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# **A Combined Polarimeter and Lidar Optimal Estimation Algorithm to Improve Aerosol Microphysical Property Retrievals**

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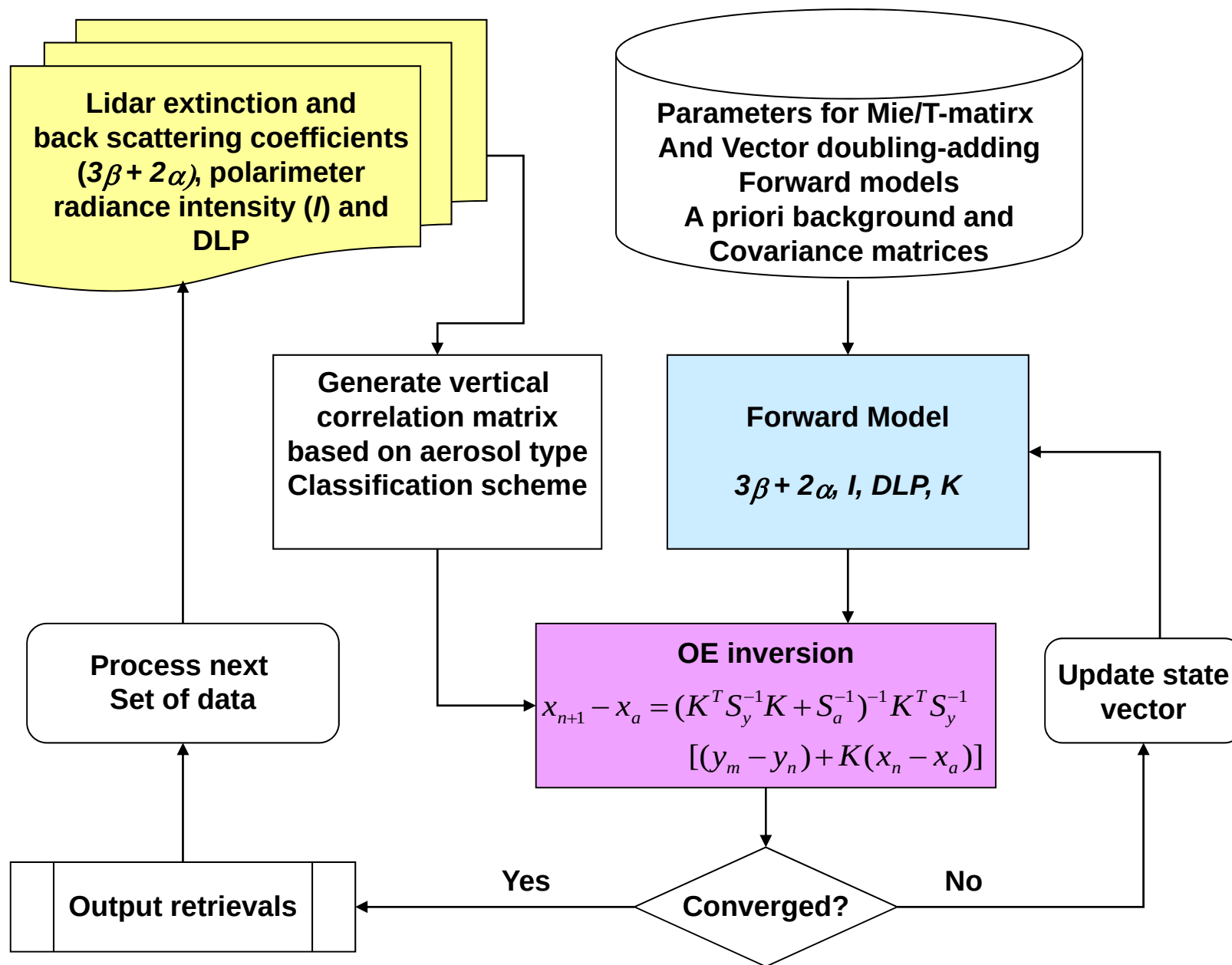


# Motivation

- OE HSRL lidar stand-alone retrieval
  - HSRL measures aerosol extinction (355, 532 nm) and backscatter (355, 532, 1064 nm)
  - Aerosol size distribution, refractive index, number/surface/volume concentrations, single scattering albedo etc
  - High vertical resolution
- OE Polarimeter stand-alone retrieval
  - Measures the I, Q, and U Stokes components
  - Measurement angles are approximately  $\pm 55^\circ$
  - Channels are centered at wavelengths 410, 469, 555, 670, 864, 960, 1594, 1880, 2264 nm
  - Better retrieval of refractive index and single scattering albedo, but limited vertical resolution
- OE provides a good framework for combined lidar polarimeter retrievals
  - Straight forward to perform simultaneous vertical profile retrieval by introducing vertical correlations and reducing the impact of random noise
  - Provides a natural way to retrieve a common set of parameters that can be fed into both lidar and polarimeter forward models
  - Provides error estimates for retrieved parameters
- Leverage extensive NASA airborne field campaigns (e.g, DAQ-TX, DAQ-CA, TCAP..)
  - Remote sensing HSRL2  $3\beta + 2\alpha$  measurements
  - Remote sensing RSP airborne measurements
  - Correlative in-situ aerosol measurements
  - All instruments are on the same airplane platform



# Flow Diagram of the OE Lidar-Polarimeter Retrieval Algorithm





# Sequence of the combined Lidar-polarimeter retrieval algorithm

- Combined retrieval will have expanded  $x$ ,  $y$ , and  $K$ :
  - $x_{n+1} - x_a = (K^T S_y^{-1} K + S_a^{-1}) K^T S_y^{-1} [(y_m - y_n) + K(x_n - x_a)]$
  - $x = [r_f(l), \sigma_f(l), rc(l), \sigma_c(l), \alpha(l), N(l), mr(l), mi(l), u, c, \tau \dots]$
  - $y = [\alpha_{355}(l), \alpha_{532}(l), \alpha_{1064}(l), \beta_{532}(l), \beta_{1064}(l), I_{\omega,\theta}, DOP_{\omega,\theta} \dots]$

$$- K = \begin{bmatrix} \frac{\partial \alpha_{355}(l)}{\partial r_f(l)} & \dots & \frac{\partial \beta_{1064}(l)}{\partial r_f(l)} & \dots & \frac{\partial I_{\omega,\theta}}{\partial r_f(l)} & \dots & \frac{\partial DOP_{\omega,\theta}}{\partial r_f(l)} \\ \vdots & \ddots & \vdots & \dots & \vdots & \ddots & \vdots \\ \frac{\partial \alpha_{355}(l)}{\partial m_i(l)} & \dots & \frac{\partial \beta_{1064}(l)}{\partial m_i(l)} & \dots & \frac{\partial I_{\omega,\theta}}{\partial m_i} & \dots & \frac{\partial DOP_{\omega,\theta}}{\partial m_i} \\ & \vdots & & \ddots & & \vdots & \\ & & 0 & \dots & \frac{\partial I_{\omega,\theta}}{\partial u} & \dots & \frac{\partial DOP_{\omega,\theta}}{\partial u} \\ & & & & \vdots & \ddots & \vdots \\ & & & & \frac{\partial I_{\omega,\theta}}{\partial \tau} & \dots & \frac{\partial DOP_{\omega,\theta}}{\partial \tau} \end{bmatrix}$$

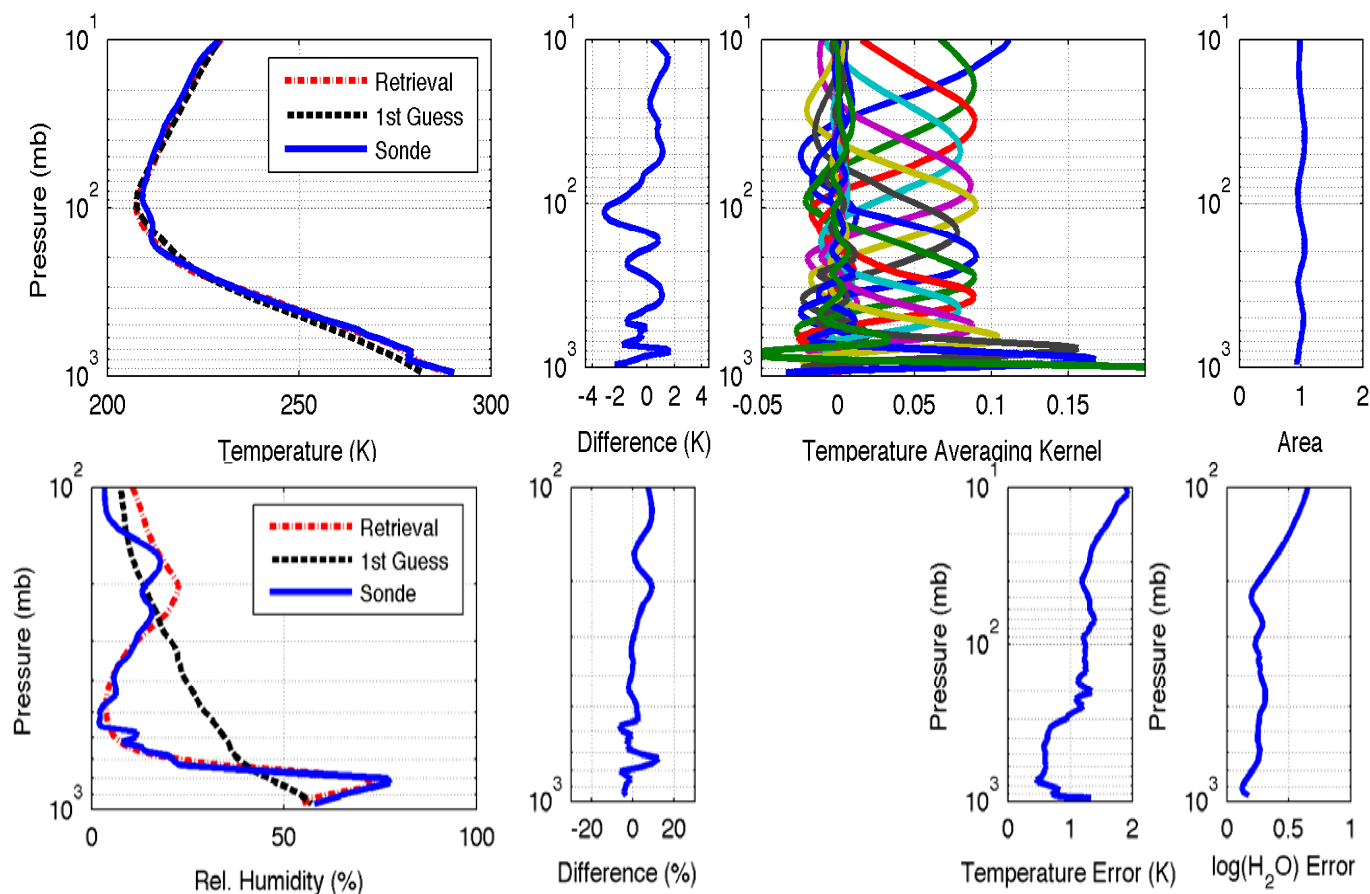
$$- \bar{m}_i = \frac{\sum_{l=1}^n w(l) m_i(l)}{\sum_{l=1}^n w(l)}$$

$$- \frac{\partial I_{\omega,\theta}}{\partial m_i(l)} = \frac{\partial I_{\omega,\theta}}{\partial \bar{m}_i} \frac{\partial \bar{m}_i}{\partial m_i(l)} = \frac{w(l)}{\sum_{l=1}^n w(l)} \frac{\partial I_{\omega,\theta}}{\partial m_i}$$



