Understanding the Plantower response to ambient aerosols as a function of particle composition, size, and meteorological conditions

How can it be used by the NPS

Schichtel, NPS - Air Resource Division

Malm and Day, CSU - CIRA

Ouimette, Sonoma Ecology Center

Prenni and Sive, NPS - Air Resource Division

Sheridan, Andrews, Ogren (retired), NOAA/ESRL

Arnott, Un of NV

PurpleAir monitors can operate unattended on solar power for extended time periods in remote locations


South

North

Barcroft Observatory

PurpleAir

PurpleAir – Inexpensive Air Quality Sensor


- PurpleAir (https://www2.purpleair.com/)
  - "A proven air quality monitoring solution for home enthusiasts and air quality professionals alike"
  - "Using a new generation of <u>laser particle counters</u> to provide real-time measurement of <u>PM1.0, PM2.5 and PM10</u>."
  - It fits in your hand and cost ~$300

- The PurpleAir sensor consists of
  - Two Plantower PMS5003 "laser particle counters"
    - Claims to counts particles > 0.3 µm and bins them into 6 size channels (>0.3, >0.5, >1.0, >2.5, >5.0, and >10.0 µm
  - Pressure, RH and temperature sensor
  - Data logger – wifi and sd card enabled

What does a PurpleAir Really Measure?

- ✓ Relative humidity
- ✓ Temperature
- ✓ Pressure
- ~~Particulate mass: PM1.0, PM2.5 and PM10~~
- ~~Aerosol size distributions~~

- The Plantower sensor is fine PM light scattering devices
  - Light Scattering (bsp) = f(RH)* α * PM
    - α, Scattering efficiency depends on aerosol size and composition
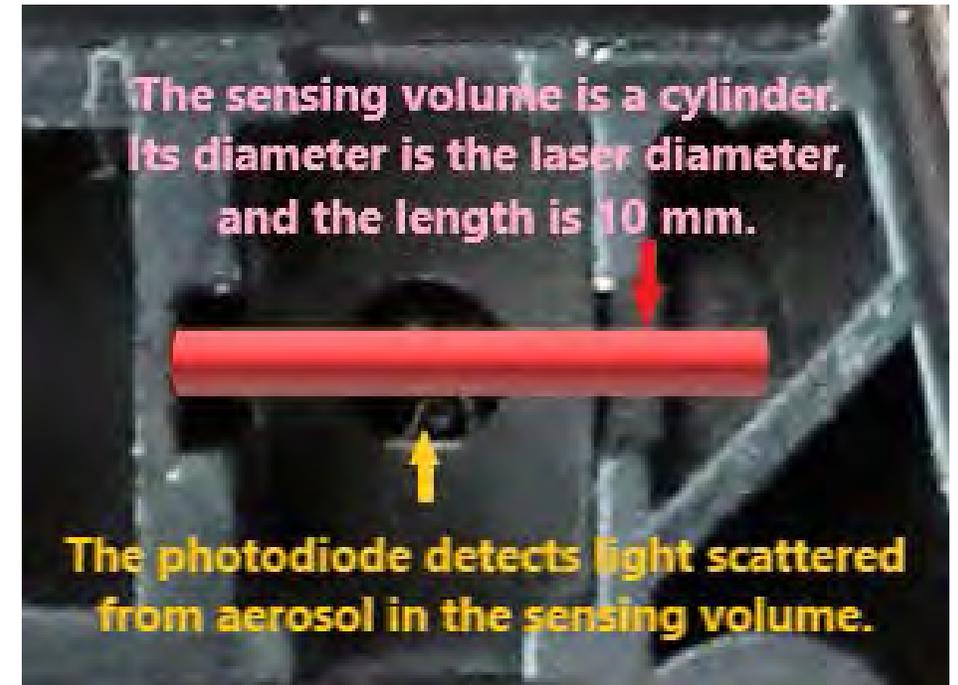   - f(RH) – accounts for increased scattering due to particle size growth with RH
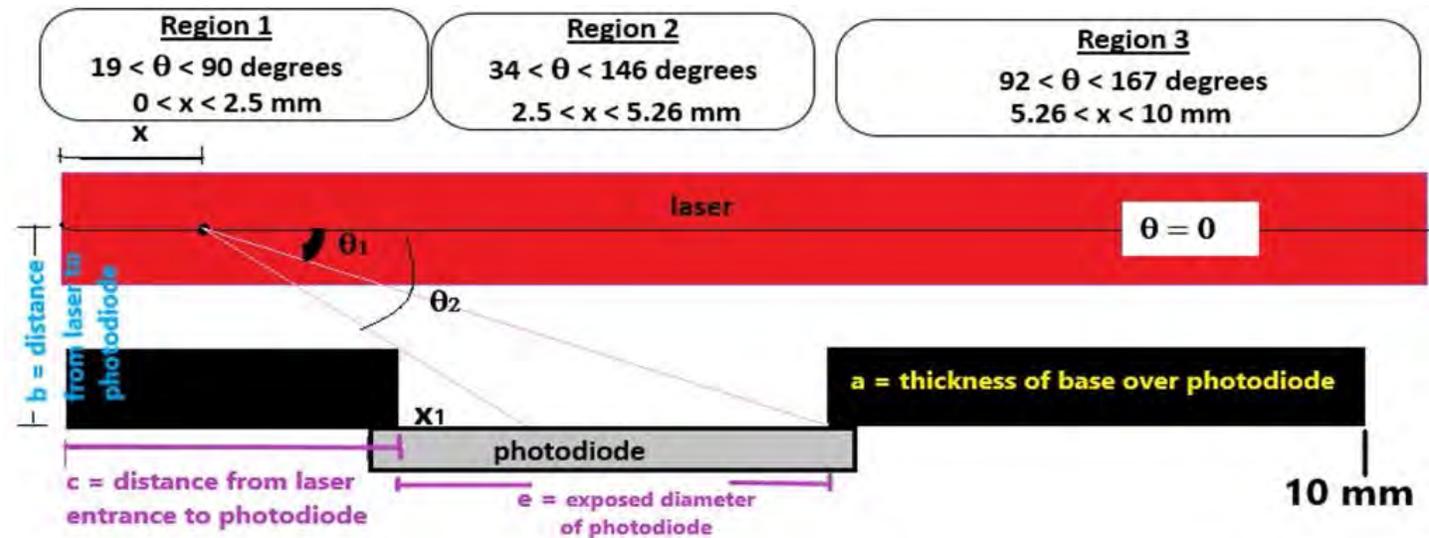
PurpleAir Temperature and RH vs Ambient
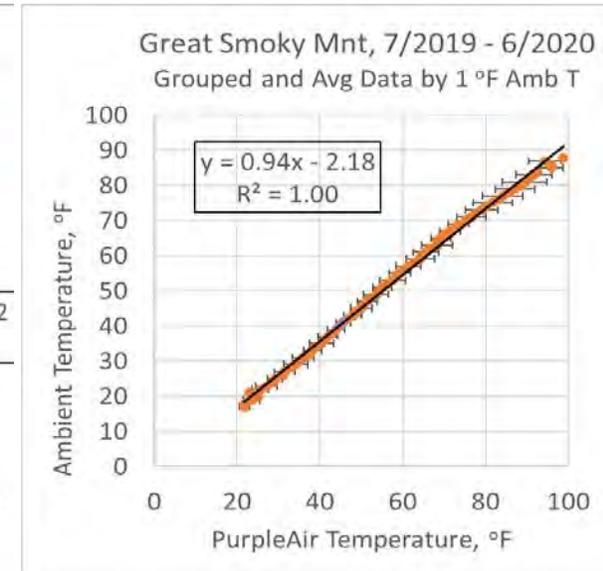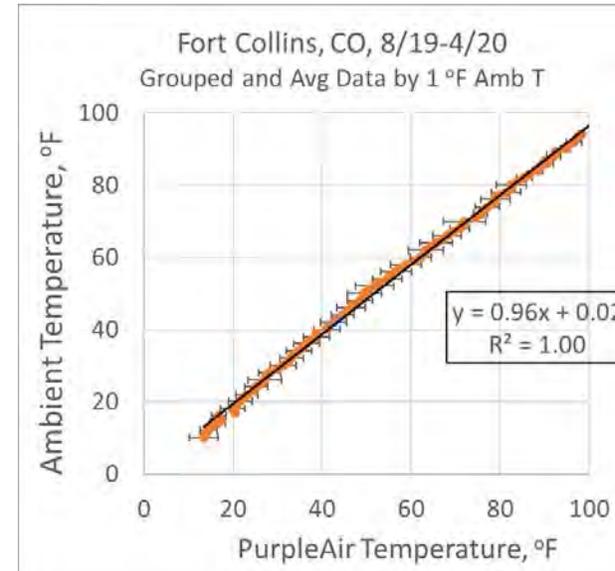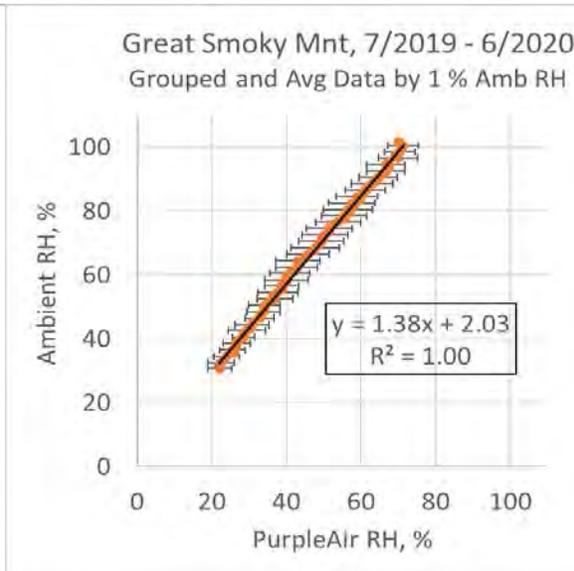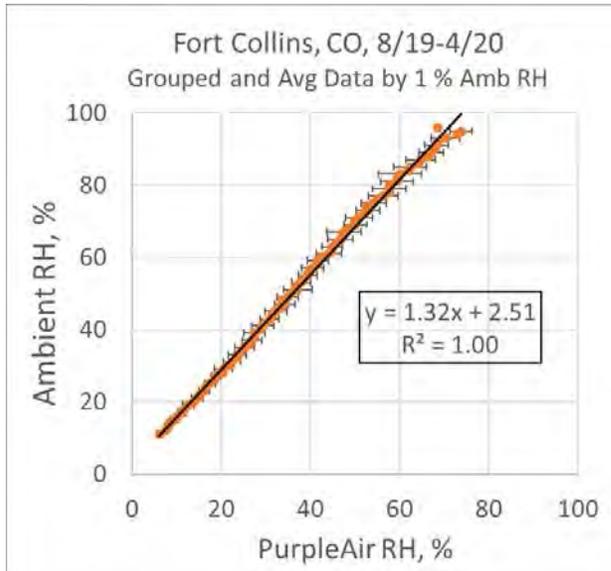
- Data were grouped into 1% ambient RH bins and 1 degree F ambient temperature bins and averaged. The error bars are the standard deviation of the PurpleAir data in each bin.

- Excellent average agreement with errors of $\sim\pm5$ %-points in RH and $\sim\pm3^{o}\,\mathrm{F}$ in temperature

- The PurpleAir RH data are significantly underestimated and should be multiplied by 1.35 and have 2% added to them. The temperature data are ~5% high on average and could be multiplied by 0.95.

- **The RH data should be multiplied by 1.35 before use.**

Why the Plantower cannot function as an optical particle counter

- **OPC's rely on at least two things:**
  - a unique relationship between particle diameter and voltage output from the detector
  - Only one particle in the sensing volume at a time

- **The Plantower fails both of these**
  - The photodiode voltage output is higher for particles of size Dp near the laser exit (x < 4 mm) than for the same size particles far from the laser exit (x > 7 mm)
 - The Plantower sensing volume is much larger than an OPC, allowing more than one particle in the sensing volume at a time

The sensing volume is a cylinder. Its diameter is the laser diameter, and the length is 10 mm.

The photodiode detects light scattered from aerosol in the sensing volume.

