Using Combined RSP and HSRL-2 Measurements to Estimate Cloud Droplet Number Concentration

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Research Questions

1. Can we combine measurements from the RSP and HSRL to calculate droplet concentration?
2. How does this new method compare to other methods?

Image credit: NASA LaRC ACTIVATE Project

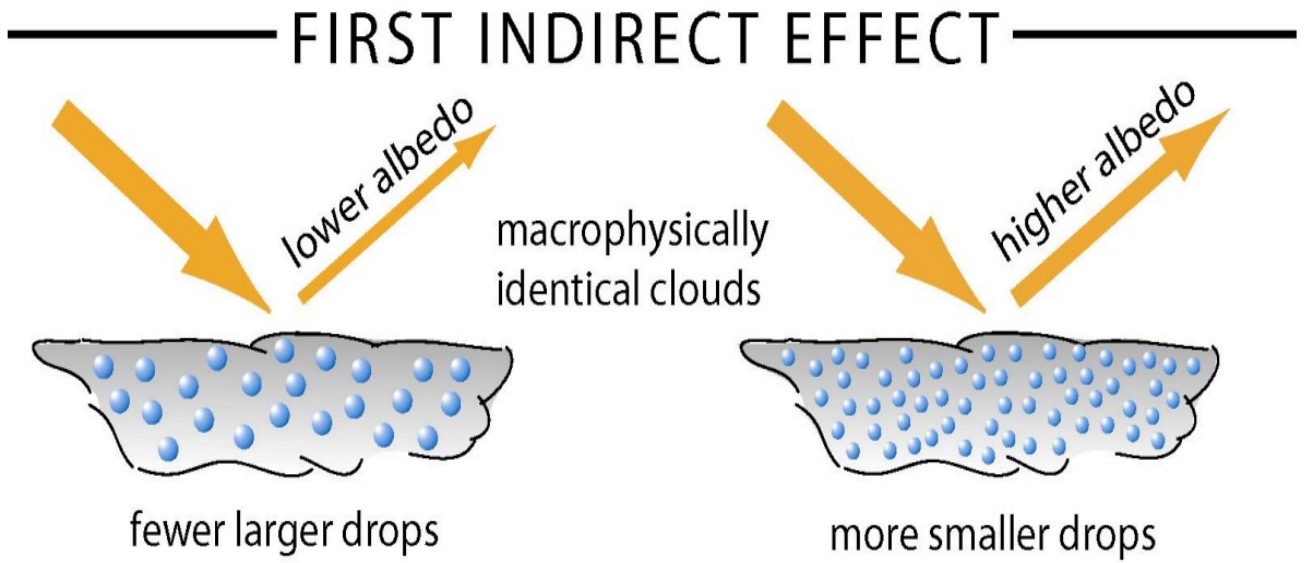
Outline

1. Droplet Concentration Review
2. Methods Overview
3. Instruments
4. ACTIVATE Campaign
5. Results
6. Discussion & Conclusions
7. Future Work

Image credit: ACTIVATE Working Folder

Droplet Concentration (N_d)

- Cloud droplet number concentration (N_d) is a cloud microphysical property
- Affects cloud evolution, precipitation, radiative forcing, and global climate
- Is an important parameter for observing the first indirect effect (Twomey, 1974)

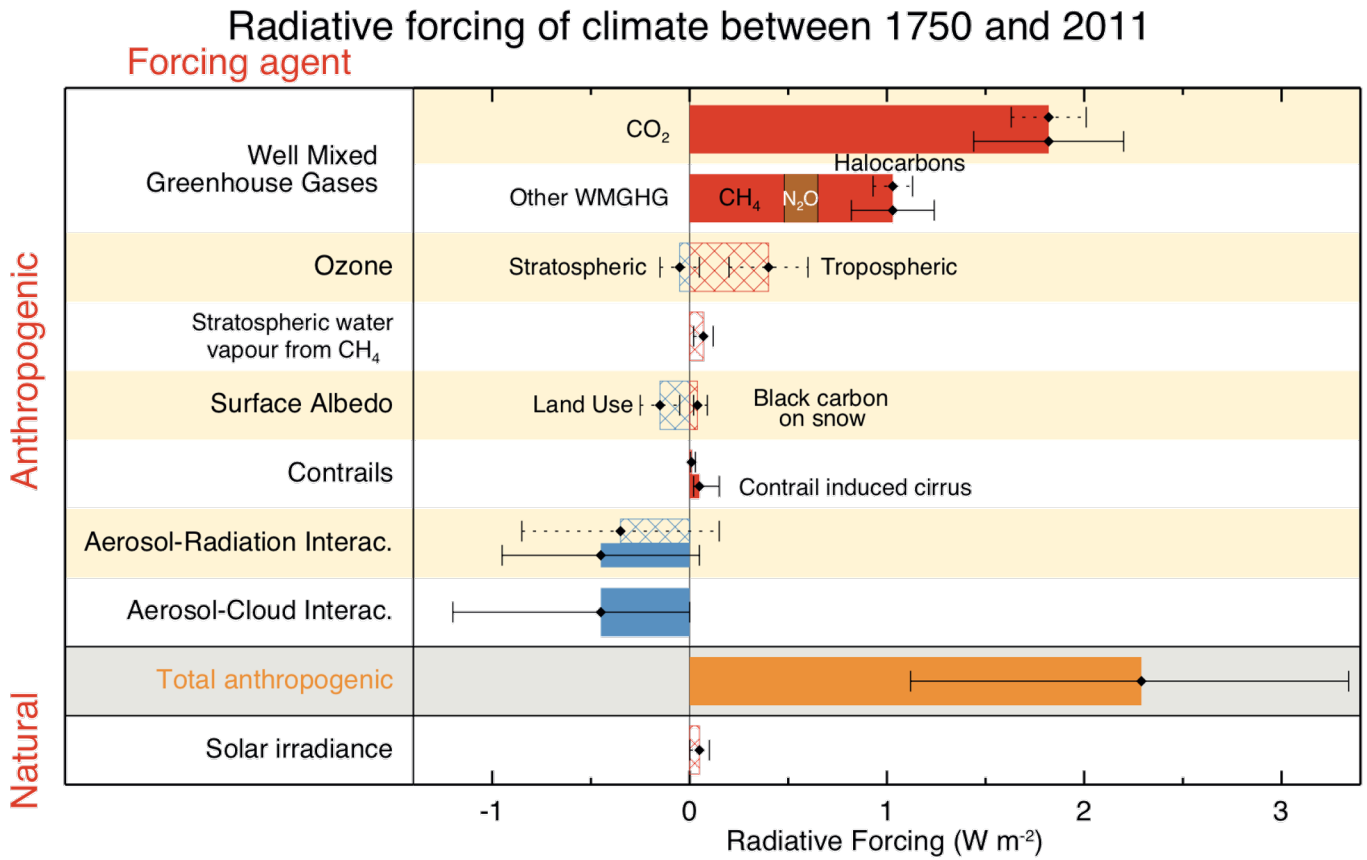


Grosvenor et al. 2018
Sinclair et al. 2019

Image credit: Rob Wood

Droplet Concentration (N_d), cont.

- Aerosol-cloud interactions makes up the largest uncertainty in our understanding of 20th-century climate change
- New methods of retrieving N_d are needed to better constrain aerosol-cloud interactions (Seinfeld et al., 2016)



Grosvenor et al. 2018
Sinclair et al. 2020

Image credit: Myhre et al. (2013)

Calculating N_d

1. Combined RSP-HSRL Method

$$N_d = \frac{\beta}{\sigma}$$

- N_d – droplet concentration
- β – in-cloud extinction (HSRL-2)
- σ – extinction cross-section (RSP)

Notes

- In-cloud extinction is from HSRL data
  - Calculated using mean integrated attenuated backscatter within the first optical depth of the cloud
- Extinction cross-section is derived from RSP data
  - r_{eff} and v_{eff} retrievals
- Expected benefits:
  - Direct measurement of N_d at cloud top
  - Requires no assumptions about vertical profile of cloud

Calculating N_d

2. Radiometric "MODIS" Method

$$N_d = \frac{\sqrt{5}}{2\pi k}\left(\frac{f_{ad} c_w \tau_c}{Q_{ext}\rho_w r_e^5}\right)^{1/2}$$

- k - "k-value", a measure of the width of the droplet size distribution
- f_{ad} - fraction of adiabatic value ≈ 0.6
- c_w - condensation rate
- Q_{ext} - extinction efficiency factor ≈ 2
- ρ_w - density of liquid water = 1,000 kg/m^3
- r_e - effective radius
- τ_c - optical thickness

Notes

- MODIS – MODerate Imaging Spectroradiometer
- Retrieved using RSP observations
  - Can be done using two effective radii
    - 863nm (Polarized R_{eff} retrieval)
      - Primarily used
    - 2260nm (NK R_{eff} retrieval)
- τ_c is susceptible to cloud 3D effects causing brightening or dimming
- Only including droplet concentration greater than 2cm^{-3}

Grosvenor et al. 2018

RSP Overview

Research Scanning Polarimeter (RSP)

1) Uniquely high angular resolution - 152 viewing angles per scene (±60°)
   - Allows for characterization of liquid water droplet sizes
2) Two mirrors – any polarization introduced from the first reflection is compensated for by the second reflection
3) Measures cloud: OT, R_{eff}, V_{eff}, CTH, thermodynamic phase, ice asymmetry parameter, N_d
4) Taken part in 27+ field campaigns

