



Planetary Boundary Layer Height and Ozone Measurement Techniques

**Department of Atmospheric and Planetary Science
Hampton University**

Seminar

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10/23/2019**



Outline

- **Part 1 The Lidar Planetary Boundary Layer (PBL) Height Detection**
 - Background of PBL Detection
 - Instrument and Algorithm for PBL Height Detection
 - Results of the PBL Height Detection
- **Part 2 The Ozone Raman Differential Absorption Lidar (DIAL)**
 - Background of Ozone Measurement
 - Ozone Raman DIAL and the wavelength selection
 - Ozone retrieval and comparison with coincident data
- **Conclusion**



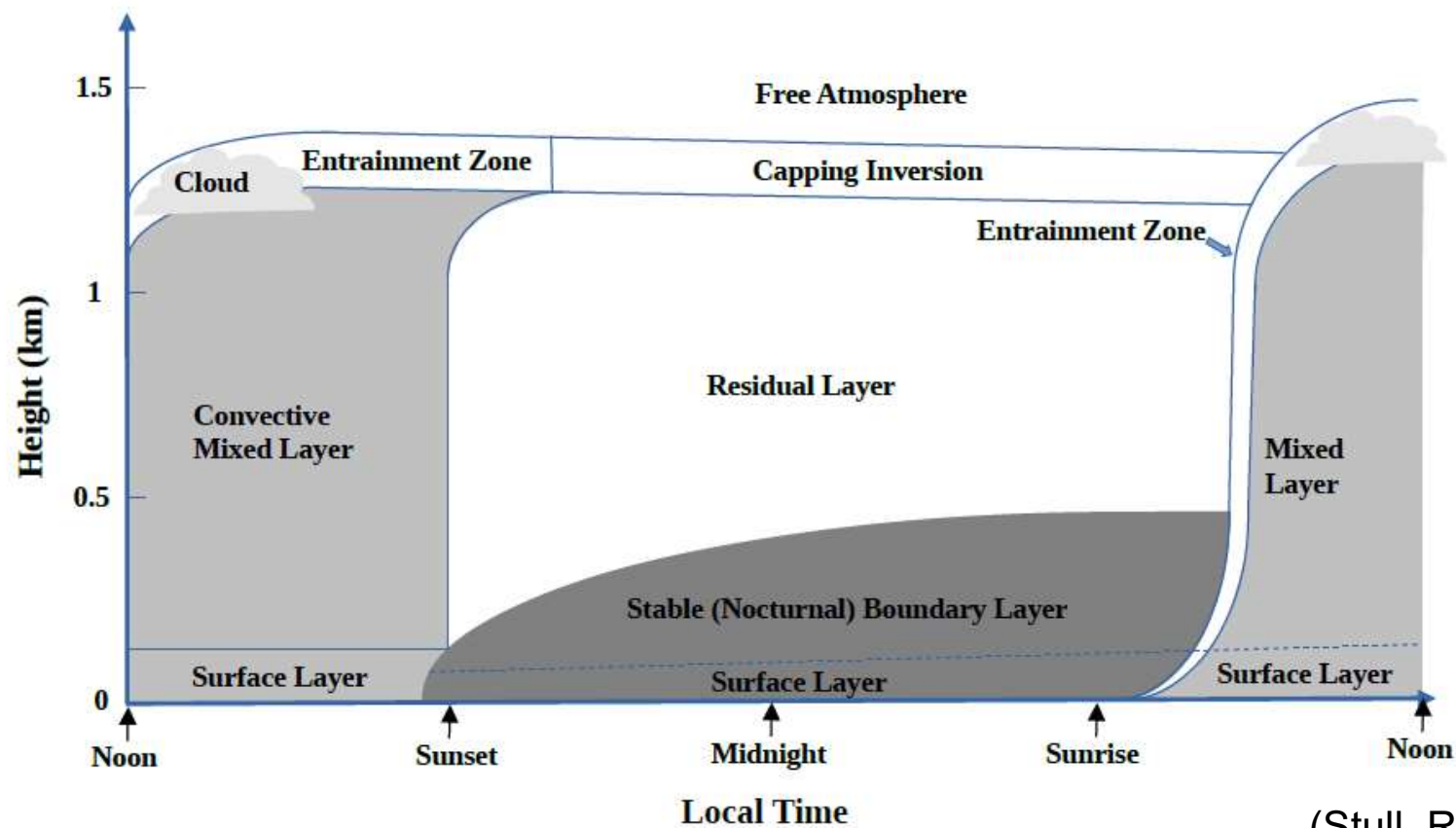
Part 1

The Lidar PBL Height Detection

Background

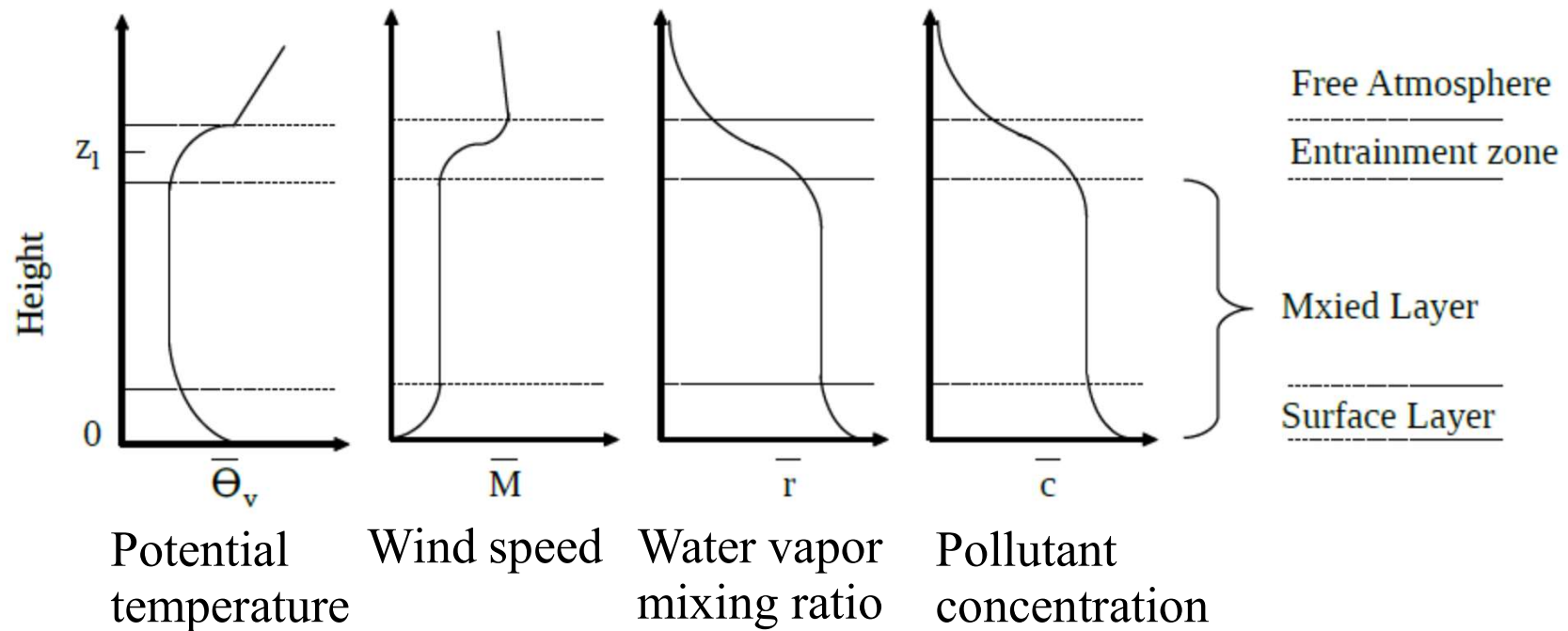
– Planetary Boundary Layer (PBL)

PBL: Lowest part of the atmosphere
Directly and strongly influenced by the Earth's surface
Responds to surface forcings within about 1 hour or less



(Stull, R. B., 2012)

Background – PBL Height



At top of PBL: Potential temperature $\uparrow$

Wind speed $\uparrow$

Water vapor mixing ratio $\downarrow$

Pollutant concentration $\downarrow$

Aerosol concentration $\downarrow$

Why lidar can detect PBL top

Background

– Method of PBL Height Detection

- **Balloon sounding**

Method: Finding altitude potential temperature ↑

Limitation: Cannot contribute to a through understanding of meteorology, high cost

- **Lidar Measurements**

Method: Finding the altitude where aerosol concentration ↓

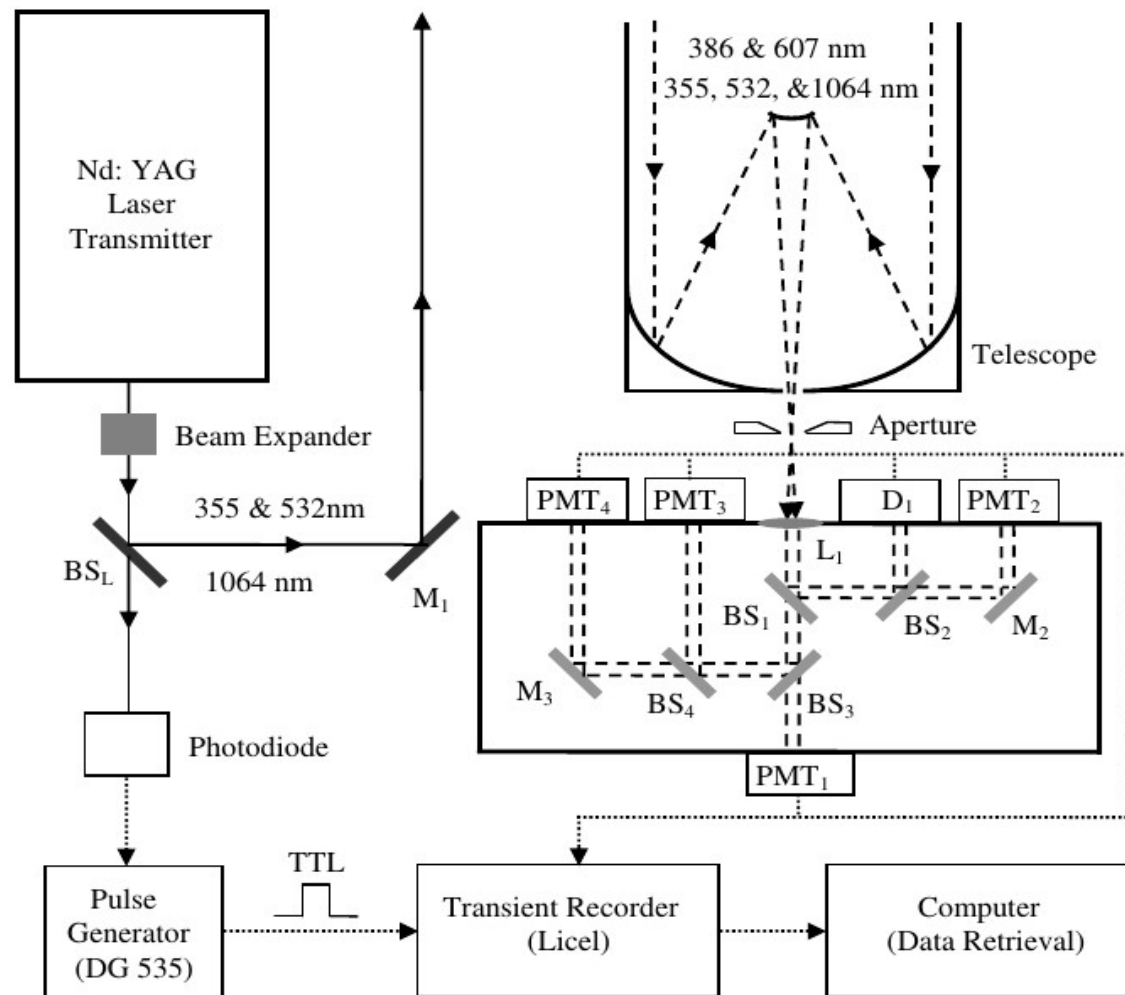
Advantage: Ranging capability, high spatial and temporal resolution, continuous measuring

- **Gradient method, Variance method, Wavelet method, multi-wavelength method**

- **The CALIPSO PBL height retrieval**

Instruments and Algorithm

– Hampton University (HU) Lidar



Instruments and Algorithm

– Specifications of HU Lidar

Table 2.1. The HU lidar component specifications.

Lidar Components	Specification
Laser Model	Powerlite DLS 9010 mJ
Nd: YAG 1064 nm	1200 mJ
Nd: YAG 532 nm	600 mJ
Nd: YAG 355 nm	400 mJ
Repetition Rate	10 Hz
Telescope Type	Cassegrain
Telescope Diameter	48 inch
Telescope FOV	1-4 mrad
1064 nm Receiver Photodiode	Perkin& Elmer C30956E-TC
355 nm Receiver PMT3	HAMAMATSU R9880U-210
386 nm Receiver PMT4	HAMAMATSU R9880U-210
532 nm Receiver PMT2	HAMAMATSU R7400-02
607 nm Receiver PMT1	HAMAMATSU R7400-02
Lidar GFF	1 Km
Pulse Generator	DG535
Data Acquisition System	Licel Transient recorder TR20-160
Vertical Resolution	7.5 m
Temporal Resolution	200 sec

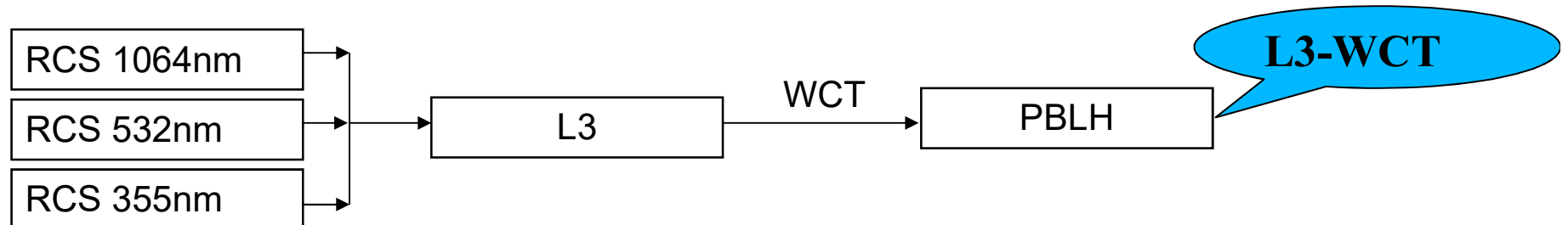
Instruments and Algorithm

– Three-wavelength PBL Height Retrieval

Step1: Estimate parameter (L3) from three-wavelength lidar signals:

1. Range correct signals (RCS) of three wavelengths $\rightarrow N(r_i)$,
 $r_i = \lambda_i/1064 \text{ nm}$ ($i = 1, 2, 3$)
2. Plot $\log(N(r))$ versus $\log(r)$ and fit a least-squares regression line
3. L3 is the slope of the regression line.