ASPRIN: Affordable Small Polarized imperfect Reciprocal Integrating Nephelometer

Region 1	Region 2	Region 3
$19 < \theta < 90$ degrees	$34 < \theta < 146$ degrees	$92 < \theta < 167$ degrees
$0 < x < 2.5$ mm	$2.5 < x < 5.26$ mm	$5.26 < x < 10$ mm

- Measures all light scattered between ~5 -175 degrees

- Plantower sensor is configured as a reciprocal integrating nephelometer, except it
  - measures some scattered light from ~ 19 - 167 degrees
    - Effective truncation angle 30 to 150 degrees
  - Uses polarized light source
  - Does not account for reflected light from sensor

Comparison of "dry" bsp and dry PA measurements
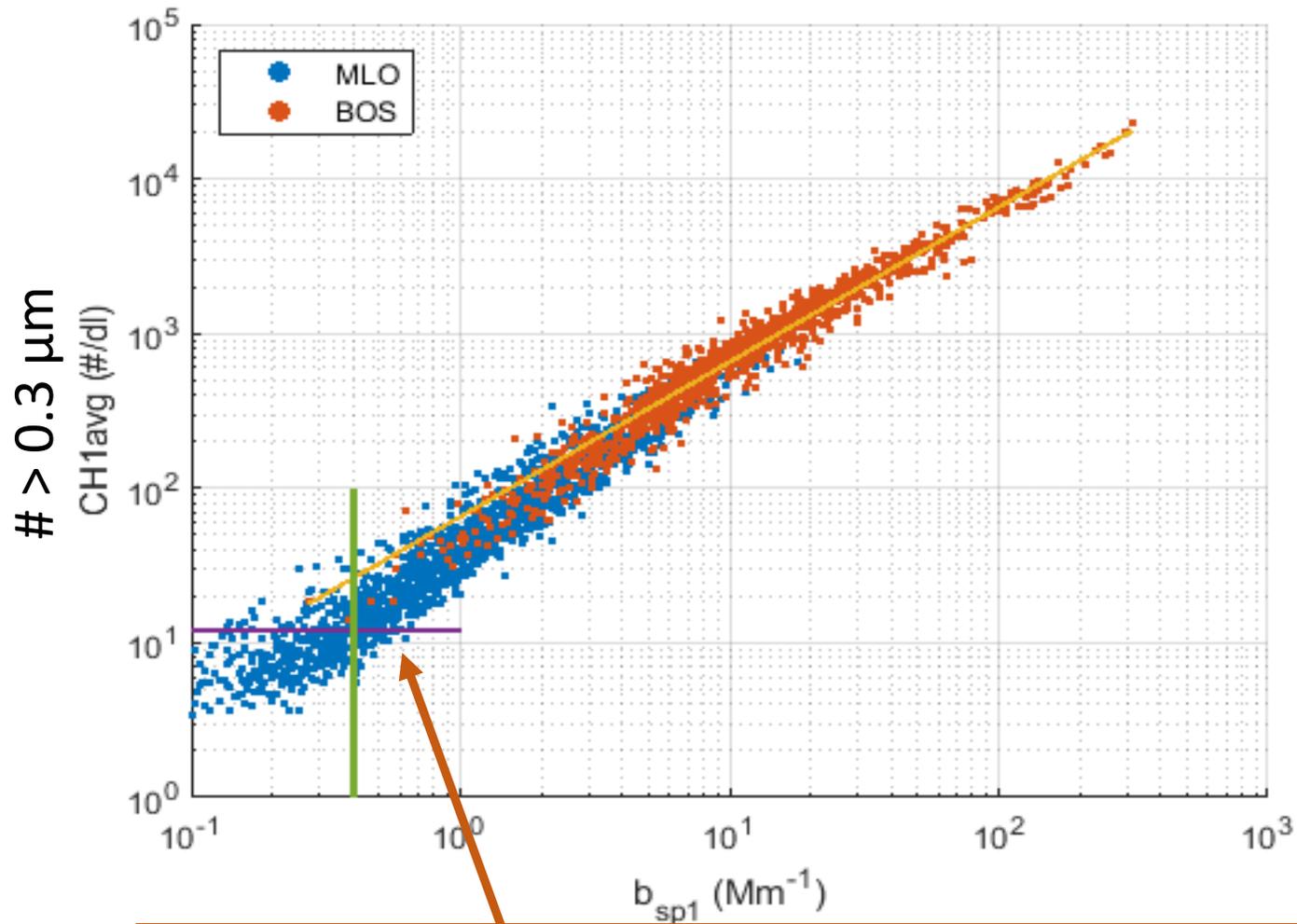
Site	1/slope	standard error	slope	R^2
BOS	0.015	2.68×10^{-5}	67.0	0.97
MLO	0.017	5.72×10^{-5}	59.0	0.85
Both BOS&MLO	0.015	2.07×10^{-5}	67.0	0.97

Fine aerosol scattering coefficient from TSI nephelometer vs. CH1avg value from PA. Yellow line represents the fit to all data. Purple line shows the additive uncertainty of 14 while bsp1 values less than the green line (0.4 Mm-1) were removed for the regression analysis)

Also notice that as bsp decreases the slope of CH1avg vs bsp decreases significantly.

ASPRIN: Affordable Small Polarized imperfect Reciprocal Integrating Nephelometer
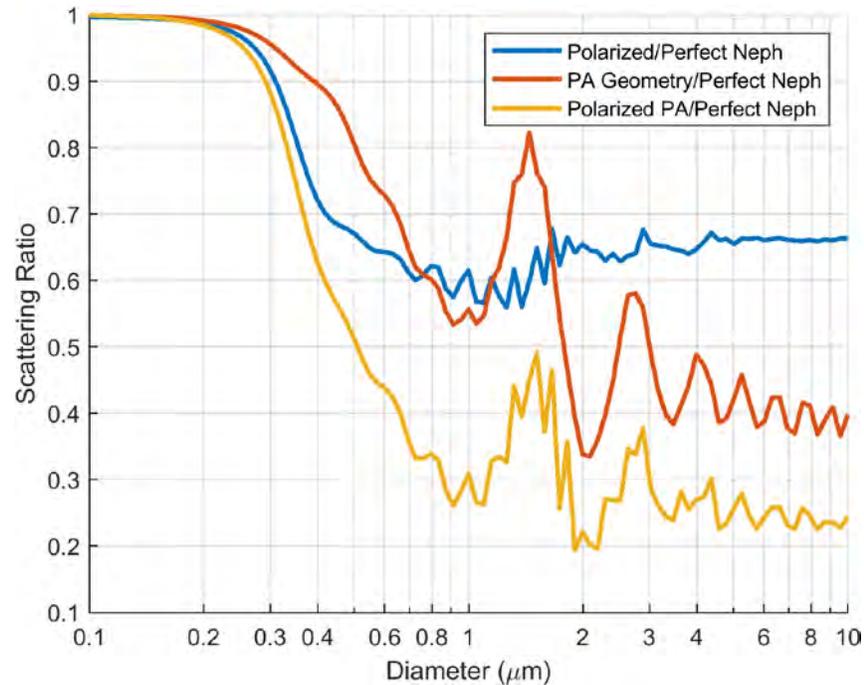
Ratio of scattering of a PA to "perfect" neph.
- with perpendicularly polarized light srce (blue)
- a PA with an unpolarized light source (red)
- a PA with a perpendicularly polarized light source (yellow)
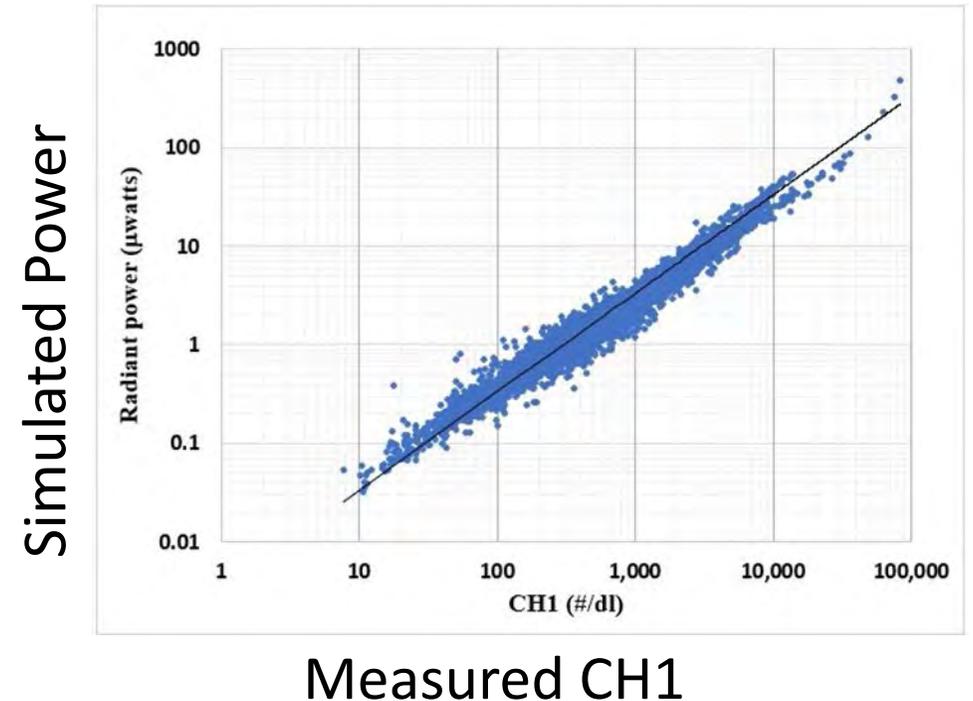
- Simulate hourly average radiant power on the photodiode using Boulder size distributions compared to the PurpleAir reported CH1

- Very good model vs measured comparison
  - Supports the supposition that CH1 is close to a raw signal

Time series of the ratio of measured PA values to measured 2win bsp ($PA_{bsp}=0.0154*PA$), the same ratio calculated using POPs number size distributions and Mie theory, and ((1/MSD)-1.5) where MSD is the mean scattering diameter. The MSD is the diameter at which ½ the scattering is from particles above that diameter and ½ is below.
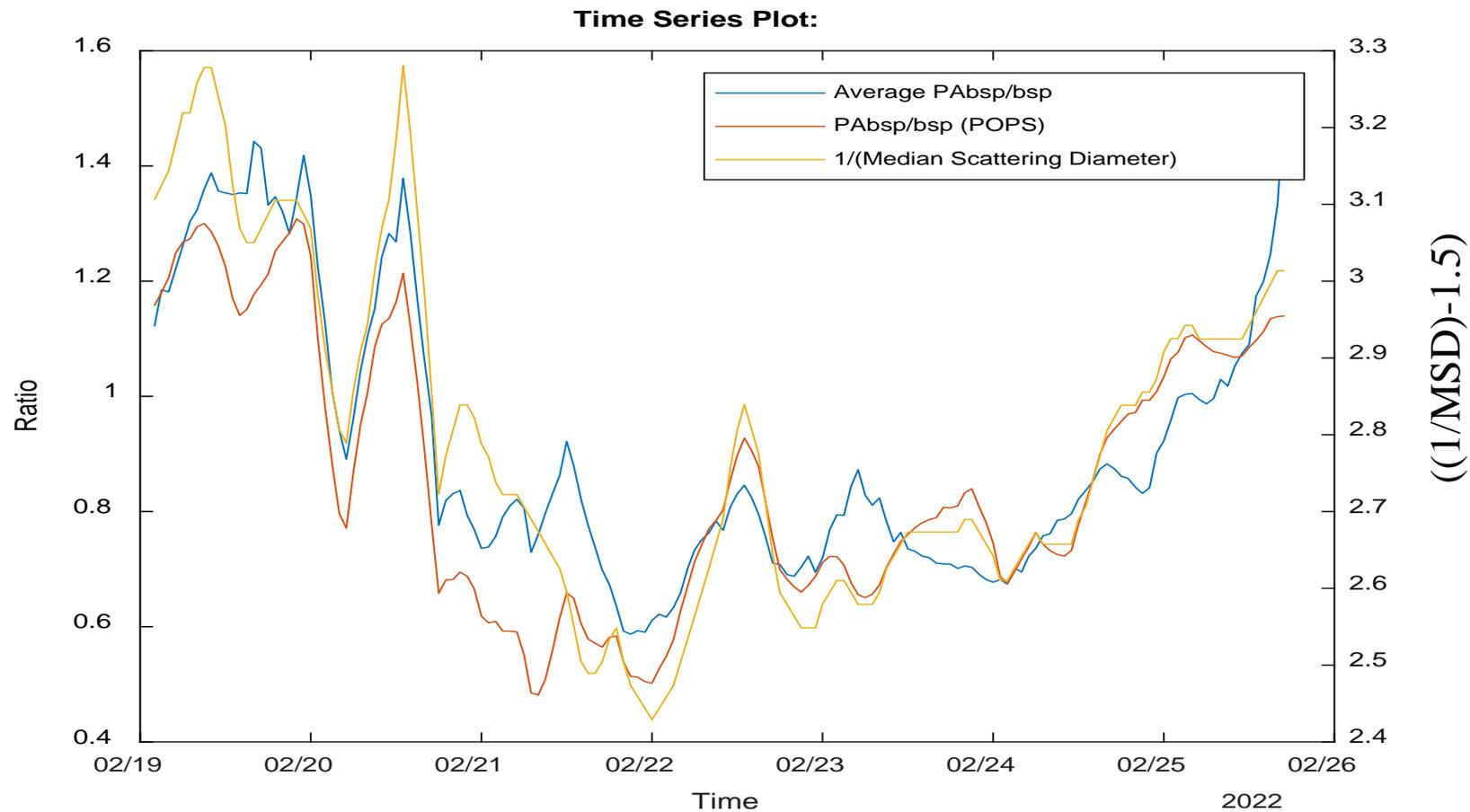

The high degree of correlation between 1/MSD and measured bsp/PAbsp is a result of significant underestimation of particle scattering by PA sensors as function of increasing particle size. Particles scattering by 1.0um are underestimated by 80% compared to 0.1um particles.

