Raman Lidar observations of the vertical profiles of aerosol optical properties and water vapour at the Pierre Auger Observatory

PIERRE AUGER OBSERVATORY

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UNIVERSITÀ DEGLI STUDI DELL'AQUILA

DSFC Dipartimento di Scienze Fisiche e Chimiche

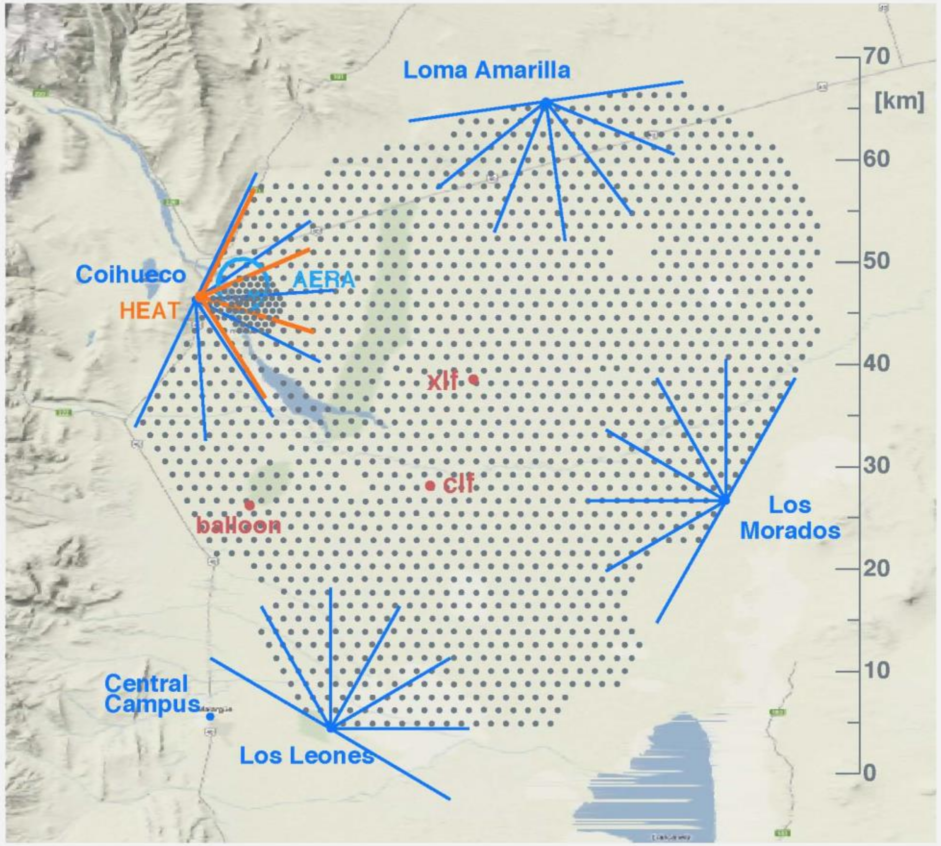
INFN Istituto Nazionale di Fisica Nucleare

Outline

1. The Auger Raman lidar
2. Aerosol backscatter coefficient
3. Vertical Aerosol Optical Depth
4. Aerosol vertical distribution
5. Water vapor mixing ratio

The Auger Raman lidar

The Raman Lidar samples vertically the part of the atmosphere above the CLF site, and the retrieved VAOD profiles have a representativeness of the aerosol optical transmission in the atmosphere over the Observatory.



CLF

The Auger Raman lidar

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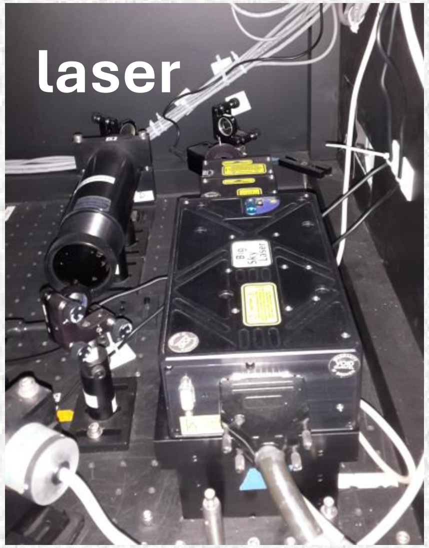
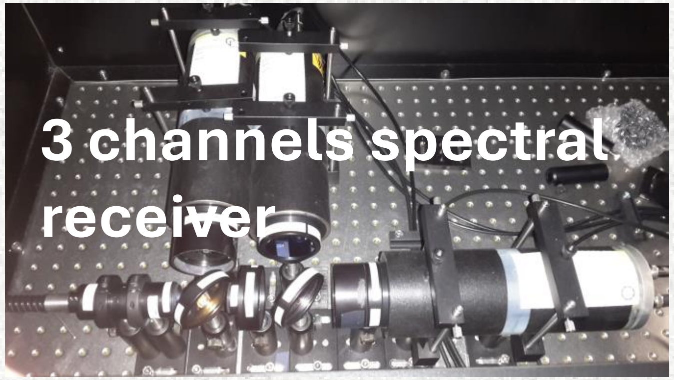
Three channels:	354.7 nm (elastic)
	386.7 nm (nitrogen)
	407.5 nm (water vapor)
Laser beam:	7 ns width
	6 mJ
	0.3 mrad divergence
	100 Hz
Telescope:	parabolic mirror
	50 cm, f/3
PMT:	Electron Tubes 9829QB
DAQ:	PC and AD





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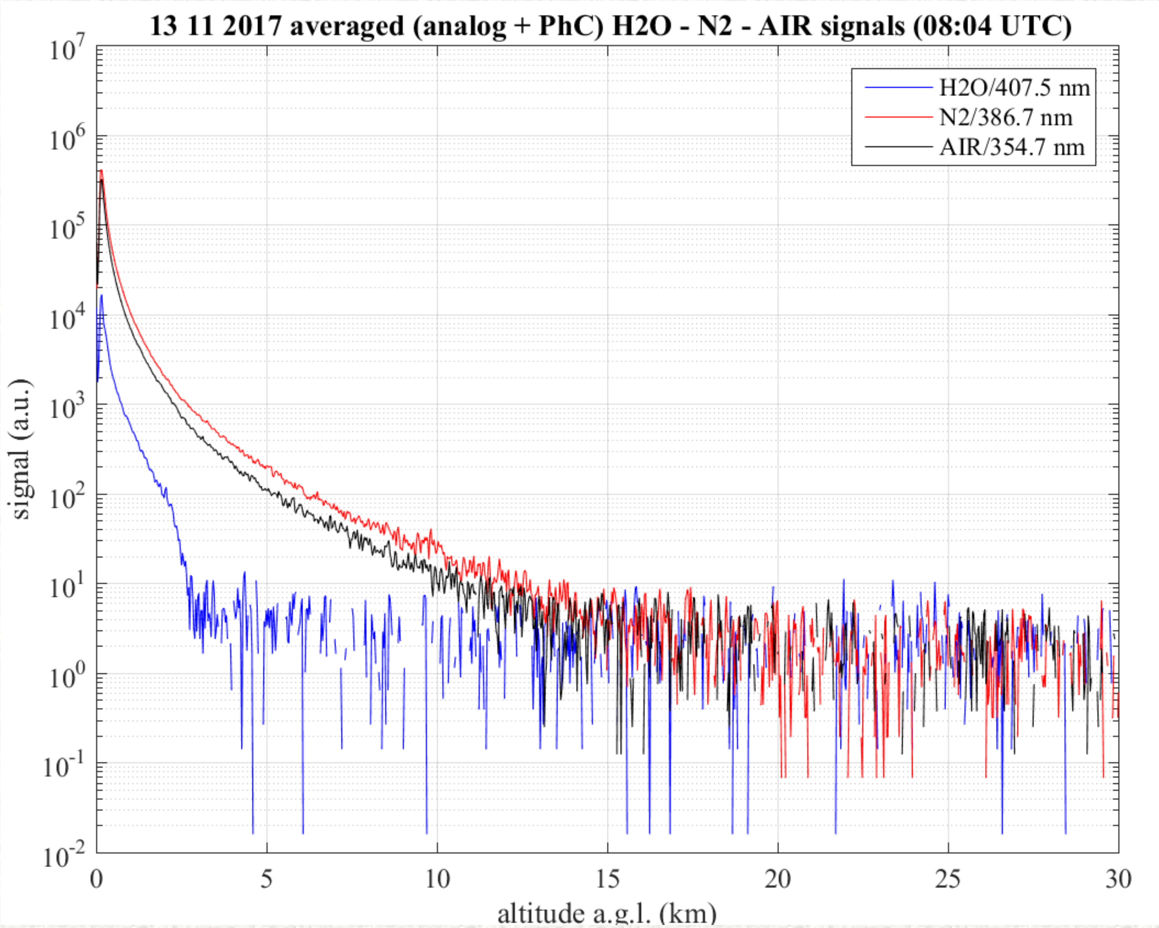


