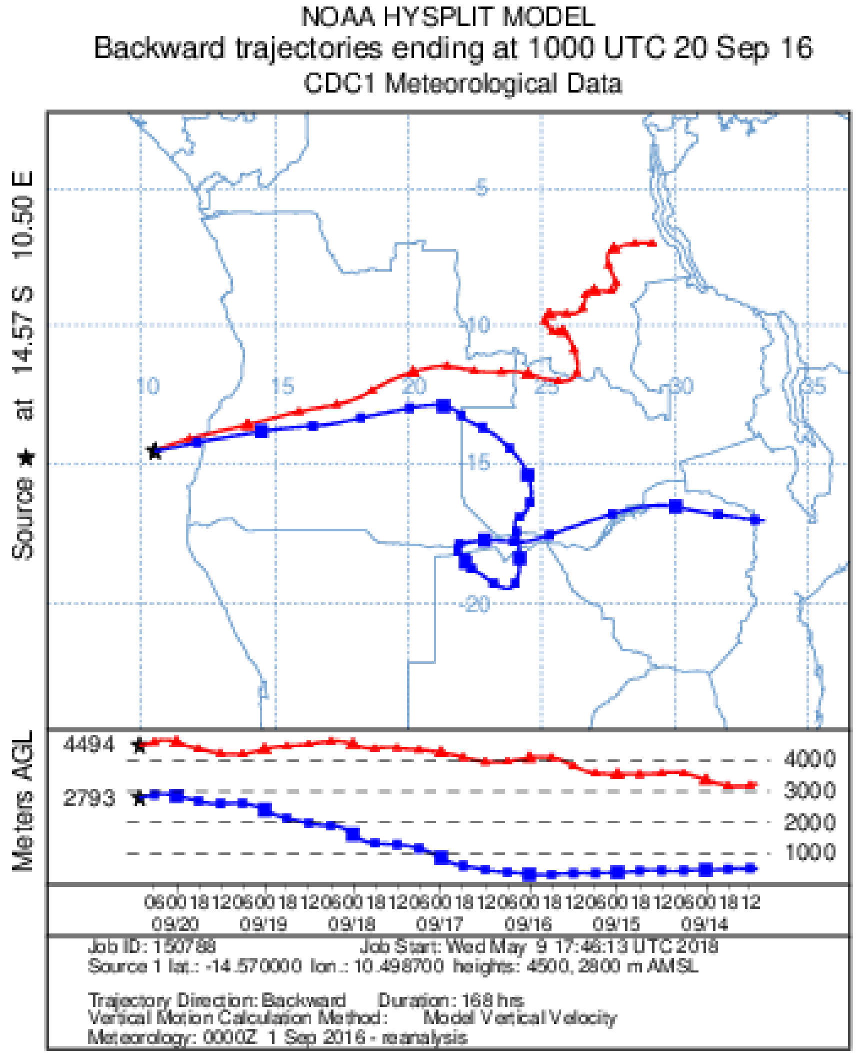
Nicolae et al. 2013 suggests that 355 nm lidar ratio > 532 nm lidar ratio only for fresh smoke (< 1 day).

Characterization of fresh and aged biomass burning events using multiwavelength Raman lidar and mass spectrometry

D. Nicolae,[1] A. Nemuc,[1] D. Müller,[2,3,4,5] C. Talianu,[1] J. Vasilescu,[1] L. Belegante,[1] and A. Kolgotin[6]

agree with similar studies carried out in different regions on the globe. Our study shows that the Ångström exponent LR_{532}/LR_{355} and the imaginary part of the refractive index can be used to clearly distinguish between fresh and aged smoke particles.