Influence of weather (RH and Wind Speed) on PA readings

# PA response relative to true bsp for a hygroscopic aerosol with sig=1.7 as a function of RH and d_g.

Fractional Difference vs dg and RH
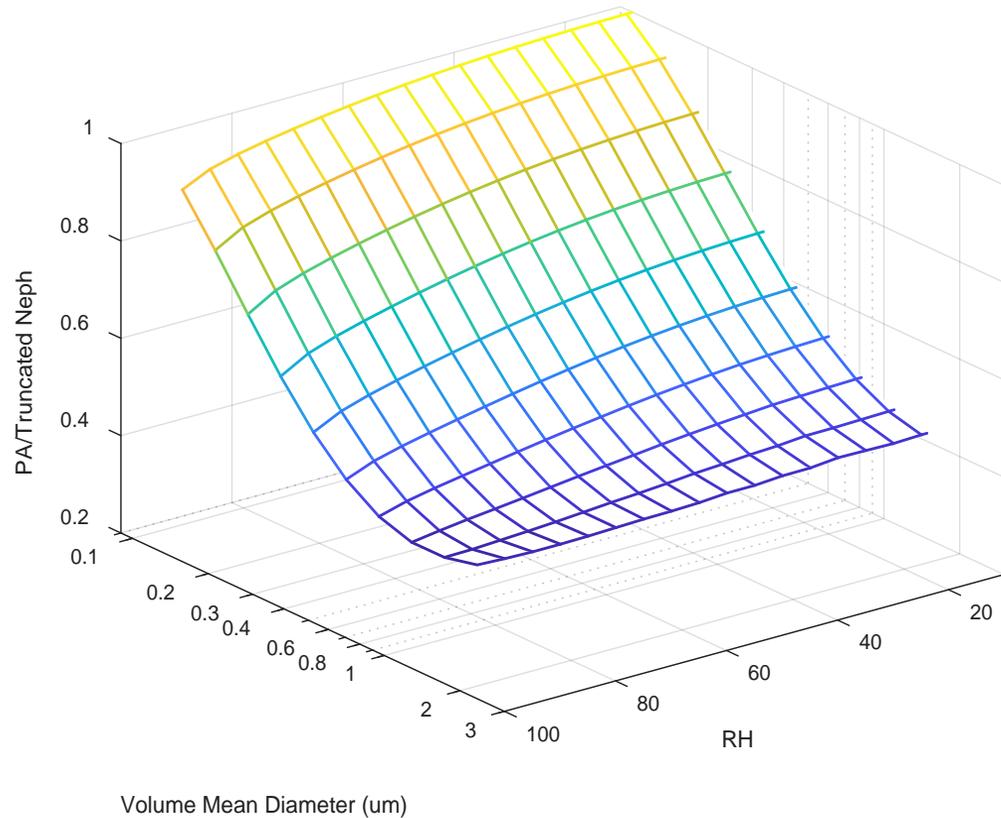
PA/bsp for sig=1.7 as a function of RH and volume mean diameter
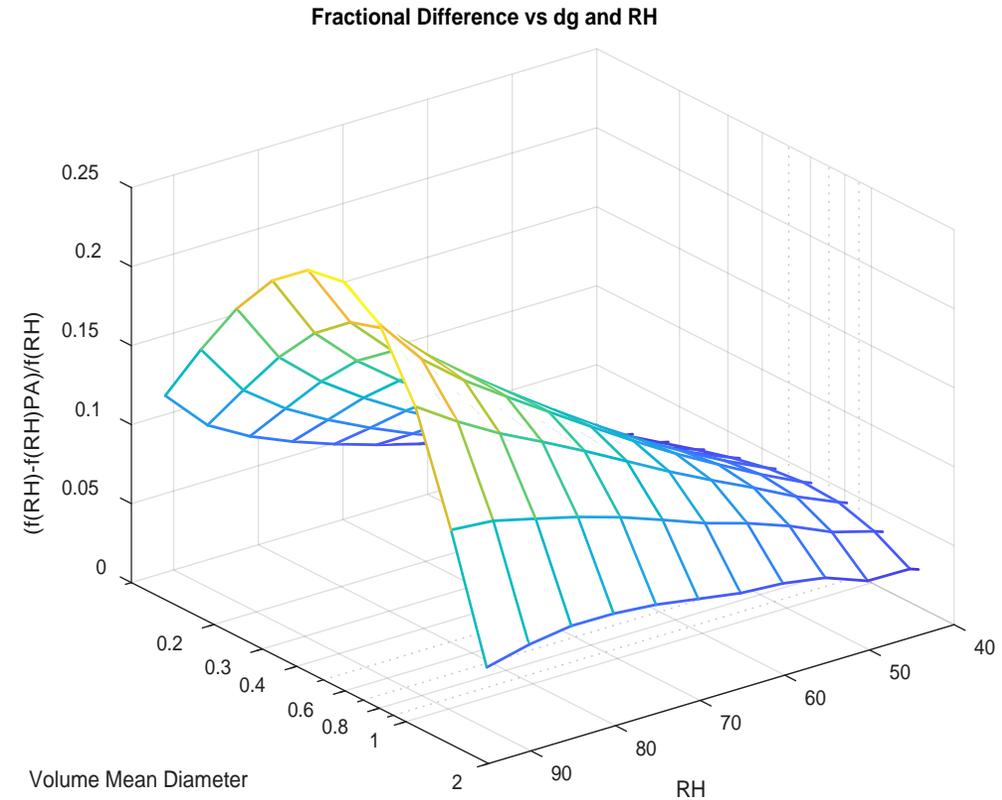
(f(RH)-f_{PA}(RH))/f(RH) for sig=1.7 as a function of RH and volume mean diameter

The relationship between decrease in PA/Neph as a function of particle size (sig=1.7) and the commensurate increase in f(RH).
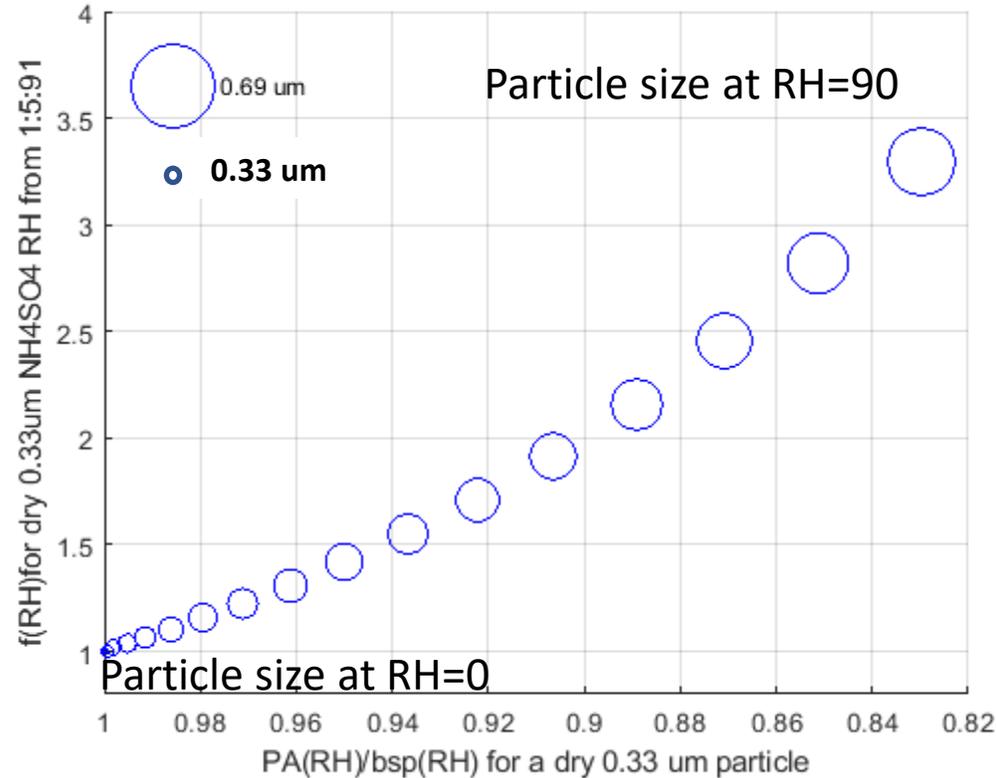
As RH increases particle size increases. The size of the open circle symbol represents the volume mean diameter which varies from 0.33 um to 0.69 um as RH increases from RH=0% to RH=90%. f(RH) is plotted on the y-axis while the ratio of PA(RH)/bsp(RH) is plotted on the x-axis. (sig=1.7)

Measuring the PA response to wet and dry particles and the the uncertainty in a PA derived f(RH)
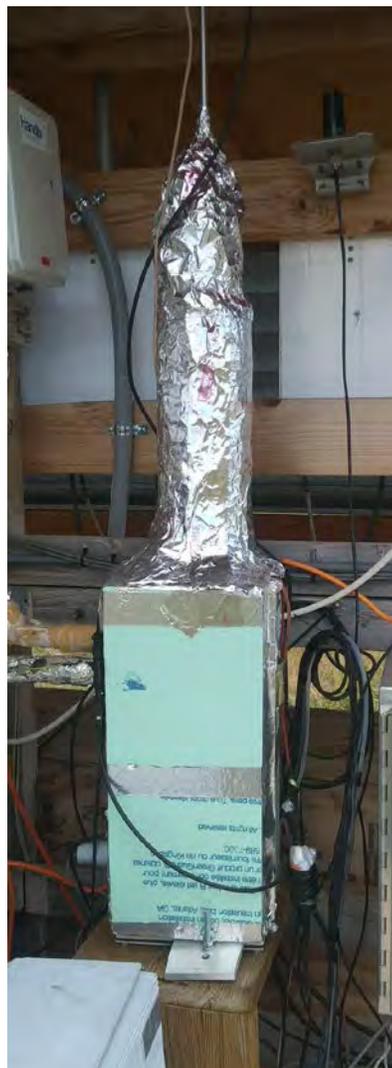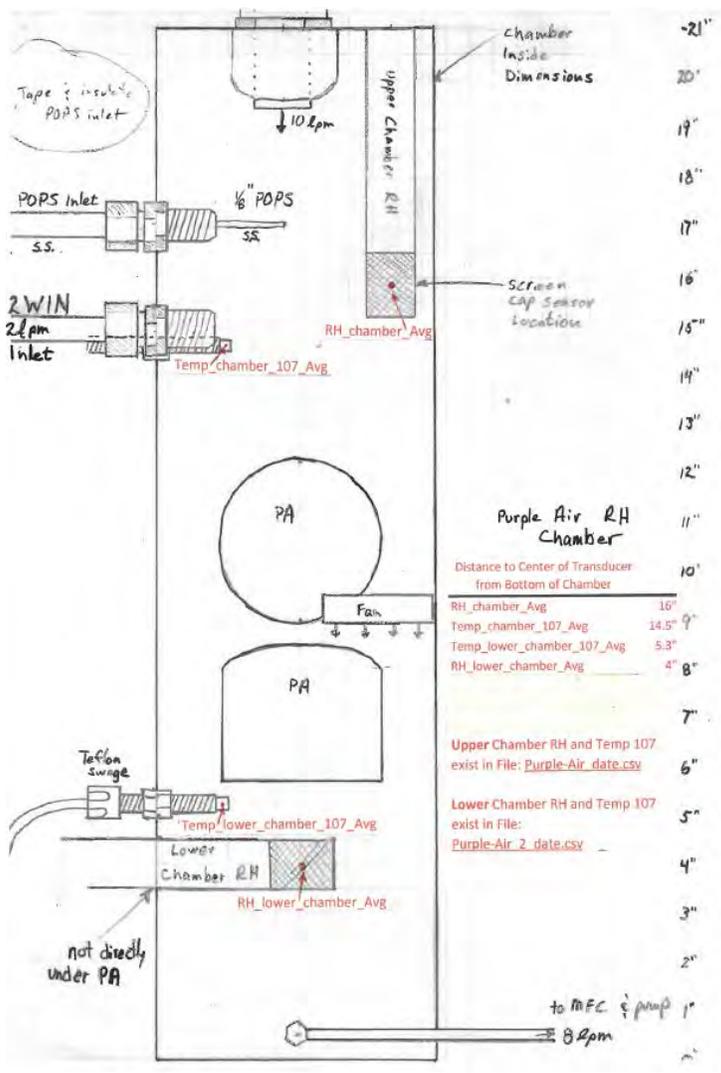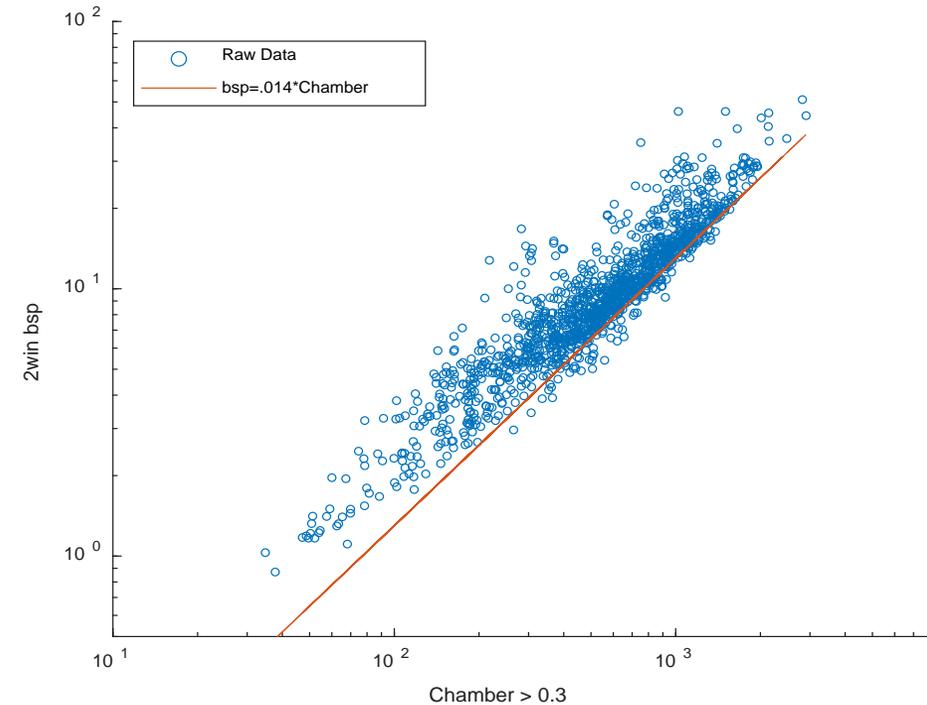