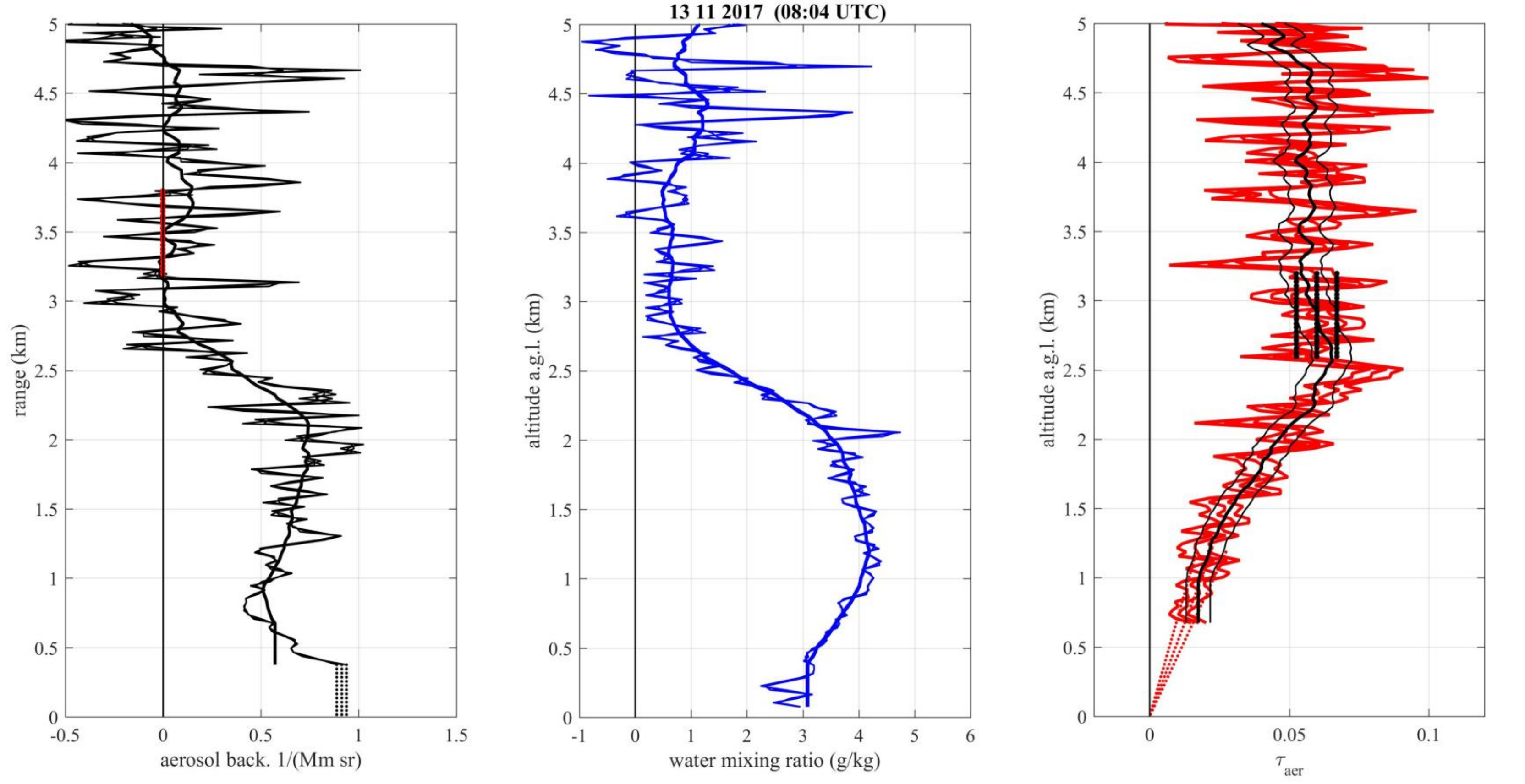
Aerosol optical properties

The main products of the Auger Raman lidar are the Vertical Aerosol Optical Depth (or its derivative), the aerosol backscatter coefficient, and the water vapor mixing ratio.

aerosol backscatter

[H2O]

VAOD



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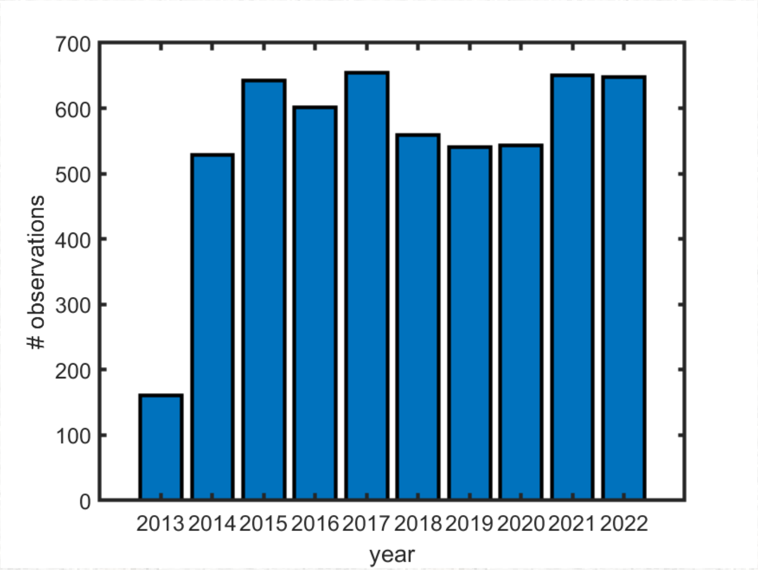
5433 Observations



# of total observations

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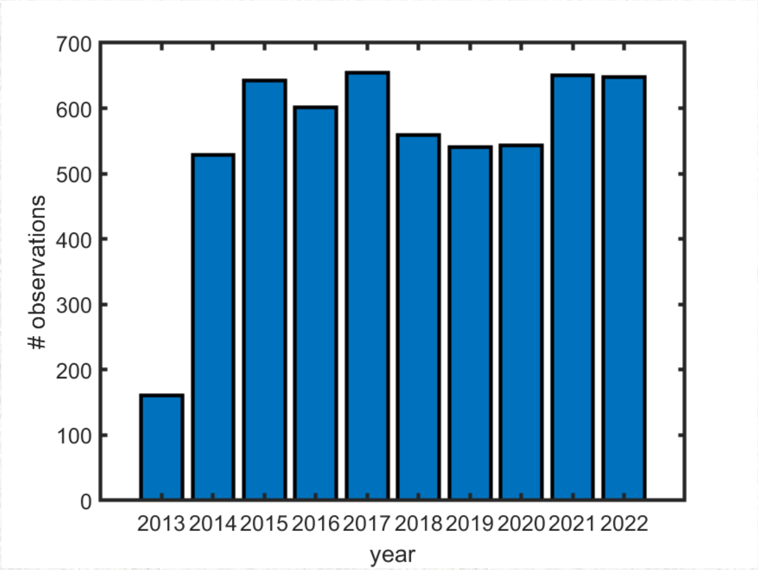
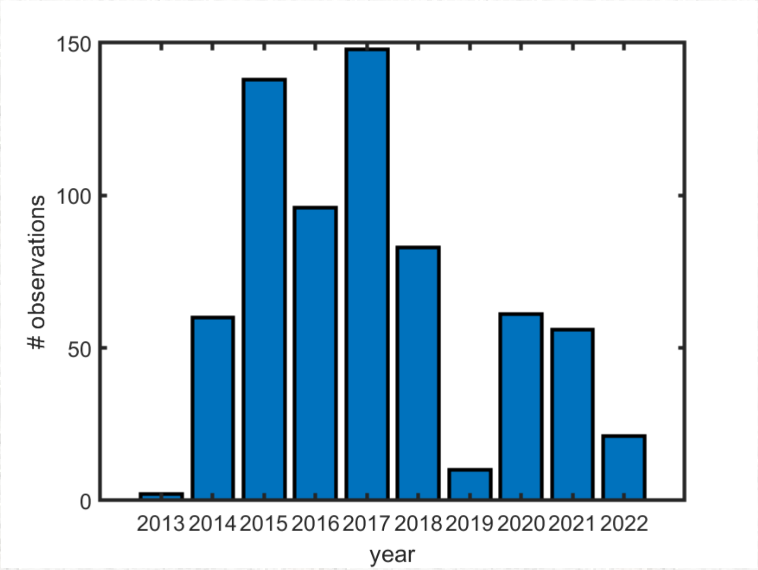