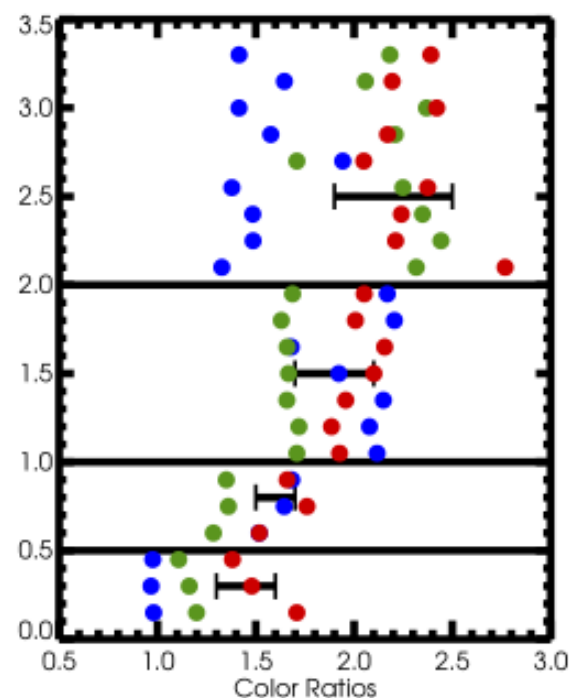
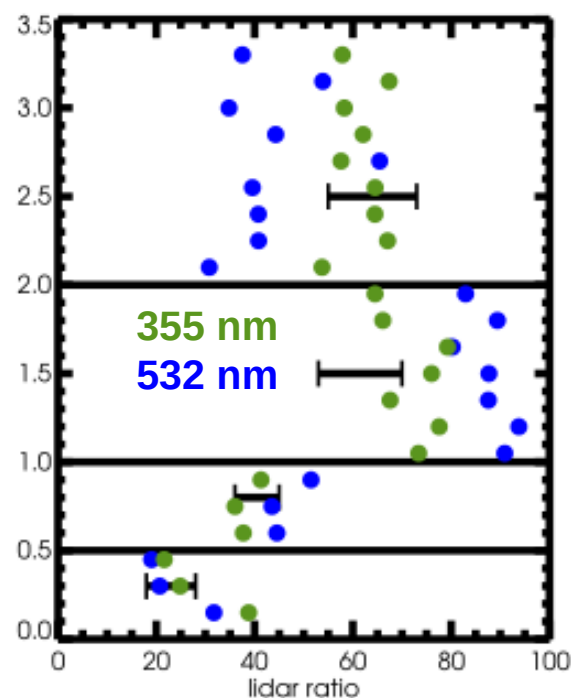
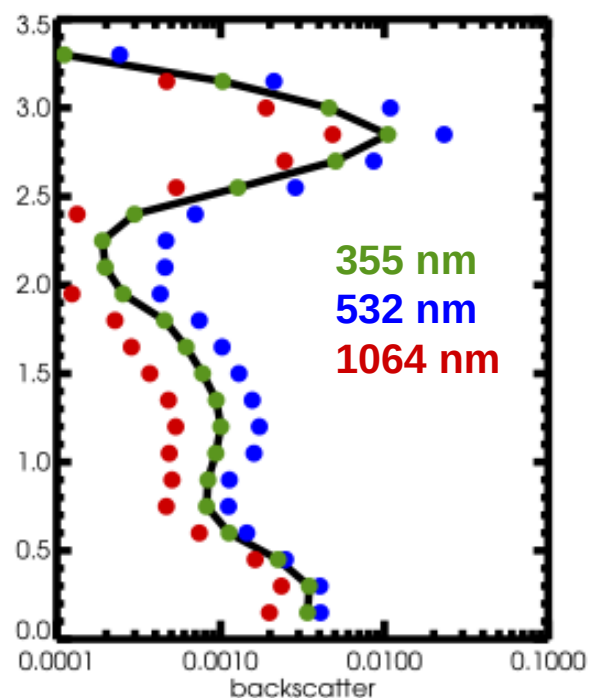
# Based on Previous Work on Profile Sounding at LaRC

- Retrieved Temperature and moisture profiles from LaRC OE algorithm
  - Good agreement with radiosonde
  - Good performance relative to operational algorithms (AIRS, CrIS, ATMS, and IASI)
  - Error estimates provided
- The same OE algorithm will be applied to the combined lidar-polarimeter Retrievals
  - Vertical correlations will be explored
  - Column and profiles information naturally handled





# Example of a 22-layer vertical profile simulations

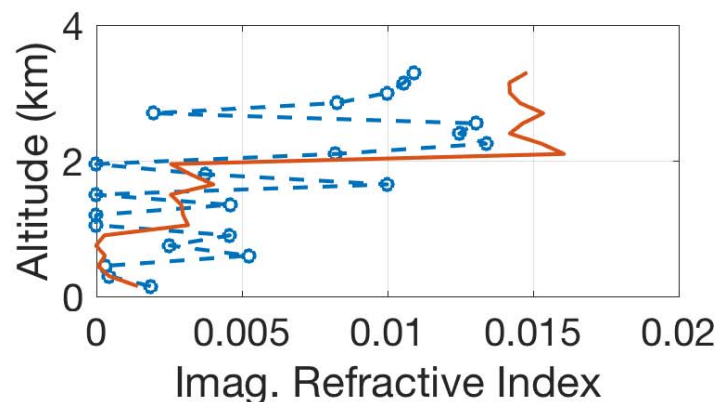
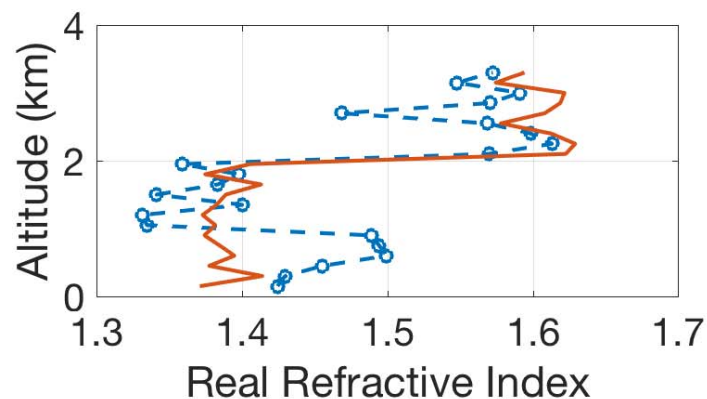
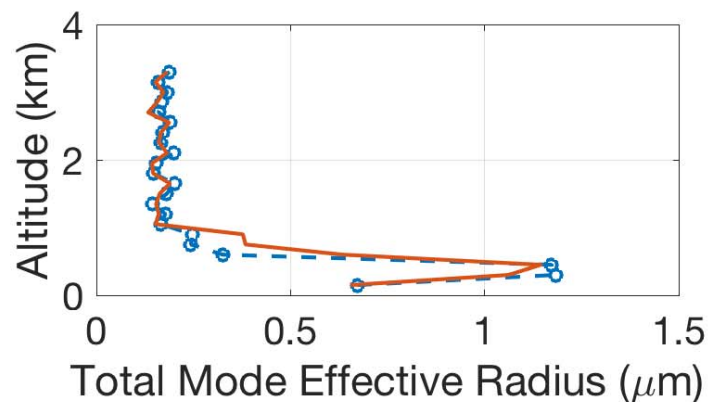
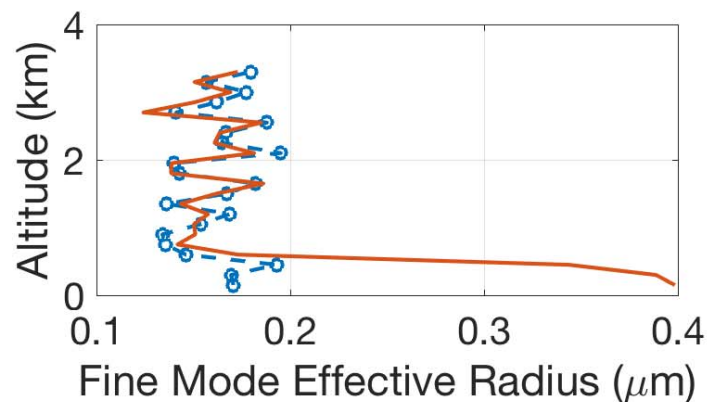
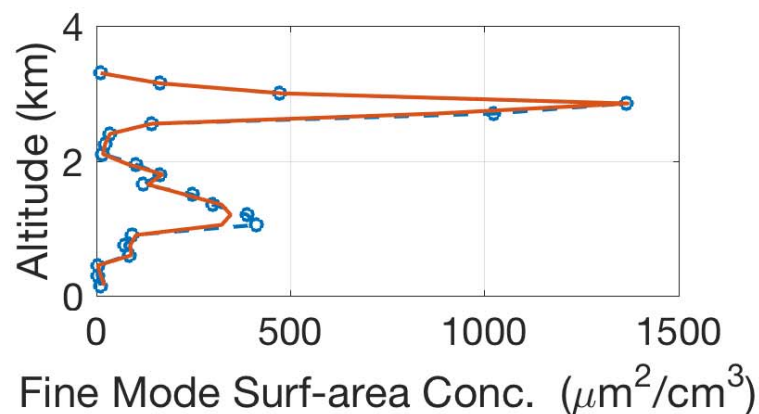
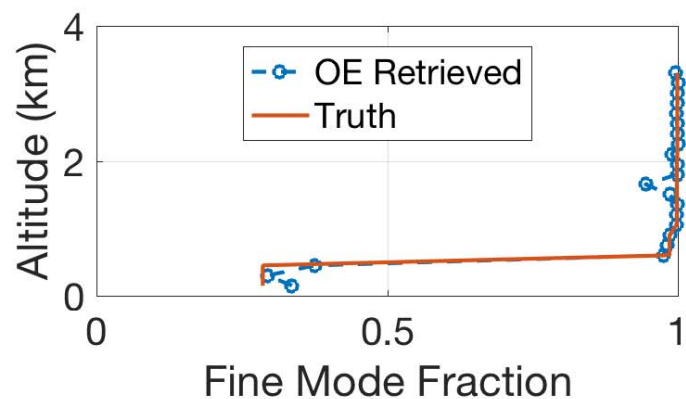


- Profile is composed of 4 simulated layers
  - marine 0-0.45 km (3 levels)
  - polluted marine mixture 0.6-0.9 km (3 levels)
  - urban 1.05 - 1.95 km (7 levels)
  - smoke 2.1 – 3.3 km (9 levels)

532/1064 nm bsc  
355/532 nm bsc  
355/532 nm ext



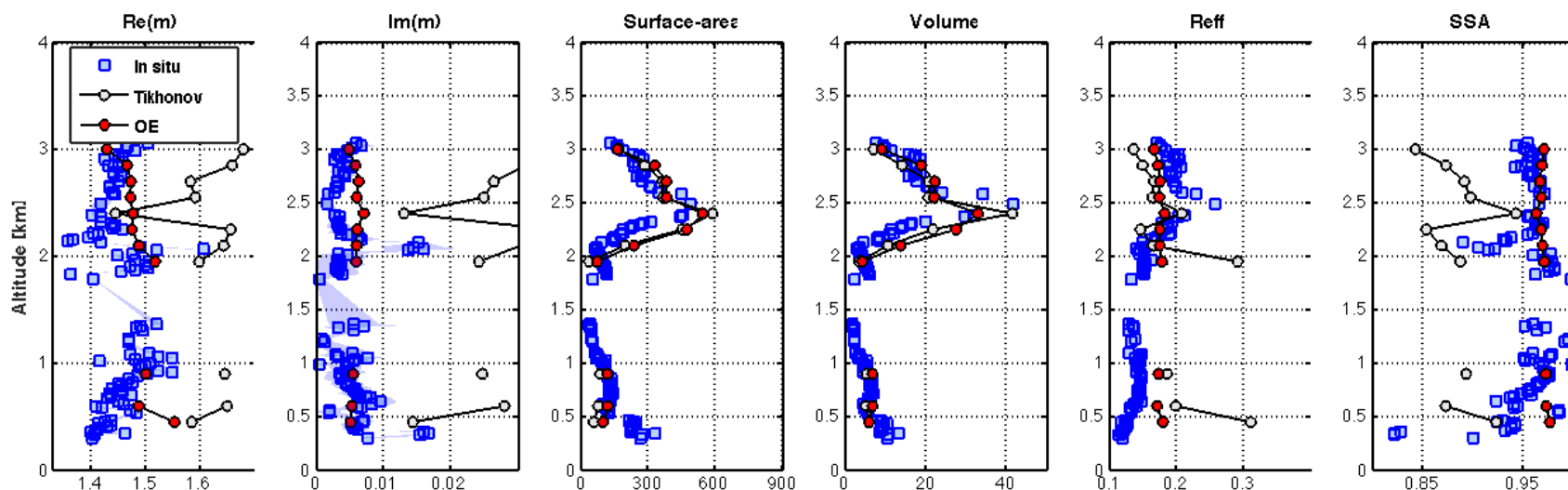
# Optimal Estimation vertical profile retrievals



