LASER REMOTE SENSING II

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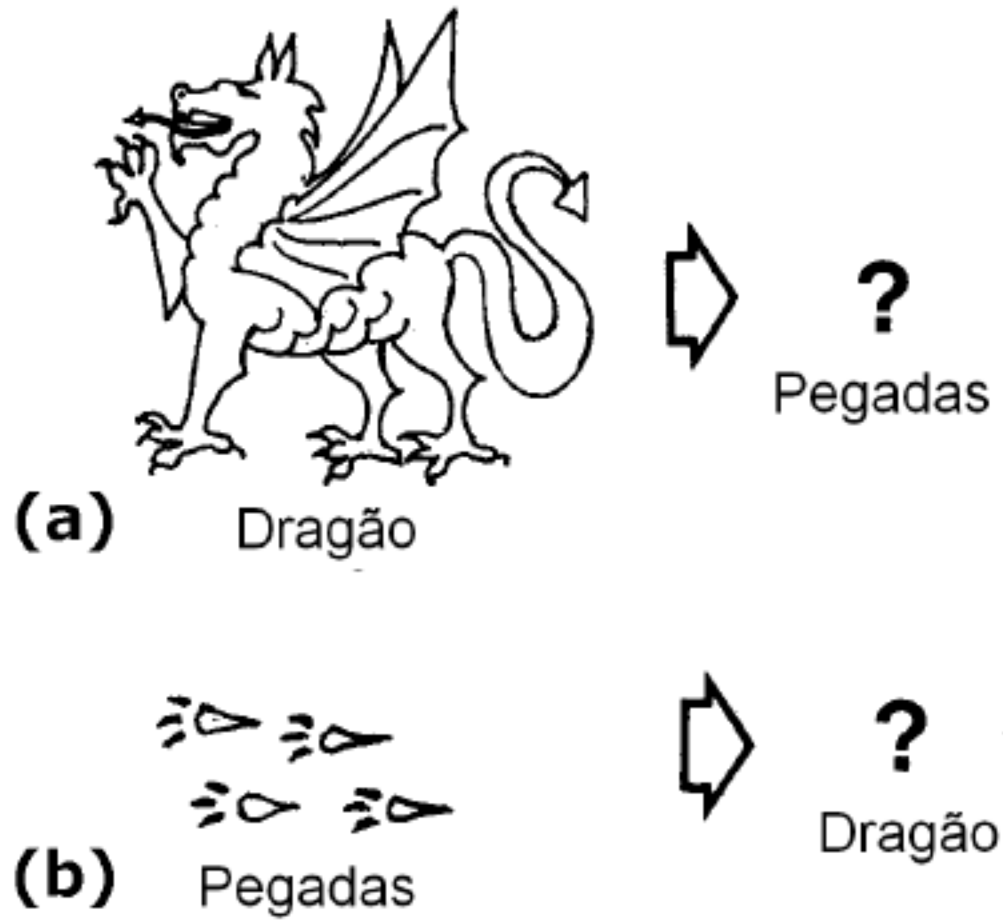
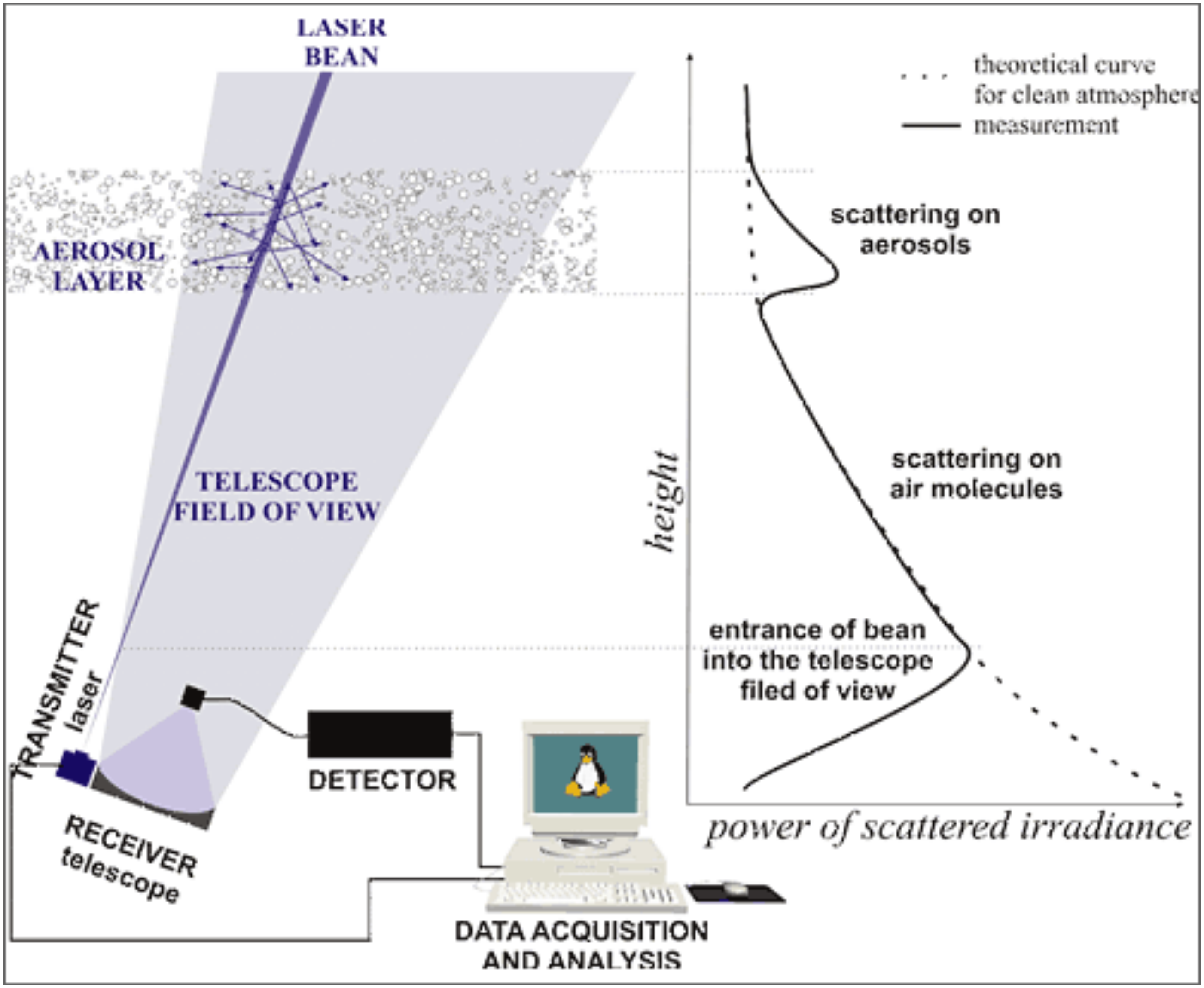
São Paulo, July 2019

The problem of the analysis of lidar data is related to problems of lidar signal interpretation. Despite the wide variety of the lidar systems developed for periodical and routine atmospheric measurements, no widely accepted method of lidar data inversion or analysis has been developed or adopted. A researcher interested in the practical application of lidars soon learns the following: (1) no standard analysis method exists that can be used even for the simplest lidar measurements; (2) in the technical literature, only scattered practical recommendations can be found concerning the derivation of useful information from lidar measurements; (3) lidar data processing is, generally, considered an art rather than a routine procedure; and (4) the quality of the inverted lidar data depends dramatically on the experience and skill of the researcher.

Kovalev & Eichinger – Elastic Lidar

Solving a lidar problem is a kind of **Inverse Problem**




LASER
BEAN
theoretical curve
for clean atmosphere
measurement
AEROSOL
LAYER
scattering on
aerosols
scattering on
air molecules
TELESCOPE
FIELD OF VIEW
height
entrance of bean
into the telescope
filed of view
TRANSMITTER
laser
DETECTOR
RECEIVER
telescope
power of scattered irradiance
DATA ACQUISITION
AND ANALYSIS

Information Available from Aerosol Lidar

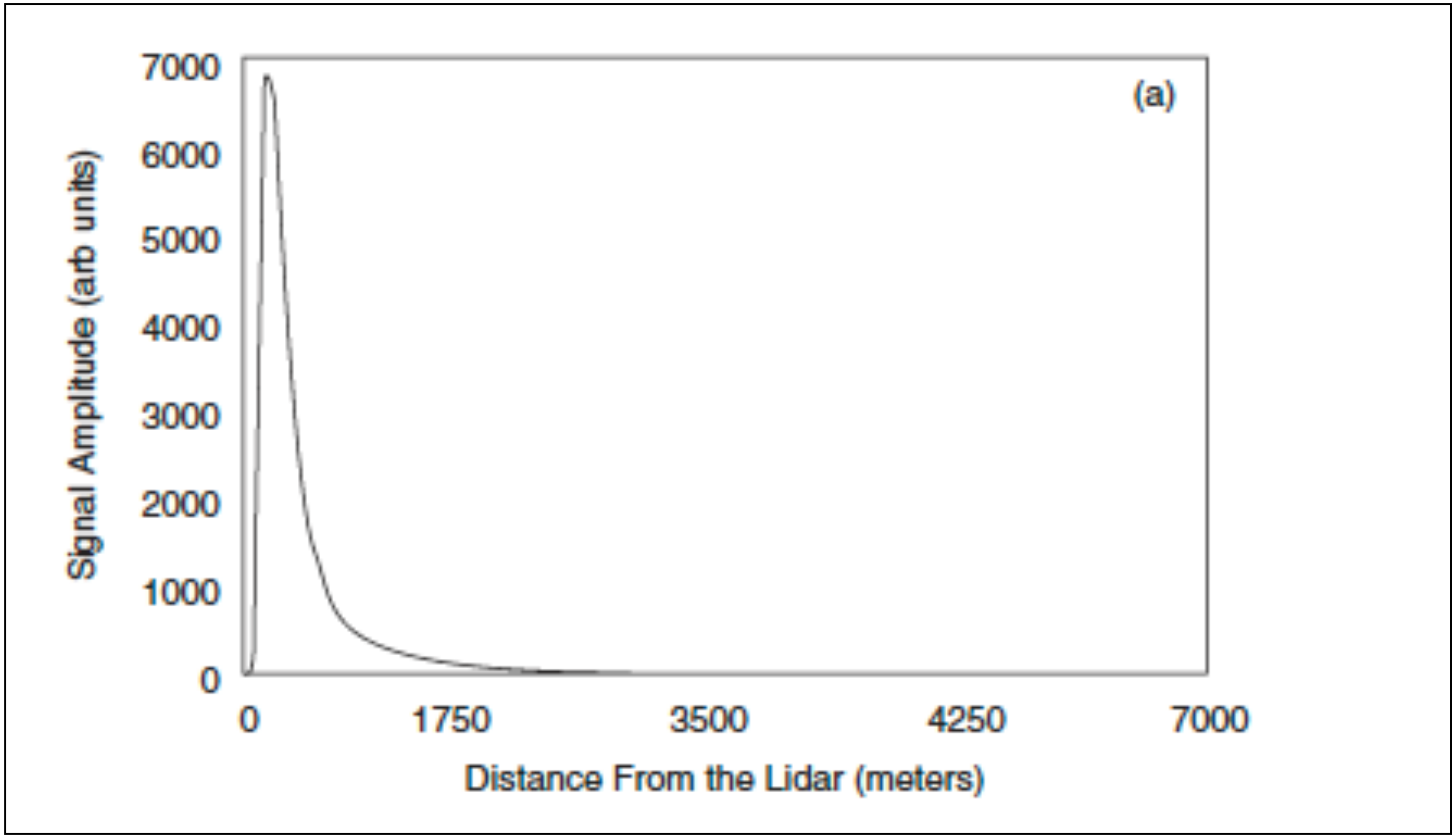
Backscatter Lidar

Backscatter Lidar+ Passive

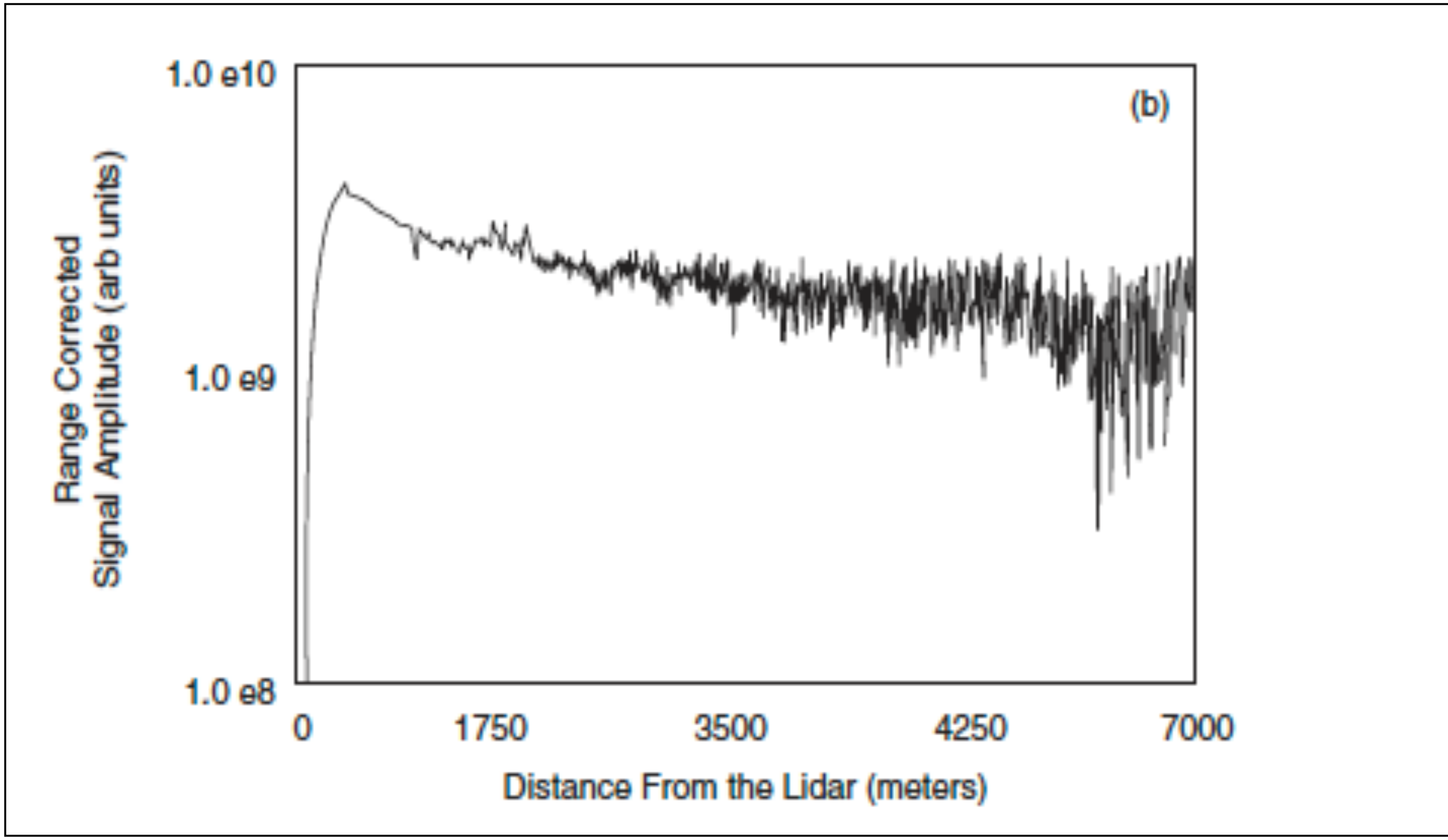
Multiwavelength Lidar

- Aerosol layer heights
- Attenuated backscatter
- Extinction profile derived from backscatter
- Extinction profile using column constraint
- Backscattering and extinction profiles at multiple wavelengths
- Particle size distribution at different heights (so volume, surface, number densities, effective radius)
- Complex refractive index and SSA

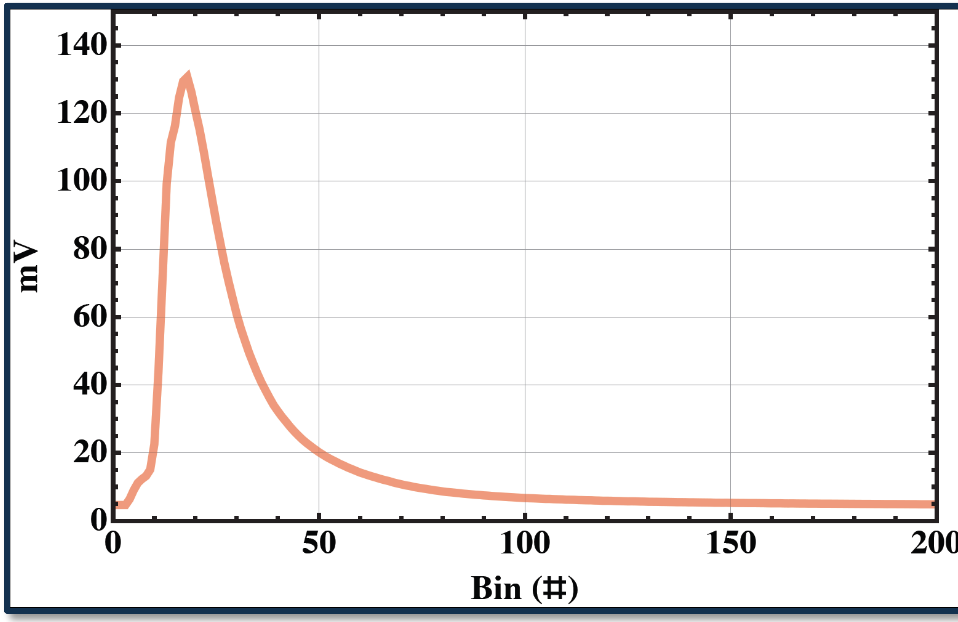
FROM RAW DATA TO ETERNITY



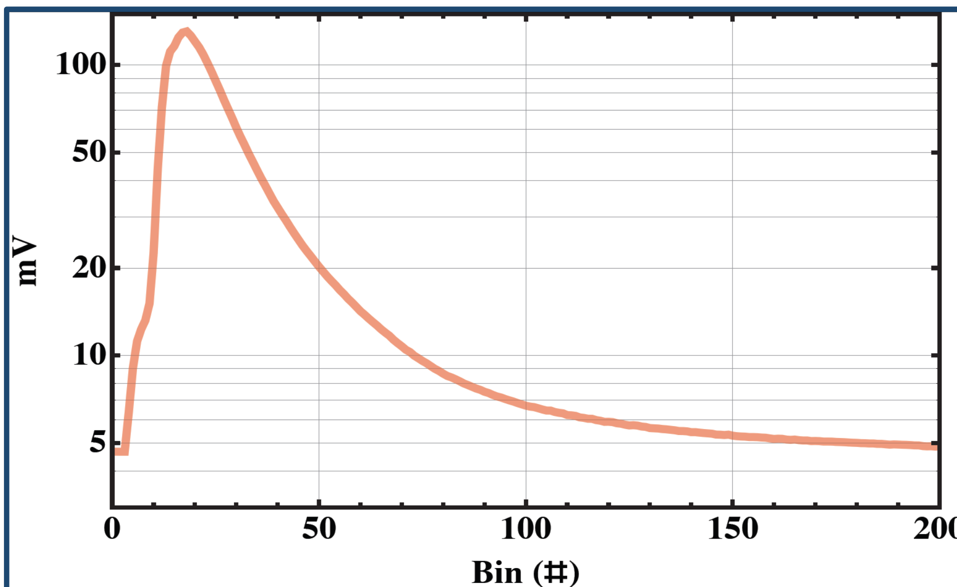
The “non-exciting” typical lidar retrieval



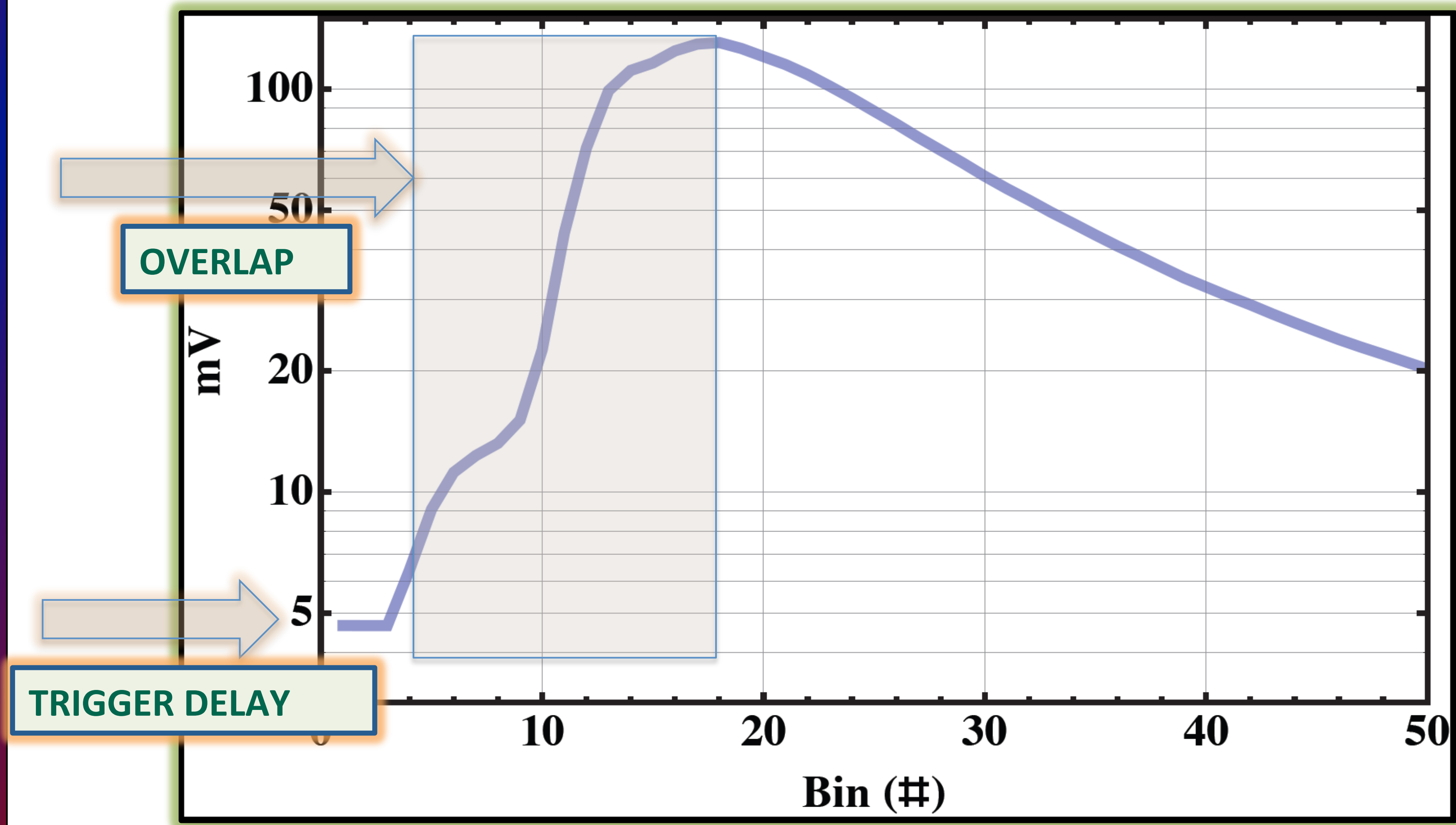
The “somehow-exciting” typical lidar retrieval