# of total observations

675 Observations



Masking for clouds, high aerosol content and bad measurements:

- VAOD threshold at fixed heights;
- Integrated β threshold at fixed heights;
- Elastic Channel first derivative.

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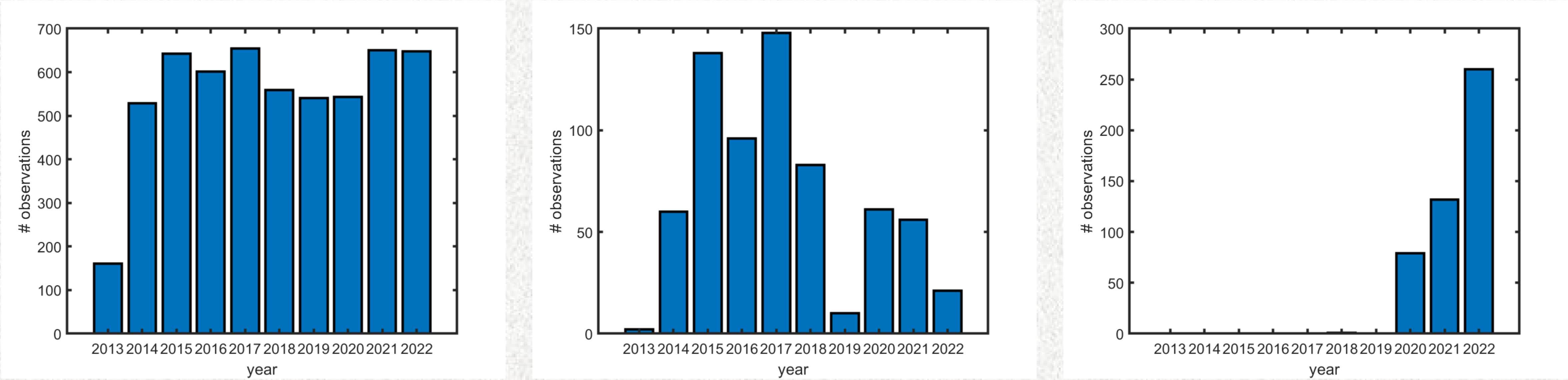

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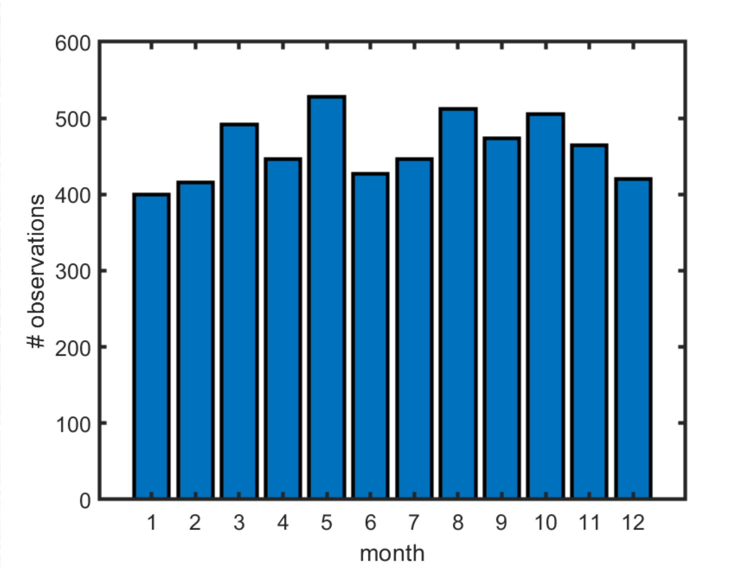

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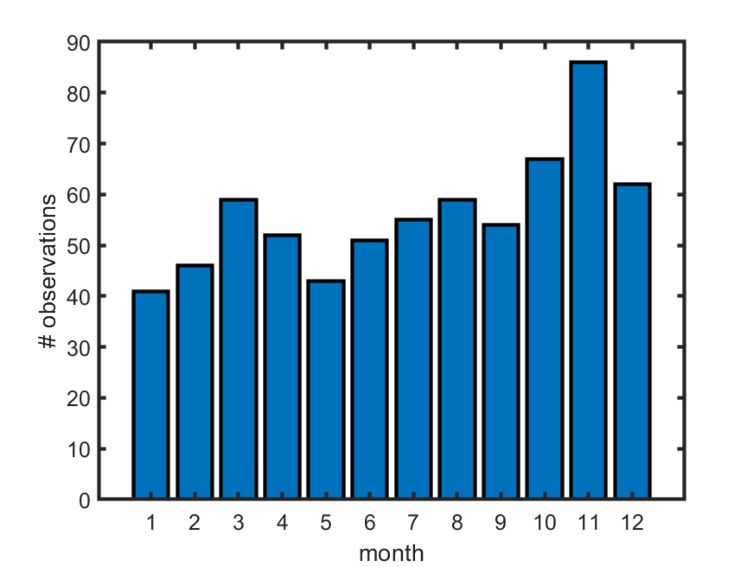

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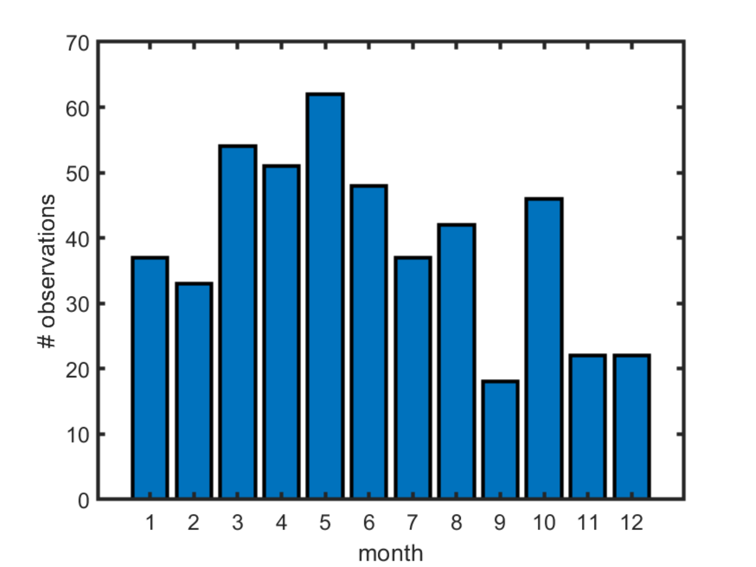