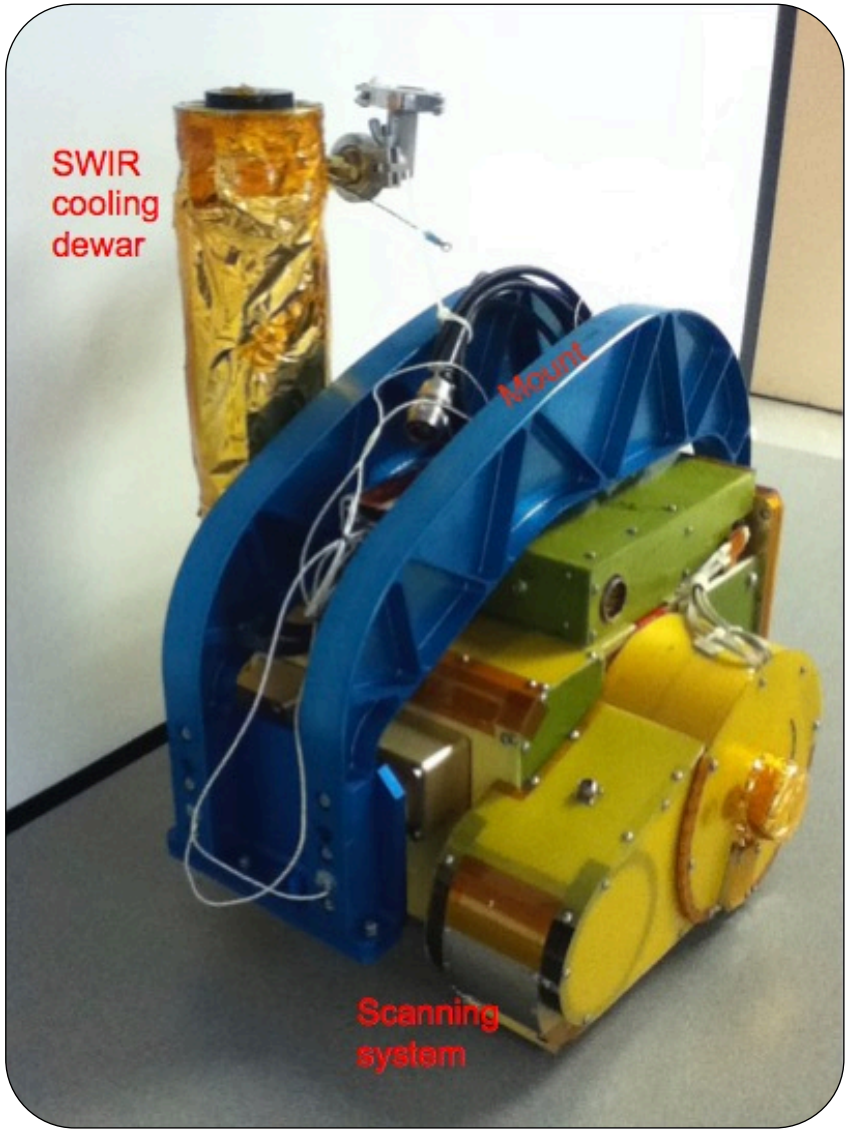


Image credit: NASA RSP Team

Cairns et al. 1999
Alexandrov et al. 2018
Sinclair et al. 2019

HSRL Overview

NASA Langley HSRL-2

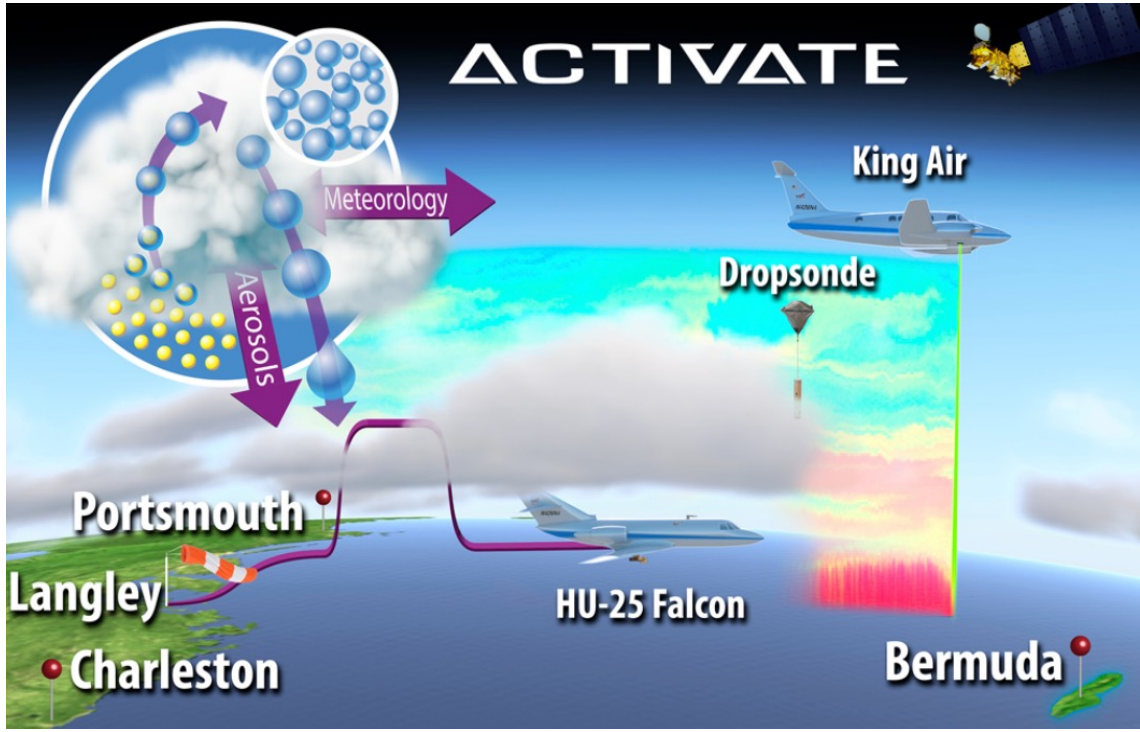
1) HSRL-2: High Spectral Resolution Lidar
2) Used to study aerosol size, composition, distribution and movement
3) Utilizes lidar rather than radar
4) Measures: aerosol extinction, backscattering, and depolarization

https://airbornescience.nasa.gov/instrument/HSRL

Image credit: Burton et al. (2019) APOLO Conf. Pres.

Introduction to ACTIVATE

- **ACTIVATE (Aerosol Cloud Meteorology Interactions Over the Western Atlantic Experiment)**
  - An air campaign part of the NASA Airborne Science Program
- Unique in its usage of two aircraft:
  - Remote sensing performed from the NASA King Air B200
  - In situ measurements collected from the NASA HU-25 Falcon



ACTIVATE
Aerosol Cloud Meteorology Interactions
Over the Western Atlantic Experiment

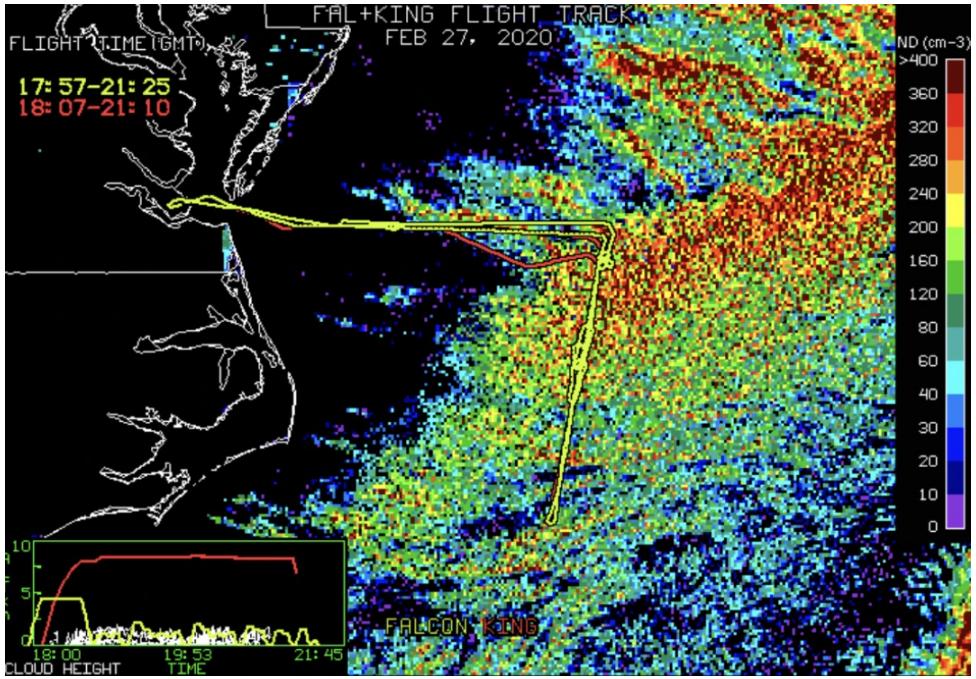
https://www-air.larc.nasa.gov/missions/activate/

