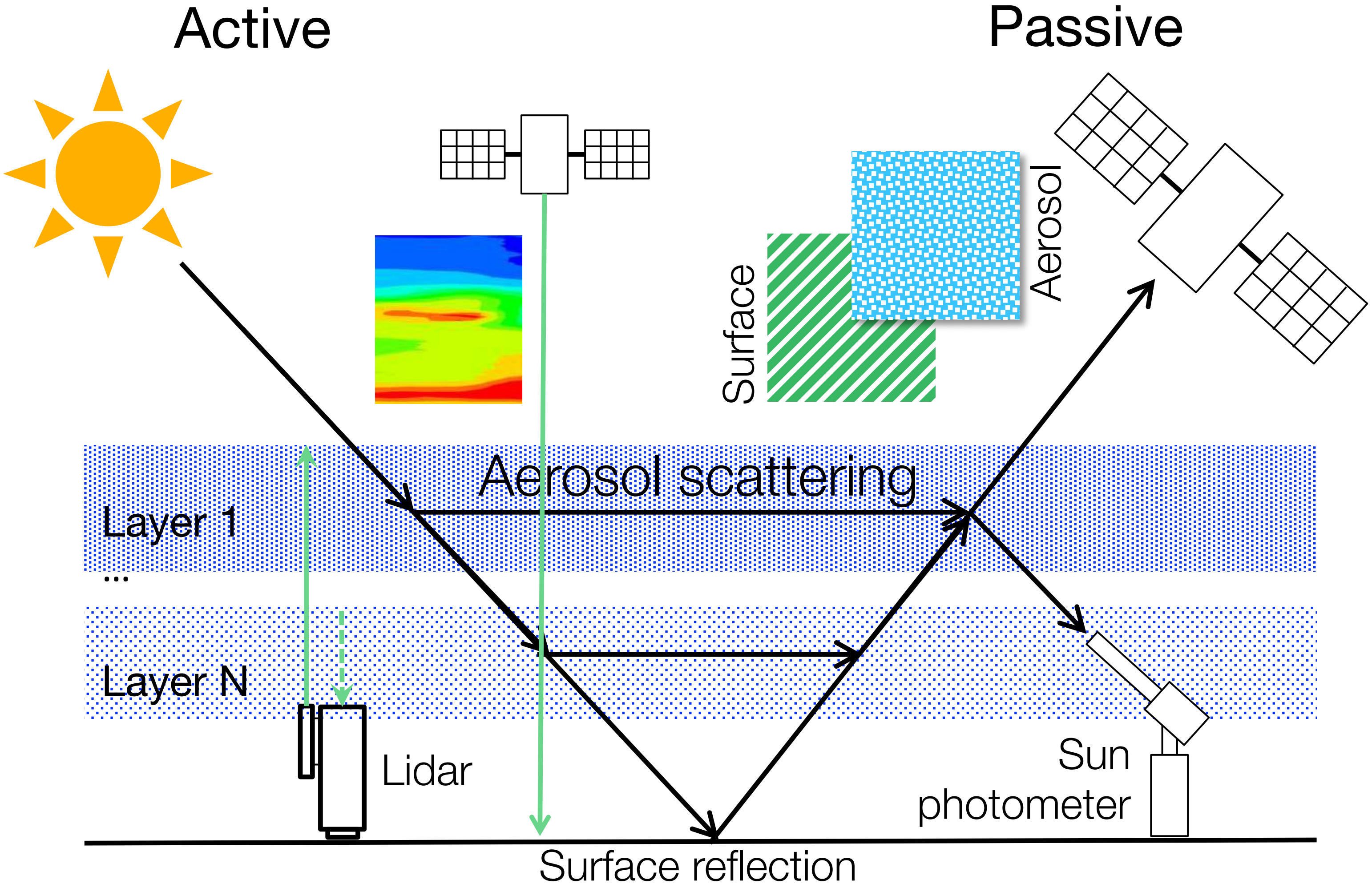
GRASP/GARRLiC

Inversion methods for atmospheric profiling of advanced aerosol properties

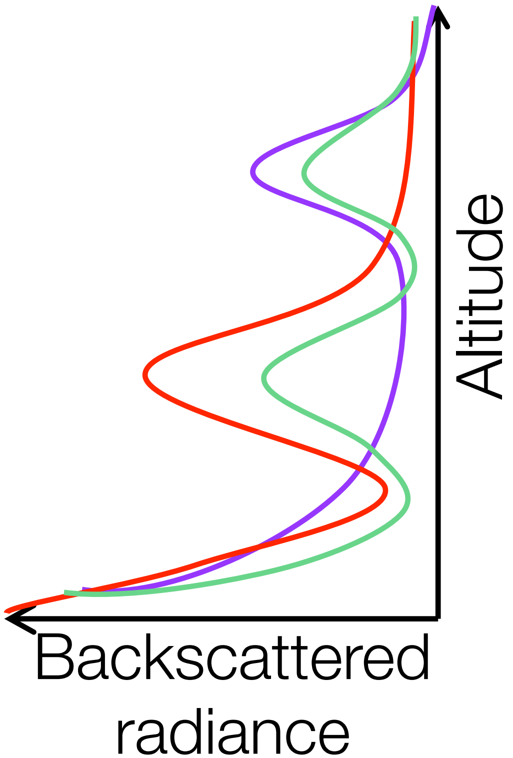
Aerosol remote sensing



Aerosol remote sensing

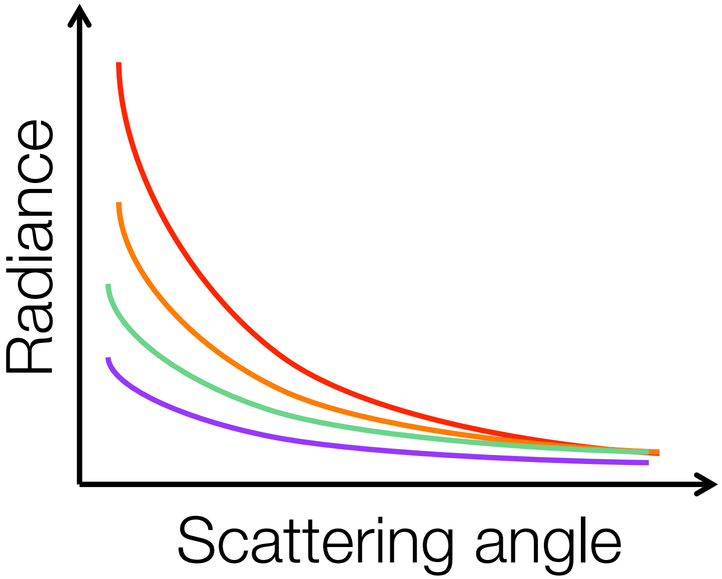
Active

- **vertical** profiles (0.2<h<15 km): $\beta(\lambda,\eta)$, $\sigma(\lambda,\eta)$ (raman only)
- Sensitivity to $P_{11}(\lambda,180^o)$



Passive

- **columnar:** $\tau(\lambda)$, $\omega_0(\lambda)$, $n(\lambda)$, $\kappa(\lambda)$, $dV(r)/d\ln r$
- Sensitivity to a wide scattering range: 3° – 150°



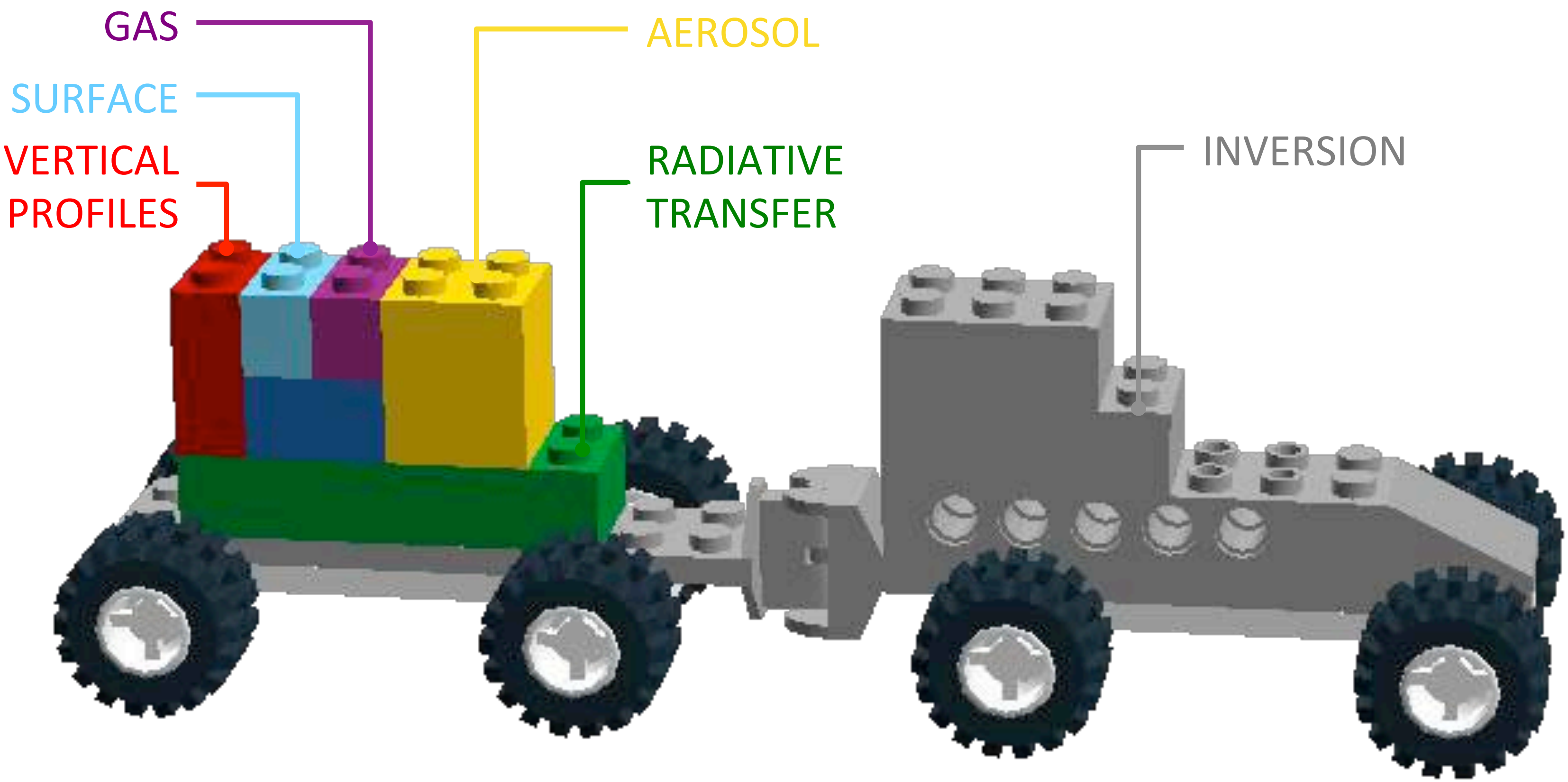
Objectives

- Advanced aerosol remote sensing based on a combination of active and passive measurements

- Benefiting from all the sensitivities of available remote sensing instruments and lessen the assumptions

- Unified aerosol model, describing both vertical and columnar aerosol properties

General GRASP idea



GRASP features

High versatility (measurements)

- suitable for satellite and ground-based measurements
- multiple instrumentation :

✓ $P_{11}(\lambda,\theta)$, $P_{12}(\lambda,\theta)$, $P_{22}(\lambda,\theta)$, $P_{33}(\lambda,\theta)$, $P_{34}(\lambda,\theta)$,$P_{44}(\lambda,\theta)$

✓ $\tau(\lambda)$, $I(\lambda,\theta)$, $Q(\lambda,\theta)$, $U(\lambda,\theta)$, $P(\lambda,\theta)$

✓ $\beta(\lambda,h)$, $\alpha(\lambda,h)$*,$\delta(\lambda,h)$*

* in process of scientific validation

GRASP features

High versatility (retrievals)

- multi-pixel (time+space) retrievals
- multi-instrumental retrievals (single & multi-pixel)
- flexible modelling

  Aerosol (mono & multi-modal)

  ✓Size distribution (5 to 22 parameters)

  ✓Complex refractive index

  ✓Vertical distribution (1 to 100 parameters)

  Surface

  ✓Surface BRDF&BPDF (land and ocean)

GRASP+LiRIC=GARRLiC

Generalized Aerosol Retrieval from Radiometer and Lidar Combined data.

Previously achieved (**LiRIC/Sinyuk et. al./Cuesta et. al.**):

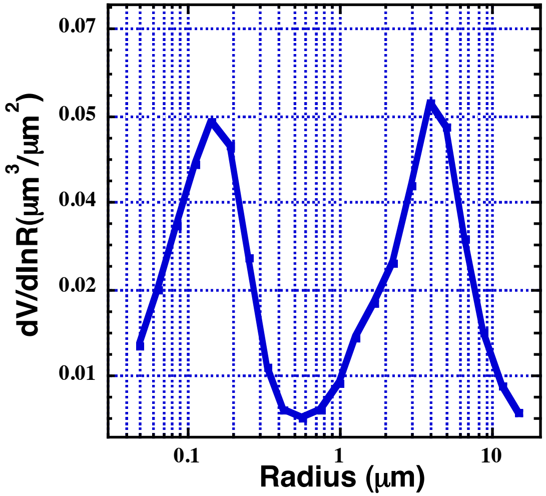
- Allows discriminations of vertical profiles of **fine** & **coarse** aerosols

New achievements (expected):

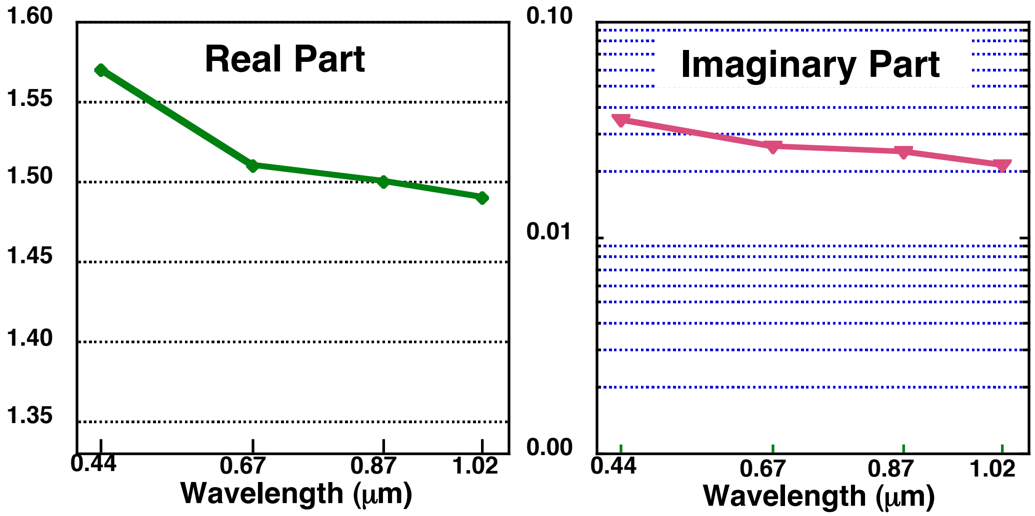
- Refractive index distinguished for **fine** & **coarse** modes
- Improvements of columnar properties, e.g.:
  particle shape, $dV(r)/d\ln r$, $P_{ij}(\lambda, 180^o)$, $S_a(\lambda)$
- Benefits from polarimetric inversions (active and passive)

Aerosol model

Particle size distribution:
0.05 μm ≤ R (22 bins) ≤ 15 μm



Complex refractive index
λ = 0.44; 0.67; 0.87; 1.02 μm



Total 31 parameter (AERONET) :

dV/lnr – size distribution (22 points);

$n(\lambda)$ и $k(\lambda)$ - refractive index (4+4 points);

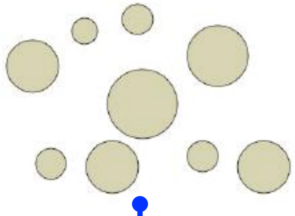
C_{spher} (%) – sphericity faction (1 point)

Mixture of spherical and spheroidal particles

retrieved parameter

C ×

spherical:



+ (1-C) ×

Randomly oriented spheroids :

(Mishchenko et al., 1997)

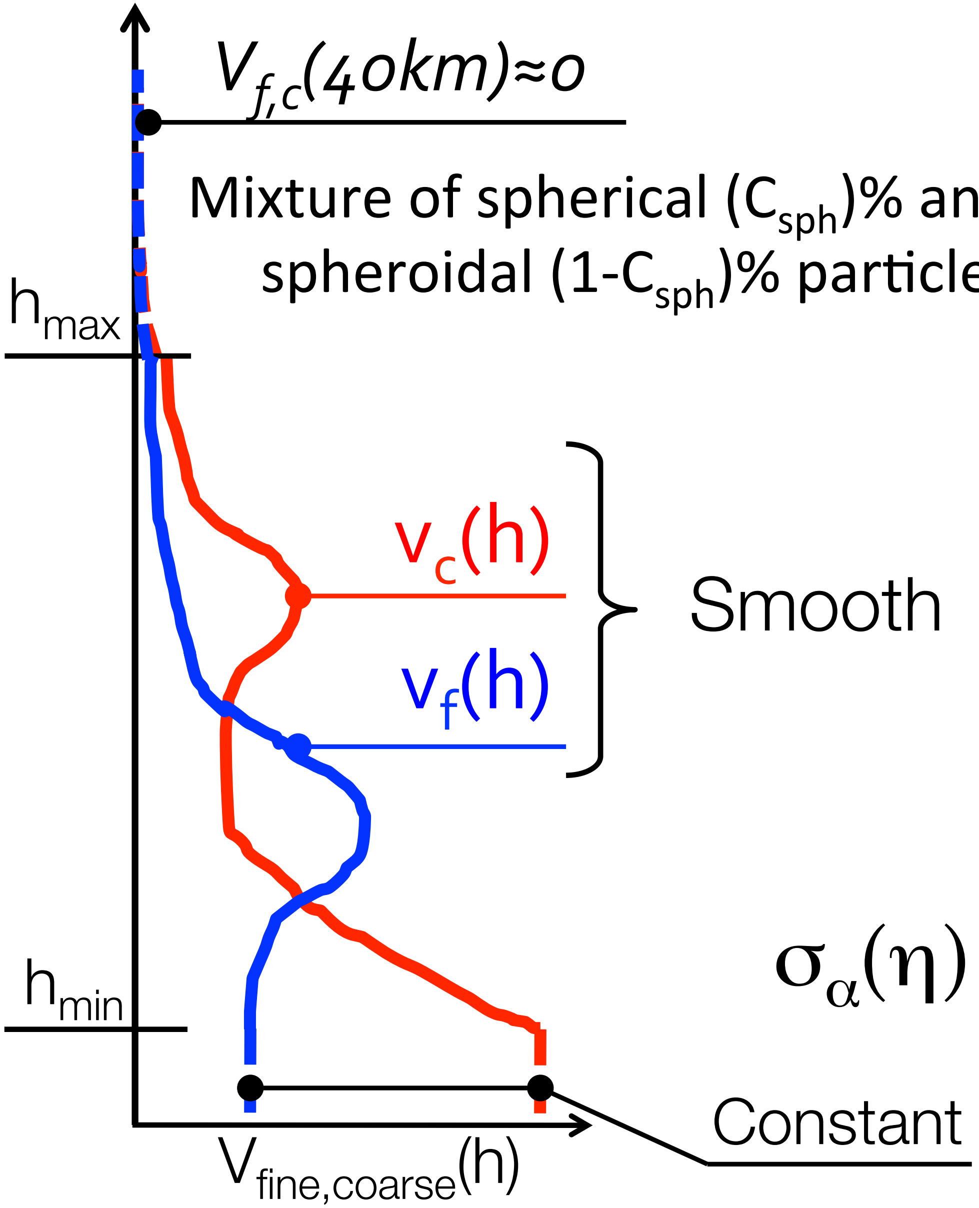
$$\tau(\lambda) = C\int_{r_{min}}^{r_{max}} K_{\tau}^{spherical}(k;n;r)V(r)dr + (1-C)\int_{r_{min}}^{r_{max}}\left(\int_{\varepsilon_{min}}^{\varepsilon_{max}} K_{\tau}^{\varepsilon}(k;n;r,\varepsilon)N(\varepsilon)d\varepsilon\right)V(r)dr$$

Shape distribution

Assumptions:

- dV/dlnr – size distribution is the same for spheres and non-spheres;
- non-spherical particles is a mixture of randomly oriented polydisperse spheroids;
- aspect ratio distribution N(ε) is fixed following Dubovik et al. 2006

Unified aerosol model



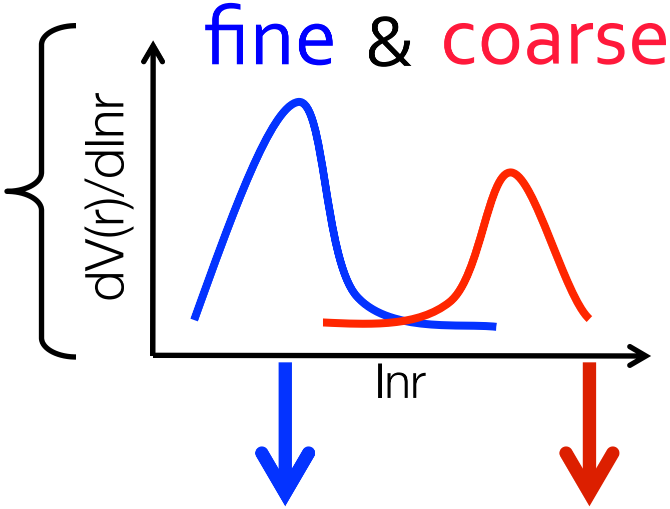
Mixture of spherical (C_{sph})% and spheroidal (1-C_{sph})% particles

Height independent:

- $dV(r)/d\ln r$,
- $n(\lambda)$, $\kappa(\lambda)$
- $\omega_o(\lambda)$, $P_{ij}(\lambda,\Theta)$

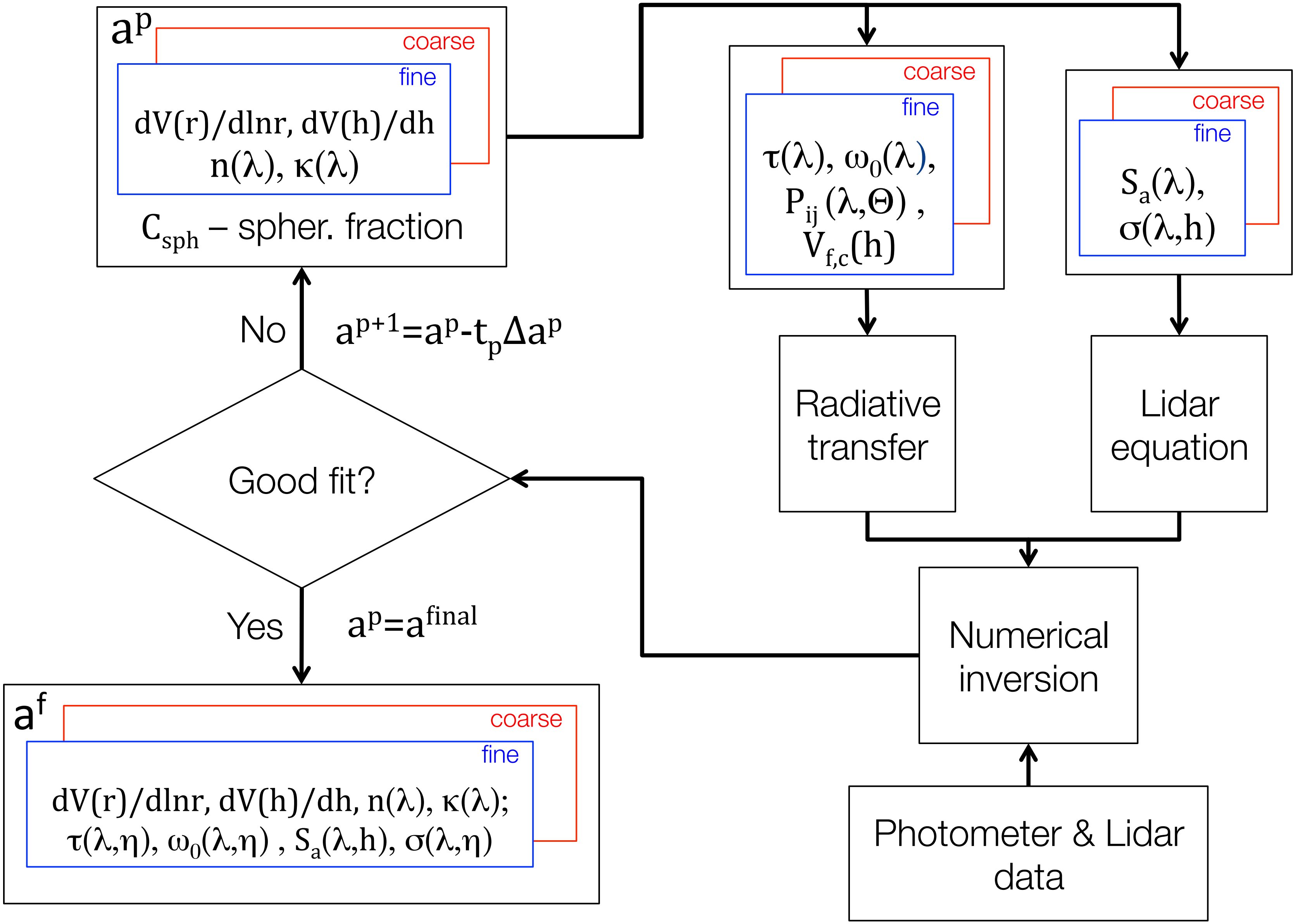
fine & coarse

Smooth



$$\sigma_\alpha(\eta) = v_f(\lambda)\tau_f^{ext} + v_c(\lambda)\tau_c^{ext}$$

General structure



a^p

coarse

fine

$dV(r)/d\ln r$, $dV(h)/dh$

$n(\lambda)$, $\kappa(\lambda)$

C_{sph} – spher. fraction

coarse

fine

$\tau(\lambda)$, $\omega_0(\lambda)$,

$P_{ij}(\lambda,\Theta)$,

$V_{f,c}(h)$

coarse

fine

$S_a(\lambda)$,

$\sigma(\lambda,h)$

Radiative transfer

Lidar equation

Numerical inversion

Photometer & Lidar data

Good fit?

