Towards a consistent retrieval of cloud/aerosol single scattering properties and surface reflectance

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Session AS5.14 «Remote Sensing of Clouds and Aerosols: Techniques and Applications»

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- The CIRCAS project
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- Results
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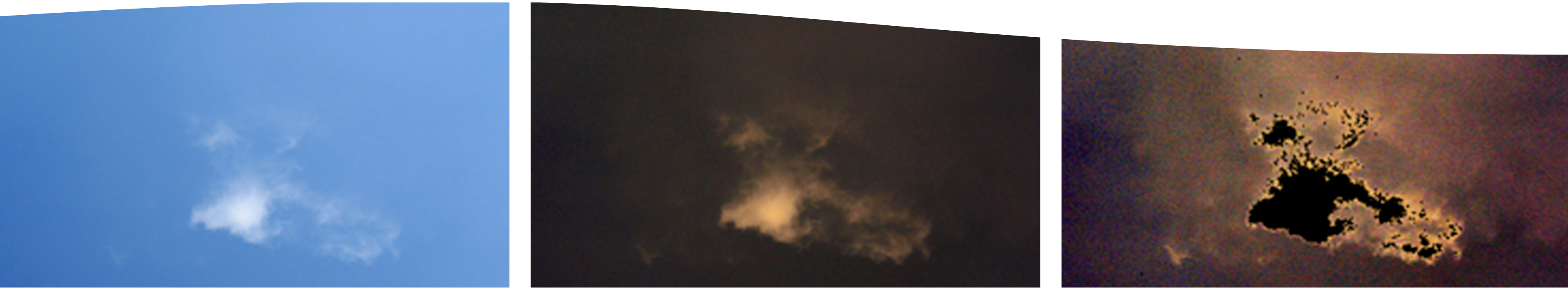
Motivation

- Different cloud masking algorithm lead to different aerosol products, as shown by the Aerosol-CCI ESA project.
- The retrieved aerosol optical thickness in the vicinity of clouds is often overestimated, due to residual cloud contamination.
- Pixels located in the transition zone between pure clouds and pure aerosols are often discarded from both cloud and aerosol algorithms. This "twilight zone" can cover up to 30% of the globe.



© Koren et al., 2007

The CIRCAS project

- The ESA-SEOM CIRCAS (ConsIstent Retrieval of Cloud Aerosol Surface) aims at providing consistent atmospheric (cloud and aerosol) and surface reflectance products derived from S3A/SLSTR observations using the same radiative transfer physics and assumptions.
- The ultimate goal of the project is to develop an aerosol retrieval algorithm not relying on any external cloud mask.
- More information at http://circas.eu/

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The CISAR algorithm – basic concepts

The CISAR algorithm is an innovative aerosol retrieval algorithm based the **continuous variations** of the state variables in the solution space to secure consistency within an **Optimal Estimation** retrieval framework.

Atmos. Meas. Tech., 11, 6589–6603, 2018
https://doi.org/10.5194/amt-11-6589-2018

Atmospheric Measurement Techniques

Joint retrieval of surface reflectance and aerosol properties with continuous variation of the state variables in the solution space – Part 1: theoretical concept

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Atmospheric Measurement Techniques

Joint retrieval of surface reflectance and aerosol properties with continuous variation of the state variables in the solution space – Part 2: application to geostationary and polar-orbiting satellite observations