$$f_{bsp}(RH) = f'(RH) f_{PA}(RH)$$

where

$$f' = \frac{b_{sp}(RH)}{PA(RH)} \frac{PA(dry)}{b_{sp}(dry)}$$

To that end ARS built a "dry" scattering chamber shown on the left

Explore some data collected from 7/5 to 8/17/2022
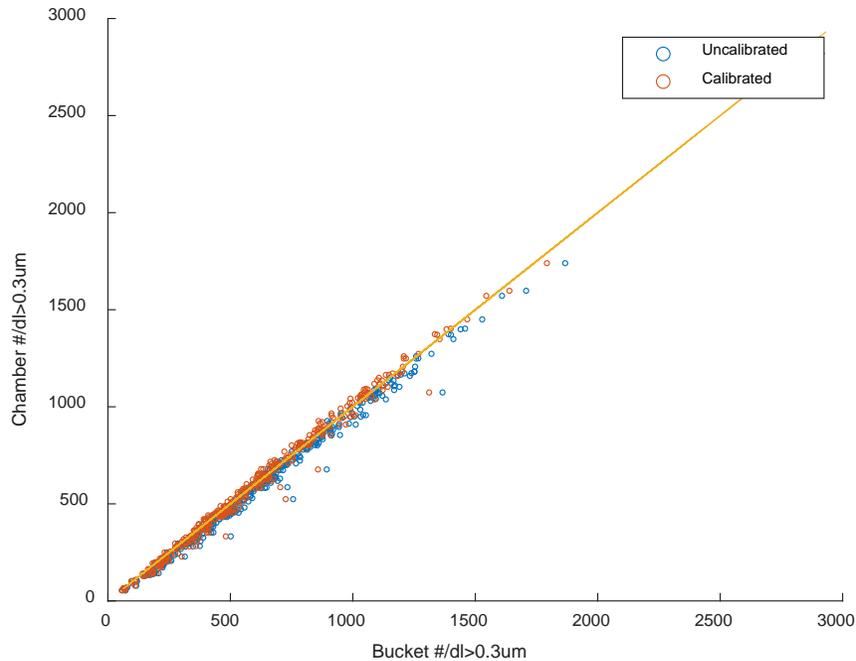
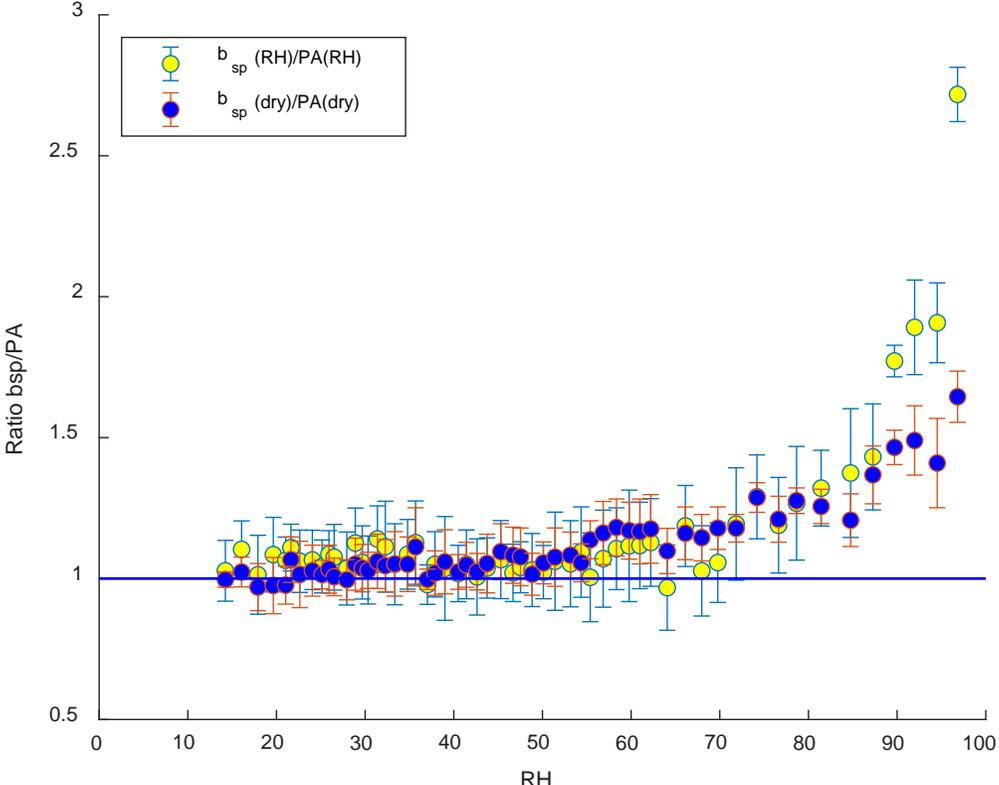Bucket PA vs Chamber PA for RH<40% - implies Chamber PA is about 5% biased high compared to Bucket PA.

2win bsp which will be used as the overall "standard" compared to the chamber PA >0.3 #/dl channel. Red line is $0.14*PA_{chamber}$.

Nephelometer and PA derived f(RH) values

$$f_{bsp}(RH) = f'(RH)f_{PA}(RH)$$

$$f' = \frac{b_{sp}(RH)}{PA(RH)}\frac{PA(dry)}{b_{sp}(dry)}$$


$$f' = \frac{f_{bsp}(RH)}{f_{PA}(RH)}$$

f'(RH) plotted as a function of RH. The implication of bsp(dry)/(0.14*PA(dry)) increasing is that the dry particle size distribution is shifting to larger sizes as a function of RH. The yellow data points, bsp(RH)/PA(RH), therefore, not only reflect PA response to overall particle hygroscopic growth but an attenuated dry PA signal resulting from larger "dry" particles at elevated RH levels.
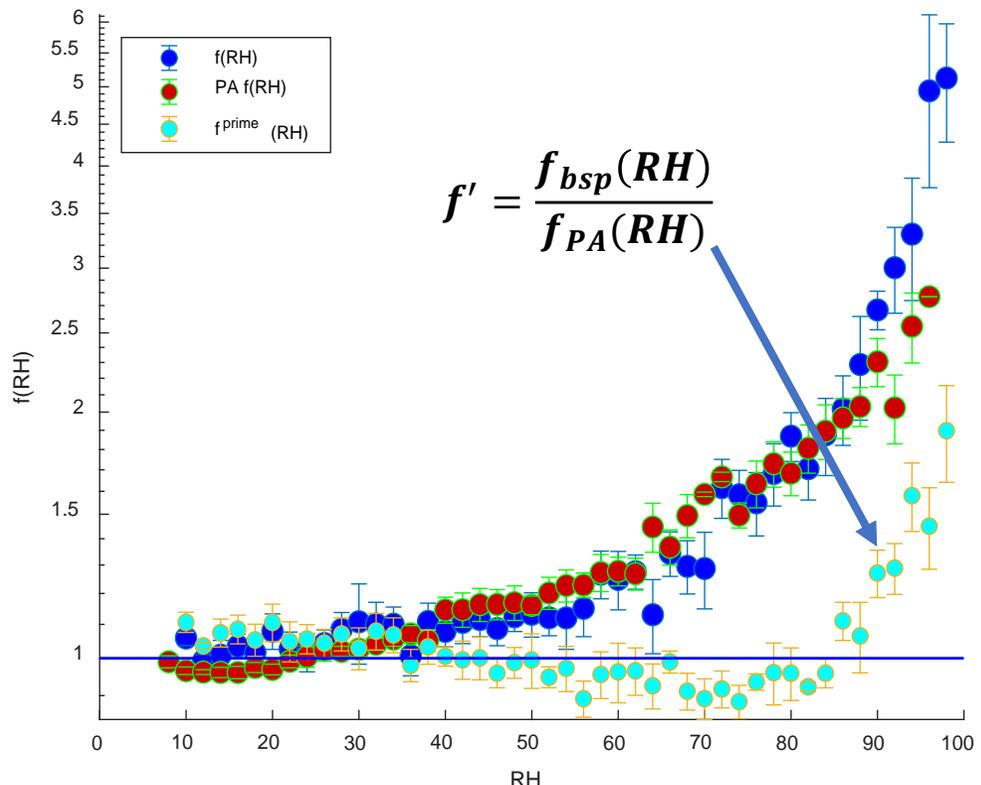
The PA and bsp f(RH) curves are, within the uncertainty, equal below about 85% RH. Below 50% the f(RH) uncertainty is about ±0.05 and between RH levels of 50% to 85 % the uncertainty increases to about ±0.1. Only at RH levels above about 90% RH do the two f(RH) values differ significantly. Within uncertainties, f'(RH) cyan data points multiplied by the red f_{PA}(RH) data points yield the blue f_{bsp}(RH) data points.