NO-LOG

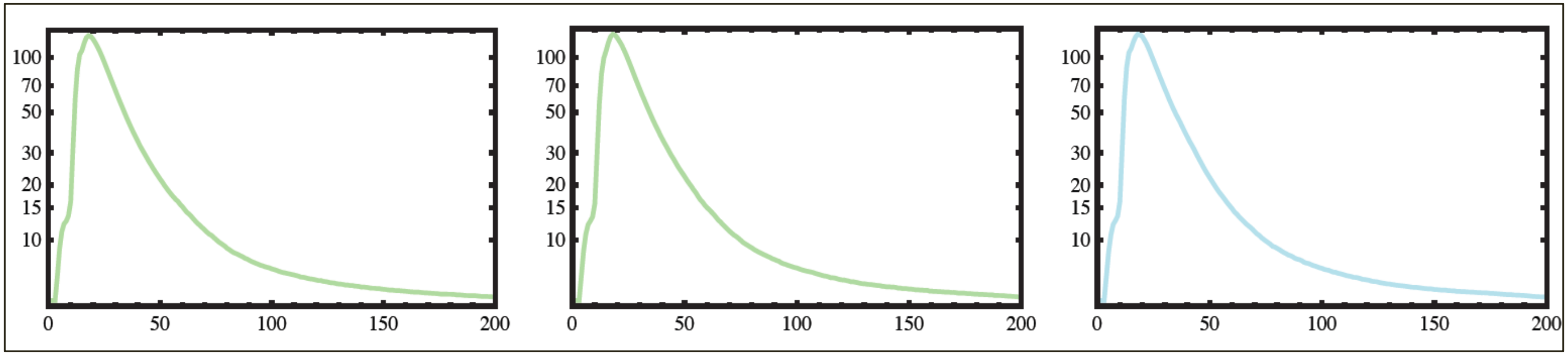


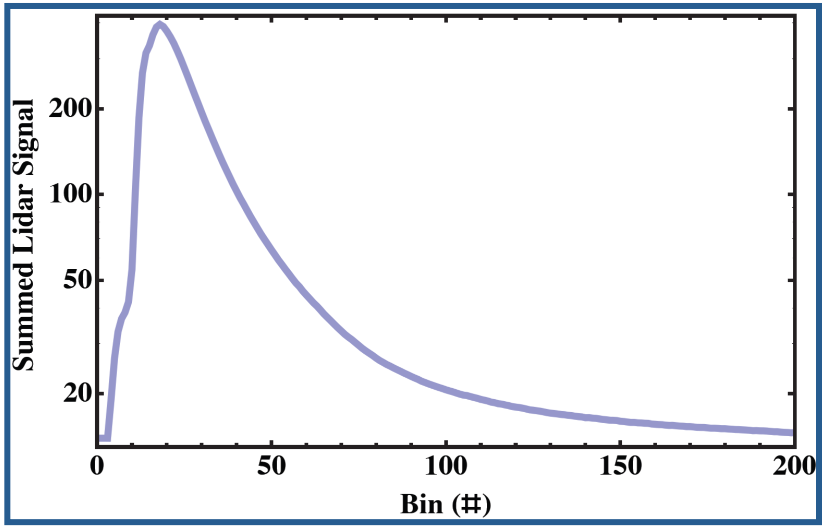
YES-LOG



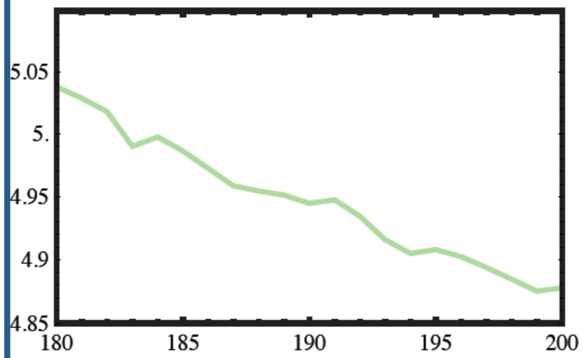
LIDAR ANALOGIC SIGNAL "CLOSE-LOOK"

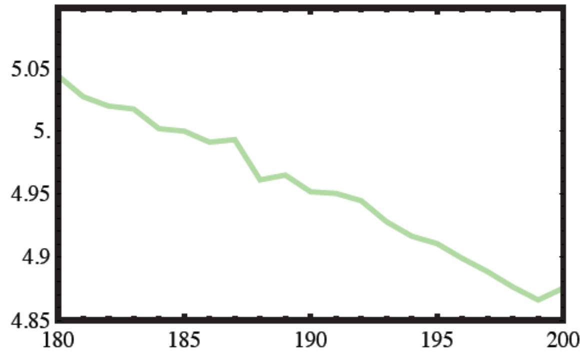
Summed Files for Data Processing

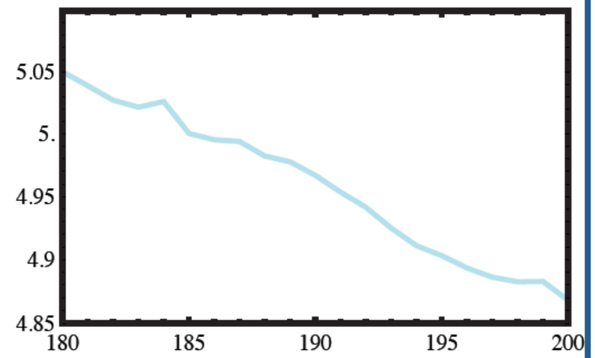




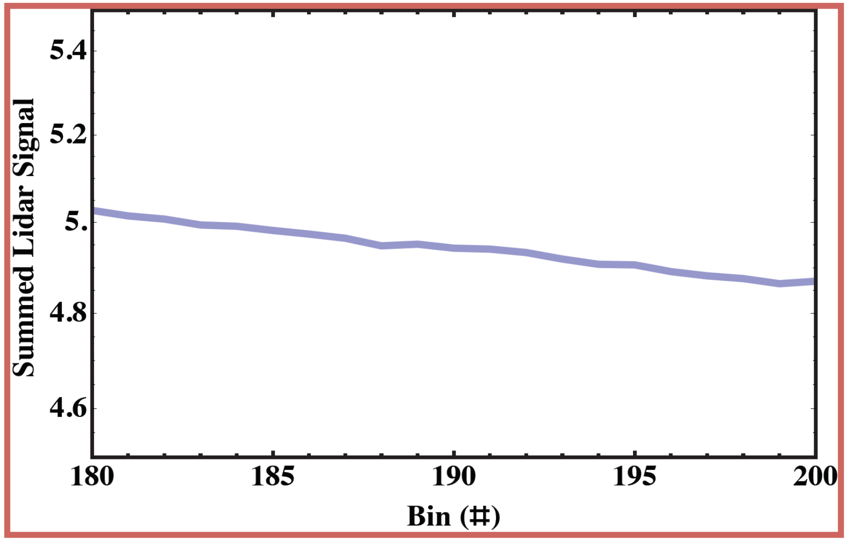
Summed Files for Data Processing



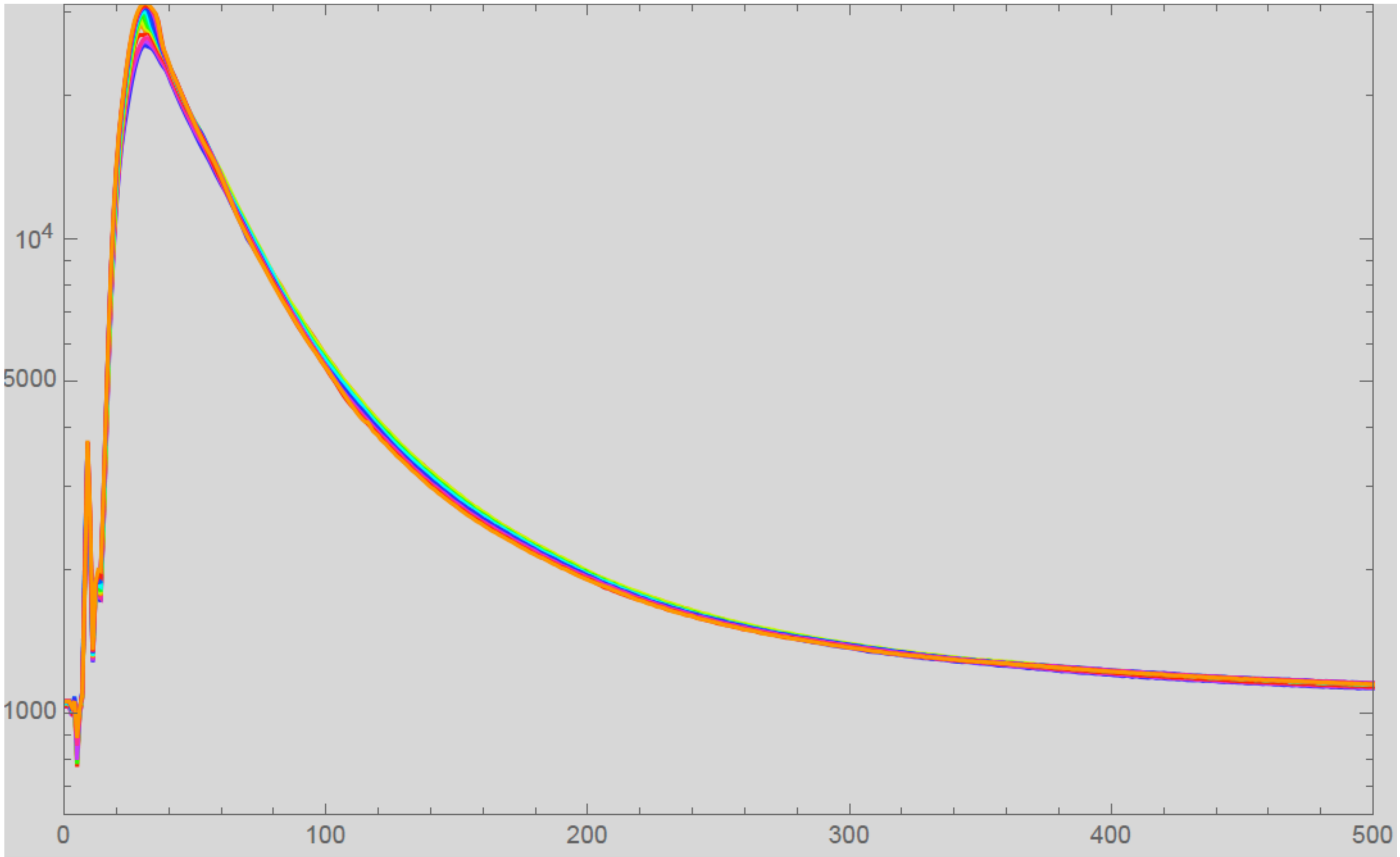




AVERAGE SIGNAL



INSPECTING THE FILES



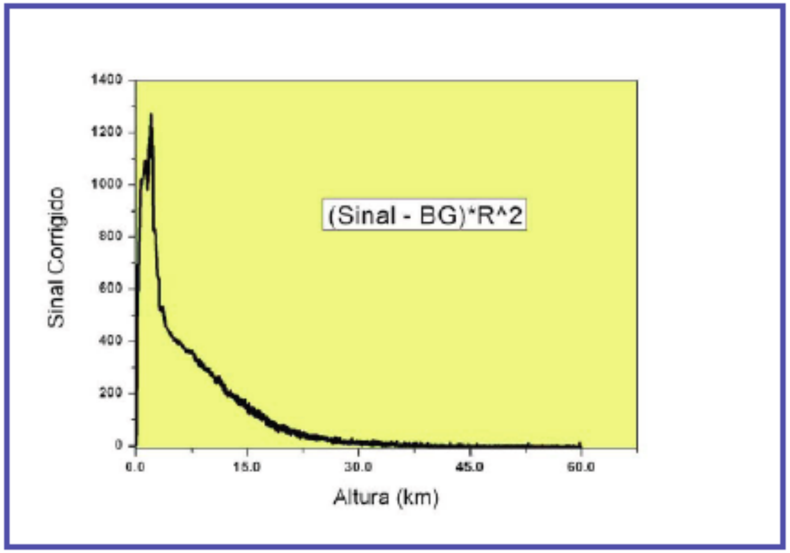
BACKSCATTER LIDARS

AEROSOL STUDIES WITH LIDARS – SOLUTIONS

RANGE CORRECTED SIGNAL

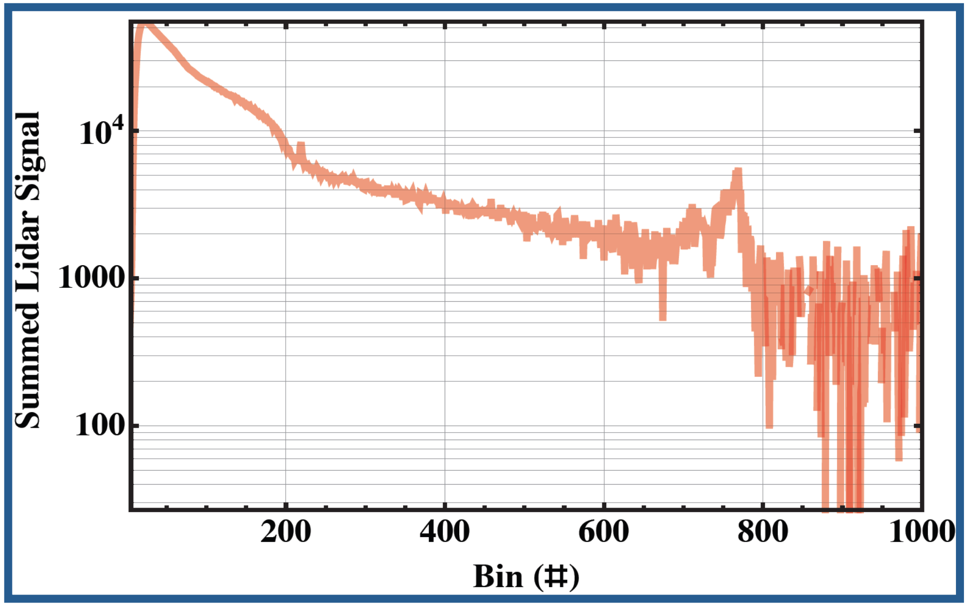
$$S(R) \equiv ln[R^2 P(R)]$$

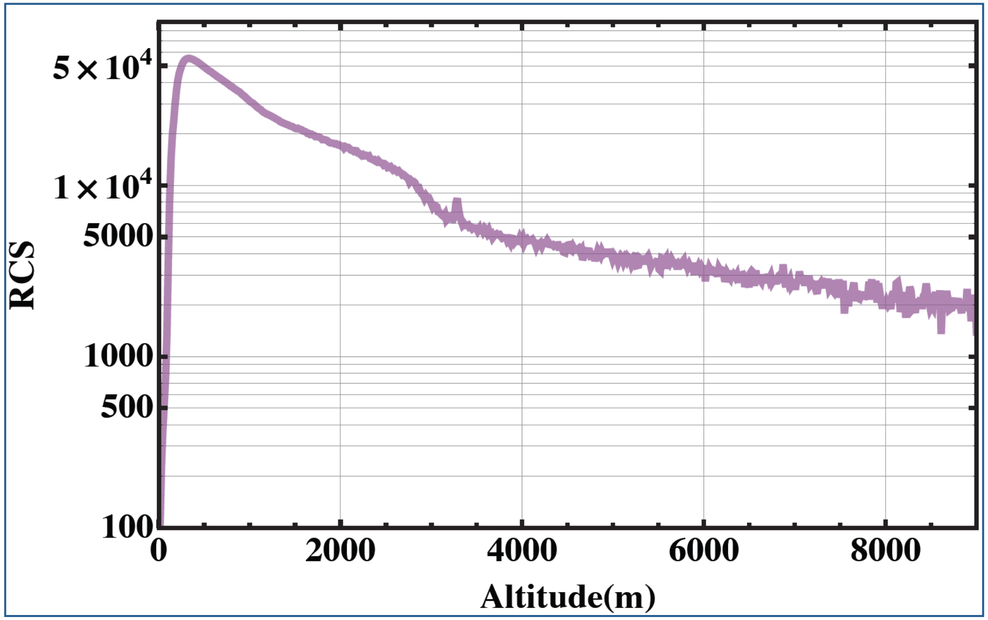
RANGE CORRECTED SIGNAL



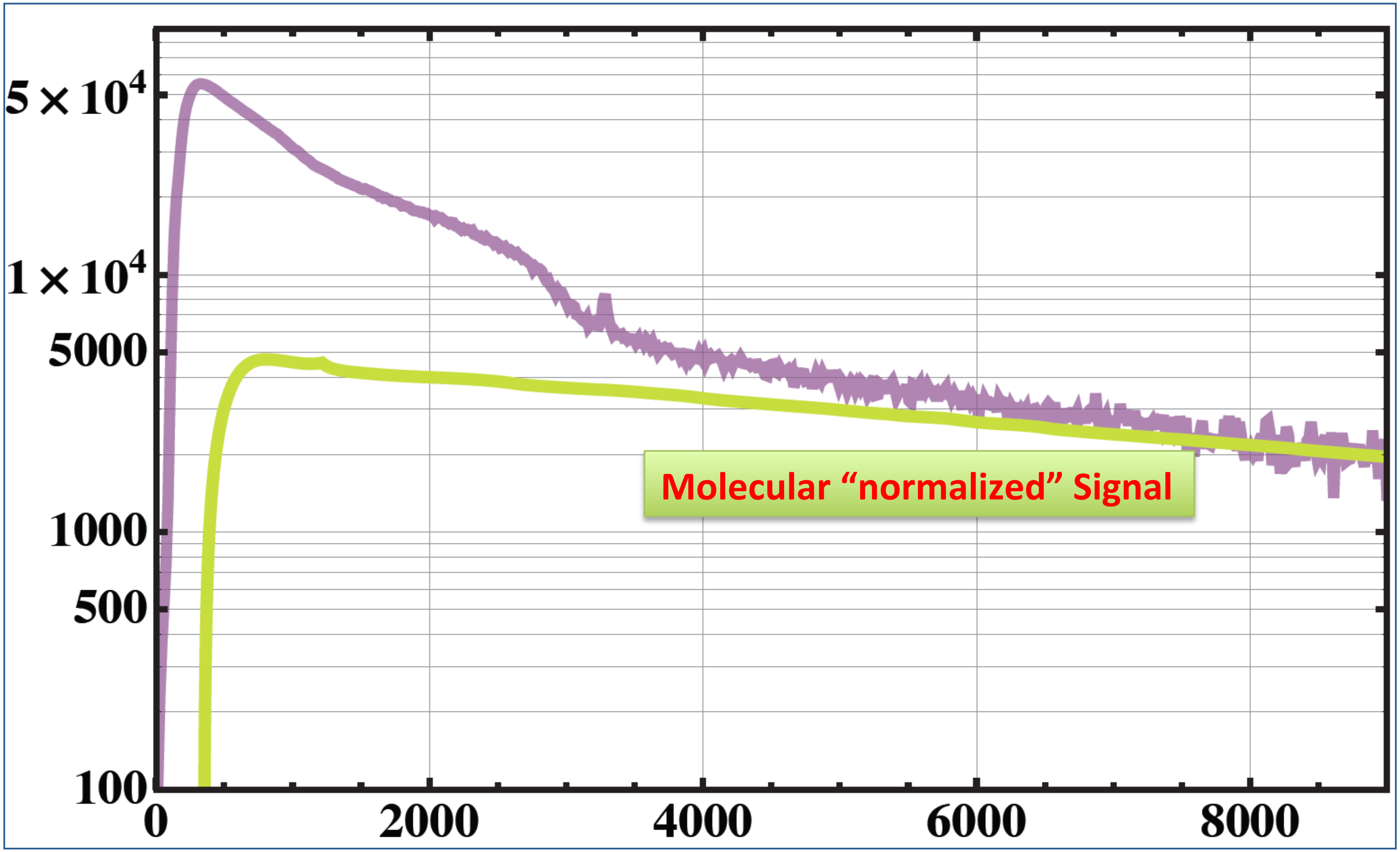
Aerosol Scattering Ratio

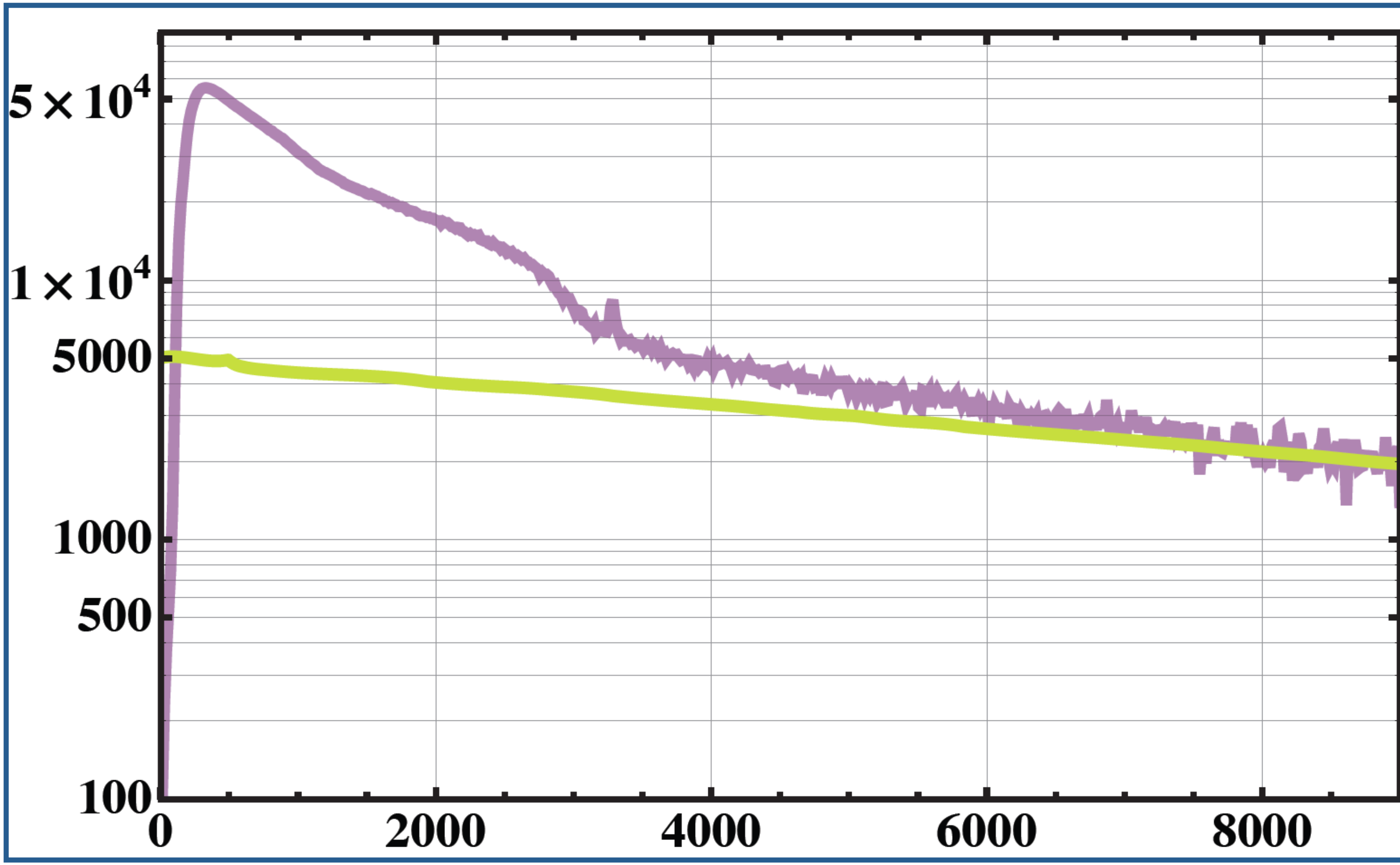
$$\mathcal{R}(\lambda_L, r) = \frac{\beta_\pi^{mol}(\lambda_L, r) + \beta_\pi^{aer}(\lambda_L, r)}{\beta_\pi^{mol}(\lambda_L, r)} = 1 + \frac{\beta_\pi^{aer}(\lambda_L, r)}{\beta_\pi^{mol}(\lambda_L, r)}$$