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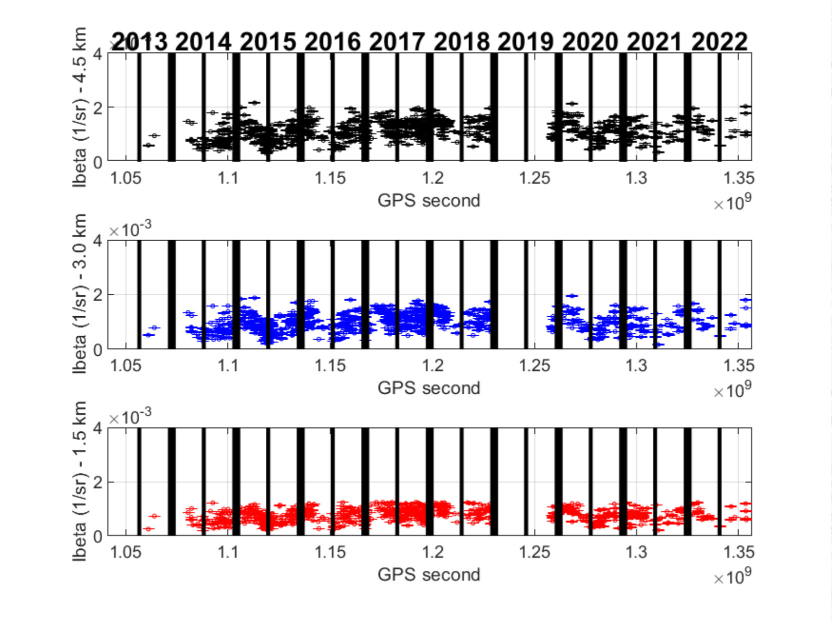
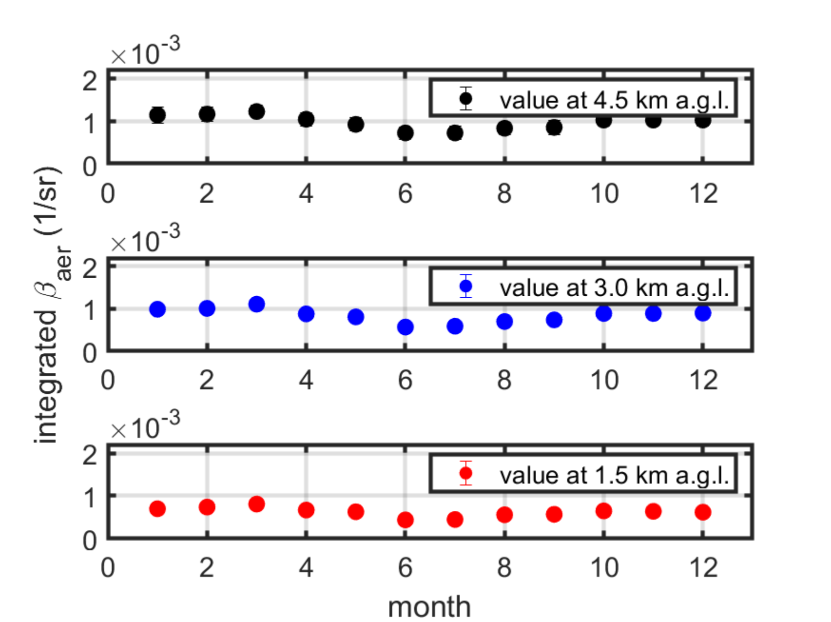
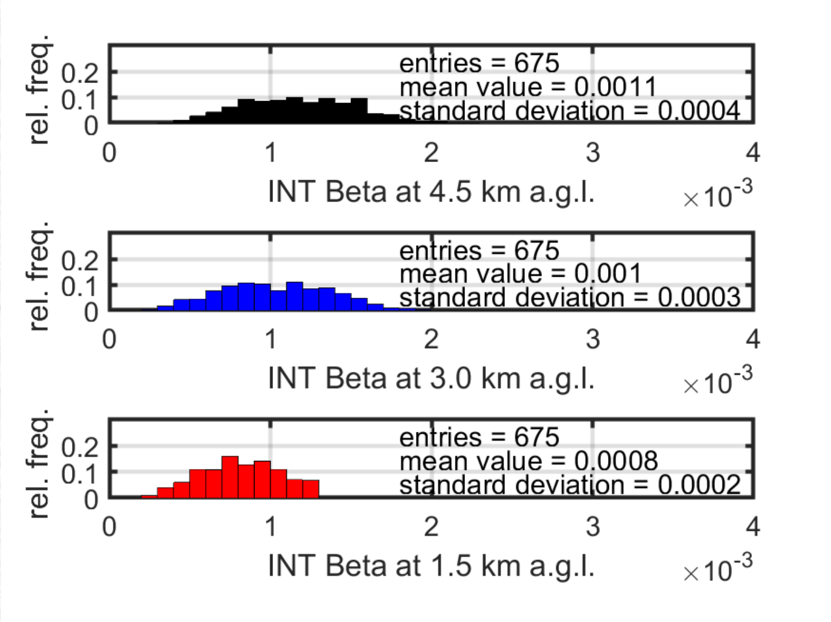
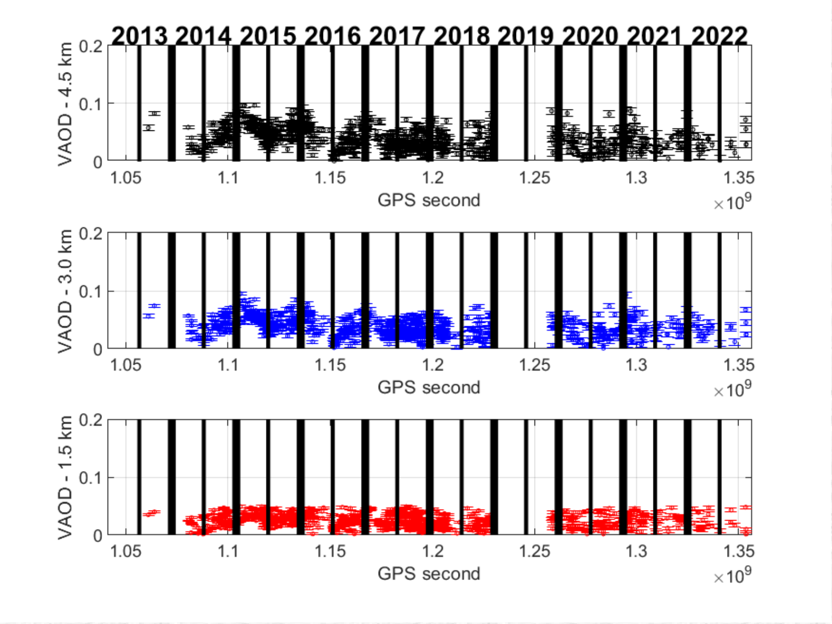
Aerosol backscatter coefficient