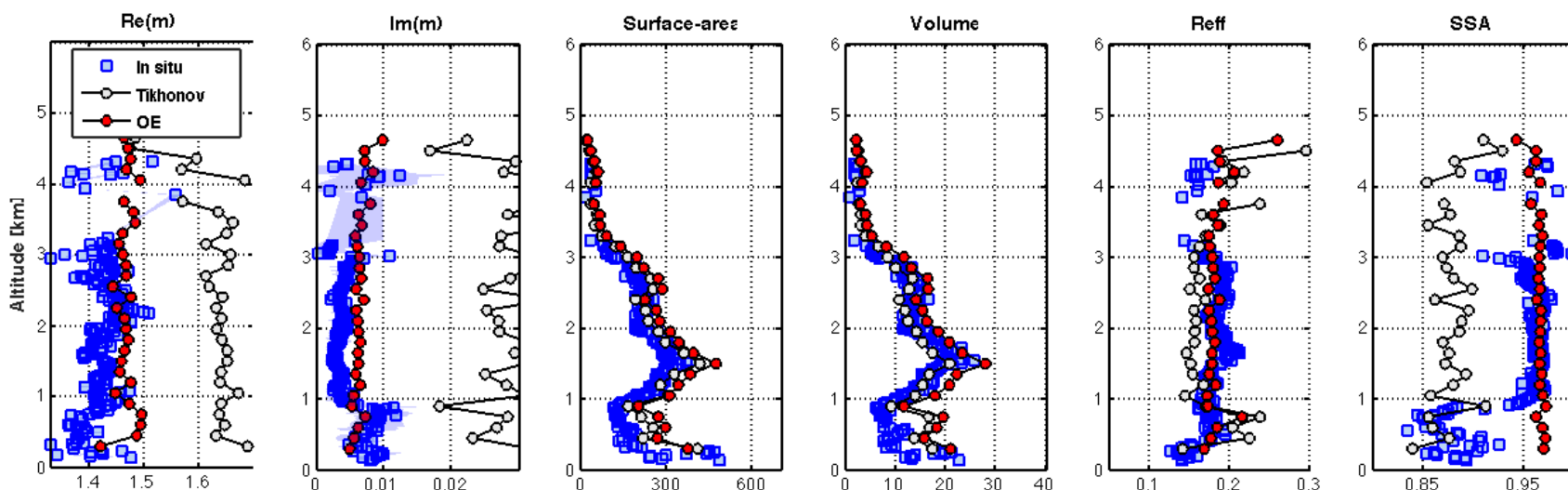


# Vertical Profiles from OE, Tikhonov, and in-Situ Measurements From DAQ TX Field Campaign

UH Moody Tower, TX, 09/13/2013, 14.82-15.06 UTC

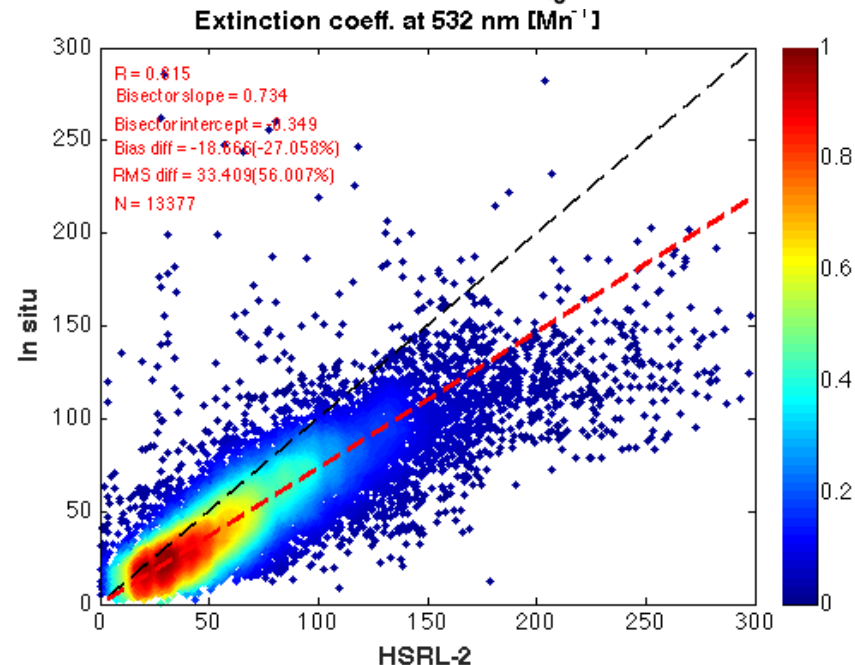
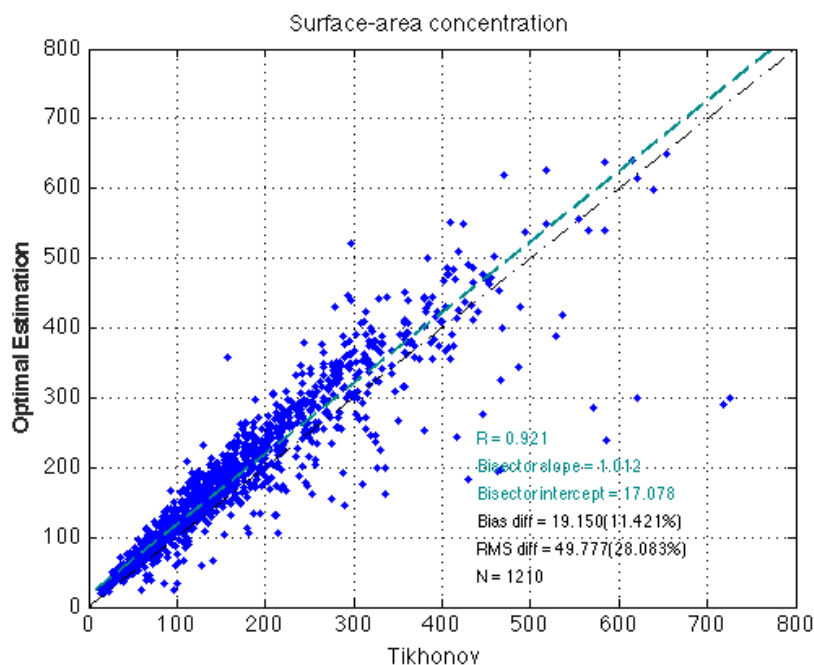
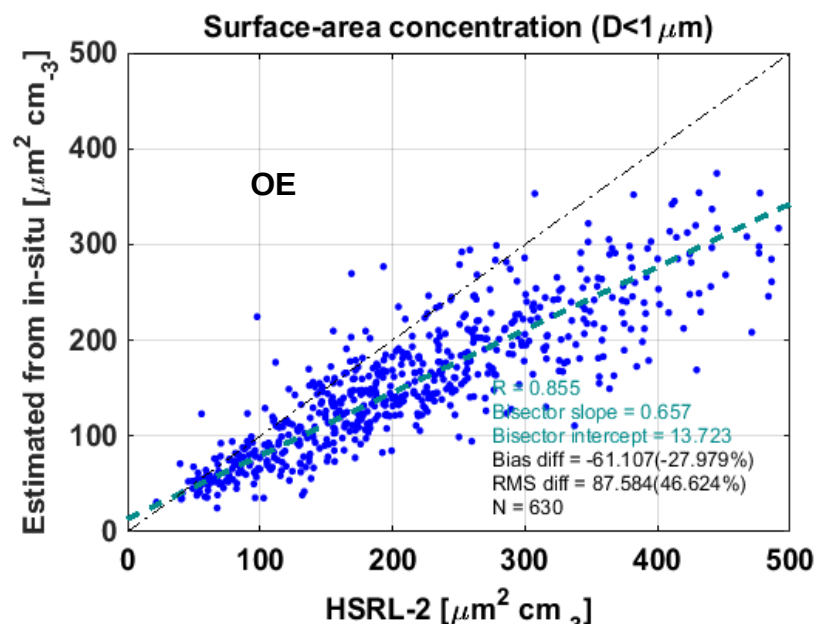
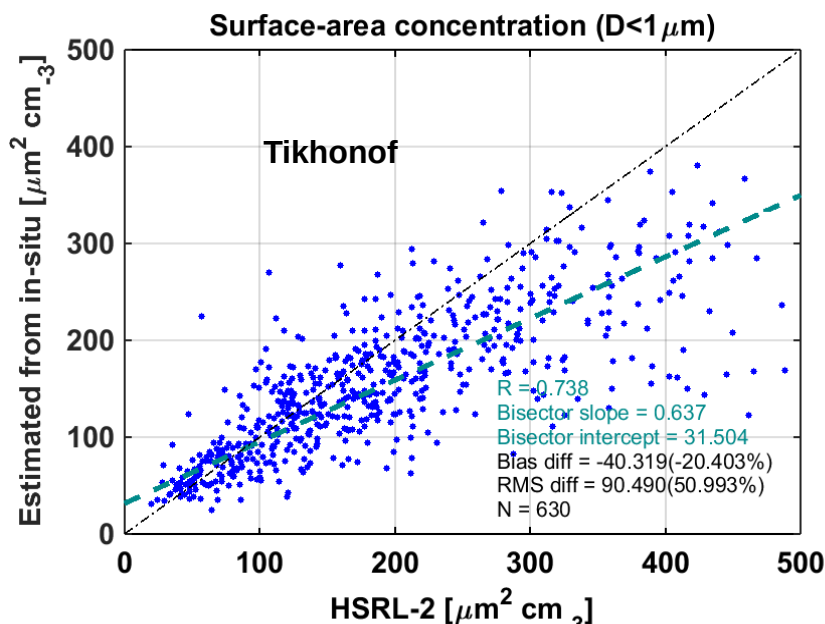


Smith Point, TX, 09/14/2013, 13.44-13.66 UTC



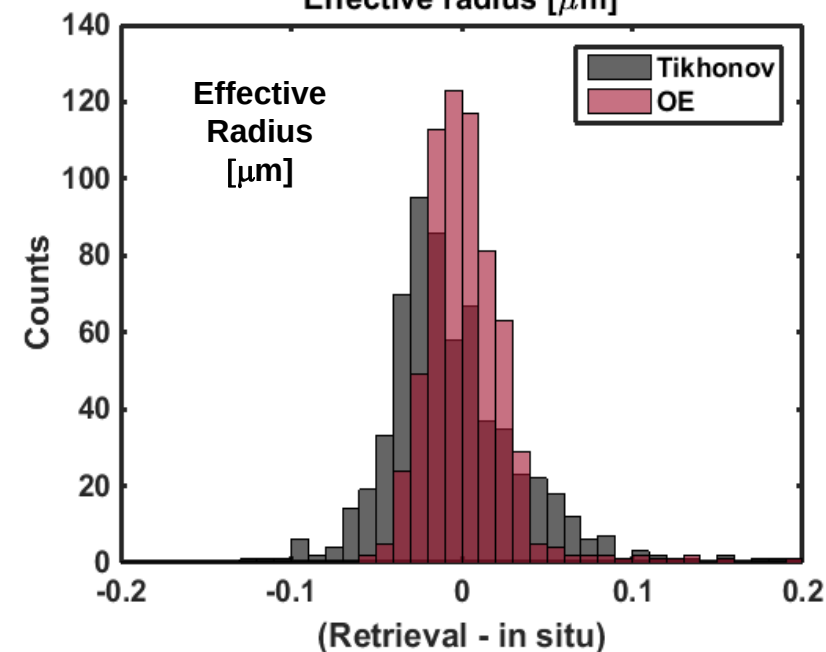
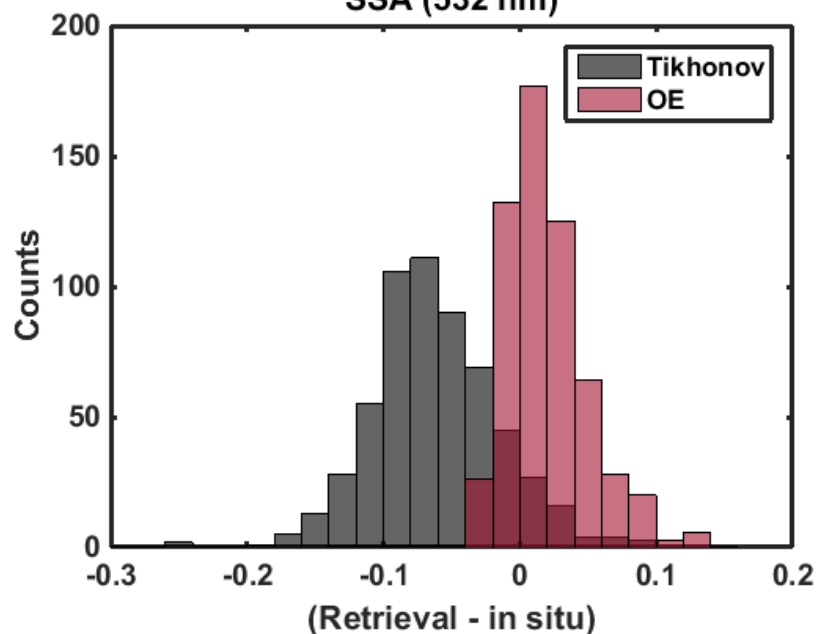
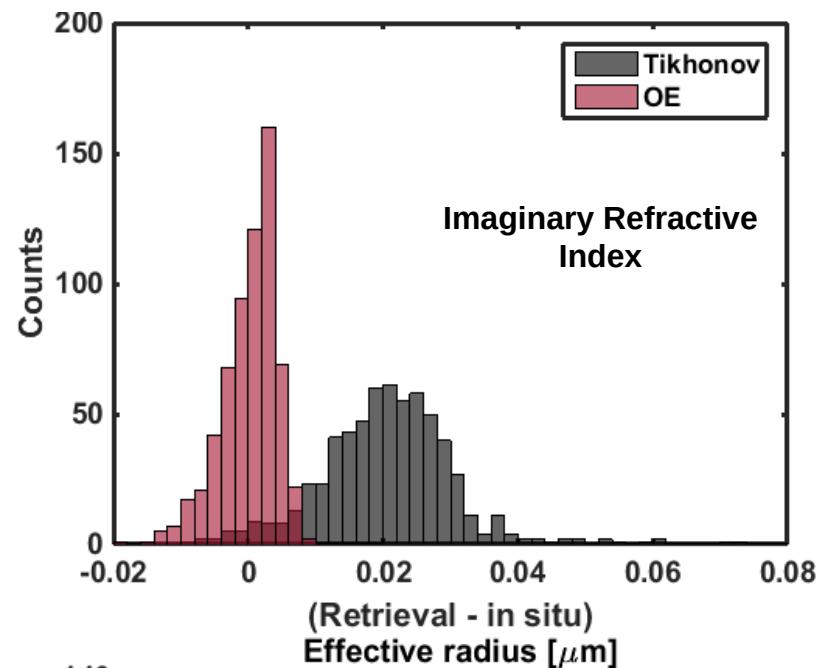
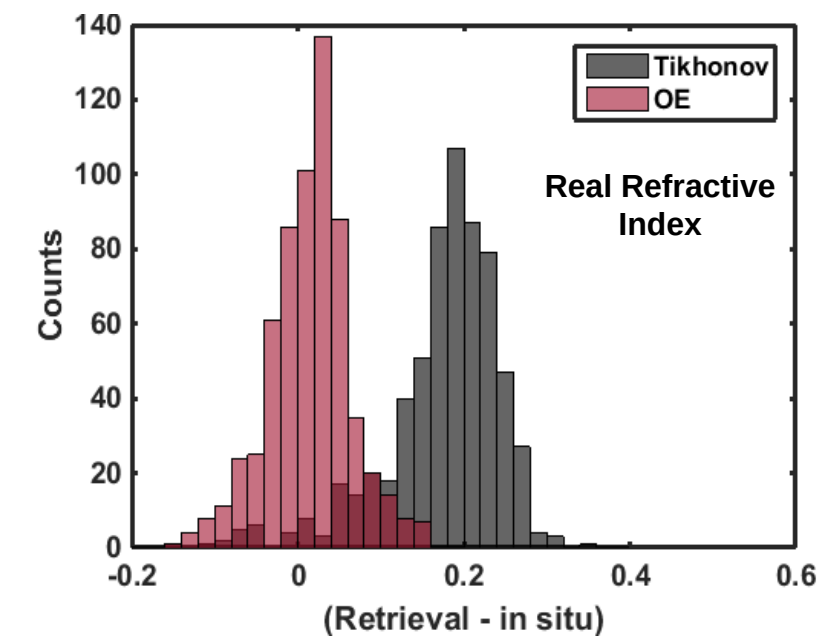