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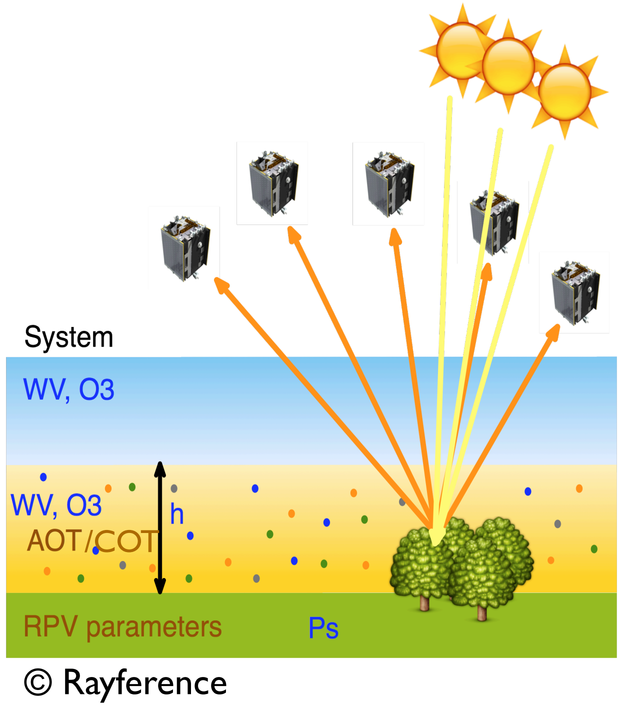
The CISAR algorithm – basic concepts

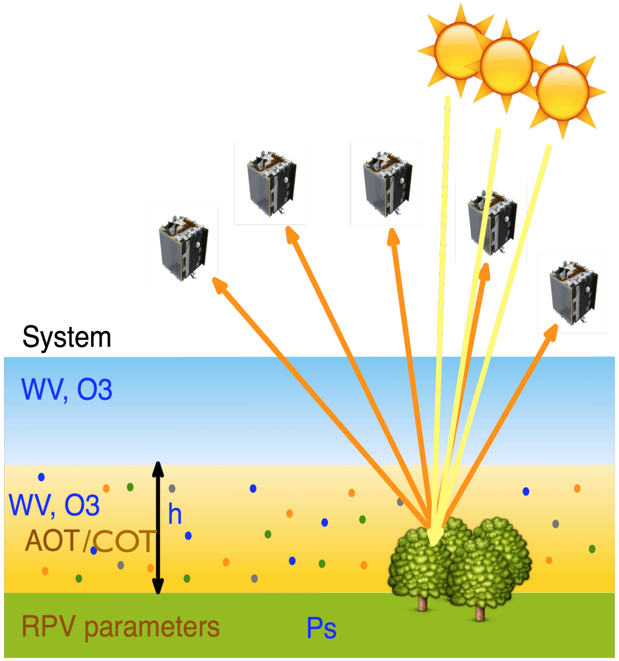
- CISAR (Combined Inversion of Surface and Aerosols) is a generic algorithm on the inversion of a coupled surface-atmosphere radiative transfer model based on FASTRE.
- The retrieval is based on an Optimal Estimation (OE) approach following the method proposed by Govaerts et al. (2010).
- The OE approach seeks the best balance between the information derived from the observations and prior knowledge.
- Satellite observations are accumulated during the so-called accumulation period. The inversion takes place at the end of this accumulation.
- Retrieval uncertainty is also estimated pixel-level based on the OE theory.



The CISAR algorithm - FASTRE

FASTRE (Govaerts and Luffarelli 2018) divides the observed scene in 3 layers:

1. The surface, which reflectance is represented with two different models for land and water respectively
2. The first atmospheric layer, where both scattering and absorption effects take place
3. The second atmospheric layer, where only gas absorption takes place