Step 2: Obtain PBL Height (PBLH) from the L3

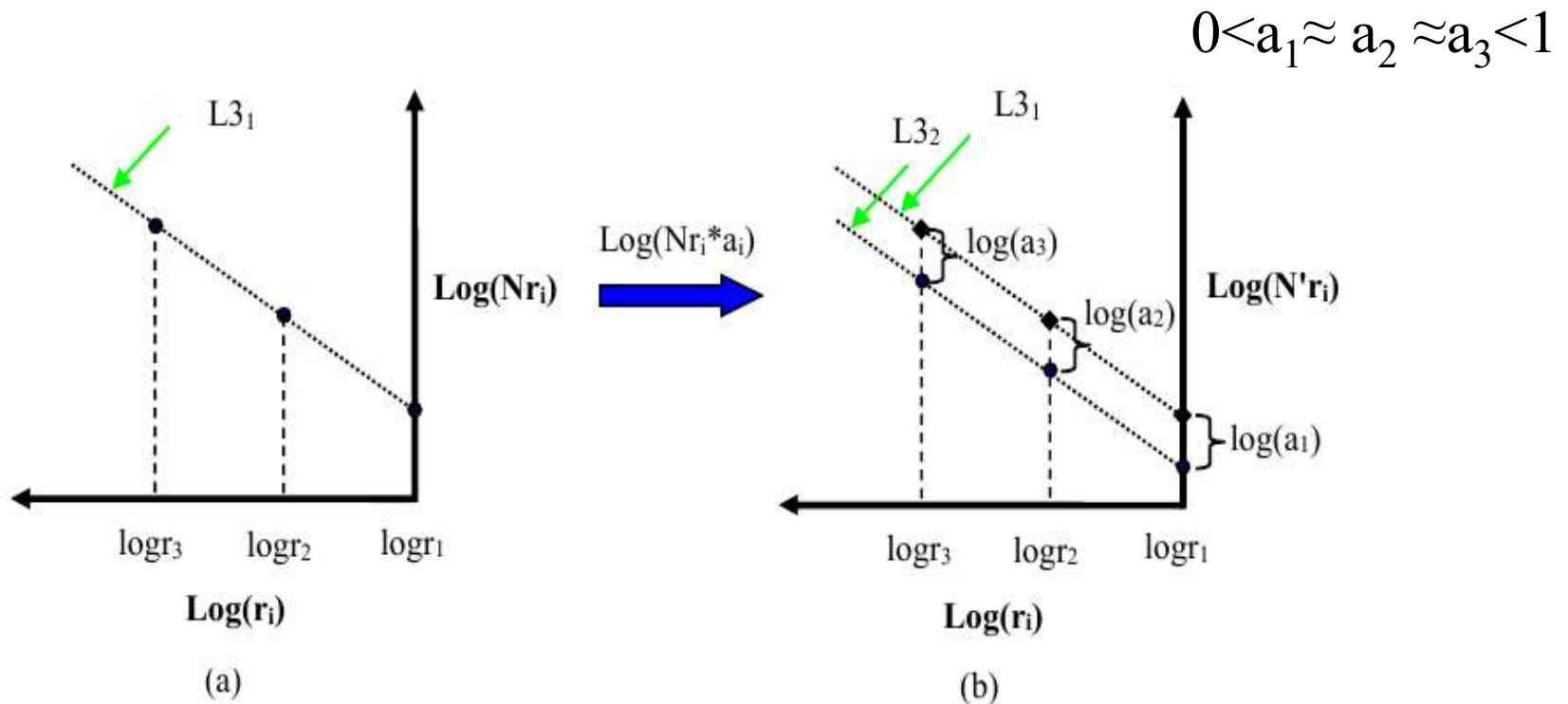


Similarly, obtain PBLH from the 1064 nm RCS signal



Instruments and Algorithm

– L3 Estimation

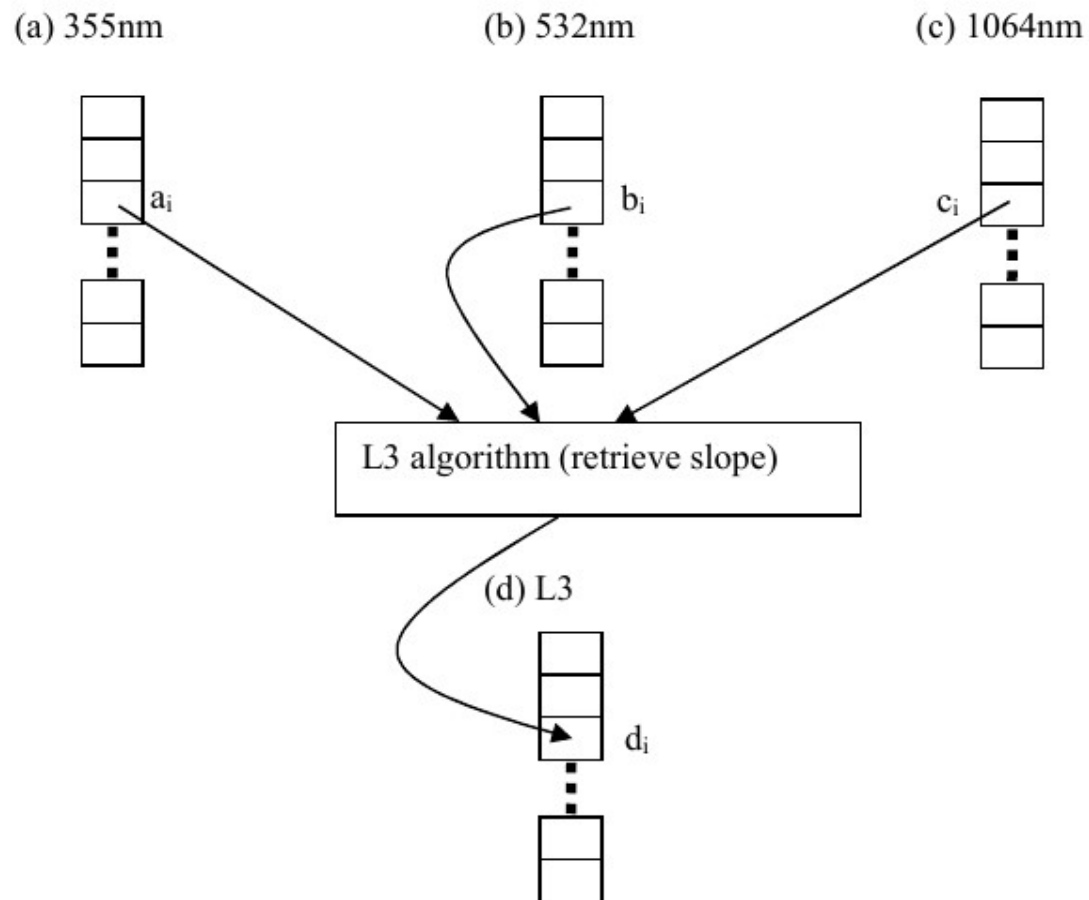


impact of GFF (a function that characterizes the amount of overlap between the telescope field-of-view and the transmitted laser beams) doesn't change the slope

Instruments and Algorithm

– L3 and Elastic Lidar Signal

Diagram for Obtain L3 from three-wavelength lidar signal



Instruments and Algorithm

– PBL Height Retrieval Method

Retrieve PBL height from L3 using Wavelet Covariance Transform
(L3-CWT)

Haar function

$$h\left(\frac{z-b}{a}\right) = \begin{cases} +1 : b - \frac{a}{2} \leq z \leq b \\ -1 : b \leq z \leq b + \frac{a}{2} \\ 0 : elsewhere \end{cases}$$

z: altitude

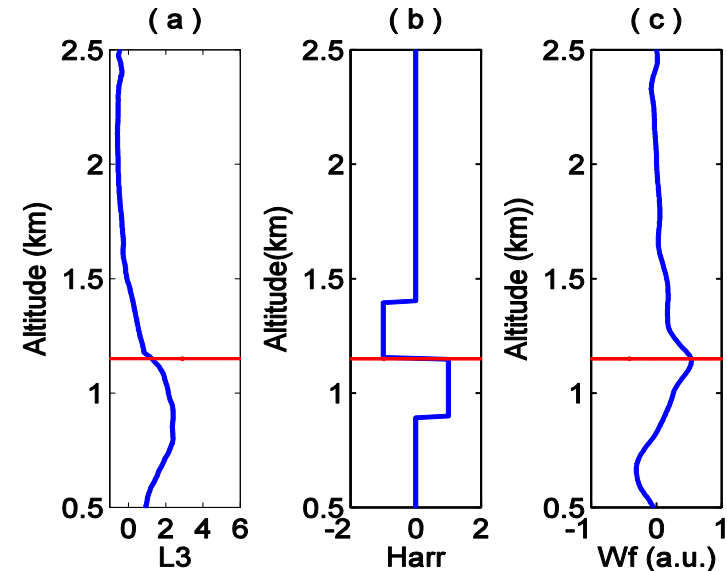
a: spatial extent

b: location at which the Haar function is centered

The covariance transform of the Harr function is defined as:

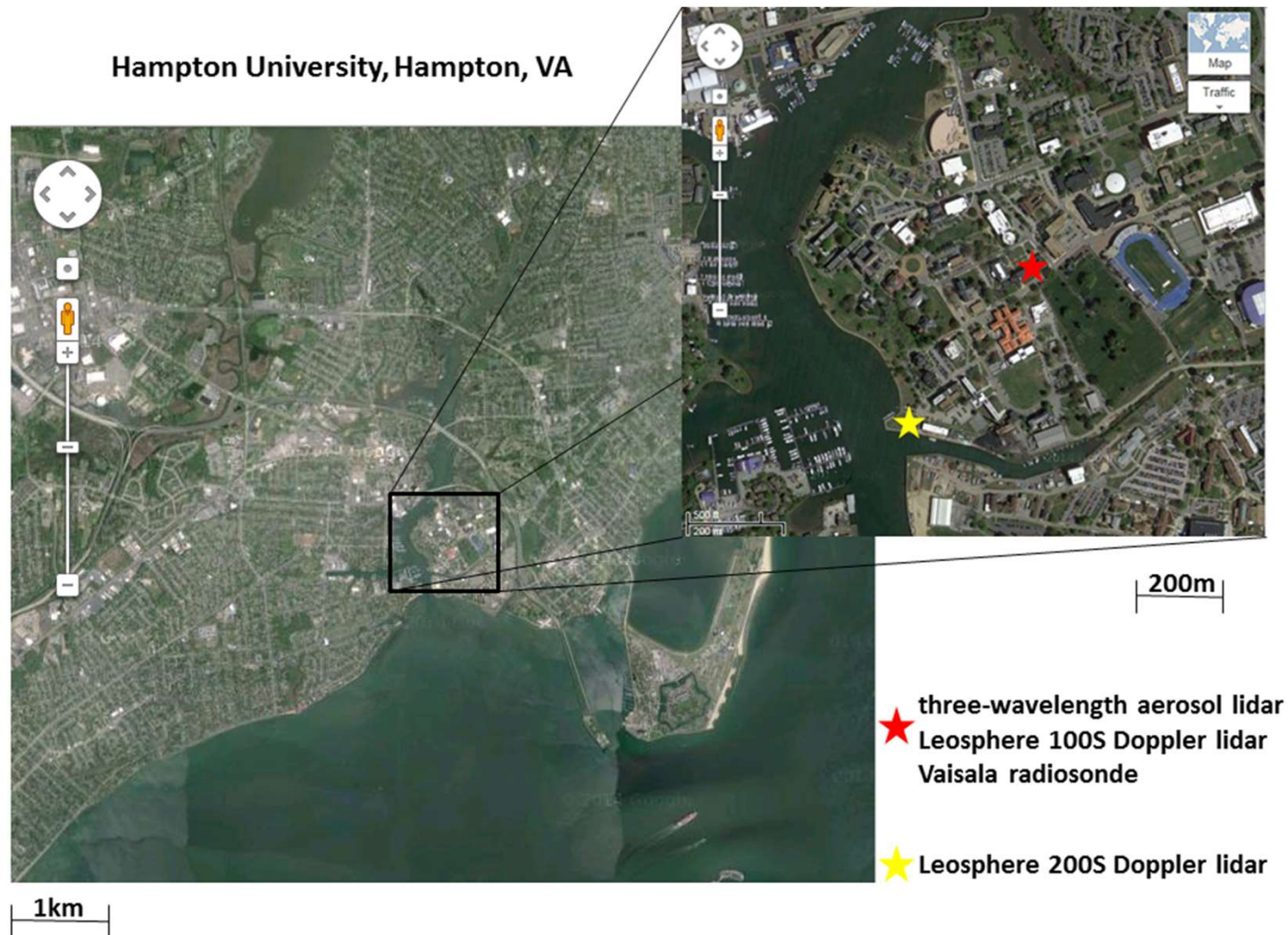
$$W_f(a, b) = \frac{1}{a} \int_{z_b}^{z_t} L3(z) h\left(\frac{z-b}{a}\right) dz$$