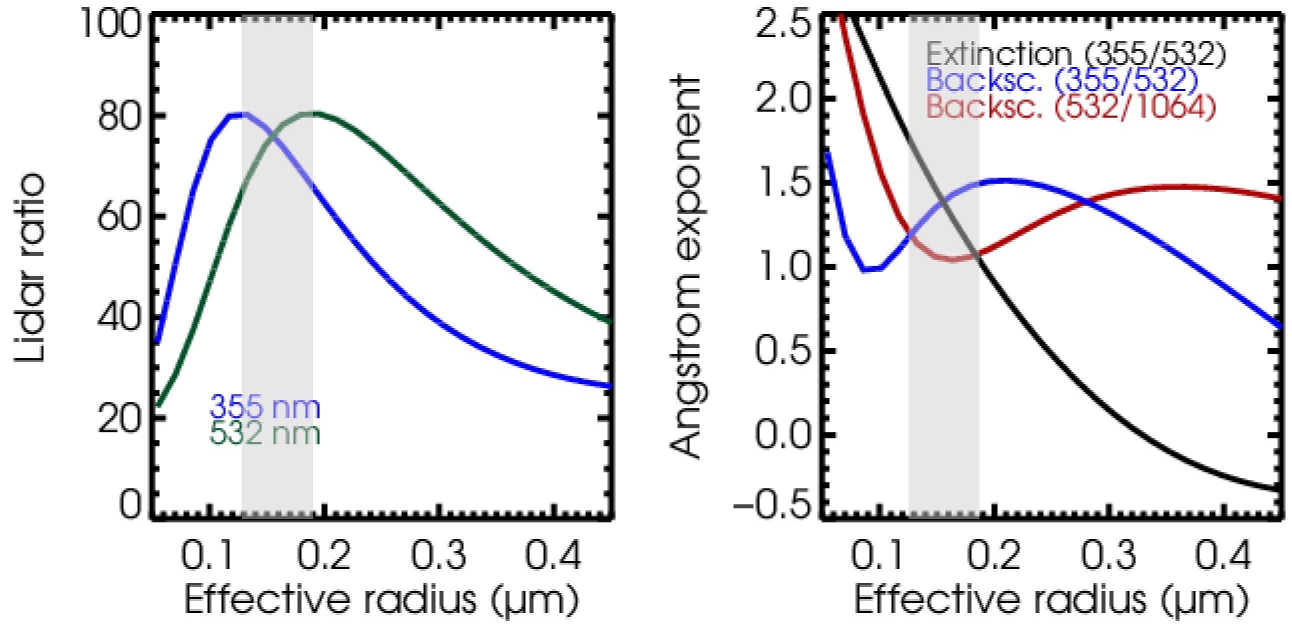
However: back-trajectories show that neither layer is younger than approximately 4 days. This is in agreement with ORACLES WRF-Chem airmass age modeling (Pablo Saide)



Optical properties from Mie modeling

- Monomodal log-normal distribution of spherical particles (simple case).
- Effective radius is varied.
- All other variables fixed: effective variance = 0.195, CRI = 1.49-i0.01325 (wavelength independent)

- As effective radius increases, and *nothing else changes*,
  - Extinction Ångström exponent decreases
  - Spectral ratio of lidar ratio reverses

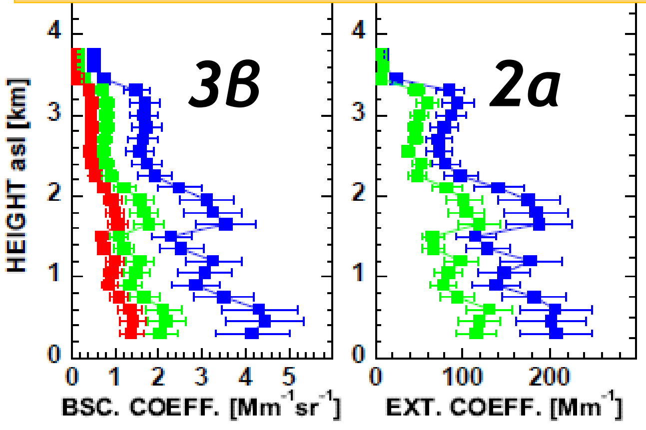


Conclusion:

- A difference in the particle size alone between the two layers is sufficient to explain the unusual observations.
- Particles with $S_a(355) > S_a(532)$ are not limited to very young smoke.