Summed Lidar Signal
10^4
1000
100
200
400
600
800
1000
Bin (#)

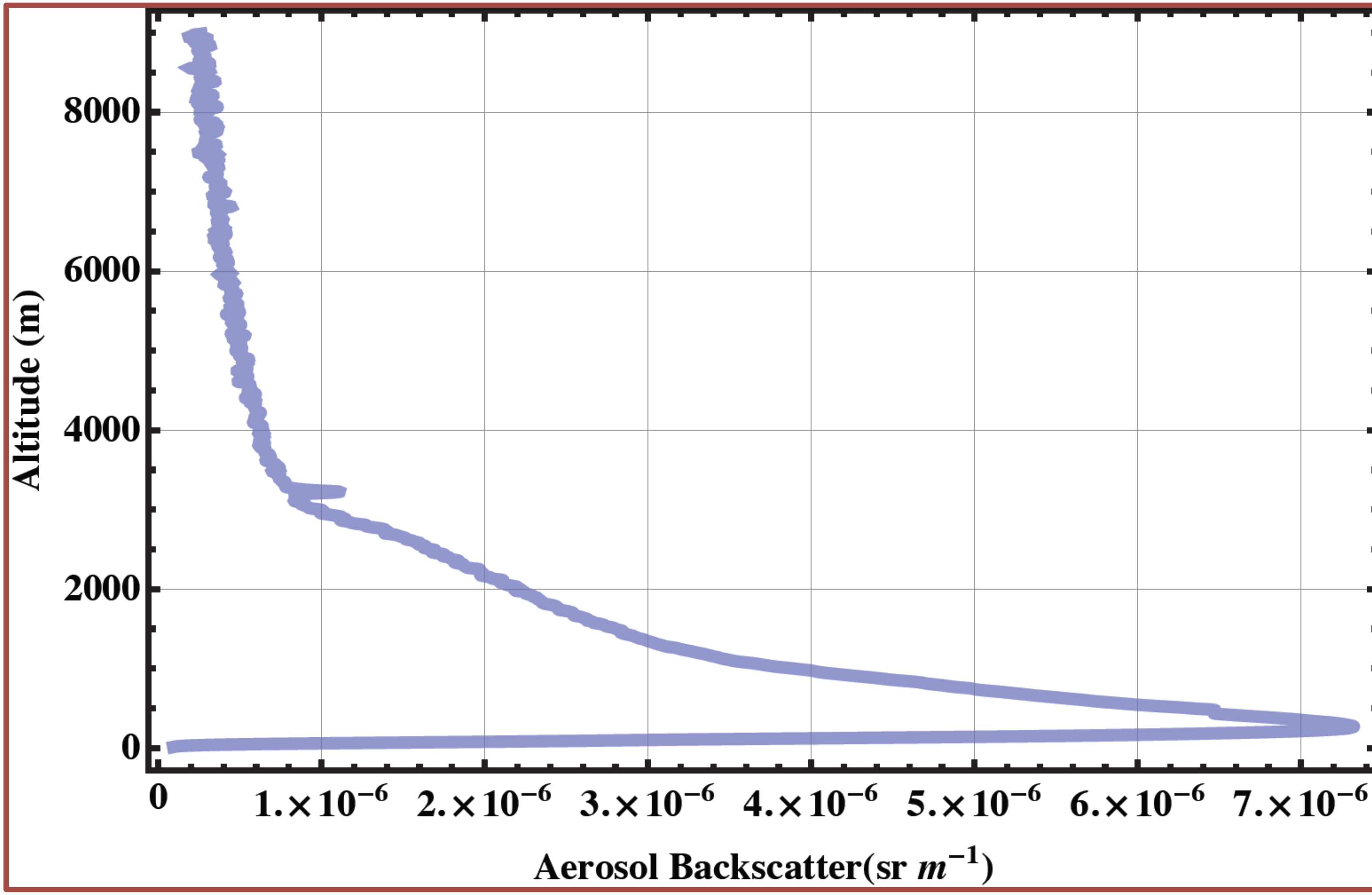

RCS
5×10^4
1×10^4
5000
1000
500
100
0
2000
4000
6000
8000
Altitude(m)

SEPARATING MOLECULES FROM PARTICLES





5 × 10^4
1 × 10^4
5000
1000
500
100
0
2000
4000
6000
8000


8000
6000
4000
2000
0
Altitude (m)
0
1.×10⁻⁶
2.×10⁻⁶
3.×10⁻⁶
4.×10⁻⁶
5.×10⁻⁶
6.×10⁻⁶
7.×10⁻⁶
Aerosol Backscatter(sr m^{-1})

AEROSOLS AS TRACERS – ATMOPHERIC DYNAMICS

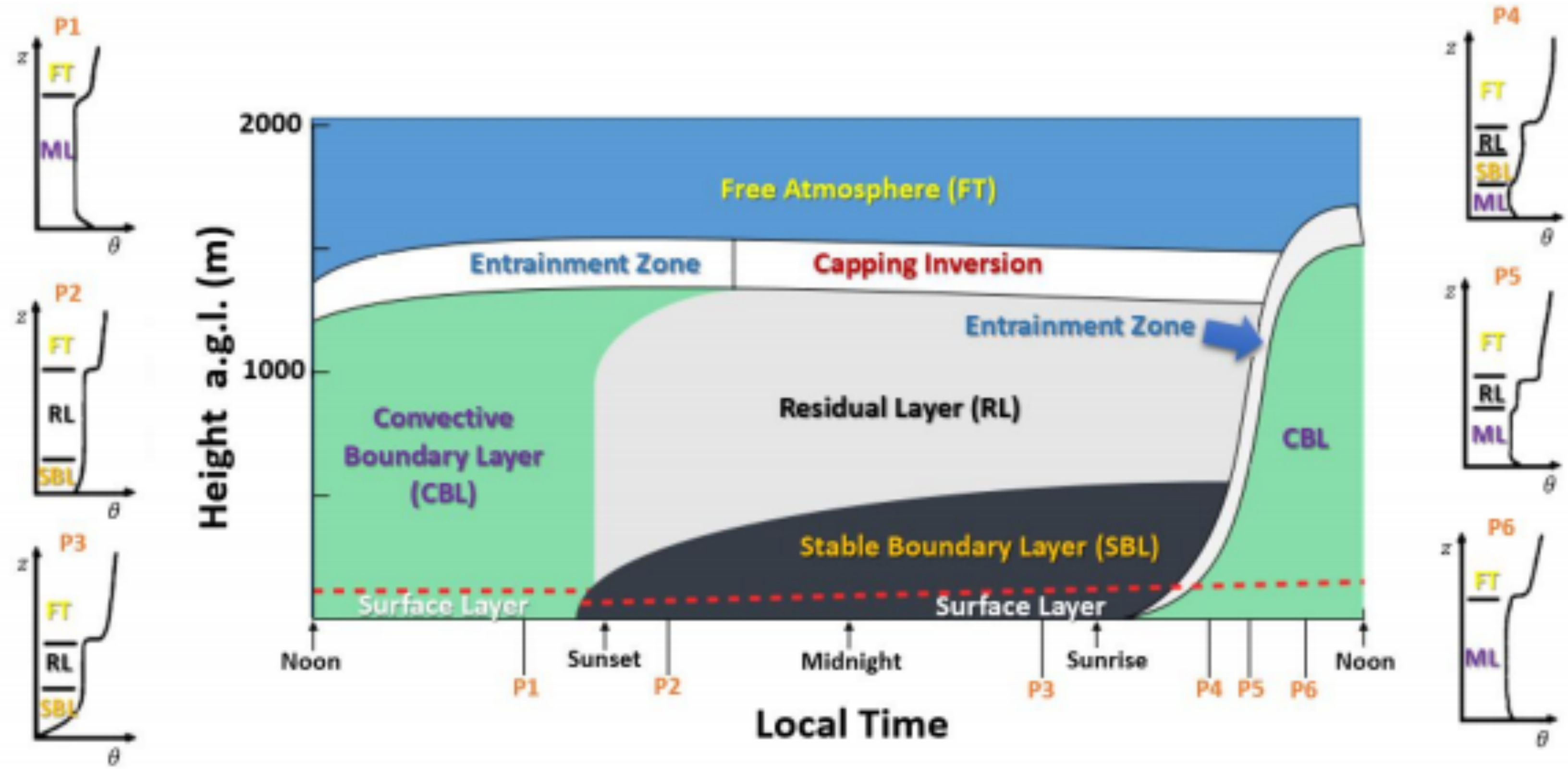


Figure 2.5: Idealized PBL daily cycle.
Source: Adapted from STULL, 1988.

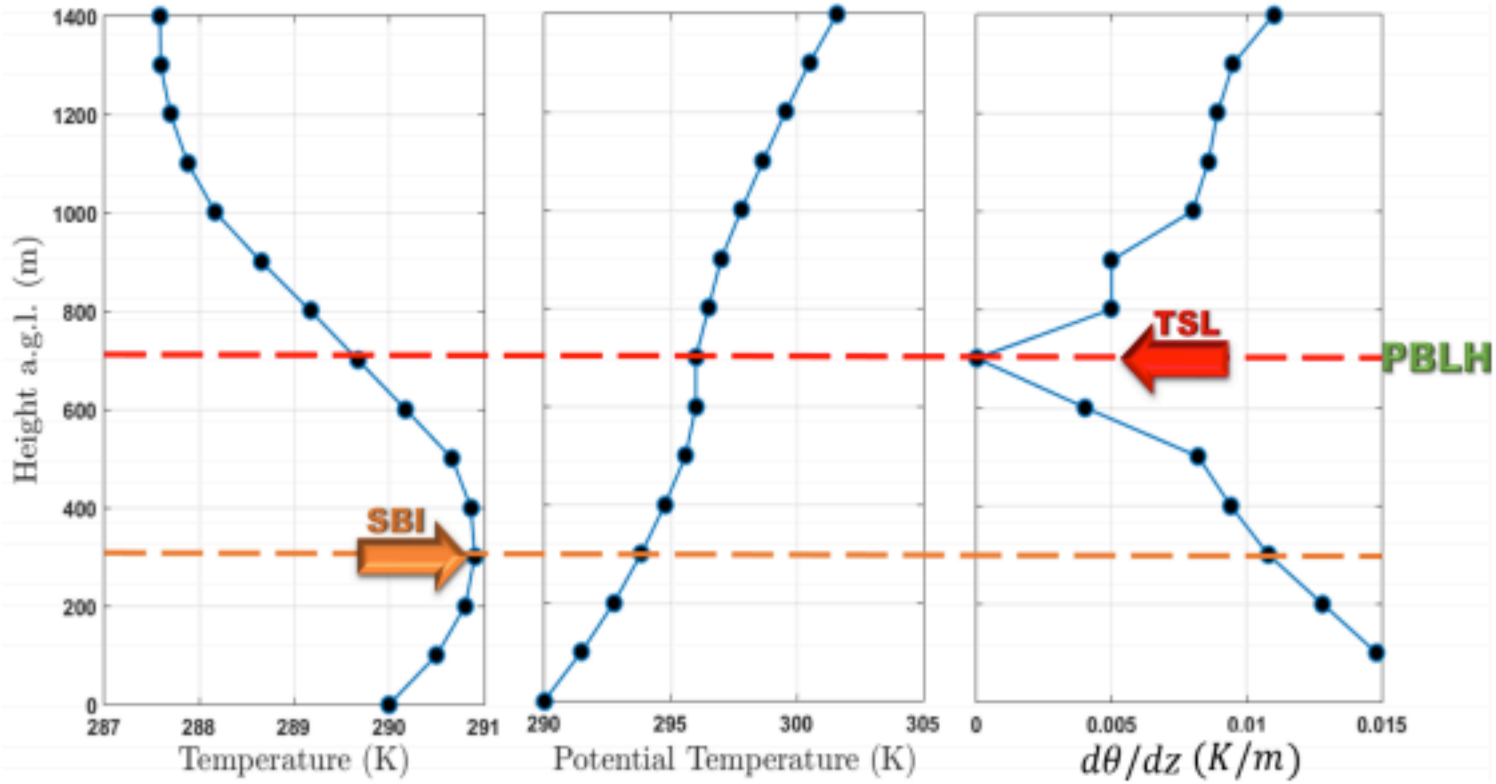
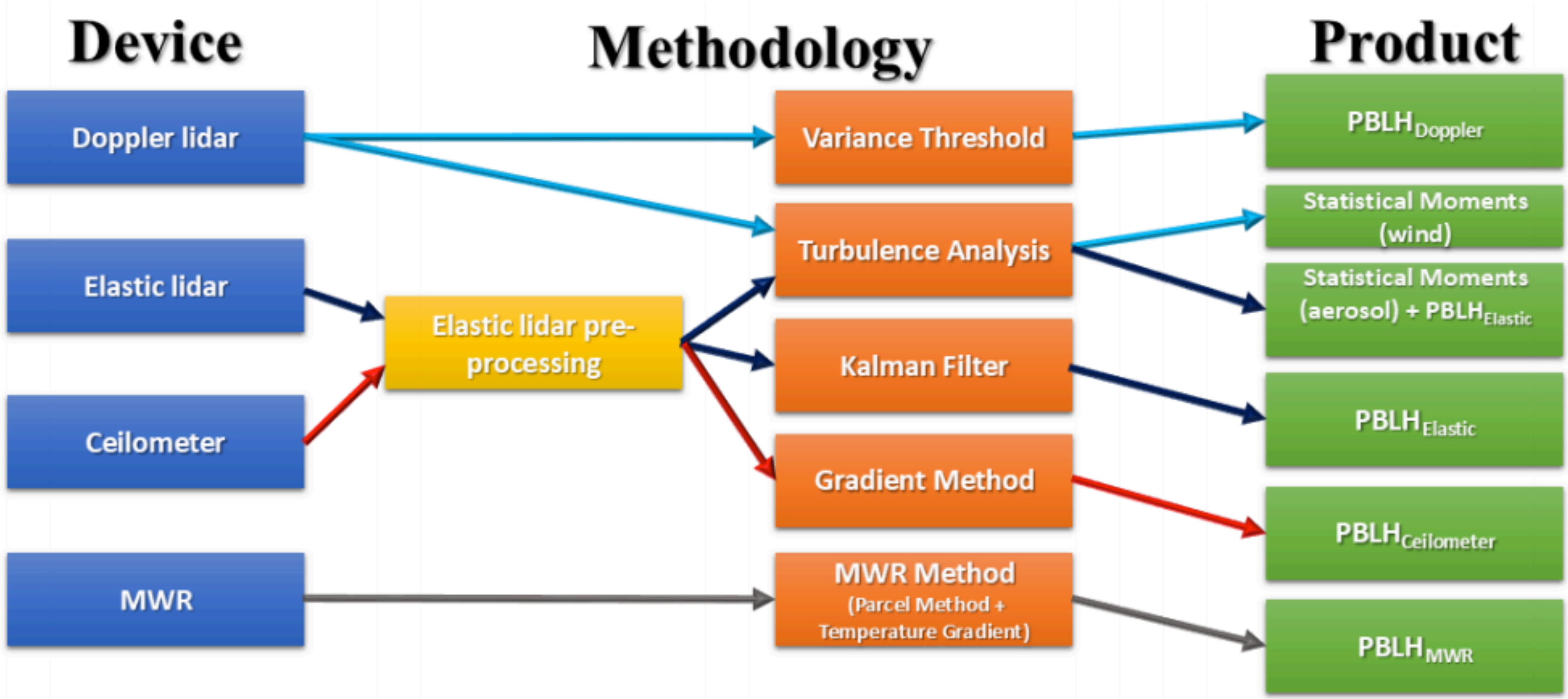


Figure 2.7: PBLH detected by Temperature Gradient Method from SBI and TSL height. Temperature (left), Potential Temperature (center) and Gradient of Potential Temperature (right). Source: Own author.