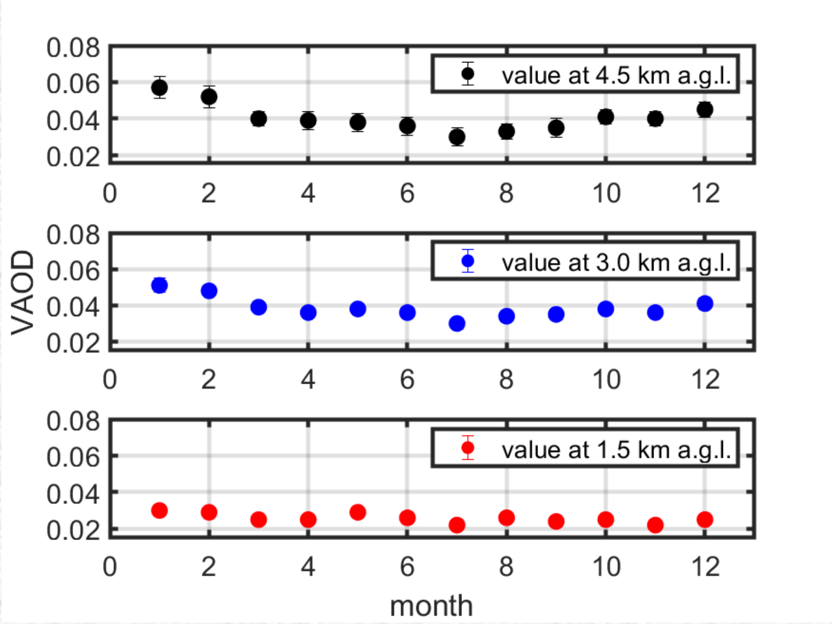


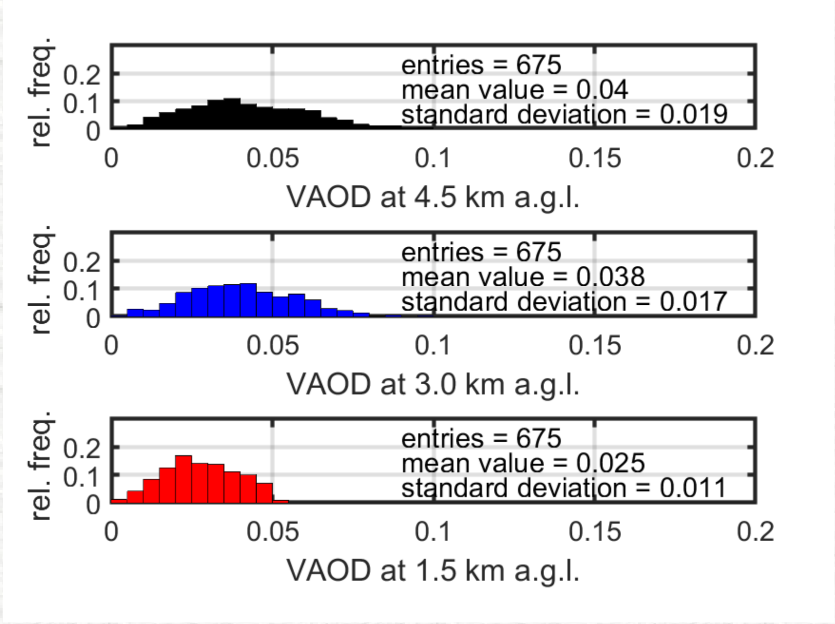




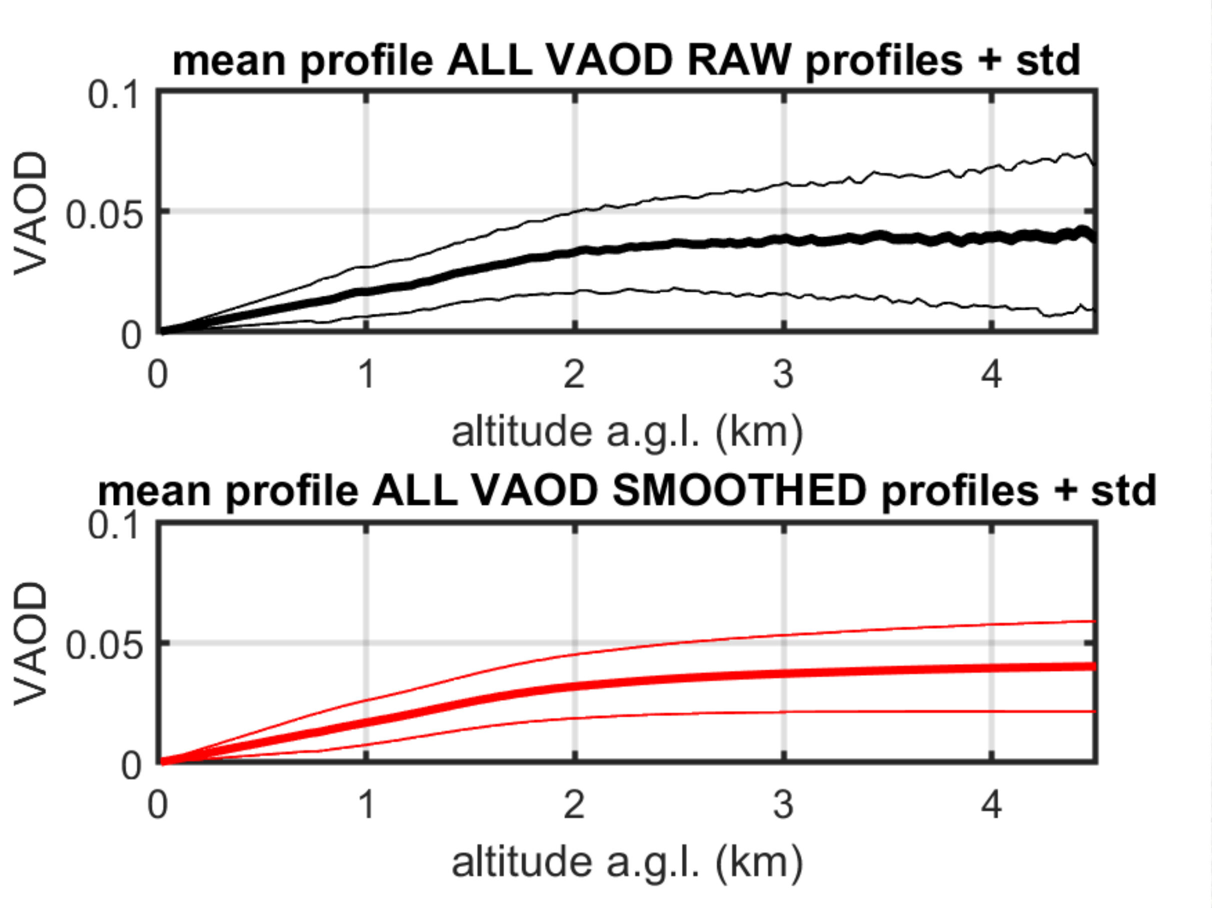
Vertical Aerosol Optical Depth







Vertical Aerosol Optical Depth - model



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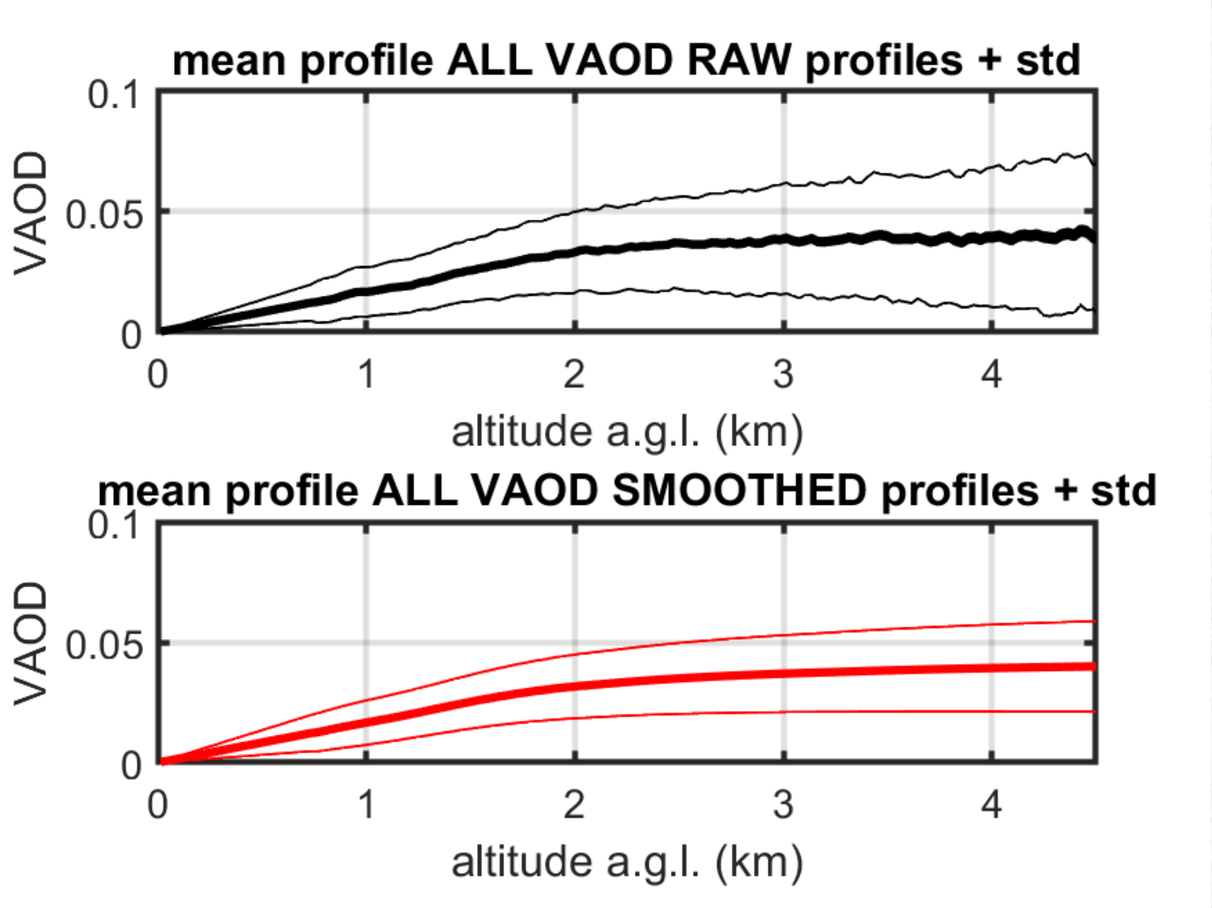
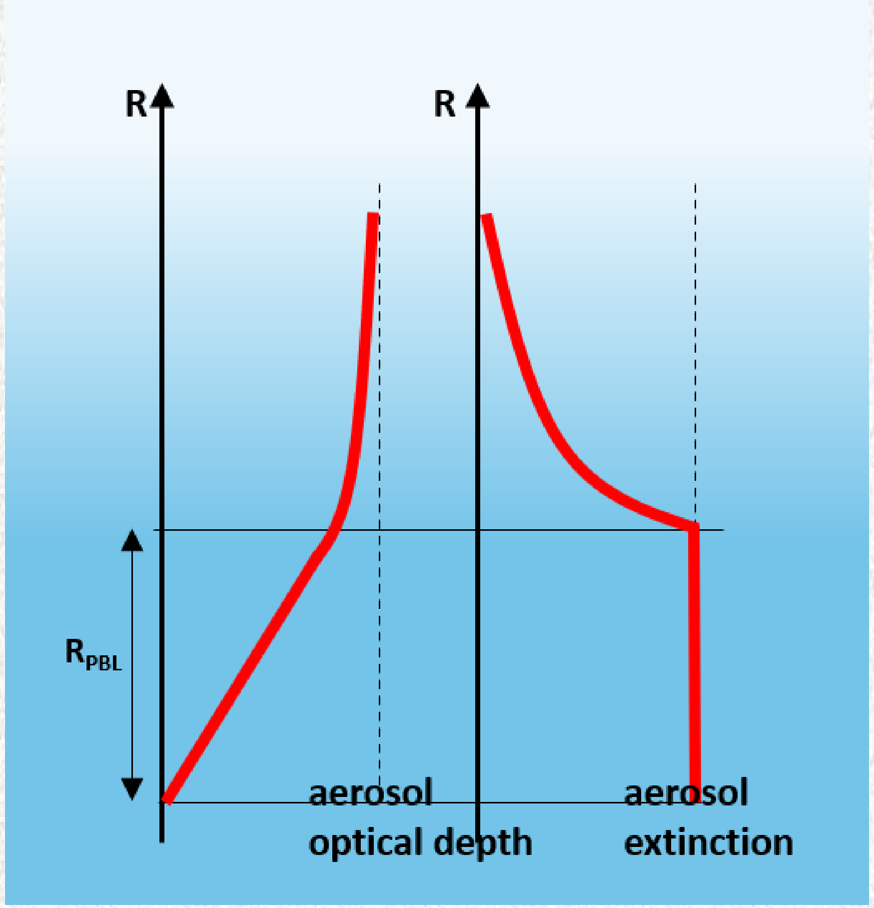




Vertical Aerosol Optical Depth - model