Lidar aerosol microphysical retrievals

Multiwavelength lidar retrieval algorithms (Müller et al, 1999; Veselovskii et al. 2002; etc)



Aerosol Backscatter:
355 nm
532 nm
1064 nm

\+

Aerosol Extinction:
355 nm
532 nm

lidar measurements

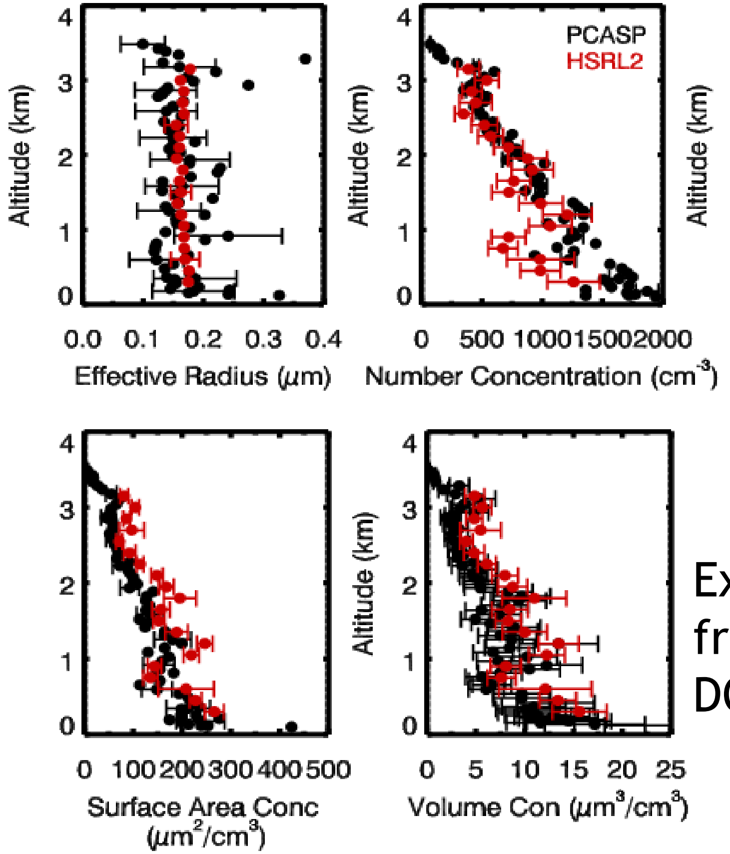
particle size distribution

INVERSION

$$\beta(\lambda) = \int K_\beta(r, m, \lambda) v(r) dr$$

$$\alpha(\lambda) = \int K_\alpha(r, m, \lambda) v(r) dr$$

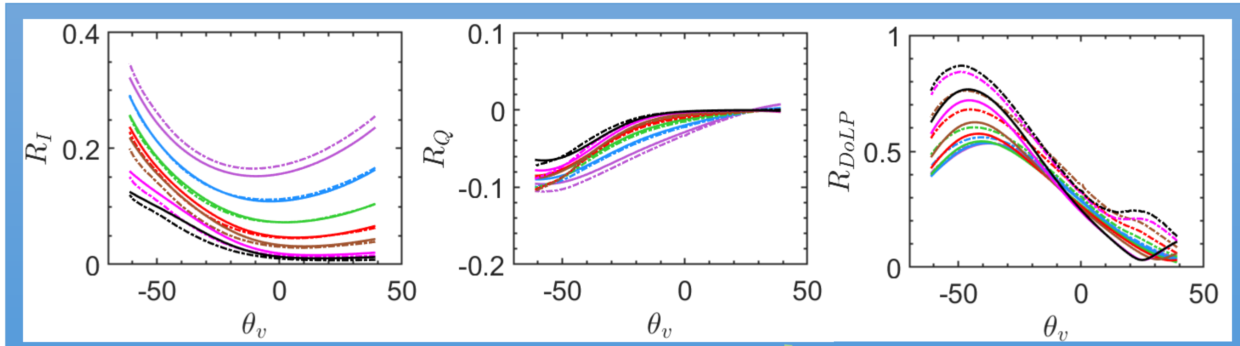
size, refractive index, wavelength

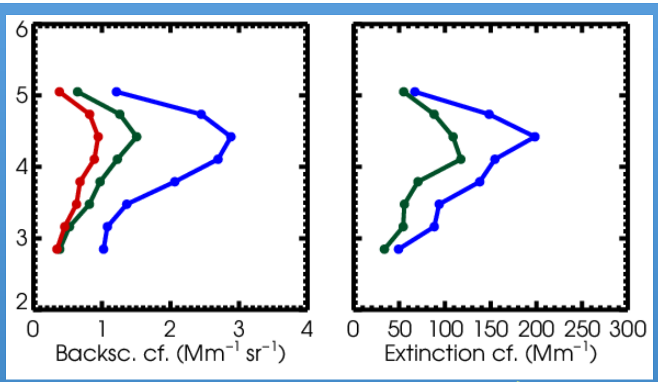


Example from DOE TCAP

- 3β+2α (i.e. 3 backscatter + 2 extinction) considered the minimum information necessary for microphysical retrievals (*Bockmann et al*, 2005)
- Lidar microphysical retrievals of effective radius and concentrations validated against in situ for 2012 TCAP mission (Müller et al., 2014, *AMT*) and 2013 DISCOVER-AQ (Sawamura et al., 2017, *AMT*)