The altitude at where the W_f get maximum value is the PBL height



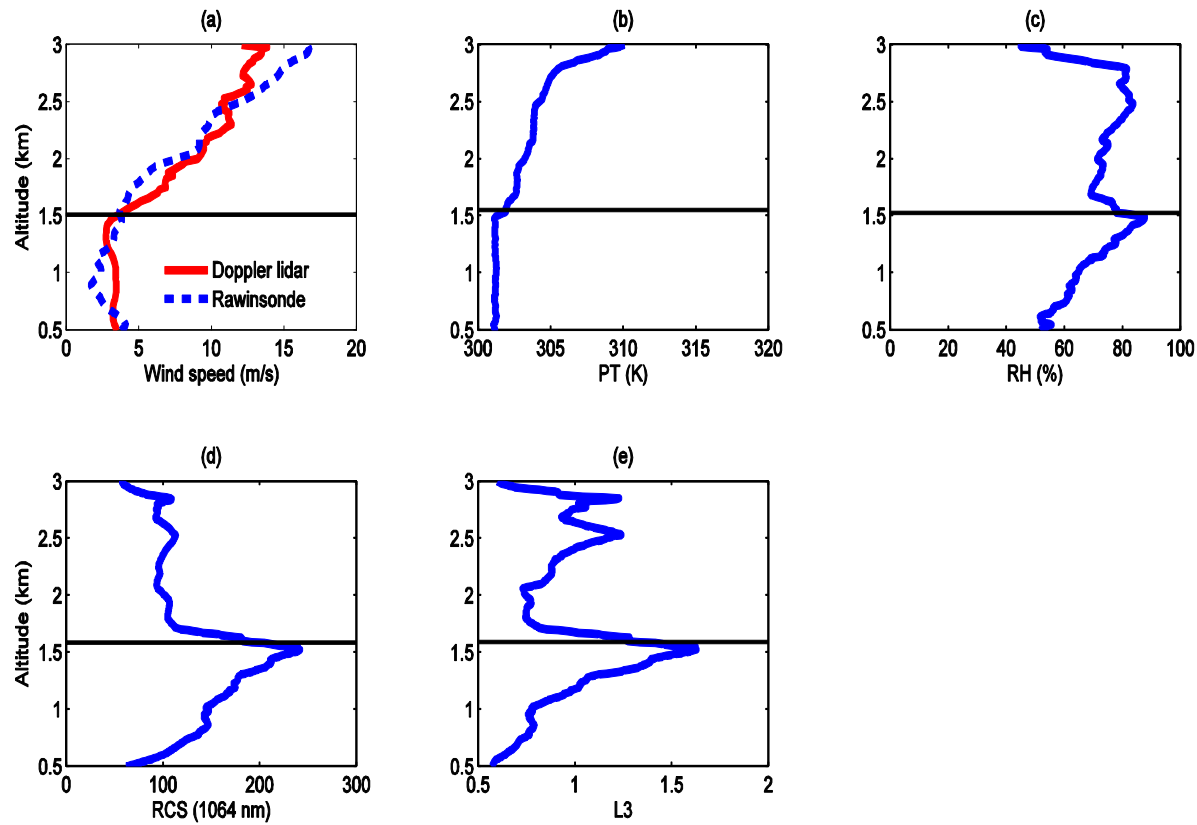
Results of PBL Height Detection

-The East Hampton Roads Aerosol Flux (EHRAF) Measurement Campaign



Results of PBL Height Detection

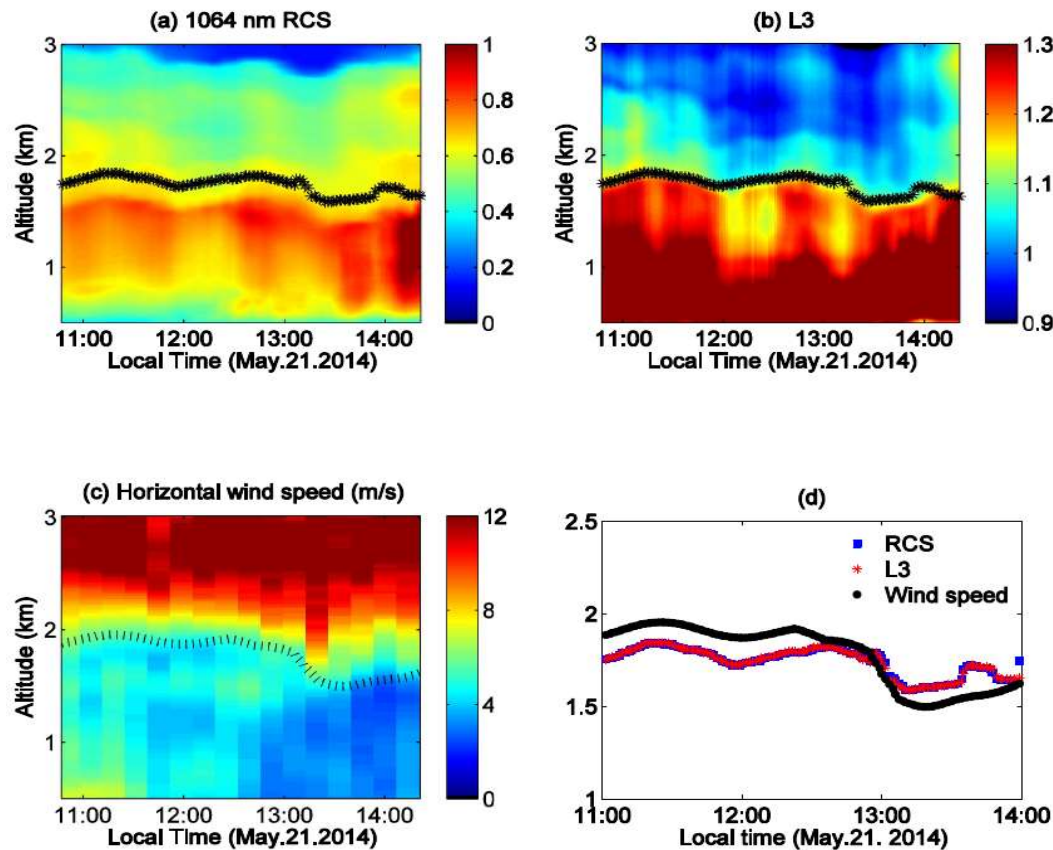
-PBL Height Derived from Different Method



PBL height derived from L3 agree well with the PBL height derived from 1064 nm RCS, potential temperature, wind, and relative humidity

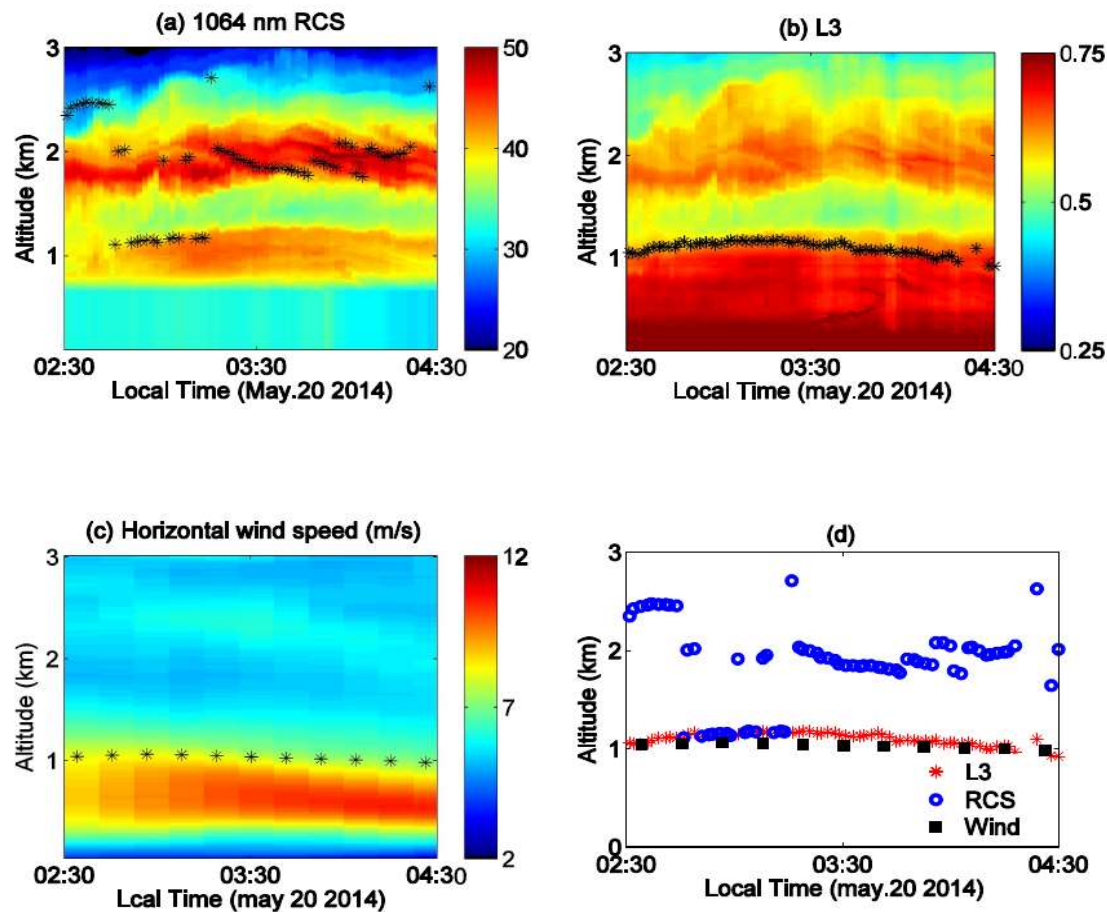
Results of PBL Height Detection

-Time Series of the PBL Height



The PBL height retrieved from L3 agree well with PBL height derived from 1064 nm RCS and horizontal wind speed

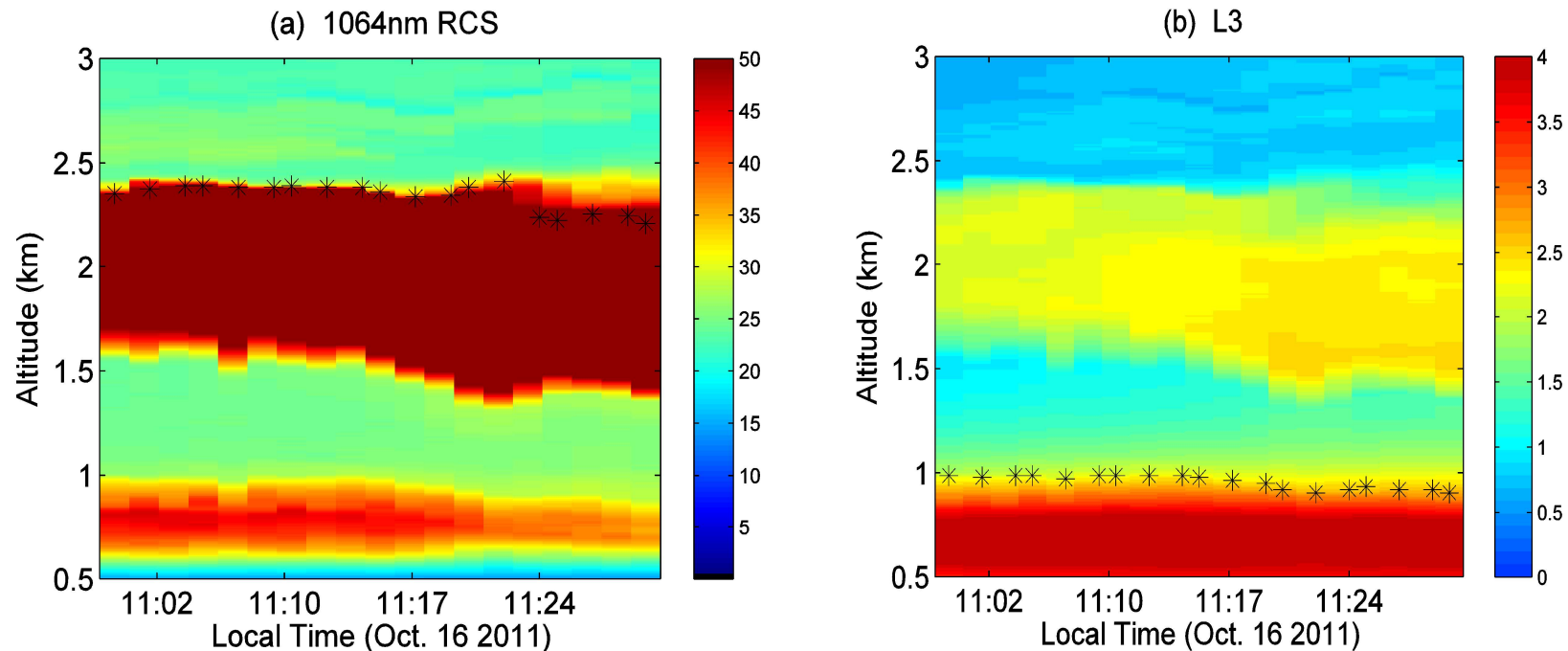
Results of PBL Height Detection - Case of Cloud Occurrence



PBL height retrieved from L3 less impact by the thin cloud above the PBL compare with PBL height derived from 1064 RCS