Device
Methodology
Product
Doppler lidar
Elastic lidar
Ceilometer
MWR
Elastic lidar pre-processing
Variance Threshold
Turbulence Analysis
Kalman Filter
Gradient Method
MWR Method
(Parcel Method + Temperature Gradient)
PBLH Doppler
Statistical Moments (wind)
Statistical Moments (aerosol) + PBLH Elastic
PBLH Elastic
PBLH Ceilometer
PBLH MWR

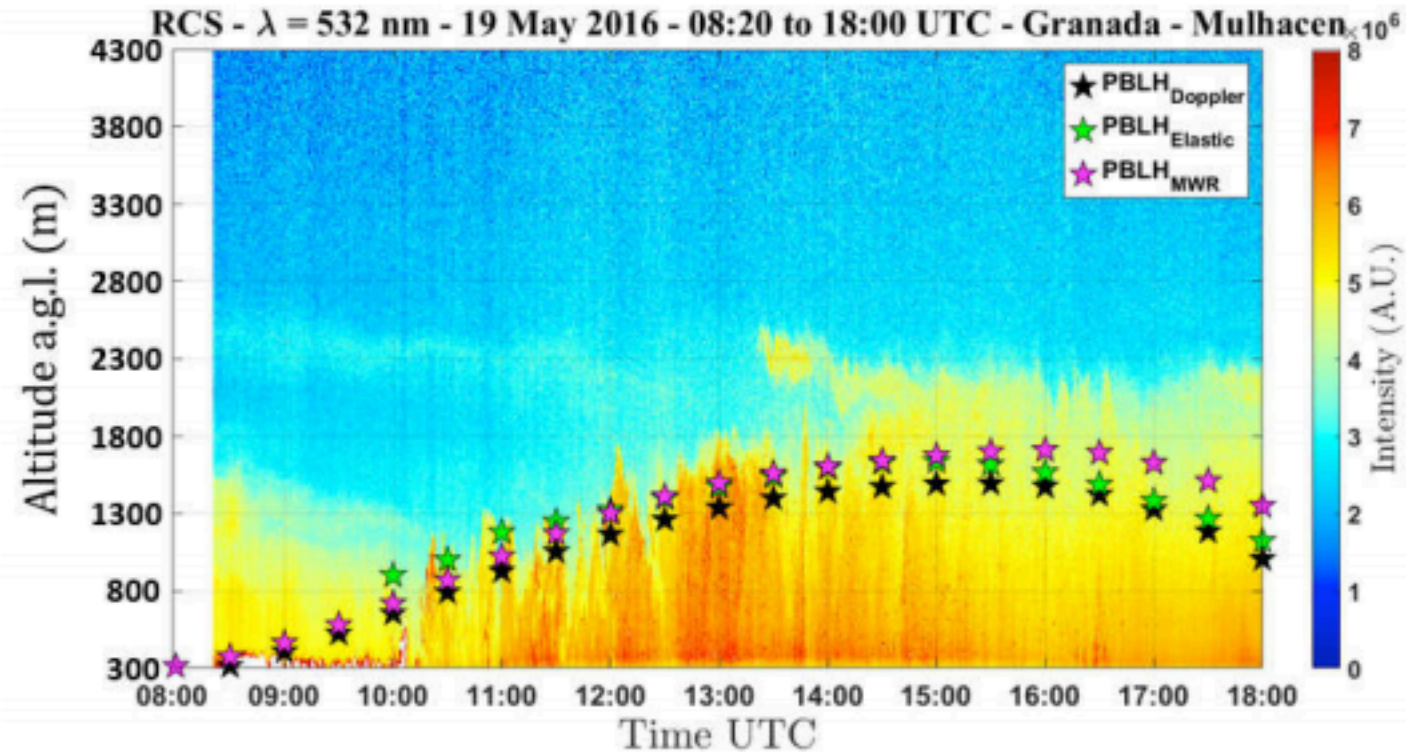
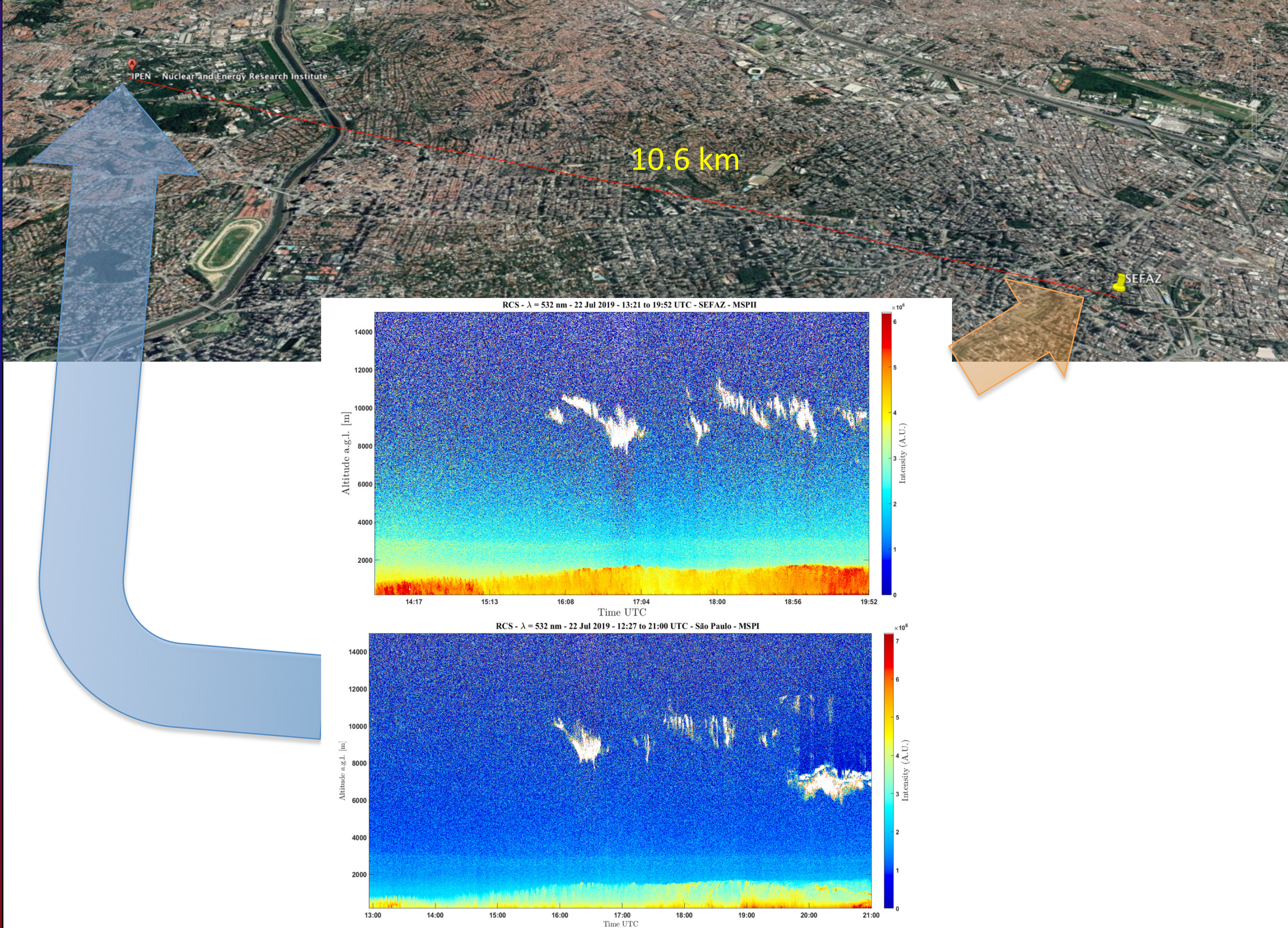


Figure 5.1 – Temporal evolution of RCS profile and PBLH provided by MWR (pink stars), elastic (green stars) and Doppler lidar (black stars)



SPSAS on Atmospheric Aerosols

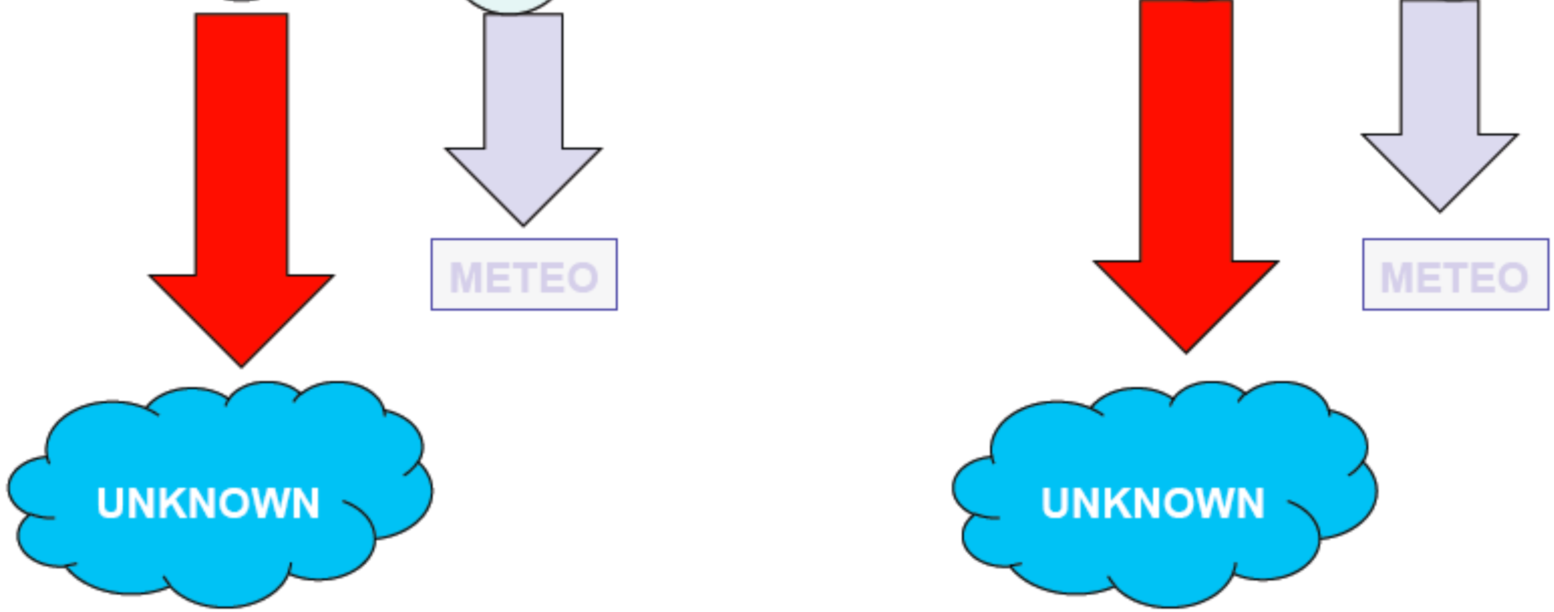
São Paulo, July 2019

AEROSOL STUDIES WITH LIDARS – SOLUTIONS

ATMOSPHERIC OPTICAL PARAMETERS

$$\beta(R) = \beta_{aer}(R) + \beta_{mol}(R)$$

$$\alpha(R) = \alpha_{aer}(R) + \alpha_{mol}(R)$$



AEROSOL STUDIES WITH LIDARS – SOLUTIONS

LIDAR RATIO

$$P(\lambda,R) = P_o \frac{A_o}{R^2} \beta_\pi(\lambda,R)\varepsilon(\lambda)\zeta(R).\left(\frac{c\tau_L}{2}\right) e^{-2\int_0^R \alpha(\lambda,r)dR}$$

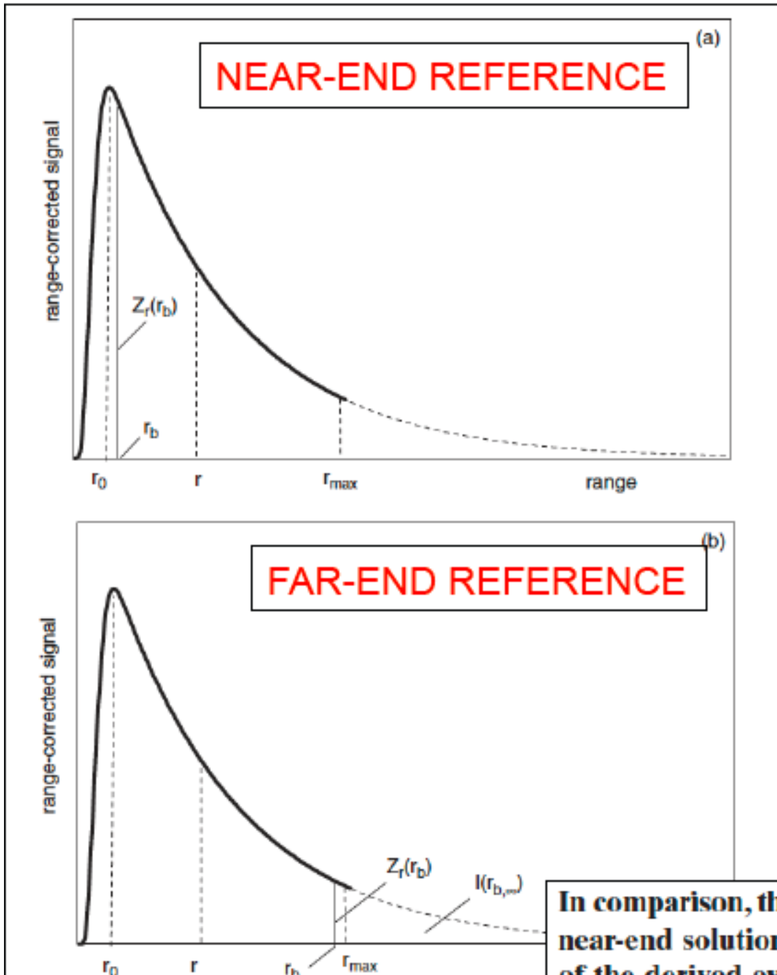
$$L_{aer}(R) = \frac{\alpha_{mol}(R)}{\beta_{mol}(R)} = \frac{8\pi}{3} sr$$

LIDAR RATIO (MOLECULAR)

$$L_{aer}(R) = \frac{\alpha_{aer}(R)}{\beta_{aer}(R)}$$

LIDAR RATIO (AEROSOL)

AEROSOL STUDIES WITH LIDARS – SOLUTIONS



In comparison, the far-end boundary point solution is much more stable than the near-end solution, at least, in turbid atmospheres. It yields only positive values of the derived extinction coefficient, κ_t, even if the signal-to-noise ratio is poor. However in clear atmospheres, it has no significant advantages as compared to the near-end solution.

KOVALEV & EICHINGER

AEROSOL STUDIES WITH LIDARS - LIDAR EQUATION SOLUTIONS

$$\frac{d\chi(R)}{dR} = \frac{1}{\chi(R)}\frac{d\chi(R)}{dR} - 2\chi(R)$$

BERNOUILLI EQUATION

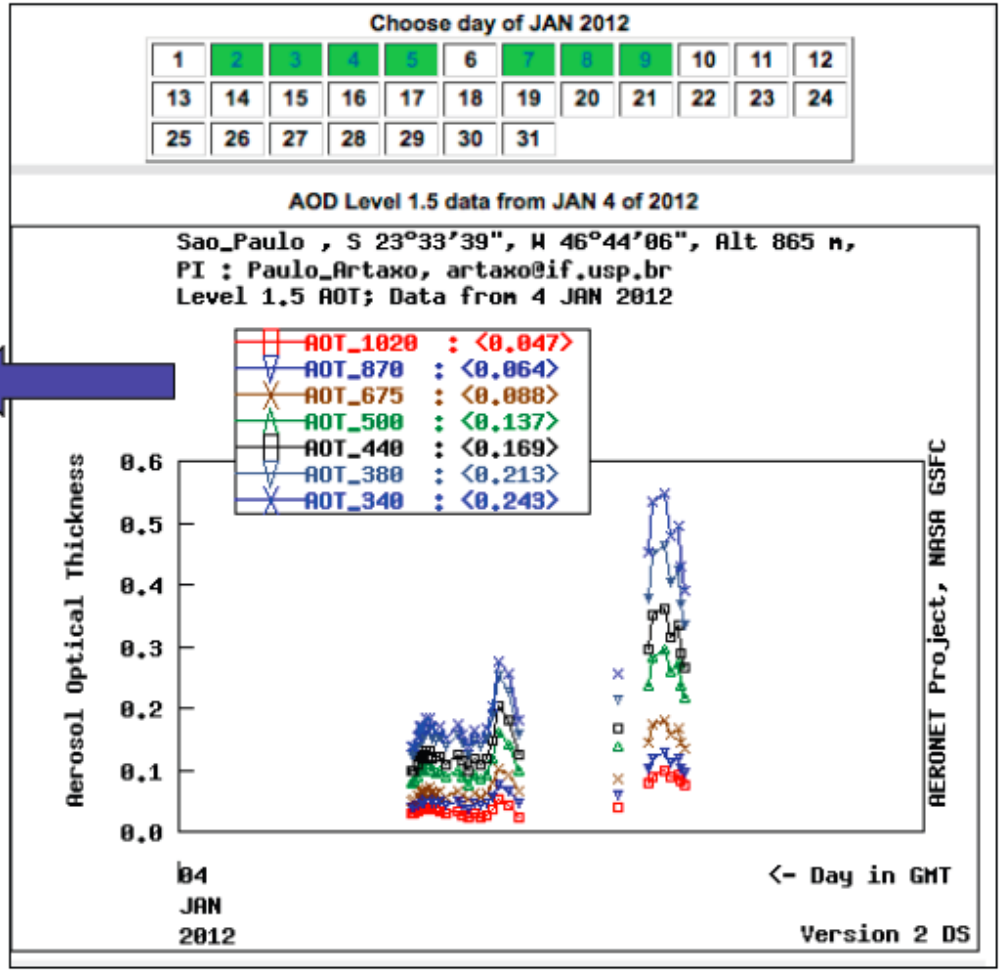
$$\chi(R) = L_{aer}\left[\beta_{aer}(R) + \beta_{mol}(R)\right]$$

1. KOVALEV & EICHINGER
2. WEITKAMP
3. MEASURES

Backscatter Lidar + Passive

AEROSOL STUDIES WITH LIDARS – AERONET CLOSURE

AOT(λ)



AEROSOL STUDIES WITH LIDARS – AERONET CLOSURE

$$AOT_{aeronet}(\lambda) \equiv \tau(\lambda, z) = \int_o^\infty \alpha(\lambda, z)dz$$

$$AOT_{aeronet} \equiv AOT_{lidar}(\lambda) = \int_o^\infty \alpha_{aer}(\lambda, z)dz$$

$$AOT_{lidar}(\lambda) = L_{aer} \times \sum \beta_{aer}(\lambda, z)\Delta z$$

Multiwavelength Lidar

- Joint use of α and β - key for successful retrieval.
- Minimum number of input data – 5.
- The most practical configuration of Raman lidar is based on tripled Nd:YAG laser:

  Three elastic channels and two nitrogen Raman (3+2)

  Backscattering β – 355, 532, 1064 nm

  Extinction α – 355, 532 nm

Retrieval of particle parameters

Lidar signals → Calculation of α and β → Particle parameters

Lidar Equation

$$P(z):\ \frac{1}{z^2}\beta(z)\exp[-2\int_0^z \alpha(z')dz']$$

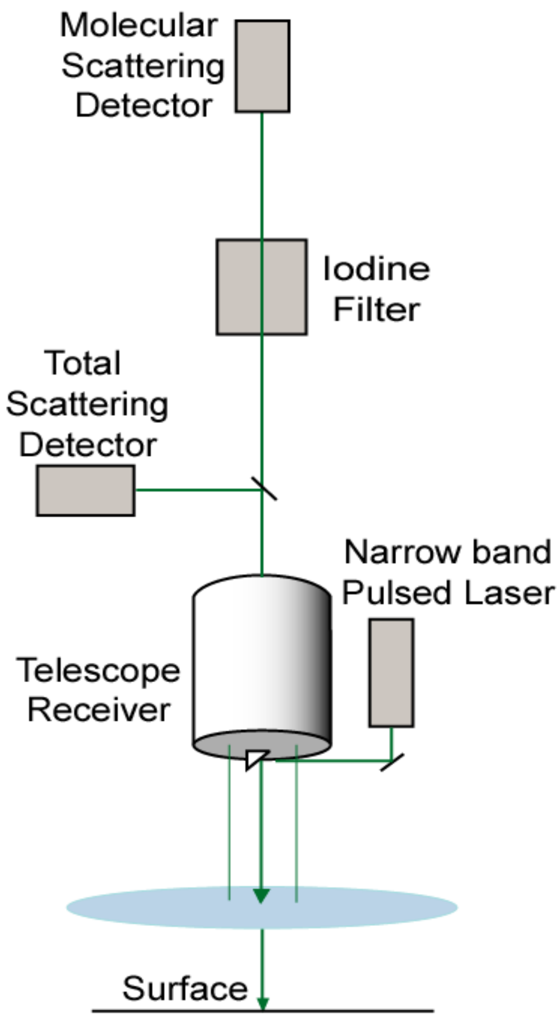
Single-wavelength equation contains two unknowns: particle extinction (α) and backscattering (β).

We need molecular scattering!

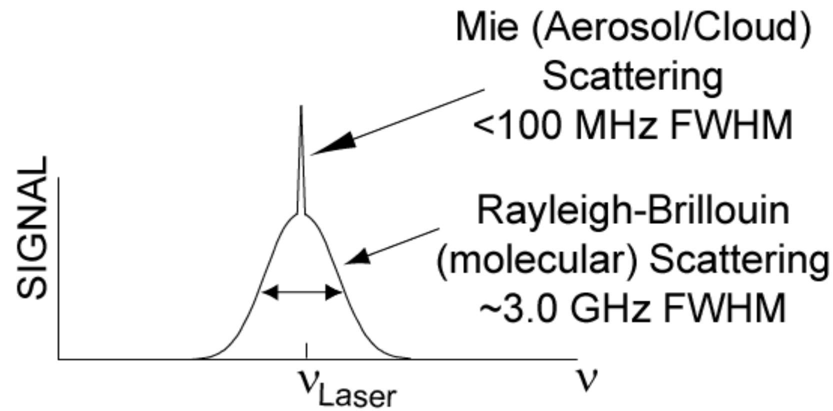
Raman lidar (or HSRL) can provide an additional equation.

$$P_R(z):\ \frac{1}{z^2}N_R(z)\exp[-\int_0^z (\alpha_\lambda(z') + \alpha_{\lambda_R}(z'))dz']$$

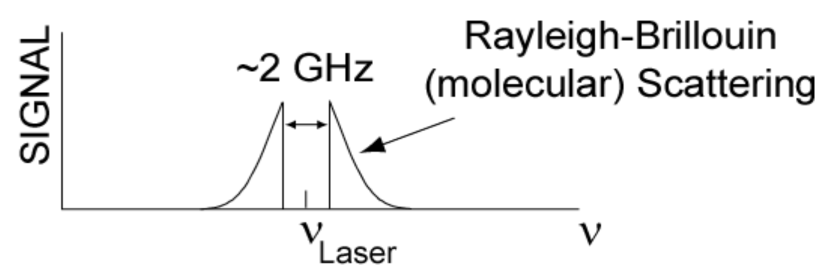
High Spectral Resolution Lidar (HSRL) Technique Iodine Vapor Filter Implementation)