No

$a^{p+1}=a^p-t_p\Delta a^p$

Yes

$a^p=a^{final}$

a^f

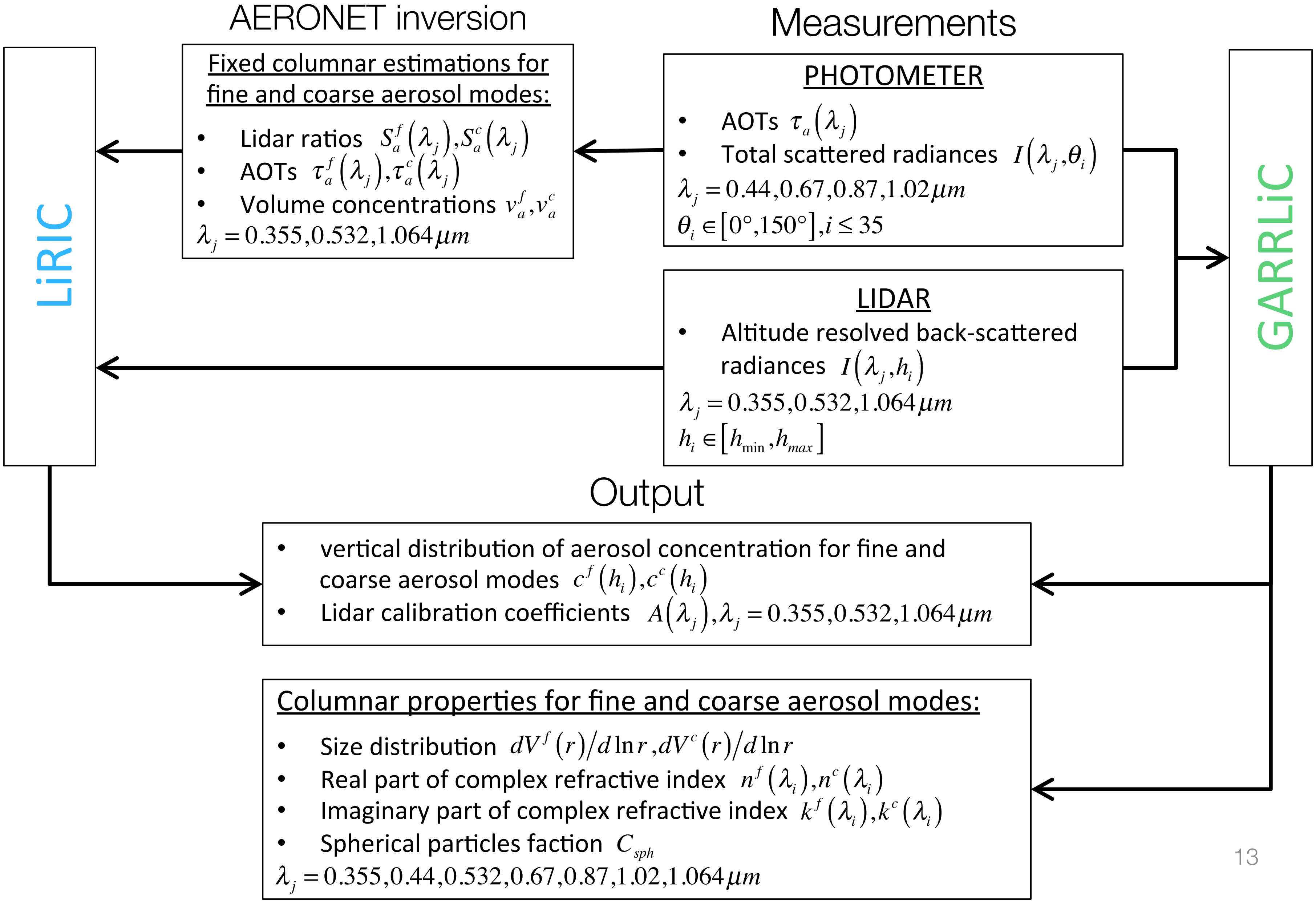
coarse

fine

$dV(r)/d\ln r$, $dV(h)/dh$, $n(\lambda)$, $\kappa(\lambda)$;

$\tau(\lambda,\eta)$, $\omega_0(\lambda,\eta)$, $S_a(\lambda,h)$, $\sigma(\lambda,\eta)$

GARRLiC/LiRIC



AERONET inversion

Fixed columnar estimations for fine and coarse aerosol modes:

- Lidar ratios $S_a^f(\lambda_j), S_a^c(\lambda_j)$
- AOTs $\tau_a^f(\lambda_j), \tau_a^c(\lambda_j)$
- Volume concentrations v_a^f, v_a^c

$\lambda_j = 0.355, 0.532, 1.064\,\mu m$

Measurements

PHOTOMETER

- AOTs $\tau_a(\lambda_j)$
- Total scattered radiances $I(\lambda_j, \theta_i)$

$\lambda_j = 0.44, 0.67, 0.87, 1.02\,\mu m$

$\theta_i \in [0°, 150°], i \leq 35$

LIDAR

- Altitude resolved back-scattered radiances $I(\lambda_j, h_i)$

$\lambda_j = 0.355, 0.532, 1.064\,\mu m$

$h_i \in [h_{\min}, h_{max}]$

Output

- vertical distribution of aerosol concentration for fine and coarse aerosol modes $c^f(h_i), c^c(h_i)$
- Lidar calibration coefficients $A(\lambda_j), \lambda_j = 0.355, 0.532, 1.064\,\mu m$

Columnar properties for fine and coarse aerosol modes:

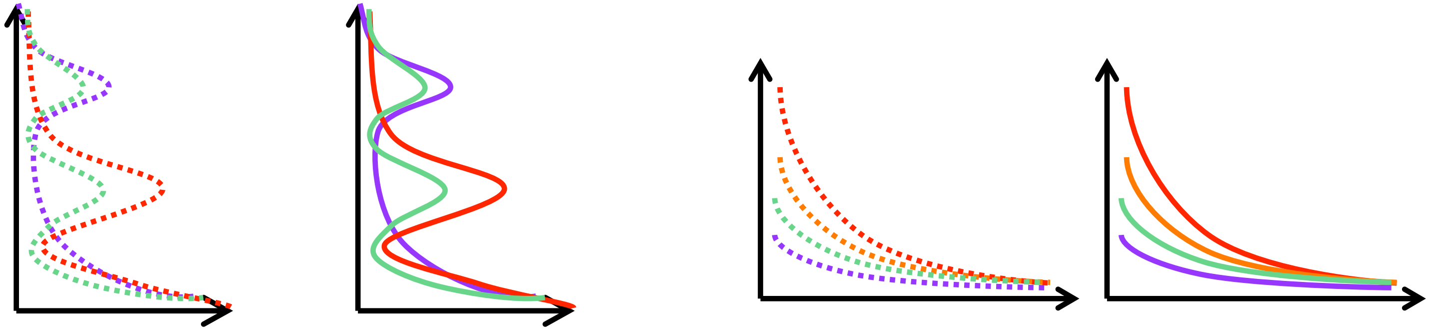
- Size distribution $dV^f(r)/d\ln r, dV^c(r)/d\ln r$
- Real part of complex refractive index $n^f(\lambda_i), n^c(\lambda_i)$
- Imaginary part of complex refractive index $k^f(\lambda_i), k^c(\lambda_i)$
- Spherical particles faction C_{sph}

$\lambda_j = 0.355, 0.44, 0.532, 0.67, 0.87, 1.02, 1.064\,\mu m$

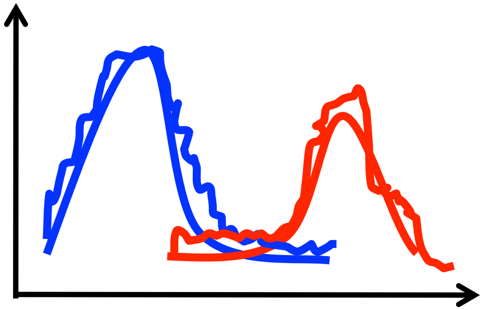
Inversion

Simultaneous maximization:

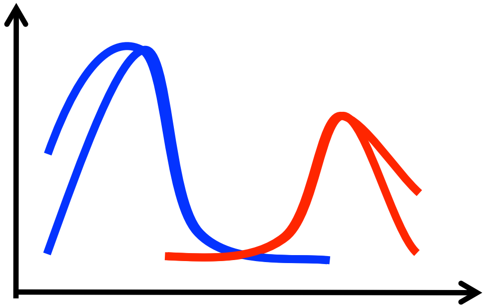
- Weighted fits of LIDAR & Photometer data $\mathbf{f}^*$



- Similarity to a priori assumptions



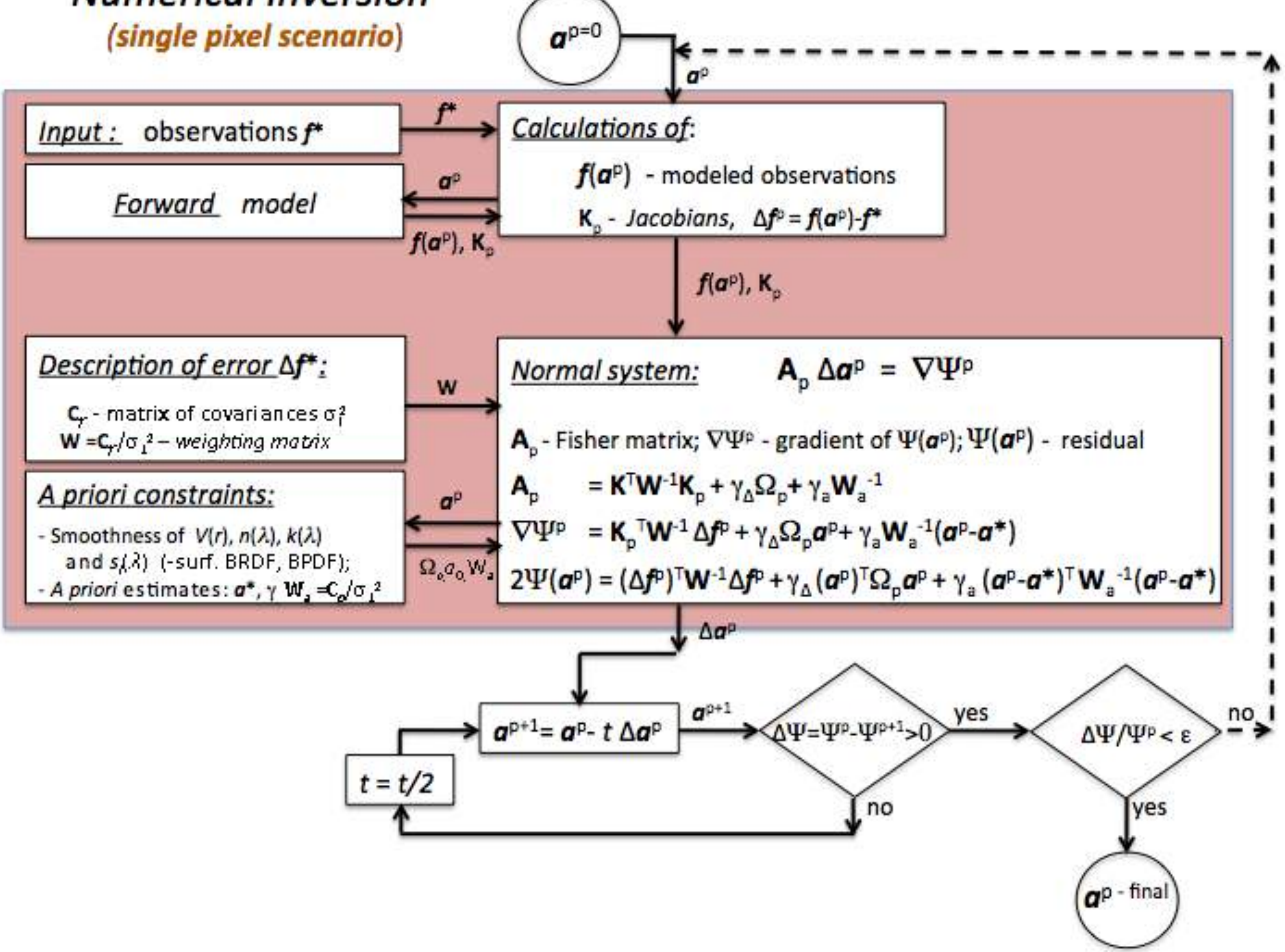
smoothness



Restrictions from neighbor pixels and a priori

Numerical Inversion

(single pixel scenario)



$a^{p=0}$

Input : observations f^*

Forward *model*

***Calculations of*:**

$f(a^p)$ - modeled observations

K_p - *Jacobians*, $\Delta f^p = f(a^p) - f^*$

Description of error Δf^*:

C_{f^*} - matrix of covariances σ_1^2

$W = C_{f^*}/\sigma_1^2$ – *weighting matrix*

A priori constraints:

- Smoothness of $V(r)$, $n(\lambda)$, $k(\lambda)$ and $s_i(\lambda)$ (-surf. BRDF, BPDF);
- *A priori* estimates: a^*, γ $W_a = C_a/\sigma_1^2$

Normal system: $A_p \Delta a^p = \nabla\Psi^p$

A_p - Fisher matrix; $\nabla\Psi^p$ - gradient of $\Psi(a^p)$; $\Psi(a^p)$ - residual

$$A_p = K^T W^{-1} K_p + \gamma_\Delta \Omega_p + \gamma_a W_a^{-1}$$

$$\nabla\Psi^p = K_p^T W^{-1} \Delta f^p + \gamma_\Delta \Omega_p a^p + \gamma_a W_a^{-1}(a^p - a^*)$$

$$2\Psi(a^p) = (\Delta f^p)^T W^{-1} \Delta f^p + \gamma_\Delta (a^p)^T \Omega_p a^p + \gamma_a (a^p - a^*)^T W_a^{-1}(a^p - a^*)$$

$a^{p+1} = a^p - t\,\Delta a^p$

$t = t/2$

$\Delta\Psi = \Psi^p - \Psi^{p+1} > 0$

$\Delta\Psi/\Psi^p < \varepsilon$

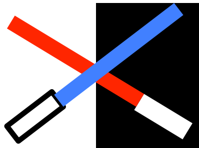
a^p - final

Some examples how GRASP can be used

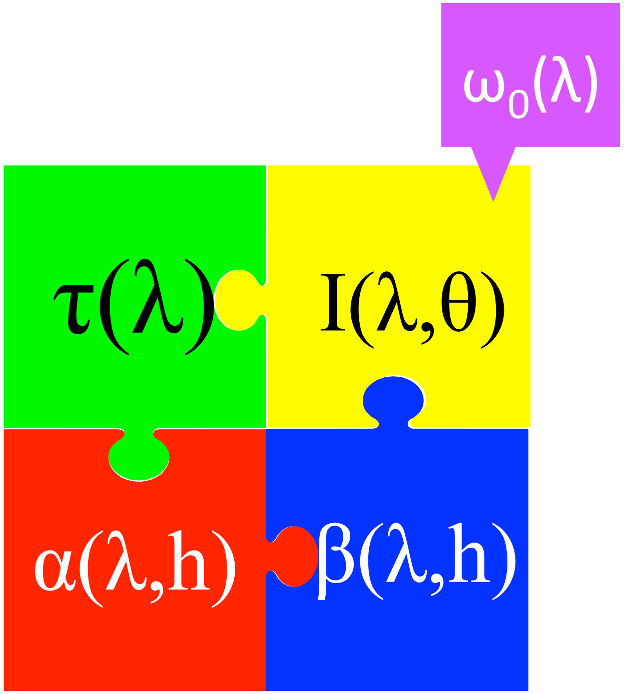
GRASP AEROSOL ABSORPTION PROFILING AT NIGHT

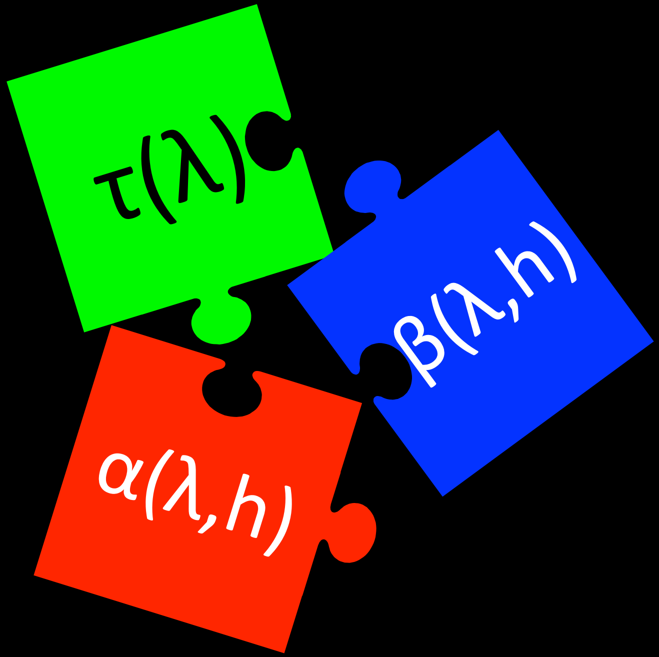
Day & Night measurements

LIGHT SIDE



DARK SIDE





Multi-temporal multi-instrumental retrievals concept

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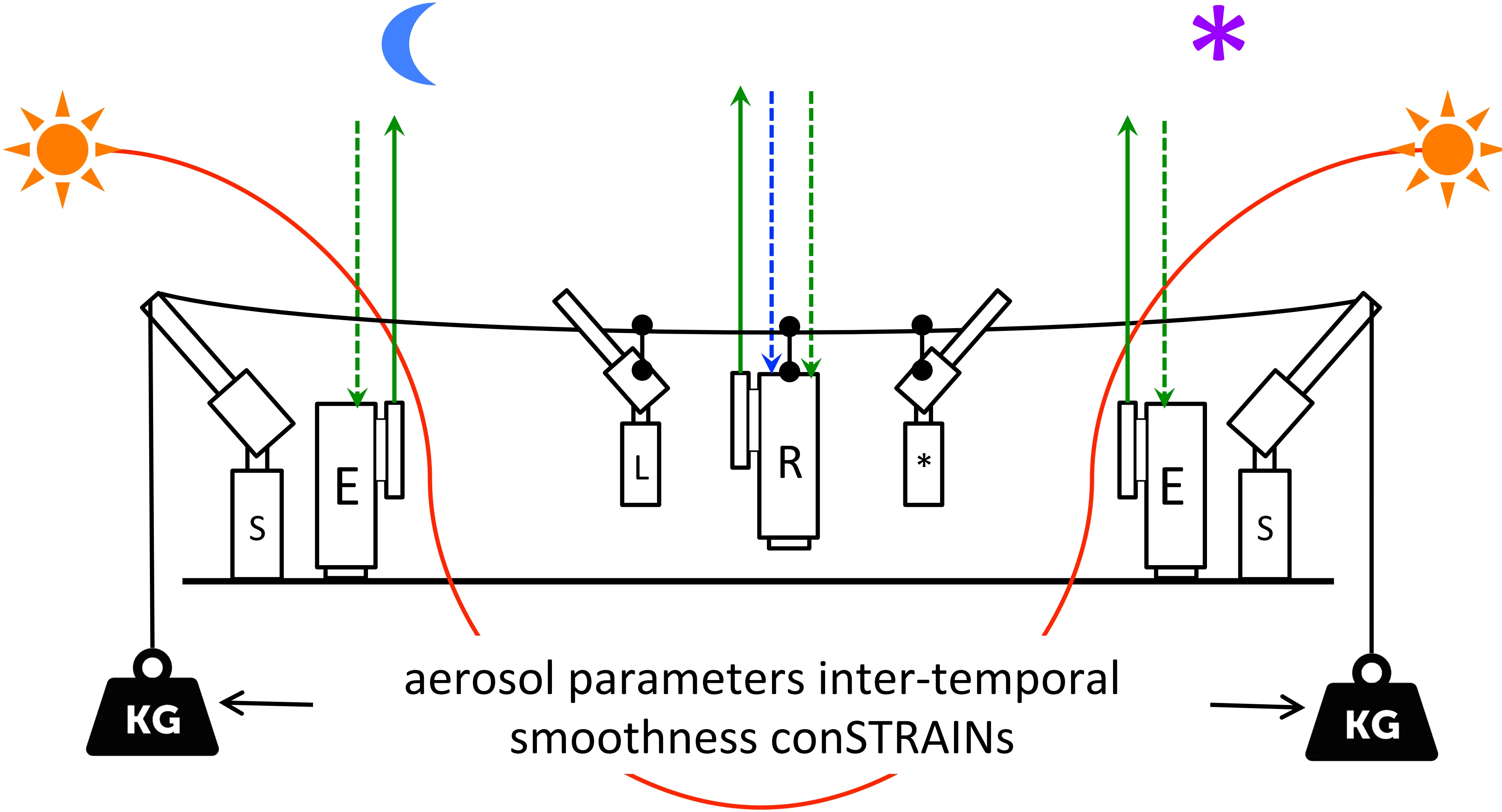
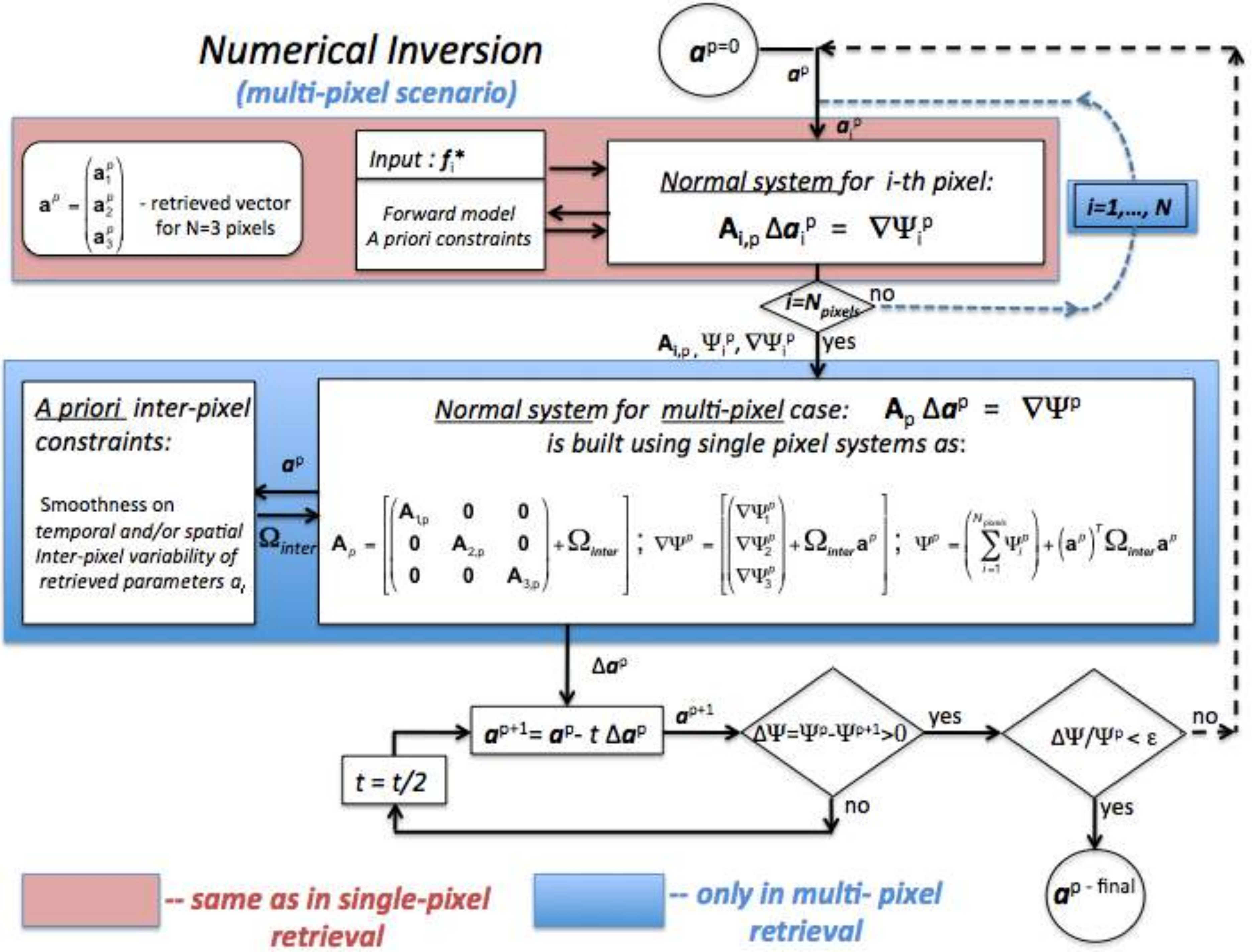
Multi-temporal multi-instrumental retrievals concept