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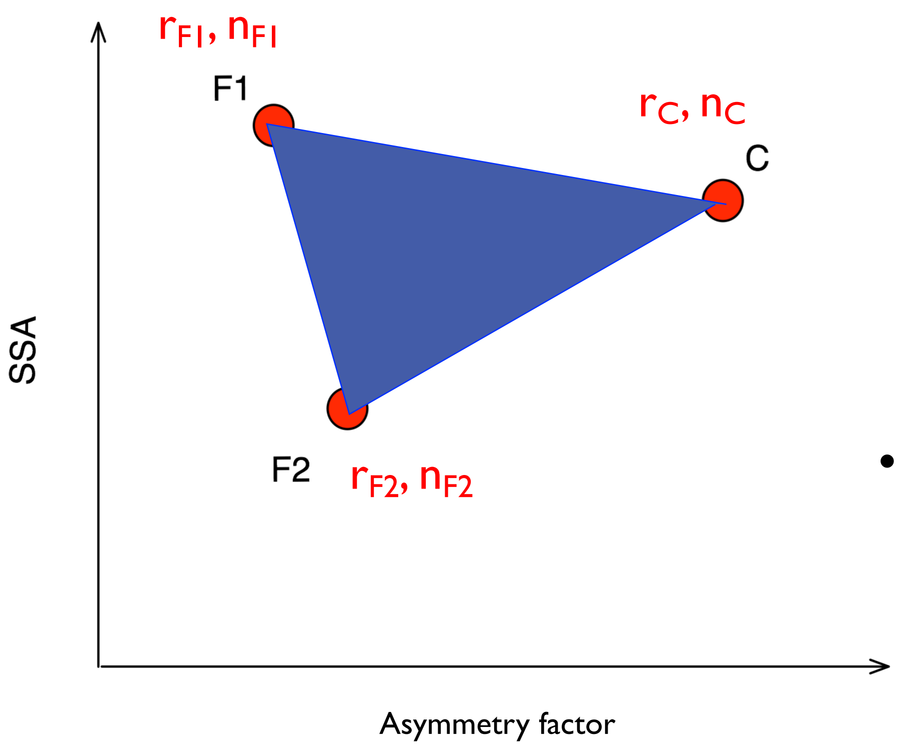
From the geometric and spectral conditions (observation), the model parameters (external) and the surface reflectance and aerosol/cloud single scattering properties (unknowns – state variables) FASTRE can simulate the signal at the satellite (TOA BRF).

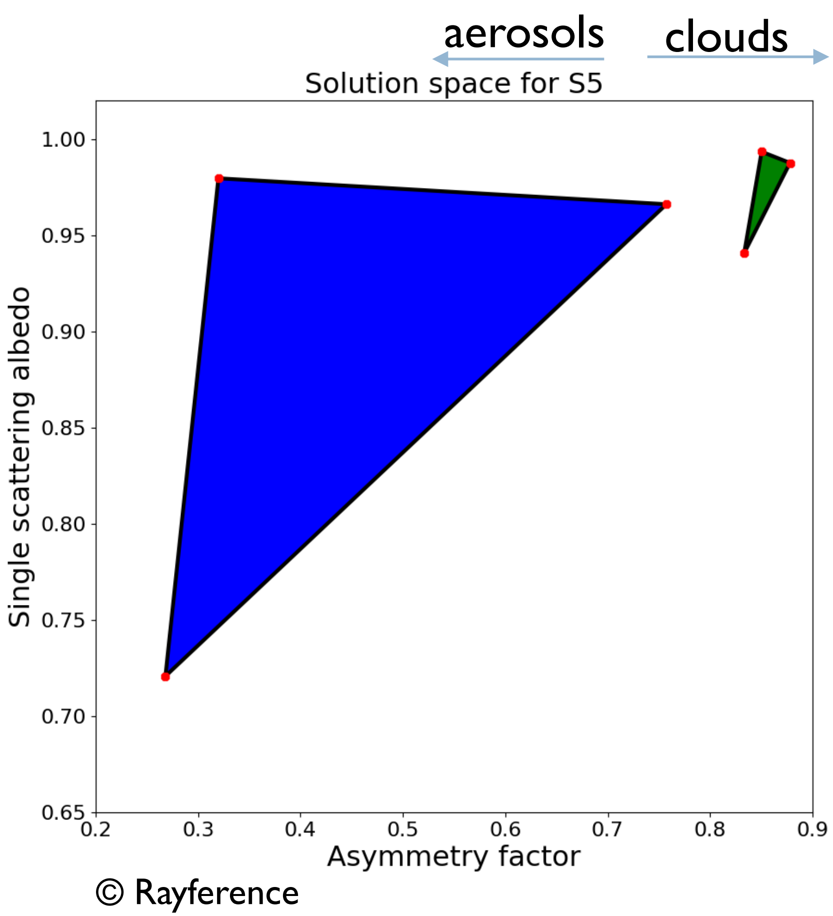
CISAR – Atmospheric solution space



LINEAR ASSUMPTION

- CISAR retrieves aerosols and cloud properties combining more predefined aerosol types (vertices), that differ for their microphysical and single scattering properties (r, n, SSA, g).
- The retrieved solution is a linear combination of the vertices v:
  - $SSA_T = \frac{\sum_v \tau_v SSA_v}{\sum_v \tau_v}$
  - $g_T = \frac{\sum_v \tau_v g_v}{\sum_v \tau_v}$