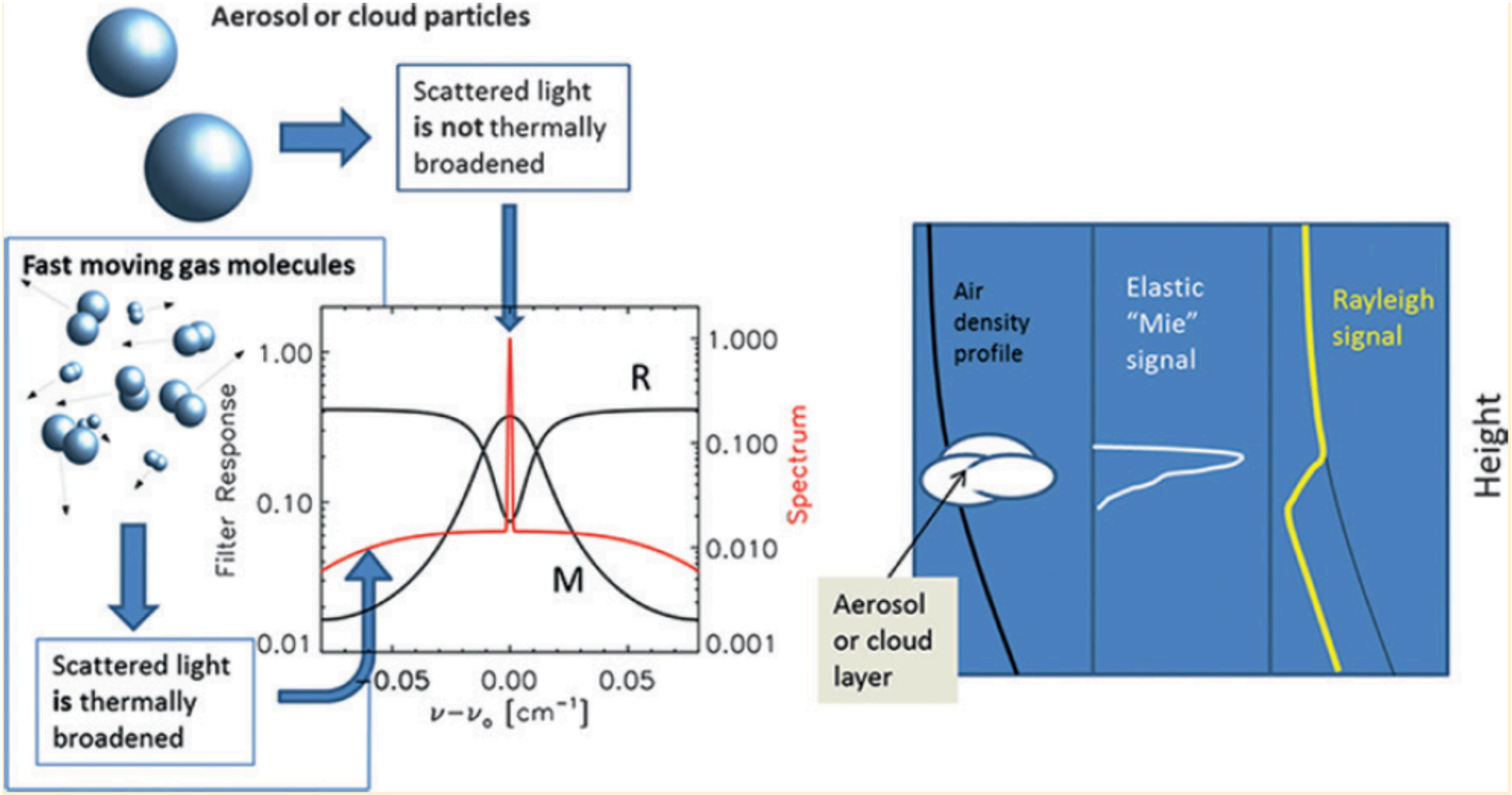


Atmospheric Scattering



Effect of Iodine Vapor Notch Filter





DOI: 10.1175/BAMS-D-12-00227.1

Retrieval of particle parameters

Requirements for retrieval algorithm

- Small number of data
- Unknown complex refractive index
- Unknown particle size distribution

We assume:

- Refractive index is size and wavelength independent;
- Particles parameters are constrained as

  $0.05\mu m < R_{min}$; $R_{max} < 20\ \mu m$;

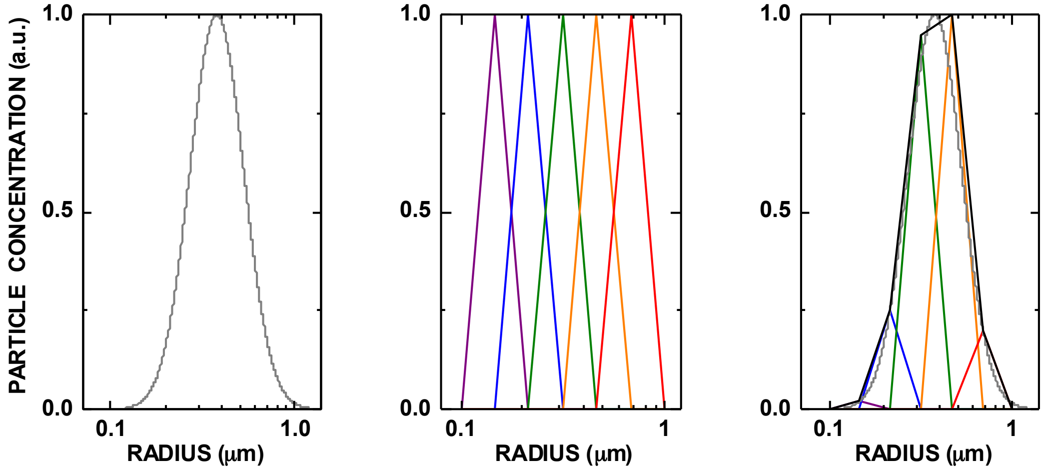
  $1.33 < m_R < 1.65$; $0 < m_I < 0.03$

Constrained inversion

Optical data (α or β) are related with PSD f(r) integral equation :

$$g_i = \int_0^\infty K_i\,(m, r, \lambda)\, f(r)\, dr$$

PSD *f(r)* is approximated by superposition of base functions B_j:



Constrained inversion

Integral equations are transformed to the system of linear equations

$$g_i = \sum_{j=1}^{N} A_{ij} C_j .$$

Here C_j – coefficients of decomposition,

Aij – integrals of base functions and kernels

Imposing constrain on solution smoothness obtain

Twomey – Tikhonov expression

$$C = (A^T A + \gamma H)^{-1} A^T g$$

γ- regularization parameter determined from input data

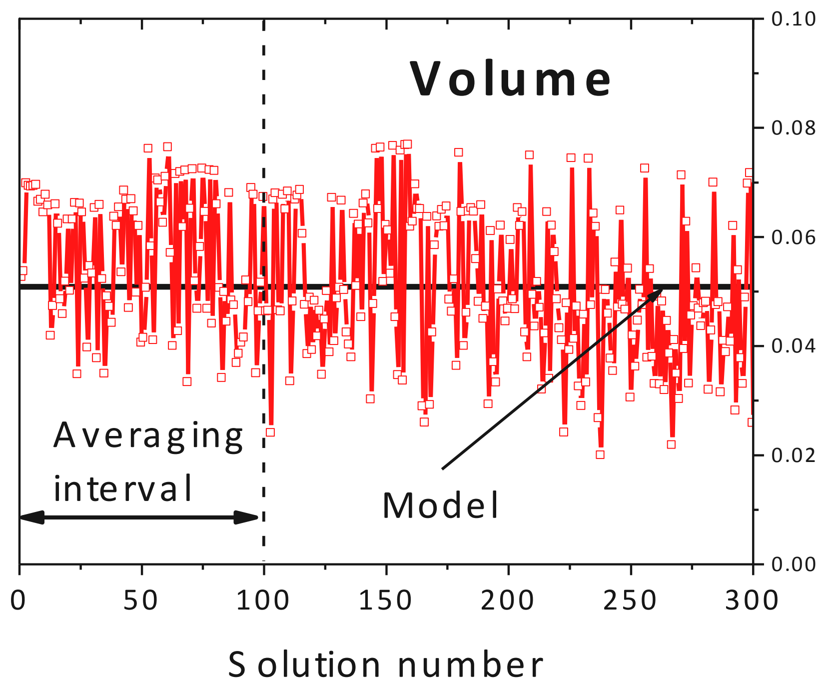
H – smoothing matrix

For every set Rmin, Rmax, m_R, m_I - the problem is well-determined: number of optical data = number of equations

Rmin, Rmax, m_R, m_I are varied and several thousands of solutions are found

Every solution is characterized by discrepancy (difference between experimental data and data calculated from solution)

Solutions are ranged and averaged



Particles parameters are retrieved from synthetic optical data; ~1% of solutions are averaged.

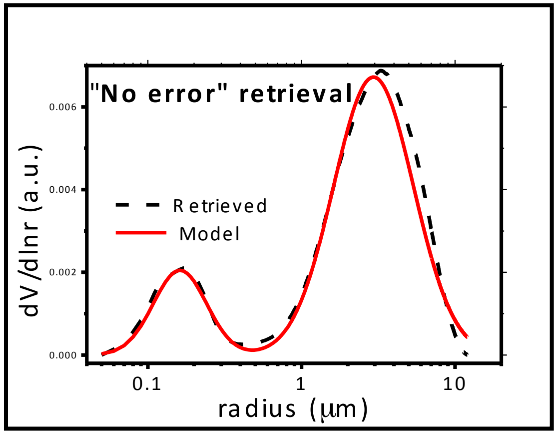
Numerical simulation

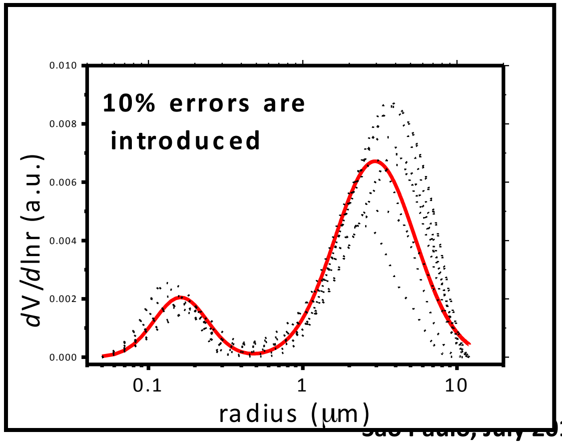
Model PSD → Synthetic input data → Introducing errors → Retrieval parameters

- Synthetic input optical data were calculated from bimodal PSDs;
- Errors in [0, ε] range were introduced in input data in a random way;

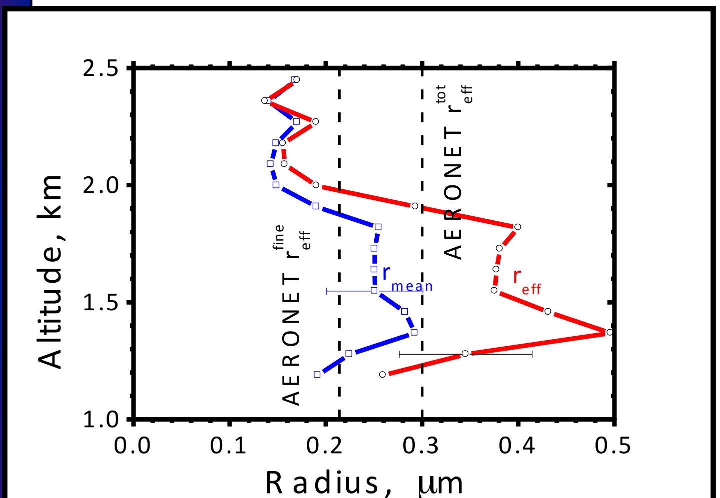
Uncertainty of particle parameters retrieval for 10% input errors:

- Effective radius, volume, surface density - ~30% accuracy
- Real part of refractive index - ±0.05
- Imaginary part of refractive index – 50% for mI>0.005





Comparison of AERONET and lidar data



Parameter		AERONET	Lidar
AOT	355	0.38	0.41±0.08
	532	0.27	0.31±0.06
V^{tot} ($\mu m^3/\mu m^2$)		0.073	(0.076±0.015)
V^{fine} ($\mu m^3/\mu m^2$)		0.05	(0.057±0.012)
r^{tot}_{eff} (μm)		0.3	0.33±0.07
r^{fine}_{eff} (μm)		0.214	0.25±0.05
m_R		1.37	1.34±0.05
m_I		0.006	0.009±0.0045

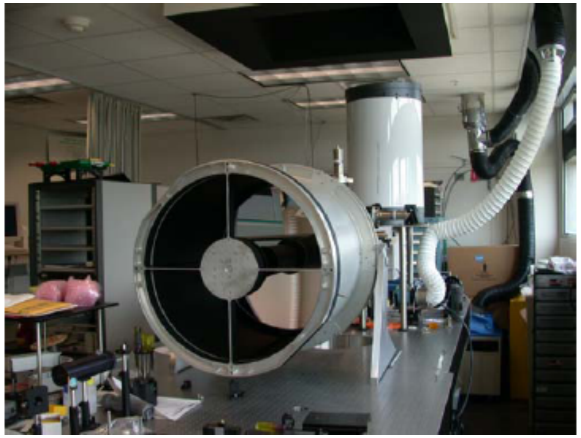
- Time lag between lidar and AERONET measurements is about 2 hours
- We have to extrapolate profiles below 1 km

DISCOVER-AQ 2011 CAMPAIGN

The P-3B aircraft carried a suite of nine scientific instruments including NASA LARC HSRL system.

14 flights occurred during June 27 - July 31 period over Baltimore – Washington area.

GSFC multiwavelength Raman lidar performed the measurements from the ground



Lidar parameters:

Telescope aperture   400 mm

Laser power   at   355 nm – 20 W

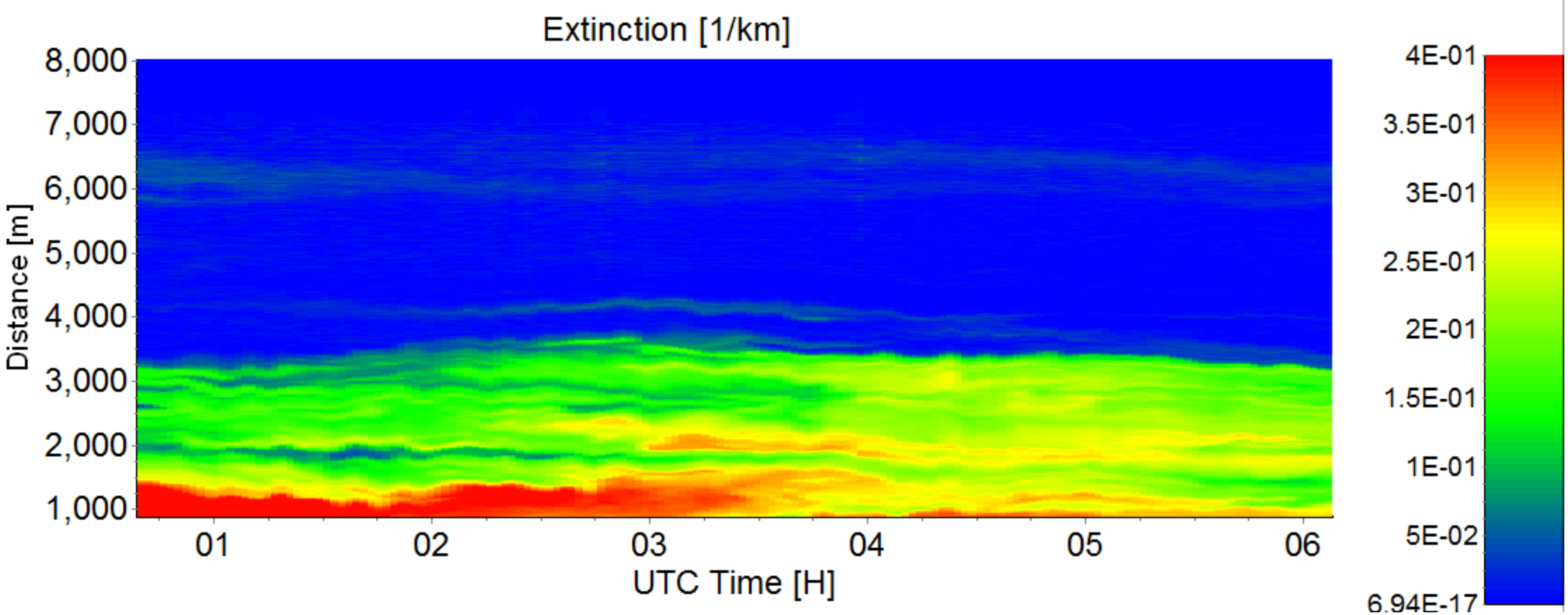
Operational wavelengths:

elastic – 355, 532, 1064 nm

Raman – 387, 608, 408 nm

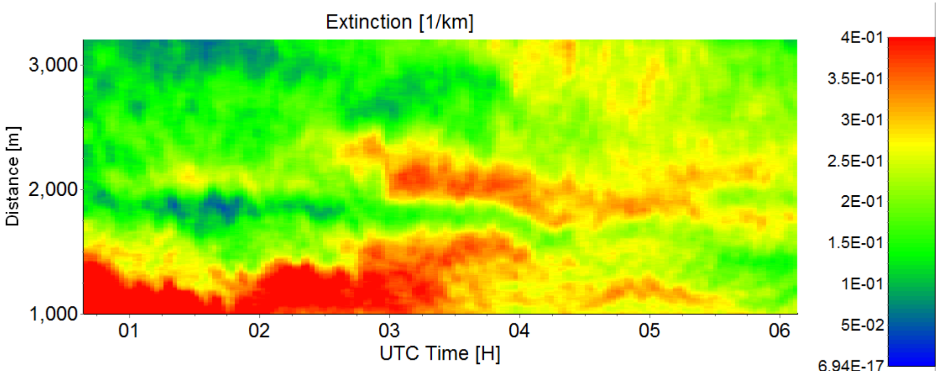
- **Temporal resolution of the measurements – 2 min.**
- **Measurements are vertical, height resolution 15 m.**
- **Sonde data are from Beltsville (~5 miles apart)**

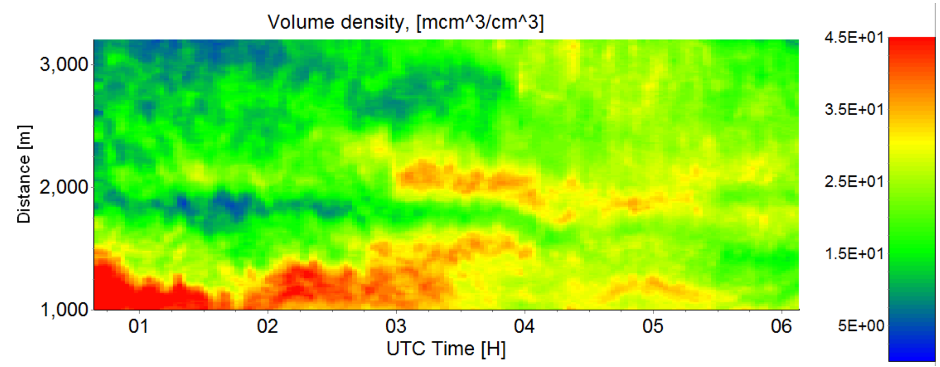
20 – 21 July measurements

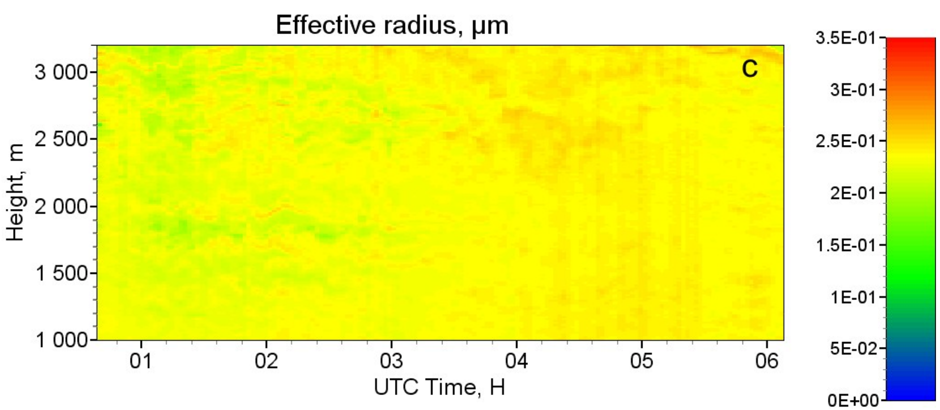


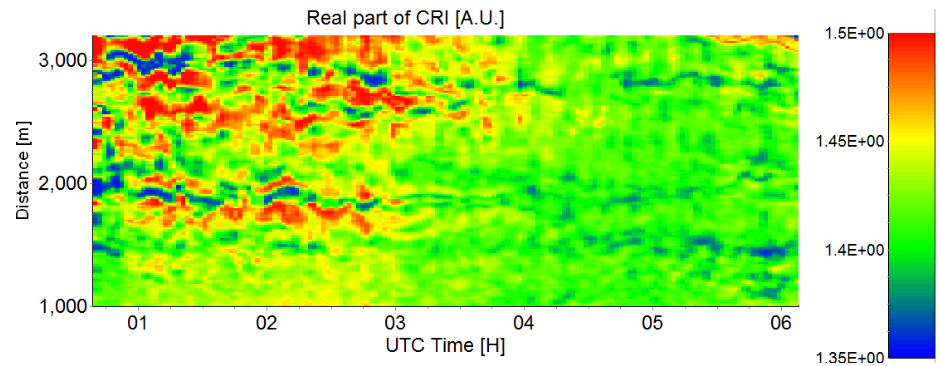
Aerosol is represented mainly by sulfates and biomass burning products. RH is insufficient for significant hygroscopic growth.