# Surface-area Concentration Retrievals vs In-situ Measurements for DAQ Texas Field Campaign





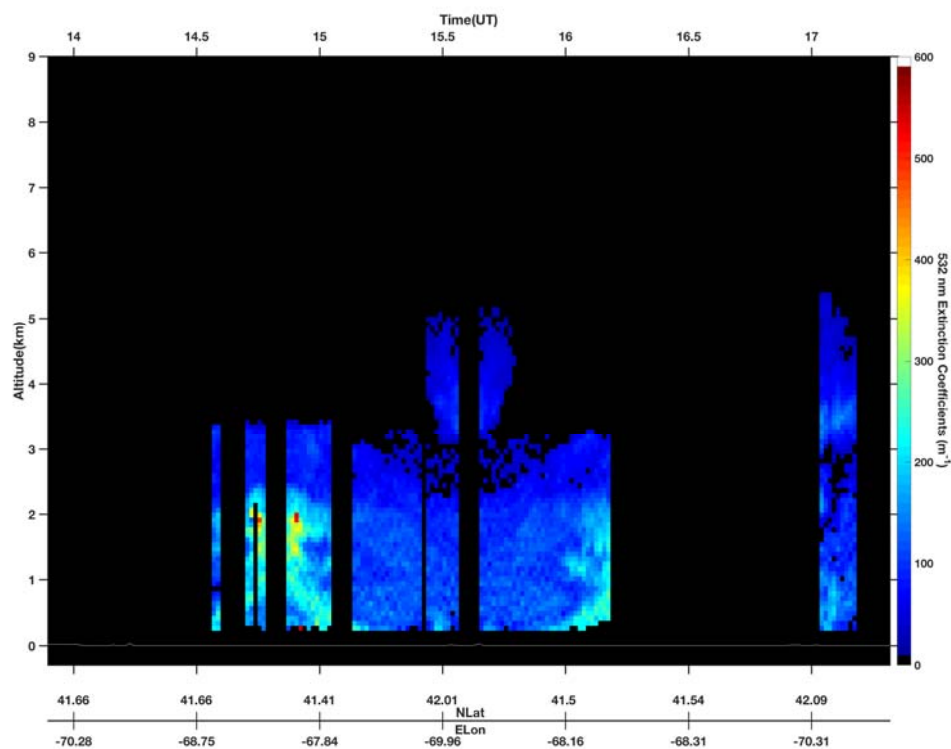
# Comparisons of Retrieved Aerosol Refractive Index, Volume Concentration, and Effective with In-situ Data