Combined lidar + polarimeter retrieval

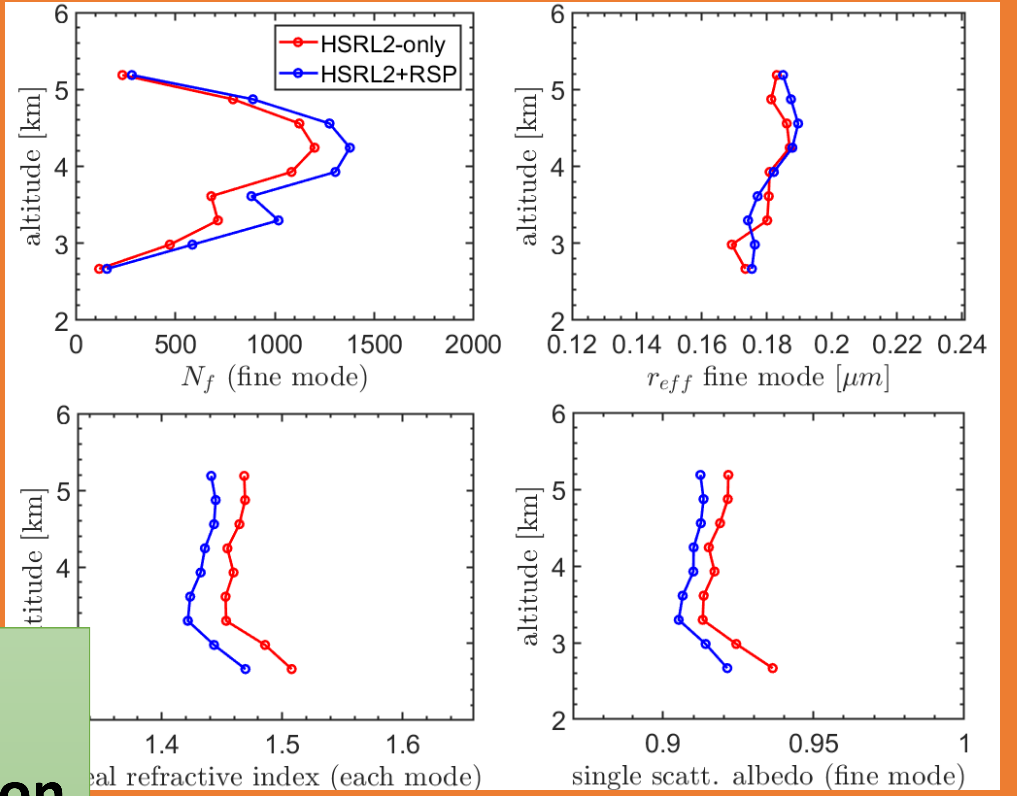




+ Forward Model

- Mie theory (spherical)
- Vector radiative transfer (Stamnes et al. 2018)
- Layer combination rules

(Preliminary)



Input measurements:

- RSP total and polarized radiances (7 wavelengths, 480 angles)
- HSRL2 vertically resolved backscatter and extinction coefficient (355, 532, 1064 nm)
- And their uncertainties

+ a priori (chosen to have weak impact)