CISAR – Atmospheric solution space



- Within CISAR, the selected aerosol and cloud classes define the portion of the $[\omega, g]$ space where aerosol properties can be continuously retrieved.
- 3 aerosol classes and 3 cloud classes are used.

CISAR – Prior information

- The OE approach seeks for the best balance between the information coming from the observation and the prior information.
- The prior information is any source of additional knowledge on the observed modelled scenario.
- In CISAR, the following sources of prior information are considered:
  - Surface model parameters magnitude and temporal variability
  - AOT magnitude
  - AOT spectral variation
  - AOT temporal variation
  - COT magnitude
  - COT spectral variation

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  - COT spectral variation

CISAR – Prior information: surface

- During each accumulation period, the surface reflectance properties are considered constant.
- The surface parameter retrieval at period t_{d-1} is used to build the prior information at period t_d.
- More accurately, the prior information at period t_d is the mean of the retrievals over the previous N_r accumulation periods:

$$x_b(t_d) = \frac{\sum_{t_i=0}^{t_d-1} \hat{x}_{t_i}}{N_r}$$

- This method is referred to as memory mechanism.

CISAR – Prior information

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Please refer to Luffarelli and Govaerts, 2019 (https://www.atmos-meas-tech.net/12/791/2019/)

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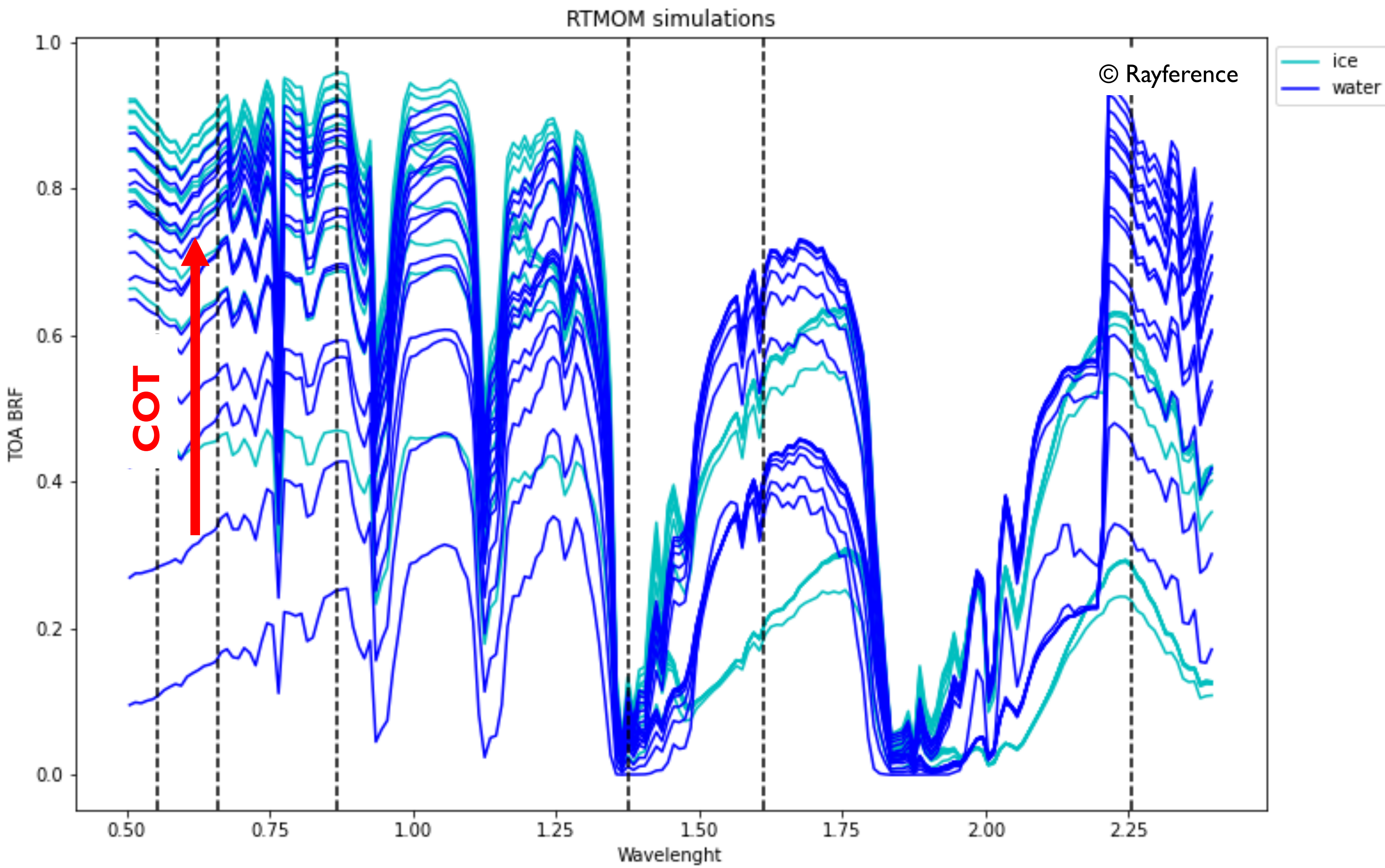
Based on RTMOM simulation