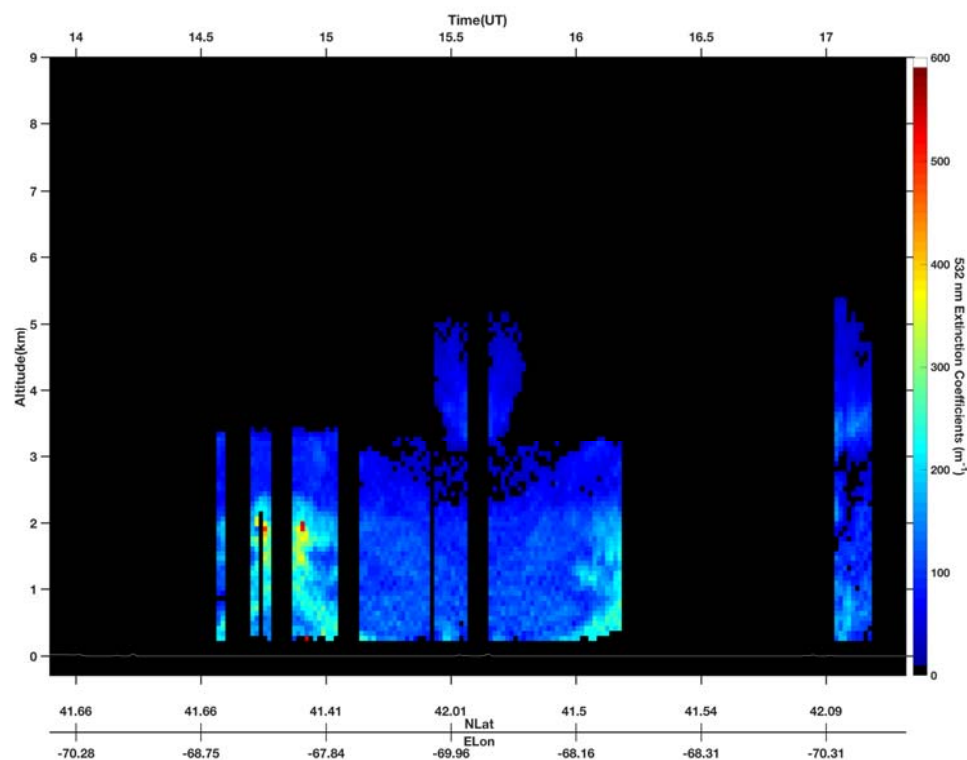


# Fine Mode Surface-area Concentration Retrieved from July 17, 2012 TCAP HSRL2

July 17, 2012



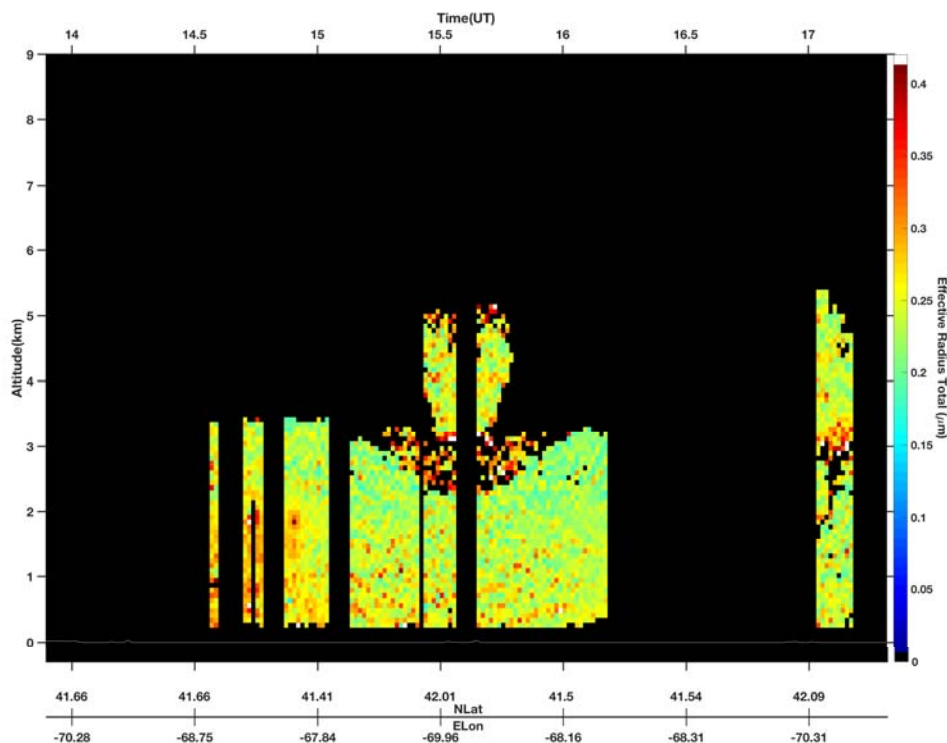
HSRL2 532 nm extinction coefficients



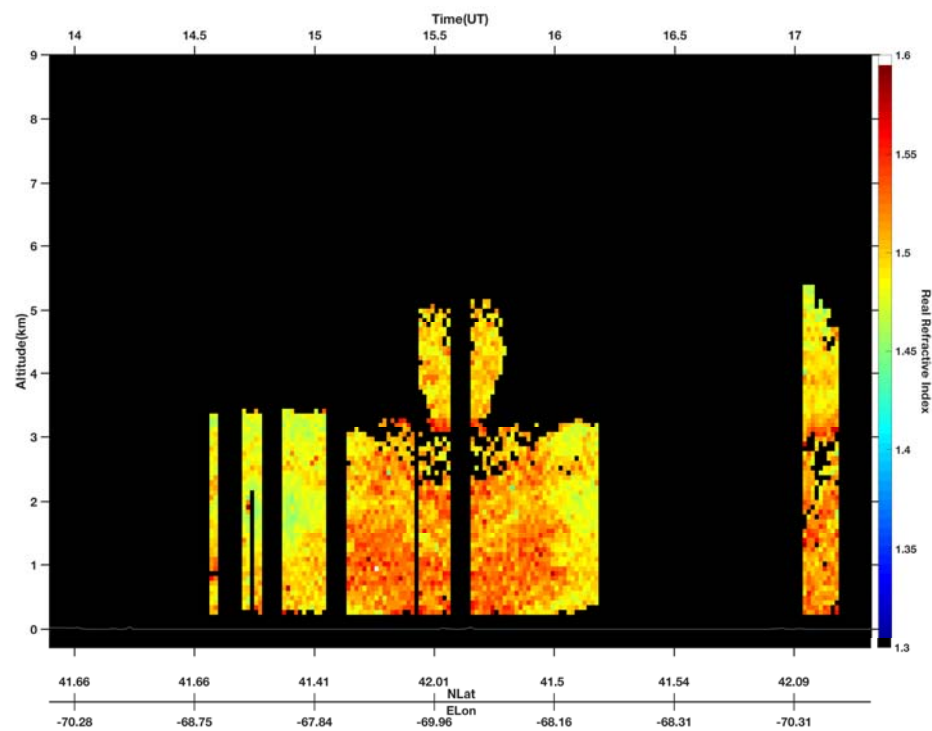
OE Retrieved surface area concentration



# Total Effective Radius from TCAP HSRL2



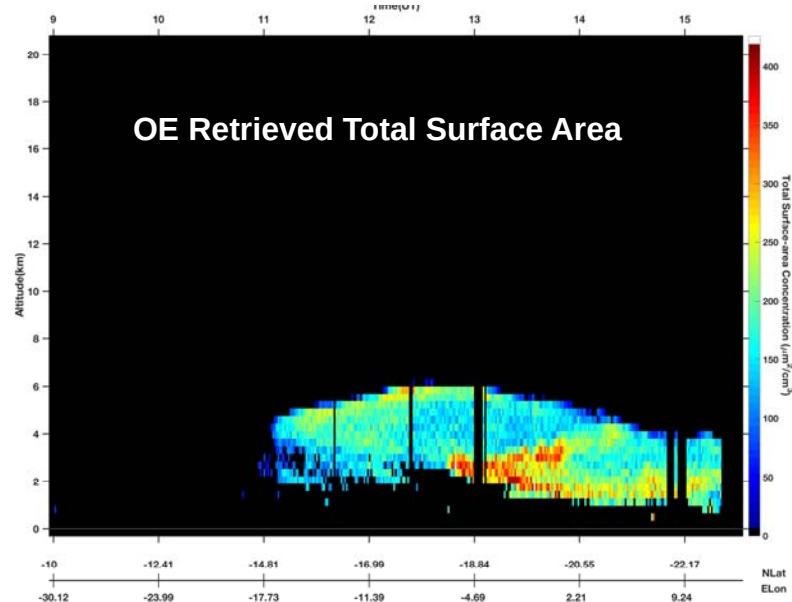
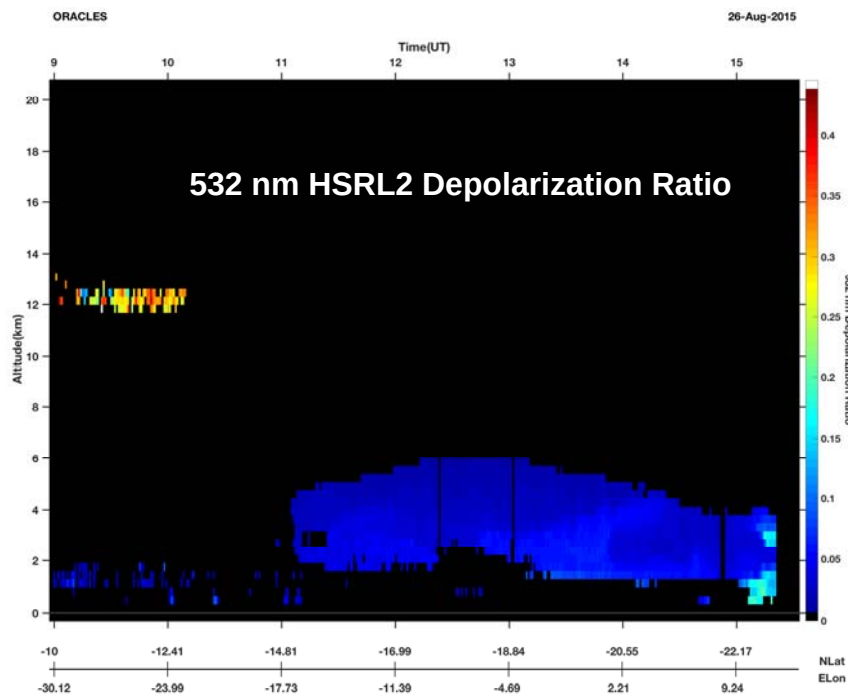
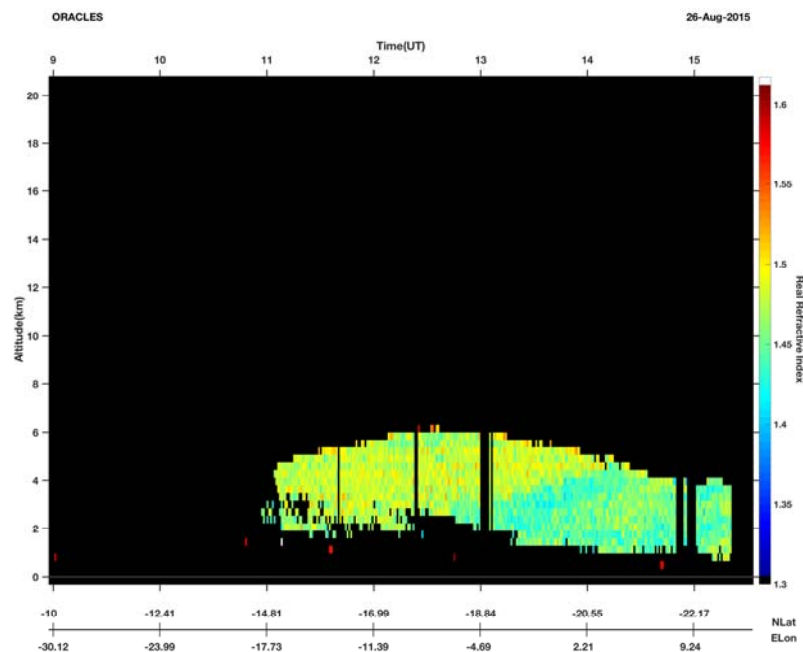
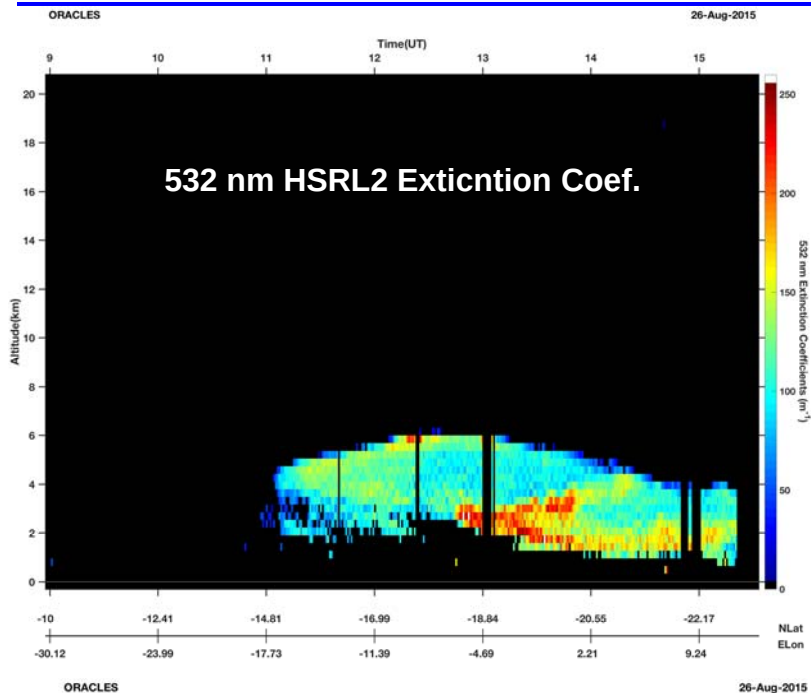
OE Retrieved effective radius



OE Retrieved real refractive index



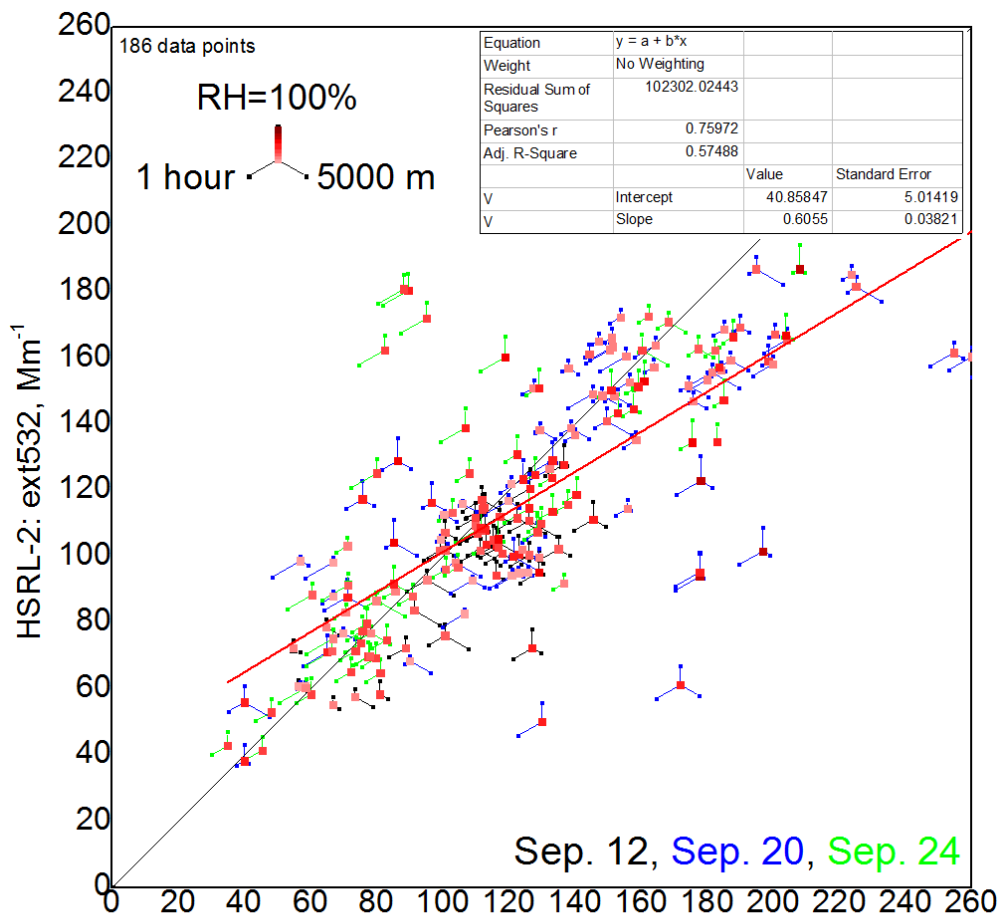
# OE HSRL2 Retrievals for ORACLES Field Campaign, Aug. 26, 2016



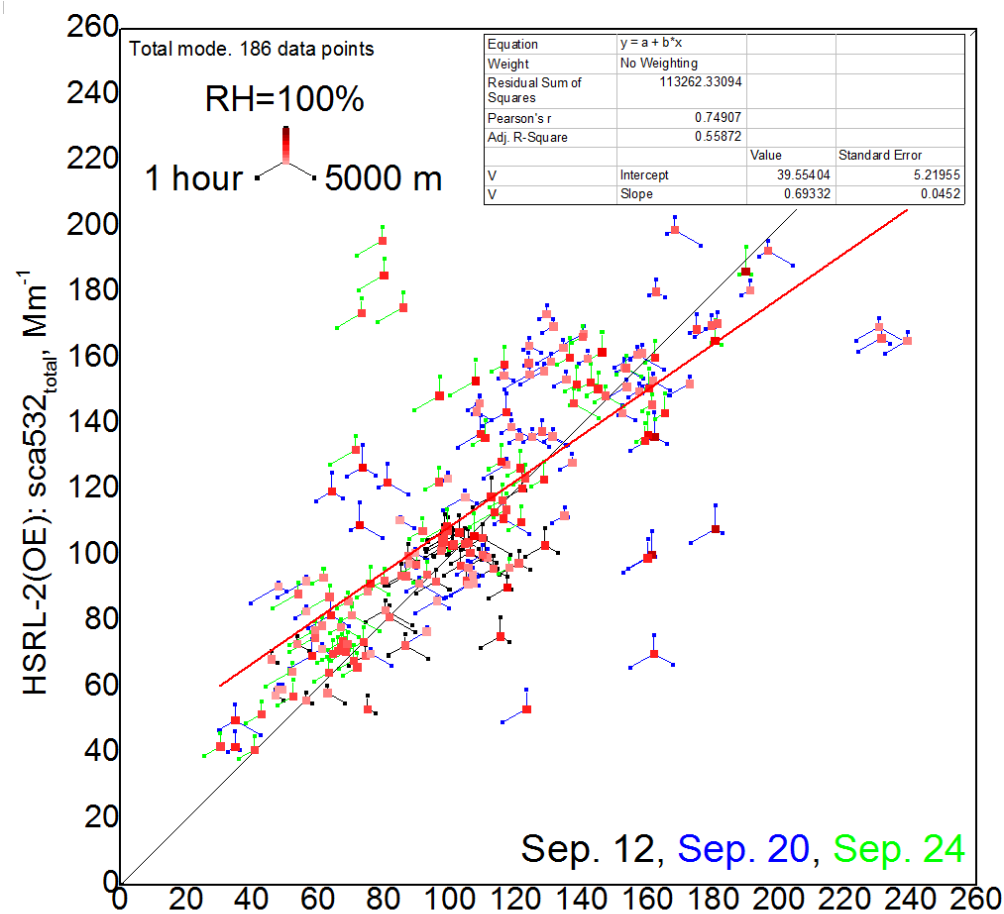


# Comparison of OE HSRL2 Retrievals with In-situ measurements (Preliminary)

- PSAP (Particle Soot Absorption Photometer) aerosol absorption coefficient at 470, 530, and 660nm: Abs
- Scattering coefficient (at 450, 550, and 700nm) from TSI 3563 integrating nephelometer #1: ScatTSI1
- HSRL2 (extinction coefficients at 532 nm)



In situ:  $(\text{abs}530 + \text{sca}530 \cdot [(100 - \text{RH}_{\text{dry}})/(100 - \text{RH}_{\text{amb}})]^{\gamma}) \cdot 273.2/T \cdot P/1013.2, \text{Mm}^{-1}$