Image credits: NASA LaRC ACTIVATE Project

2/27/2020 Overview

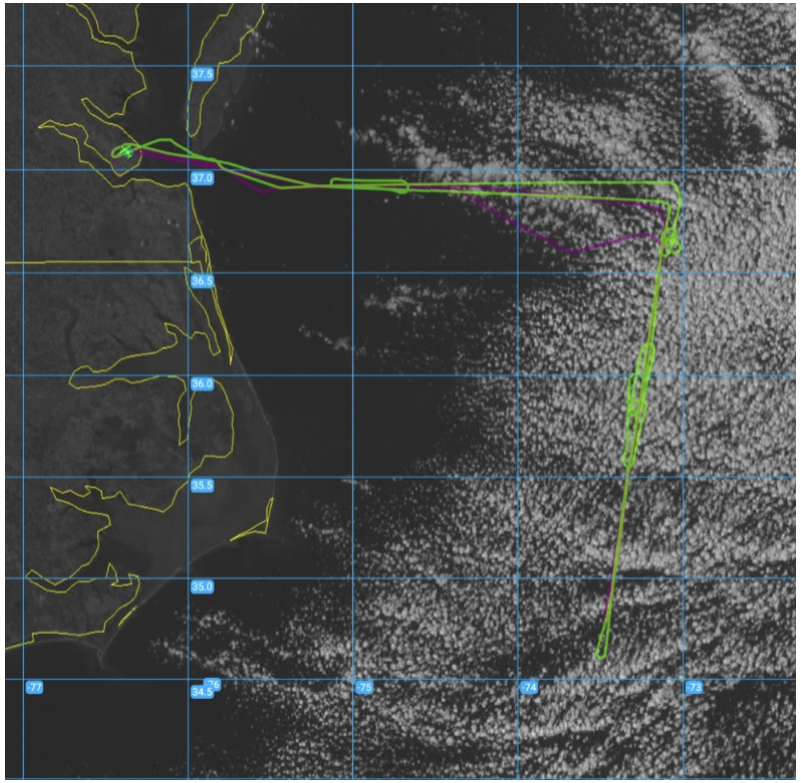
1. 2/27/2020 chosen for:
   - First day for good amount of combined data from each instrument
   - Consistent cloud cover
   - Enough variation in droplet concentration to observe covariance between retrievals from different methods
2. Particularly interested in:
   - 19-20 (UTC)

2/27/2020 Heatmap of Droplet Concentration

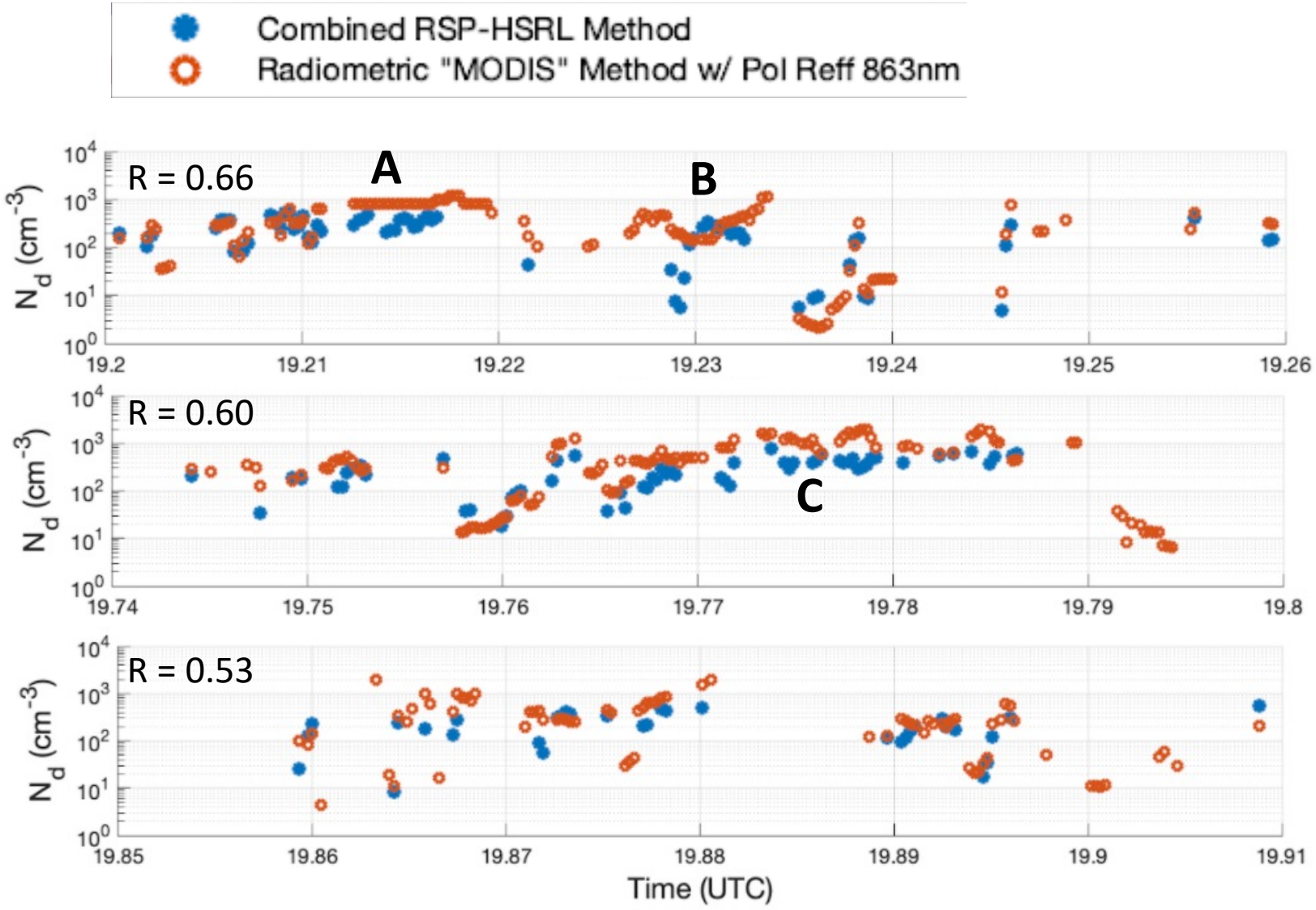


Images credit: ACTIVATE Working Folder

Path of Flight for 2/27/2020, Satellite View



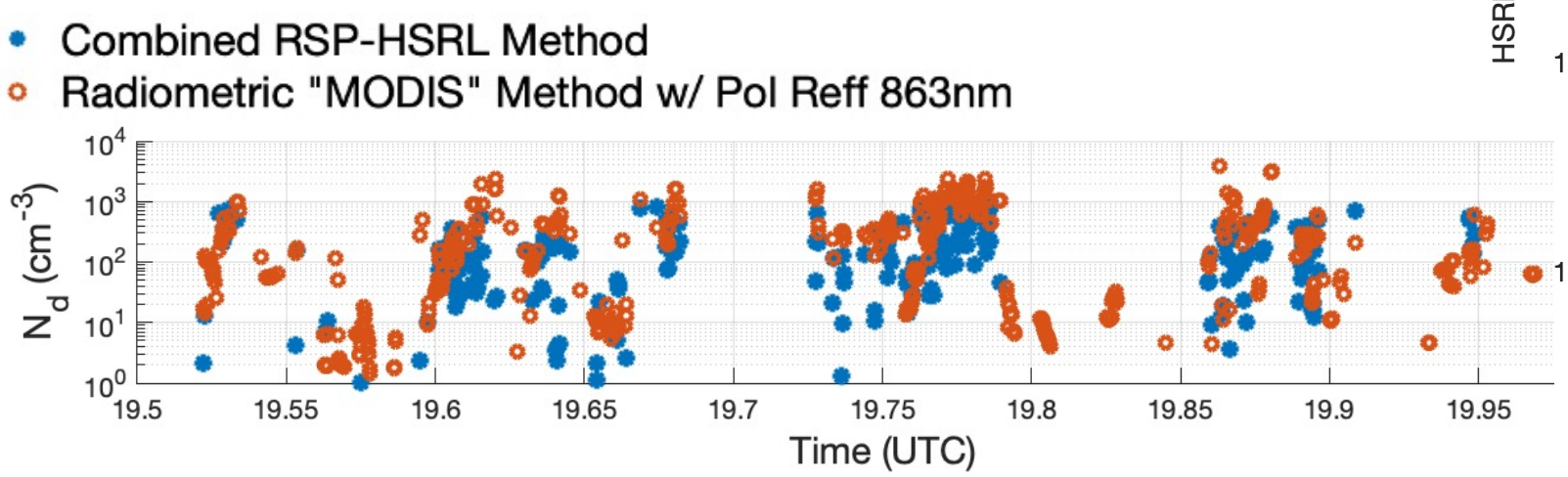
Results: Radiometric "MODIS" Method vs. Combined Method Covariance in Time Series