Results of PBL Height Detection

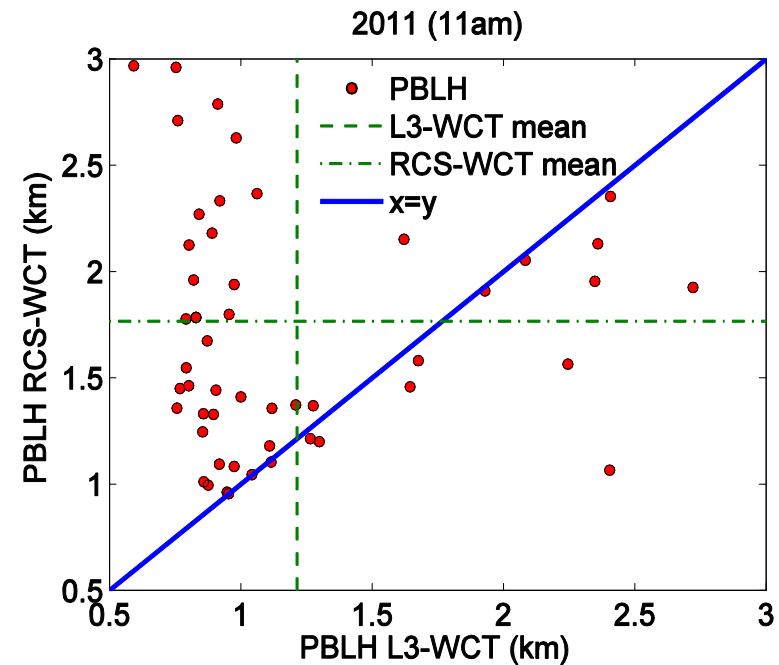
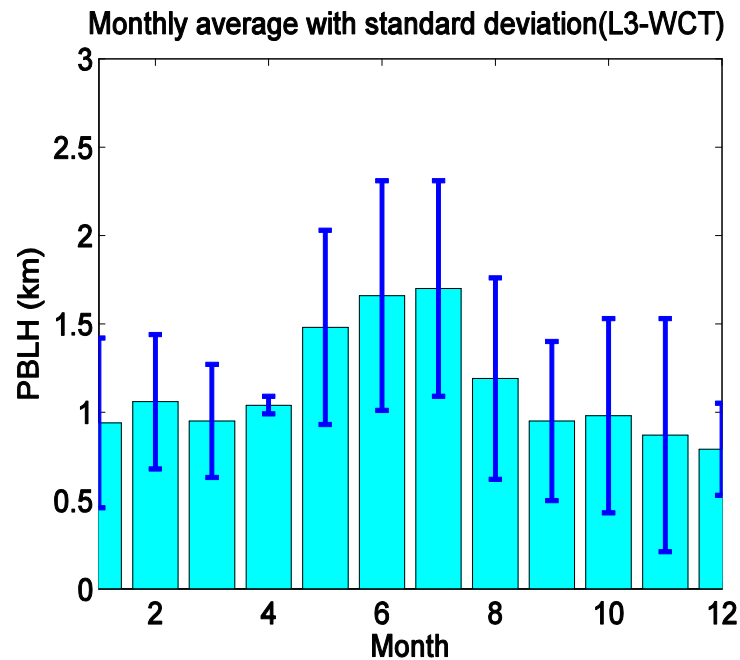
- Case of Plume Occurrence



PBL height retrieved from L3 less impact by the plume above the PBL compare with PBL height derived from 1064 RCS.

Results of PBL Height

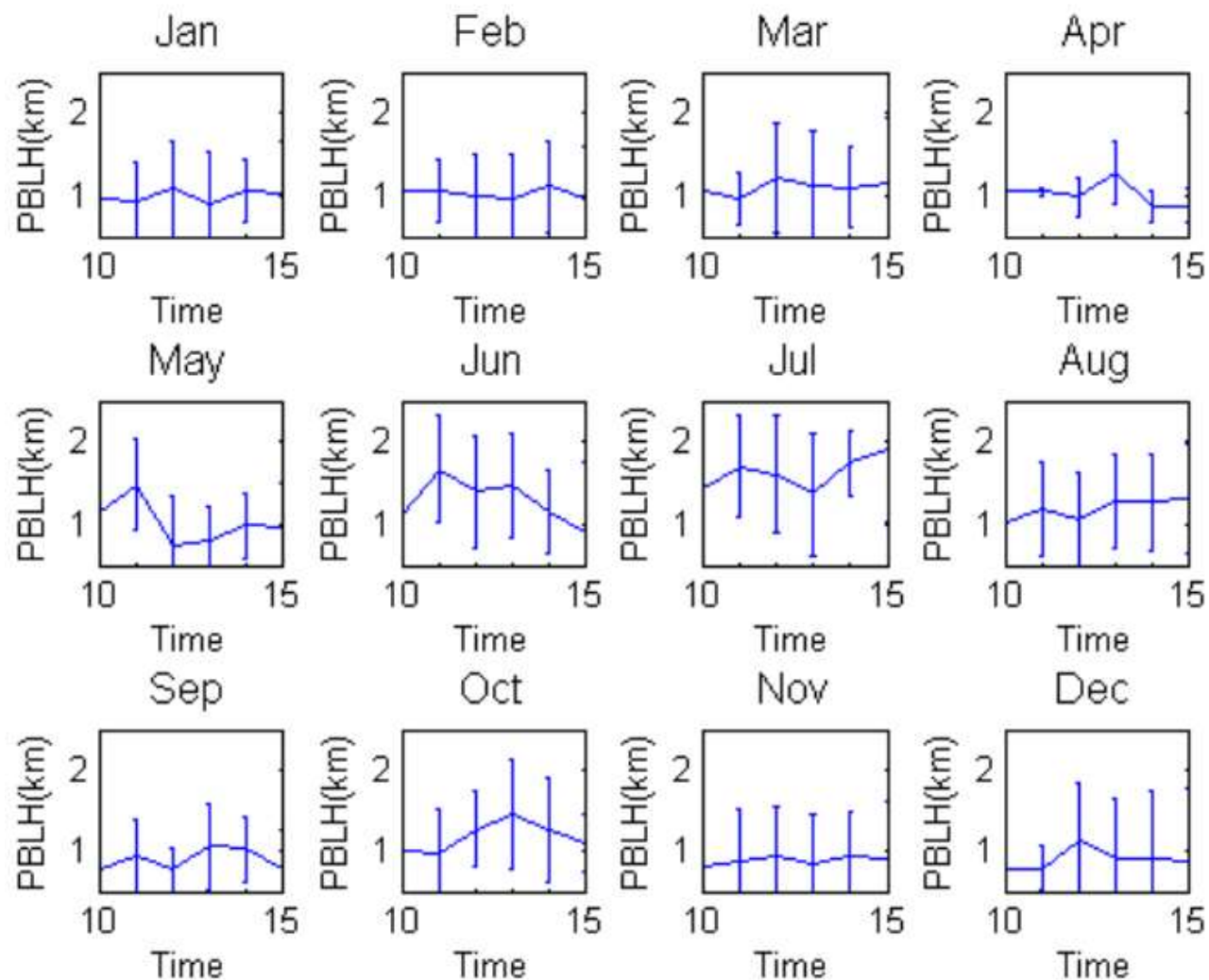
–One-year PBL Height at 2011



2011 monthly variation of PBL height obtained from applying the L3-WCT

Results of PBL Height

– One-year PBL Height at Different Time

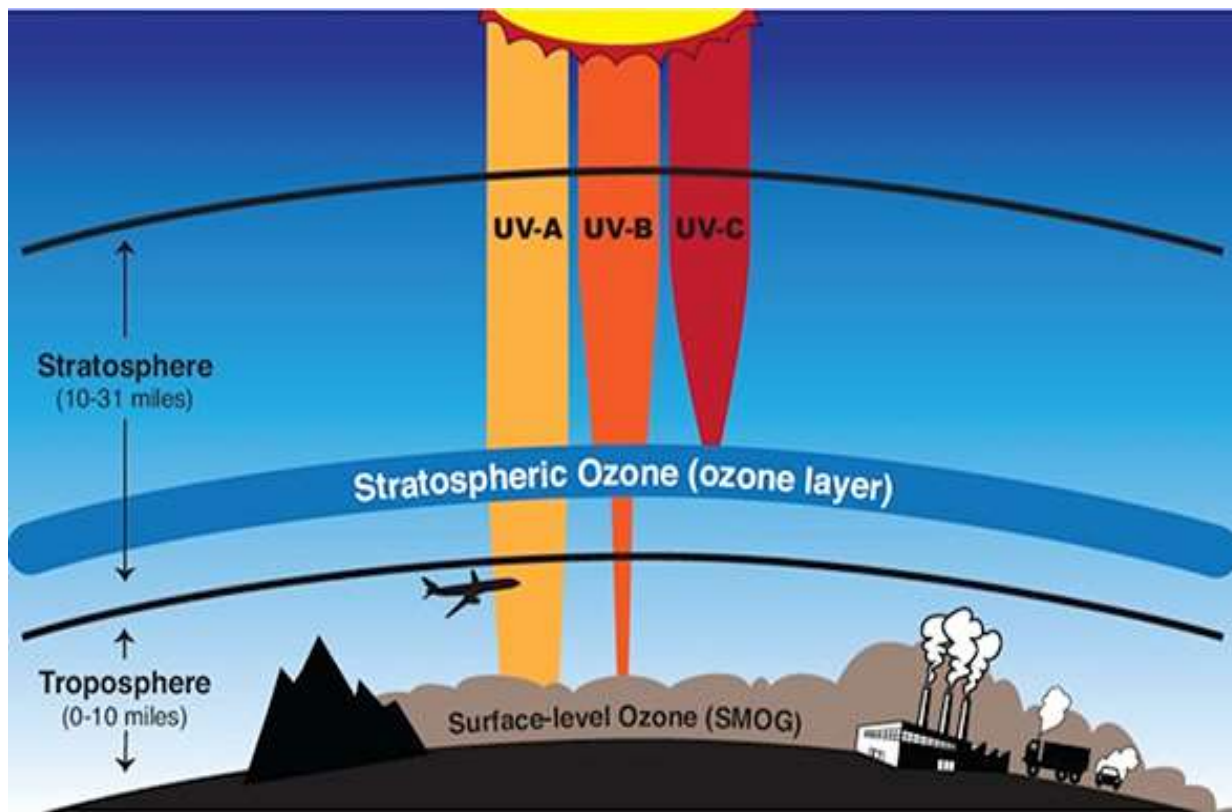


Part 2

The Ozone Raman DIAL

Background – Why O₃ Important

- * Important for health of human, animal, and plant



Credit: NASA UV-A:320-400nm, UV-B:290-320nm, UV-C:290-100nm

Background – History of O₃ Measurement

- **Ozone detection instrument and methods**
 - **Ozonesonde**
 - **Differential Optical Absorption Spectrometer (DOS)**
 - **Satellite (SAGE series, HALEO, SBUV, TOM, OMPS, MLS)**
 - **Ozone DIAL**
 - **Ozone Raman DIAL**

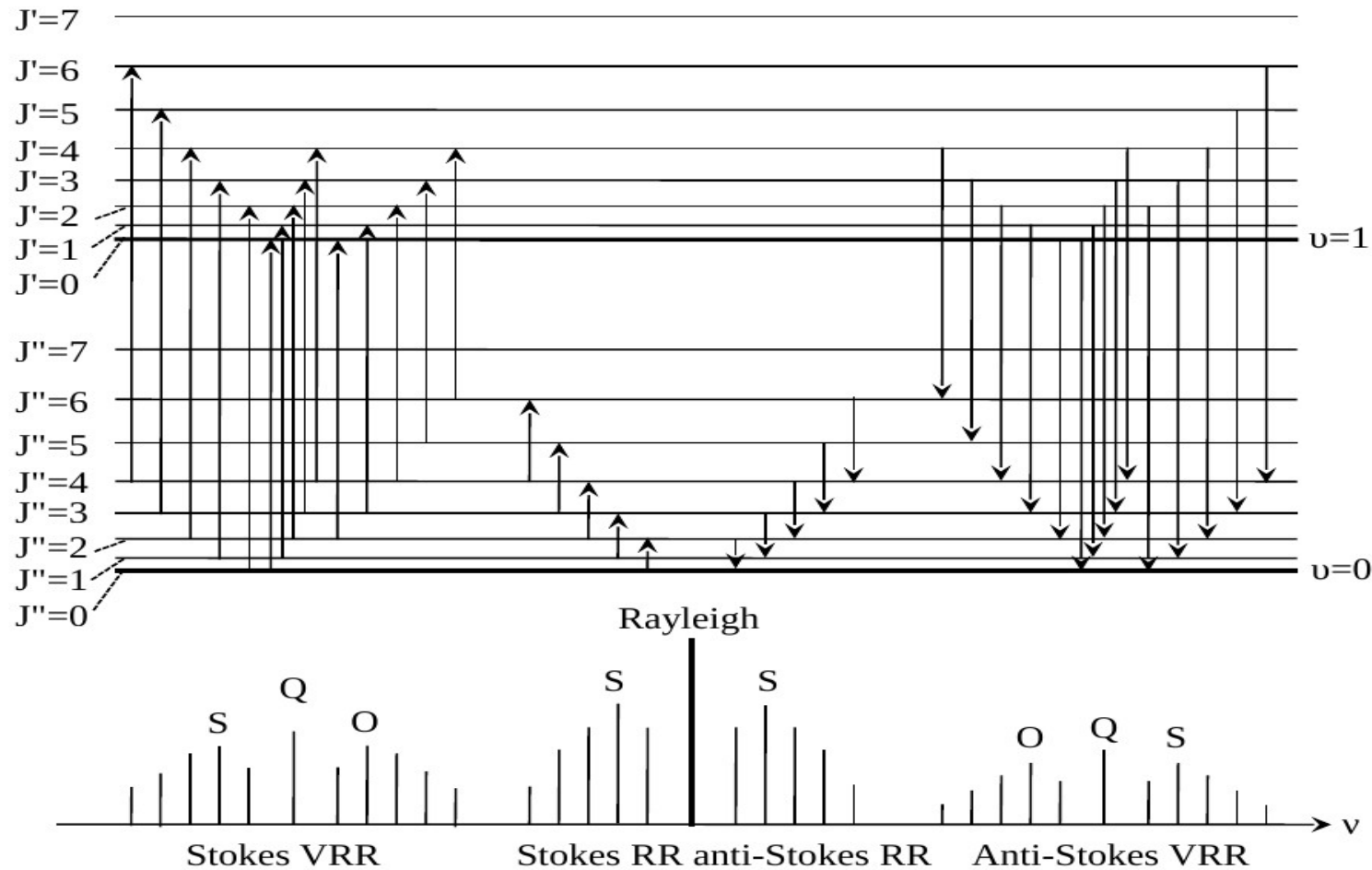
Advantage of ozone Raman DIAL:

Less impact by the aerosol backscattering than the conventional DIAL

Simple retrieval algorithm

Raman Spectrum for Ozone DIAL

* Raman Spectrum for Molecule

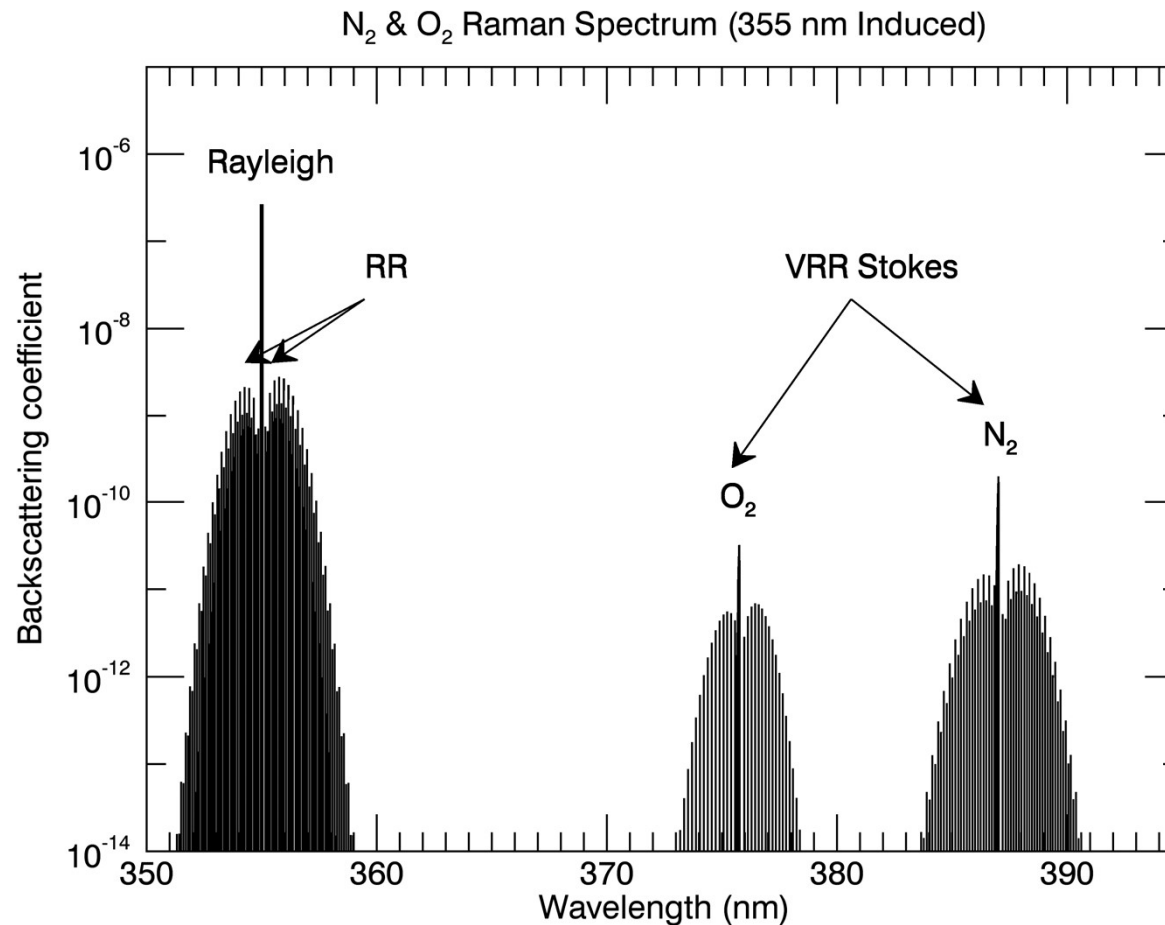


VR: Vibrational Raman

VRR: Vibrational-Rotational Raman

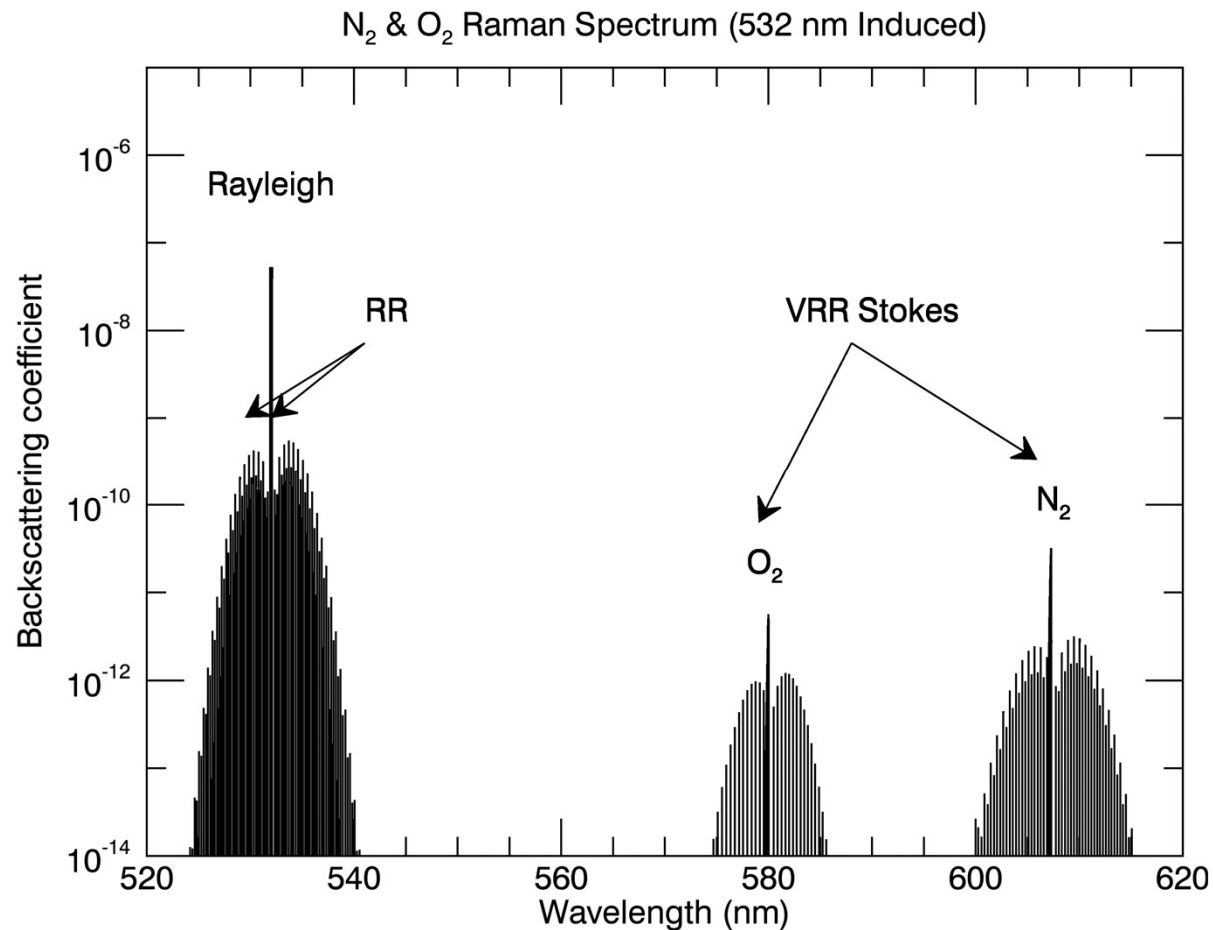
Raman Spectrum for Ozone DIAL

* Raman Spectrum for N_2 and O_2 (excited by 355 nm laser)

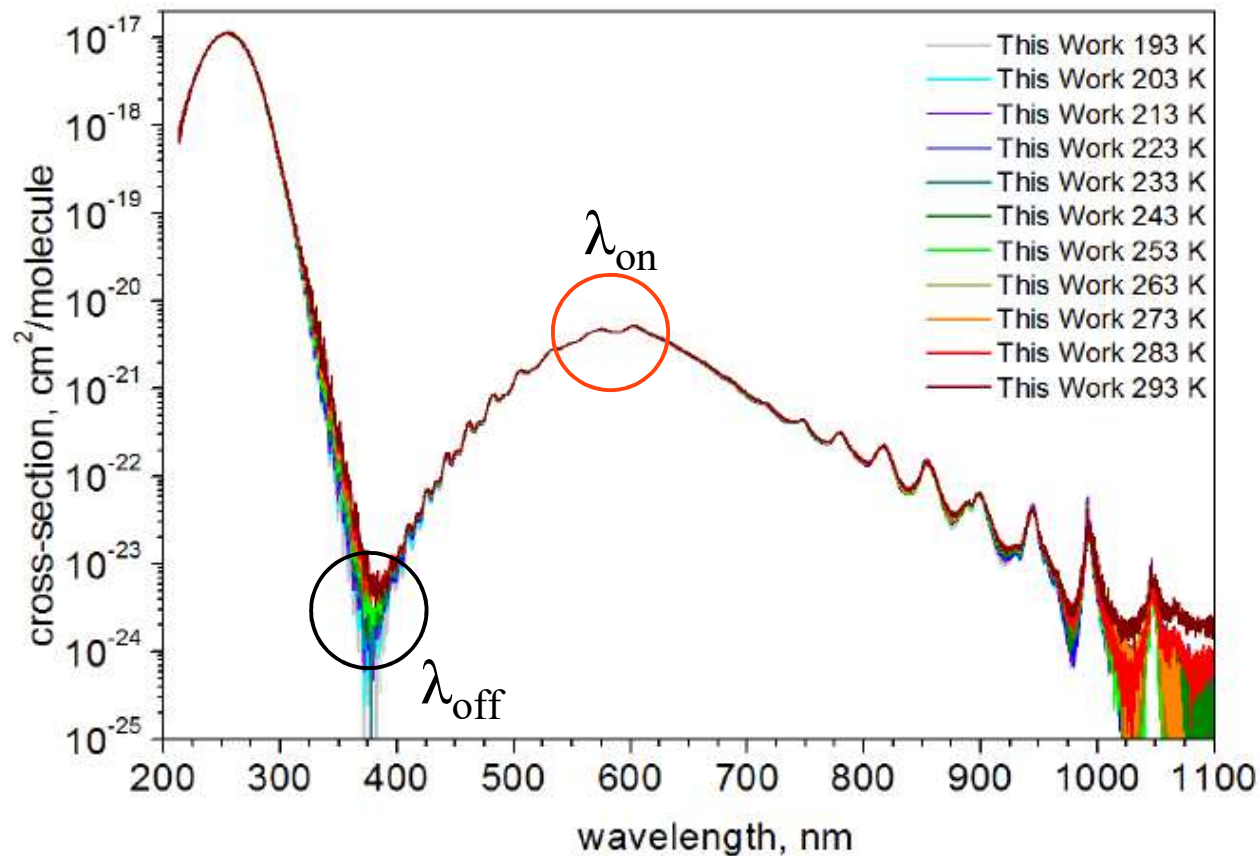


Raman Spectrum for Ozone DIAL

* Raman Spectrum for N_2 and O_2 (excited by 532 nm laser)



O₃ Absorption Cross Section



The ozone cross-section in the UV/vis/NIR at 11 temperature from 193k to 293K (Serdyuchenko et al., 2014)

The Algorithm of Ozone Raman DIAL

$$N(\lambda_X^R, z) = K(\lambda_L, \lambda_X^R) \frac{O(z)}{z^2} \Delta z n_x(z) \beta(\lambda_L, \lambda_X^R, z) \exp\left\{-\int_0^z [\alpha(\lambda_L, z') + \alpha(\lambda_X^R, z')] dz'\right\}$$

↑ Raman Signal ↑ Constant Overlap function ↓ Number density of N₂ or O₂ ↓
 Raman differential backscattering cross section ↑ Extinction coefficient ↑

$$\frac{N(\lambda_{on}, z)}{N(\lambda_{off}, z)} = \frac{K(\lambda_{L,on}, \lambda_{on}) n_{N_2}(z) \beta(\lambda_{L,on}, \lambda_{on}, z) \exp\left\{-\int_0^z [\alpha(\lambda_{on}, z') + \alpha(\lambda_{L,on}, z')] dz'\right\}}{K(\lambda_{L,off}, \lambda_{off}) n_{N_2}(z) \beta(\lambda_{L,off}, \lambda_{off}, z) \exp\left\{-\int_0^z [\alpha(\lambda_{off}, z') + \alpha(\lambda_{L,off}, z)] dz'\right\}}$$