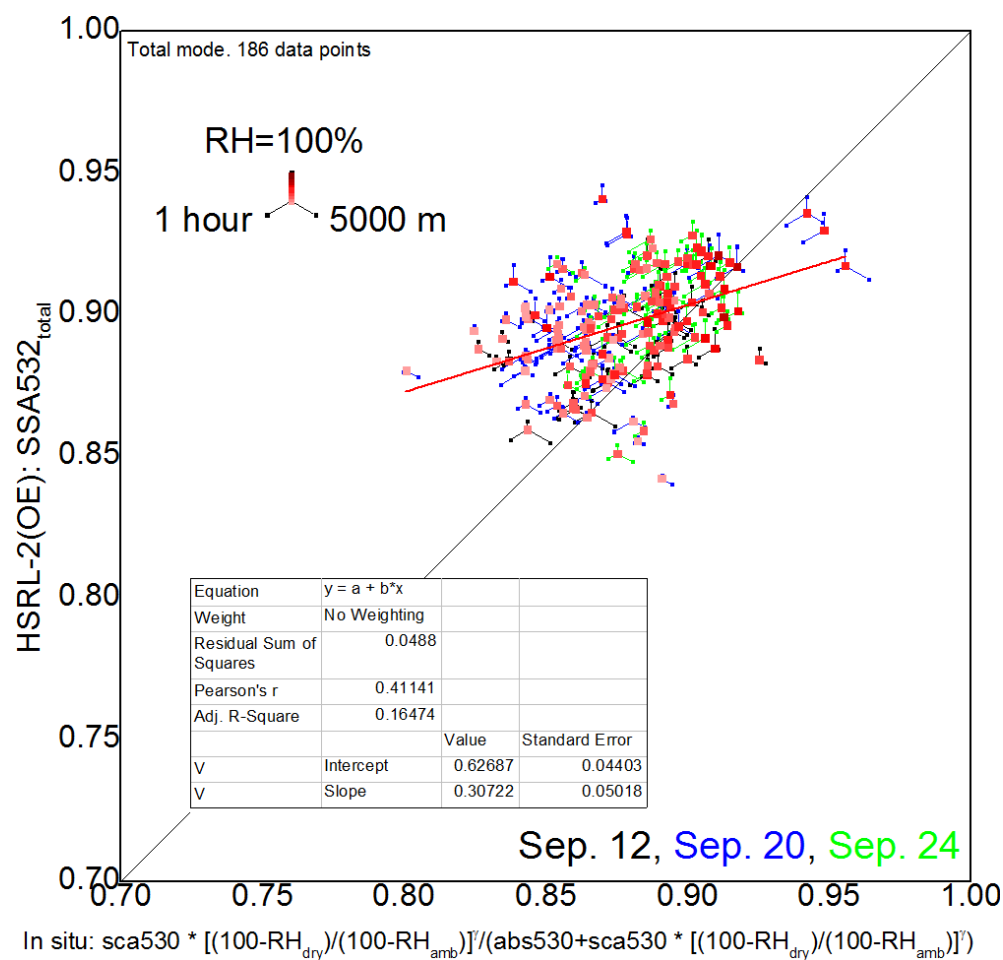
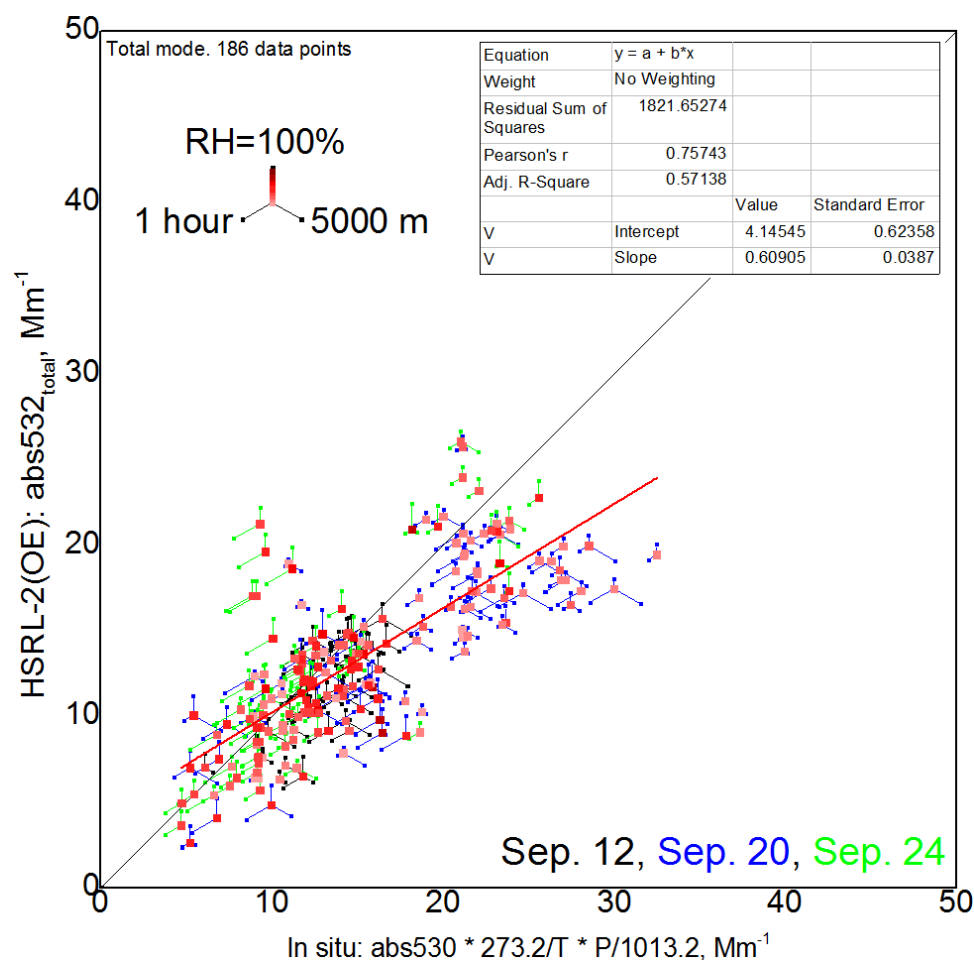


In situ:  $\text{abs}530 \cdot \text{SSA}530 / (1 - \text{SSA}530) \cdot [(100 - \text{RH}_{\text{dry}})/(100 - \text{RH}_{\text{amb}})]^{\gamma} \cdot 273.2/T \cdot P/1013.2, \text{Mm}^{-1}$



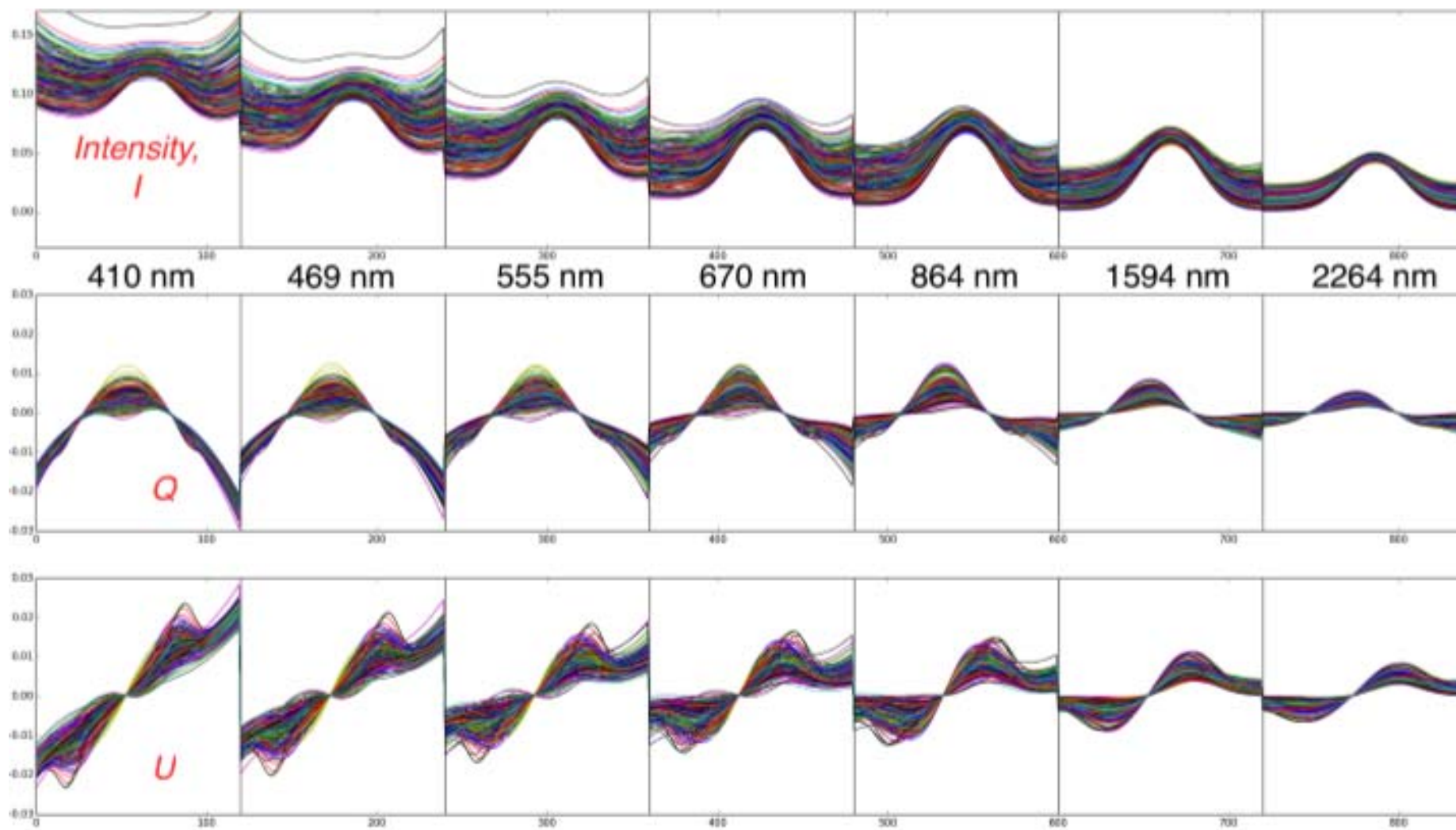
# Comparison of OE HSRL2 Retrievals with In-situ measurements (Preliminary)

- PSAP (Particle Soot Absorption Photometer) aerosol absorption coefficient at 470, 530, and 660nm: Abs
- Single scattering albedo (at 470, 530, and 660nm), calculated from PSAP and TSI nephelometer data: SSA





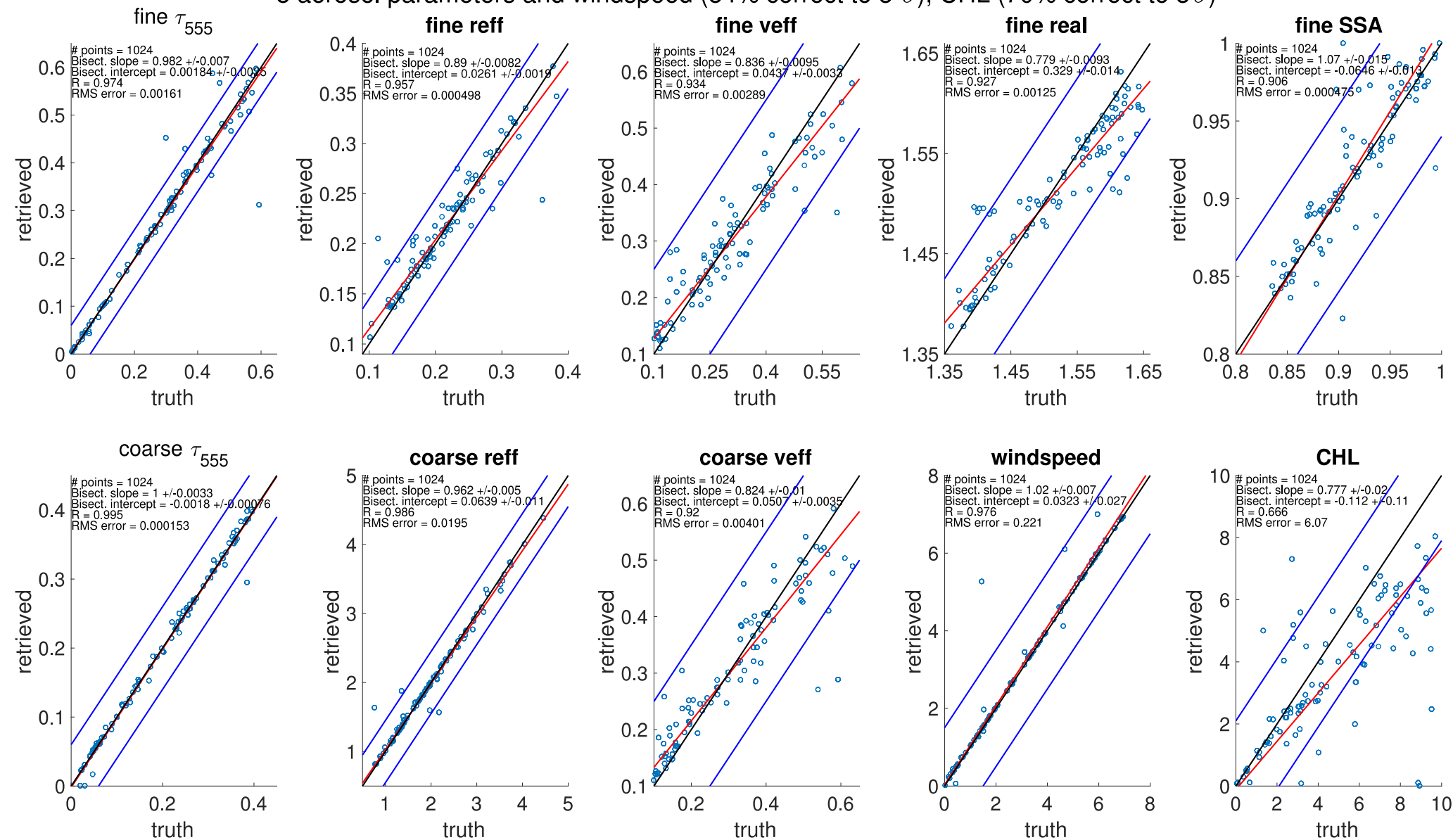
# Simulated RSP Polarized Radiances at different observation angles and wavelength