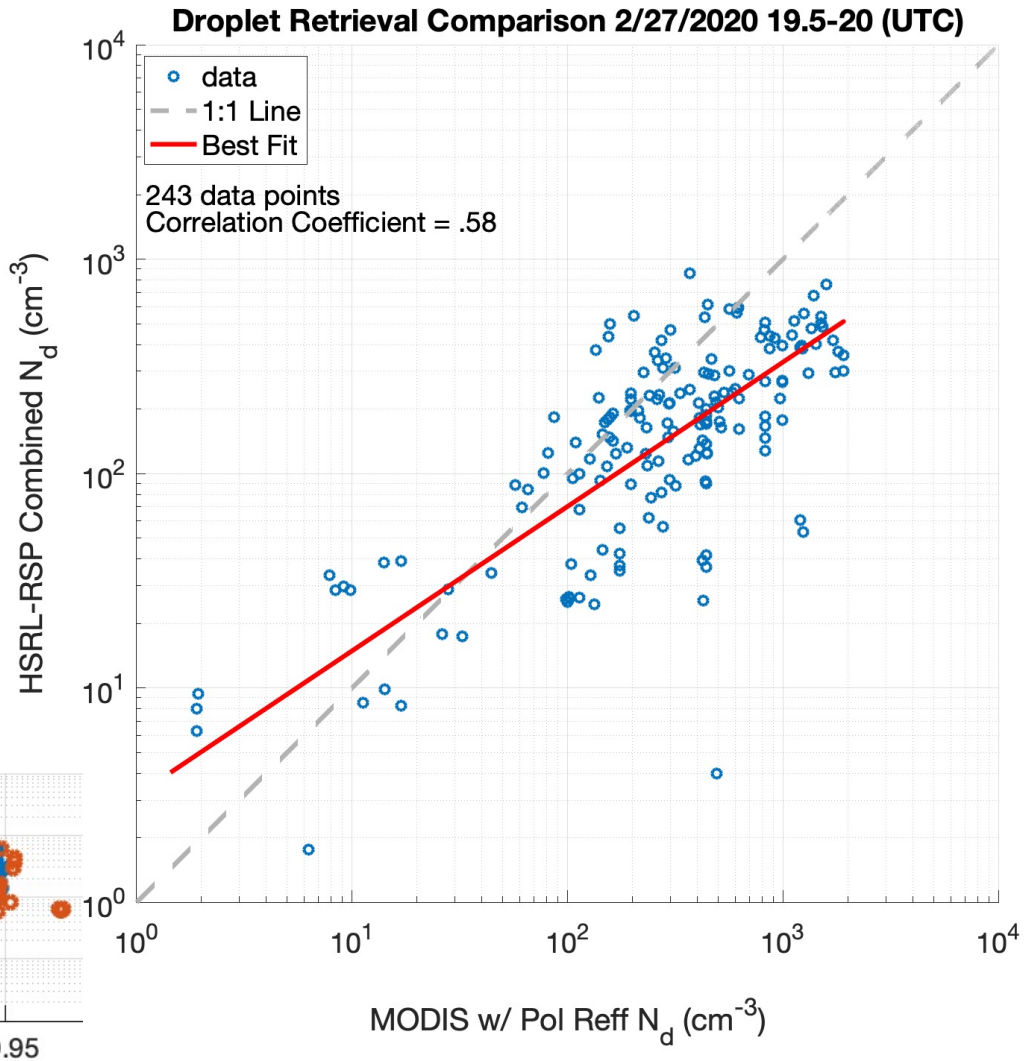


	Combined $\bar{N}_d \pm \sigma$	MODIS $\bar{N}_d \pm \sigma$
19.2-19.26	229 ± 146	403 ± 37
19.74-19.8	296 ± 186	567 ± 539
19.85-19.91	222 ± 143	361 ± 396

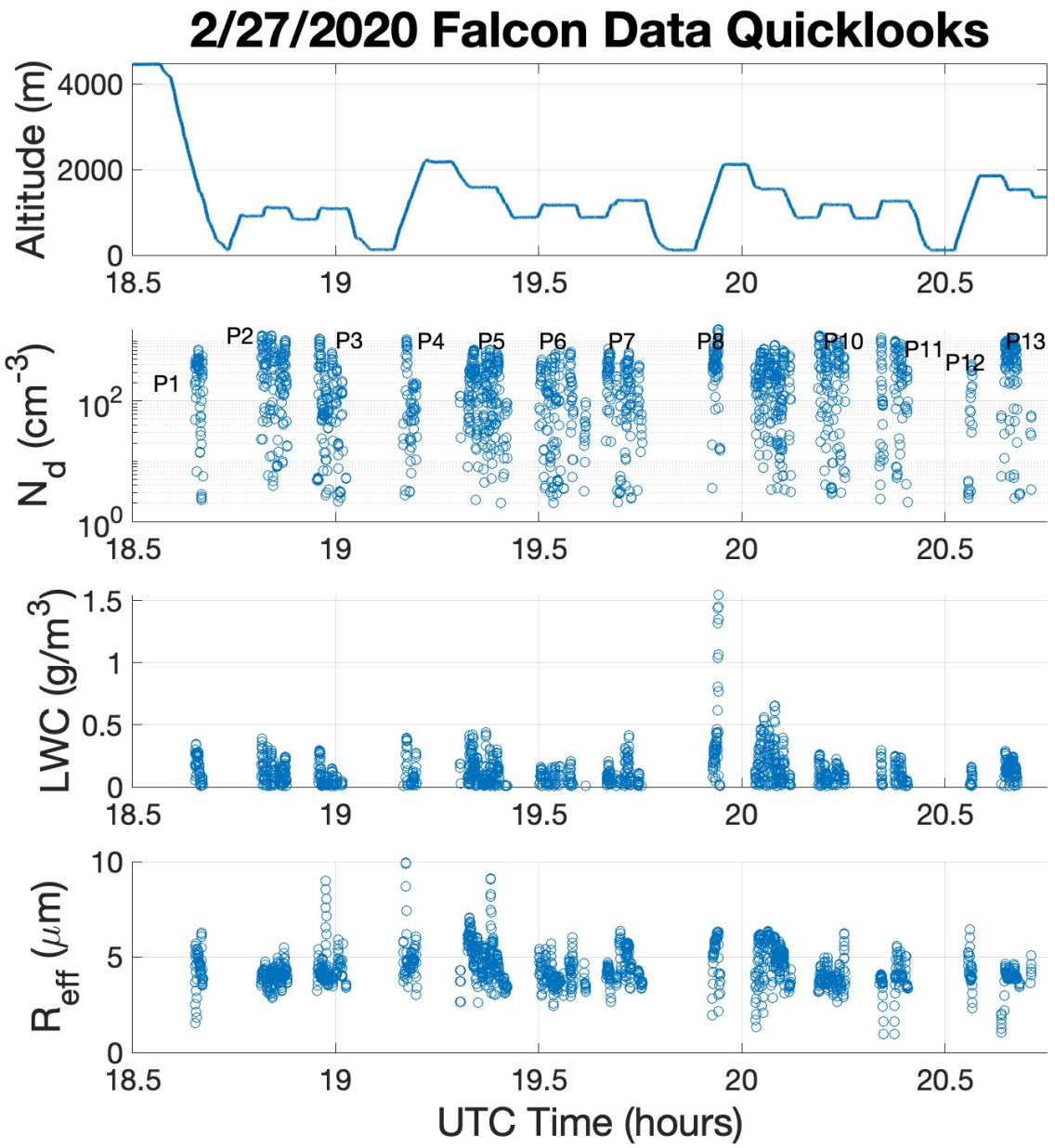
Results: 2/27/2020, 19.5-20.0 (UTC)

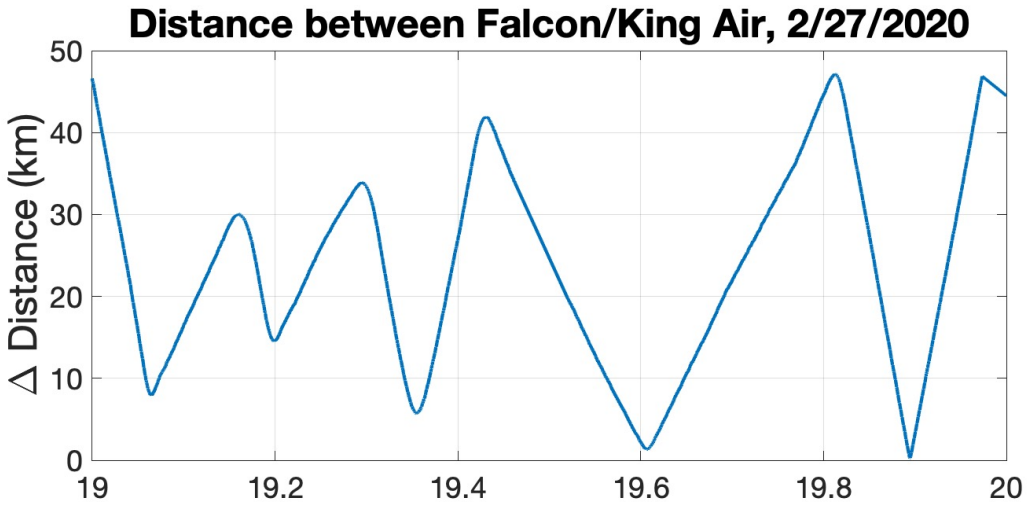
1) Scatterplot below shows a clear covariance between combined method and radiometric Nd values
2) However, despite covariance, radiometric values are certainly higher
    1) Skew of scatterplot to the right
3) Combined method works best over cloud centers