Influence of wind on PA measurements
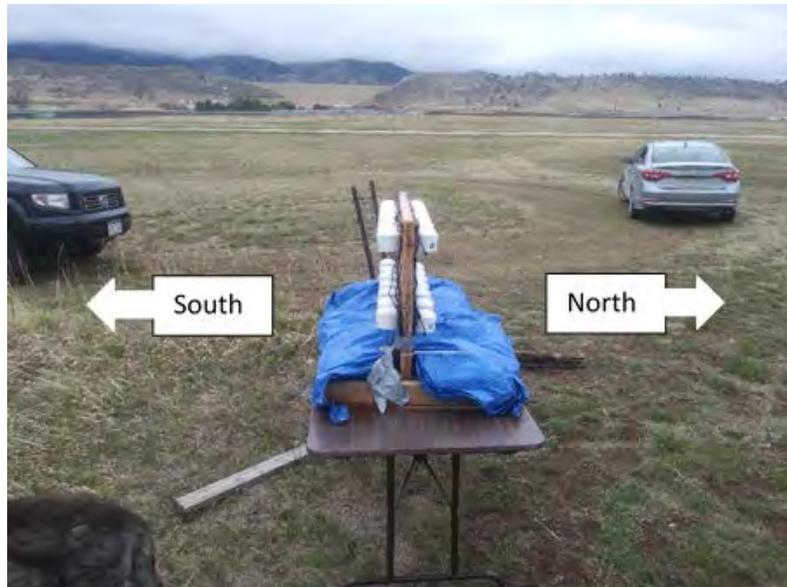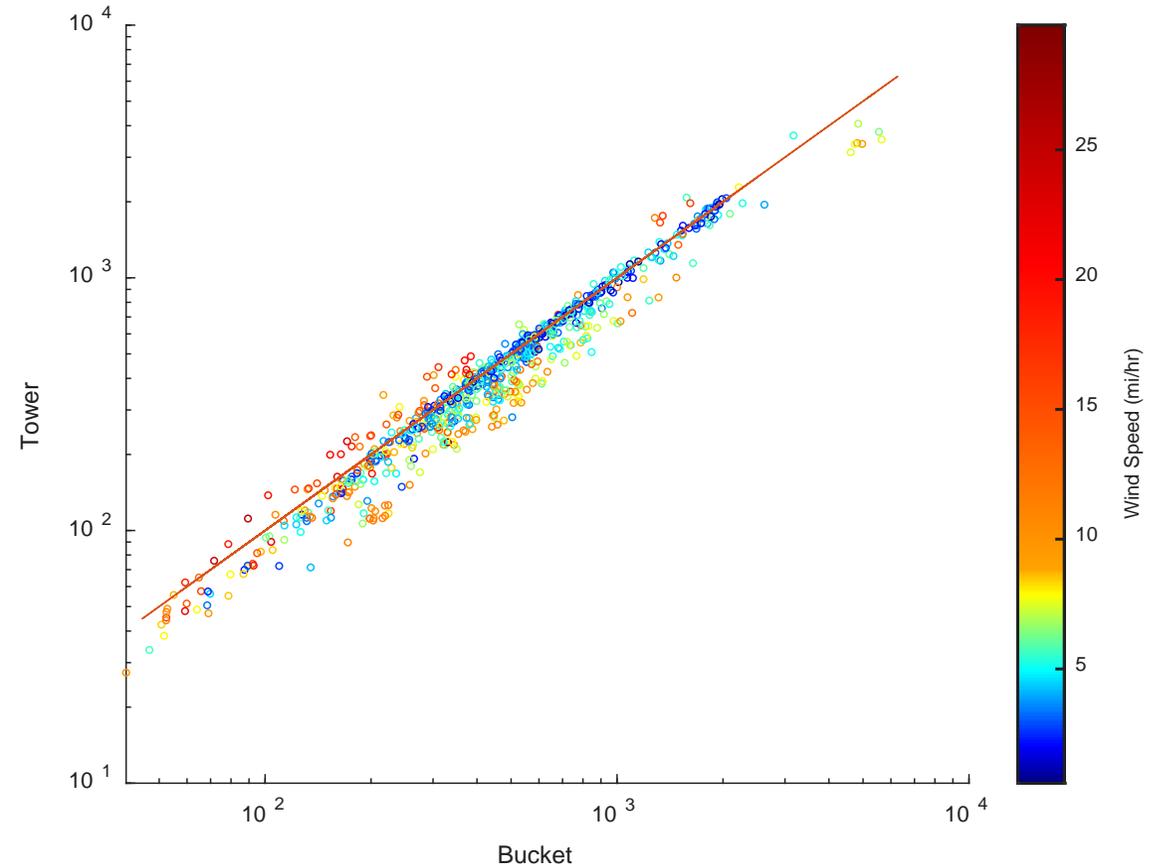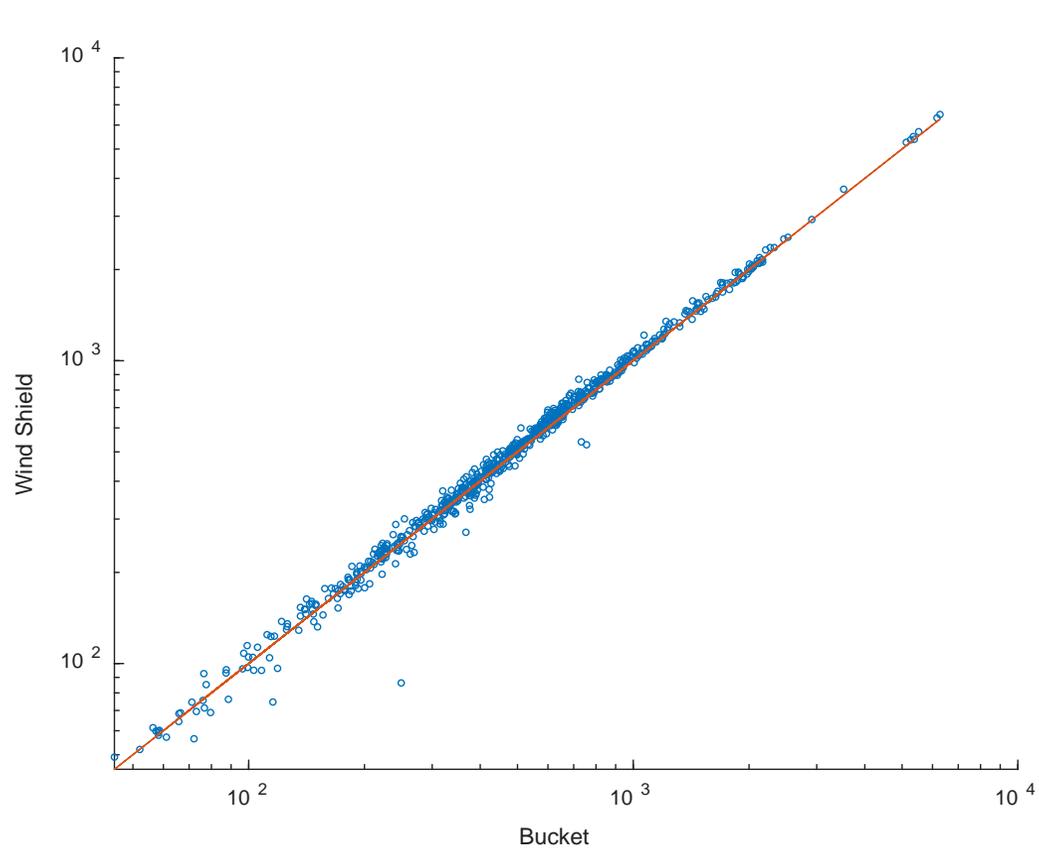
- The PA behind the wind shield and in the bucket are highly correlated
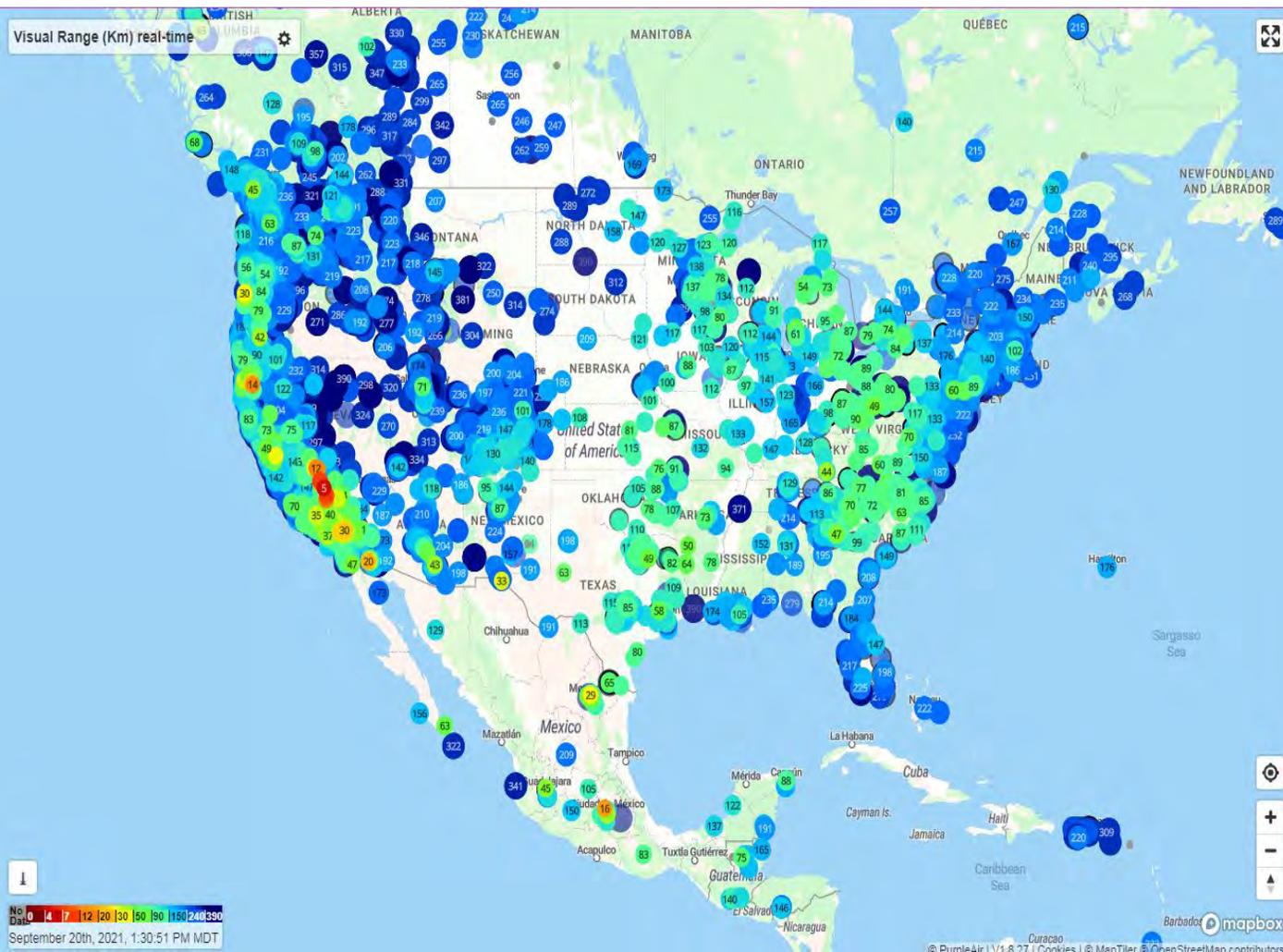- The unshielded PA over and underestimates scattering with high wind speeds
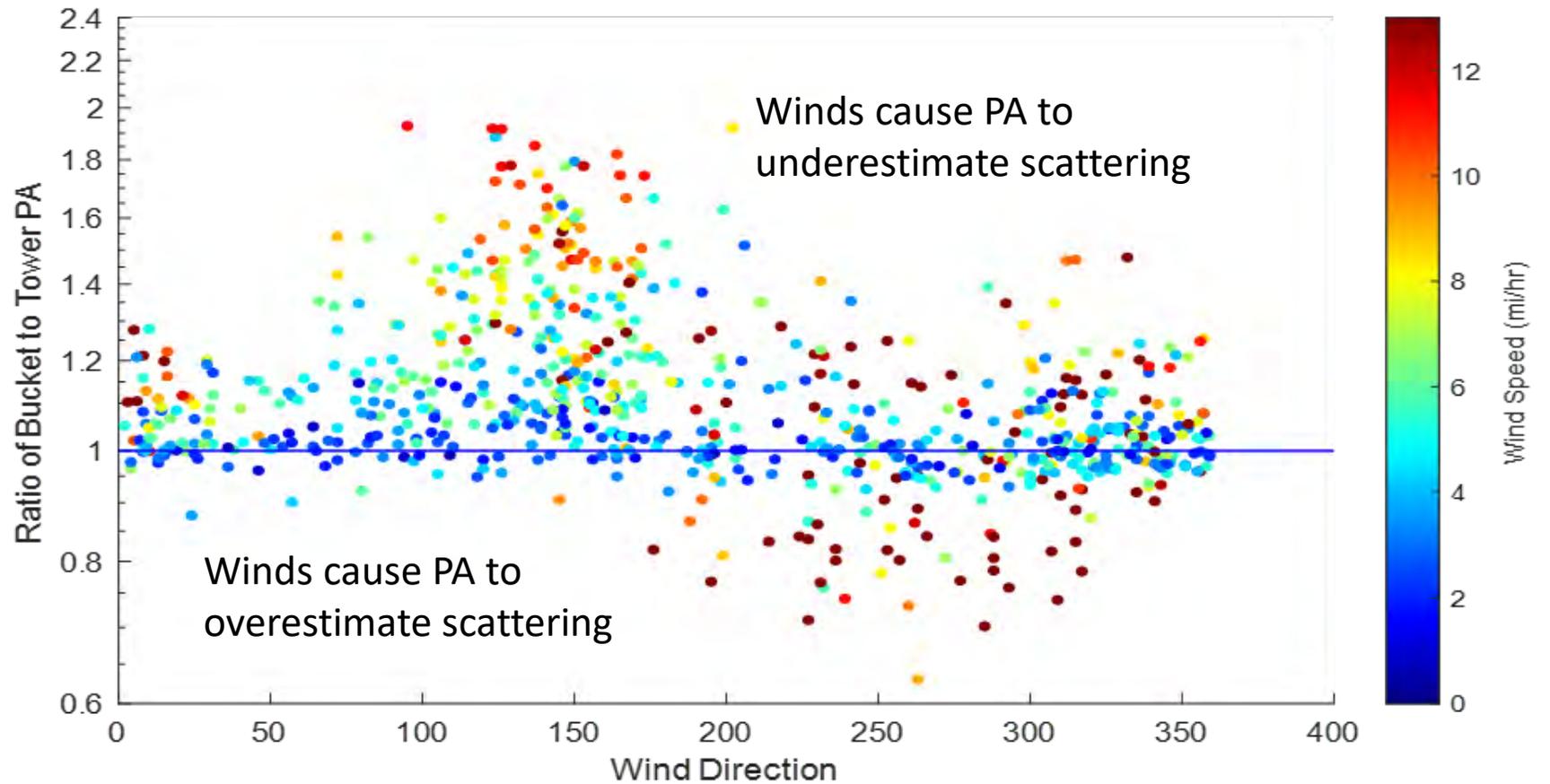
- High wind speeds from the northeast decrease PA scattering reading and winds from the southwest increase the PA scattering reading
- Tower interferes with winds from the north

How can PAs be used by the NPS and IMPROVE

- Can't replace nephelometers but can provide high time resolution data to supplement IMPROVE data and interpretations

- National visibility monitoring network

- Provide visibility metrics at NPS visibility webcams

- NPS Smoke monitoring network
  - Inform visitors and staff on potentially unhealthy levels a smoke/air pollution

- As part of an NPS air pollution awareness system
  - A system of inexpensive gaseous and particle monitors providing information on air quality
  - Provide some air quality information in unmonitored park units
  - Could be used to inform staff and visitors on air quality levels and educate them on air quality issues

Fine particulate light scattering (Mm^{-1})

- $b_{sp1} = 0.015 * >0.3\text{um}$

# Deciview (DV)

- $DV = 10*\ln((10+1.3*b_{sp1}) / 10)$

Standard Visual Range (km)

- $VR = 3900 / (10 + 1.3\, b_{sp1})$
- Note, the maximum visual range is 390 km, which occurs at bsp1 = 0, i.e. $VR = 3900 / (10+0) = 390$ km
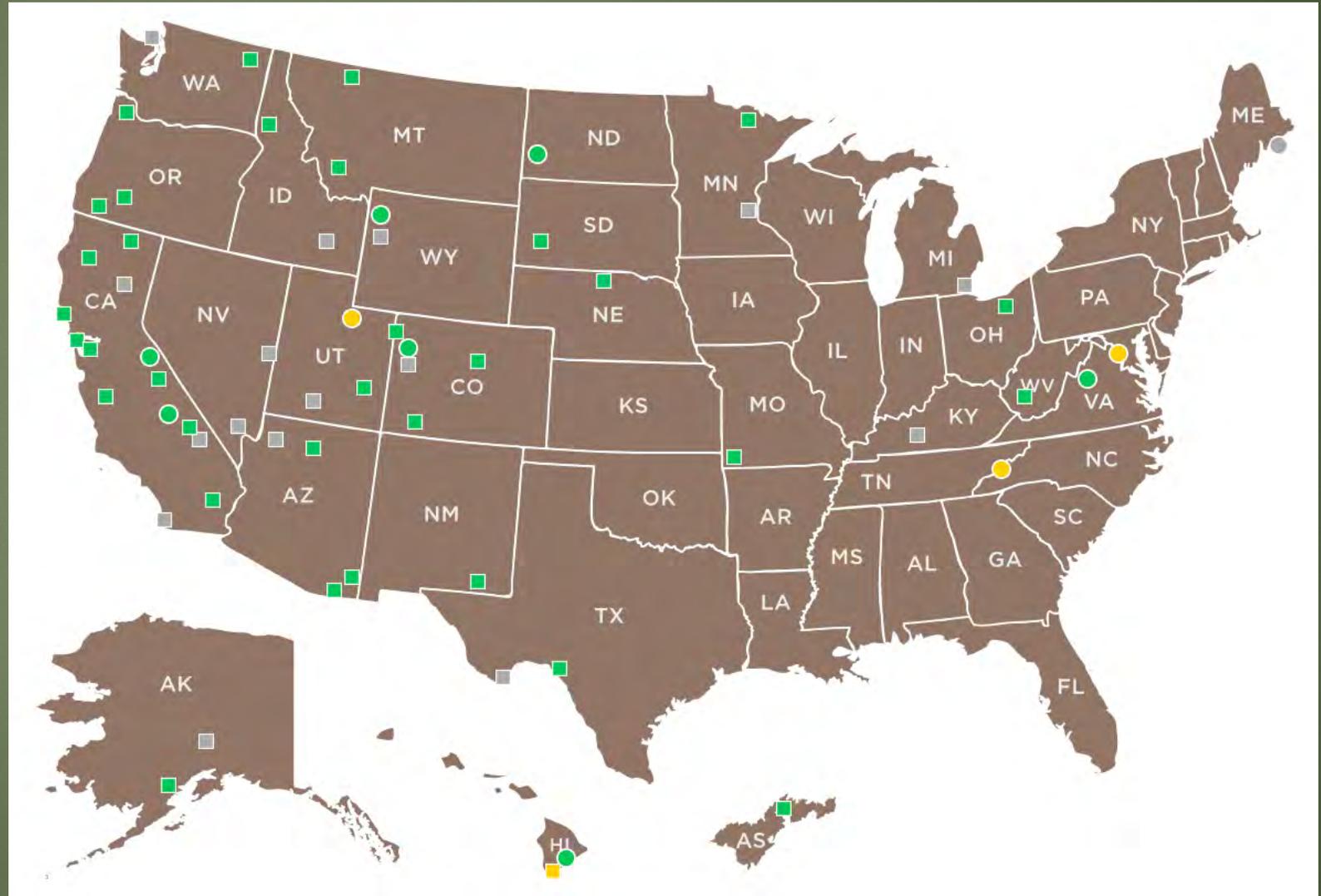
2021 Smoke Monitoring Pilot Program