CISAR – Prior information: clouds

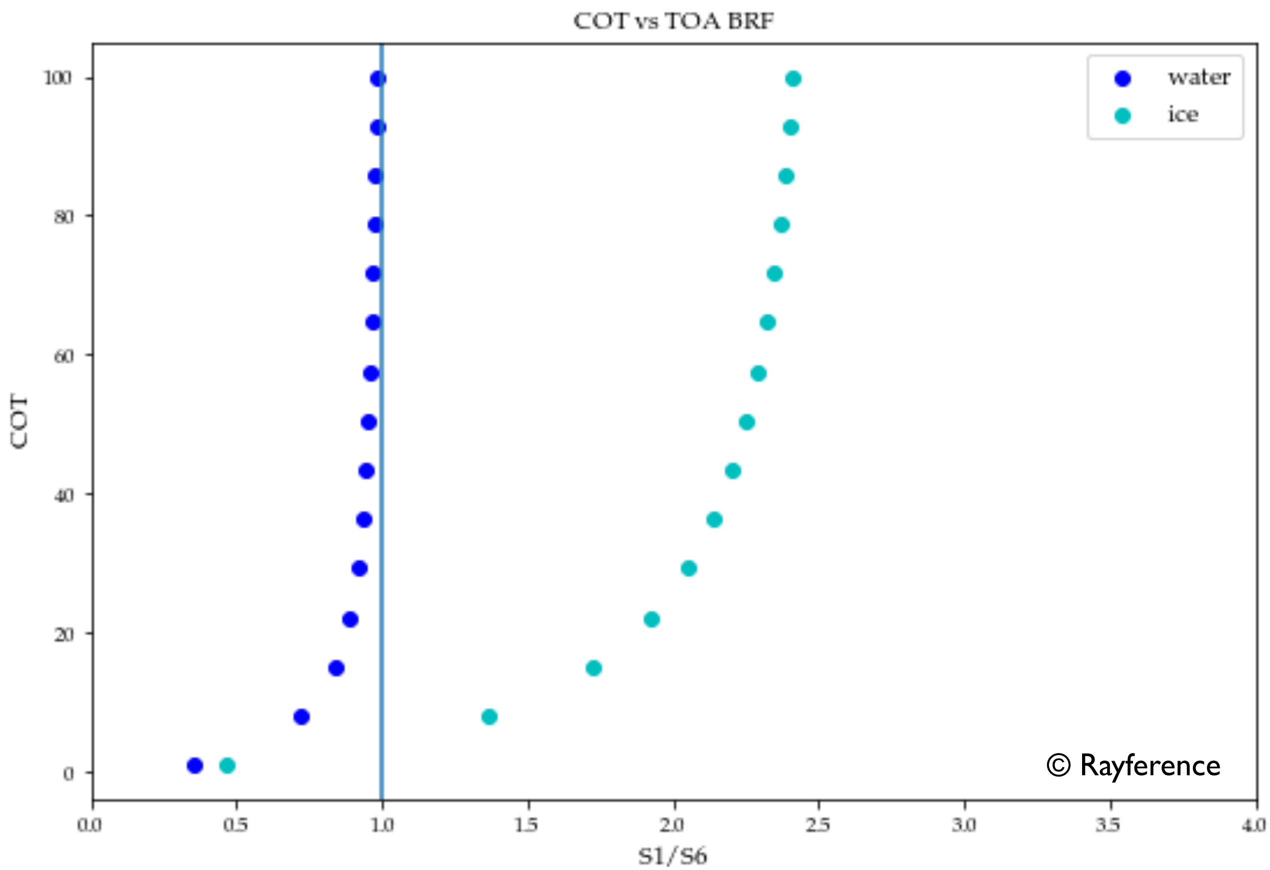
- RTMOM is a 1d is a one-dimensional radiative transfer model that simulates photon propagation in a plane-parallel atmosphere (Govaerts, Y. M. 2006. “RTMOM V0B.10 User's Manual.” EUMETSAT).
- Using RTMOM, the TOA BRF is simulated with a black Lambertian surface and both ice and water clouds of different optical thicknesses.