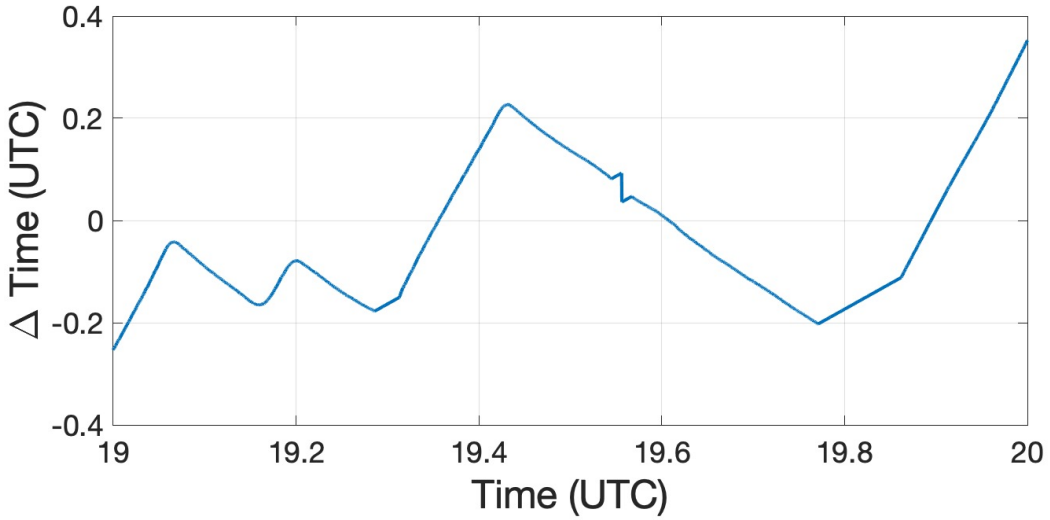




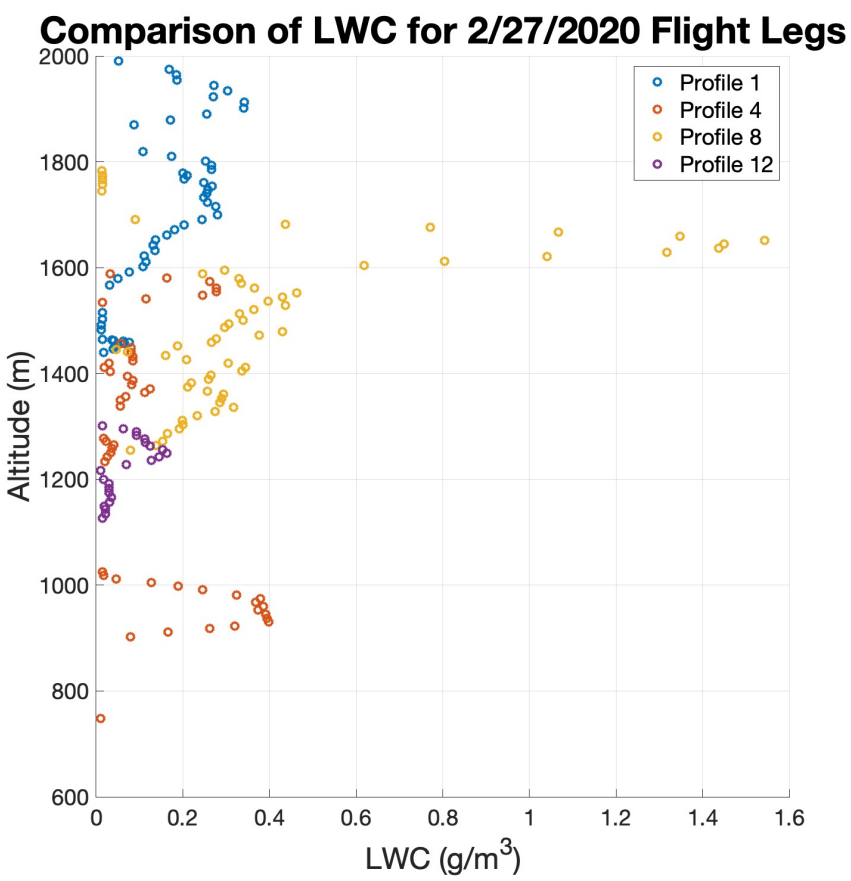
Results: Falcon Quicklooks 2/27/2020,

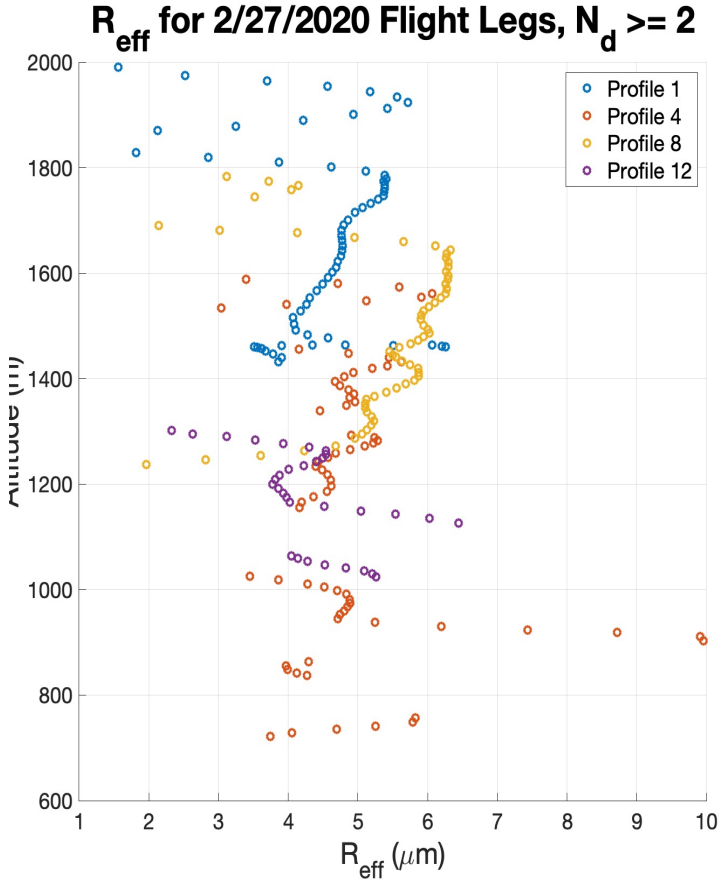


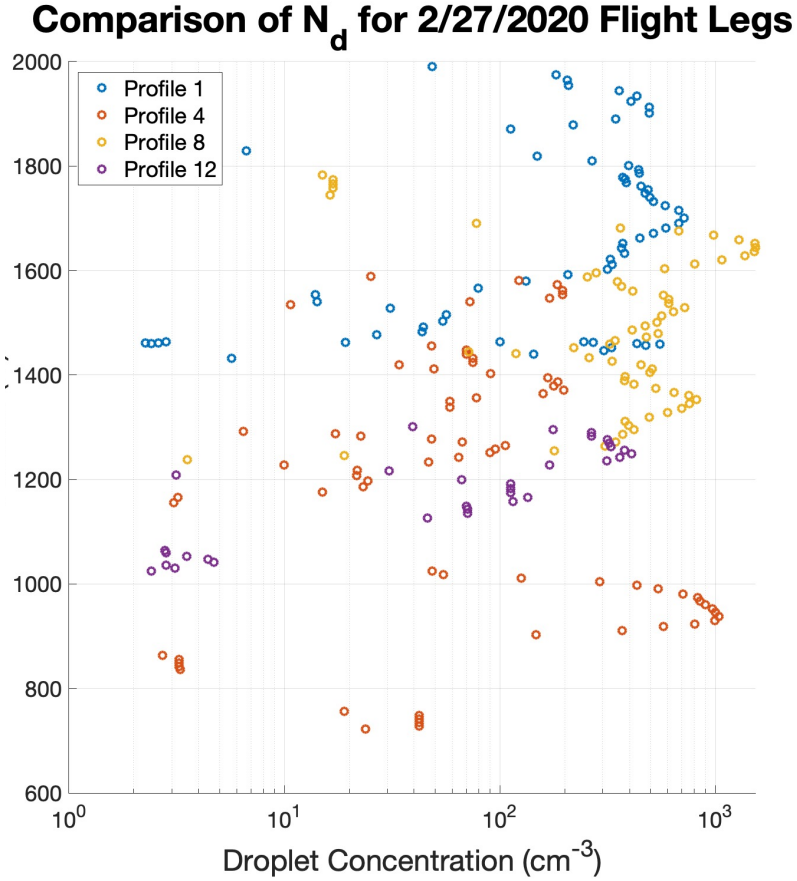




Results: Vertical Profiles of Droplet Concentration for the Falcon







Results: Determination of Cloud Edge, Falcon Data

1) Comparing mean & standard deviation for Falcon profiles
2) When the floor for liquid water content is raised from .01 to .025, the mean value for all data raises from 355 cm^{-3} to 414 cm^{-3}
3) This demonstrates the significance of choosing an arbitrary floor for LWC