Inversion

Optimal Estimation

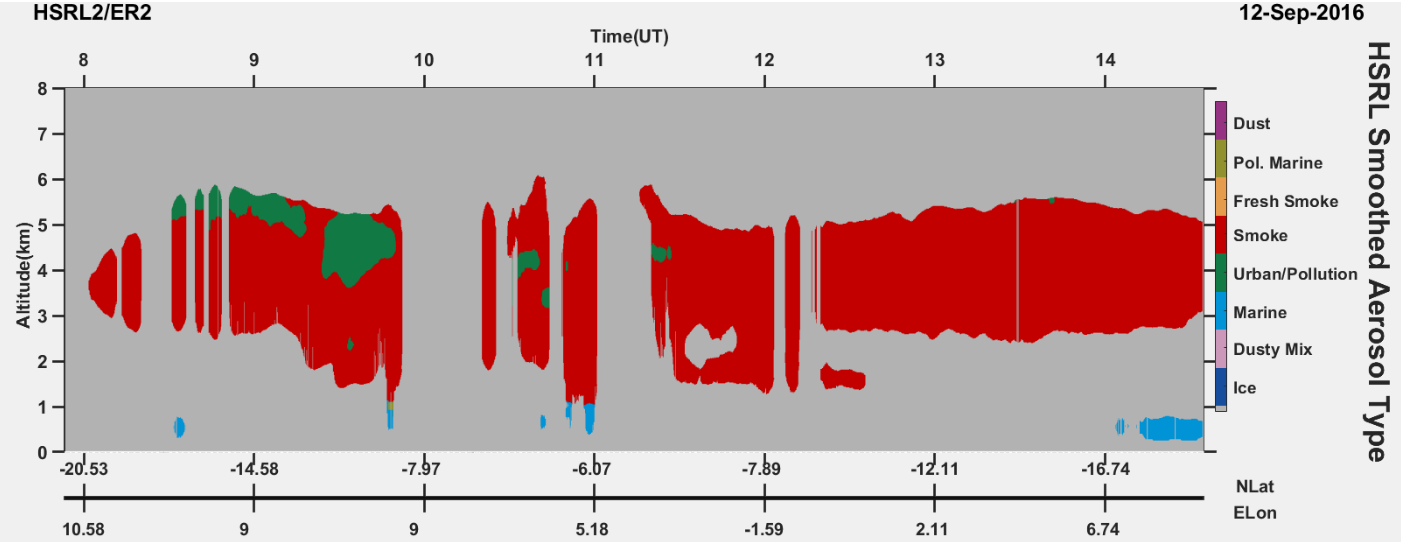
Optimizes result to fit measurements within uncertainty

Output:

Vertically resolved particle concentrations, effective radius, and absorption

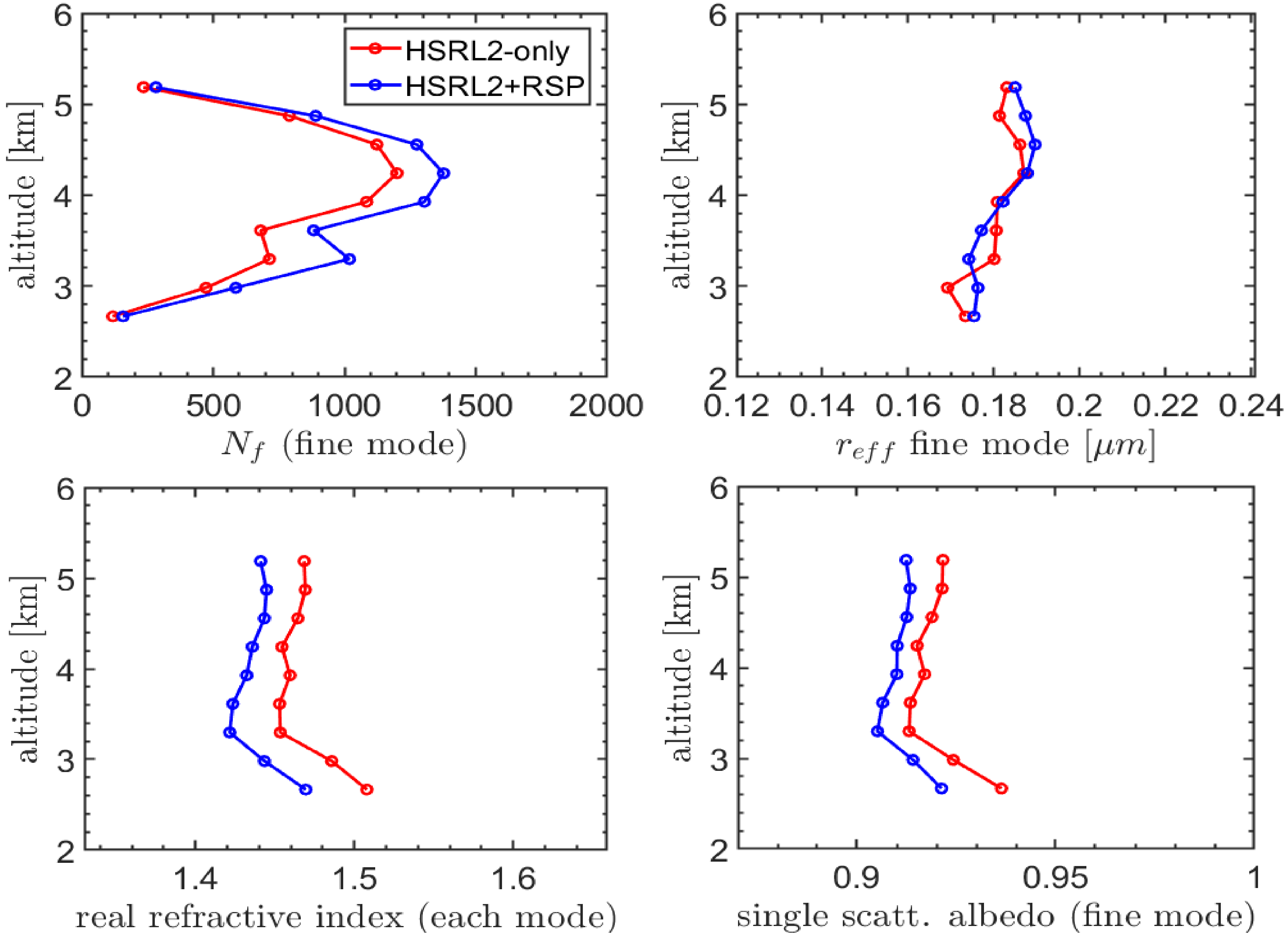
Layer combination rules

- Lidar = vertically resolved ; polarimeter = column-only
- Retrieval state vector = aerosol state for each lidar level, but retrieving all with the radiative transfer is prohibitive
- Continuous layers with similar properties identified using HSRL aerosol typing
- Effective state variables represented by combining values *within a layer of similar properties*
  - Effective size distribution matches optical measurements by matching 1st, 2nd, 3rd moments
  - Effective complex refractive index is assumed by weighted averaging
- Combined analytic Jacobian describes combination of lidar and polarimeter parts, e.g.



$$\frac{dy^{pol}}{dr_f^{lid}(i)} = \frac{\partial y^{pol}}{\partial r_f^{pol}} \frac{\partial r_f^{pol}}{\partial r_f^{lid}(i)} + \frac{\partial y^{pol}}{\partial \sigma_f^{pol}} \frac{\partial \sigma_f^{pol}}{\partial r_f^{lid}(i)}$$