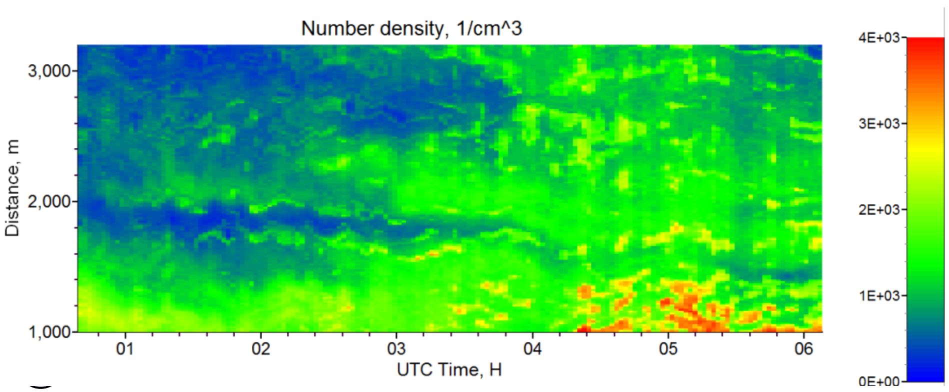
Retrieval of height – temporal distributions of particle parameters

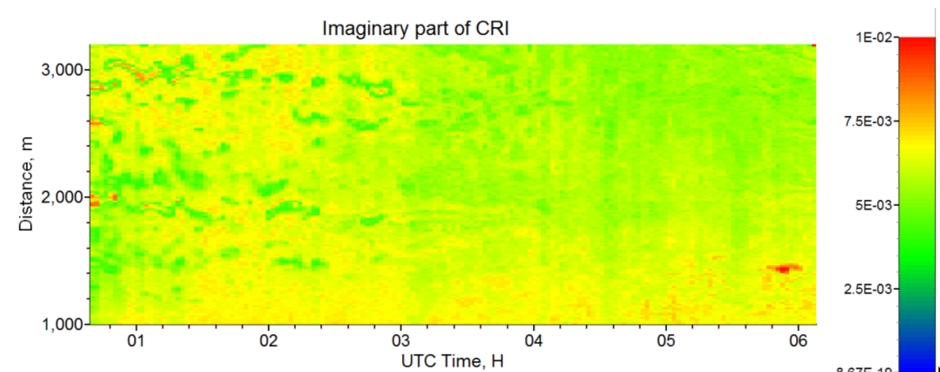






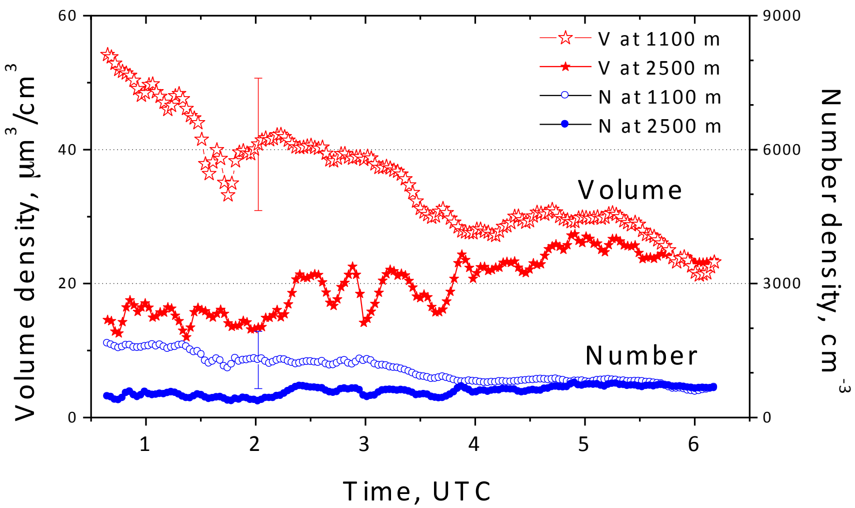


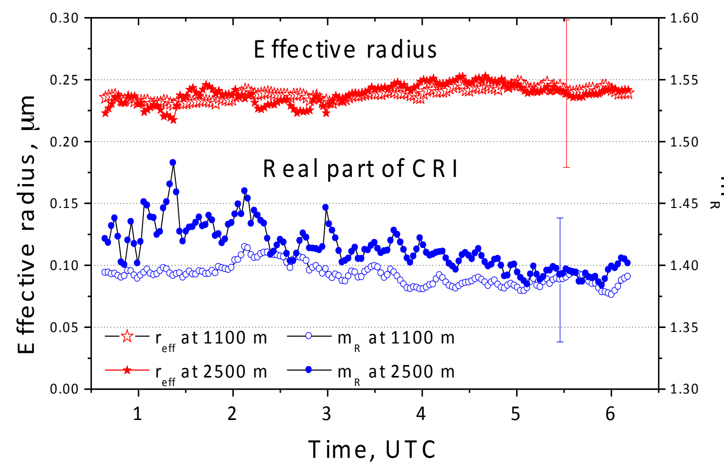




Time-series of particle parameters

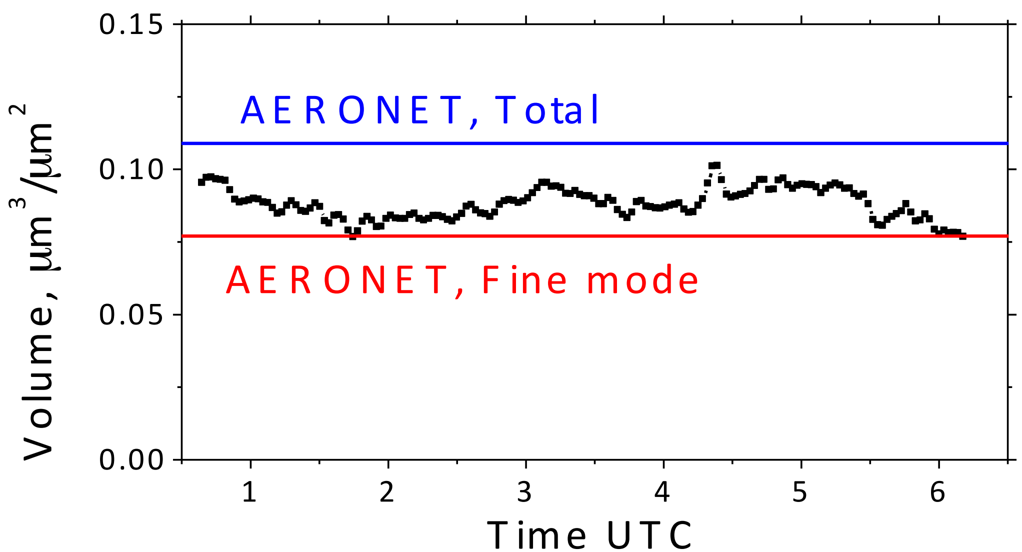
Particle density, effective radius and real part of CRI are shown for 1100 and 2500 m layers





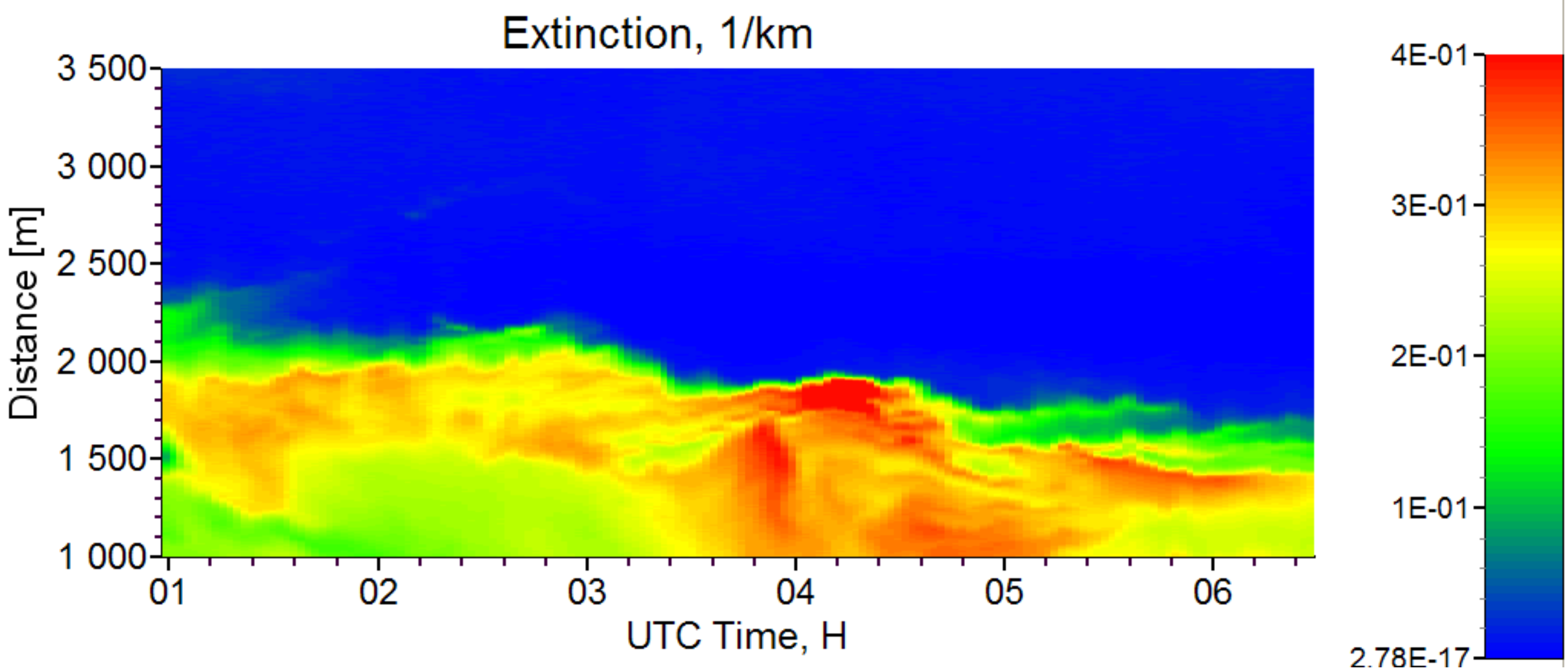
Volume and number density present strong variations while effective radius is quite stable

Lidar derived column volume

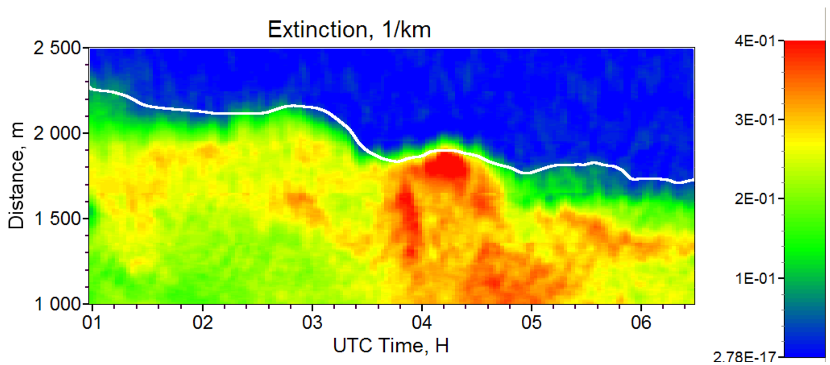


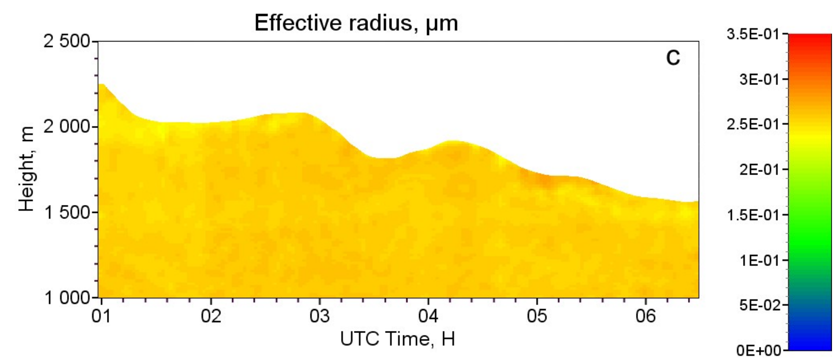
Volume profiles are extrapolated as constant below 1000 m.
For comparison AERONET results at 23:00 UTC are shown.

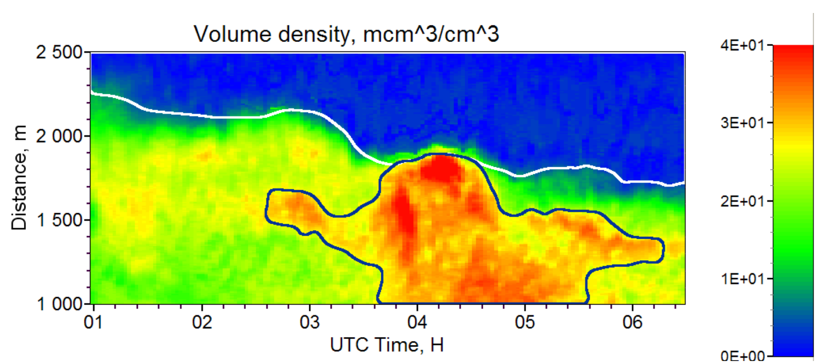
21 – 22 July measurements

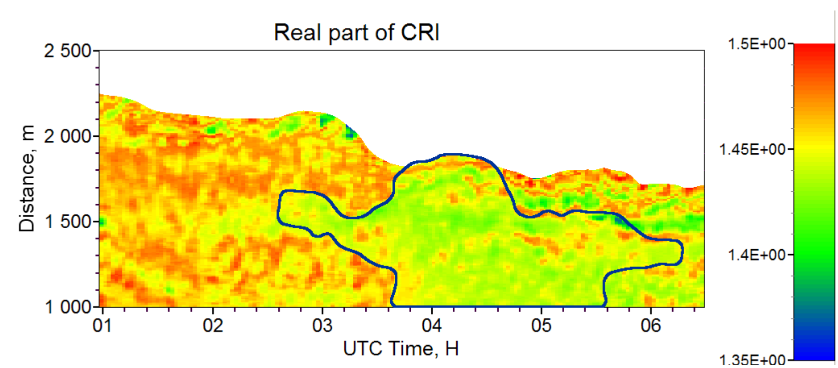


Height temporal distributions of particle parameters

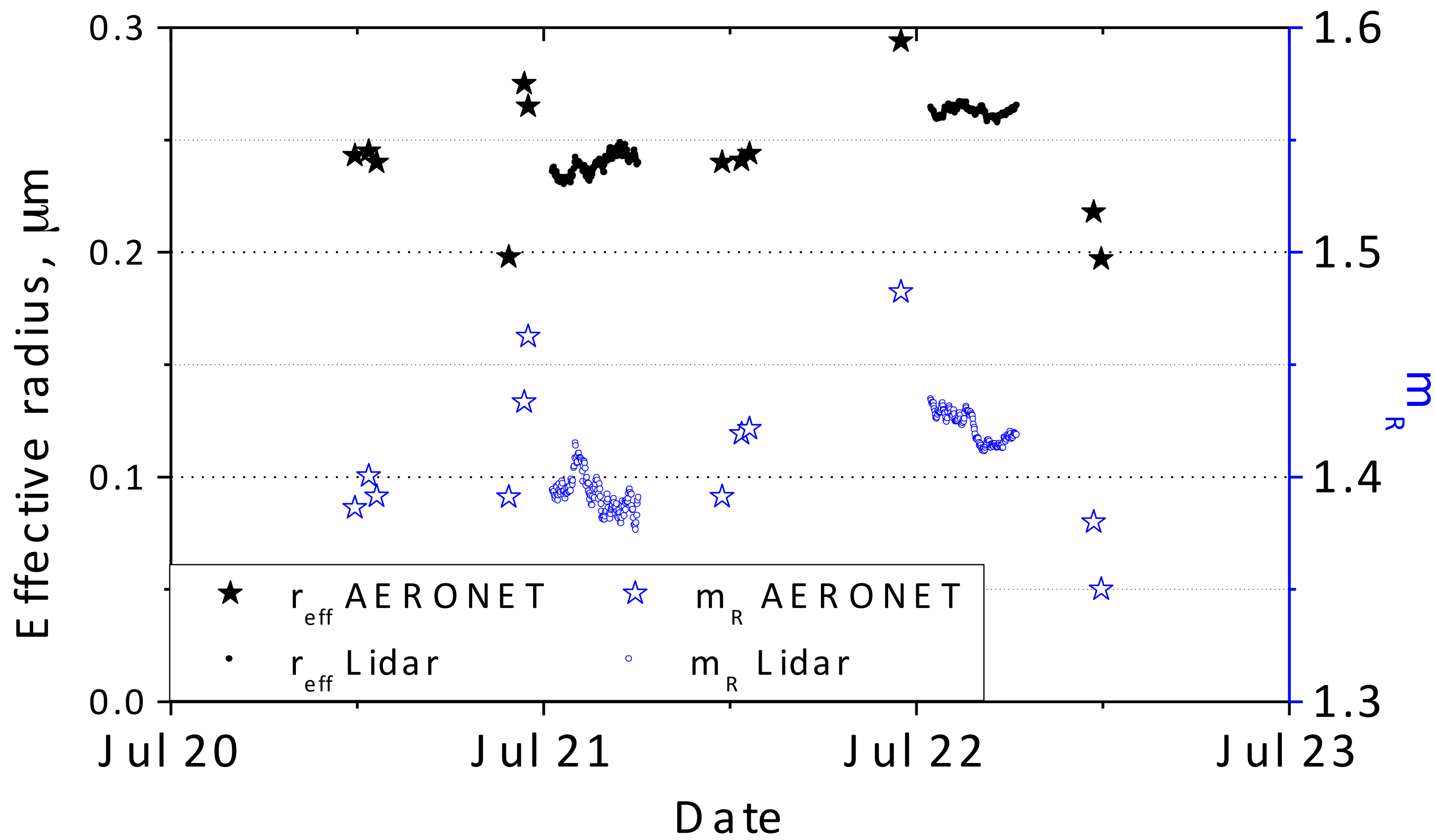








Comparison with AERONET



How many wavelengths do we need?

1λ + AERONET	**Particle concentration**
2λ + AERONET	**Profiles of effective radius and concentration (LIRIC)**
3λ	**For known refractive index – particle radii and concentration**
3+1	**For many cases – radii, concentration, RI**
3+2	**Particle size distribution, RI**
3+2+1δ	**Treatment of dust mixtures**
3+2+3δ	**Aerosol classification**

NETWORKS

Global Atmosphere Watch

GAW

GALION: The GAW Aerosol Lidar Observation Network.

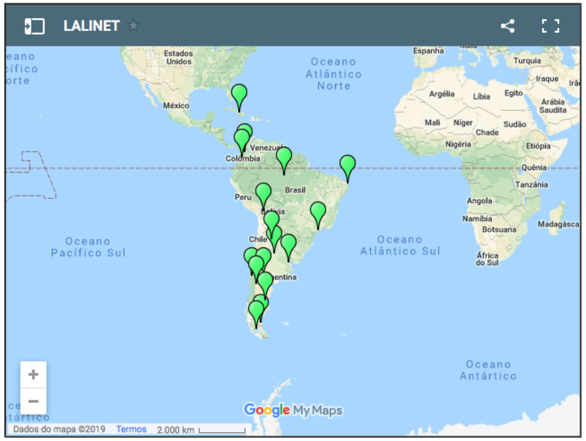
AD-Net | CREST | EARLINET | CORALNET | MPLNET | LALINET

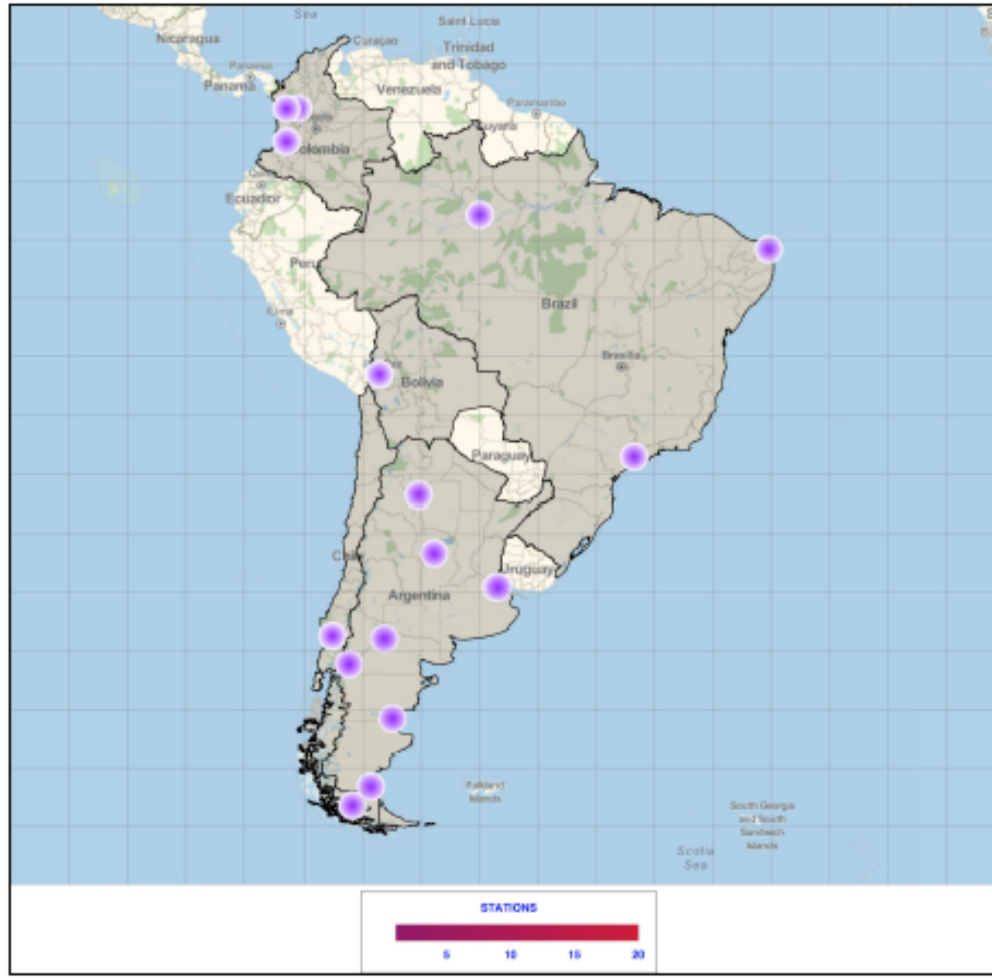
- **Consolidate the measurement and data acquisition protocols**

- **Establish a QA/QC routine among all stations**

- **Improve and establish an unified data analysis routine common to all stations, e.g., Single Calculus Chain**

- **Create a scientifically signficant distributed database,e.g., lidar ratio, particle extinction, backscatter, angstrom exponents and particle depol. regional values that can be assimilated to air quality & forecast models and validation missions.**


LALINET
Estados Unidos
México
Oceano Atlântico Norte
Espanha
Turquia
Argélia
Líbia
Egito
Iraque
Arábia Saudita
Mali
Níger
Chade
Sudão
Nigéria
Etiópia
Quênia
Tanzânia
Angola
Namíbia
Botsuana
Madagáscar
África do Sul
Colombia
Brasil
Peru
Chile
Oceano Pacífico Sul
Oceano Atlântico Sul
Oceano Antártico
Google My Maps
Dados do mapa ©2019
Termos
2.000 km

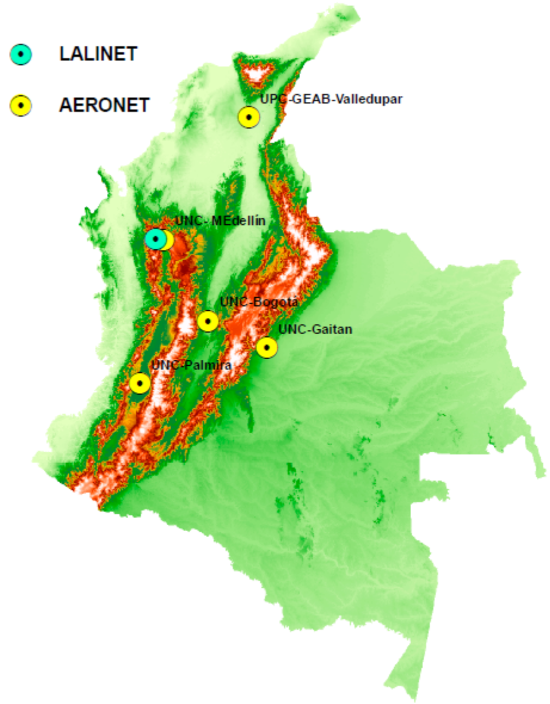

Nicaragua
Saint Lucia
Trinidad and Tobago
Panama
Venezuela
Colombia
Ecuador
Peru
Brazil
Brasília
Bolivia
Paraguay
Uruguay
Argentina
Falkland Islands
South Georgia and South Sandwich Islands
STATIONS
5
10
15
20