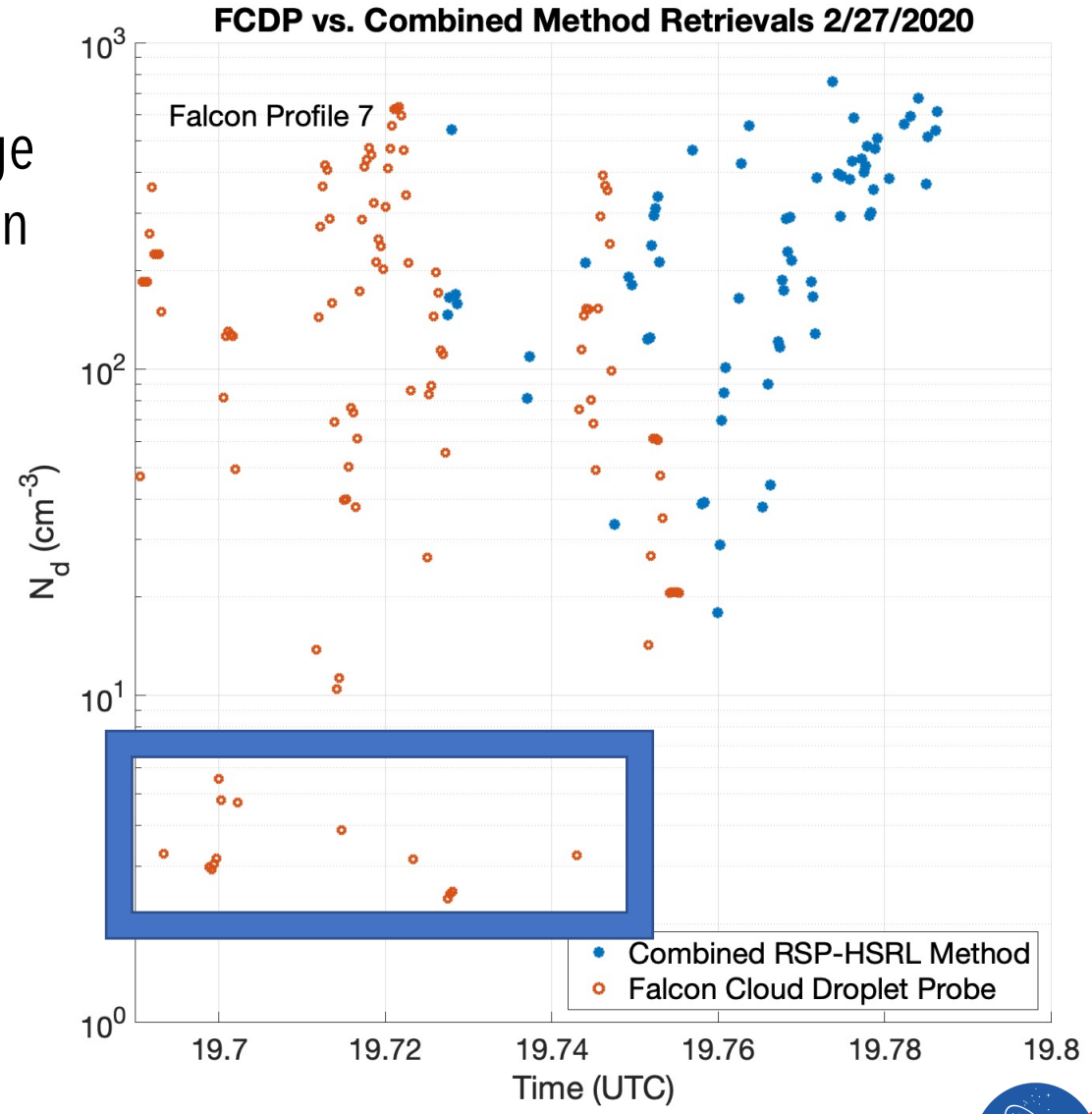
LWC >= .01 & Nd >= 2				
Profile	Start Time (UTC)	End Time (UTC)	Nd (cm^-3) (mean)	Nd (cm^-3) (std. dev.)
P1	18.65	18.67	284	209
P2	18.82	18.88	361	325
P3	18.96	19.02	188	236
P4	19.17	19.2	215	303
P5	19.31	19.42	225	201
P6	19.5	19.61	171	183
P7	19.67	19.75	225	193
P8	19.93	19.94	473	178
P9	20.03	20.12	252	207
P10	20.19	20.25	380	364
P11	20.34	20.41	337	326
P12	20.56	20.57	179	128
P13	20.64	20.68	603	299

Color Key for Nd
0-99
100-199
200-299
300-399
400-499
500-599
600-699
700-799

Results: Comparison of Falcon and Combined Method Data

1) Non-collocated Falcon data
2) Falcon data points in the blue square are near/at cloud edge
3) Back of the envelope calculation of time difference between retrievals yields average time difference of 4.75 minutes
    1) <5 min difference in time between cloud retrievals agrees with the timeseries
    2) Measurements are made in approximately the same location

P7	Nd (cm^-3) (mean)	Nd (cm^-3) (std. dev.)
FCDP	225	193
Combined	286	185
MODIS	558	526



Conclusions & Discussion

1) Combined RSP-HSRL shows covariability with "MODIS" method
   - Combined method appears to be less susceptible to cloud 3D effects
   - Combined method appears to work well over a range of droplet concentrations

2) Further comparisons to Falcon data are needed for determining accuracy of combined method
   - Removing cloud edge will reduce variability
   - An initial comparison shows promise

3) Radiometric "MODIS" method calculations of Nd appear to be biased high
   - Likely from cloud 3D effects saturating the optical thickness retrieval
   - Fraction of adiabaticity
   - Can use in situ measurements to evaluate the fraction of adiabaticity used in the "MODIS" method

Image credit:
https://www.nasa.gov/centers/langley/news/researchernews/rn_TCAP.html

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1) Papers:
- Grosvenor, D. P., Sourdeval, O., Zuidema, P., Ackerman, A., Alexandrov, M. D., Bennartz, R., ... & Deneke, H. (2018). Remote sensing of droplet number concentration in warm clouds: A review of the current state of knowledge and perspectives. *Reviews of Geophysics*, *56*(2), 409-453.
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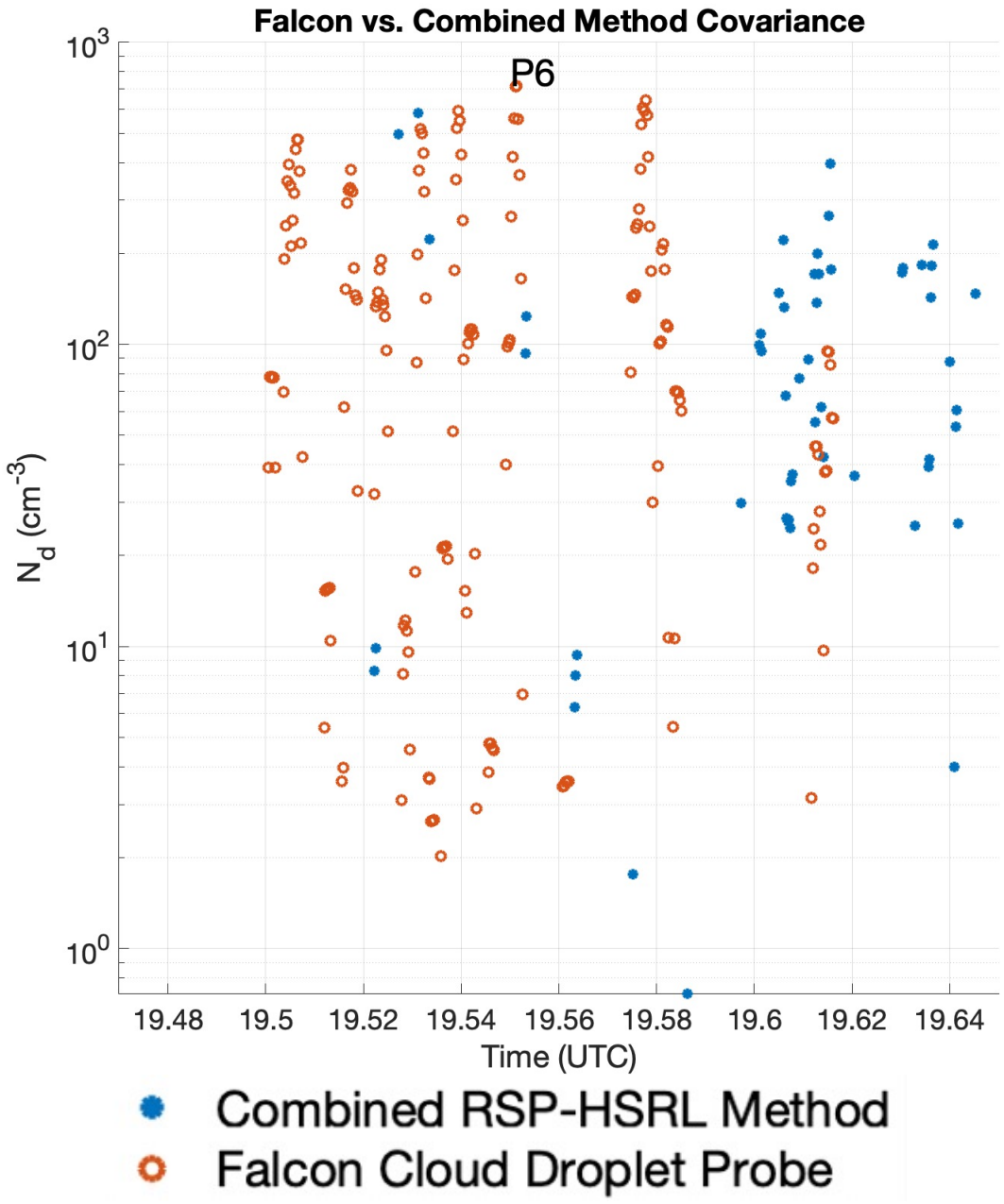
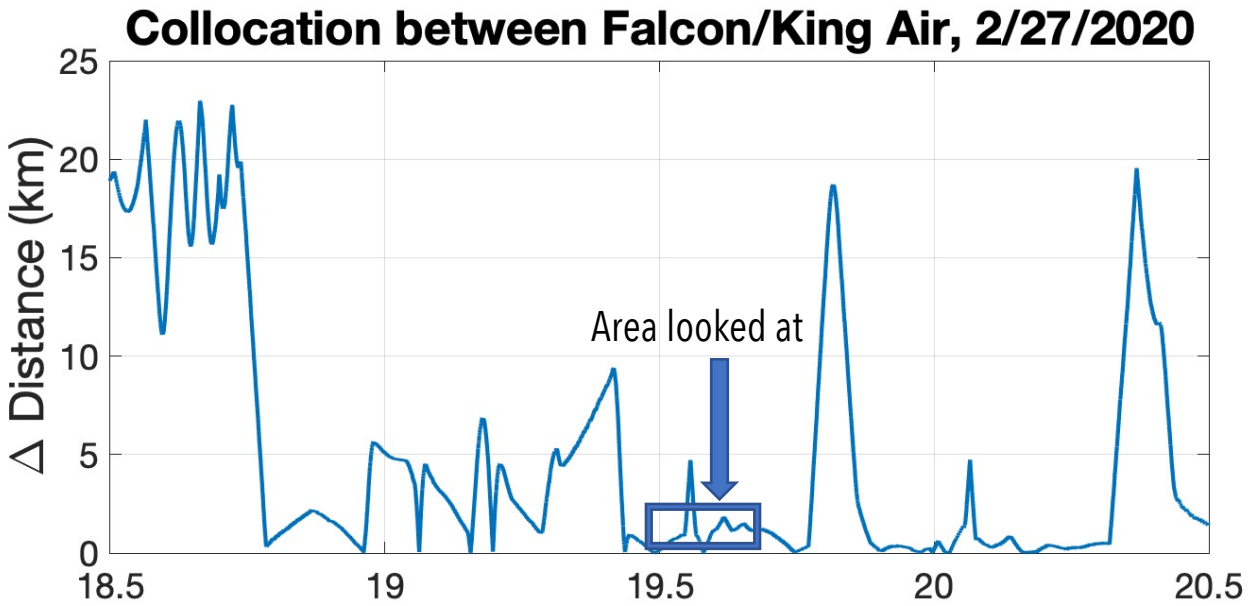
1) Pictures:
- https://atmos.uw.edu/~robwood/teaching/591/ATMS_591_Twomey_1977.pdf
- ACTIVATE Working Folder
- https://www.nasa.gov/feature/langley/probing-the-hazy-mysteries-of-marine-clouds
- https://www.nasa.gov/centers/langley/news/researchernews/rn_TCAP.html
- https://www.nasa.gov/mission_pages/icebridge/instruments/KingAir.html
- Burton et al. (2019) APOLO Conf. Pres.
- Myhre et al. (2013)