▶ Provide real-time, in-park monitoring of particulate matter for a large number of parks (on a limited budget) using PurpleAirs

▶ Make the data readily accessible to parks

▶ Be consistent with EPA Fire and Smoke Page

   ▶ NowCast AQI

      ▶ Relates hourly data to the AQI

      ▶ NowCast AQI intended to be responsive to rapidly changing air quality conditions, such as during a wildfire

▶ Provide resources to interpret and utilize the data for management decisions

Barkjohn et al., 2020 Presentation
Int'l Smoke Symposium

22
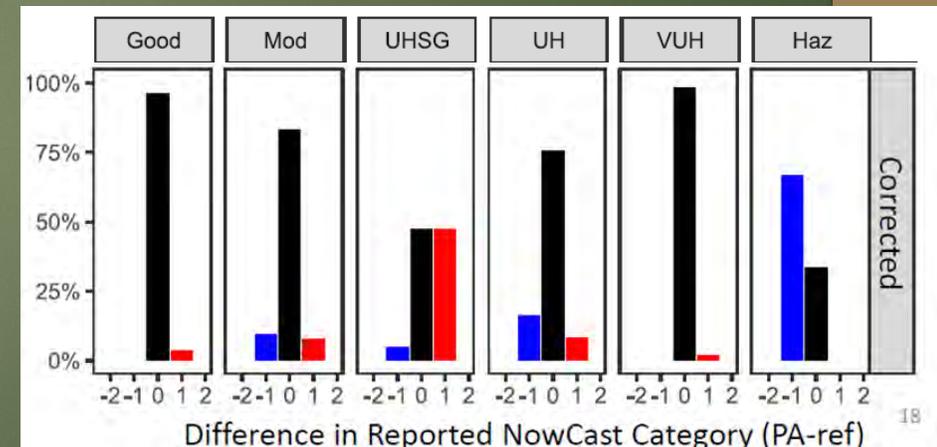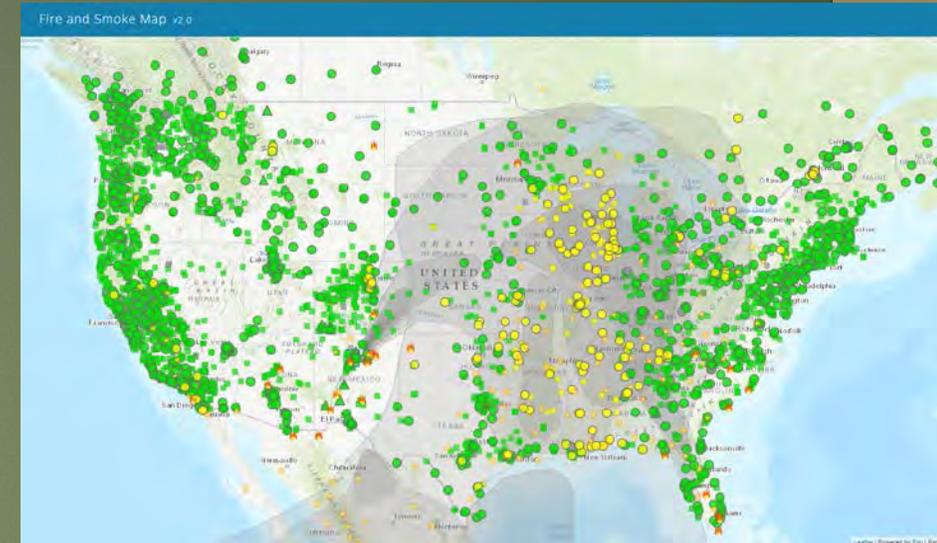
Smoke Monitoring Pilot Program

- Over 80 PurpleAirs operating in 60 parks

- 25 of these are in parks that have no other AQ monitoring

- Data are available on ARD LiveData webpage, webcam page and can be added to park pages.

- Also automatically loaded PurpleAir and EPA Fire and Smoke pages.

Needs for deployment in a Routine Network for Quantitative Scattering measurements

- The PurpleAir provides a reproducible estimate of fine light scattering but is influenced by hygroscopic growth similar to but less than a nephelometer
- PurpleAirs need to be shielded from high wind speeds.
  - Putting the PAs under a bucket seems to provide adequate shielding
- Not shown, but PAs can have large systematic differences between units
  - To use in a quantitative manner need to calibrate individual PAs, currently we do acceptance testing requiring multipole PAs to be within 10%
- Need to understand the long-term stability of PAs
  - What is the sensor drift?
  - Deployed PAs last for 1 to 2 years, but we have had some running for 3+ years.

Expanded Field Campaign at Christman Field campaign

- Light scattering measurements (minute)
  - PM2.5 scattering: 2win (near ambient, dry); NGN3 (heated); TSI (heated)
  - Total scattering: Optec open air (Ambient); Air Photon (heated?), soft PM10 cut point
- PurpleAir light scattering measurements
  - 2 dry, PM2.5 PAs
  - 2-4 ambient PAs
- Dry size distribution and particle # concentration
  - Scanning mobility particle size (CPC with DMA) – 0.05 < Dp < 0.87 microns
  - APS – 0.5 < Dp < 20 microns (TSI APS 3321)
  - Ambient and dry POPS - 0.1 < Dp < 3 microns
- High time resolution mass concentration
  - Inorganic ions: Pills system
  - Carbonaceous aerosols: Sunset continuous OC/EC instrument
- IMPROVE speciated aerosols, 24 hr every third day
- 5 weeks sampling that began October 6st

?

Time series of the ratio of measured PA values to measured 2win bsp ($PA_{bsp}=0.0154*PA$), the same ratio calculated using POPs number size distributions and Mie theory, and ((1/MSD)-1.5) where MSD is the mean scattering diameter. The MSD is the diameter at which ½ the scattering is from particles above that diameter and ½ is below.
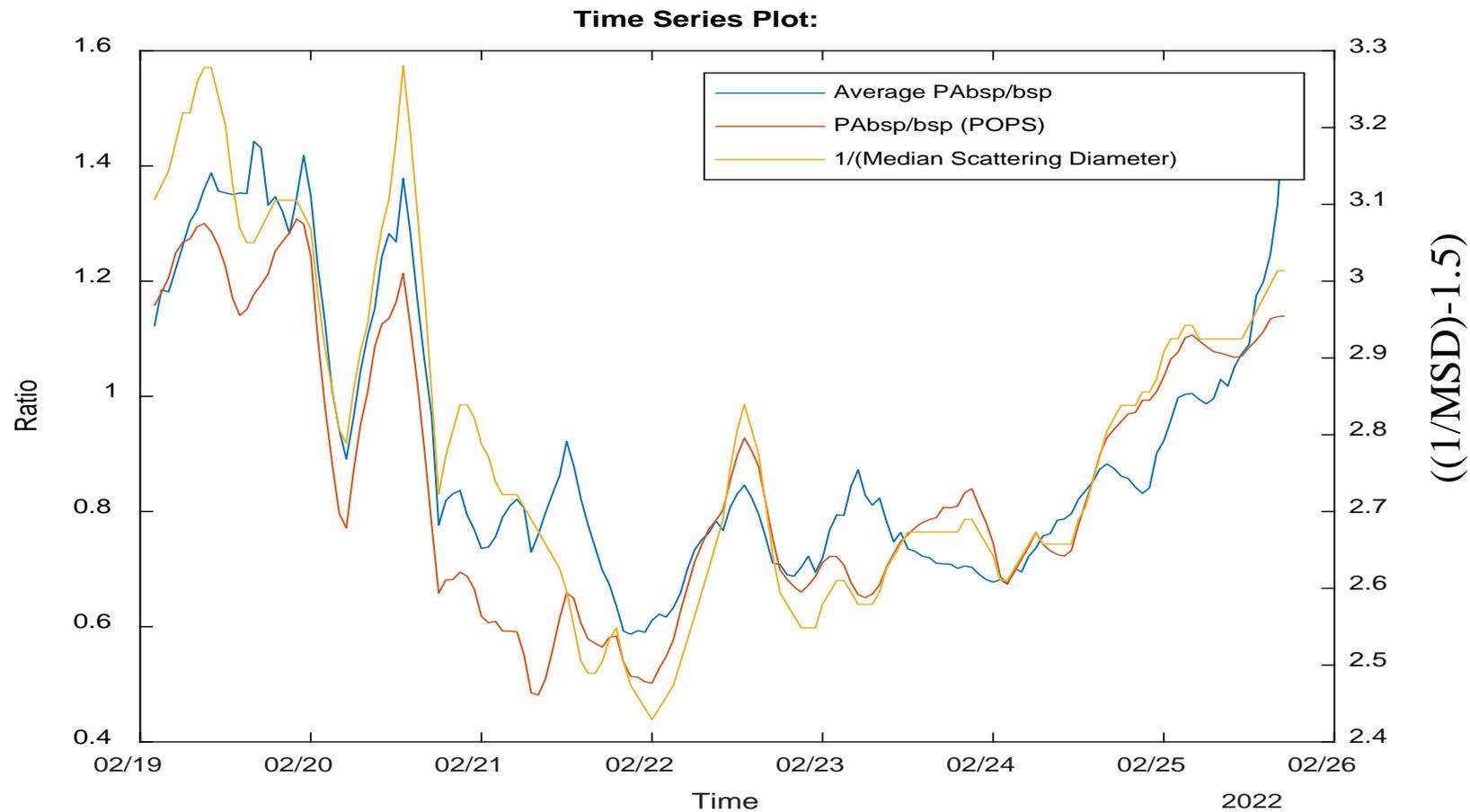
The high degree of correlation between 1/MSD and measured bsp/PAbsp is a result of significant underestimation of particle scattering by PA sensors as function of increasing particle size. Particles scattering by 1.0um are underestimated by 80% compared to 0.1um particles.