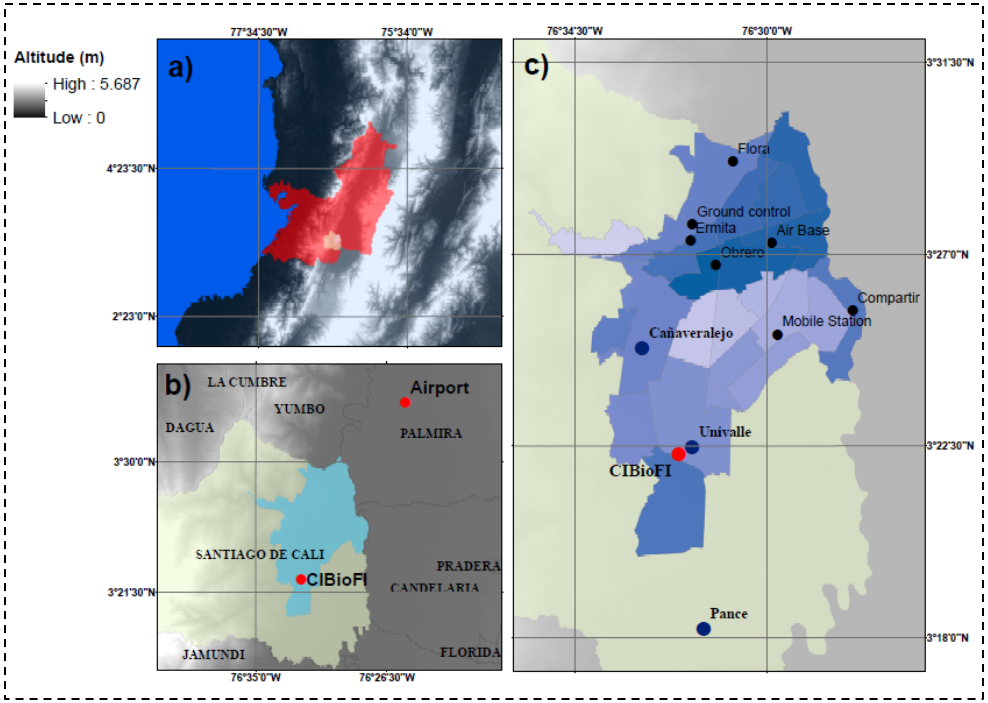
ST.	ID	LAT LON ALT(m)	Detected Channels (nm)
Buenos Aires	*VMA*	-34.56^o -58.51^o *10*	*1064, 532^p & 355^p*
Buenos Aires	*SMN*	-34.56^o -58.42^o *10*	*1064, 607, 532^p, 387 & 355^p*
Neuquen	*NQN*	-38.95^o -68.14^o, *266*	*1064, 532^p, 266& 355^p*
Bari- loche	*BRC*	-41.15^o 71.16^o *837*	*1064, 607, 532, 387 & 355*
Com- modoro	*CDR*	-45.79^o -67.46^o *48*	*1064, 532 & 355*
Rio Gallegos	*RGL*	-51.60^o -69.32^o *20*	*355, 308 & 355*
Rio Gallegos II	*SRG*	-51.61^o -69.31^o *17*	*1064, 607, 532^p, 387 & 355^p*
Cordoba - HRSL	*COR*	-31.68^o -63.87^o *322*	*1064, 607, 532^p, 408, 387 & 355^p*
Punta Arenas	*PAR*	-53.22^o -70.88^o *15*	*1064, 607, 532^p, 408, 387 & 355^p*
Tucuman	*TUC*	-26.79^o -65.21^o *485*	*1064, 607, 532^p, 408, 387 & 355^p*

ST.	ID	LAT LON ALT(m)	Detected Channels (nm)
S. Paulo	*SPU*	-23.56^o -46.74^o *740*	*1064, 607, 532, 531, 408, 387 & 355*
S. Paulo	*SPT*	*Trans- portable*	*607, 532*
Manaus	*MAO*	-02.89^o -59.97^o *30*	*408, 387, 355*
Natal	*NAT*	-05.82^o -35.20^o *12*	*1064, 532^p & 355^p*
Temuco	*TMU*	-38.73^o -72.60^o *108*	*532*
Medellin	*MED*	$+06.22^o$ -75.57^o *1545*	*1064, 532 & 355*
Medellin CIBioFi	*MEC*	$+03.37^o$ -76.53^o *982*	*1064, 532 & 355*
Medellin SIATA	*MES*	$+03.37^o$ -76.53^o *1538*	*355^p*
La Paz	*LPZ*	16.53^o 72.07^o *3500*	*532*

- **Tropospheric studies**
  - **PBL height determination**
  - **Aerosol**
  - **Cloud studies**
- **Stratospheric studies**
  - **Volcanic eruptions**
  - **Ozone**
- **Satellite Validation**
- **Outreach**
- **TSM studies** NEW

lalinet-loci complex terrain





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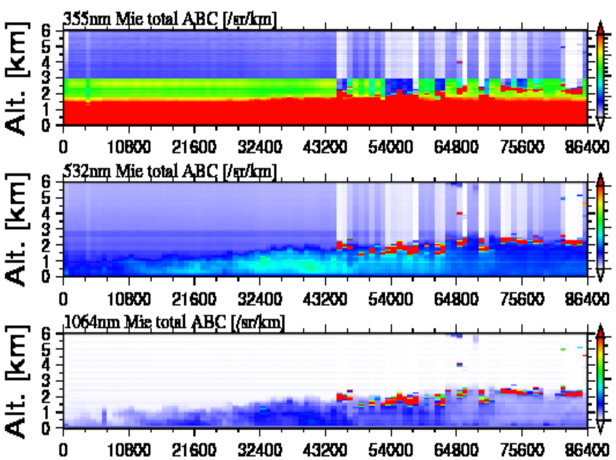
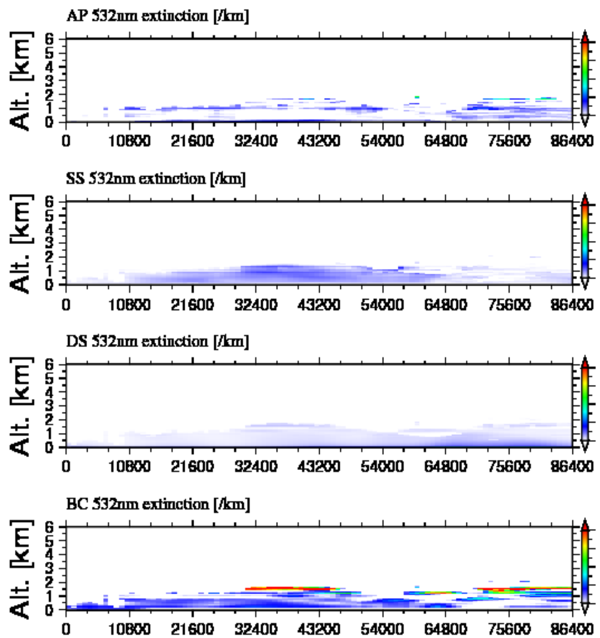
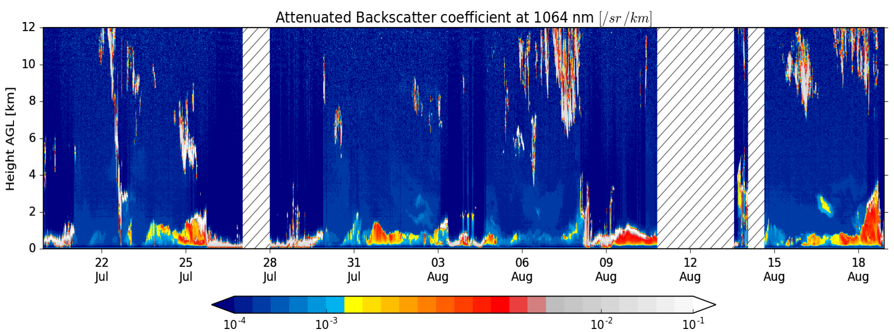
lalinet-troposphere: pbl studies

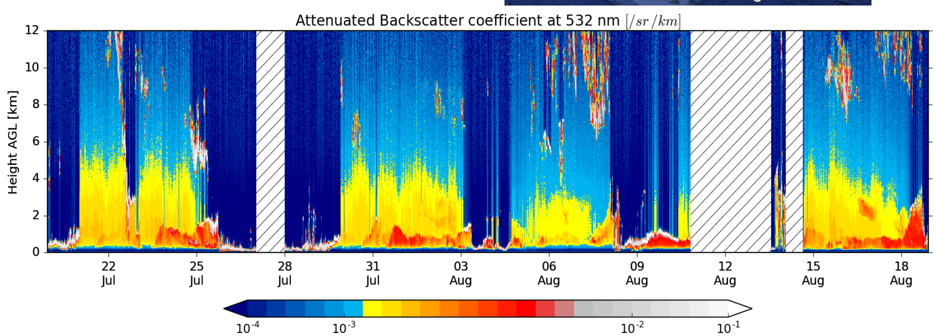
lalinet-troposphere: aerosol typing





AEROSOL CLASSIFICATION





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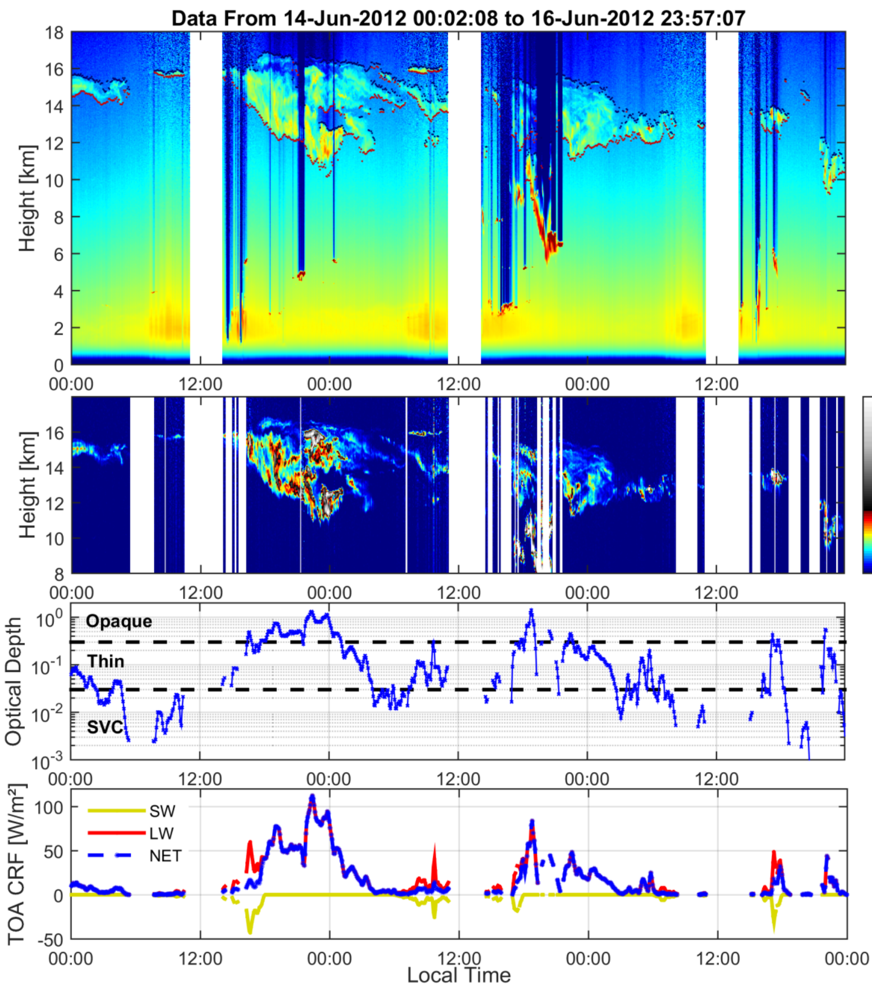
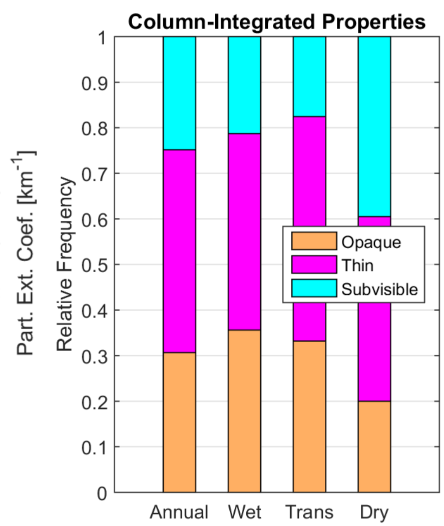
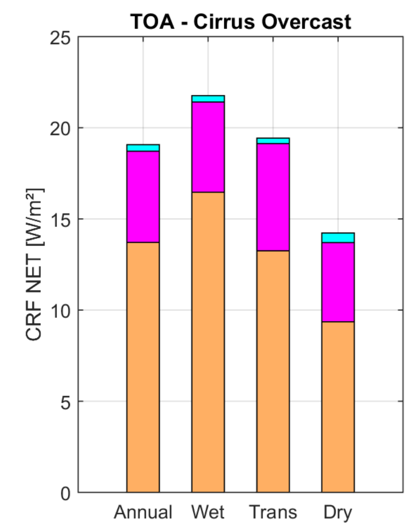
lalinet-troposphere: cirrus cloud forcing



		CRF$_{SW}$ [W/m²]	CRF$_{LW}$ [W/m²]	CRF$_{NET}$ [W/m²]
All sky				
libRadtran	BOA	-5,0 ± 0,4	1,25 ± 0,04	-3,7 ± 0,2
	TOA	-5,7 ± 0,5	21,0 ± 0,6	15,3 ± 0,4





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lalinet-stratosphere: capability extension

Scientific goals:

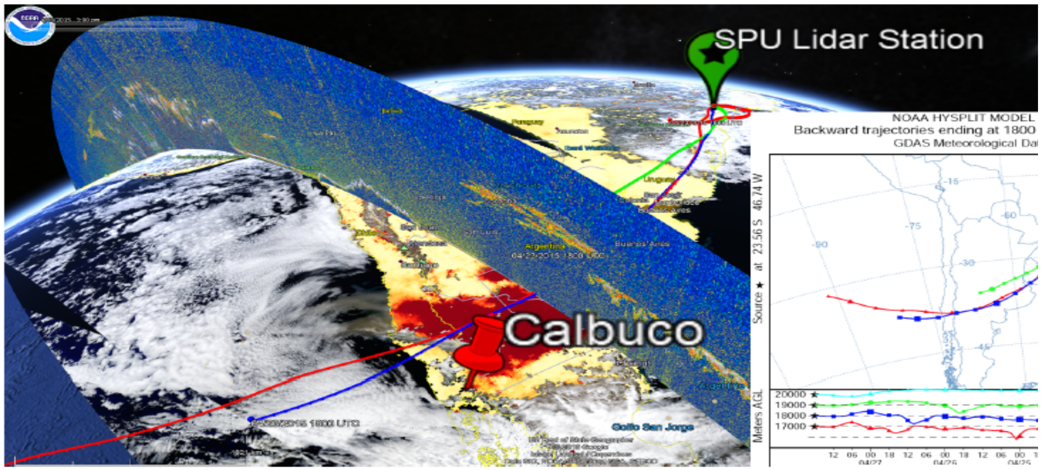
- Establishing standardized, aerosol backscattering measurements in UTLS.
- Production of standardized processing algorithms, measurement methodologies and its quality control.

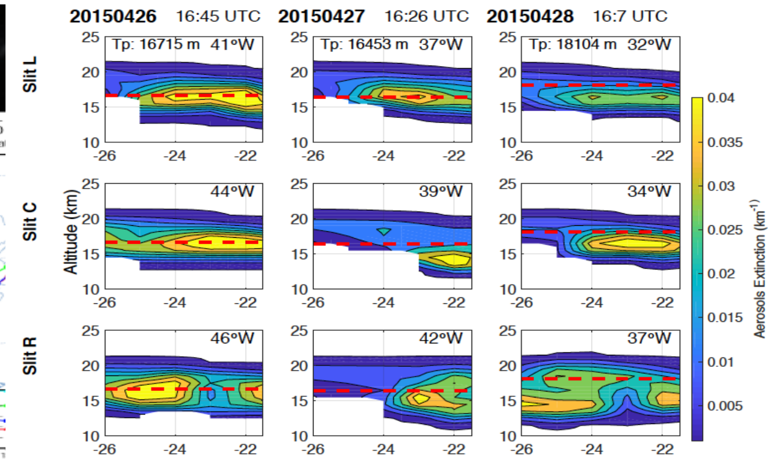
Look for funds for new lidars (UTLS) approach:

- Evaluate the existing lidar capabilities .
- Determine alternatives without technological changes.

Antuña-Marrero, J. C., E. Landulfo, et al.,, 2018: One step further in the objectives of LALINET: preparation for the next major volcanic eruption & validations of the UTLS aerosols measurements from EarthCare and Sage III satellite missions. Poster, *Chapman Conference on Stratospheric aerosol in the post-Pinatubo era: Processes, Interactions and Importance*, 18-23 March, Puerto de la Cruz, Tenerife, Spain.

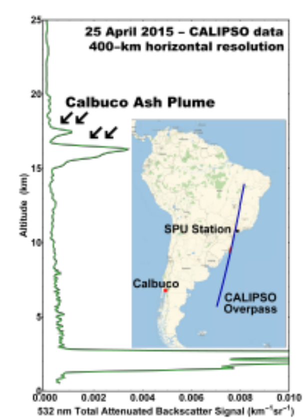
lalinet-stratosphere: volcanic eruptions

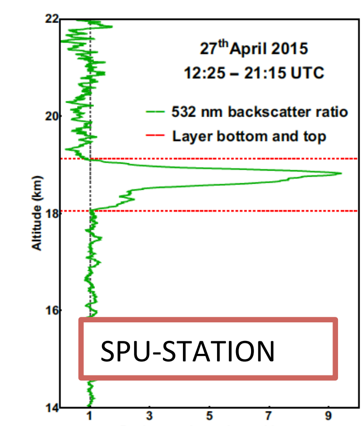




The OMPS Limb Profiler Analysis

Location	Layer Height (km)	AOD at 532 nm	LR (532nm)	LR (355nm)	Ångström 355/532	Type
Leipzig	2.6–4.3	0.35	60 ± 5	60 ± 5	0.03 ± 0.40	Ash
Munich	2.6–3.5	-	50–60	50 ± 5	−0.11 ± 0.18	Pure dry ash
Potenza	2.0–3.0	-	42 ± 2	50 ± 3	1.4 ± 0.2	Sulfates with some ash
Evora	2.7–3.7	0.07	39 ± 2	32 ± 4	0.68 ± 0.63	Fresh volcanic particles
Granada	2.6–2.9	-	47 ± 7	48 ± 16	0.066 ± 0.005	
Cabauw	2.7–6.0	0.53	42 ± 1	44 ± 24	0.30 ± 0.03	Sulfate-ash mixture
Athens	3.0–4.8	0.05	67 ± 13	89 ± 3	0.57 ± 0.26	Aged ash/sulfates
Athens	2.5–3.0	0.04	76 ± 5	78 ± 3	1.72 ± 0.06	Sulfates
Brazil	18–19.3	0.16	76 ± 27	63 ± 21	0.61 ± 0.58	Sulfates with some ash





Synergetic Aerosol Layer Observation After the 2015 Calbuco Volcanic Eruption Event

Fábio J. S. Lopes [1,*], Jonatan João Silva [1,2], Juan Carlos Antuña Marrero [3], Ghassan Taha [4] and Eduardo Landulfo [1]

Remote Sens. 2019, *11*, 195; doi:10.3390/rs11020195

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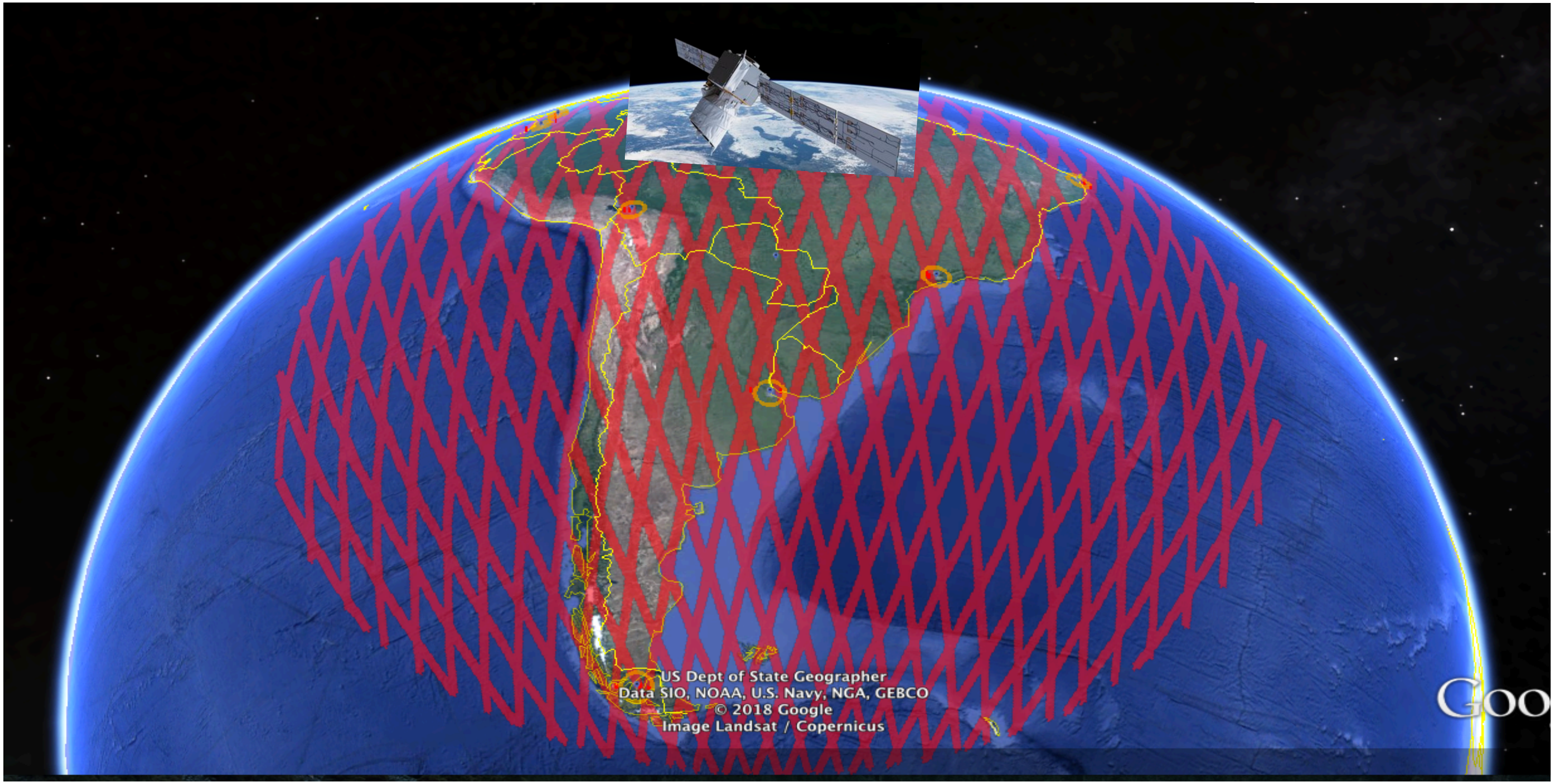
lalinet: satellite validation