Combined lidar + polarimeter retrieval



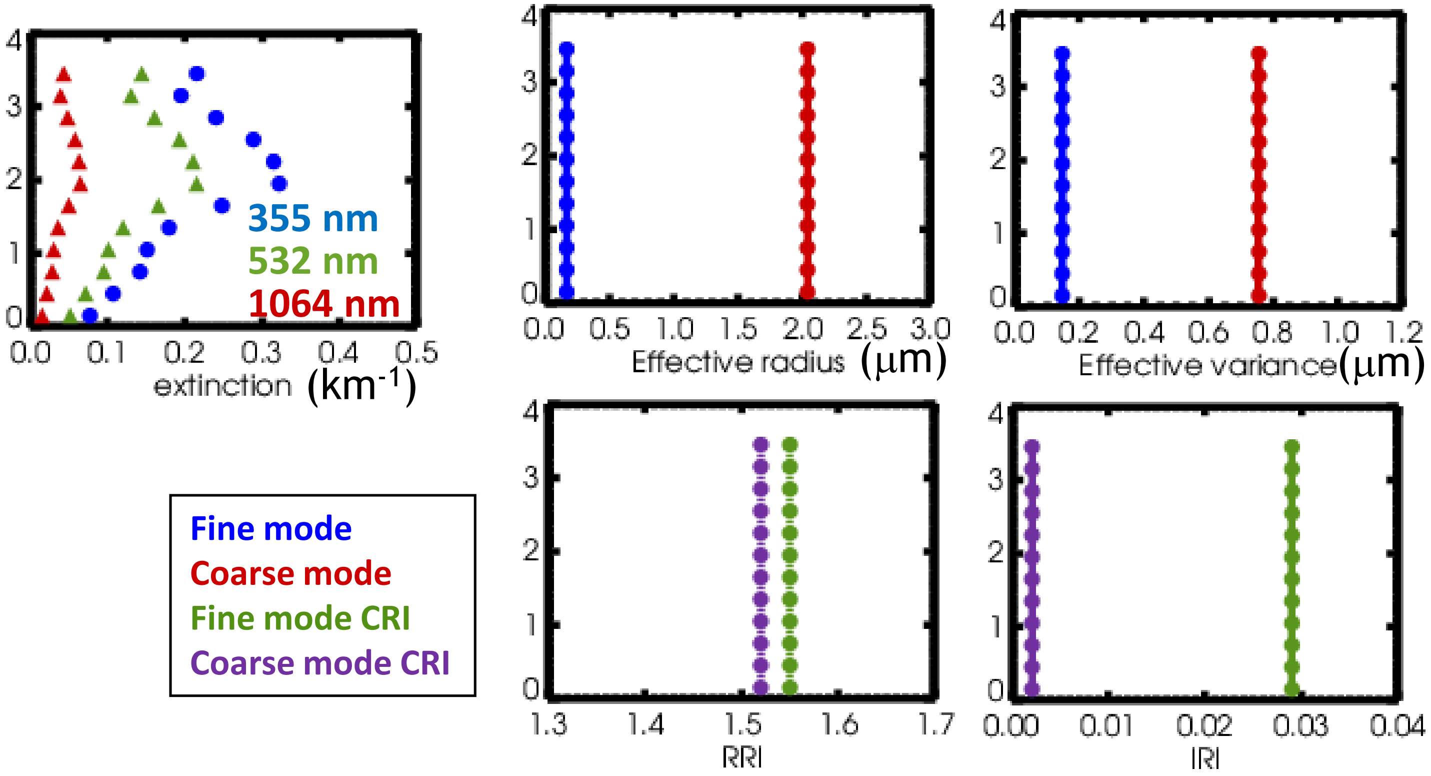
Preliminary result
12 September 2016
ORACLES

Information content study

Propagated uncertainties (Rodgers 2000)

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

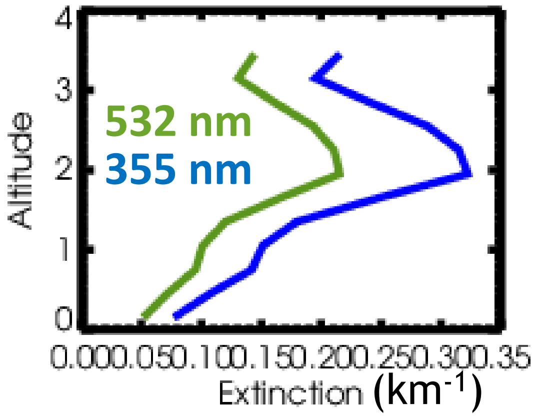
- **J** = Jacobian matrix = partial derivatives of measurements with respect to state = linearized forward model
- $\mathbf{S}_\varepsilon$= measurement error covariance matrix
- $\mathbf{S}_\mathbf{a}$ = a priori covariance matrix



- Inputs:
  - Aerosol profiles of microphysics
    - for cases or "slices" of state space
    - here, simulated smoke
  - Forward model
    - Mie theory (spherical particles), radiative transfer (Stamnes 2018)
  - Measurement errors
  - A priori uncertainties
    - Here: the full possible range taken by the microphysics variables (intended to have little impact)
    - However, the method also can accommodate using situational a priori from a climate model or aerosol typing