# OE Polarimeter Simulation Retrieval Results

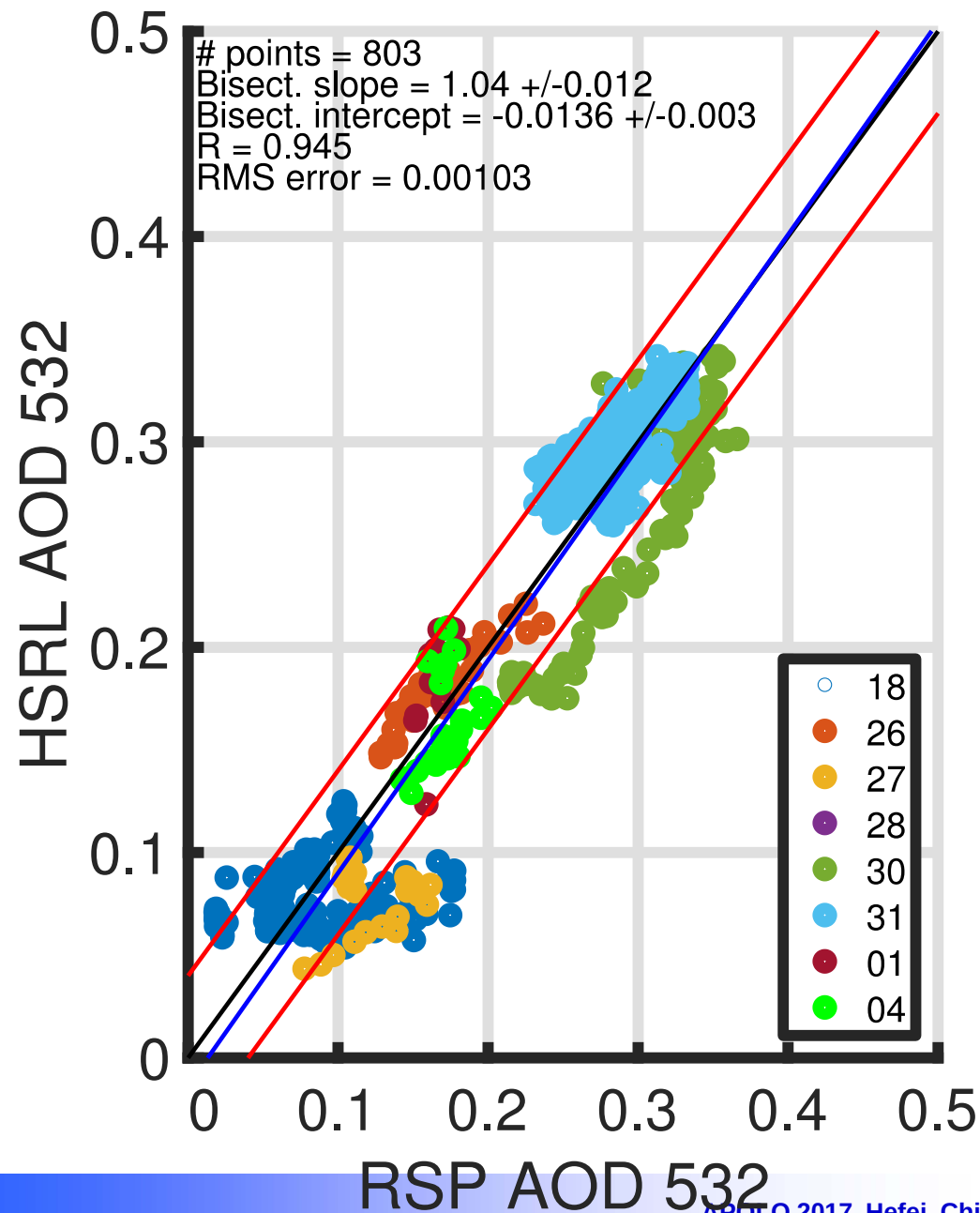
8 aerosol parameters and windspeed (84% correct to  $3\sigma$ ), CHL (70% correct to  $3\sigma$ )



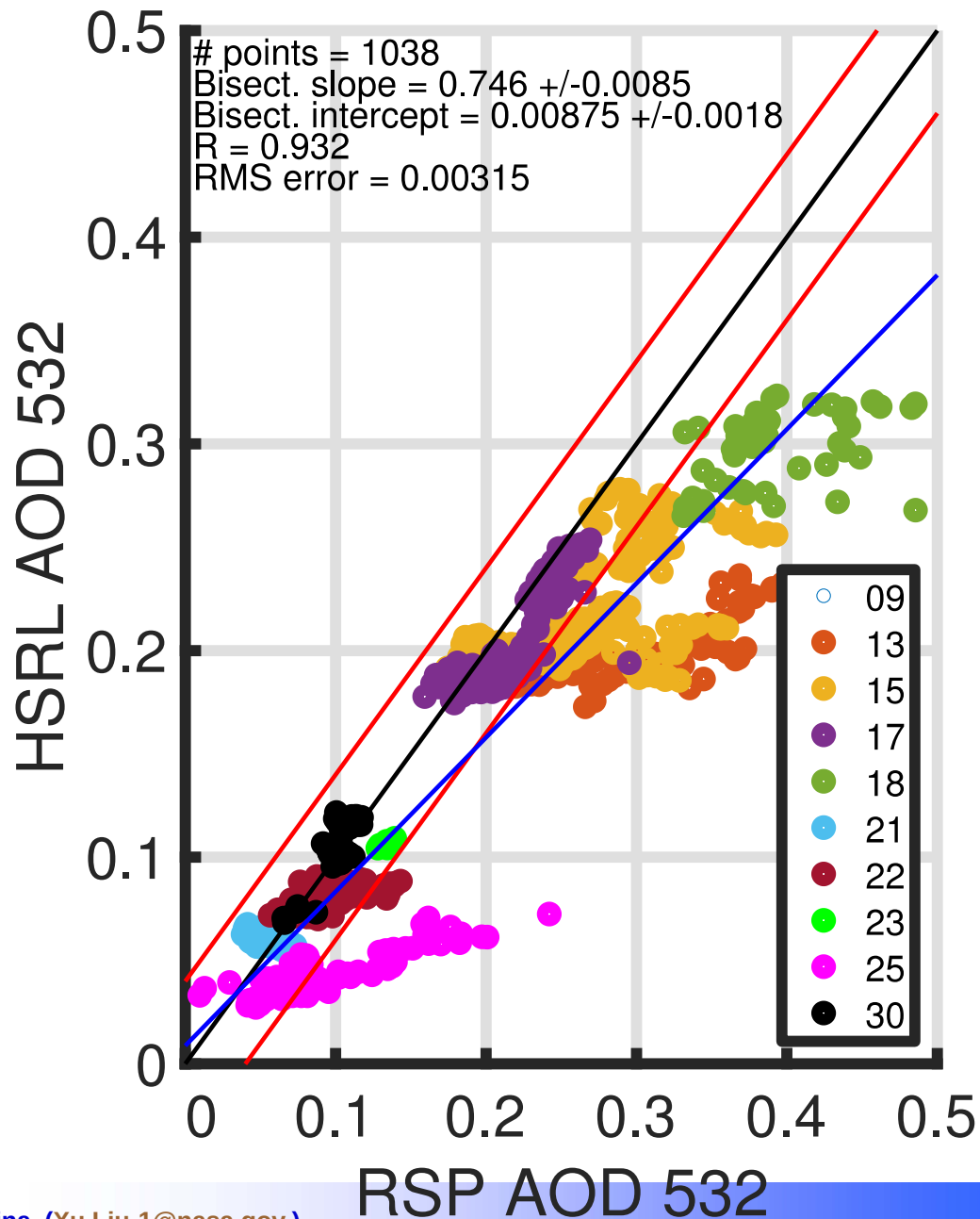


# Comparison of aerosol products vs HSRL (real data)

NASA SABOR campaign (better cirrus reporting)



DOE TCAP campaign

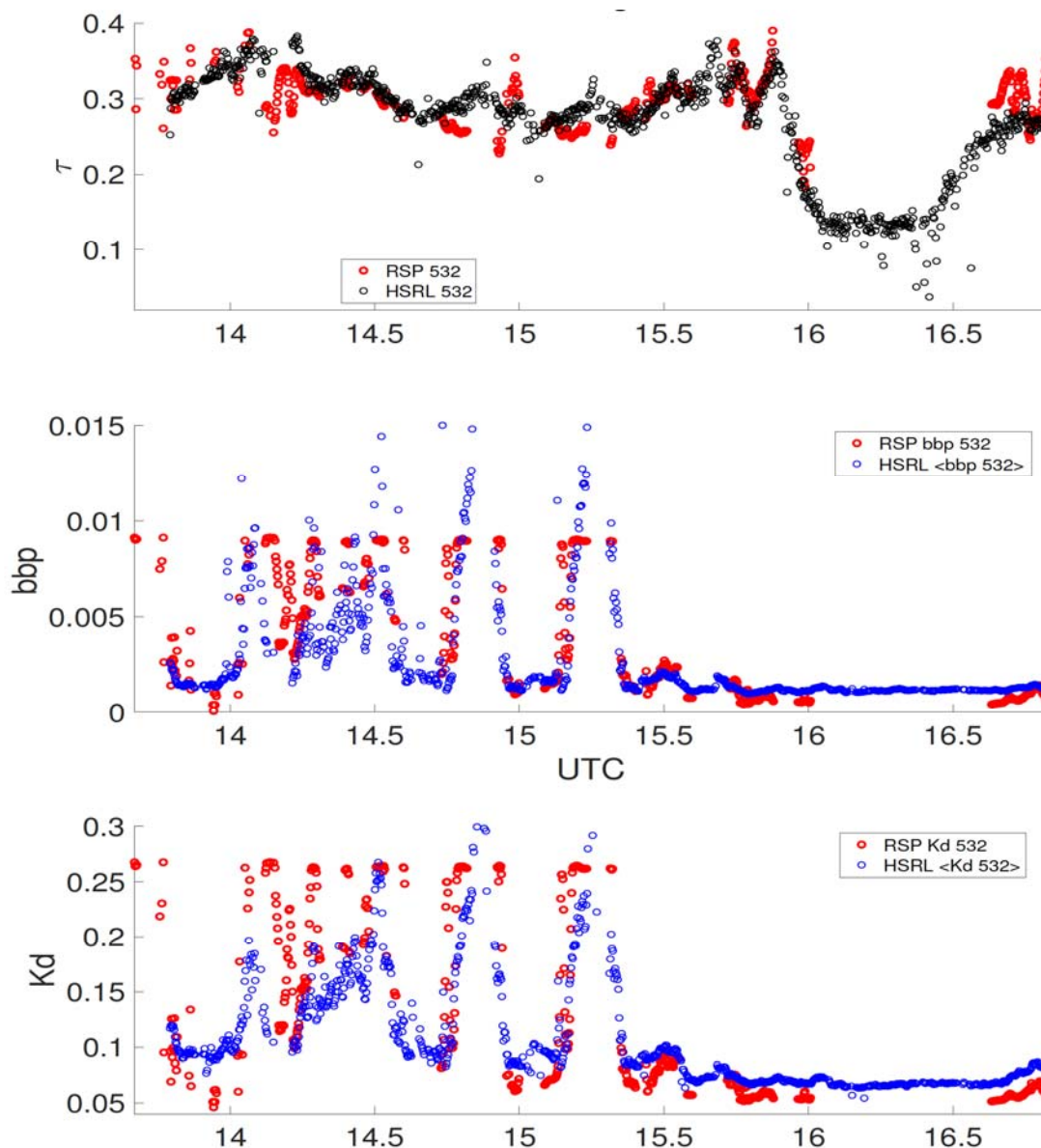
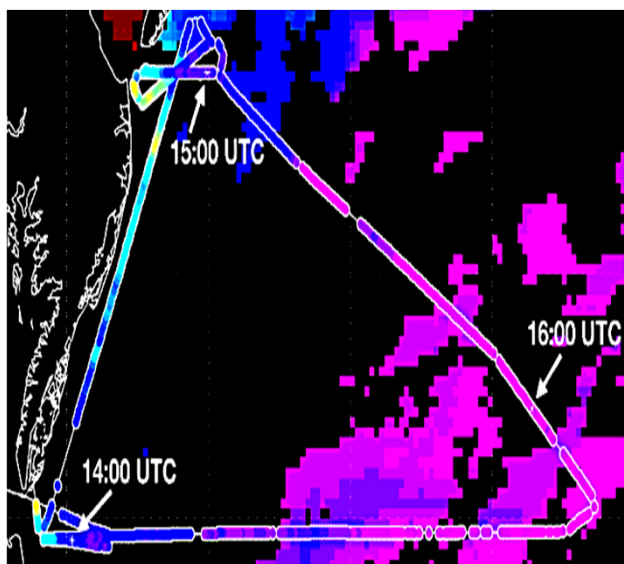