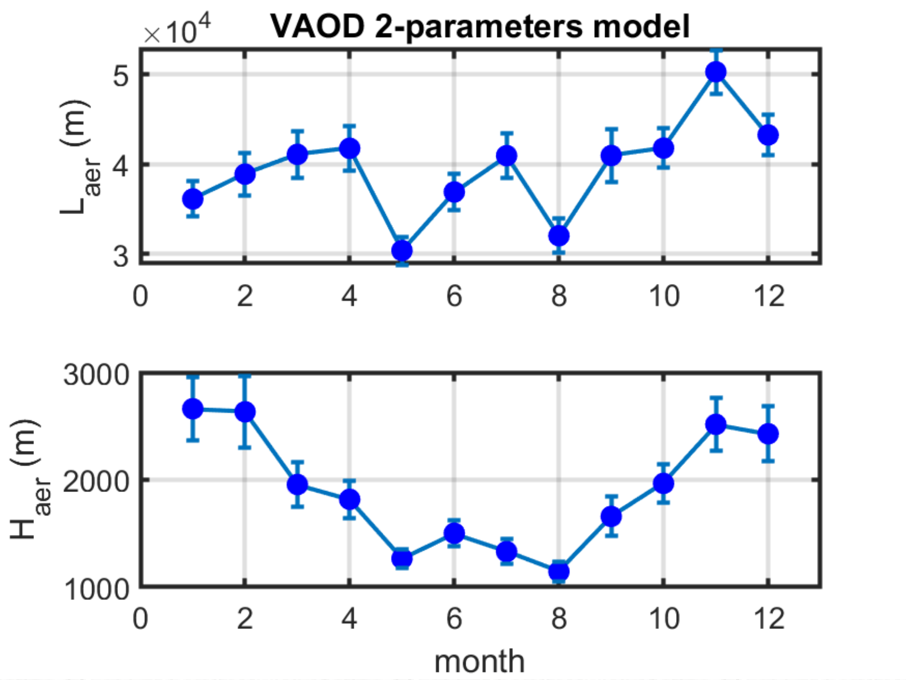
2-parameter model

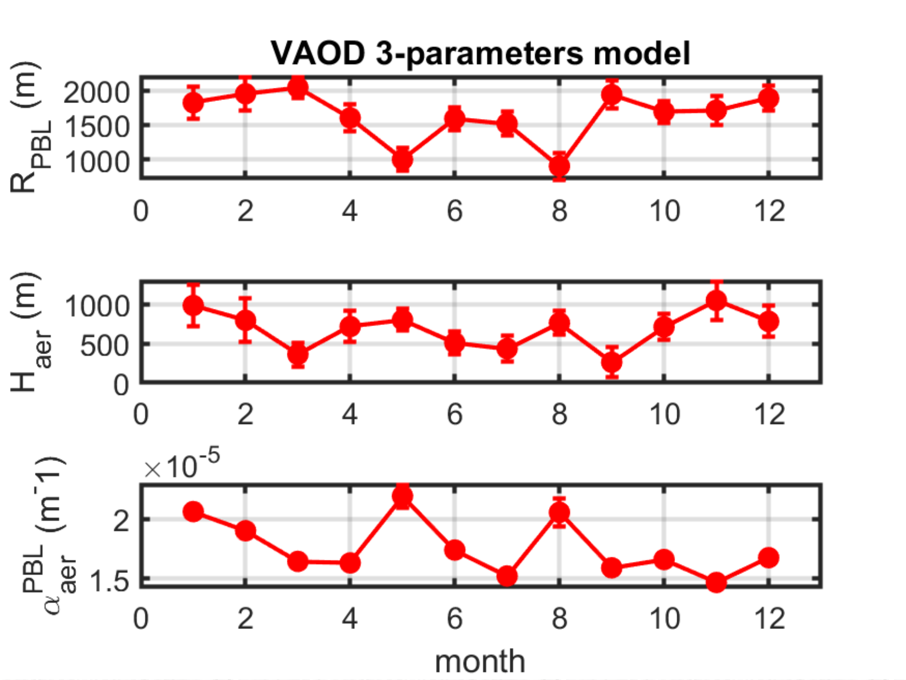
$$VAOD(R) = \frac{H_{aer}}{L_{aer}}\left(1 - e^{-R/H_{aer}}\right)$$

3-parameter model

$$VAOD(R) = \alpha_{aer}^{PBL} R, \qquad R < R_{PBL}$$

$$VAOD(R) = \alpha_{aer}^{PBL} R_{PBL} - \alpha_{aer}^{PBL} H_{aer}\left[e^{-\frac{(R - R_{PBL})}{H_{aer}}} - 1\right], \qquad R \geq R_{PBL}$$