POPs Dry (<40%RH) Volume Size Distributions

Mean 0.32 ± 0.19 (um)
Geomean 0.28 (um)
Geosig=1.4
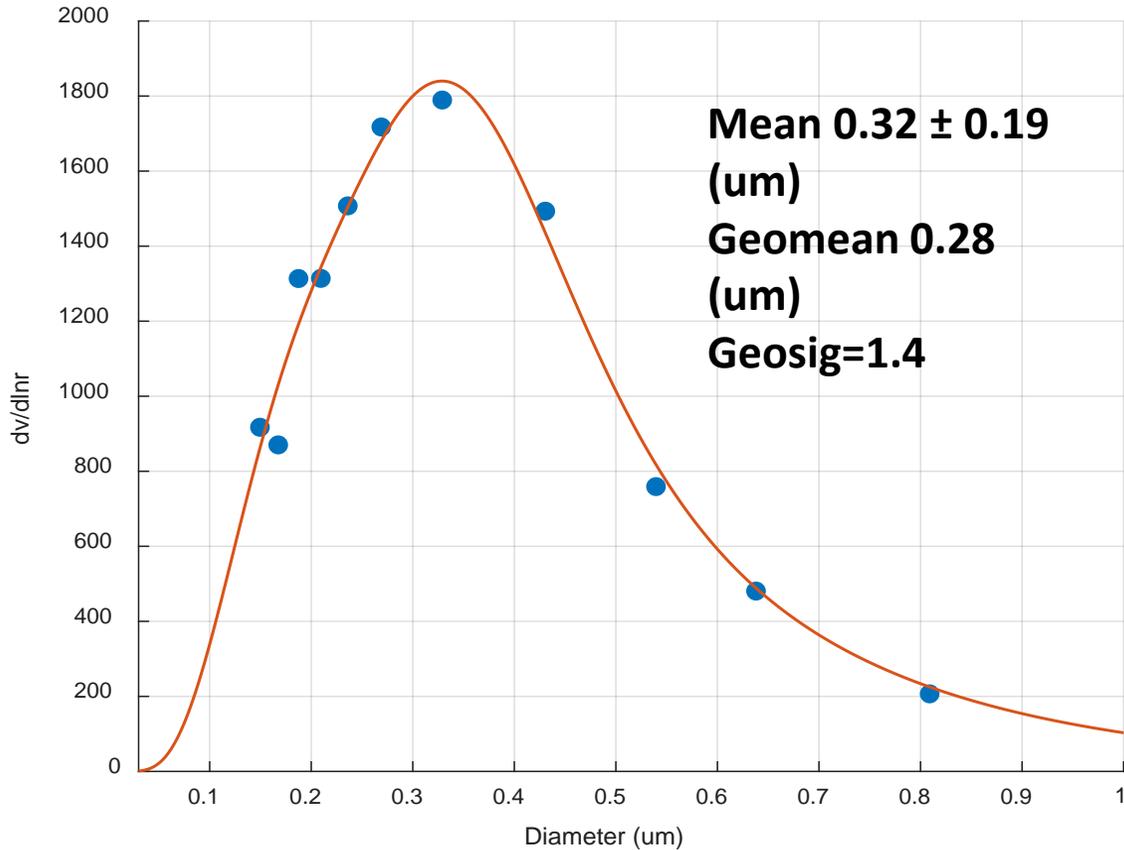
Average volume size distribution of entire time period
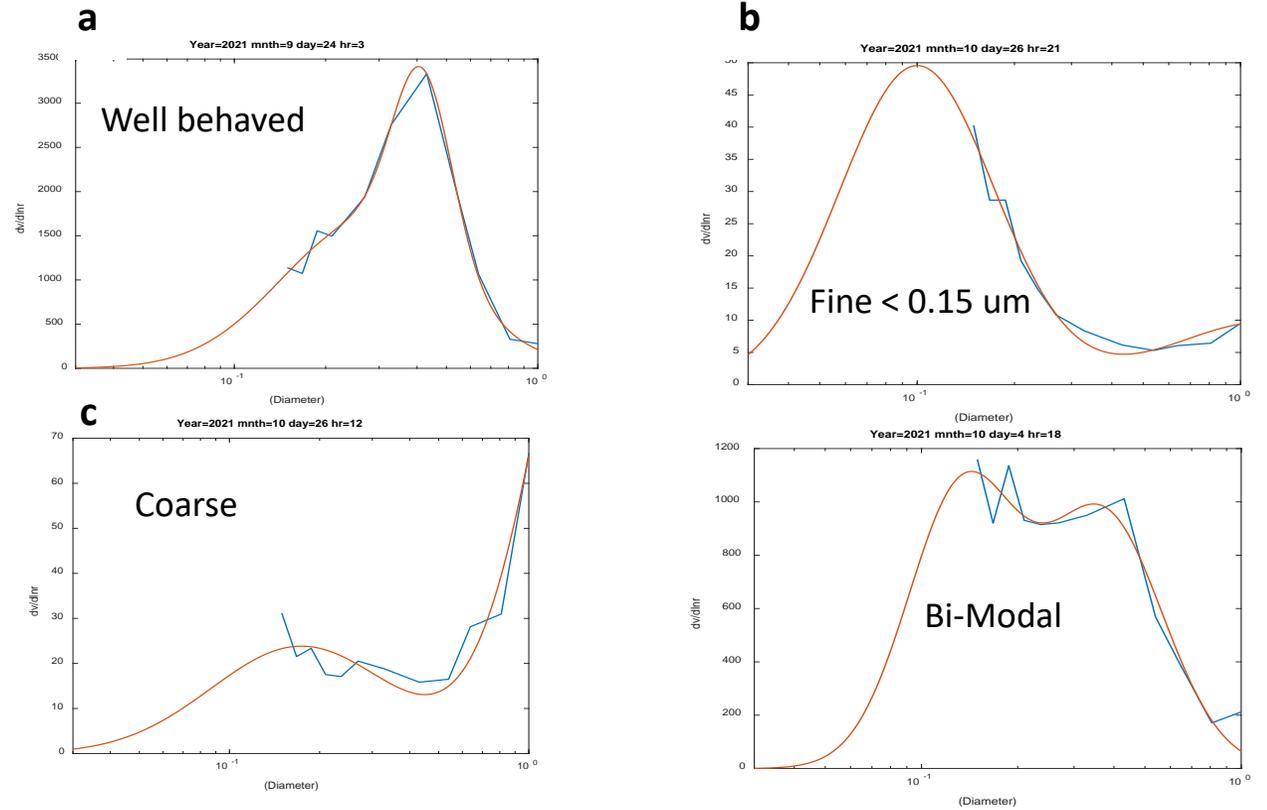
Examples of some volume size distributions that deviate from the average

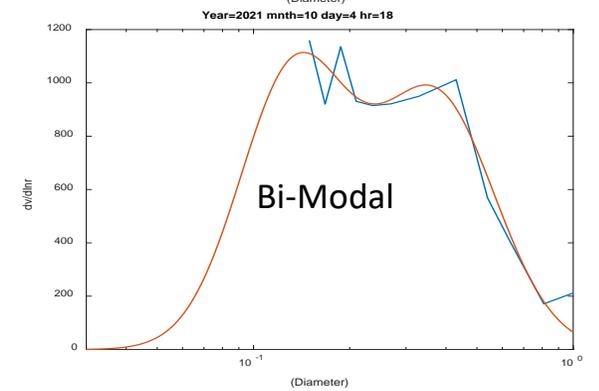Some assumption required to make scattering estimates from POPS

- Spherical particles
- Internally mixed particles (no pure species and assume index of refraction)
- Scattering at measured RH (can't adjust for RH)

Additional Information with PILS data
- Volume weighted densities
- Volume weighted index of refractions
- Species weighted d/do growth functions (invoke ZSR)
- Scattering of hygroscopic species as a function of RH

To theoretically explore actual PA response hygroscopic aerosols there is a need for measurement of aerosol species. (PILS and Carbon)

PILS measurements of SO4, NO3, NO2, Cl, NH4, Na, Ca, and K were made every 15 min from 9/21/2021 to 10/29/2021. 15 min values were average to an hour and are shown in a temporal plot of the ion concentrations below
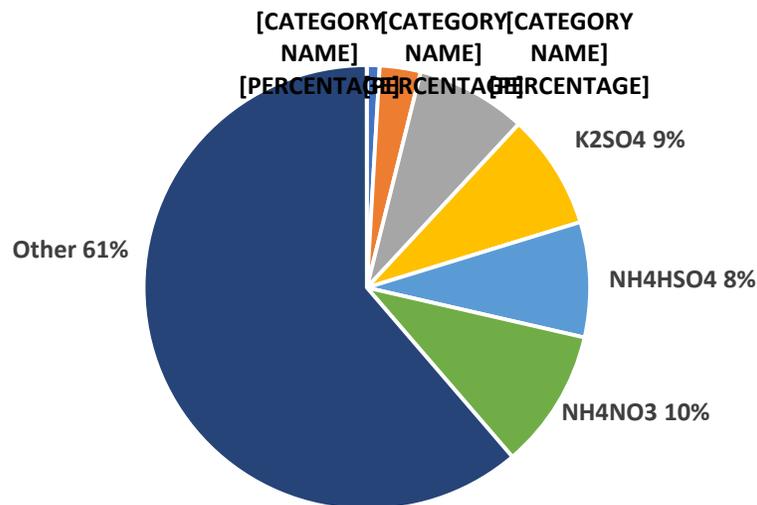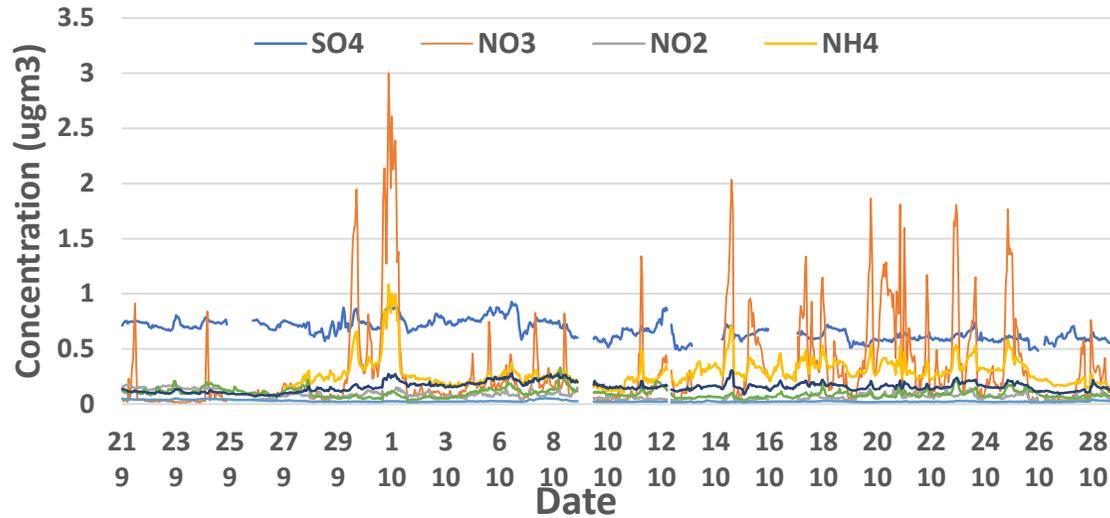

1.66*cl+1.5*no2   % assume cl is NaCl, nitrite is nano2,
k2so4=2.2*k;   %convert k to k2so4
so4k2=.45*k2so4;   % amount of sulfate in k2so4
caso4=3.4*ca;   %convert ca to caso4
so4ca=.71*caso4;   %amount of sulfate in caso4
remso4=so4-so4ca-so4k2; %subtract ca and k sulfate from total sulfate
Nh4no3=1.29*no3   % all no3 as ammonium nitrate
ambisul=1.2*remso4;   % convert remaining sulfate and ammonium to ammonium bisulfate
pils=1.66*cl+1.5*no2+caso4+k2so4+ambisul+1.29*no3

other=bsp/3.2-(pils);   % Assumed other was OMC for density and index of refraction purposes

To calculate the size distribution of particles at specific RH levels the POP's size distributions were first theoretically "dried" out to RH=1% and then "grown" to correspond to the RH in the sensor of interest. Given the index of refraction and growth factors associated with each instrument the ambient nephelometer (OPTEC), "dry" nephelometer (2win), ambient and "dry" PMS values can be calculated.
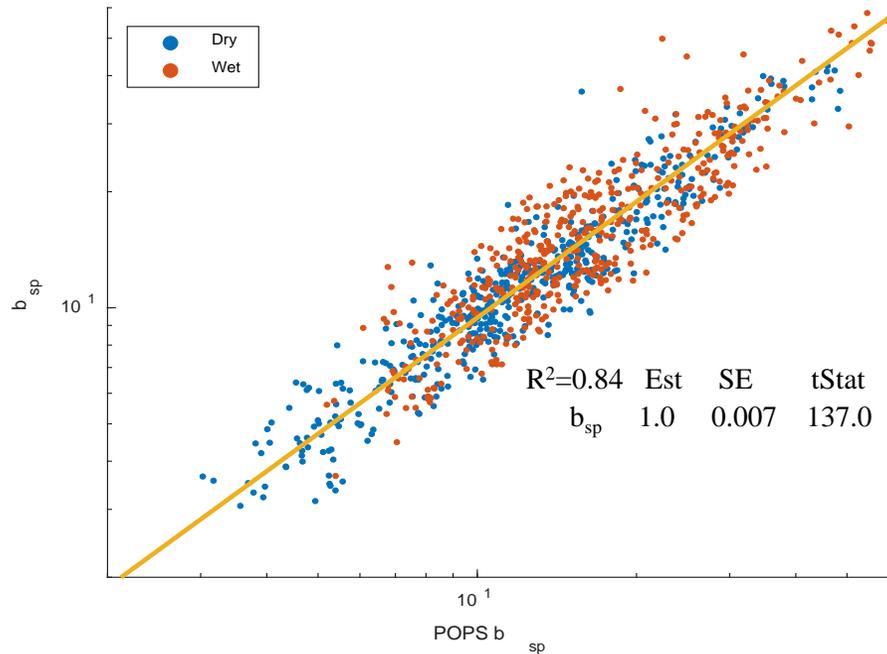
A scatter plot comparing measured atmospheric scattering, b_{sp}, to scattering calculated using POP's and PIL's data both for dry and ambient RH conditions
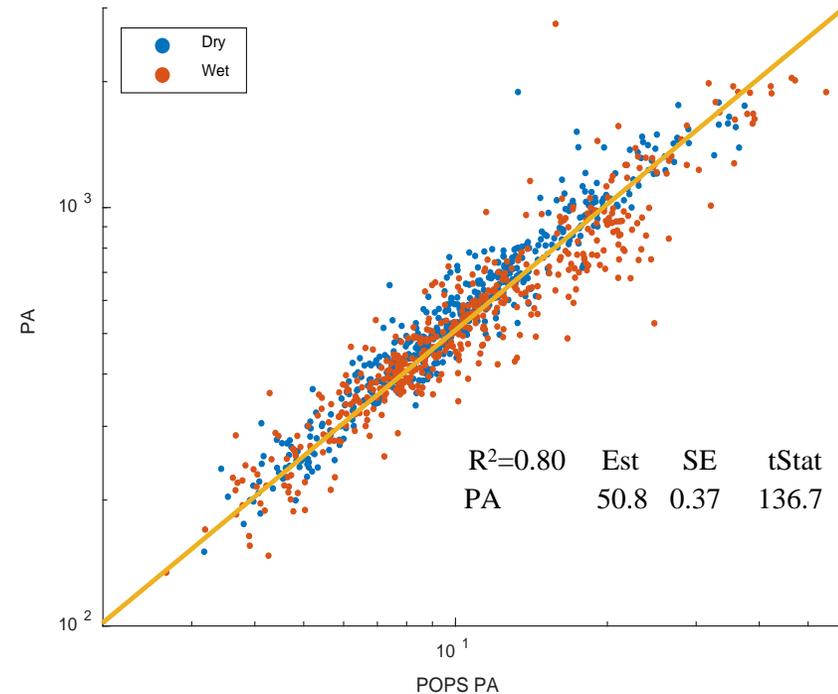
A scatter plot of measured ambient and dry PMS values as a function of calculated values proportional to PMS scattering intensity derived from the POP's and PILs measurements and use of the scattering model derived for the PMS physical and optical configuration.