2) Websites:
- https://www-air.larc.nasa.gov/missions/activate/
- https://airbornescience.nasa.gov/instrument/HSRL

Results: Falcon Collocation and Comparison Profile 6

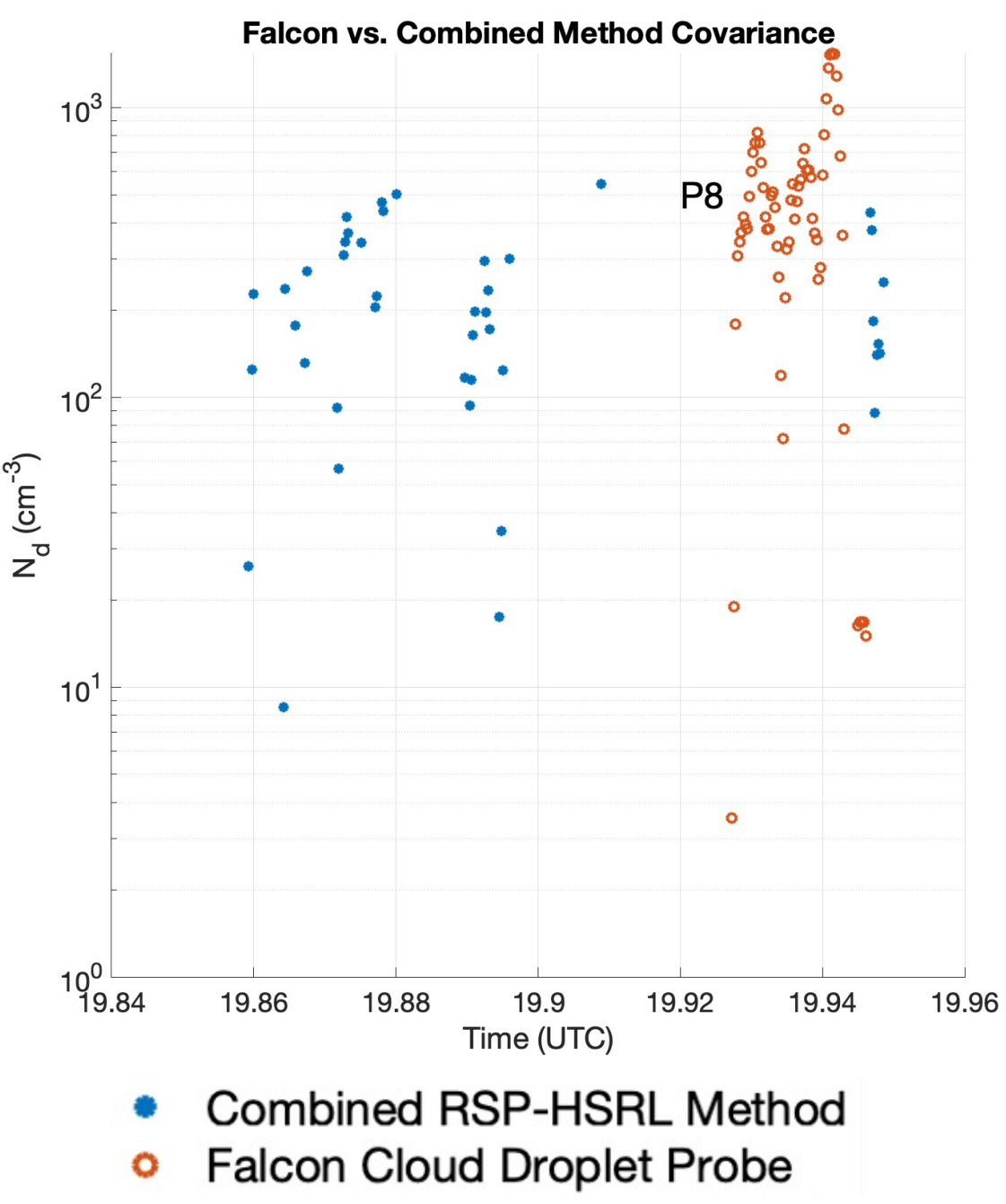


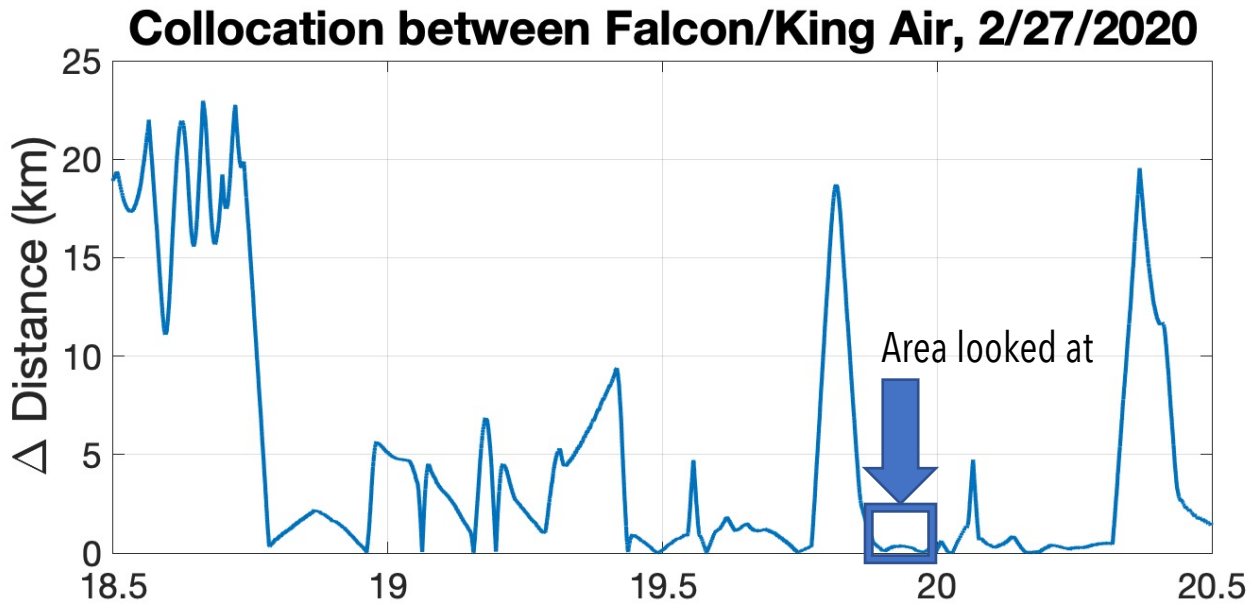


1) Mean difference between these collocated points is 1.16 km (in this time range)
2) Profiles show similar shape

P6	Nd (cm^-3) (mean)	Nd (cm^-3) (std. dev.)
FCDP	171	183
Combined	112	118
MODIS	185	261