Take derivative of logarithm of the ratio of on and off Raman signal to retrieve the O₃ number density:

$$n_{O_3}(z) = RDN - RDP - RDM - RDG$$

The Algorithm of Raman DIAL

$$n_{O_3}(z) = RDN - RDP - RDM - RDG$$

$$RDN = \frac{1}{\Delta\sigma_{O_3}} \frac{d}{dz} \left\{ \ln \left[\frac{N(\lambda_{off}, z)}{N(\lambda_{on}, z)} \right] \right\}$$

$$RDP = \frac{\Delta\alpha_p}{\Delta\sigma_{O_3}} = \frac{1}{\Delta\sigma_{O_3}} [(\alpha_p^s(\lambda_{L,on}, z) + \alpha_p^s(\lambda_{on}, z) - \alpha_p^s(\lambda_{L,off}, z) - \alpha_p^s(\lambda_{off}, z)) + (\alpha_p^a(\lambda_{L,on}, z) + \alpha_p^a(\lambda_{on}, z) - \alpha_p^a(\lambda_{L,off}, z) - \alpha_p^a(\lambda_{off}, z))] \quad (2.3.15)$$

$$RDM = \frac{\Delta\alpha_m}{\Delta\sigma_{O_3}} = \frac{1}{\Delta\sigma_{O_3}} [(\alpha_m^s(\lambda_{L,on}, z) + \alpha_m^s(\lambda_{on}, z) - \alpha_m^s(\lambda_{L,off}, z) - \alpha_m^s(\lambda_{off}, z))] \quad (2.3.16)$$

$$RDG = \frac{\Delta\alpha_g}{\Delta\sigma_{O_3}} = \frac{1}{\Delta\sigma_{O_3}} \left[\sum_Y n_Y(z) \sigma_{g,Y}^a(\lambda_{L,on}, z, T) + \sum_Y n_Y(z) \sigma_{g,Y}^a(\lambda_{on}, z, T) - \sum_Y n_Y(z) \sigma_{g,Y}^a(\lambda_{L,off}, z, T) - \sum_Y n_Y(z) \sigma_{g,Y}^a(\lambda_{off}, z, T) \right] \quad (2.3.17)$$

$$\Delta\sigma_{O_3} = \sigma_{O_3}(\lambda_{L,on}) + \sigma_{O_3}(\lambda_{on}) - \sigma_{O_3}(\lambda_{L,off}) - \sigma_{O_3}(\lambda_{off}) \quad (2.3.18)$$

The Algorithm of Raman DIAL

* Wavelength pair available for Ozone Raman DIAL

	λ_{On} (nm)	λ_{Off} (nm)	$\text{O}_3 \Delta\sigma$ (cm ²) (293 K)	$\text{NO}_2 \Delta\sigma$ (cm ²) (293 K)
Case 1	353	386	2.34e-22	-1.850e-19
Case 2	607	386	4.968e-21	-5.8493e-19
Case 3	607	580	0.492 e-21	-0.222e-19

Note: 353 nm is the O₂ and N₂ RR excited by 355nm

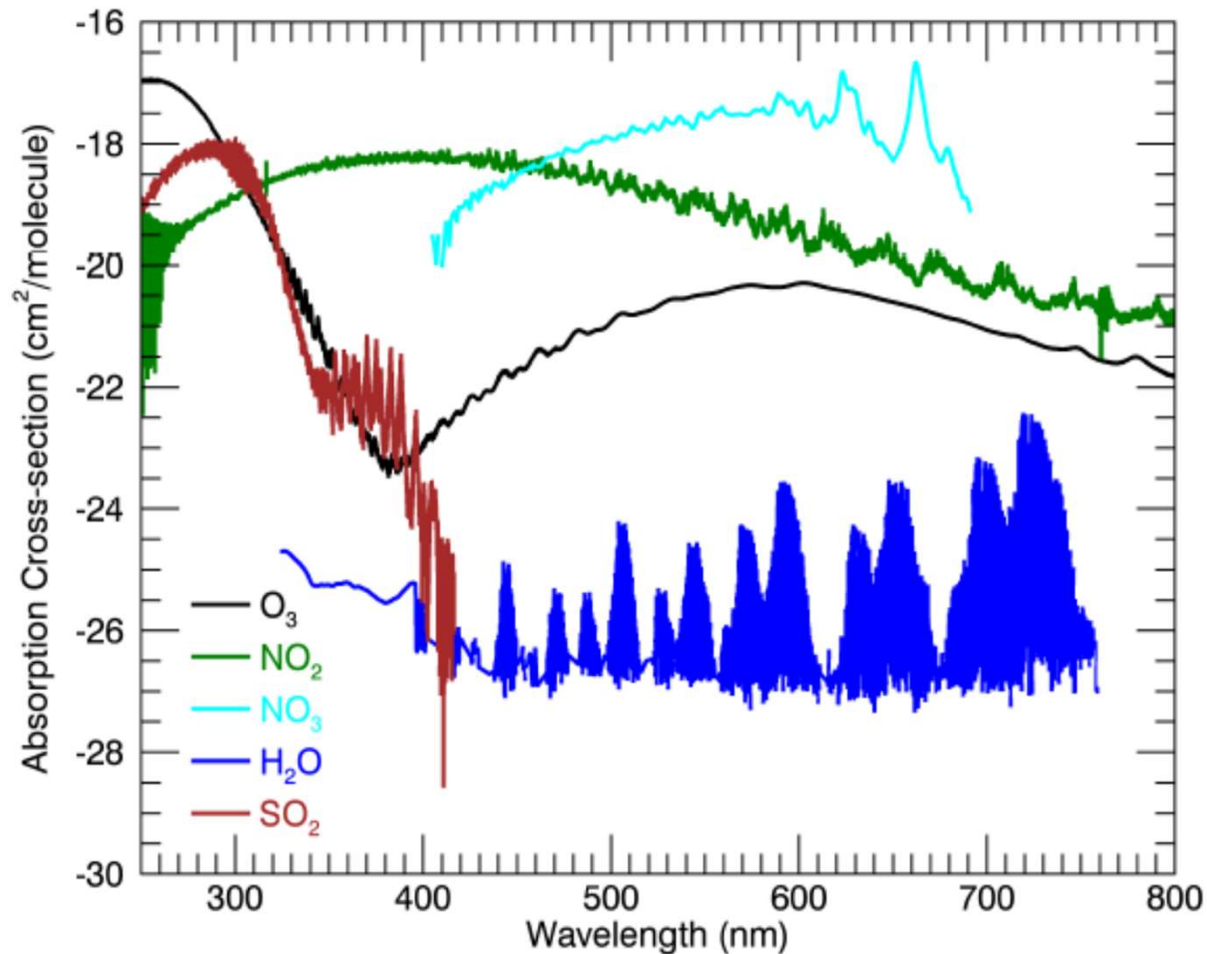
386 nm is the N₂ VR excited by 355 nm

580 nm is the O₂ VR excited by 532nm

607 nm is the N₂ VR excited by 532 nm

The Impact of Other Atmospheric Species

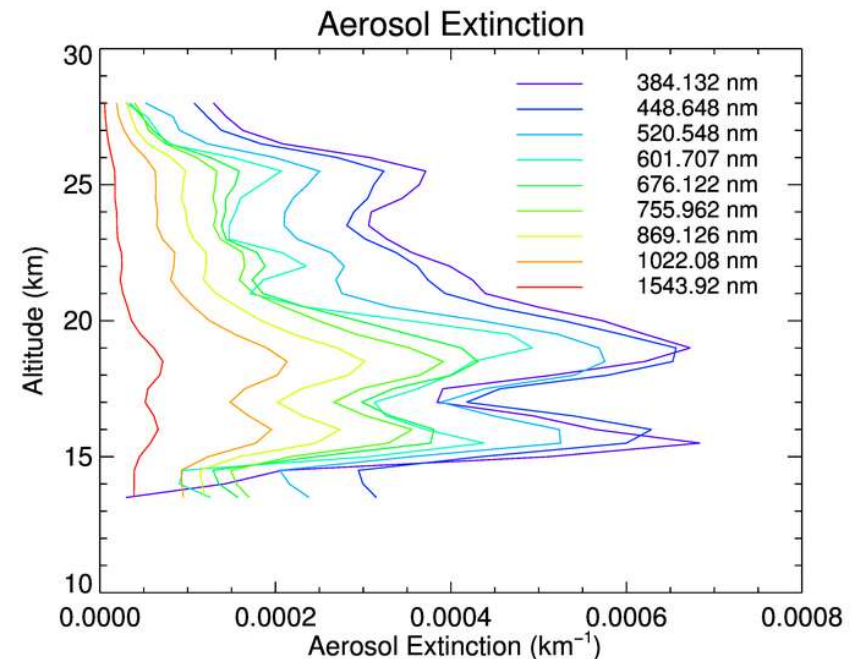
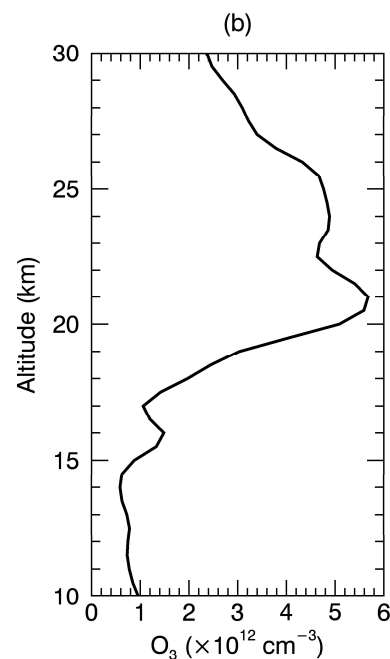
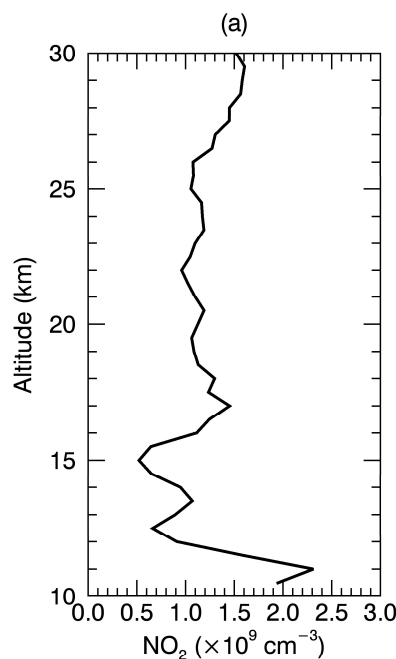
The absorption cross-section for O_3 , NO_2 , NO_3 , H_2O , and SO_2



Wavelength Pair Selection

-- Simulation Using SAGE III-ISS Data

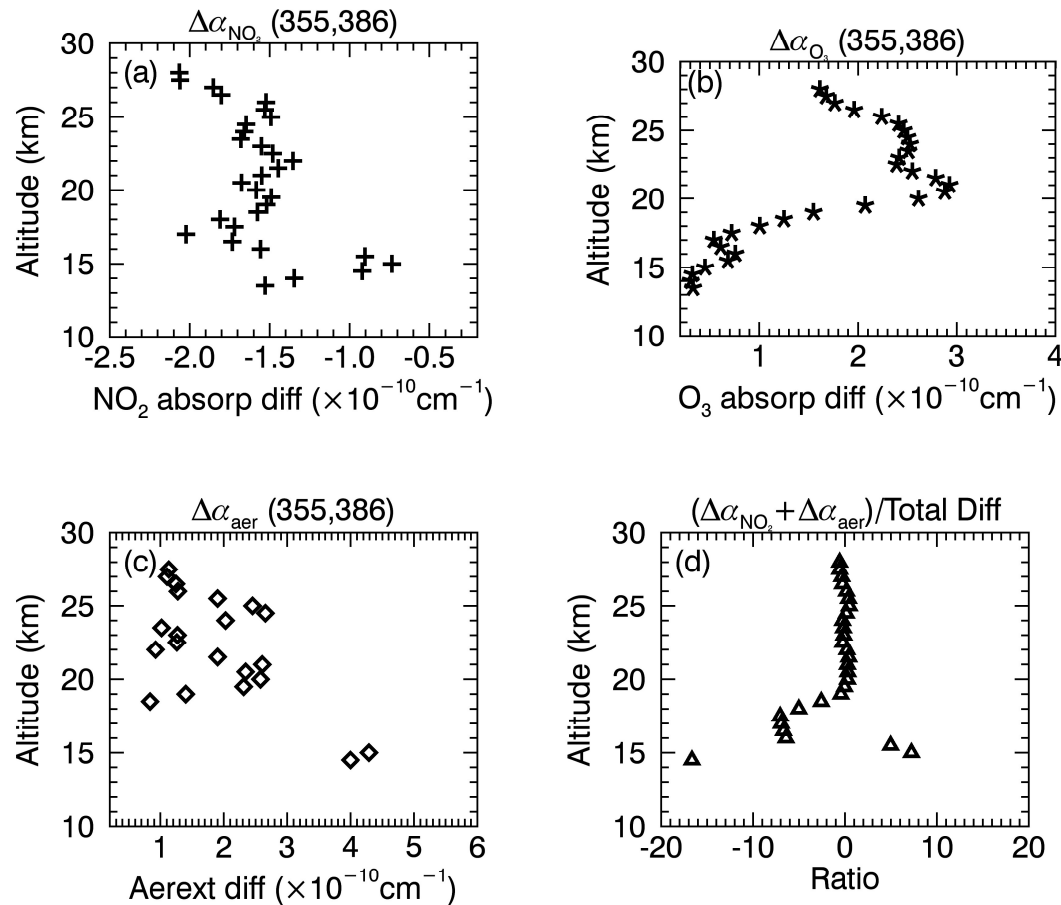
- * Ozone absorption coefficient using SAGE III-ISS O₃ data
- Criteria for choose SAGE III-ISS profile**
Latdiff < 5° , londiff < 5° (1/11/2018, local time 18:22)
latdiff = 2.618° londiff = 0.852° distance = 252.11 km