LatAm Lidar Network

LALINET AEOLUS CAL/VAL

aeolus



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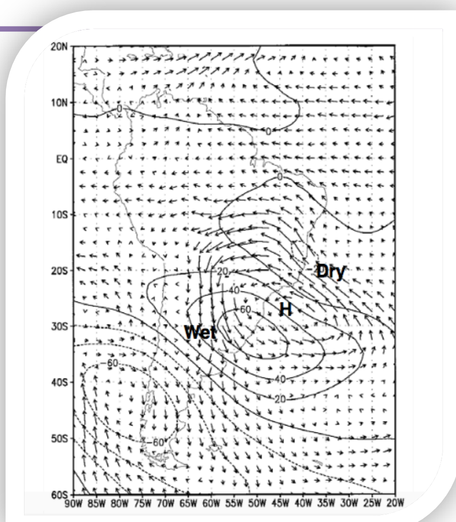
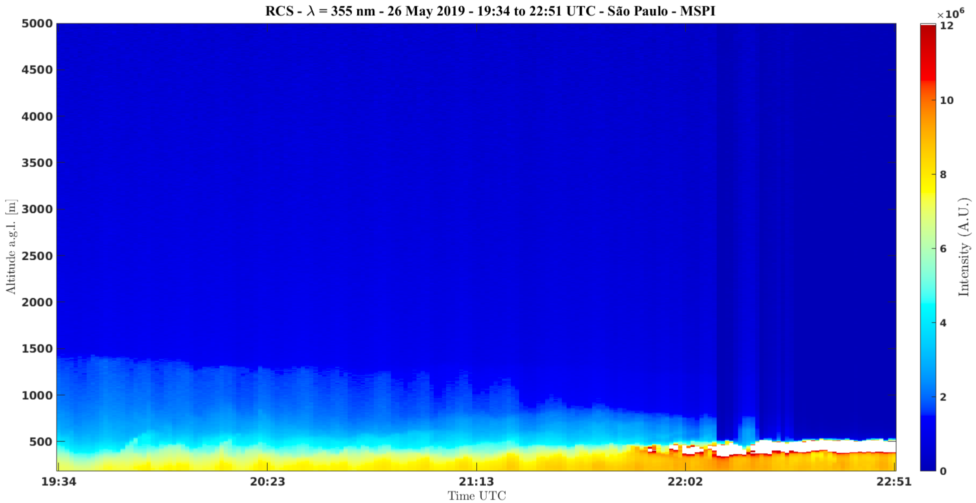
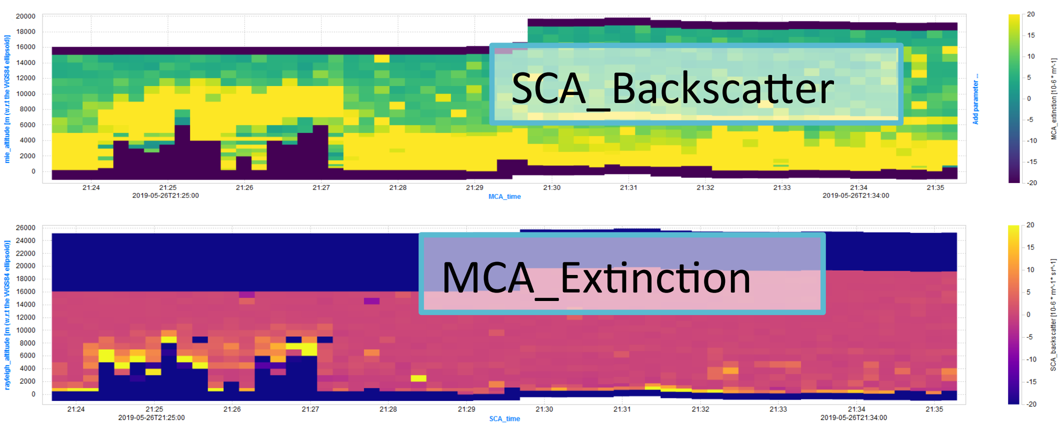
Lalinet satellite validation

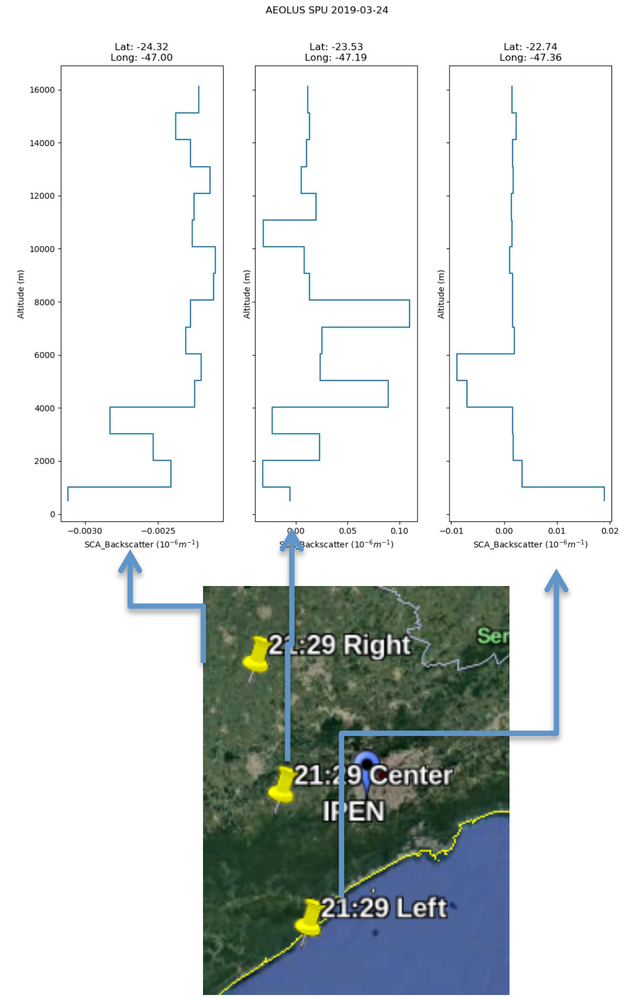
- SPU Lidar station – AEOLUS Validation –
- 66 overpasses since 04th November 2018
- 2 overpasses by week - Sundays – 08:49 and 21:29 UTC
- Horizontal distance from SPU Station ~ 102 km
- SPU Lidar Station:
  - 20 correlative measurements since 04th November 2018 - 30% of the overpasses
- Access L2A data - VirES Aeolus Service - https://aeolus.services/
- L2A data products: SCA - Standard Correct Algorithm – Backsc. and extinction profiles



lalinet: satellite validation







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lalinet: outreach

WLMLA (Year)	Place	Attendees				Papers	
		LA(%)	**RW(%)**	**Total**	**ST (%)**	**PO**	**OR**
I (2001)	Camagüey, **Cuba**	9 (39)	14 (61)	23	5 (22)	5	14
II (2003)	Camagüey, **Cuba**	13 (52)	12 (48)	25	13 (52)	2	25
III (2005)	Popayán, **Colombia**	41 (79)	11 (21)	52	26 (50)	6	25
IV (2007)	Ilhabela, **Brazil**	30 (71)	12 (29)	42	20 (48)	16	29
V (2009)	Buenos Aires, **Argentina**	42 (65)	23 (35)	65	21 (32)	31	31
VI (2011)	La Paz, **Bolivia**	52 (81)	12 (19)	64	32 (50)	15	21
VII (2013)	Pucón, **Chile**	35 (76)	11 (24)	46	19 (41)	20	24
VIII (2015)	Cayo-Coco, **Cuba**	29 (71)	12 (29)	41	15 (37)	25	19
IX (2016)	Santos, **Brazil**	41 (84)	8 (16)	49	20 (41)	29	23
X(2018)	Medellin, **Colombia**	49(89)	6(11)	55	35(63)	23	13

SPSAS on Atmospheric Aerosols

lalinet: outreach

Assessment of atmospheric optical

Properties during biomass burning

Events and

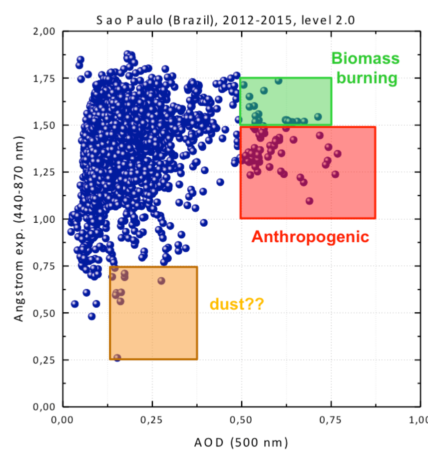
Long-range transport of desert dust

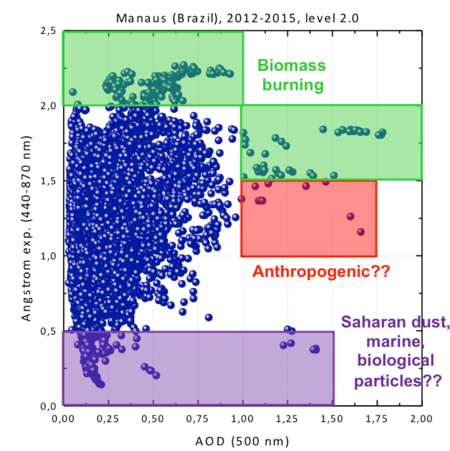
Building a bridge between EARLINET and LALINET

ALCANTARA EUROPEAN SPACE AGENCY – INOE(Rumania), LMD (Germany) & UGR (Spain)

SPU + MAO + NAT

1. Student Training – Lical
2. QC/QA @ LALINET sites
3. Coordinated Campaigns
4. SCC x LALINET Algorithms





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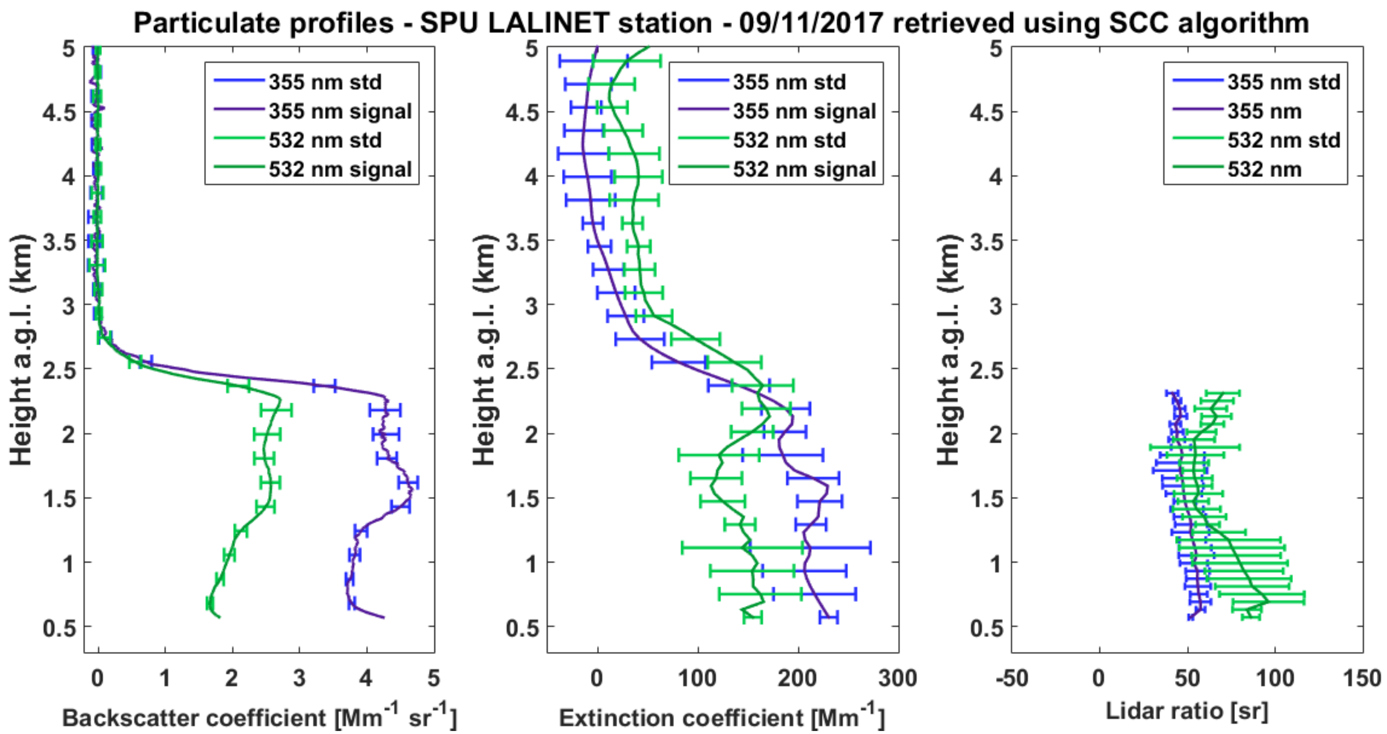
lalinet: outreach



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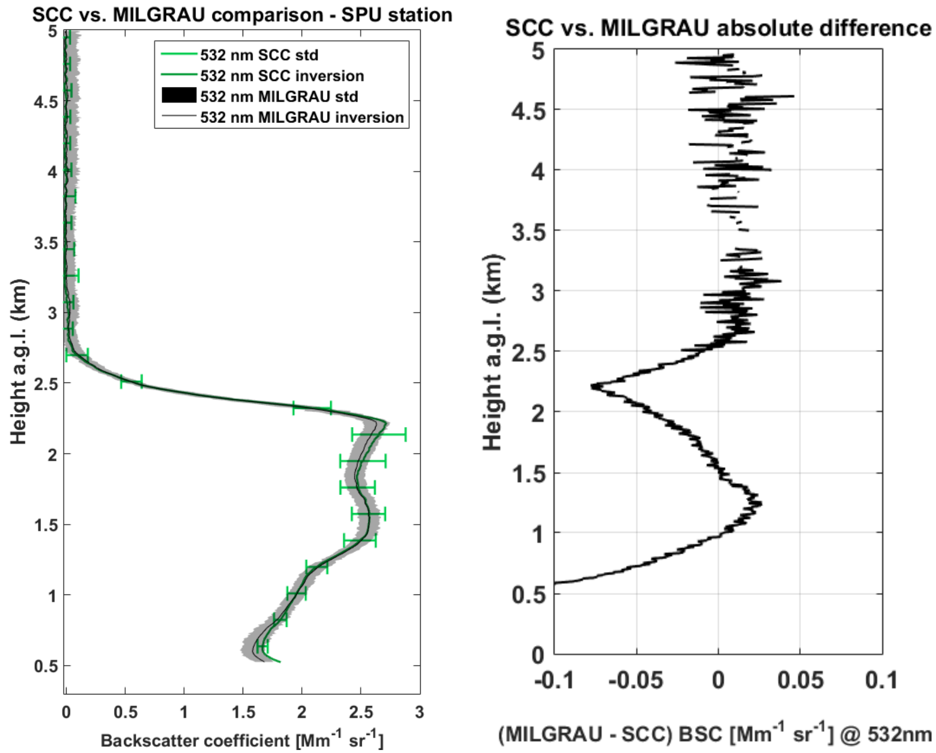
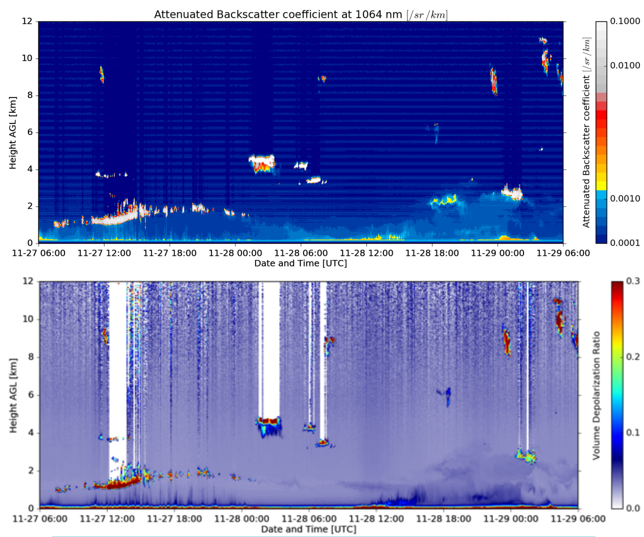
lalinet: outreach

- SCC data data comparison with MILGRAU



lalinet: outreach

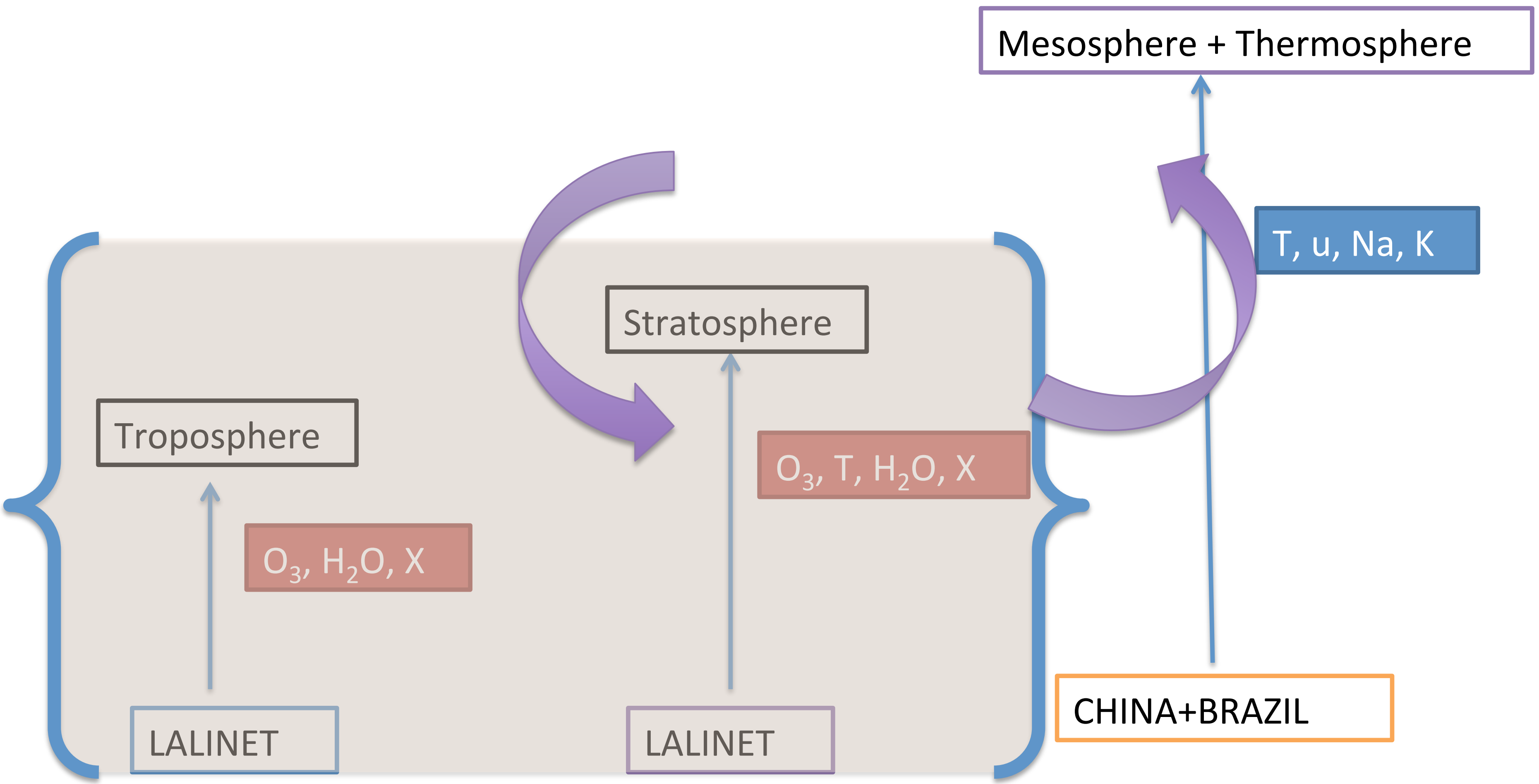


Supercooled low clouds

Multiwavelenght Raman depol LIDAR

Landulfo et al.

lalinet: TSM coupling



Landulfo et al.

lalinet: acknowledgements

SPSAS on Atmospheric Aerosols