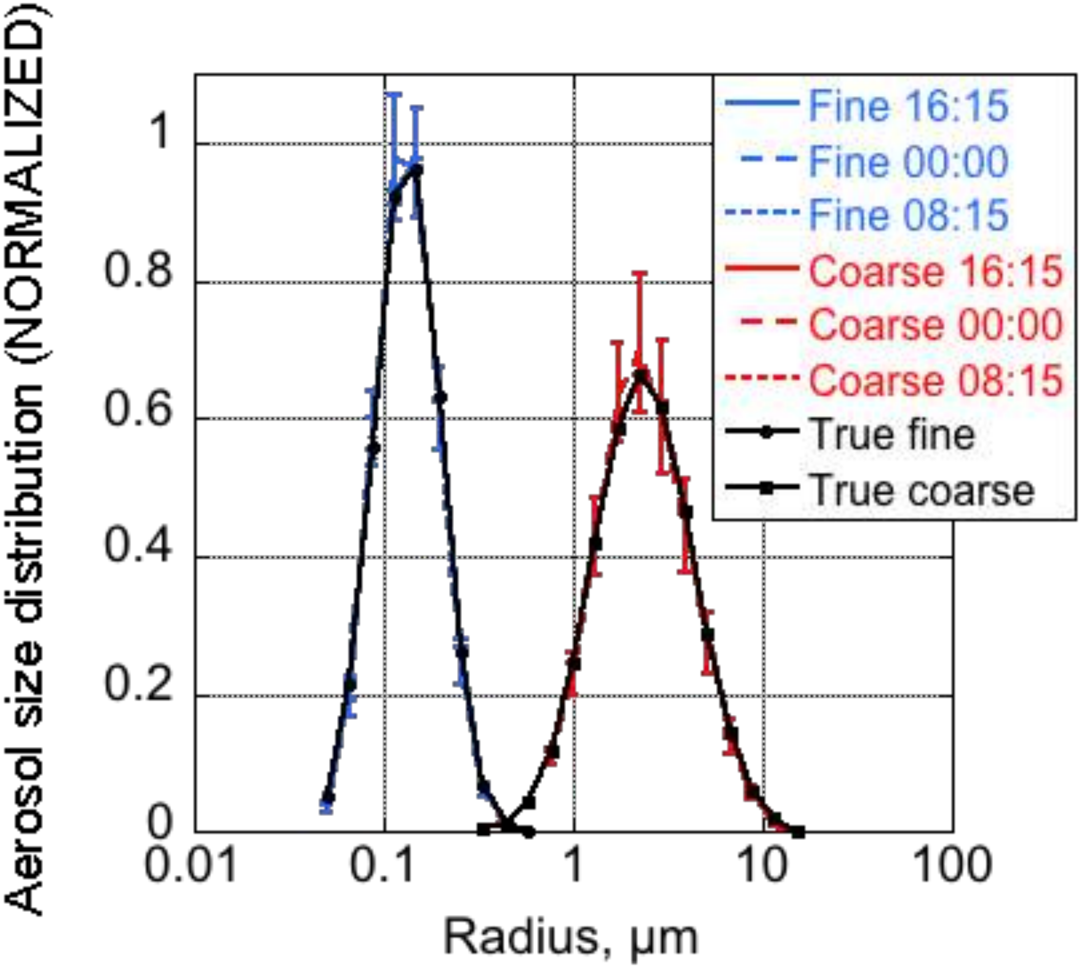
aerosol parameters inter-temporal smoothness conSTRAINs


Numerical Inversion
(multi-pixel scenario)
$a^{p=0}$
a^p
a_i^p
$\mathbf{a}^p = \begin{pmatrix} \mathbf{a}_1^p \\ \mathbf{a}_2^p \\ \mathbf{a}_3^p \end{pmatrix}$ - retrieved vector for N=3 pixels
Input : f_i^*
Forward model
A priori constraints
Normal system for i-th pixel:
$\mathbf{A}_{i,p}\,\Delta a_i^p = \nabla\Psi_i^p$
i=1,..., N
$i=N_{pixels}$
no
yes
$\mathbf{A}_{i,p},\ \Psi_i^p,\ \nabla\Psi_i^p$
A priori inter-pixel constraints:
Smoothness on temporal and/or spatial Inter-pixel variability of retrieved parameters a_i
a^p
Ω_{inter}
Normal system for multi-pixel case: $\mathbf{A}_p\,\Delta a^p = \nabla\Psi^p$
is built using single pixel systems as:
$\mathbf{A}_p = \left[\begin{pmatrix} \mathbf{A}_{1,p} & 0 & 0 \\ 0 & \mathbf{A}_{2,p} & 0 \\ 0 & 0 & \mathbf{A}_{3,p} \end{pmatrix} + \Omega_{inter}\right];\ \nabla\Psi^p = \left[\begin{pmatrix} \nabla\Psi_1^p \\ \nabla\Psi_2^p \\ \nabla\Psi_3^p \end{pmatrix} + \Omega_{inter}\mathbf{a}^p\right];\ \Psi^p = \left(\sum_{i=1}^{N_{pixels}} \Psi_i^p\right) + \left(\mathbf{a}^p\right)^T \Omega_{inter}\mathbf{a}^p$
Δa^p
$a^{p+1} = a^p - t\,\Delta a^p$
a^{p+1}
$\Delta\Psi = \Psi^p - \Psi^{p+1} > 0$
yes
no
$t = t/2$
$\Delta\Psi/\Psi^p < \varepsilon$
no
yes
$a^{p\text{ - final}}$
-- same as in single-pixel retrieval
-- only in multi- pixel retrieval

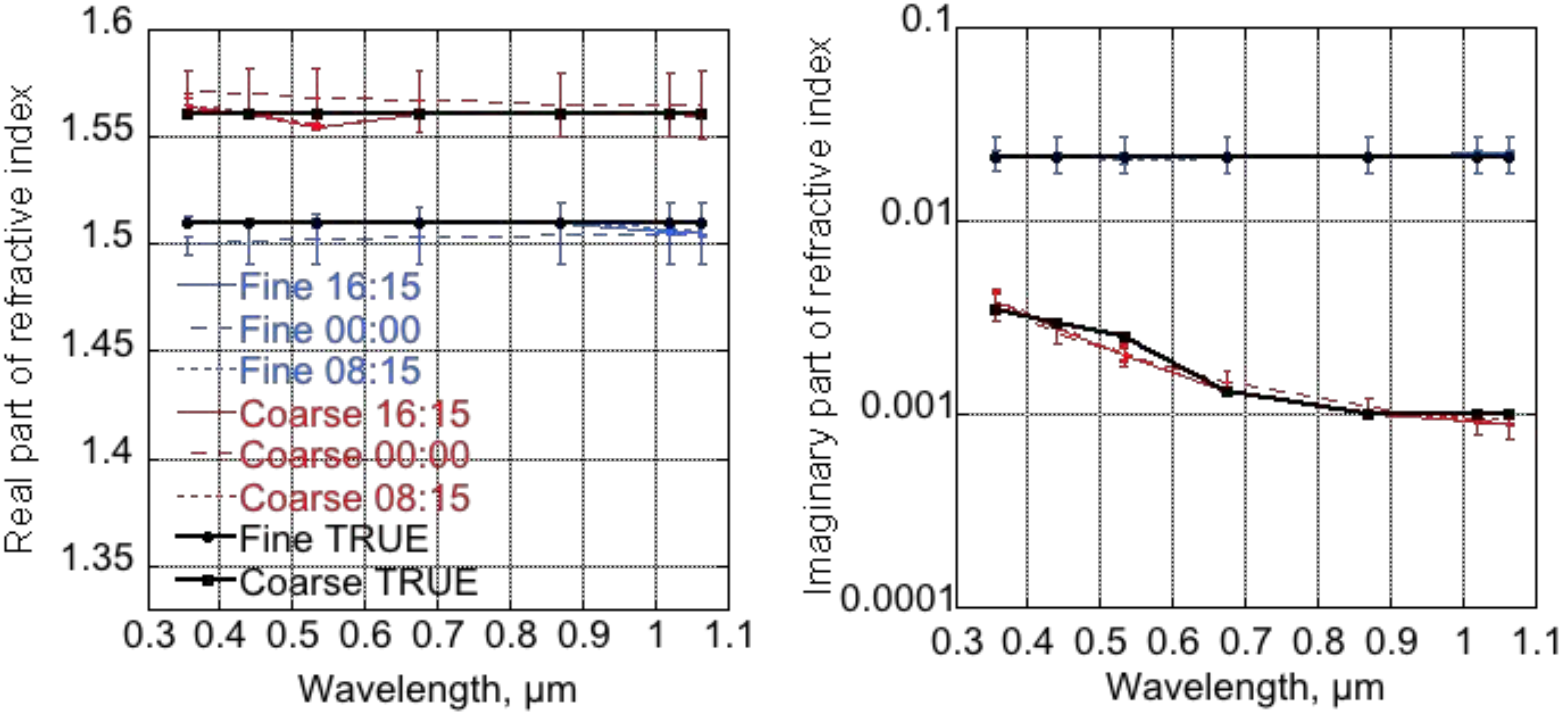
Sensitivity study

- 50/50 mixture of smoke and dust
- continuous lidar measurements
- Sun photometer measurements in the evening and in the morning
- aerosol gradually decreases in concentration
- aerosol type and proportion mixture don’t change

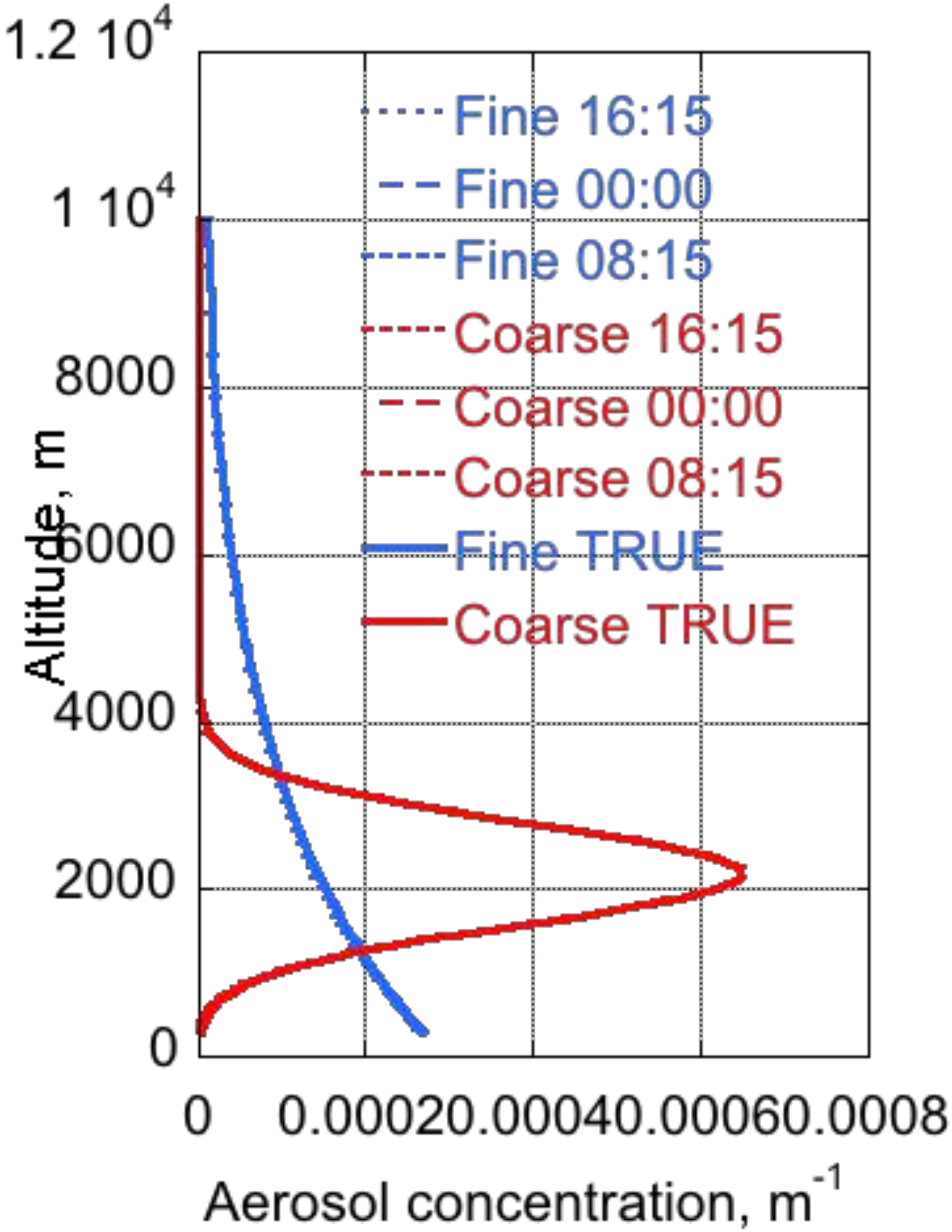
Sensitivity study: size distribution



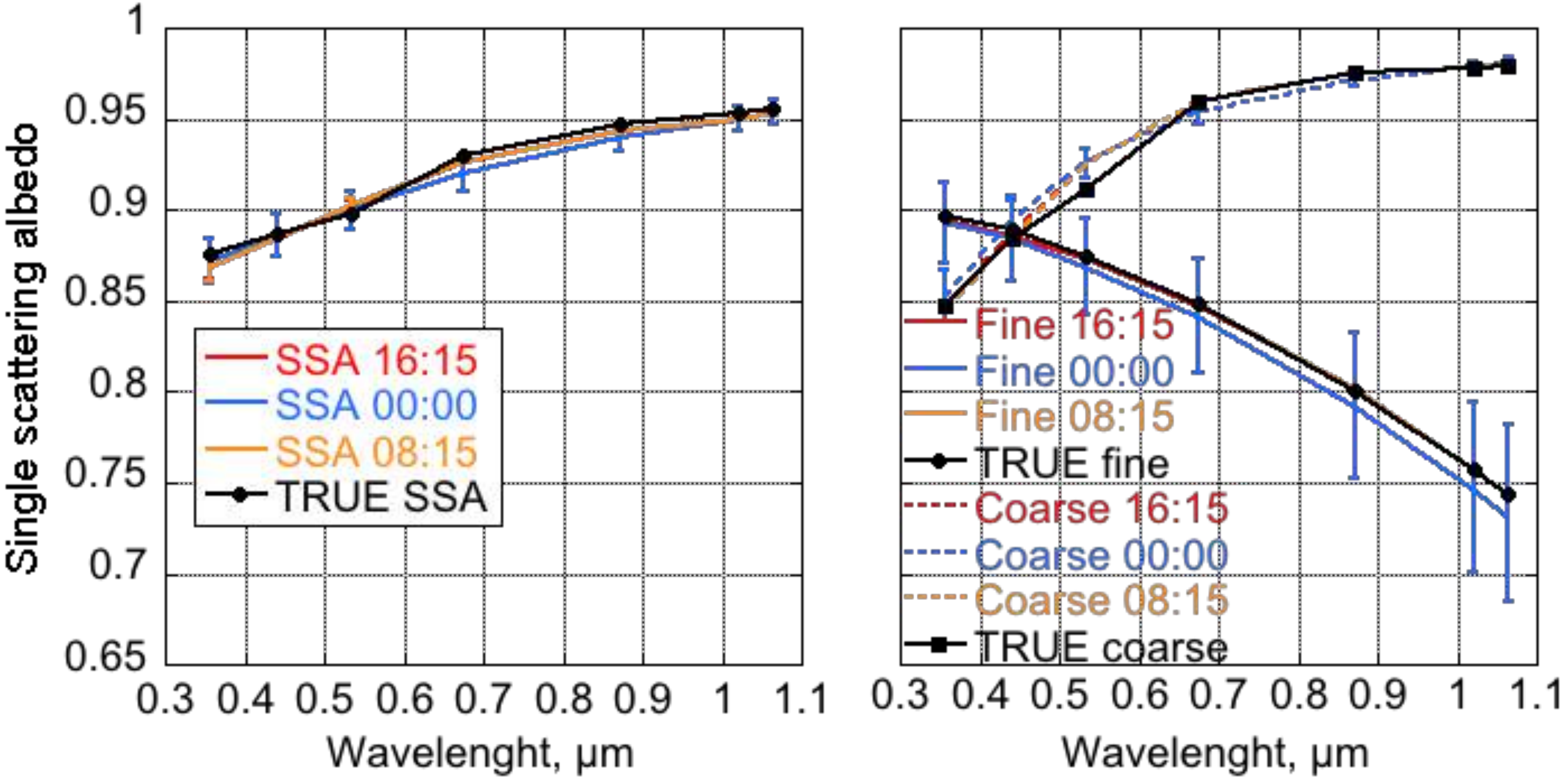
Sensitivity study: refractive indices



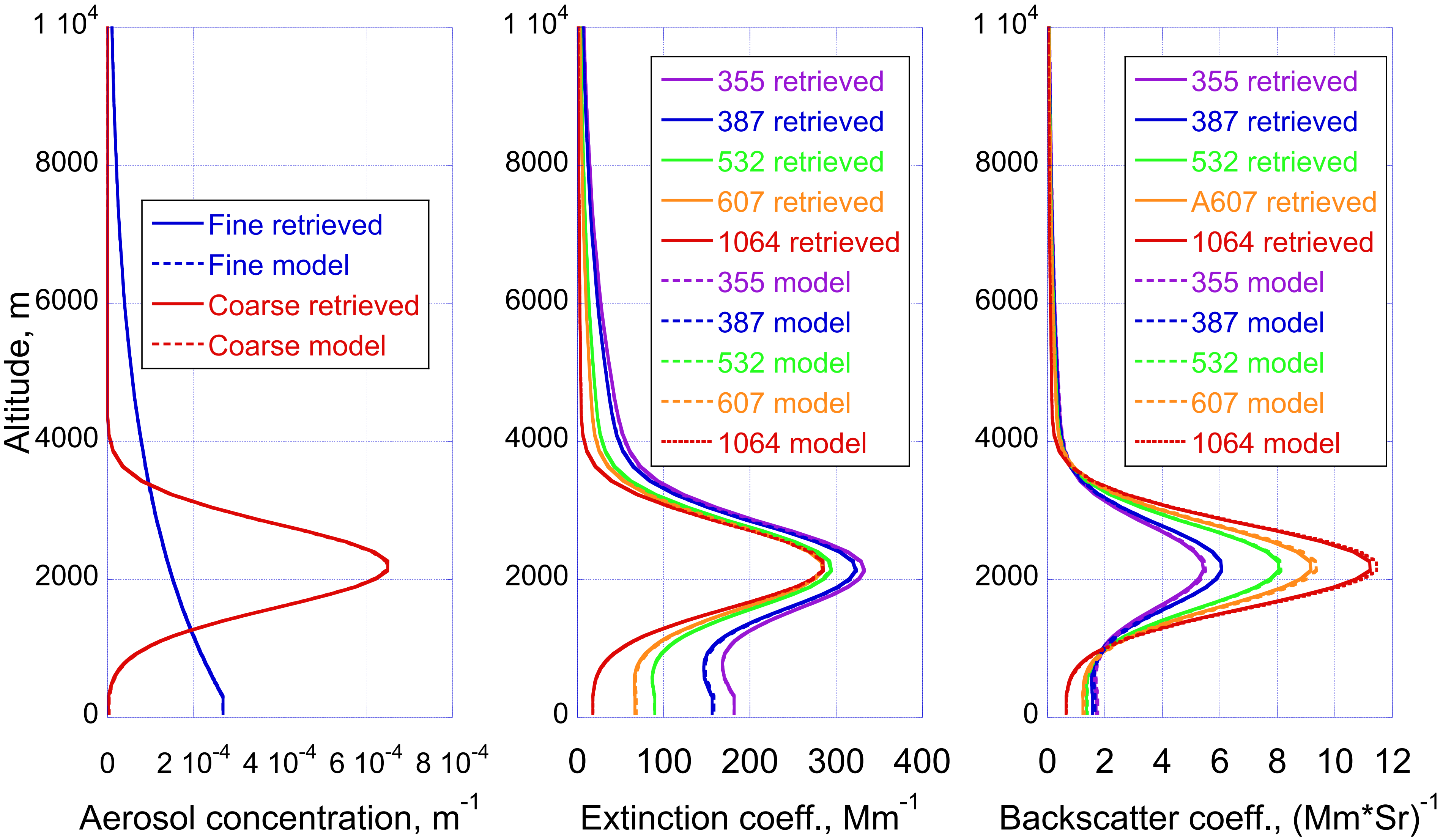
Sensitivity study: vertical distribution