Comparisons of measured and derived f(RH) values using PILS and POPS data.
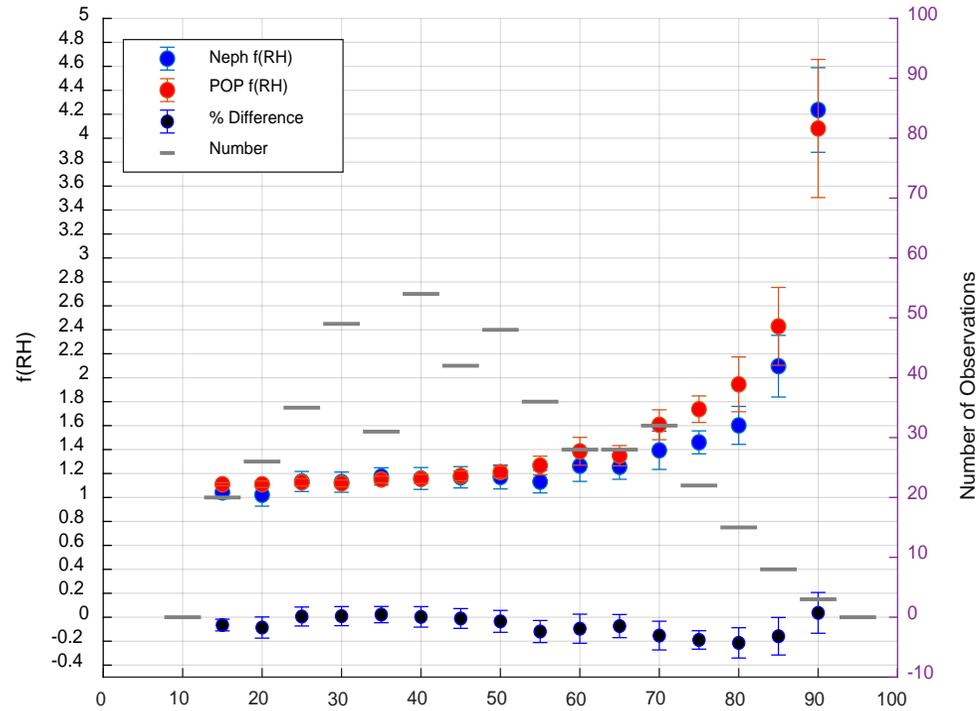
Measured nephelometer f(RH) is compared to the f(RH) theoretically calculated from the POPS_PILS dataset.
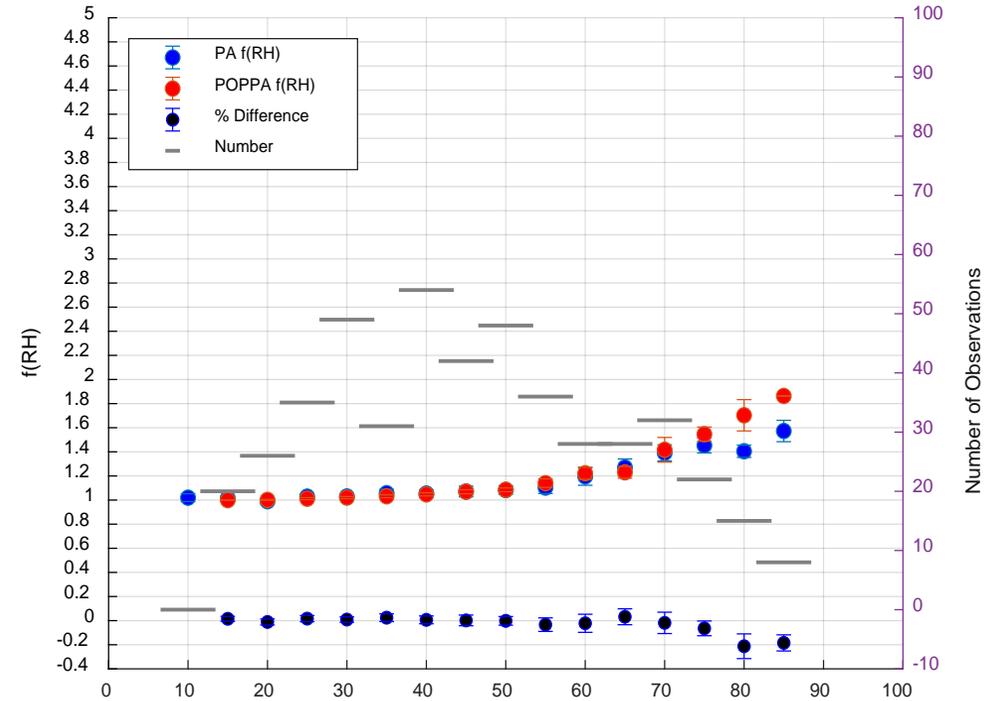
Measured PA f(RH) is compared to the PA f(RH) theoretically calculated from the POPS_PILS dataset.

Project Objectives

- Determine the PurpleAir response to particle size distributions
  - Evaluate current model of PA size distribution response
- Understanding and modeling the PA dependence on relative humidity
- Determining the cause of the differences between the Optec open air and 2Win PM2.5 nephelometer measurements

What are the desirable set of measurements to make in the up-coming Christman Field campaign

- Measurements
  - Light scattering measurements (minute)
    - PM2.5 scattering: 2win (near ambient, dry); NGN3 (heated); TSI (heated)
    - Totalish scattering: Optec open air (Ambient); Air Photon (heated?), soft PM10 cut point
  - PurpleAir light scattering measurements
    - 2 dry, PM2.5 PAs
    - 2-4 ambient PAs
  - Dry size distribution and particle # concentration
    - Scanning mobility particle size (CPC with DMA) – 0.05 < Dp < 0.87 microns
    - APS – 0.5 < Dp < 20 microns (TSI APS 3321)
    - Ambient and dry POPS - 0.1 < Dp < 3 microns
  - Ambient or humidified size distribution would be desirable, but above and beyond
  - High time resolution mass concentration of inorganic and organic carbon species (15 minute but hour OK)
    - Inorganic ions: Pills system
    - Carbonaceous aerosols: Sunset continuous OC/EC instrument
  - IMPROVE speciated aerosols, 24 hr every third day
  - *Need a monitoring site baby sitter
- Time Frame of measurements
 - Currently planned for 5 weeks this fall which means October - November

ASPRIN: Affordable Small Polarized imperfect Reciprocal Integrating Nephelometer
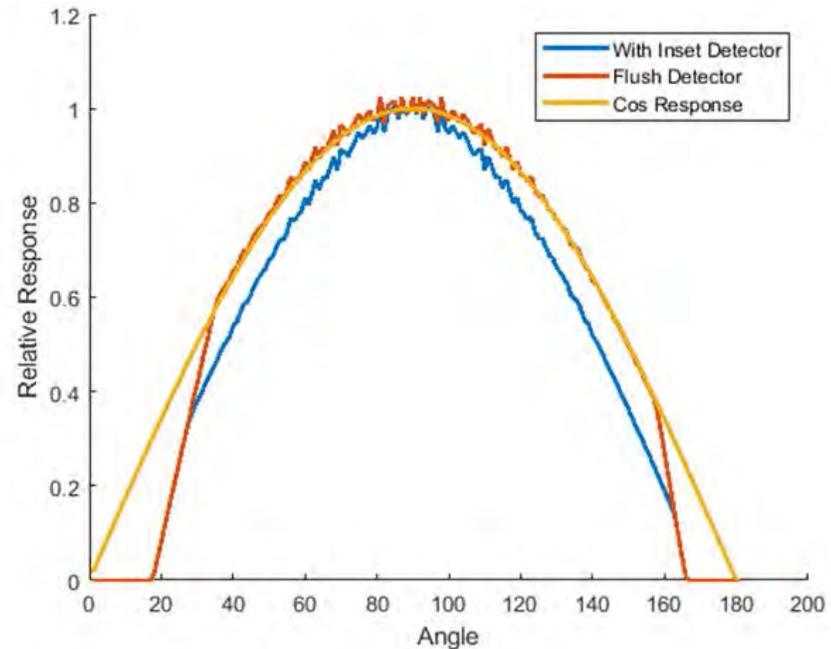
- Relative response of the photodetector assuming isotropic scattering
- PurpleAirs behave as an integrating light scattering instrument, and not particle counter
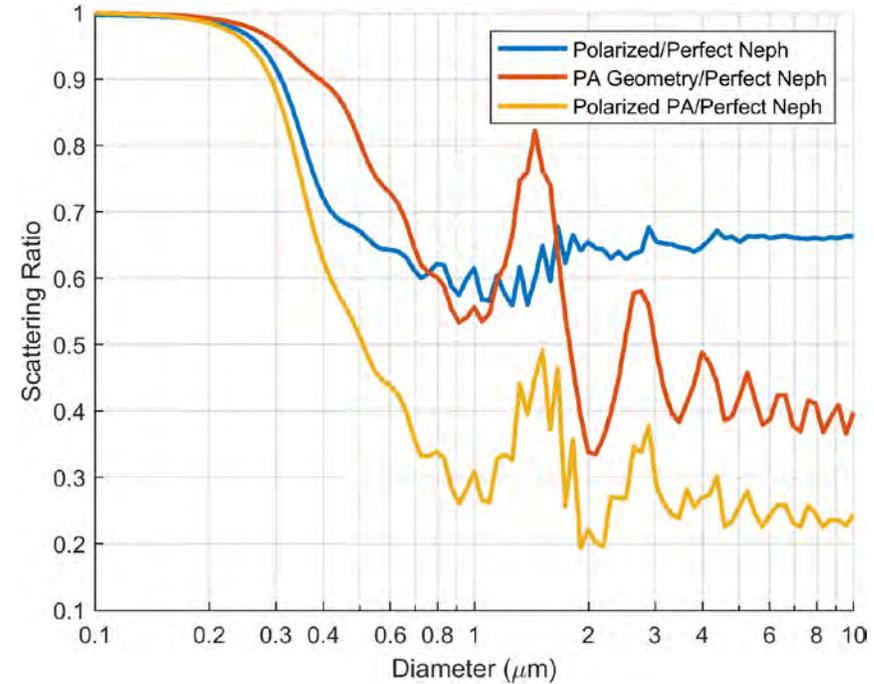
Ratio of scattering of a "perfect" nephelometer to a nephelometer
- with perpendicularly polarized light source (blue)
- a PA with an unpolarized light source (red)
- a PA with a perpendicularly polarized light source (yellow)
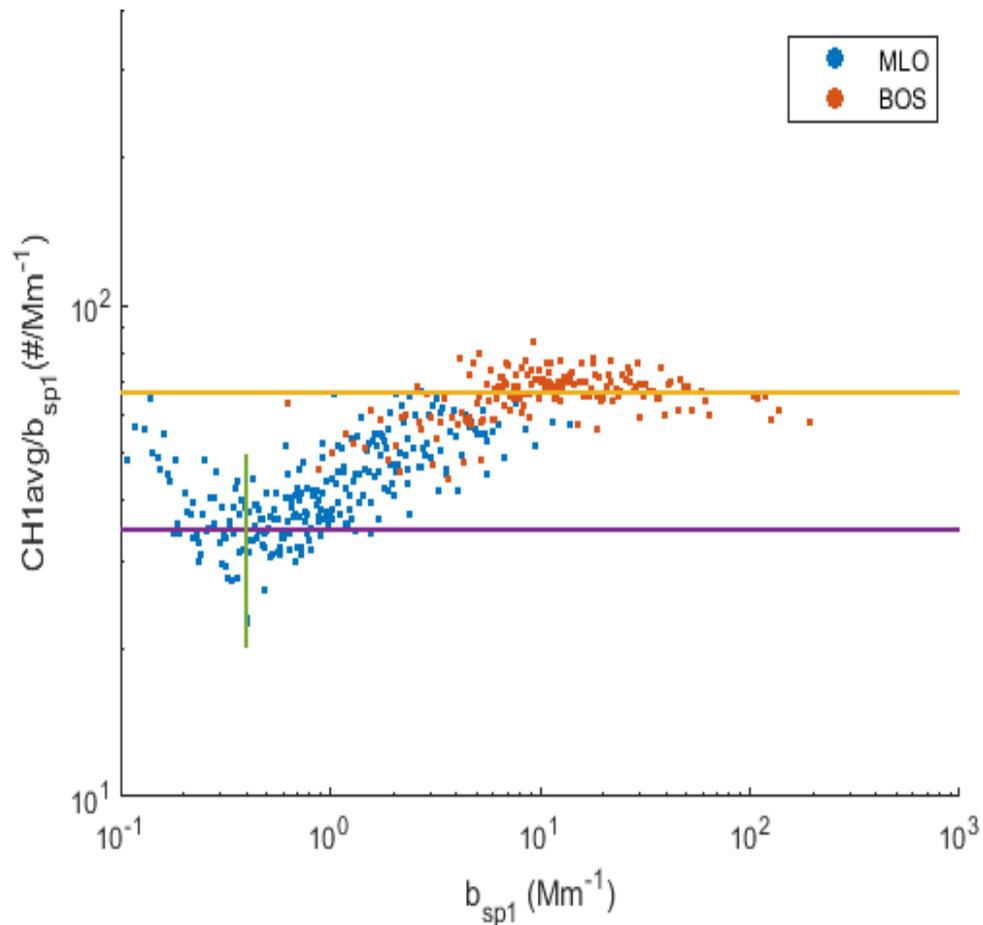
Ratios of CH1 and measured scattering, bsp1, as a function of measured bsp1 for MLO and BOS. Green line corresponds to 0.4 Mm-1 while the purple line, a ratio of 35 (1/35=0.028), corresponds to the additive uncertainty of 14. Yellow line corresponds to a CH1avg/bsp1 ratio of approximately 67 (1/67=0.015), the slope of CH1avg vs. bsp1 above about 5 Mm-1.

Why does the CH1/bsp ratio change as a function of bsp (Particle Size!!!!)?