CISAR – Prior information: clouds



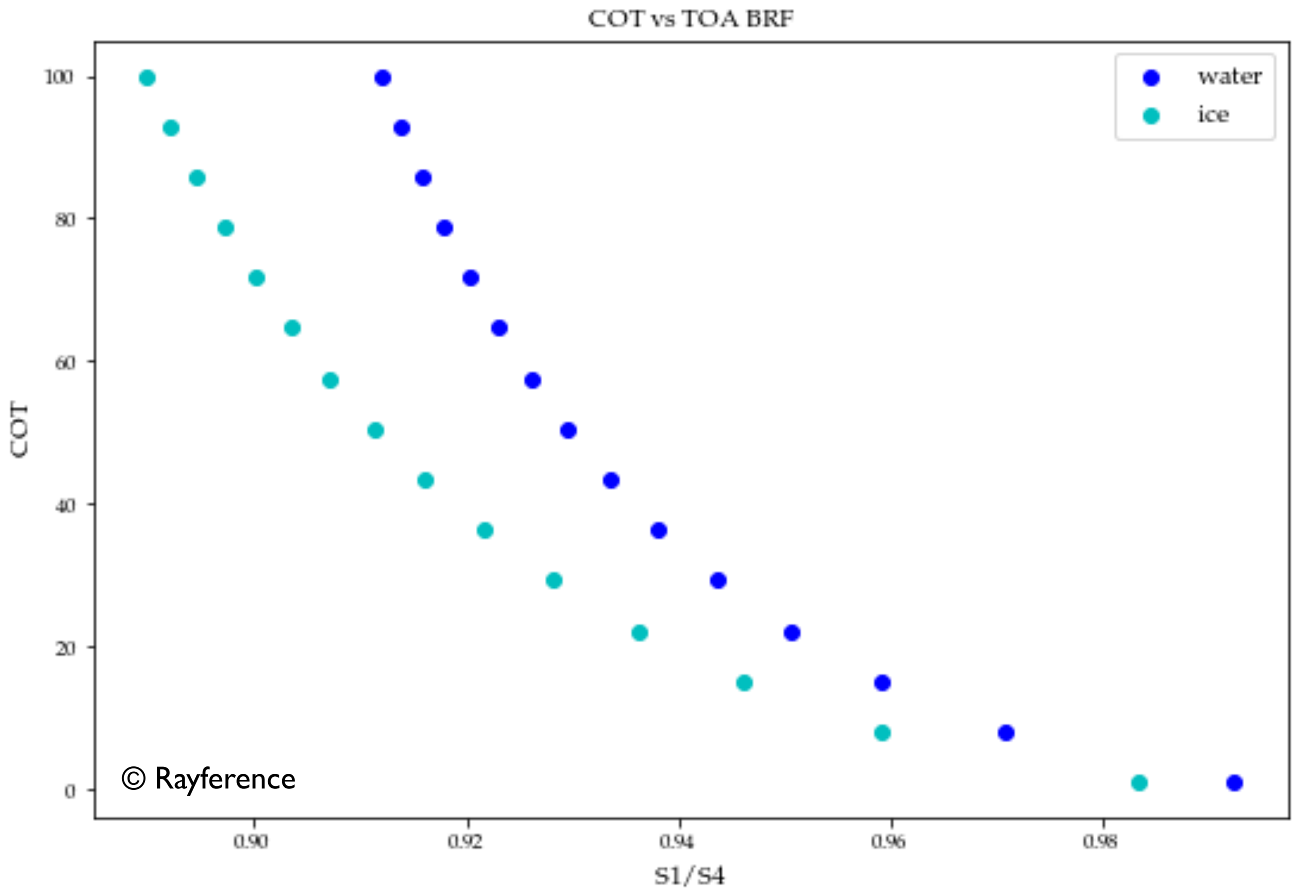
CISAR – Prior information: clouds

- It can be seen from the previous slide, that ice clouds are brighter in band S1 than S6, while water clouds show similar reflectance in the 2 bands.
- In CISAR, this information is used to build the prior informarion on the cloud phase.



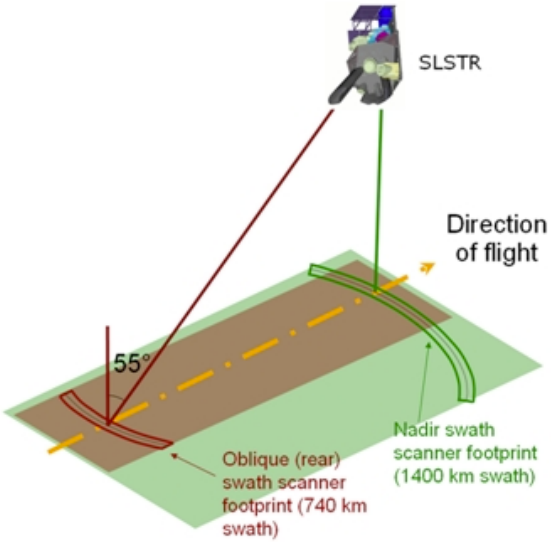
CISAR – Prior information: clouds