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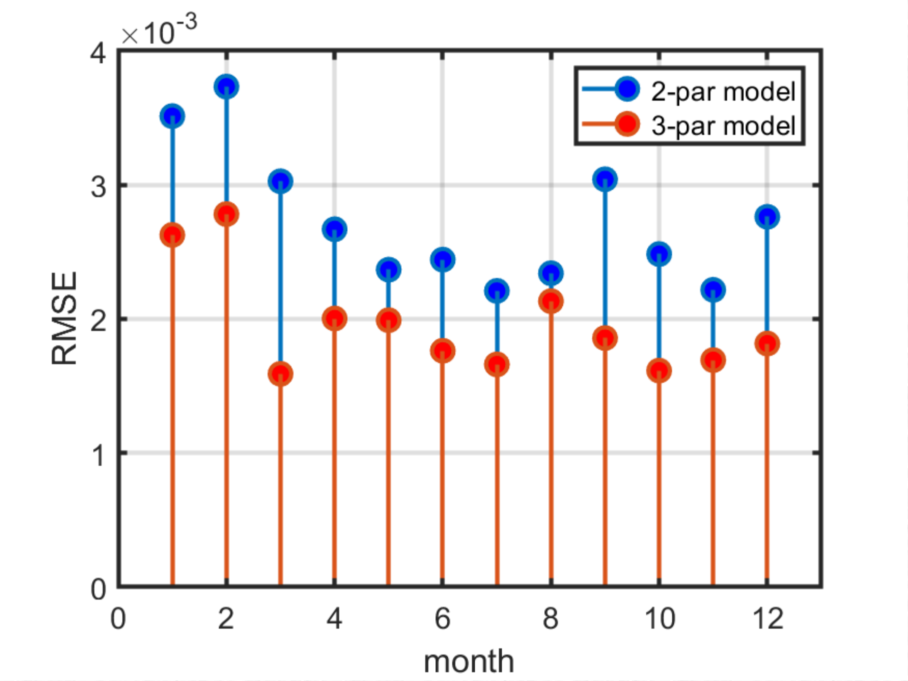
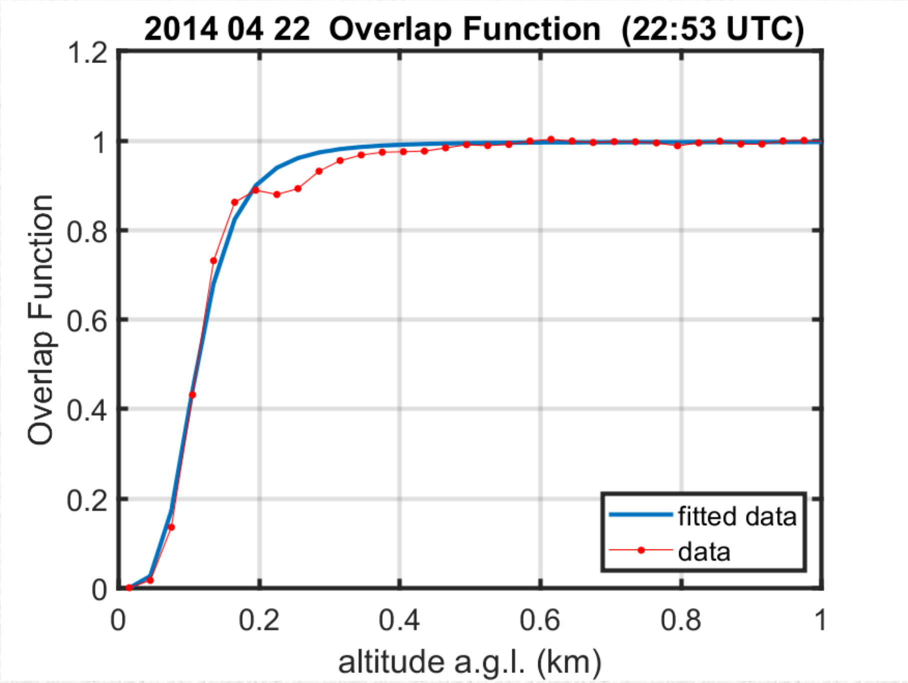


Vertical Aerosol Optical Depth – overlap function

Deviation between β_{Raman} and $\beta_{Elastic}$ contains information about the incomplete overlap



$$y = A_2 + \frac{A_1 - A_2}{\left[1 + \left(\frac{x}{x_0}\right)^p\right]}$$

Logistic Function (Rogelj 2014)

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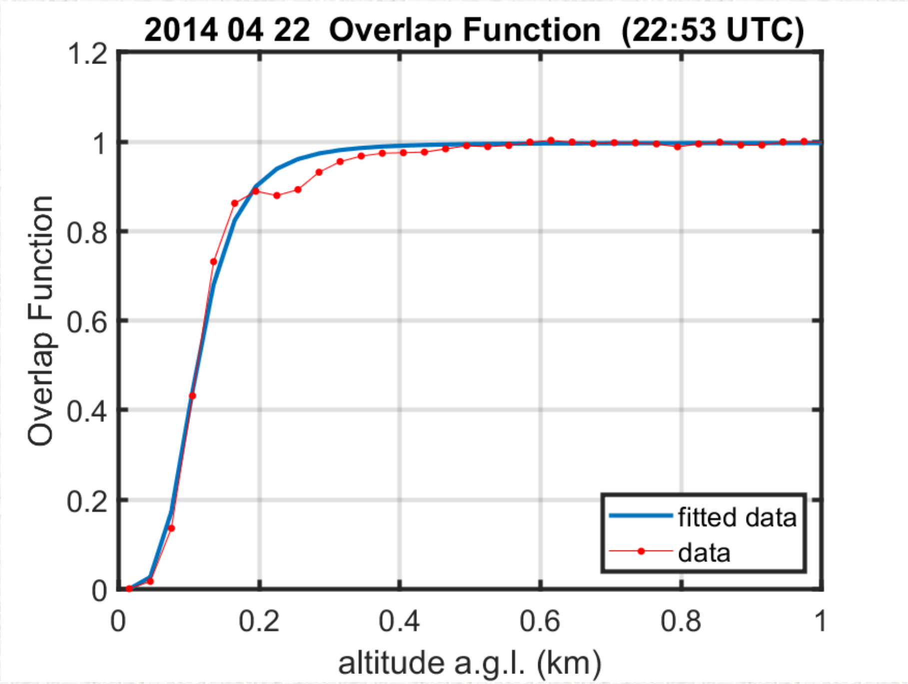