Wavelength pair selection

-- Simulation Case 1

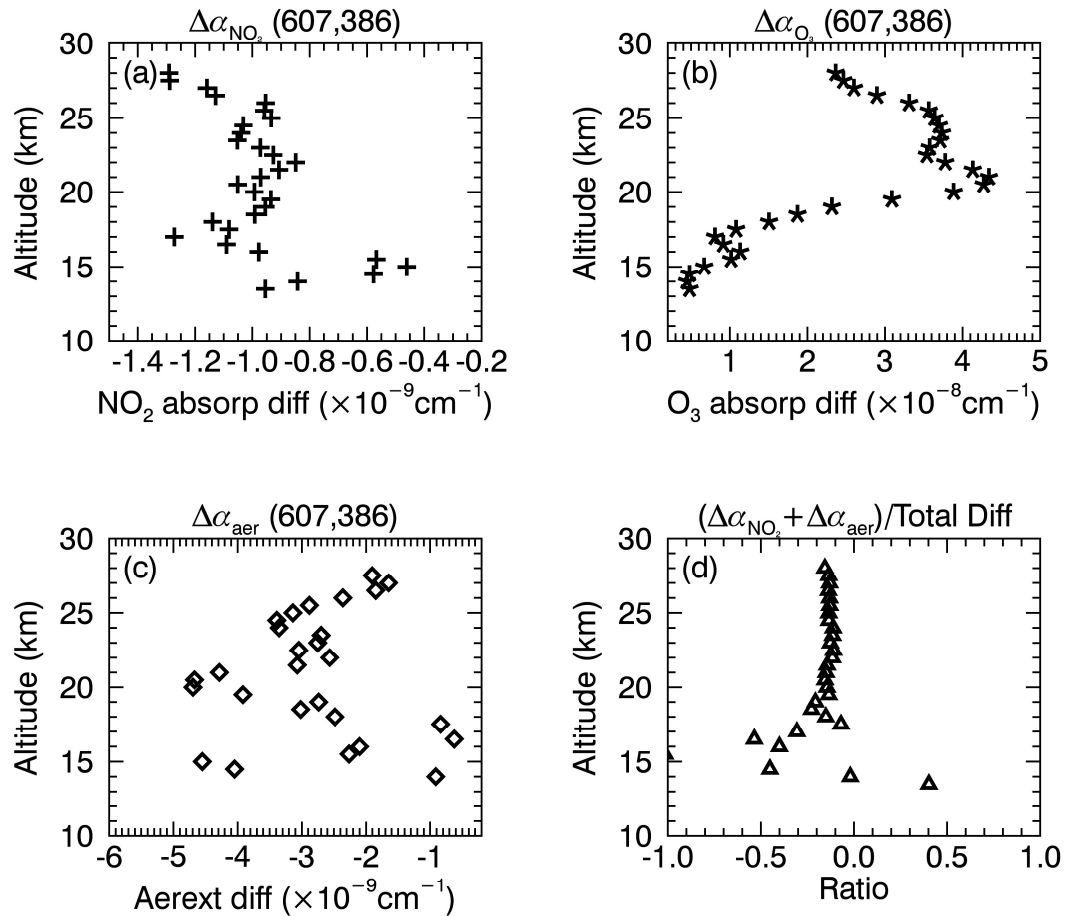
Case 1: (353-386 nm)



Wavelength Pair Selection

-- Simulation Case 2

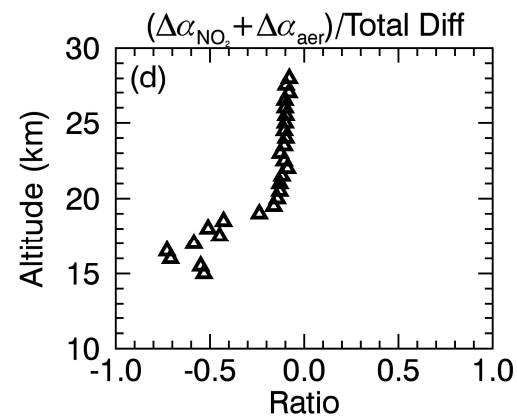
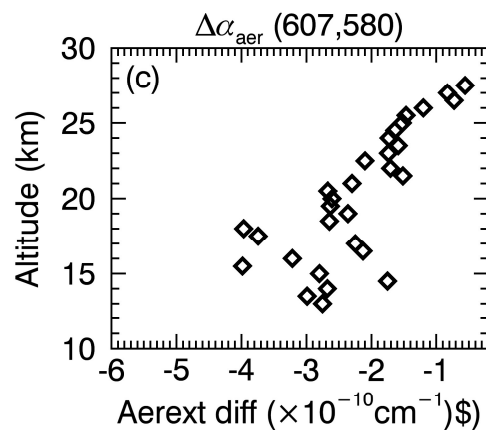
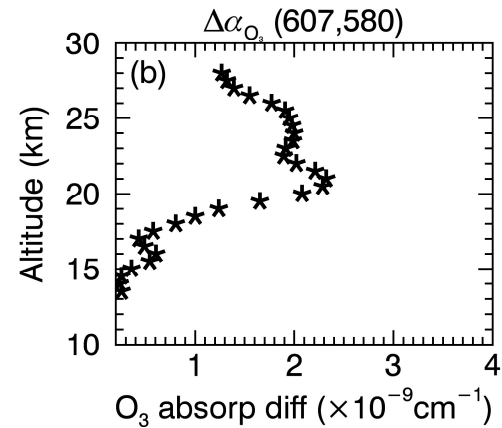
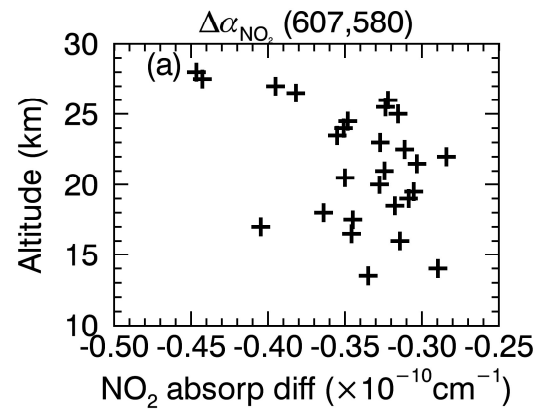
Case 2: (607-386 nm)



Wavelength Pair Selection

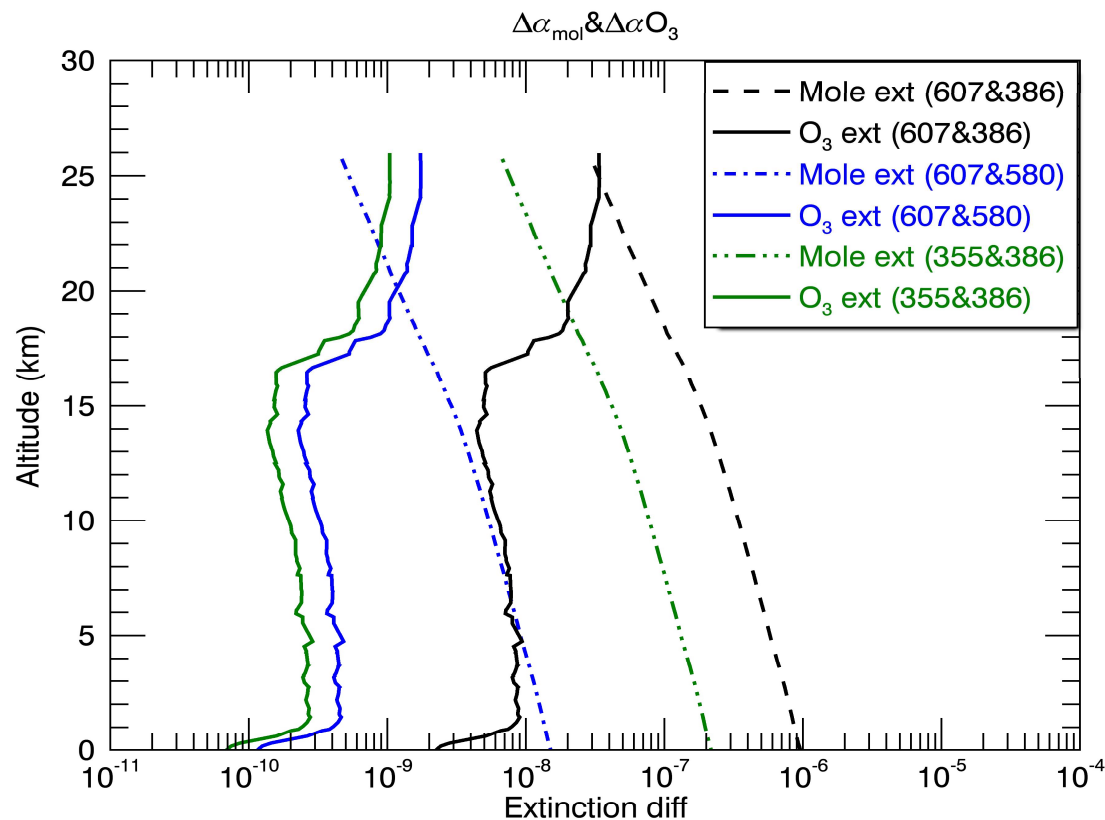
--Simulation Case 3

Case 3: (607-580 nm)



The Impact of the Molecule

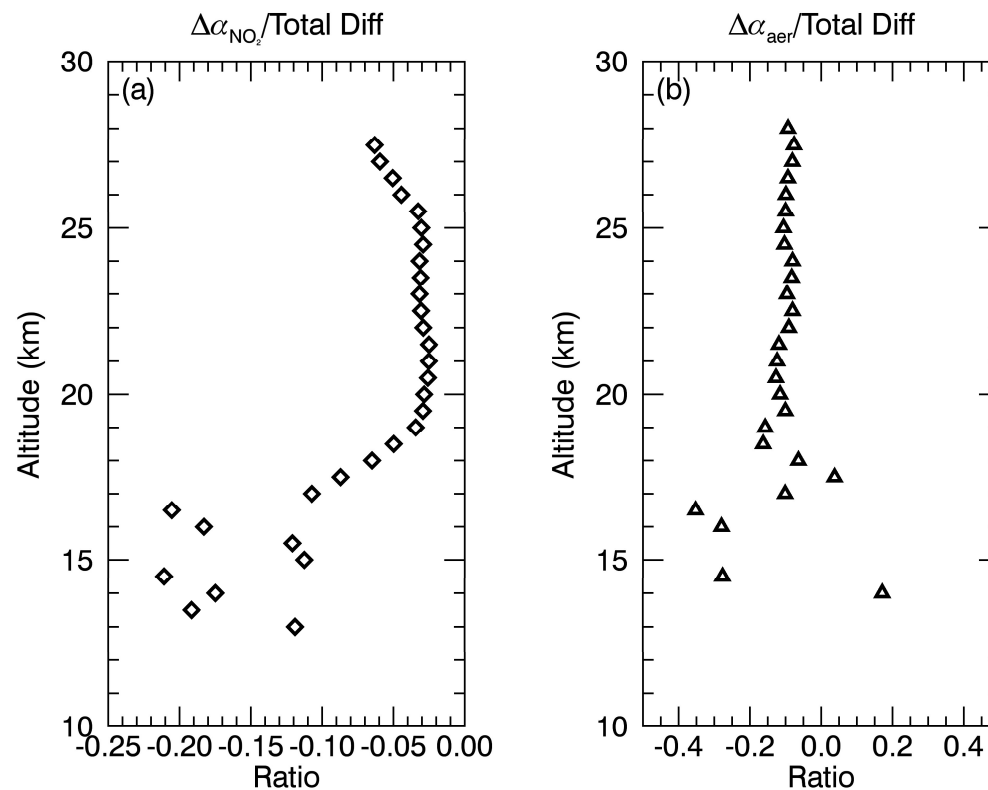
The molecule extinction difference and the ozone extinction difference for different on and off wavelength pair



Wavelength Pair Selection

--The Impact of NO₂ and Aerosol on O₃ Retrieval

Separate the NO₂ and aerosol impact (607-386 nm)



Wavelength Pair Selection for Raman DIAL

Result for wavelength selection:

353 and 386 nm case: $(\Delta\alpha_{\text{NO}_2} + \Delta\alpha_{\text{are}})/\text{toat diff} < 0.6$ (19-25 km)

607 and 386 nm case: $(\Delta\alpha_{\text{NO}_2} + \Delta\alpha_{\text{are}})/\text{toat diff} < 0.2$ (19-25 km) ●

607 and 580 nm case: $(\Delta\alpha_{\text{NO}_2} + \Delta\alpha_{\text{are}})/\text{toat diff} < 0.15$ (19-25 km)

The aerosol extinction contribute most of the error for
Raman DIAL ozone retrieval from 15 km to about 30 km
for 607 and 386 nm pair

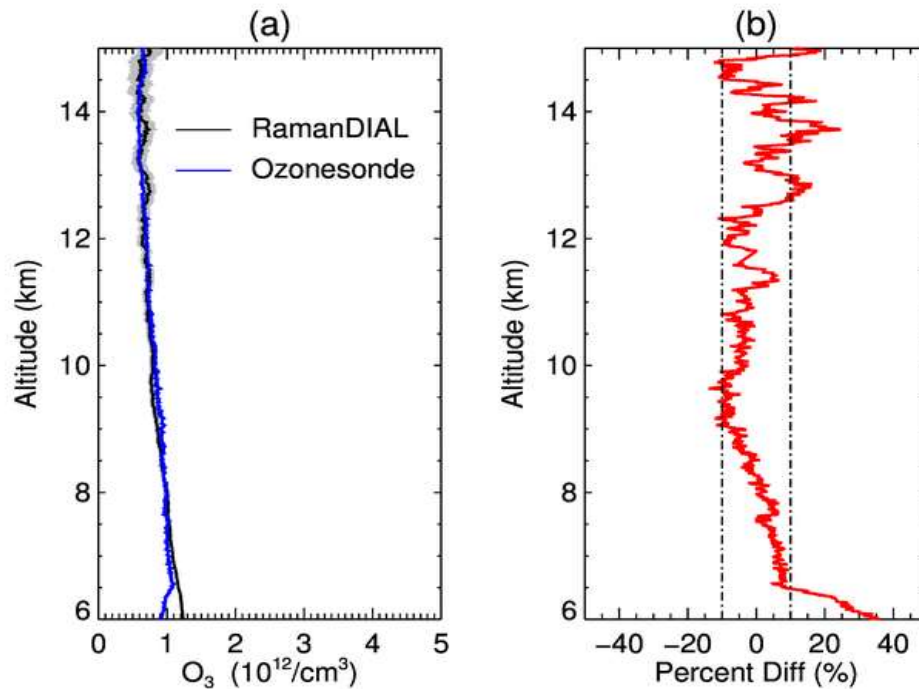
The impact of the NO_2 was ignored to simplify the algorithm

Molecule term could be correct by using the T and P from the
Balloon data

Aerosol extinction could be corrected by using Raman aerosol method
or Fernald method

Rama DIAL O₃ Retrieval and Validation

Results on August 29, 2018 (0:00 am to the 4:30 am)
The O₃ profile retrieved from the Raman DIAL compared with O₃ profile
Provided by ozonesonde launched in HU.