- The prior information on the COT magnitude is instead built from the ratio between the TOA BRF in S1 and the TOA BRF in S4.



Application to SLSTR

- SLSTR acquires observation with a dual view at 500m resolution with 6 bands (S1-S6) in the visible and near infrared part of the spectrum.
- Due to coregistration issues between the nadir and the oblique view, the CISAR algorithm is applied to superpixels with 5 km resolution.



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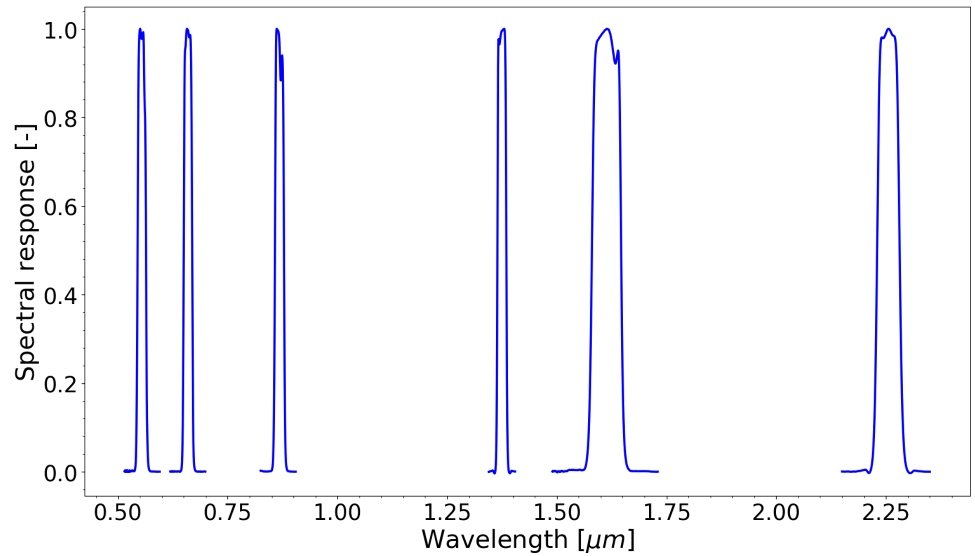