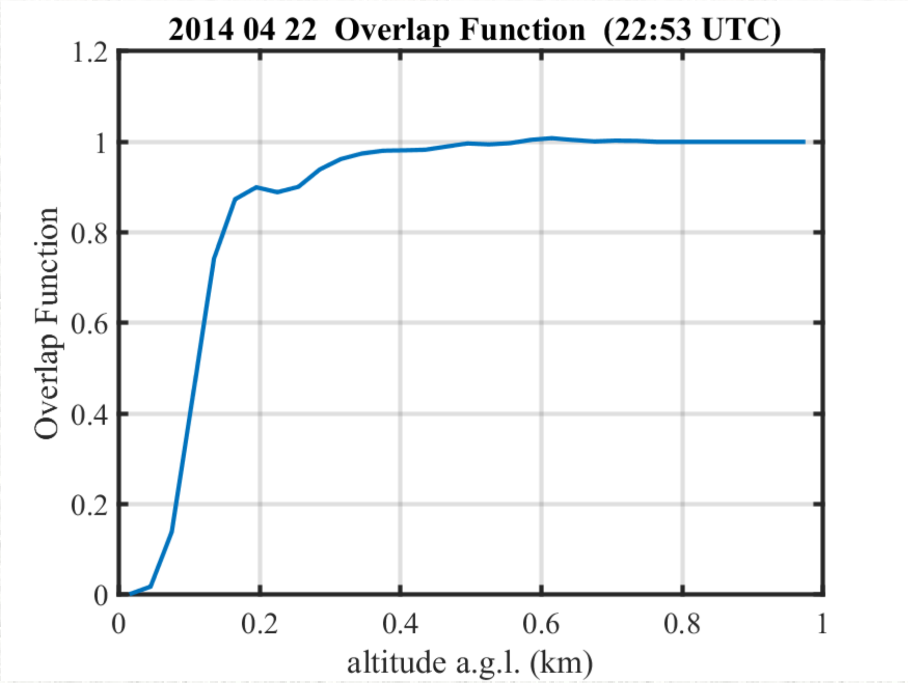

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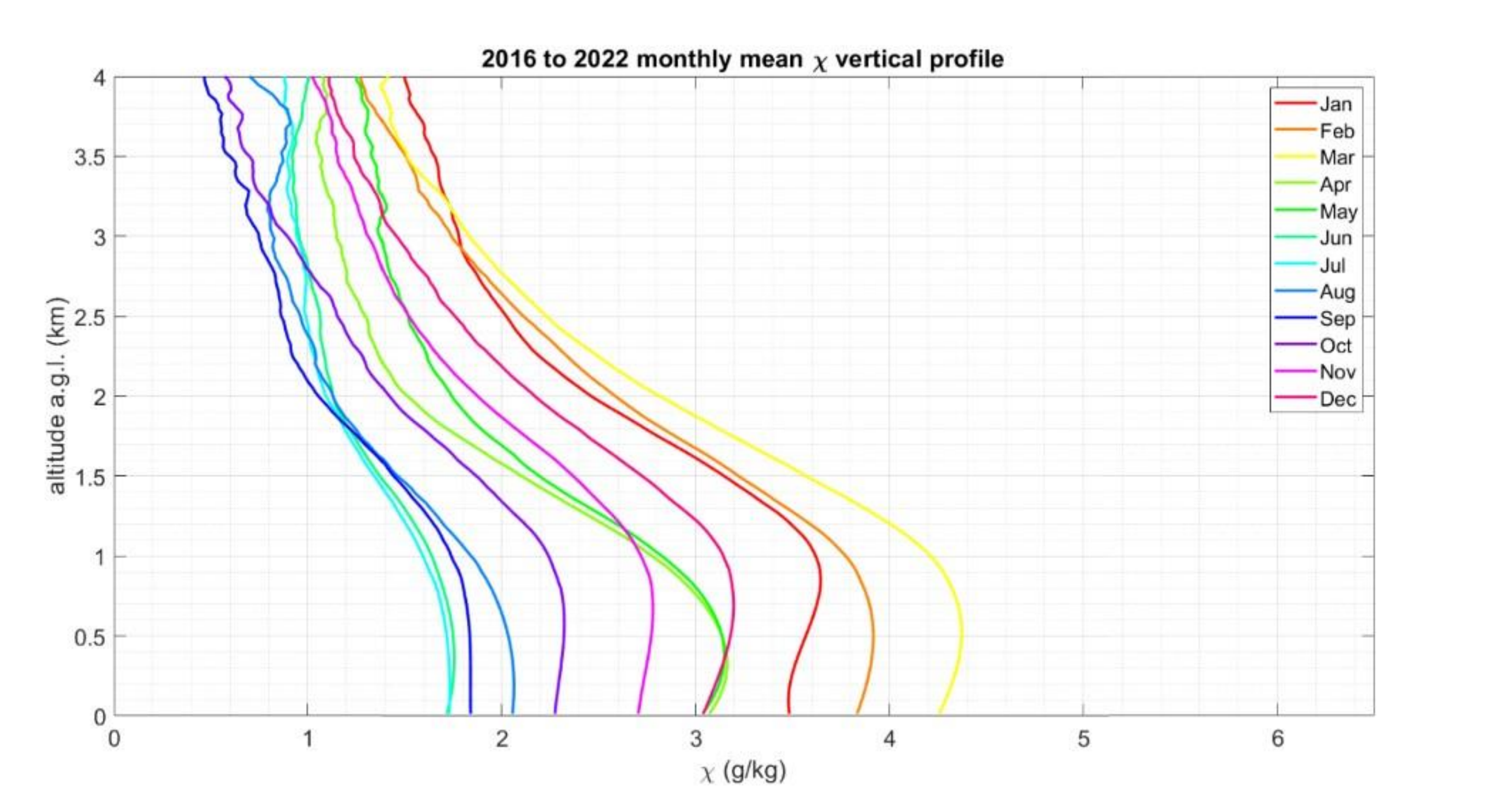
From VAOD and hypotesis on aerosol distribution

Water vapor mixing ratio

From Gomez L V – Master thesis (2023)



Conclusions

- The Auger Raman Lidar is measuring the aerosol optical properties @355 nm since November 2013;
- Masking for clouds, high aerosol content and bad measurements selects 675 out of 5433 observations;
- The measured vertical profiles of the aerosol optical depth, backscatter, and water vapor mixing ratio show a seasonal dependence;
- The shape of the vertical aerosol optical depth can be represented with a 2-parameters model or a 3-parameters model;
- The overall mean/std VAOD at 4.5 km a.g.l. is 0.040 ± 0.019.

THANK YOU

Raman lidar performance

Minimum measurable VAOD at 355 nm ~ 0.005

Sources of Errors: **Random/Statistical**

Systematic

$$VAOD = -\frac{1}{1+\left(\frac{\lambda_0}{\lambda_{N2}}\right)^{k}} \log \frac{\boldsymbol{L_{N2}} R^2}{T_{mol}^{\lambda_0} T_{mol}^{\lambda_{N2}} n_{mol}}$$

Overlap function from VAOD

Measurements: L_{N2} $L_{N2} = L_0 O$ O -> Overlap Function

$$VAOD = -\frac{1}{1+\left(\frac{\lambda_0}{\lambda_{N2}}\right)^k}\log\frac{L_{N2}R^2}{T_{mol}^{\lambda_0}T_{mol}^{\lambda_{N2}}n_{mol}} + B$$

Linear Fit in [R1 R2] -> VAOD offset

Hypothesis: $VAOD' = \alpha R, R < R_2$

$$VAOD' = -\frac{1}{1+\left(\frac{\lambda_0}{\lambda_{N2}}\right)^k}\log\frac{L_O R^2}{T_{mol}^{\lambda_0}T_{mol}^{\lambda_{N2}}n_{mol}}, R < R_2$$

$$VAOD - VAOD' = -\frac{1}{1+\left(\frac{\lambda_0}{\lambda_{N2}}\right)^k}\log O$$

$$\log O = (VAOD' - VAOD)\left[1+\left(\frac{\lambda_0}{\lambda_{N2}}\right)^k\right]$$

Lidar equation inversion

Klett-Fernald Method (elastic):

$$\beta_{aer}(R) + \beta_{mol}(R) = \frac{S(R)e^{-2\int_{R_0}^{R}[L_{aer}(r)-L_{mol}]\beta_{mol}(r)dr}}{\frac{S(R_{0)}}{\beta_{aer}(R_0)+\beta_{mol}(R_0)} - 2\int_{R_0}^{R} L_{aer}(r)S(r)T(r,R_0)dr}$$

Ansmann Method (Raman):

$$\alpha_{aer}(R,\lambda_L) = \frac{\frac{d}{dR}\left[\ln\frac{N_R(R)}{R^2P(z,\lambda_L,\lambda_R)}\right] - \alpha_{mol}(R,\lambda_L) - \alpha_{mol}(R,\lambda_R)}{1+\left(\frac{\lambda_L}{\lambda_R}\right)^k}$$

$$\beta_{aer}(R,\lambda_L) = -\beta_{mol}(R,\lambda_L) + CN_R(R)\frac{P(R,\lambda_L)T(R,\lambda_R)}{P(R,\lambda_L,\lambda_R)T(R,\lambda_L)}$$

$$LR_{aer}(R,\lambda_L) = \frac{\alpha_{aer}(R,\lambda_L)}{\beta_{aer}(R,\lambda_L)}$$

$$m(R) = K\frac{P_{H_2O}(R,\lambda_L,\lambda_{R_2})}{P_{N_2}(R,\lambda_L,\lambda_{R_1})}\frac{exp\left\{-\int_0^R[\alpha_{aer}(R',\lambda_{R_1})+\alpha_{mol}(R',\lambda_{R_1})]\,dR'\right\}}{exp\left\{-\int_0^R[\alpha_{aer}(R',\lambda_{R_2})+\alpha_{mol}(R',\lambda_{R_2})]\,dR'\right\}}$$