Results: Falcon Collocation and Comparison Profile 8





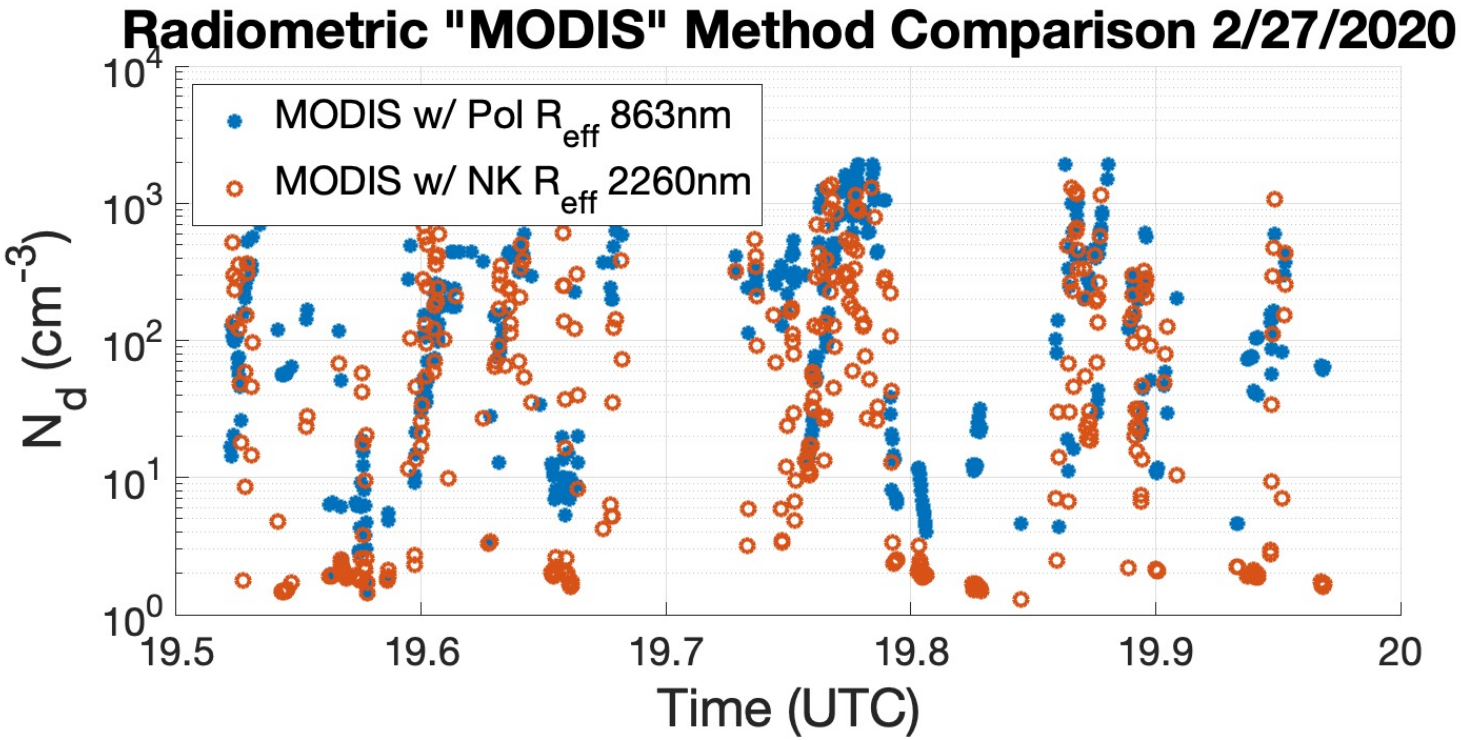
1) Mean difference between these collocated points is 1.56 km (in this time range)
2) Profiles show similar shape

P8	Nd (cm^-3) (mean)	Nd (cm^-3) (std. dev.)
FCDP	473	177
Combined	222	139
MODIS	294	358

Preliminary Results: Radiometric "MODIS" Method, 863nm vs. 2260nm

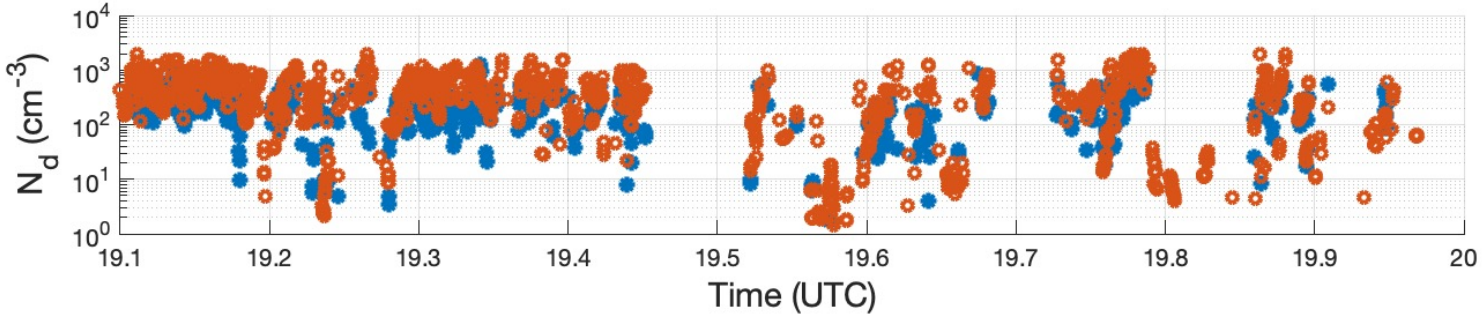
1) Both droplet concentrations use the same radiometric "MODIS" method
2) Different effective radii used
   - Polarimetric – 863nm band
   - Nakajima King (NK) – 2260nm band
3) Correlation coefficient of 0.60 is similar to correlation coefficient between combined and radiometric methods

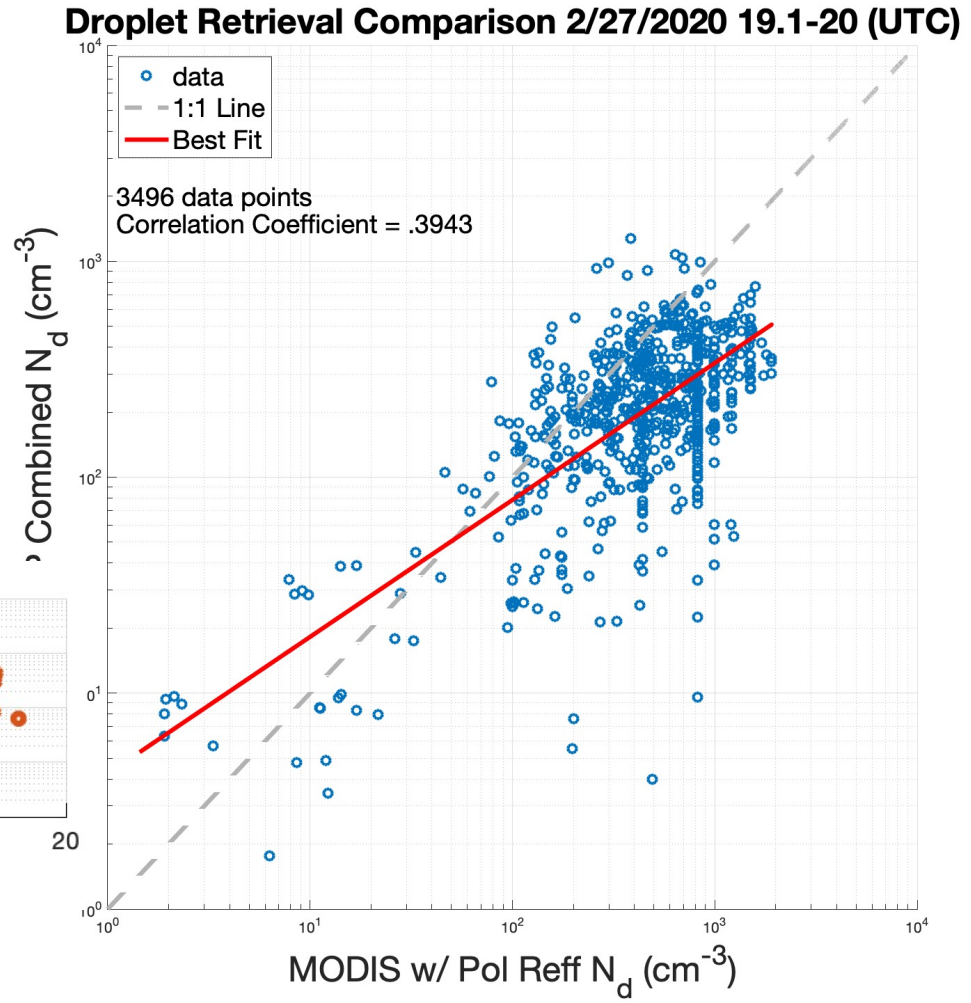
19.5-20	Mean Nd	S.D.
"MODIS" Pol	307	408
"MODIS" NK	226	333



Results: Radiometric "MODIS" Method vs. Combined Method Scatterplots

1) Correlation coefficient is 0.3943 for 19.1-20 (UTC)
2) Compared to .5811 for 19.5-20 (UTC)
3) Relatively high degree of covariance over fairly long stretch





Uncertainty Estimation

Radiometric method

$$\left|\frac{\partial N_d}{N_d}\right|^2 = \left|\frac{1}{2}\frac{\partial c_w}{c_w}\right|^2 + \left|\frac{1}{2}\frac{\partial f_{ad}}{f_{ad}}\right|^2 + \left|\frac{1}{2}\frac{\partial \tau_c}{\tau_c}\right|^2 + \left|\frac{\partial k}{k}\right|^2 + \left|\frac{5}{2}\frac{\partial r_e}{r_e}\right|^2 + \left|\frac{\partial N_d}{N_d}\right|^2_{other}$$

$$\left|\frac{\partial N_d}{N_d}\right|^2 = \left|\frac{1}{2} * .08\right|^2 + \left|\frac{1}{2} * .3\right|^2 + \left|\frac{1}{2} * .25\right|^2 + |.13|^2 + \left|\frac{5}{2} * .27\right|^2 + |.3|^2 = 0.60225$$

$$\left|\frac{\partial N_d}{N_d}\right| = 78\%$$

Combined RSP-HSRL-2 method

$$\left[\frac{\delta N_d}{N_d}\right] = \left(\left[\frac{\delta \overline{\sigma_e}(H)}{\overline{\sigma_e}(H)}\right]^2 + \left[\frac{\delta \beta}{\beta}\right]^2\right)^{1/2}$$

$$0.15 \qquad 0.20 \qquad = 25\%$$

Polarimetric method

$$\left[\frac{\delta N_d}{N_d}\right] = \left(\left[\frac{\delta \tau}{\tau}\right]^2 + \left[\frac{\delta \overline{\sigma_e}(H)}{\overline{\sigma_e}(H)}\right]^2 + \left[\frac{\delta H}{H}\right]^2\right)^{1/2}$$

- mean uncertainty of $r_{eff} < 0.1$ μm (Alexandrov et. al., 2012)

$$0.17 \qquad 0.15 \qquad 0.20 \qquad = 30\%$$

$$0.17 \qquad 0.15 \qquad 0.30 \qquad = 38\%$$