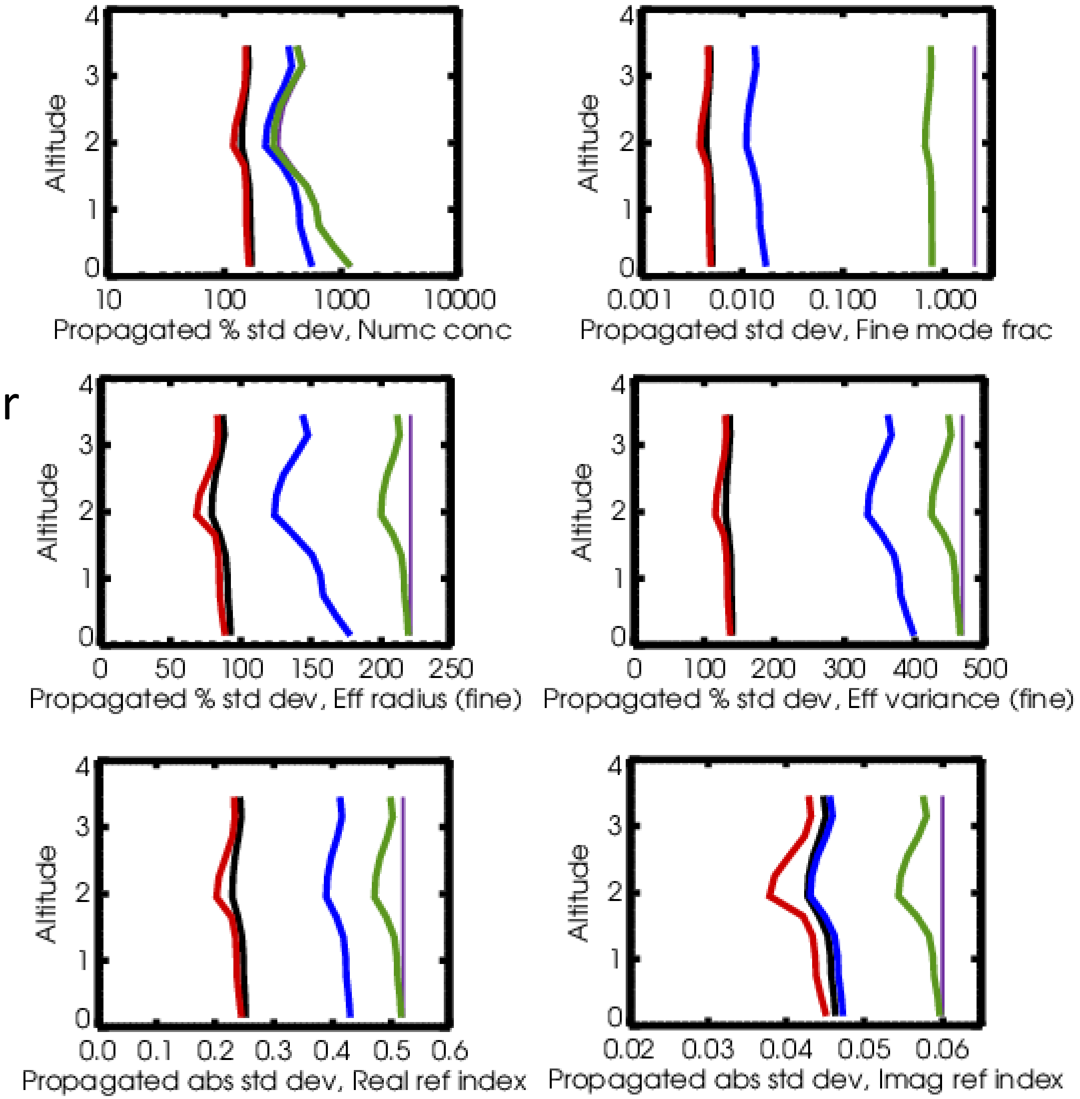
Burton, S. P., et al.: Information content and sensitivity of the 3β + 2α lidar measurement system for aerosol microphysical retrievals, AMT, 2016.

Reduction of uncertainties by combined measurements



12 levels of simulated smoke

- Contribution of measurements to the reduction of error
- Propagated errors for lidar+polarimeter < lidar only < polarimeter < prior
- Quantitative results vary with aerosol microphysical state and assumed input errors
- Results for polarimeter depend on the number of levels used to represent the state



Prior
Polarimeter contribution
3β+2α lidar contribution
3β+2α lidar + polarimeter
2β+1α lidar + polarimeter

Summary

- High Spectral Resolution Lidar provides useful information about vertically resolved aerosol microphysical properties in the atmosphere that are not otherwise available
- HSRL measurements reflect sensitivity to vertically resolved amount, size, shape, and composition of aerosol
- The combination of lidar with polarimeter takes advantage of complementary information for a more complete vertically resolved aerosol microphysical retrieval
- A lidar + polarimeter combined retrieval algorithm is being developed at NASA Langley
- Information content analysis provides complementary understanding of the combined measurement sensitivity and retrieval capabilities
- Both the combined retrieval tool and the information content analysis tools are being used in ACCP analysis of instrument configurations