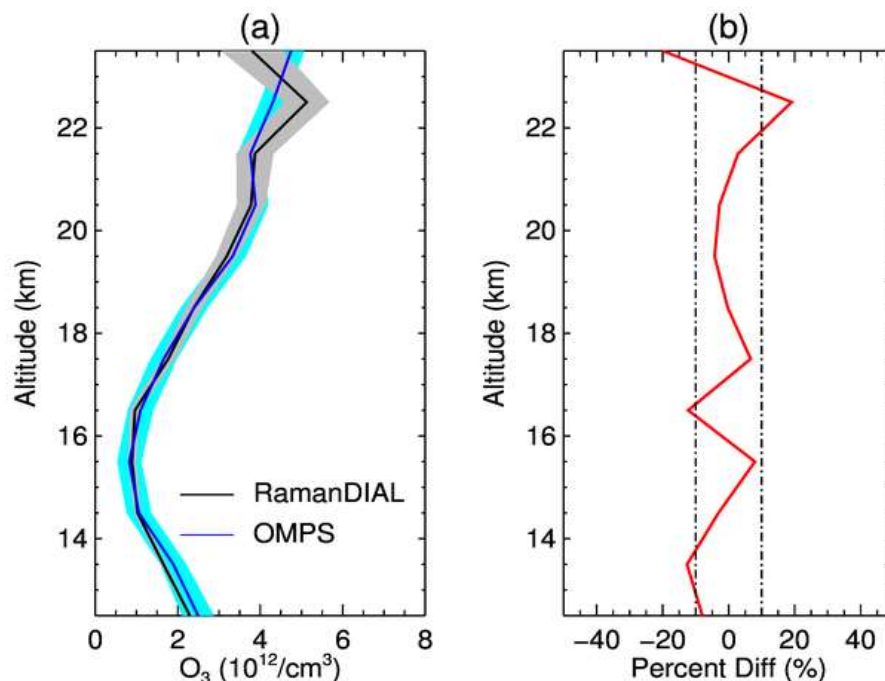


**The difference
mostly less than
10% between 7
and 15 km**

Rama DIAL O₃ Retrieval and Validation

O₃ profile measured on March 6, 2019 (from 7:00 pm on March 05, 2019, to 9:00 am on March 06, 2019)

OMPS coincident O₃ profile was compared with the ozone profile retrieved from Raman DIAL



**The difference
mostly less than
10% between 13
and 23 km**

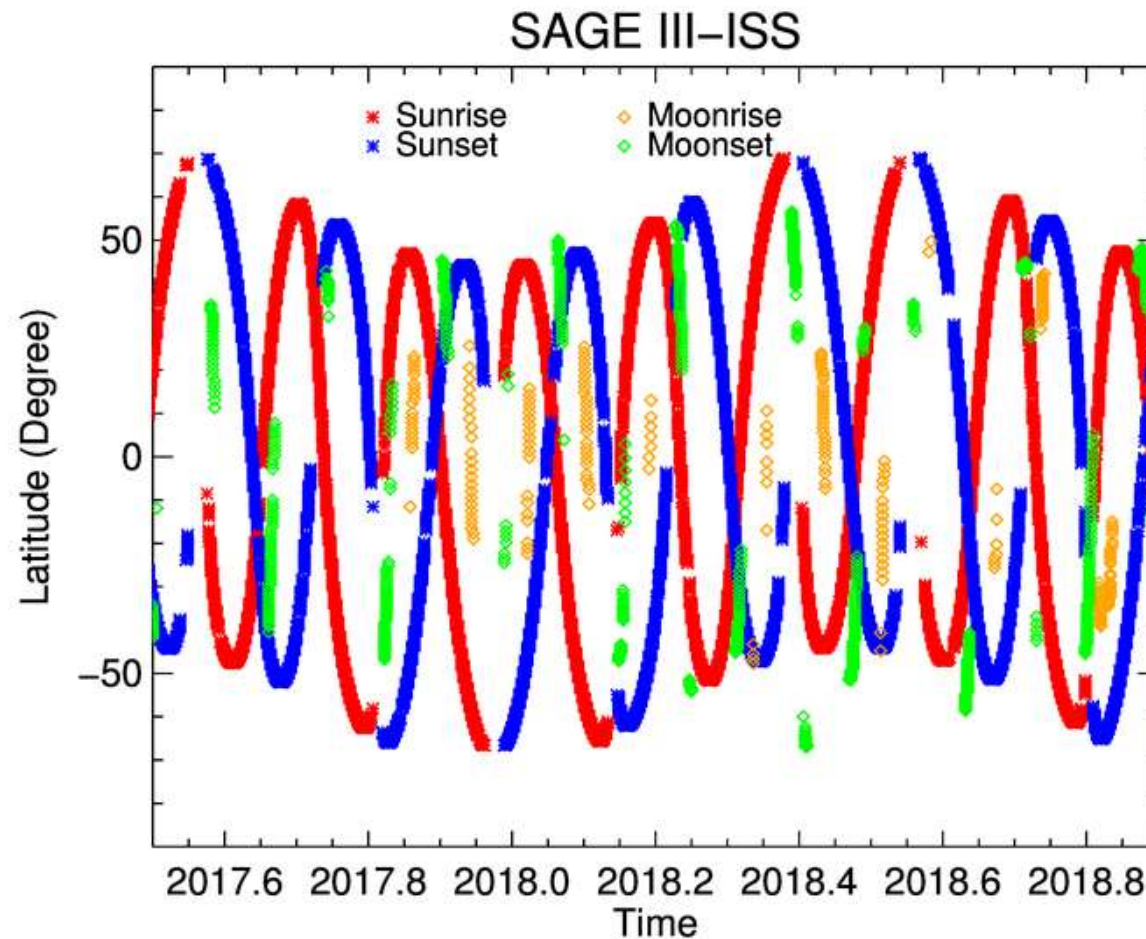
Conclusion

- Method to calculate L3 from three-wavelength lidar signal
- PBL height derived from L3 and RCS by using the WCT
- L3-WCT method has capability to decrease the impact of the GFF and the occurrence of plume
- Result of one-year PBL height detection in 2011
- The possibility of detect the ozone from the Raman DIAL worked on UV-Visible band
- Impact of the molecule on O₃ detection
- Simulation of the impact of the aerosol and NO₂ on O₃ detection
- Raman DIAL O₃ retrieval and validation

The End
Thanks!
Any Questions?

Back Up- The SAGE III-ISS data validation

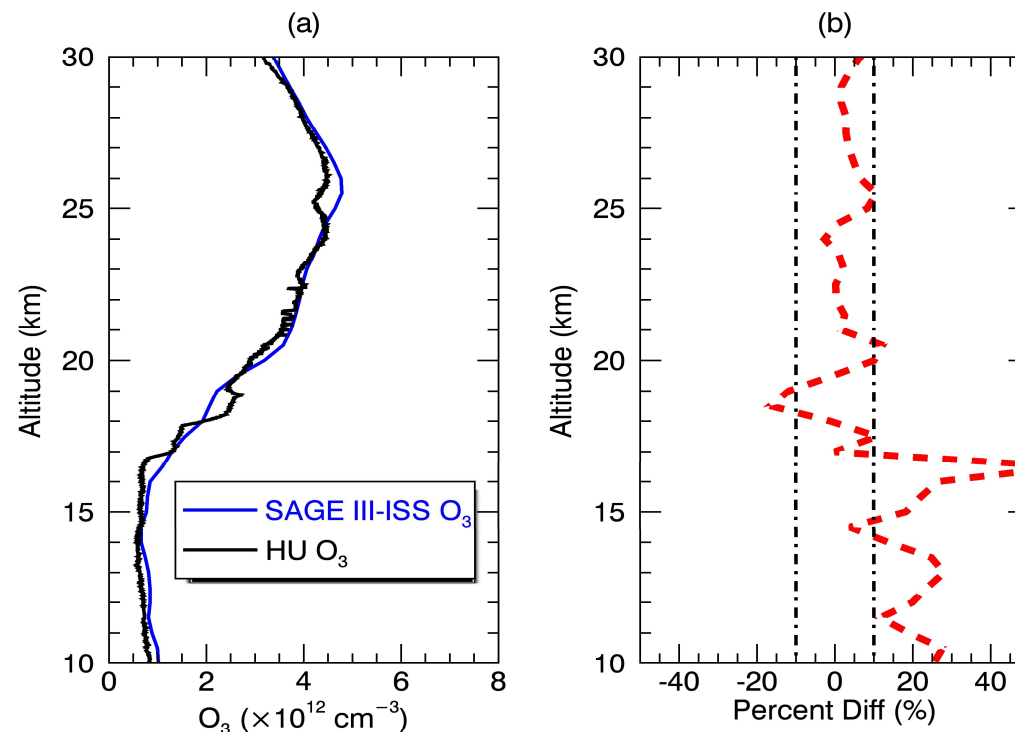
SAGE III-ISS orbit



Comparison between O₃ profiles from the SAGE III-ISS and HU Ozone sonde

The comparison between the HU ozonesonde and the coincident OMPS ozone profile.

Less than 10% off between 20 and 30 km



Seasonal O₃ comparison between SAGE III-ISS and ACE-FTS

Data used in comparison:

SAGE III-ISS: level 2 Version 5.1

ACE-FTS: Level 2 version 3.5/3.6 data

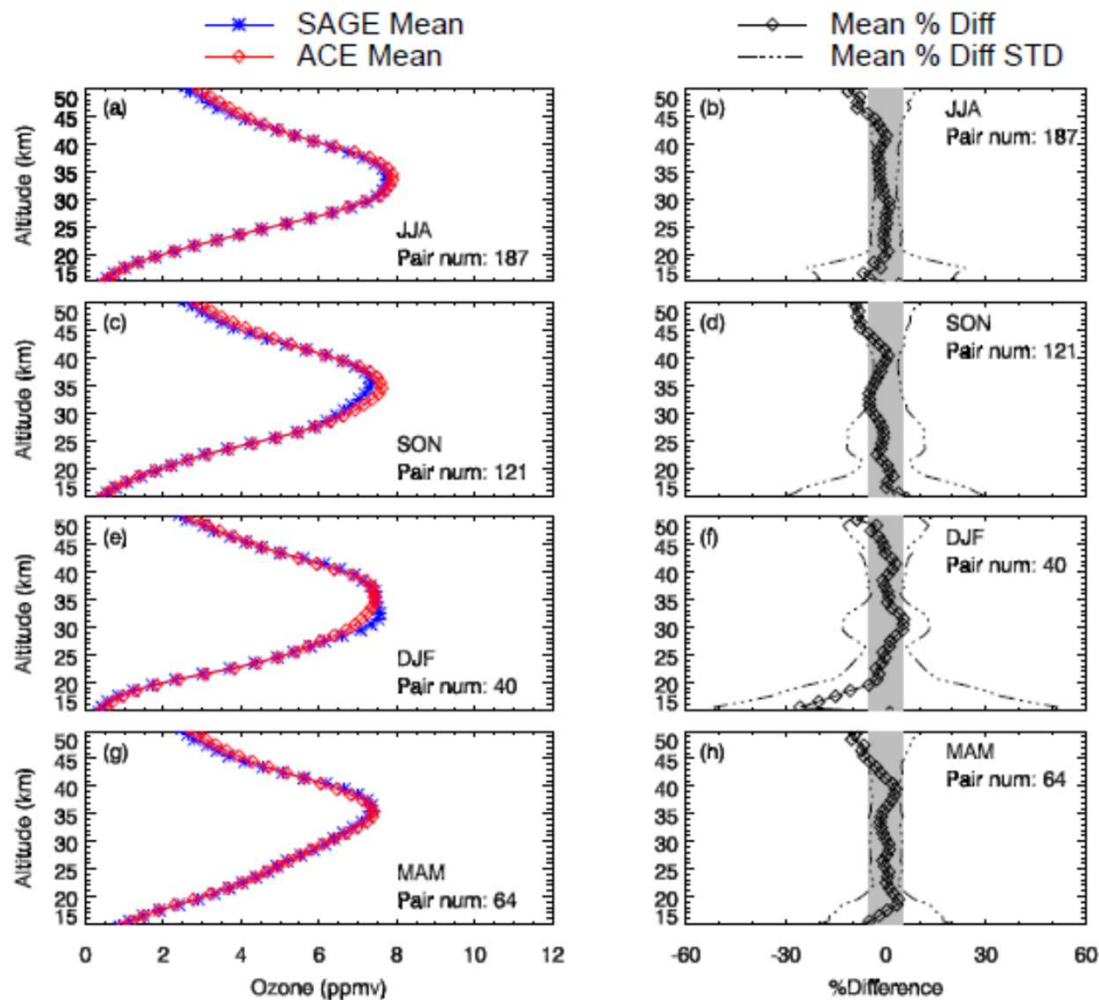
Criterion used for finding the coincidence :

Latitude difference $< 5^\circ$

Longitude difference $< 10^\circ$

Time difference < 4 hour

O₃ Seasonal average comparison with standard deviation of difference



The grey shade region
In the part of the right
figure show $\pm 5\%$
difference

Zonal mean O_3 and percent difference for two mission (June, 2017-November, 2018)