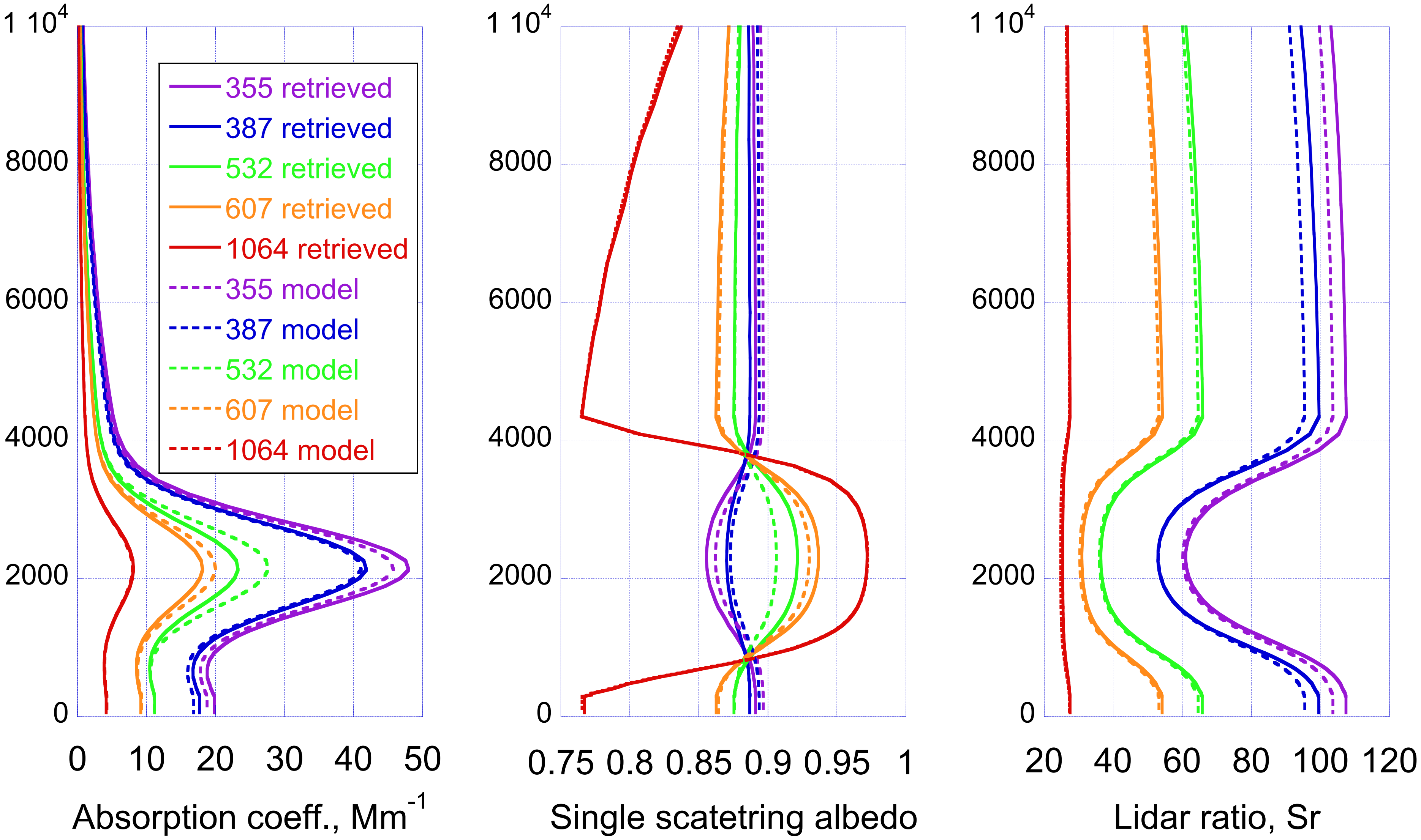
Sensitivity study: columnar SSA



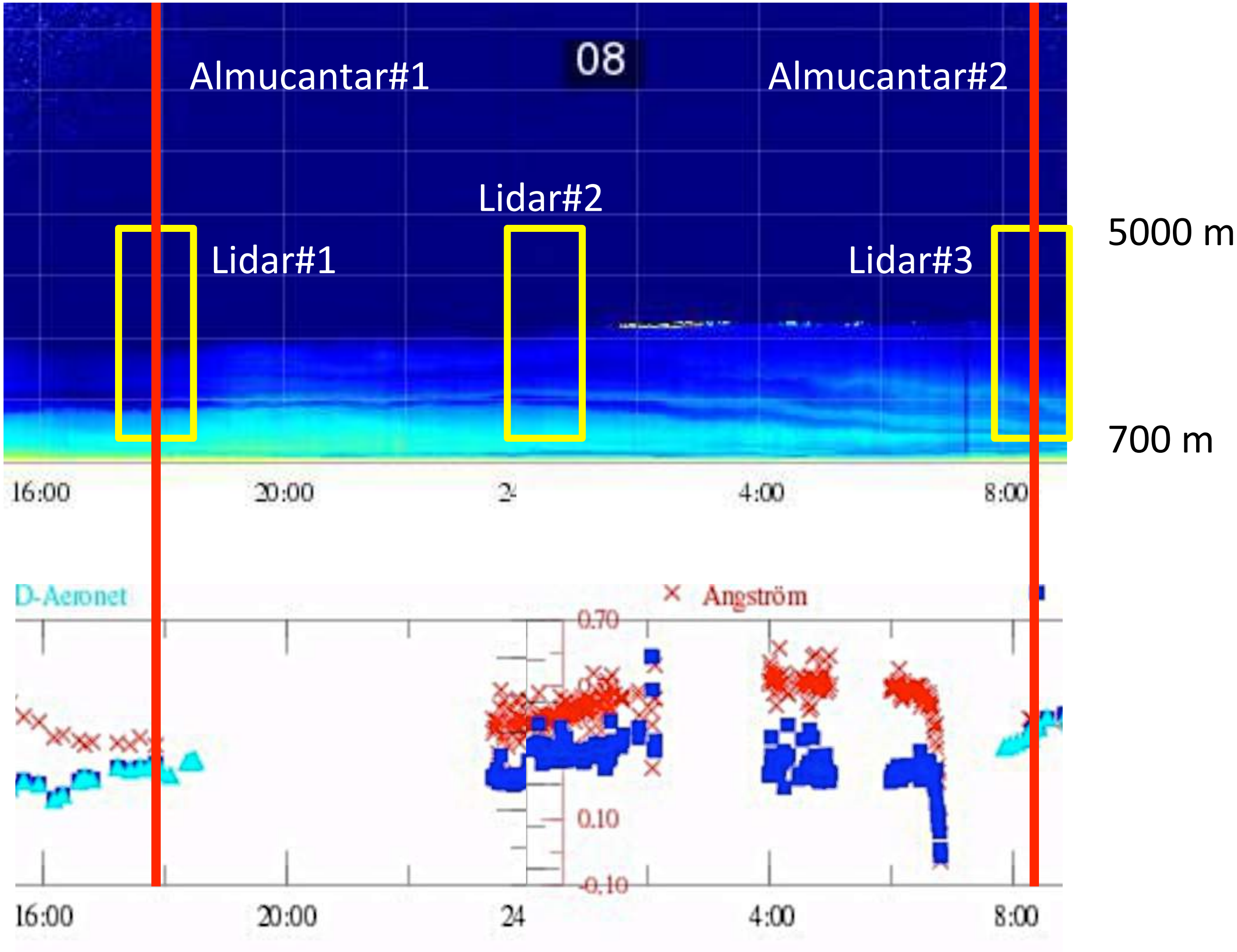
Sensitivity study: now with more RAMAN



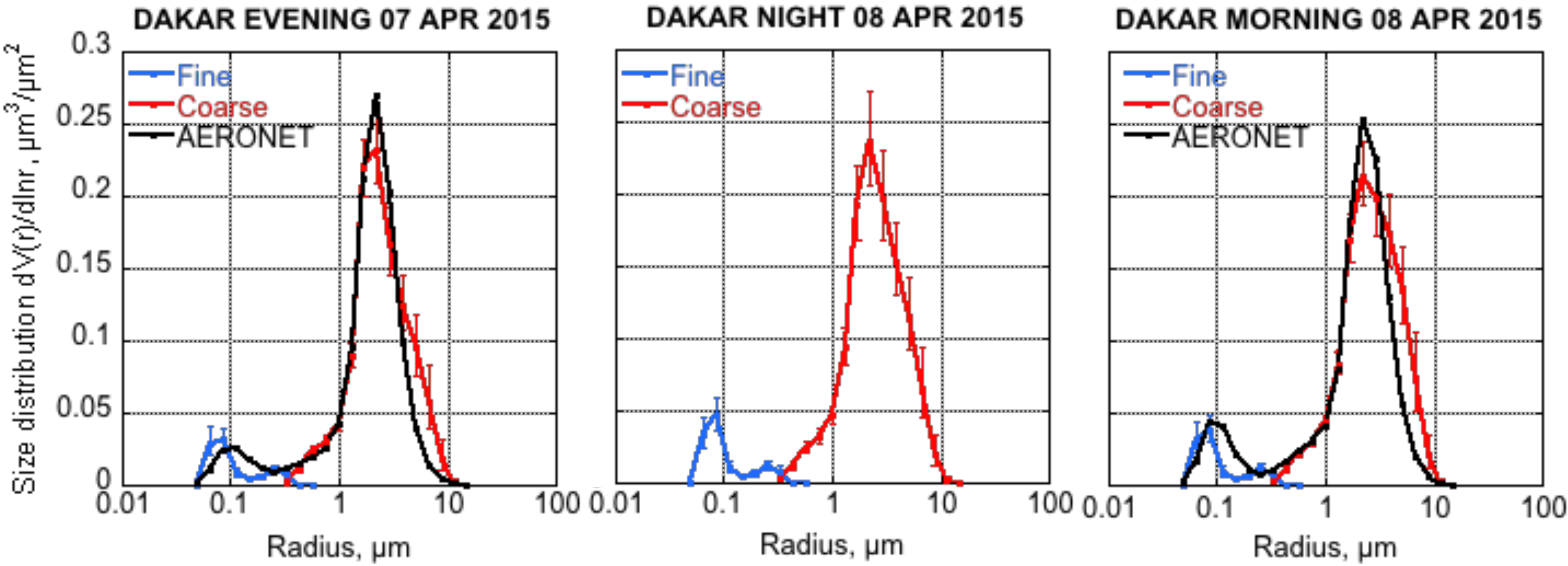
Sensitivity study: now with more RAMAN



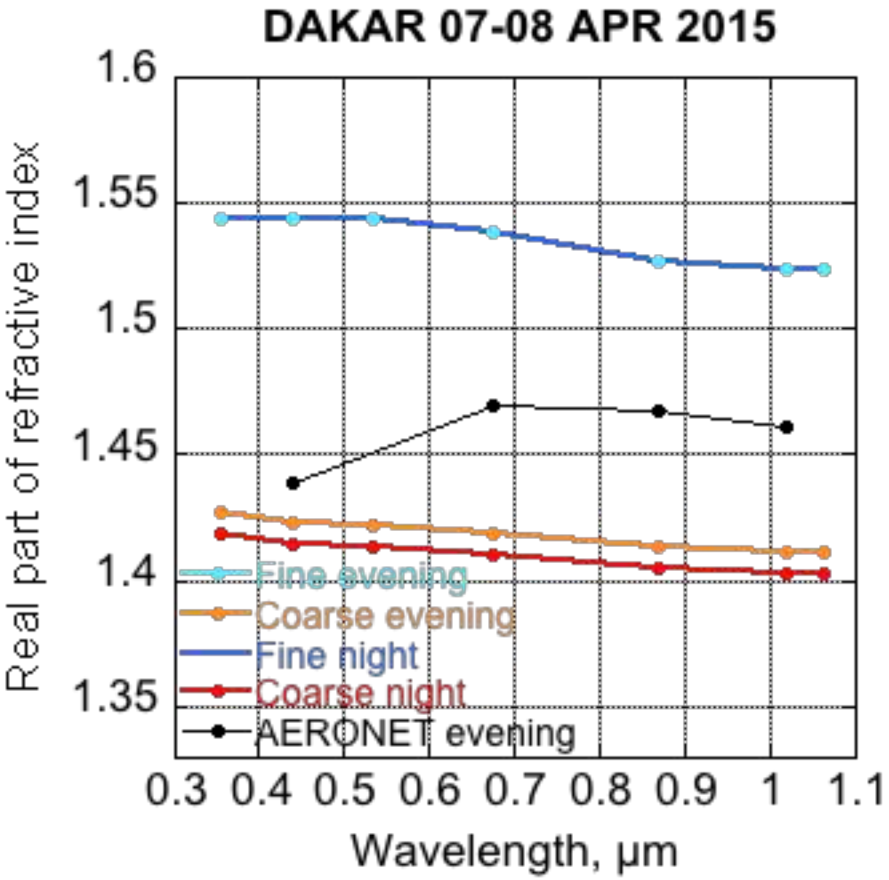
SHADOW campaign retrievals
7–8 APR 2015

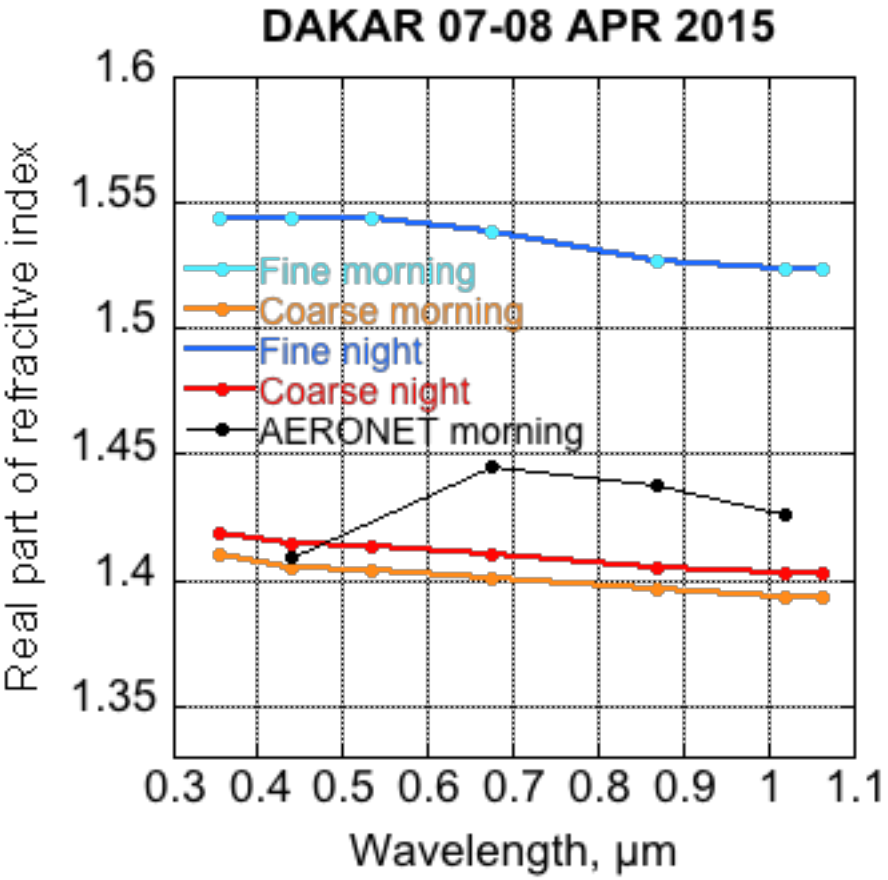


SHADOW retrieval: size distribution

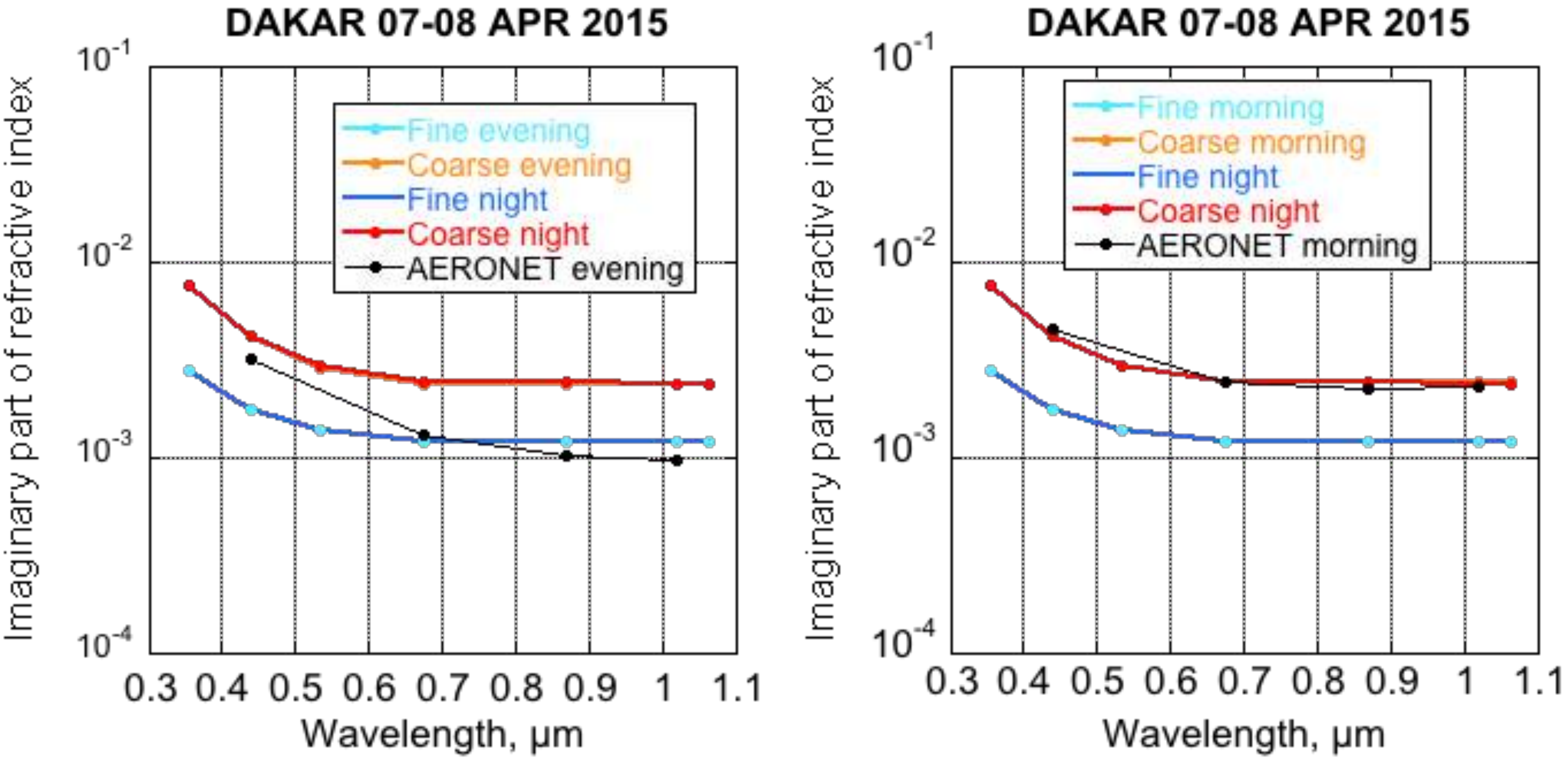


SHADOW retrieval: refractive indices

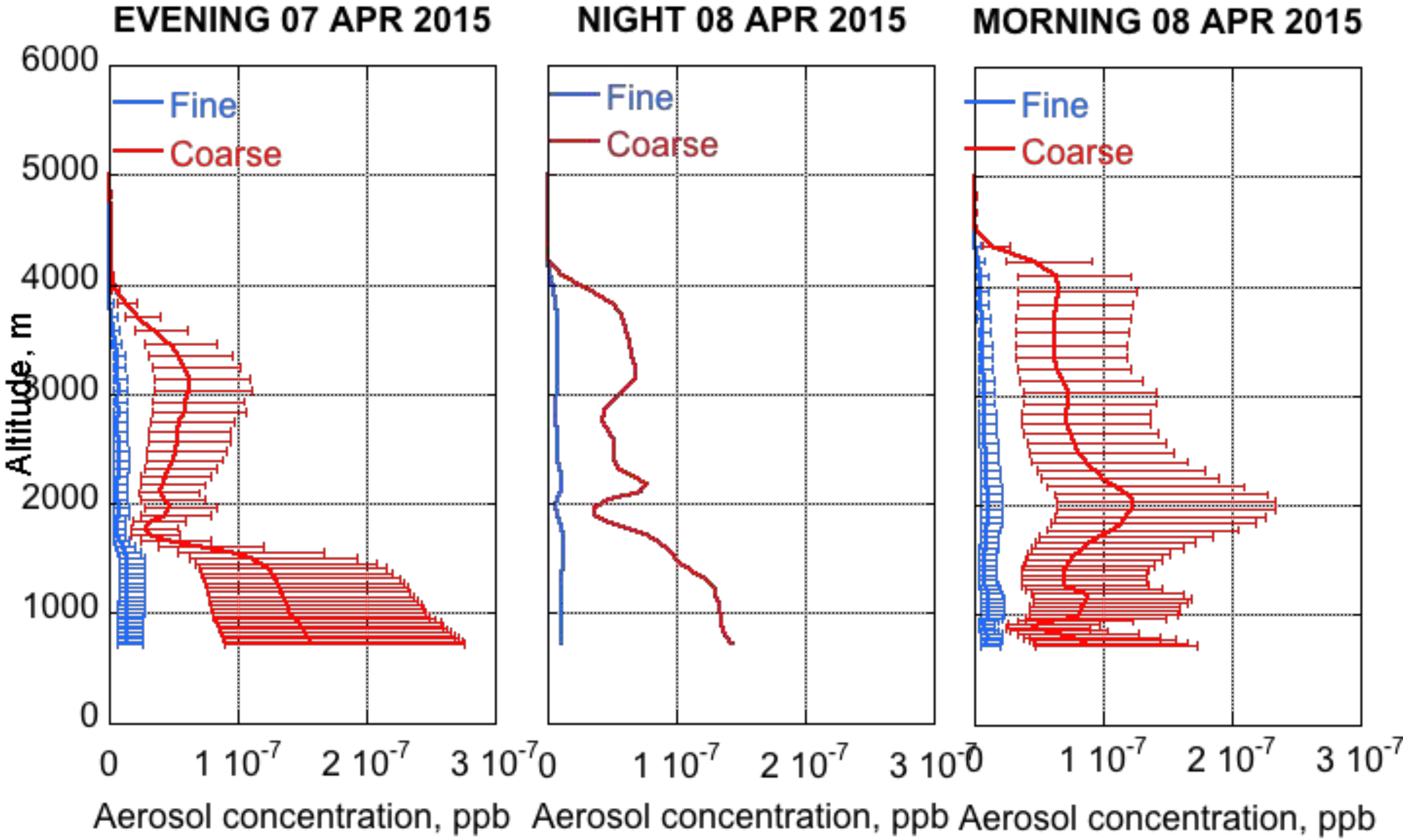




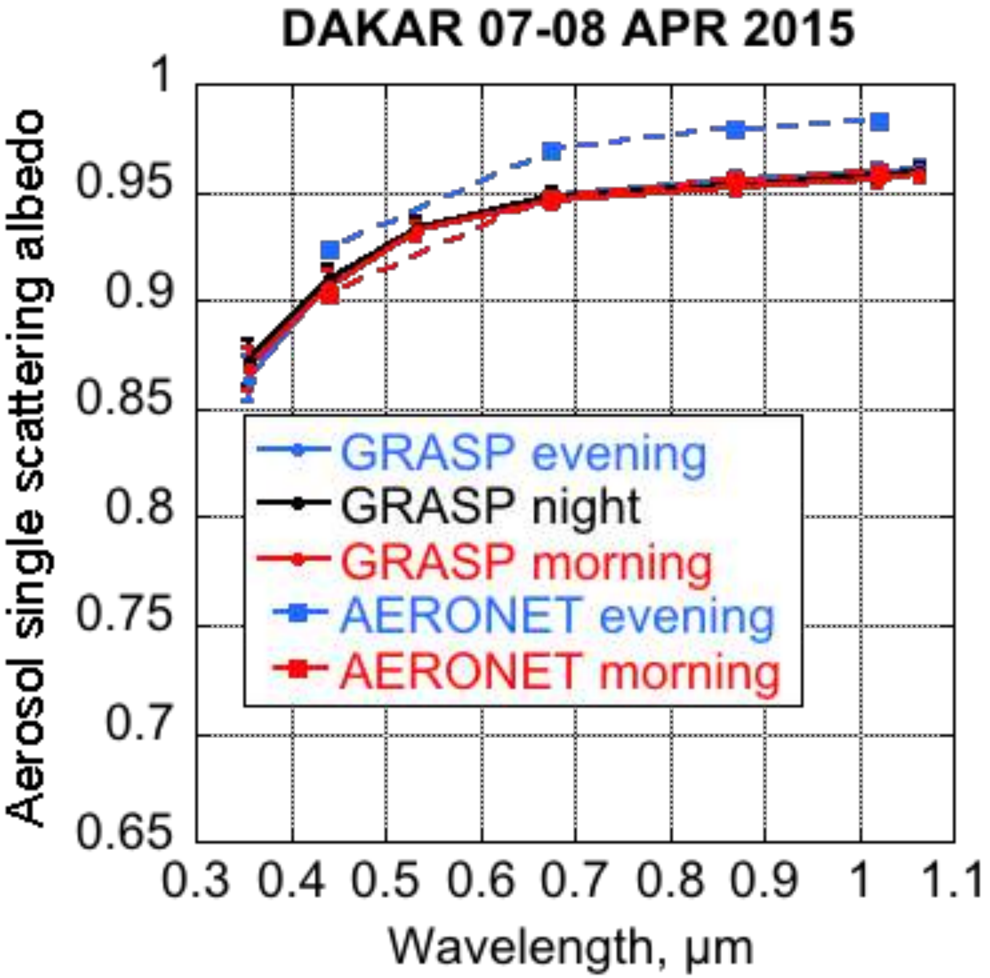
SHADOW retrieval: refractive indices



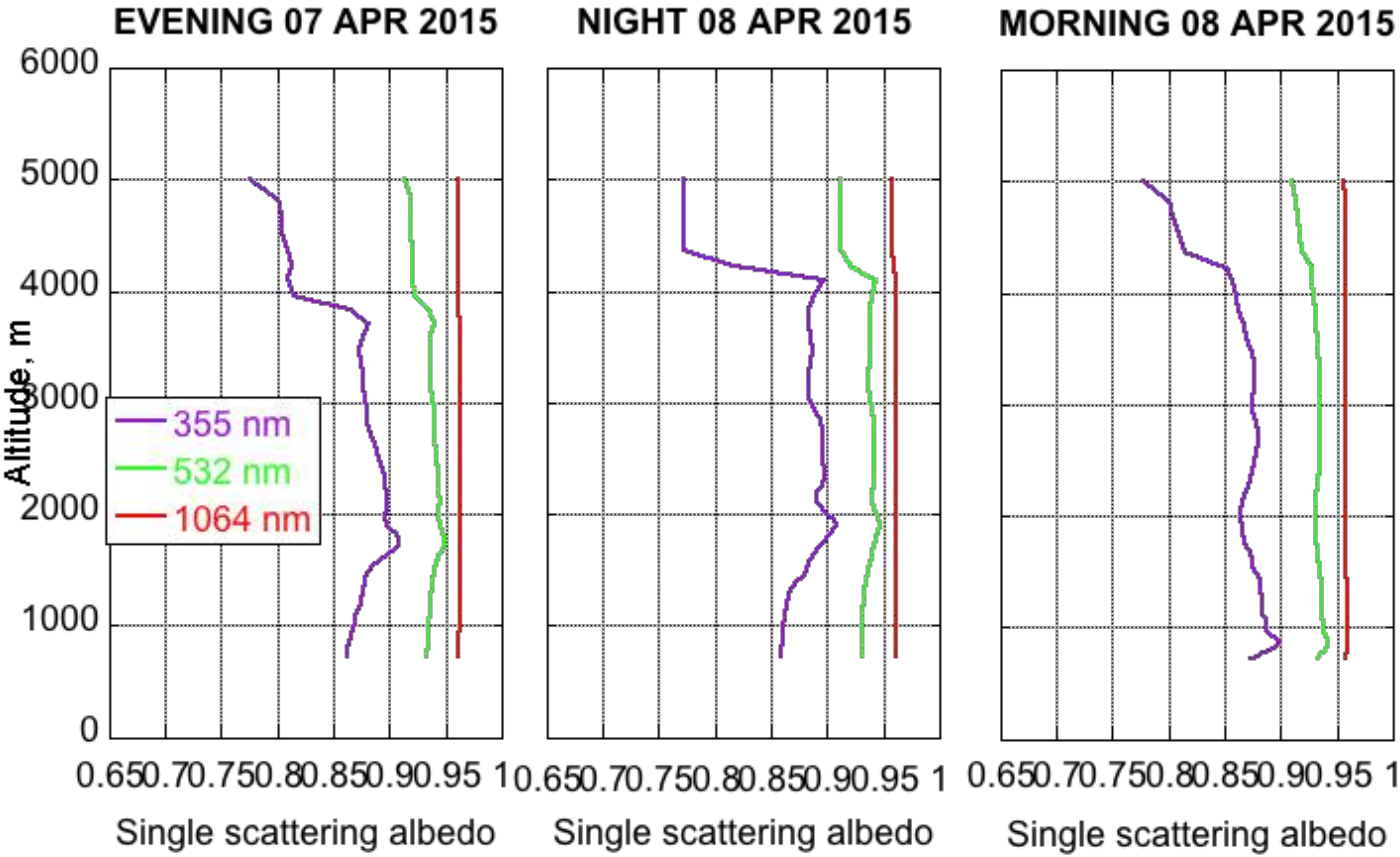
SHADOW retrieval: vertical distribution



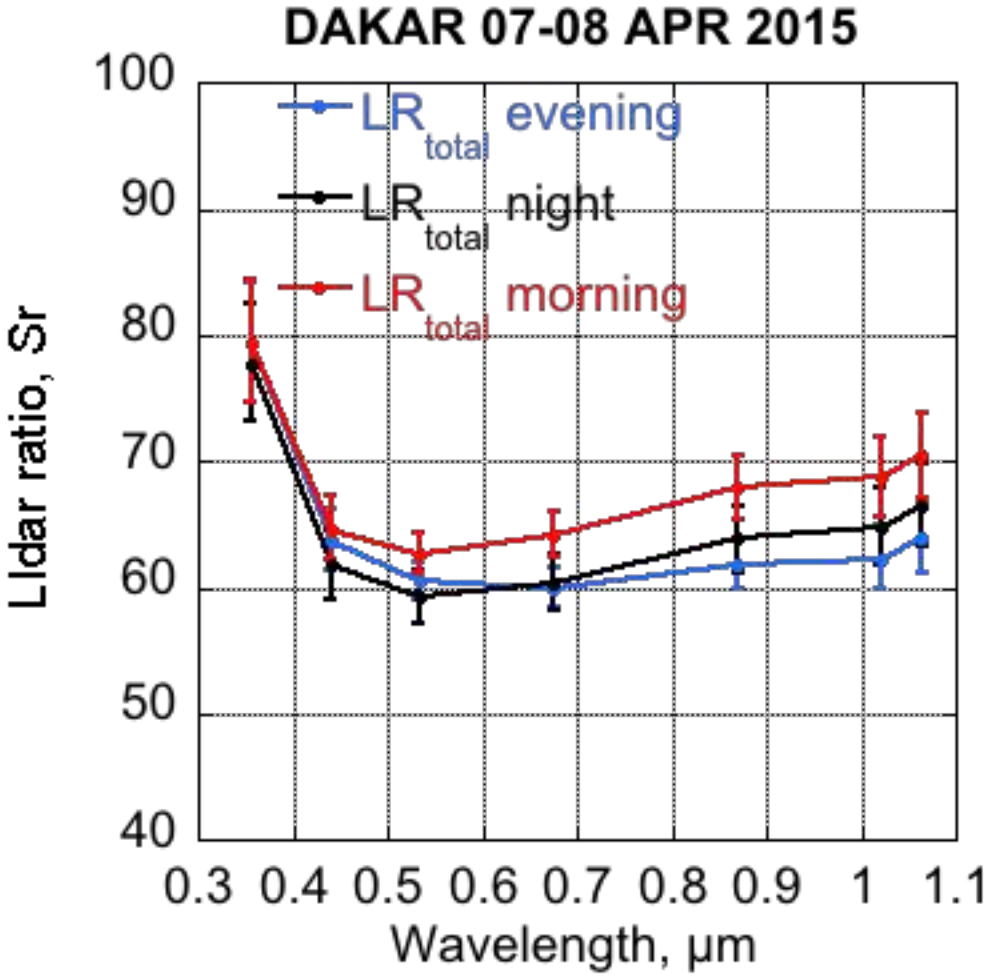
SHADOW retrieval: columnar SSA



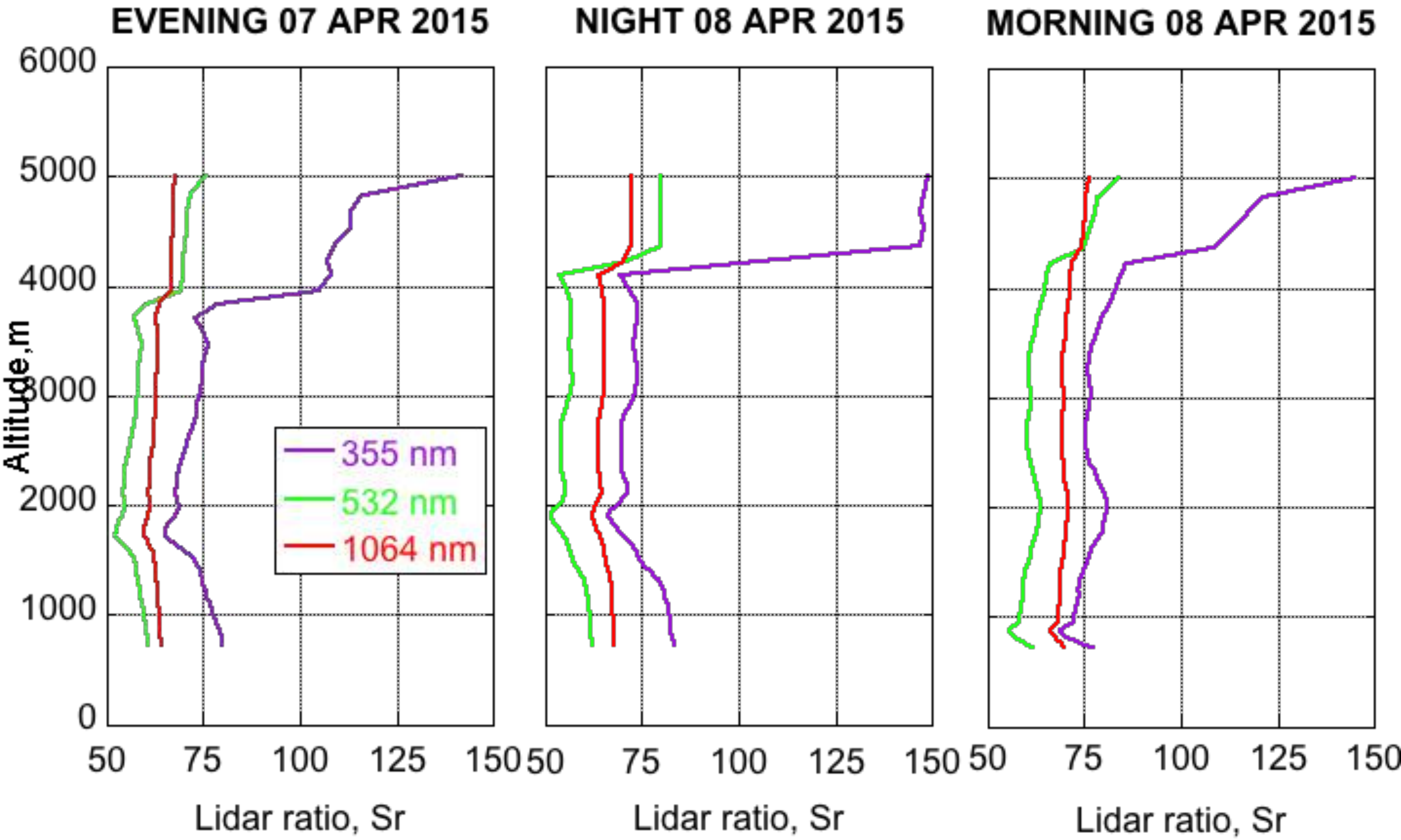
SHADOW retrieval: vertical SSA