# OE Polarimeter Retrievals for NASA SABOR Field Data

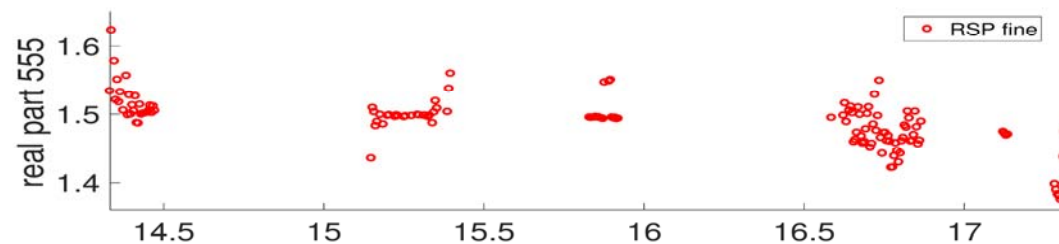
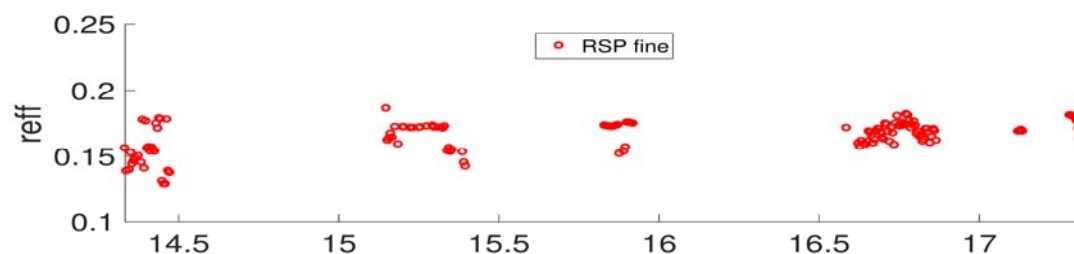
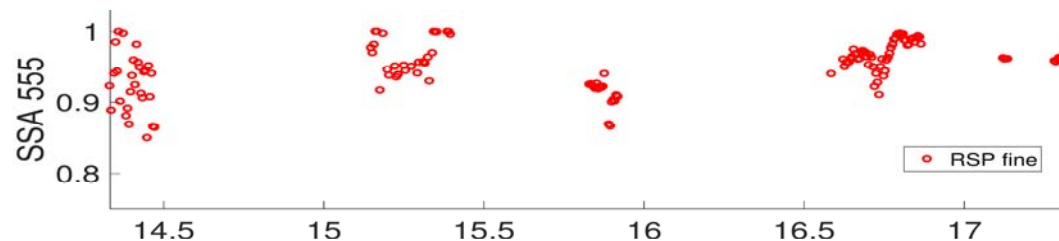
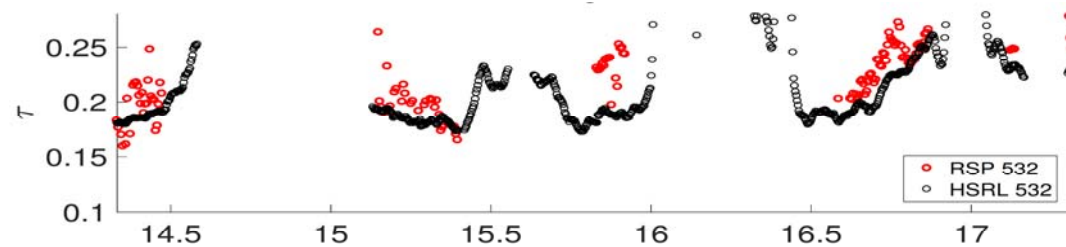
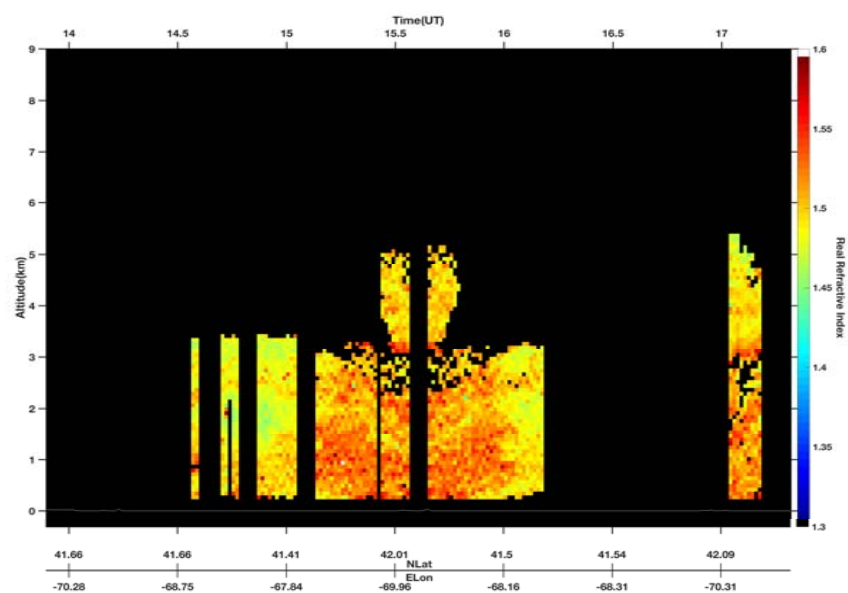
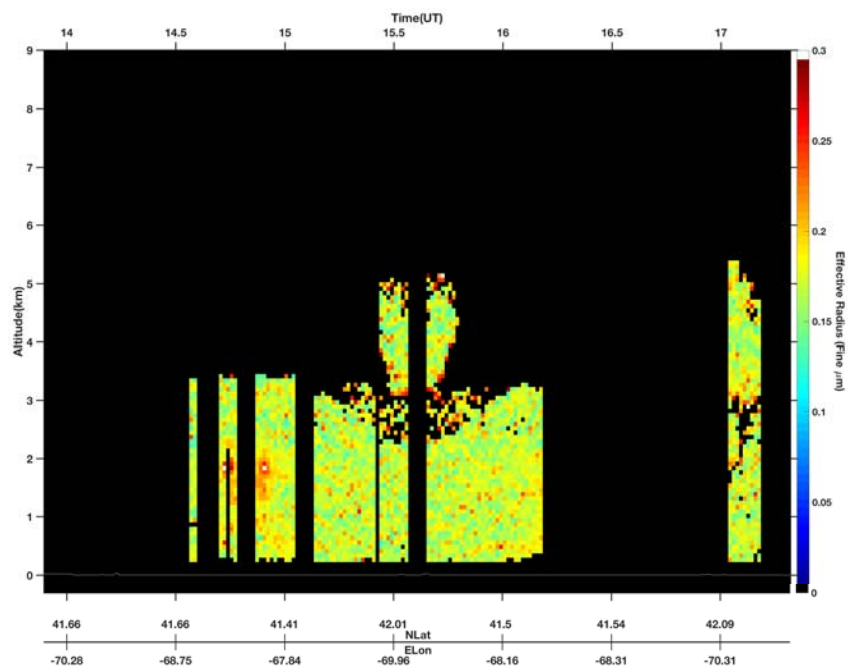
NASA SABOR campaign (07/31/2014). Note: there was cirrus above the aircraft around ~14 UTC and ~15.75 UTC.

- HSRL1 is now capable of measuring important **ocean color** parameters  $K_d$ , the diffuse attenuation coefficient, and  $bbp$ , the hemispherical integrated particulate backscatter.
- MAPP also retrieves surface properties.
- The MAPP ocean surface products are currently the **chlorophyll concentration** (from which we can compute  $K_d$  and  $bbp$ ) and the **wind speed**.
- Initial results of  $K_d$  and  $bbp$  between RSP/MAPP and HSRL1 look promising.





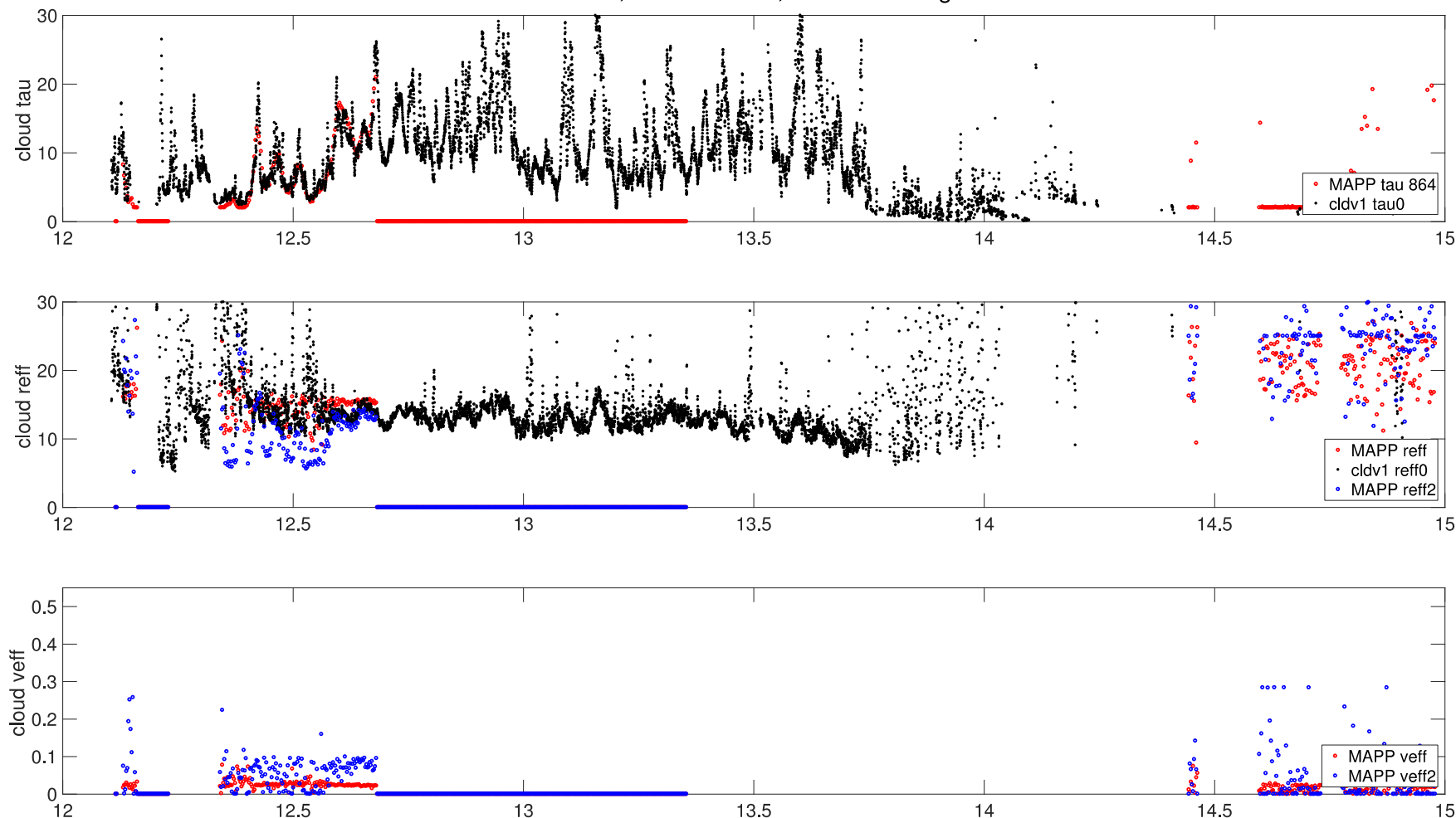
# Retrievals from NASA TCAP Campaign





# OE Retrieved Cloud Properties From ORACLES RSP Data

ORACLES 20160912 AAC MAPP v1.46, 638 retrievals, 23.2% converged





# Summary and conclusions

- OE retrieval algorithm developed and tested for Lidar-only and Polarimeter-only modes
  - Simultaneously performs vertical profile retrievals for HSRL2 data
    - Retrieves 8 basic parameters and other parameters such as SSA and absorption can be calculated
    - Traditional methods perform retrievals layer by layer
    - Needed for combined lidar and polarimeter retrievals
  - Retrieves aerosol, cloud, and surface properties from RSP polarimeter data
    - Retrieves 8-10 parameters depends on cloud and surface conditions
    - Aerosol parameters consistent with LIDAR retrievals
    - LIDAR vertical information used in defining the aerosol layers
  - Simulation/retrieval studies performed
    - Retrieval performance verify
    - Error estimates for retrieved parameters provided by the algorithm
- Algorithm has been applied for the following NASA and DOE field data
  - DISCOVER-AQ, SABOR, TCAP, ORACLES, CHARM
  - The retrieved aerosol properties compare well with in-situ measurements
- Future work
  - Extend polarimeter retrieval to land surface
  - Combined Lidar/Polarimeter Retrieval
    - Implemented
    - In the process of testing the performance