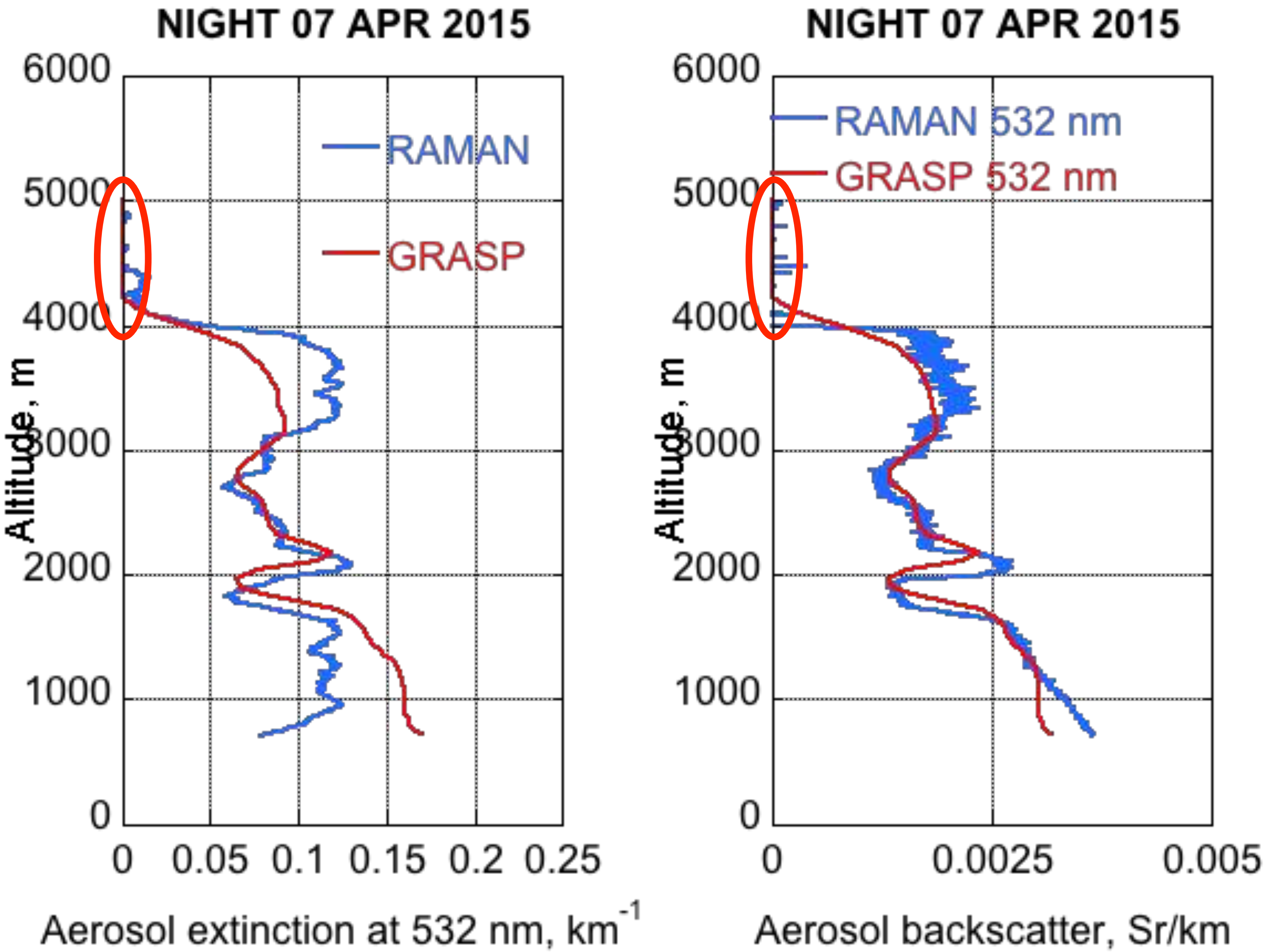
SHADOW retrieval: columnar Lidar Ratio



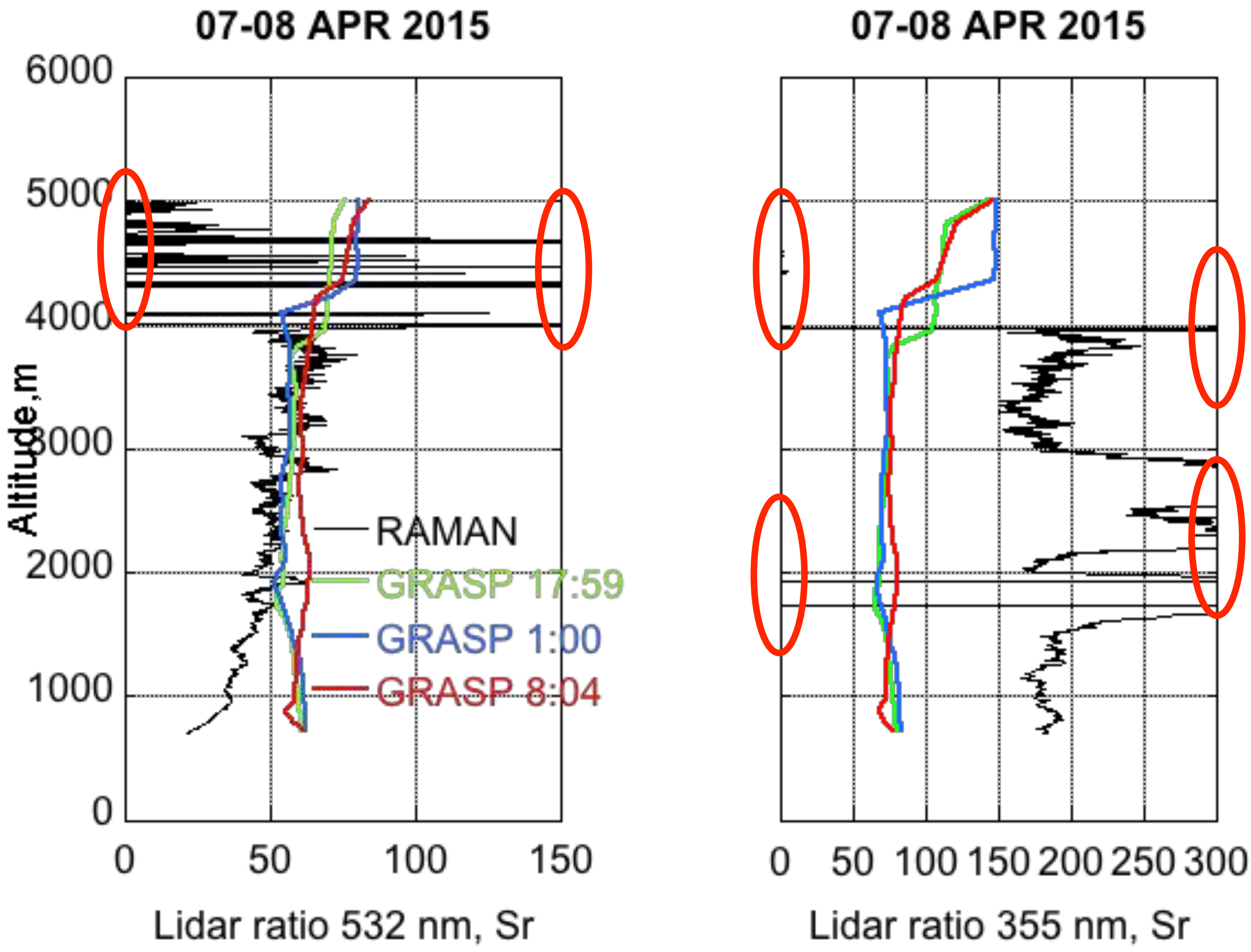
SHADOW retrieval: vertical Lidar Ratio



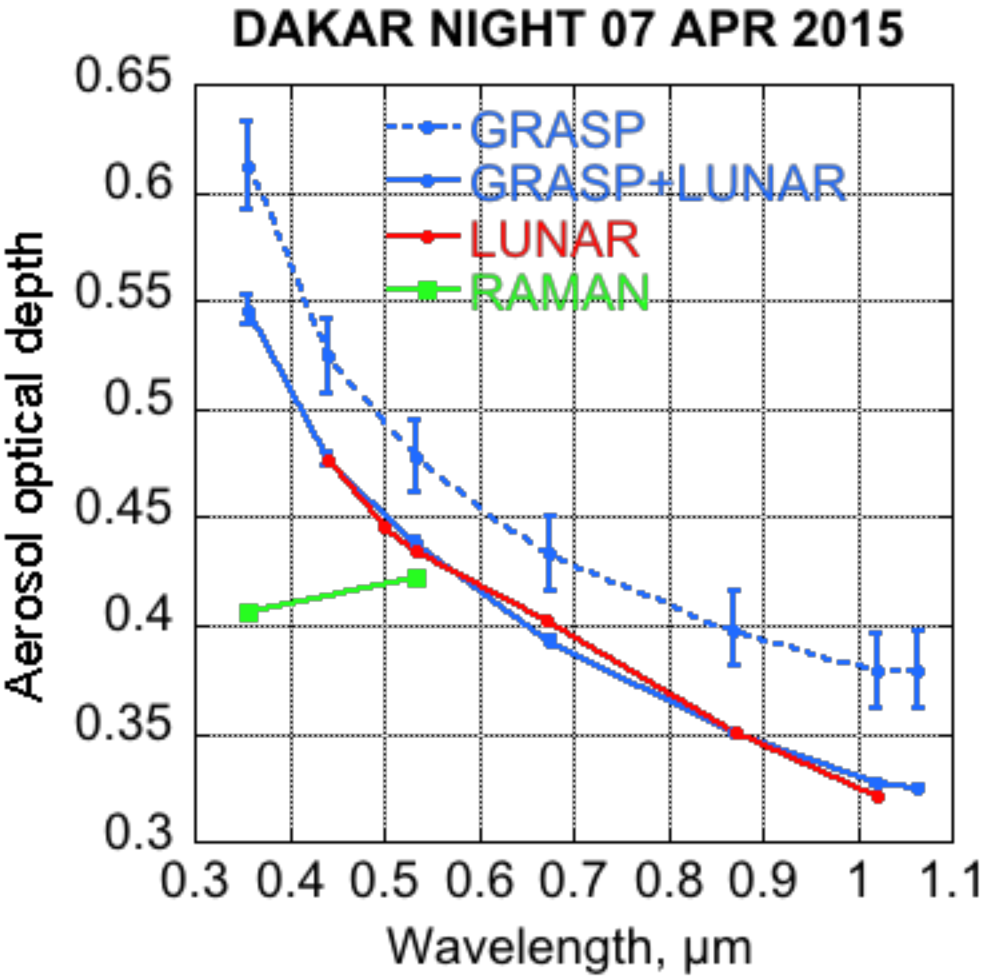
SHADOW retrieval: GRASP vs RAMAN



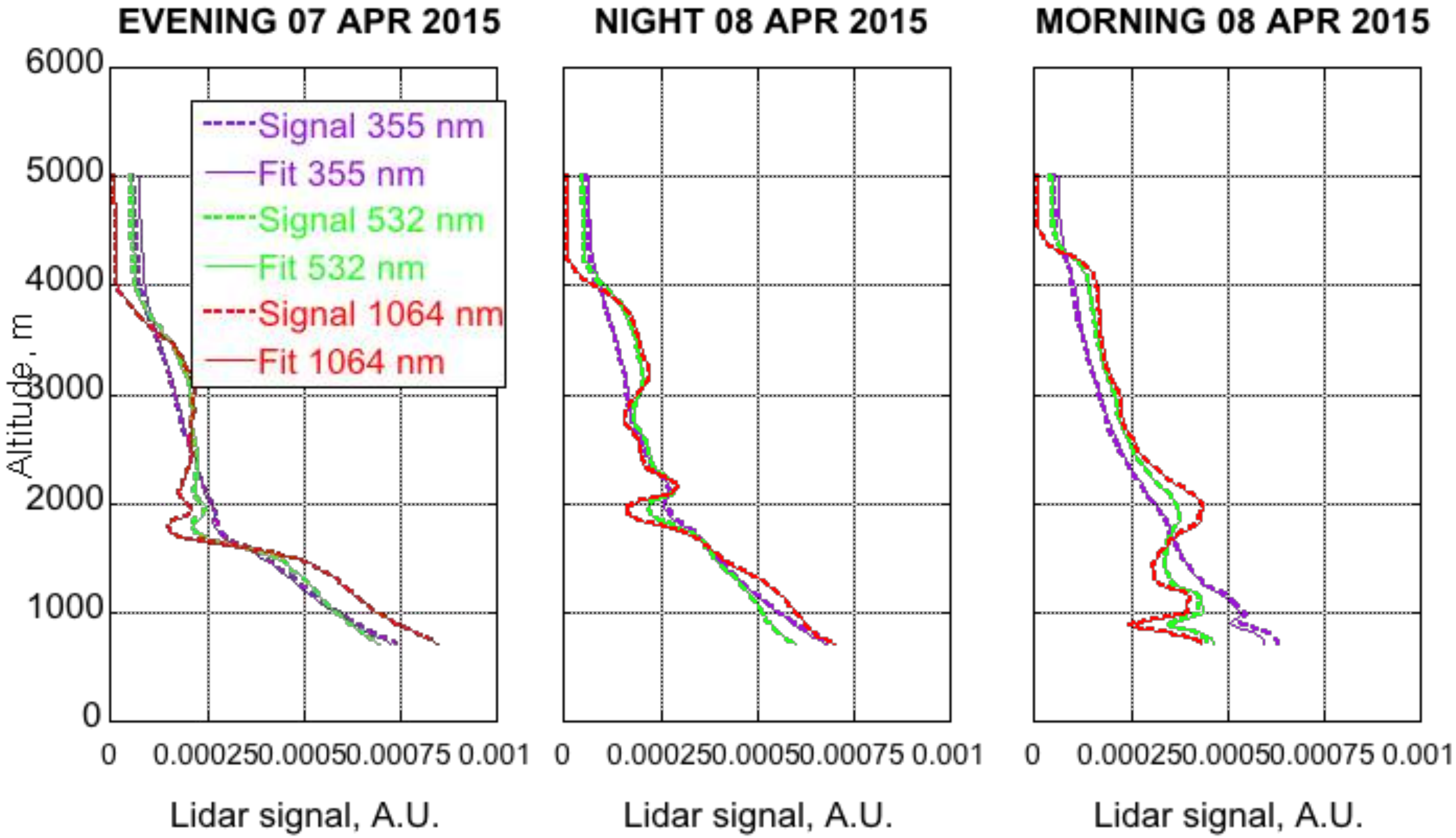
SHADOW retrieval: GRASP vs RAMAN



SHADOW retrievals: AOD



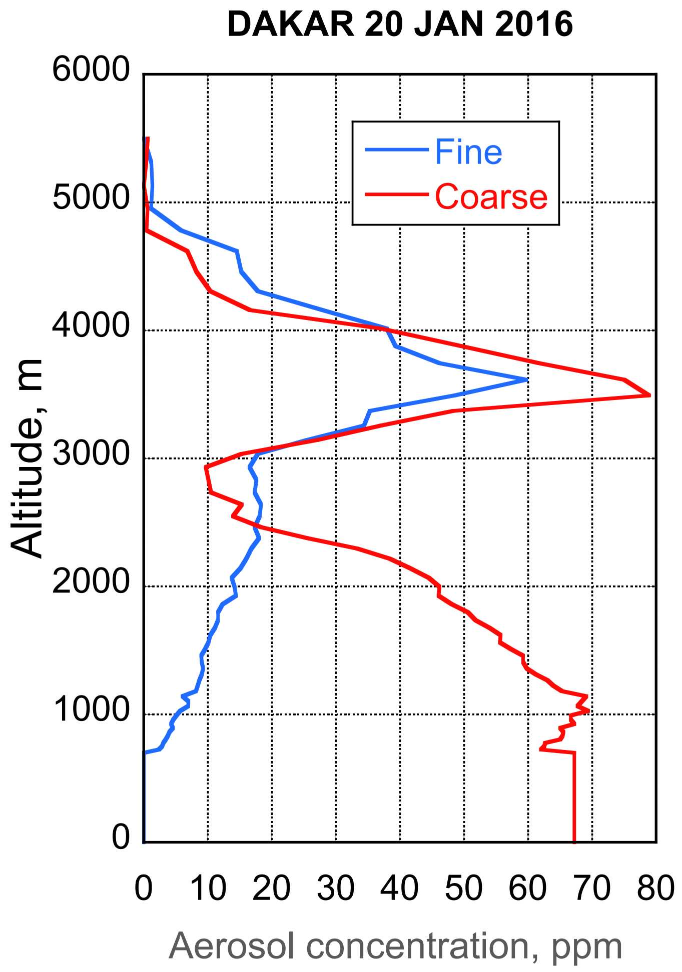
SHADOW retrieval: lidar fits

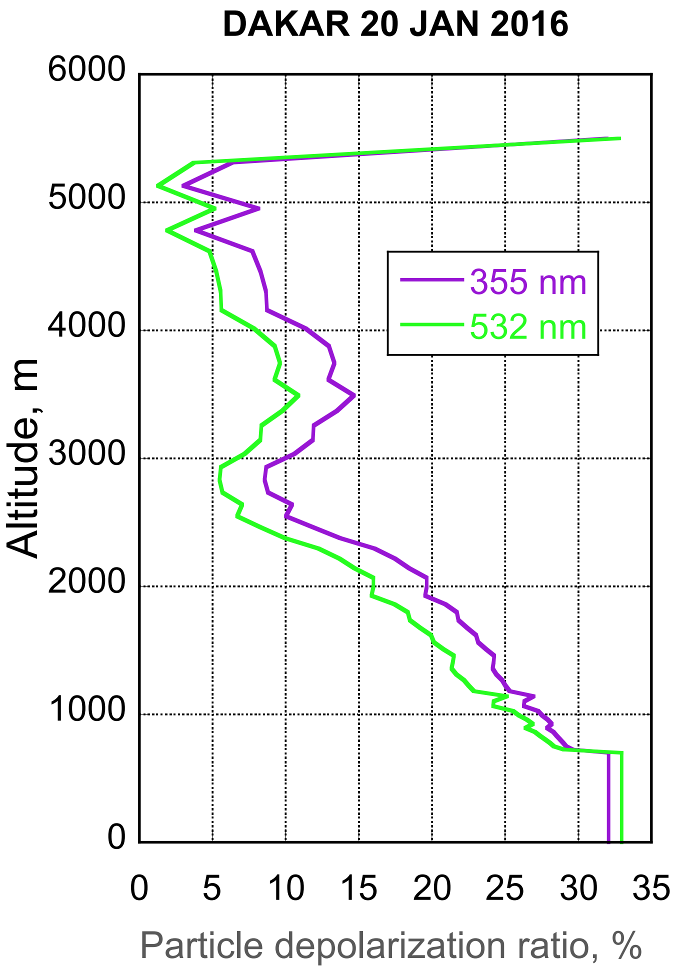


The first **results by Qiaoyun Hu** showing depolarization retrievals

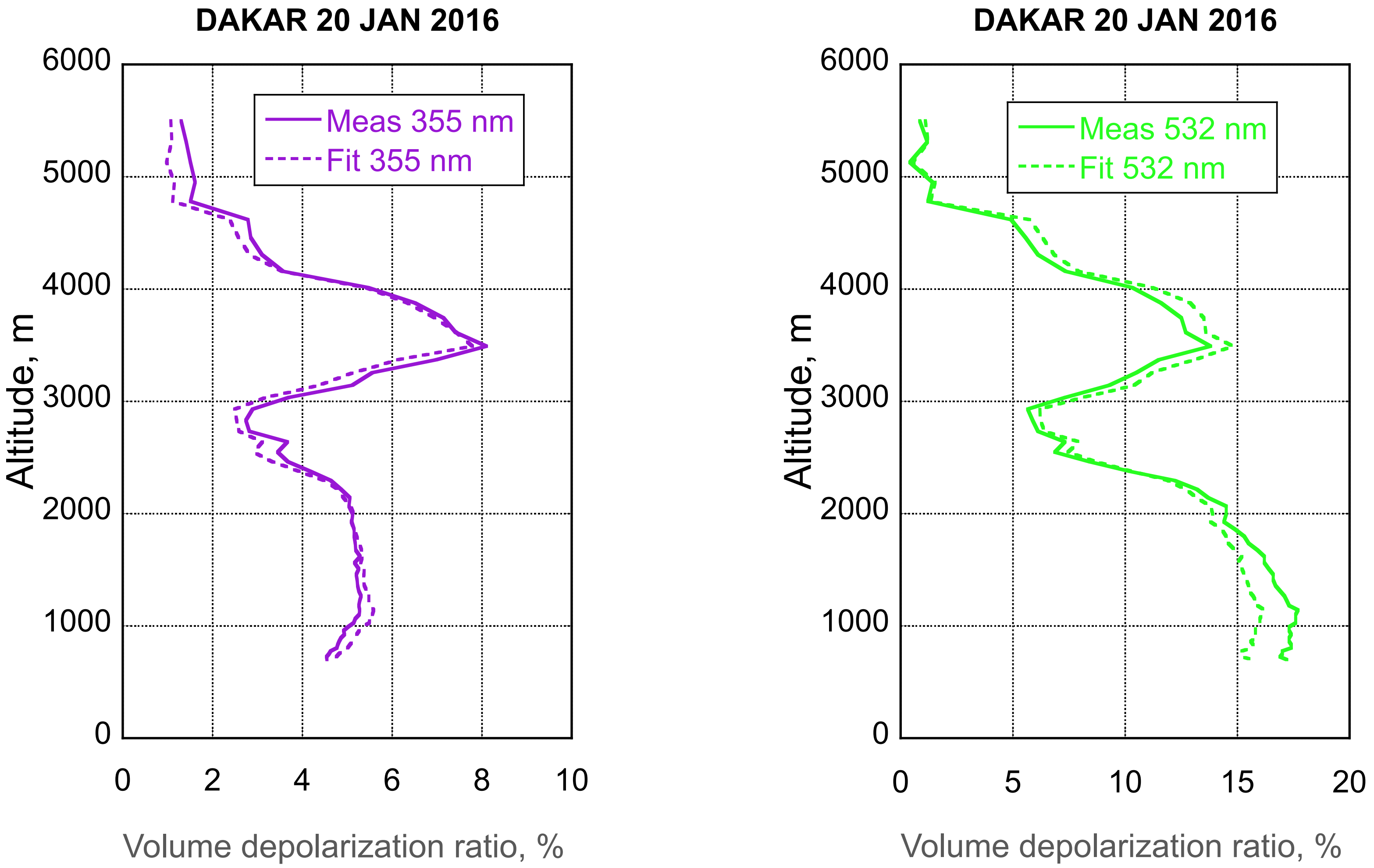
GRASP AEROSOL DEPOLARIZATION PROFILING

SHADOW retrieval: particle depolarization profile





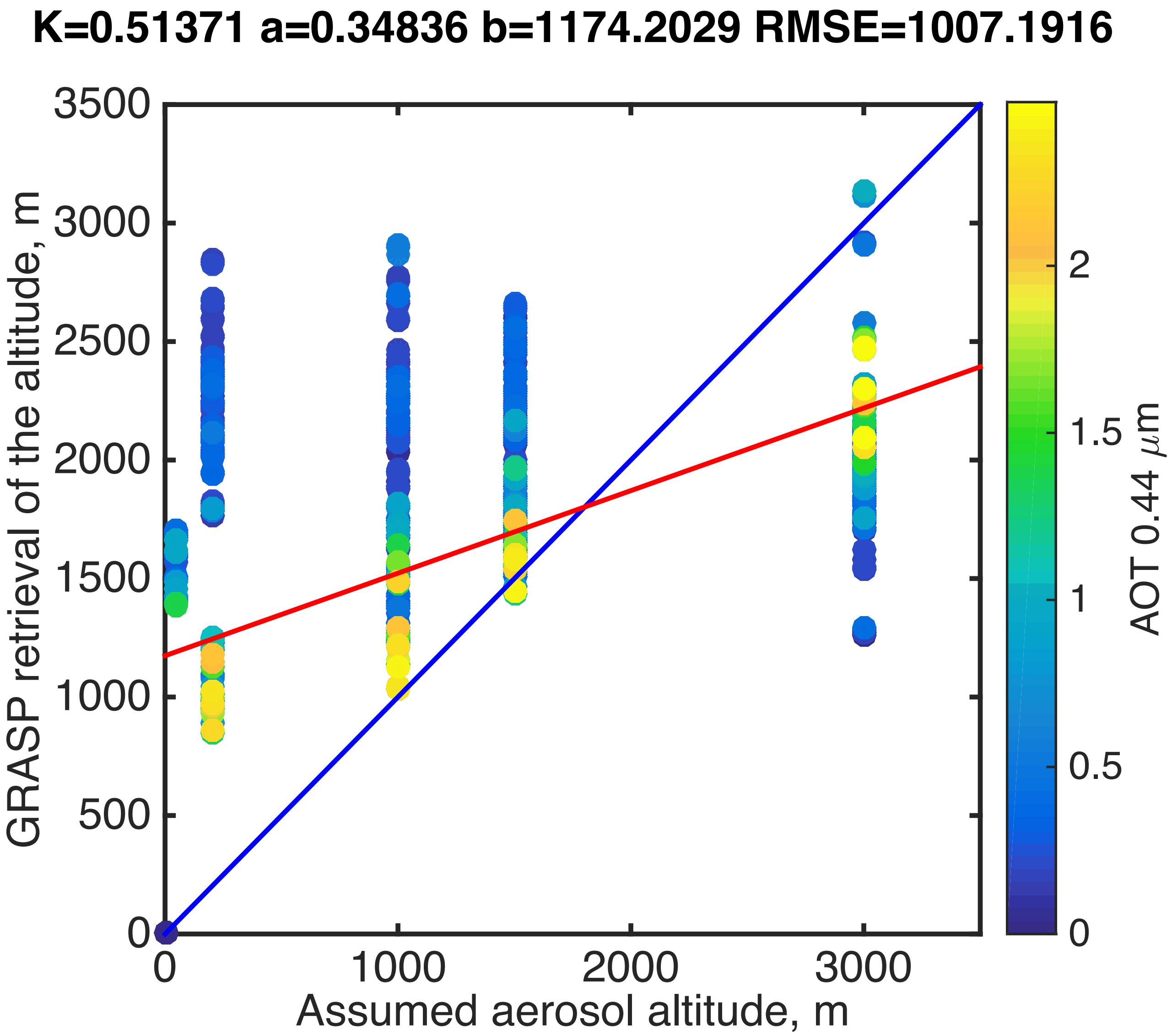
SHADOW retrieval: VDPR fits



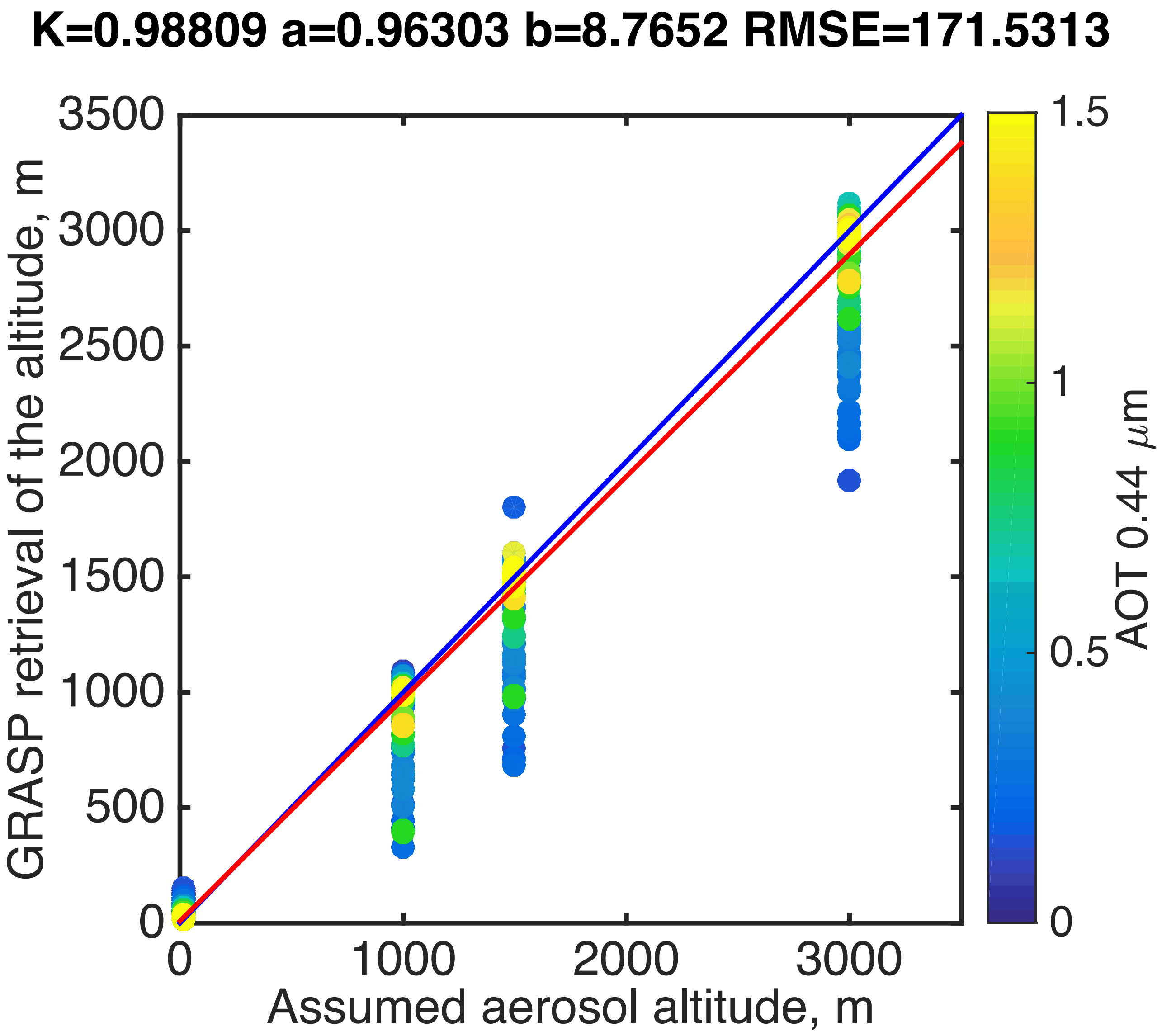
Can we do profiling without lidars?

GRASP POLARIMETRIC PROFILING

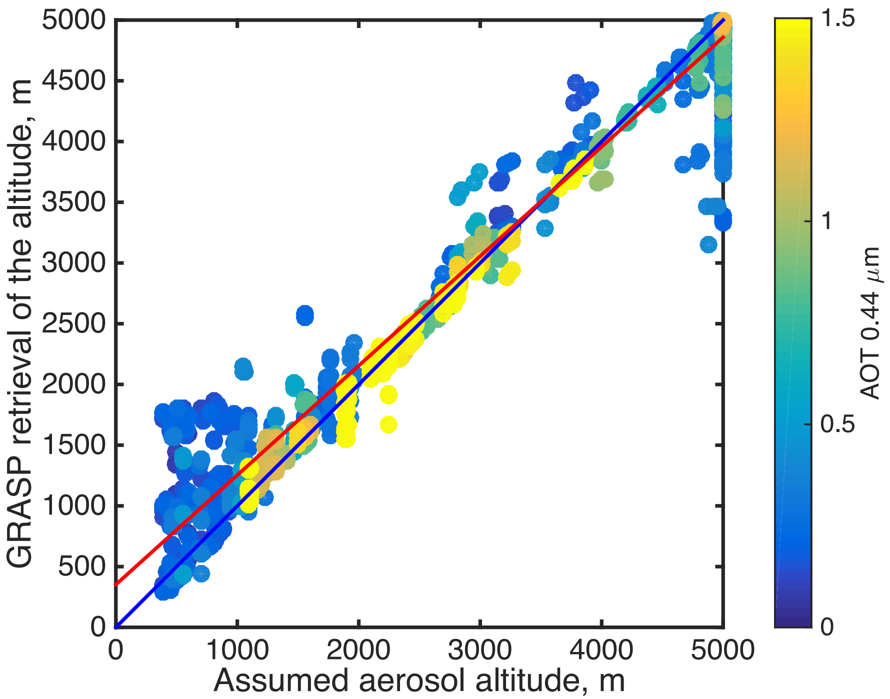
GRASP POLDER threshold profile



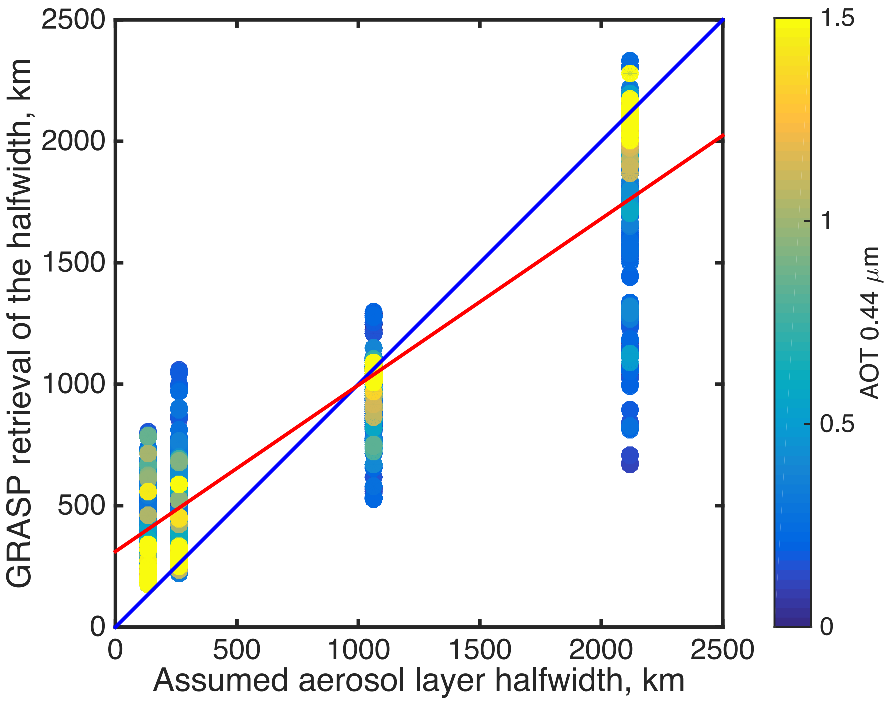
GRASP POLDER exponential profile



GRASP POLDER Gaussian profile

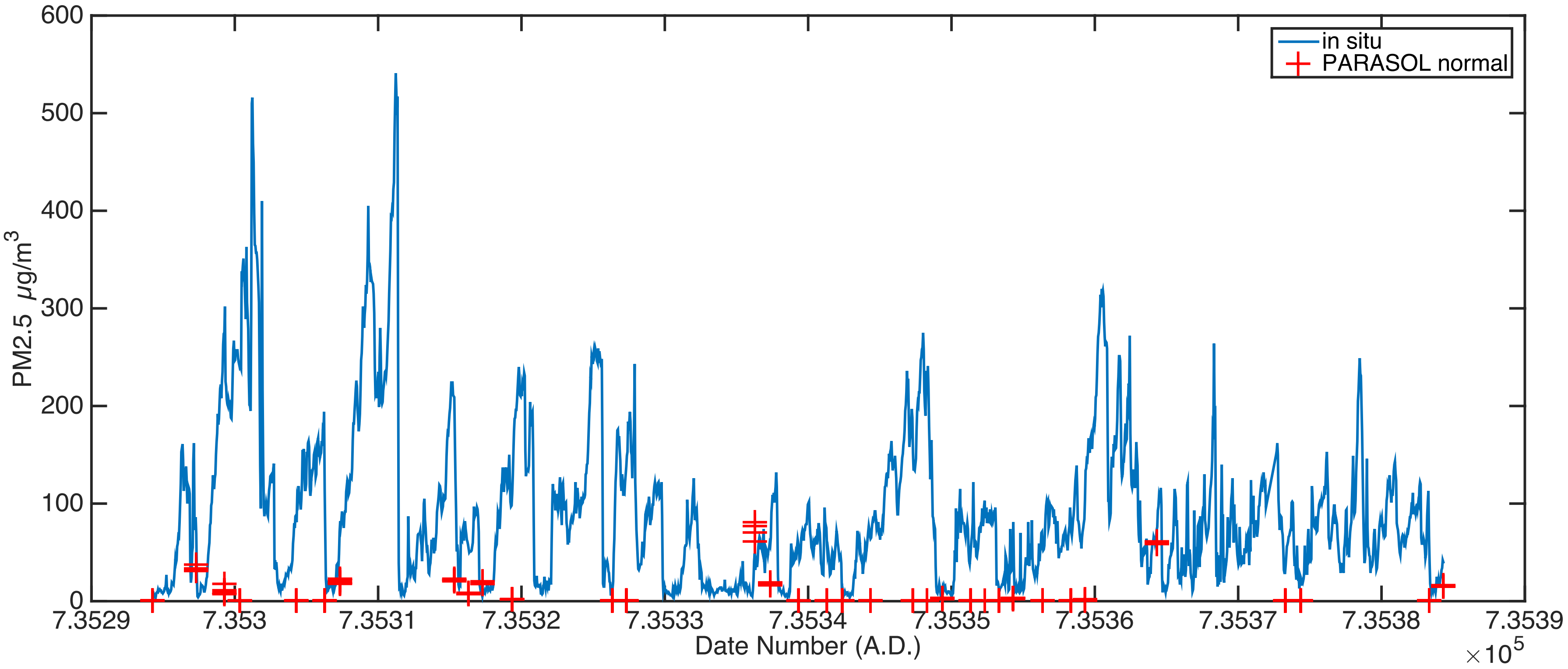


K=0.9832 a=0.90127 b=352.2162 RMSE=358.2394

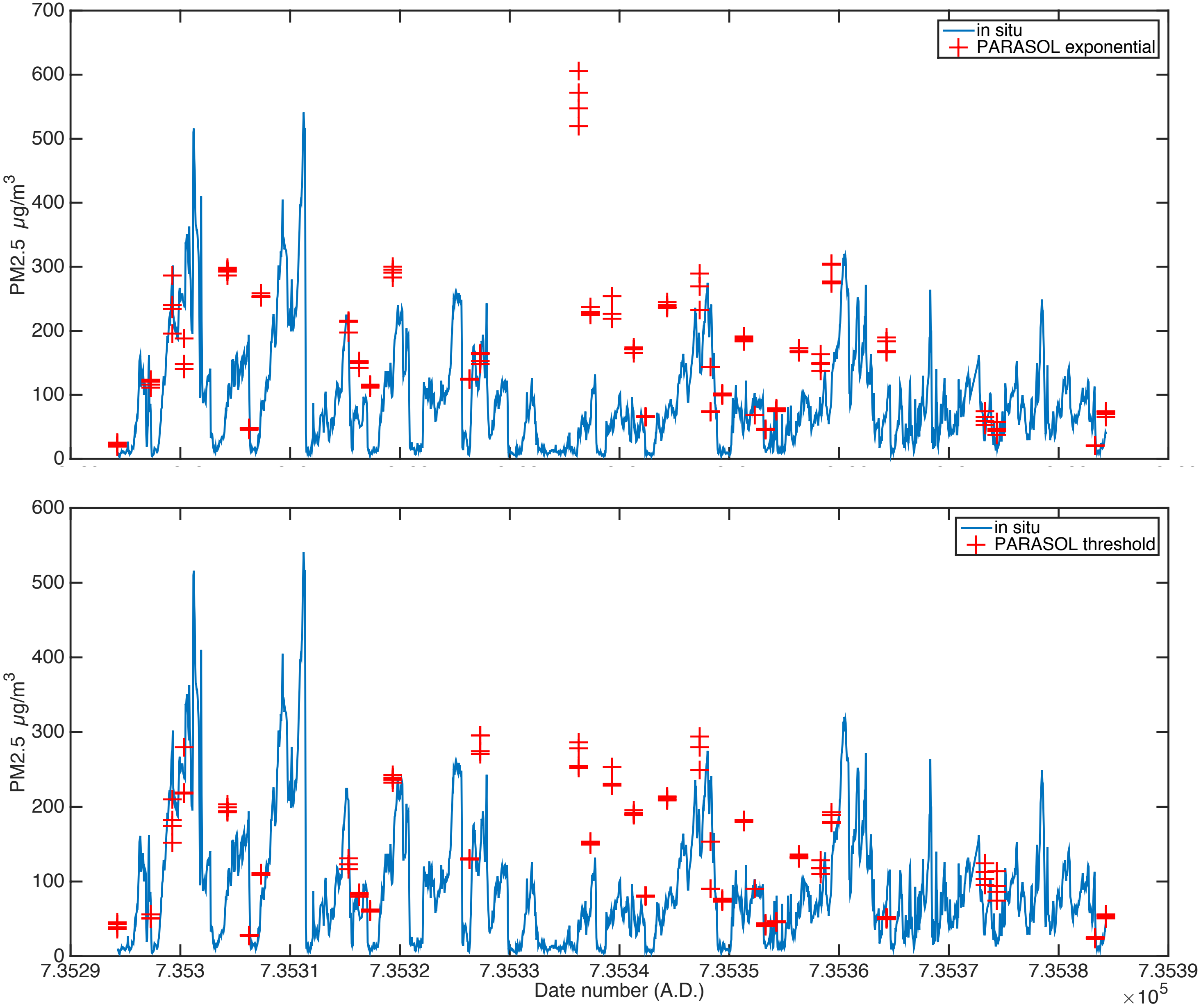


K=0.90601 a=0.68508 b=311.1249 RMSE=356.8278

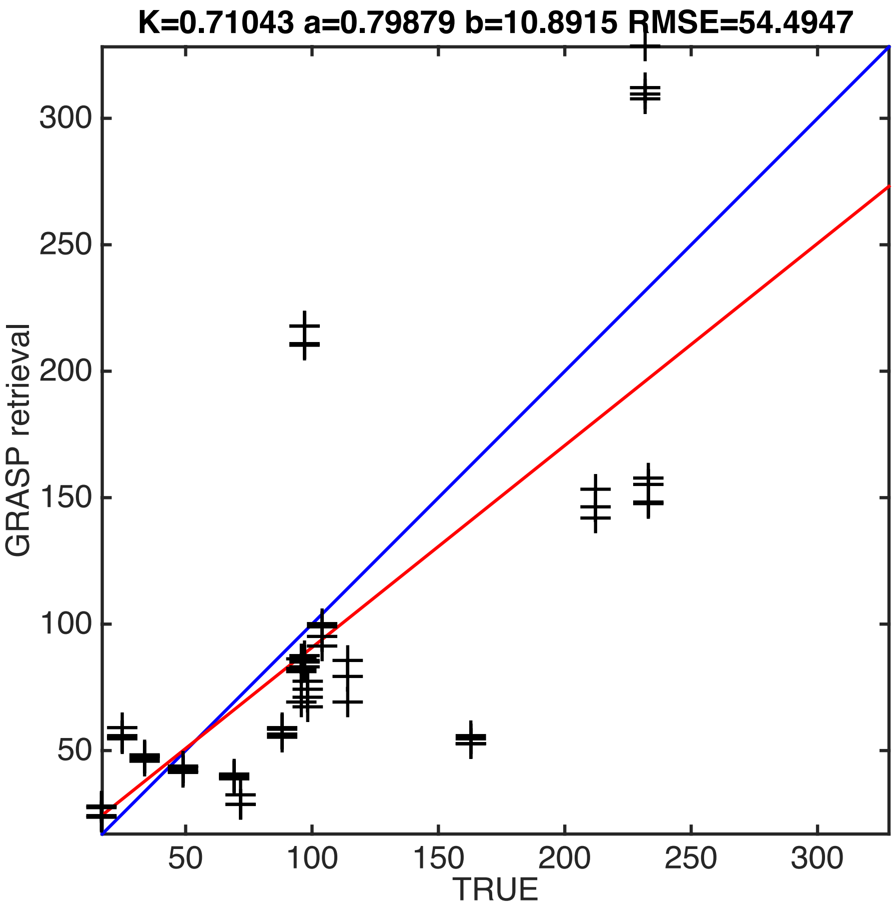
GRASP POLDER profiling: ground level



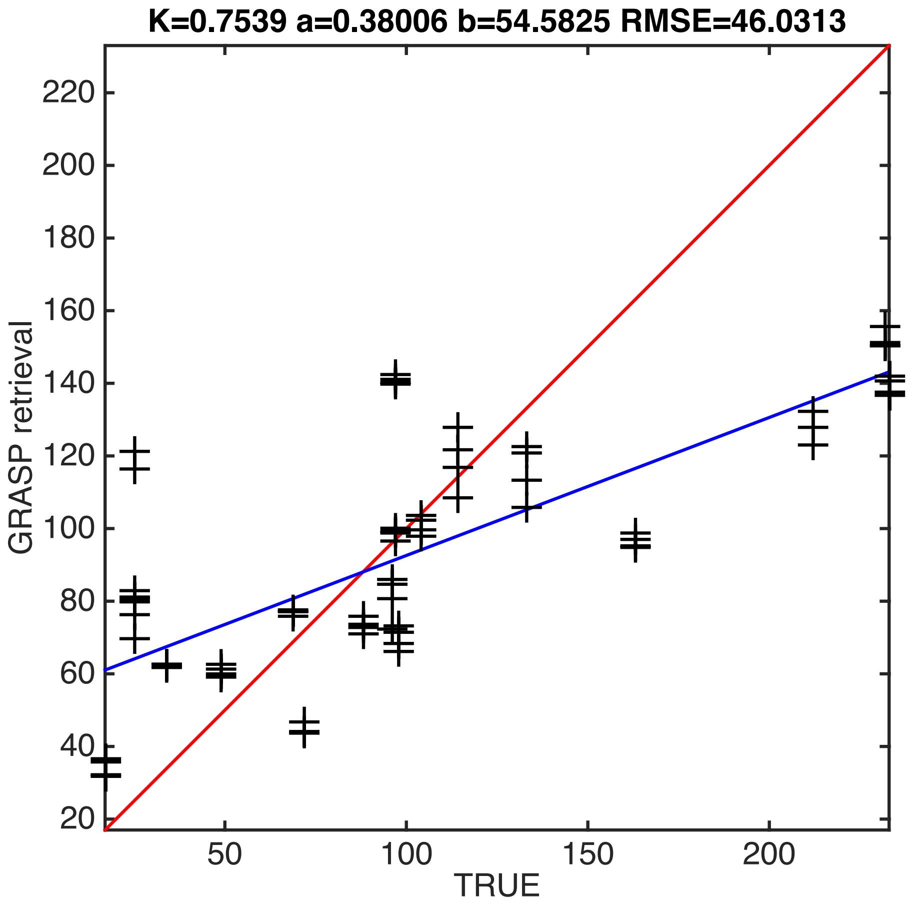
GRASP POLDER profiling: ground level



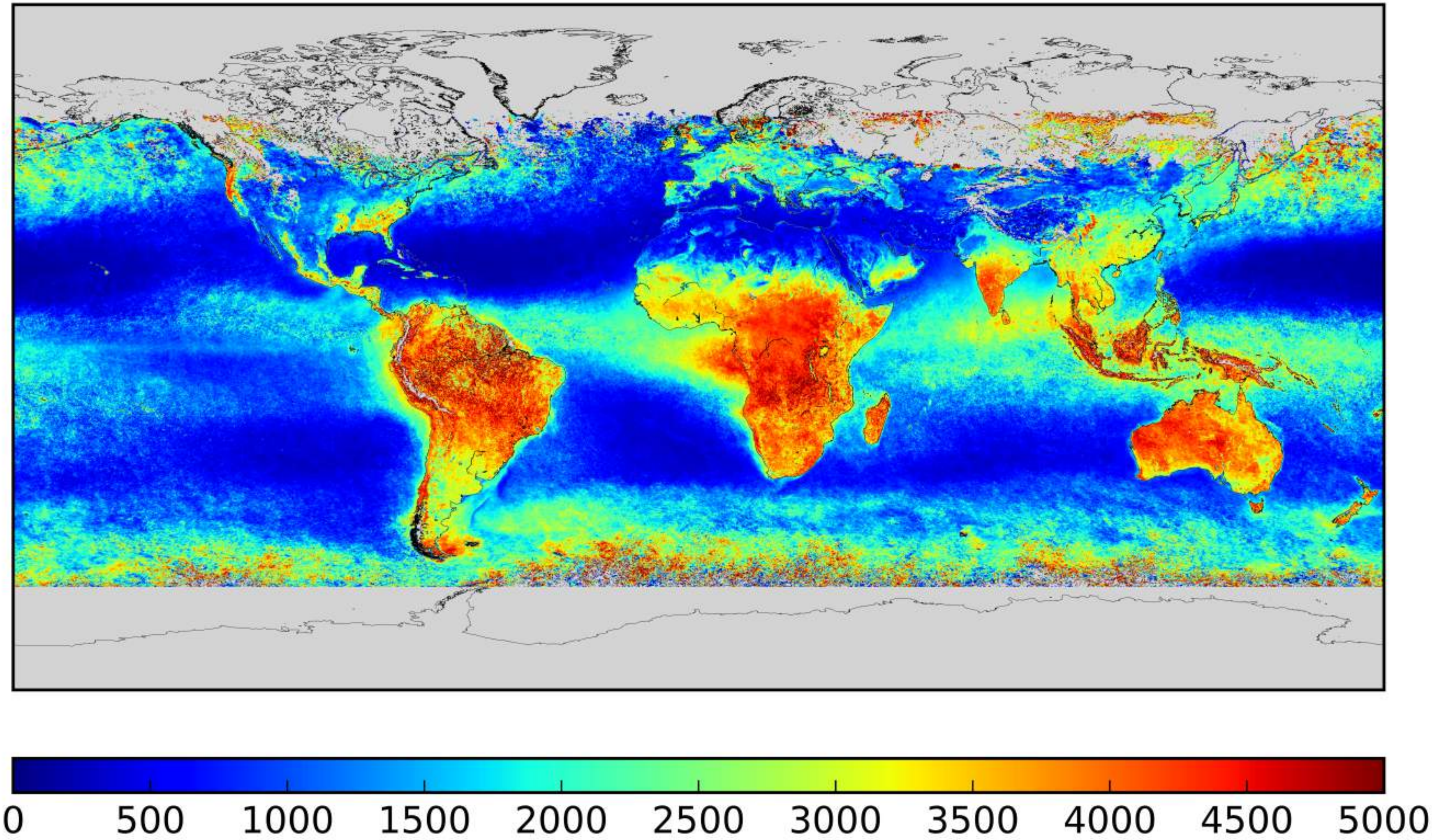
GRASP POLDER profiling: ground level



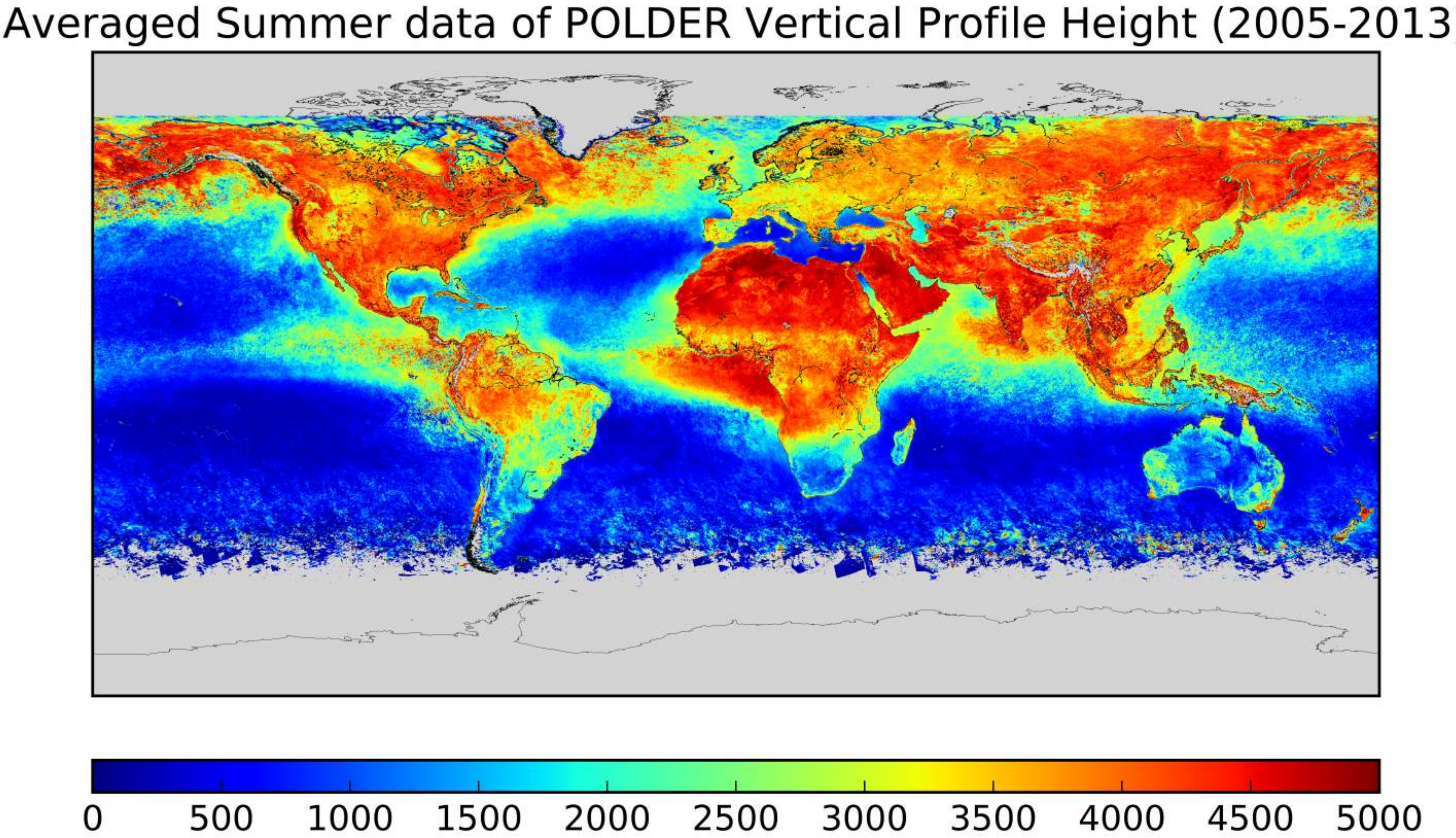
K=0.71043 a=0.79879 b=10.8915 RMSE=54.4947



K=0.7539 a=0.38006 b=54.5825 RMSE=46.0313



Averaged Winter data of POLDER Vertical Profile Height (2005-2013)


Averaged Summer data of POLDER Vertical Profile Height (2005-2013
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

Taking the most of profile retrievals

GRASP/GARRLIC HOW TO

What you can get from GRASP/GARRLiC

- Mode resolved* aerosol properties:
  - (SD, VD, CRI, %SPH) + RAND_ERR + BIAS
- Mode resolved* columnar optical properties:
  - AOD(λ), SSA(λ), AAOD(λ), LR(λ) + RAND_ERR + BIAS
  - P_{ij}(0–180°, λ), i&j<4
- Vertical profiles* of optical properties
  - EXT(h, λ), SSA(h, λ), ABS(h, λ), LR(h, λ), β(h, λ), P_{ij}(h, λ)

*at least <u>two lidar wavelength </u>needed

How to: get vertical profiles of aerosol properties

- Extinction:

$$\tau^{fine}(\lambda)\times VD^{fine}(h)+\tau^{coarse}(\lambda)\times VD^{coarse}(h)$$

- Absorption :

$$\tau^{f}(\lambda,h)\times VD^{f}(h)\times(1-SSA^{f}(\lambda))+\tau^{c}(\lambda)\times VD^{c}(h)\times(1-SSA^{c}(\lambda))$$

- SSA:

$$(EXT(\lambda,h)-ABS(\lambda,h))/EXT(\lambda,h)$$

How to: get vertical profiles of aerosol properties

- $\beta(h, \lambda)$

  $\tau^f(\lambda)\times VD^f(h)/LR^f(\lambda)+\tau^c(\lambda)\times VD^c(h)/LR^c(\lambda)$

- $LR(h, \lambda)$:

  $EXT(\lambda,h)/\beta(h, \lambda)$

- $SCA(h, \lambda)$:

$\tau^f(\lambda)\times SSA^f(\lambda)\times VD^f(h) + \tau^c(\lambda)\times SSA^c(\lambda)\times VD^c(h)$

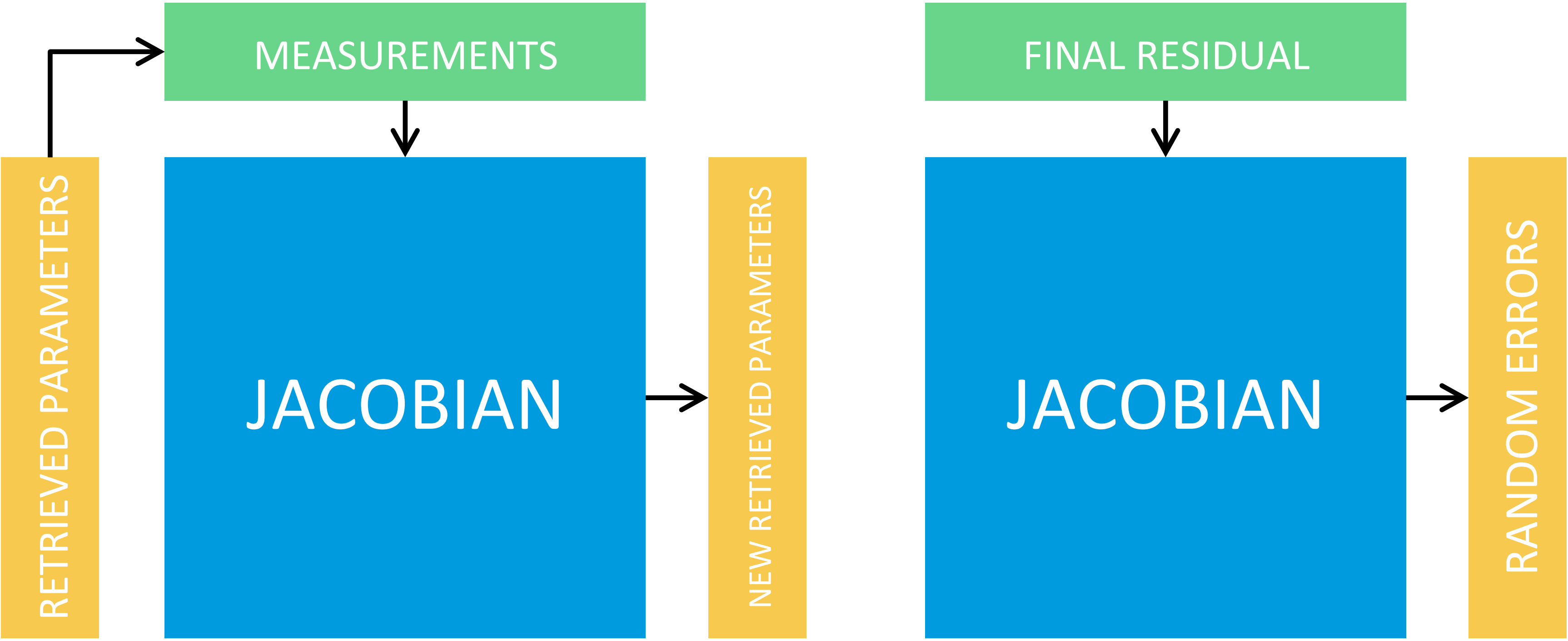
- $P_{ij}(\lambda,h,\theta)$:

  $(P_{ij}{}^f(\lambda,\theta)\times SCA^f(\lambda,h) + P_{ij}{}^c(\lambda,\theta)\times SCA^c(\lambda,h))/(SCA^f(\lambda,h) + SCA^c(\lambda,h))$

- $\Delta(\lambda,h)$

  $(P_{11}(\lambda,h,180°)–P_{22}(\lambda,h,180°)) / (P_{11}(\lambda,h,180°) +P_{22}(\lambda,h,180°))$

Understanding errors:
random errors of retrieved parameters



MEASUREMENTS

RETRIEVED PARAMETERS

JACOBIAN

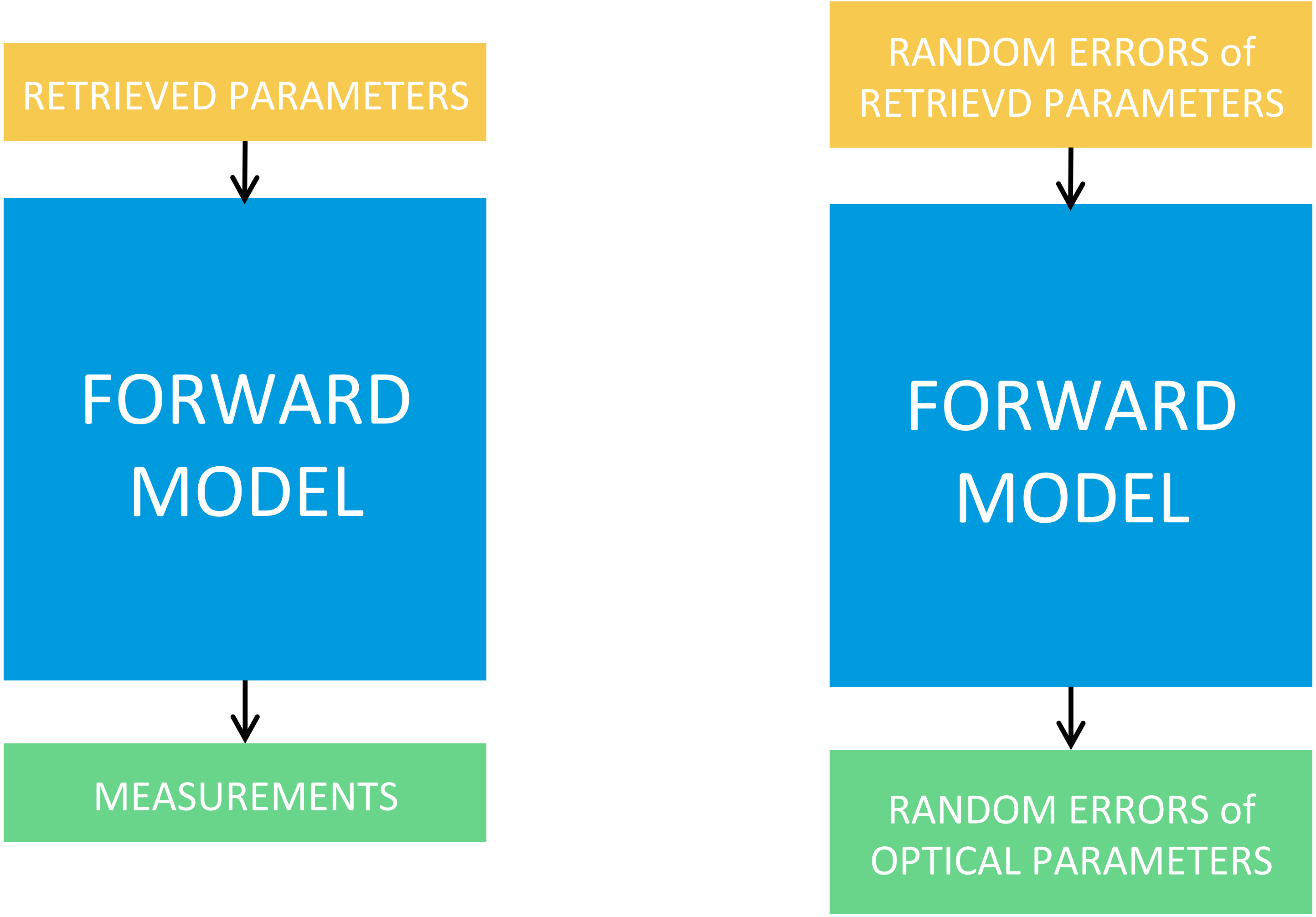
NEW RETRIEVED PARAMETERS

FINAL RESIDUAL

JACOBIAN

RANDOM ERRORS

Understanding errors:
random errors of optical parameters



RETRIEVED PARAMETERS

FORWARD MODEL

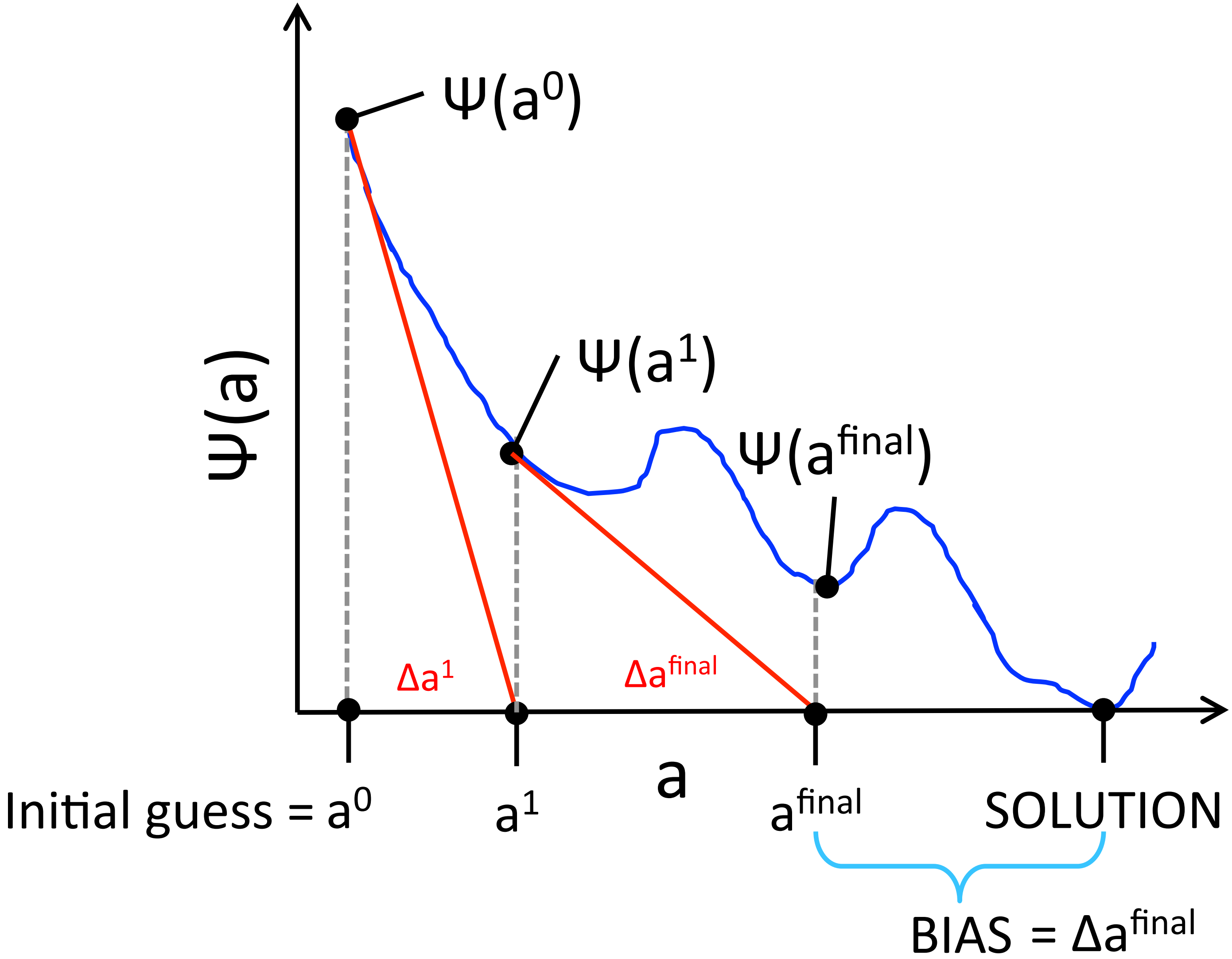
MEASUREMENTS

RANDOM ERRORS of RETRIEVD PARAMETERS

FORWARD MODEL

RANDOM ERRORS of OPTICAL PARAMETERS

Understanding errors: bias



How to: get error bars from GRASP

- Get total deviation (if needed)

$$\sigma_a = SQRT(\sigma_{rand}^2 + \sigma_{bias}^2)$$

- Standard deviations are provided in log scale

$$a^* = a \pm \sigma_a$$

- Return to a normal scale

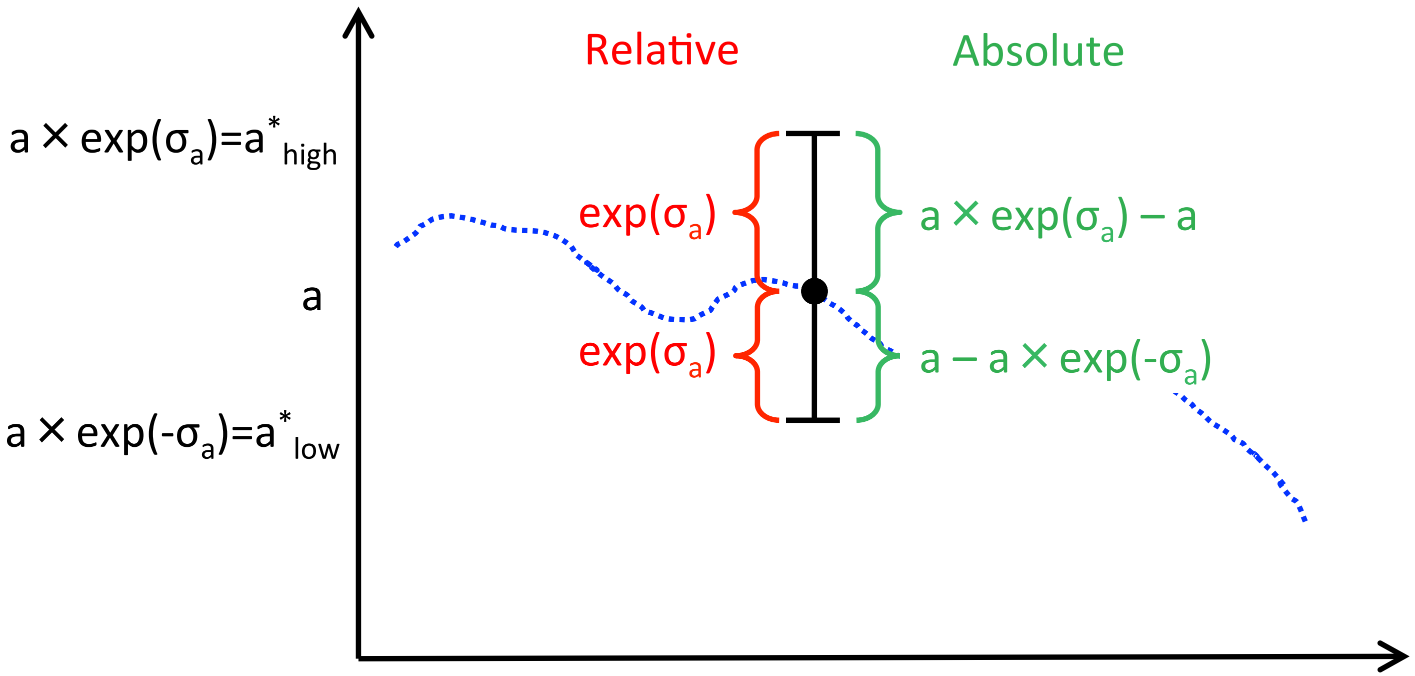
$$\exp(a^*) = \exp(a \pm \sigma_a)$$

- WARNING: Parameters are given in normal scale already

$$a^* = a \times \exp(\pm \sigma_a)$$

How to: get error bars from GRASP

Know your plotting software



Relative

Absolute

$a \times \exp(\sigma_a) = a^*_{high}$

$\exp(\sigma_a)$

$a \times \exp(\sigma_a) - a$

a

$\exp(\sigma_a)$

$a - a \times \exp(-\sigma_a)$

$a \times \exp(-\sigma_a) = a^*_{low}$

How to get errors for your profiles

- Modify the code so it'll calculate the profiles and errors and share it with everybody!

- Try the partial derivative estimation*:

$$\sigma_{\tau}^{f}(\lambda)\times VD^{f}(h)+\sigma_{\tau}^{c}(\lambda)\times VD^{c}(h)+$$
$$\tau^{f}(\lambda)\times\sigma_{h}^{f}(h)+\tau^{c}(\lambda)\times\sigma_{h}^{c}(h)$$

*not scientifically strict, since properties are co-dependent

What you should do to your data, and what you shouldn’t

GRASP/GARRLIC LIDAR DATA PREPARATION

Your part: Geometry, Range, Background & other corrections

- LE for elastic lidar:

$$P_s = G(R)\frac{A(\lambda)}{R^2}[\beta(\lambda, R)][T^2(\lambda, R)] + P_B$$

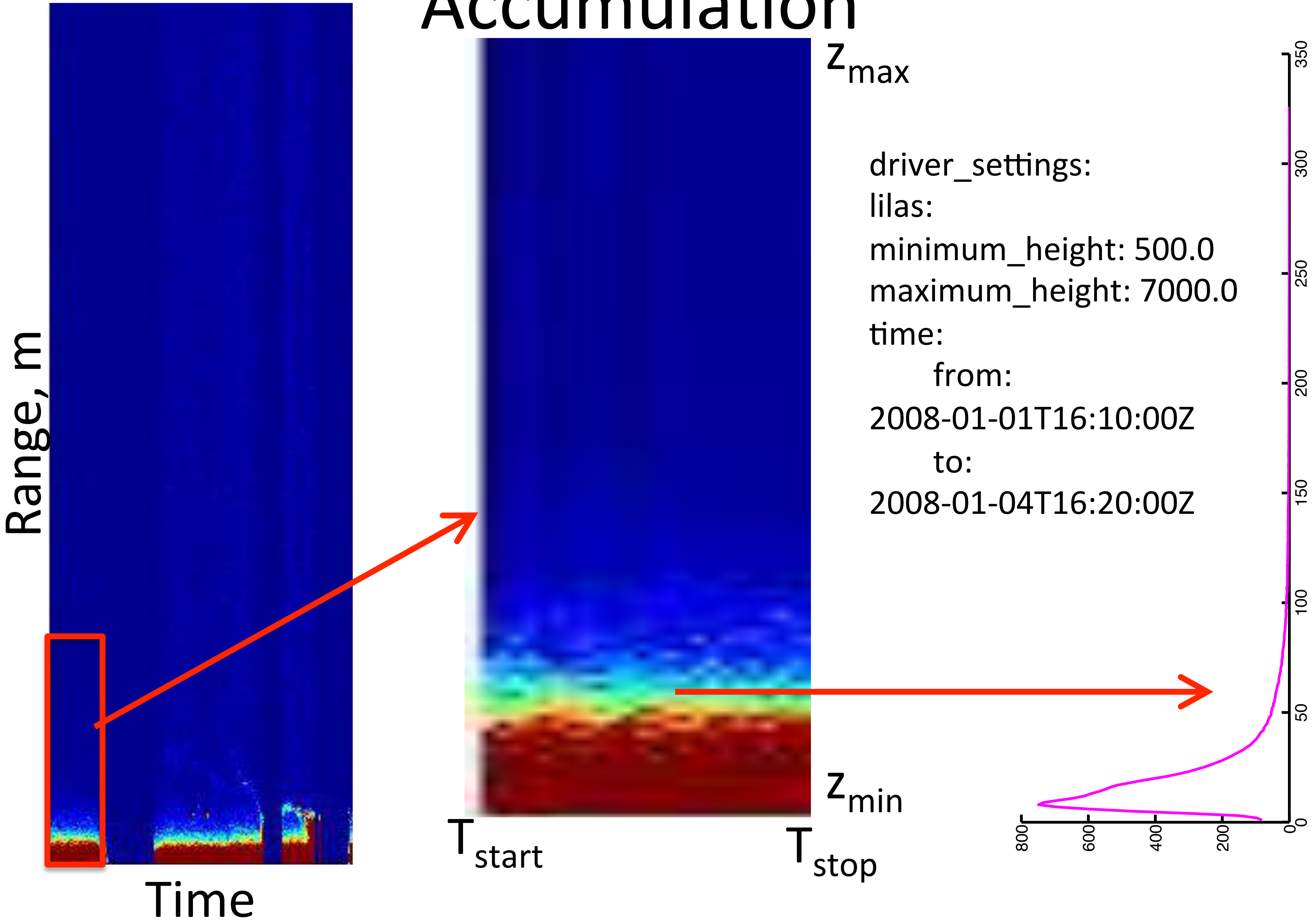
- Signal correction:

$$S^*(z_i) = (P^*(z_i) - B^*){z_i}^2 = (P^*(i\Delta z) - B^*)i^2\Delta z^2$$

B* — estimation of background (usually P* averaged between 50 and 60 km)

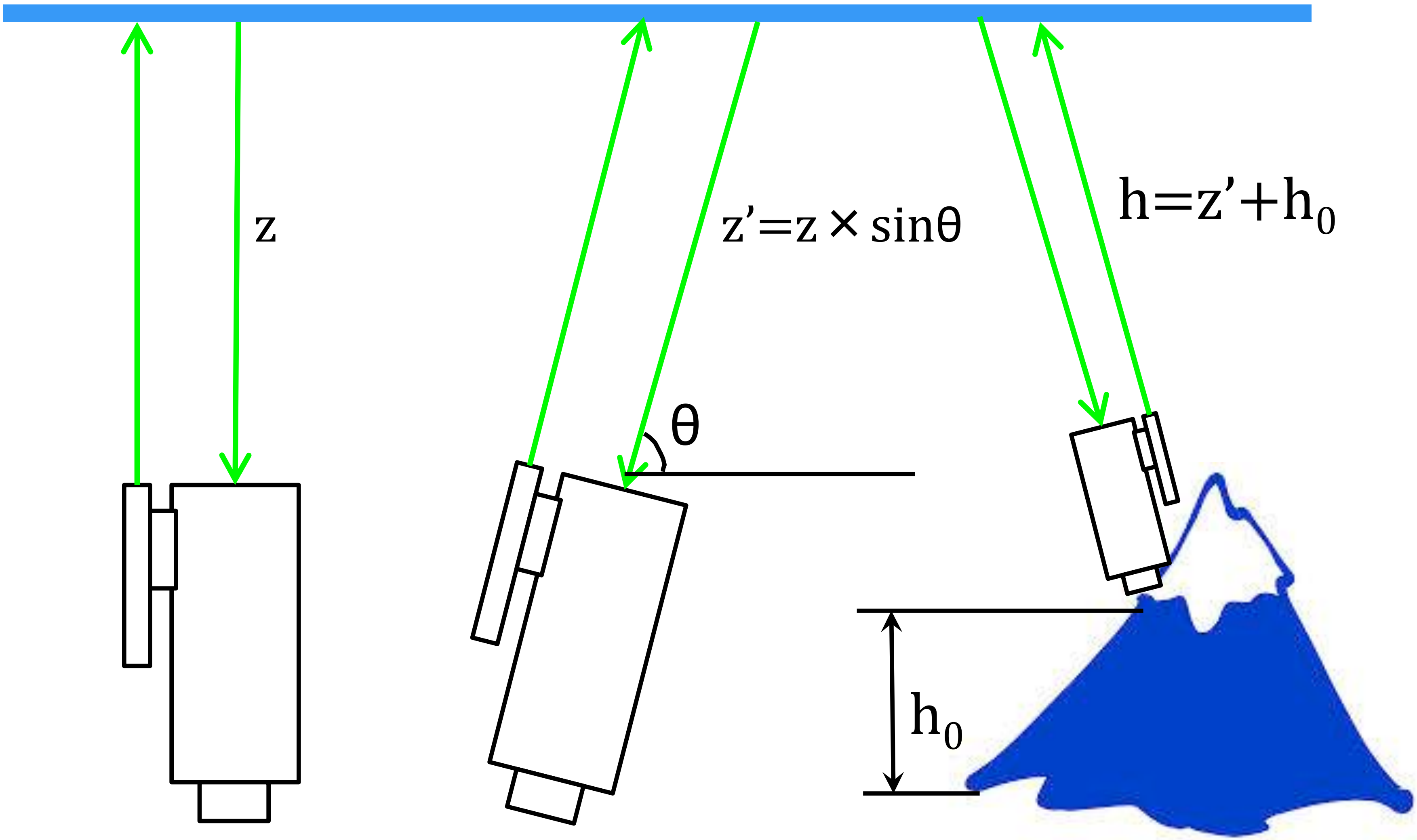
- dead time and other technical corrections should be applied

Driver part: Step 1. Signal cropping & Accumulation

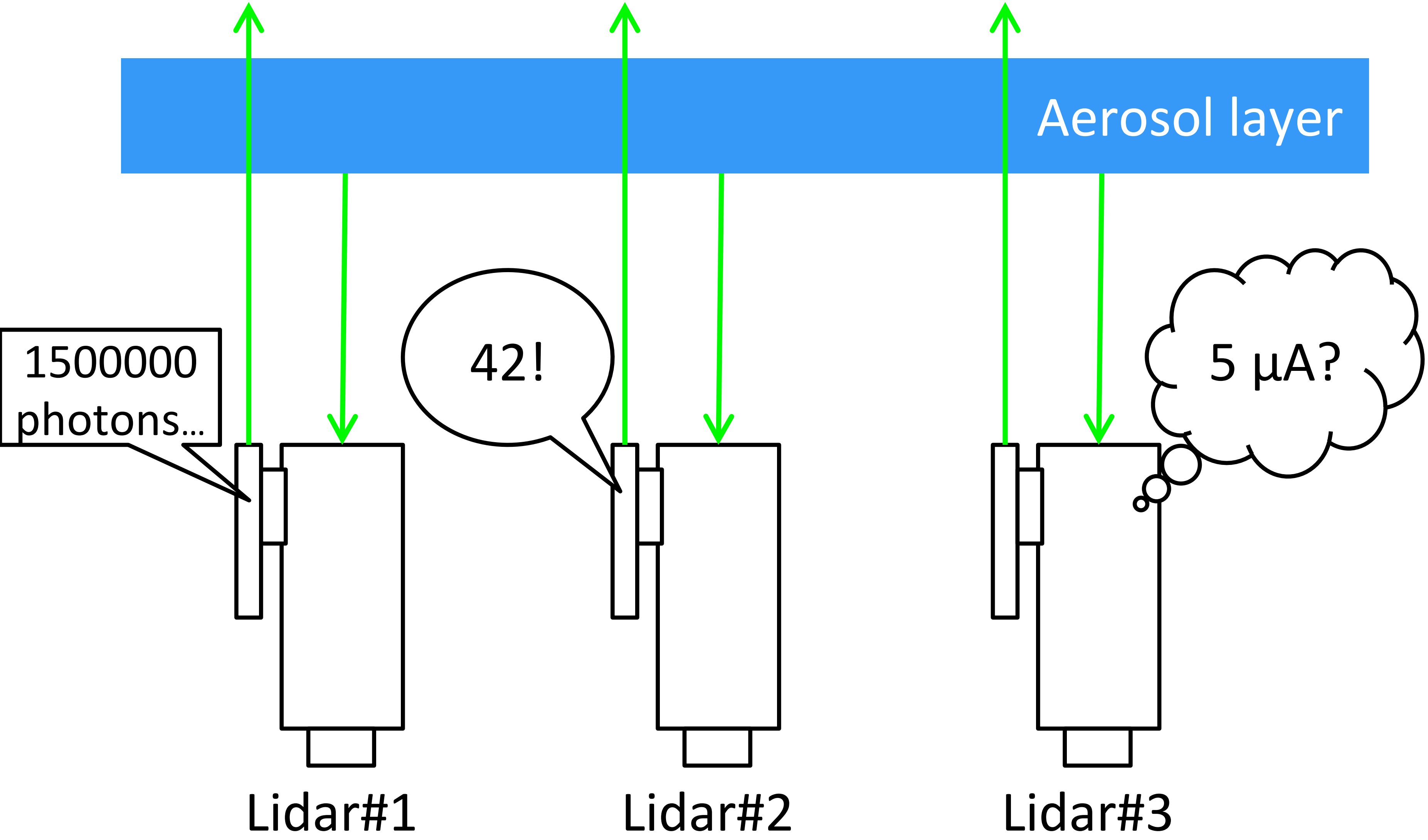


```
driver_settings:
lilas:
minimum_height: 500.0
maximum_height: 7000.0
time:
        from:
2008-01-01T16:10:00Z
        to:
2008-01-04T16:20:00Z
```

Range, Distance. Height. Altitude.



lidar calibration. Why?



Calibration on reference point.

- Reference point — range where we suppose to have only Rayleigh scattering. Easily calculated:

$$S^*(z_{ref}) = \frac{A}{R(z_{ref})}\beta_m(z_{ref})T^2(z_{ref})$$

$$C = \frac{1}{A} = \frac{S^*(z_{ref})}{R(z_{ref})}\beta_m(z_{ref})T^2(z_{ref})$$

- If we choose reference wrong:

$$R(z_{ref}) = \frac{\beta_m(z_{ref})}{\beta_m(z_{ref}) + \beta_a(z_{ref})}$$

Driver part: Step 2. Calibration.

- No need for manual reference point signal calculation & selection
- Less assumptions
- No need to retrieve additional parameters

$$S^{*}_{cal}(z_i) = \frac{S^{*}(z_i)}{\sum_{i=1}^{N} S^{*}(z_i)}$$

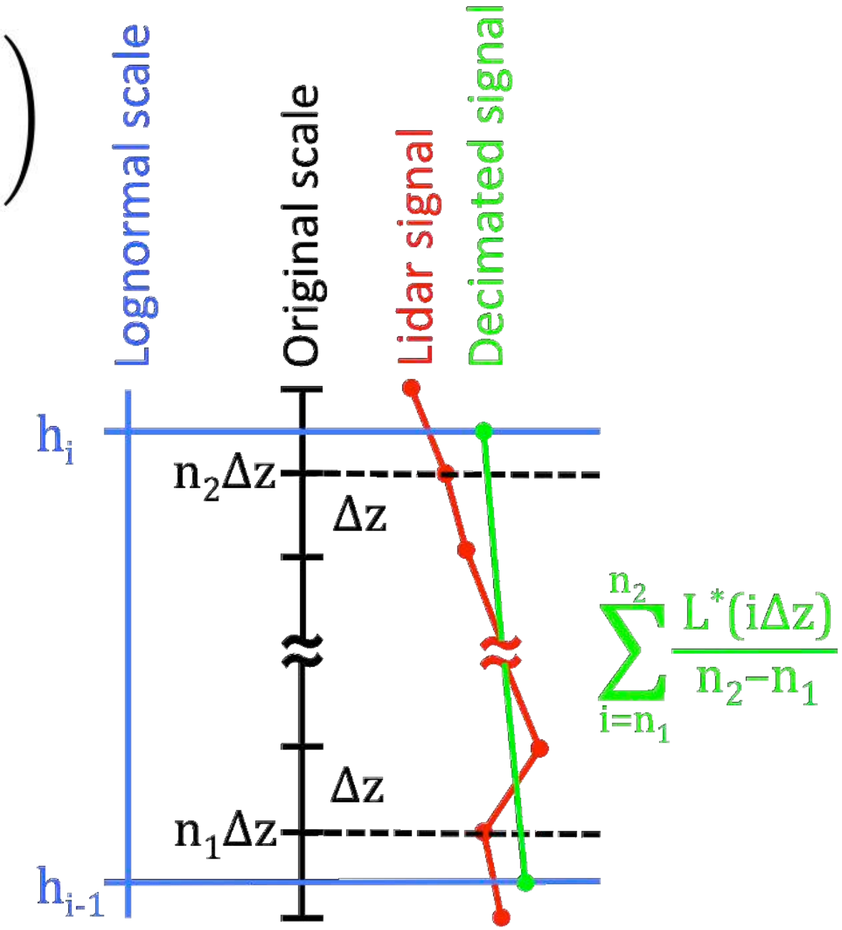
Driver part: Step 3. Averaging. Decimation.

- Logarithmical altitude scale.

$$h_i = z_{max}\exp\left(\frac{\ln(z_{max}/z_{min})(i-1)}{N_h - 1}\right)$$

Altitude grows noise grows, aerosol variation drops.

$$L^*(h_i) = \sum_{j=n_1}^{n_2} \frac{L^*(j\Delta z)}{n_2 - n_1}$$



How to: get vertical profiles of aerosol properties

- $\beta(h, \lambda)$

$$\tau^f(\lambda)\times VD^f(h)/LR^f(\lambda)+\tau^c(\lambda)\times VD^c(h)/LR^c(\lambda)$$

- LR:

$$EXT(\lambda,h)/\beta(h, \lambda)$$

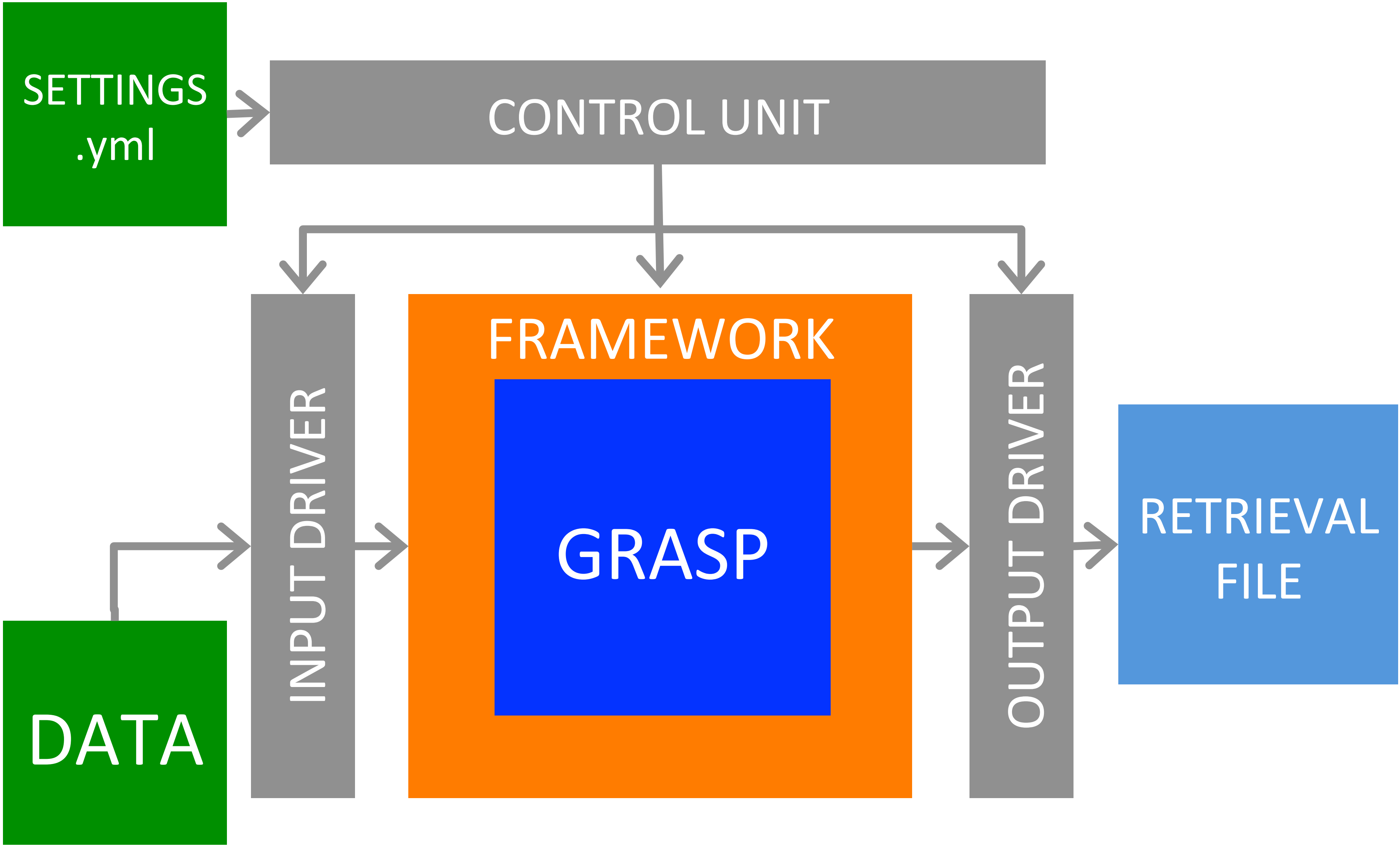
- $P_{ij}(\lambda,h,\theta)$:

$$(P_{ij}^f(\lambda,\theta)\times\tau^f(\lambda)\times SSA^f(\lambda)\times VD^f(h)+$$
$$P_{ij}^c(\lambda,\theta)\times\tau^c(\lambda)\times SSA^c(\lambda)\times VD^c(h))/$$
$$(\tau^f(\lambda)\times SSA^f(\lambda)\times VD^f(h)+\tau^c(\lambda)\times SSA^c(\lambda)\times VD^c(h))$$

- $\Delta(\lambda,h)$

$$(P_{11}(\lambda,h,180°)-P_{22}(\lambda,h,180°)) / (P_{11}(\lambda,h,180°)+P_{22}(\lambda,h,180°))$$

General structure



Documentation

- requirements, installation and short description of the input data structure:

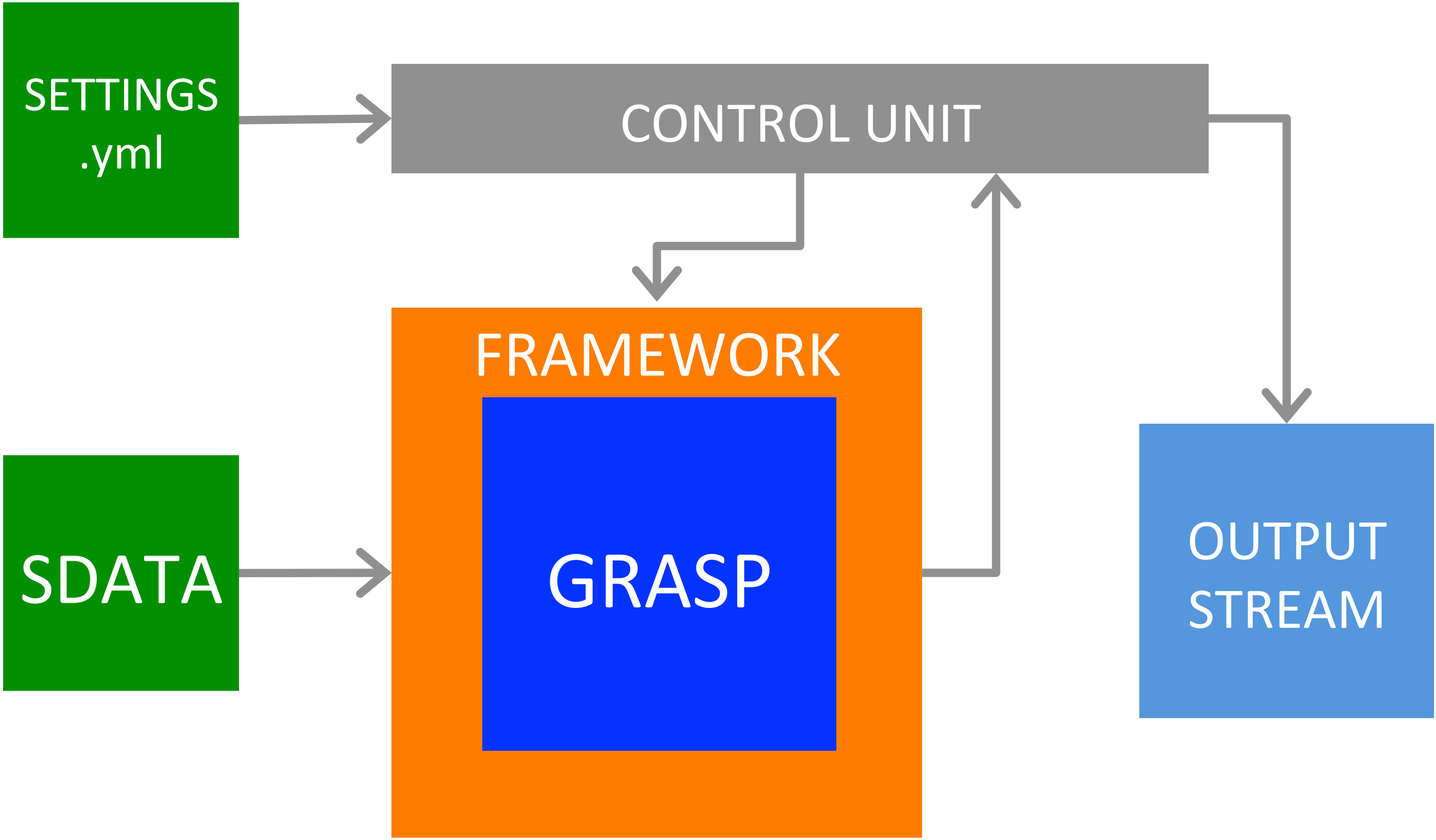
http://www.grasp-open.com/doc/

- type `grasp help` to get full description of all possible settings options
- Scientific part:

Dubovik et. al. AMT 2011 doi:10.5194/amt-4-975-2011

Lopatin et. al. AMT 2013 doi:10.5194/amt-6-2065-2013

How to run GRASP



SETTINGS .yml

CONTROL UNIT

FRAMEWORK

GRASP

SDATA

OUTPUT STREAM

How to run GRASP

- Open file

/examples/lidar_and_sunphotometer/
settings_example_lidar_sunphotometer_inversion.
yml