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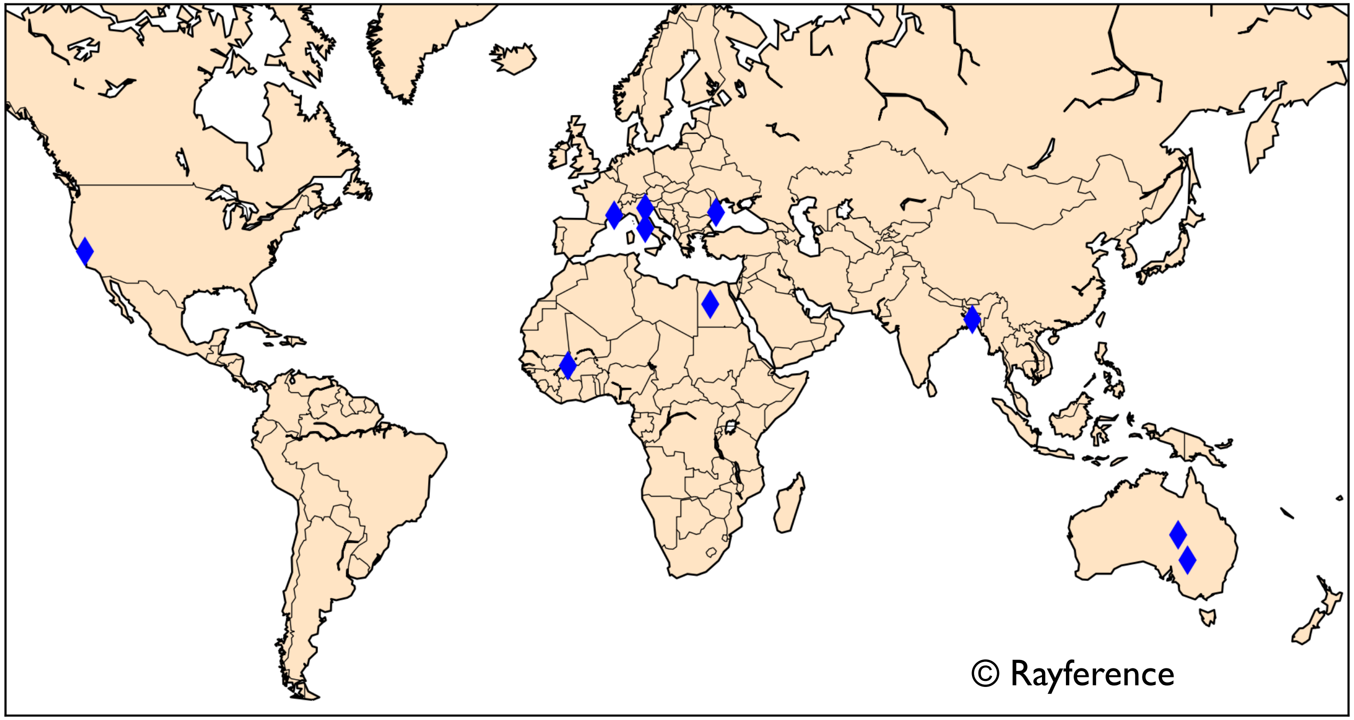
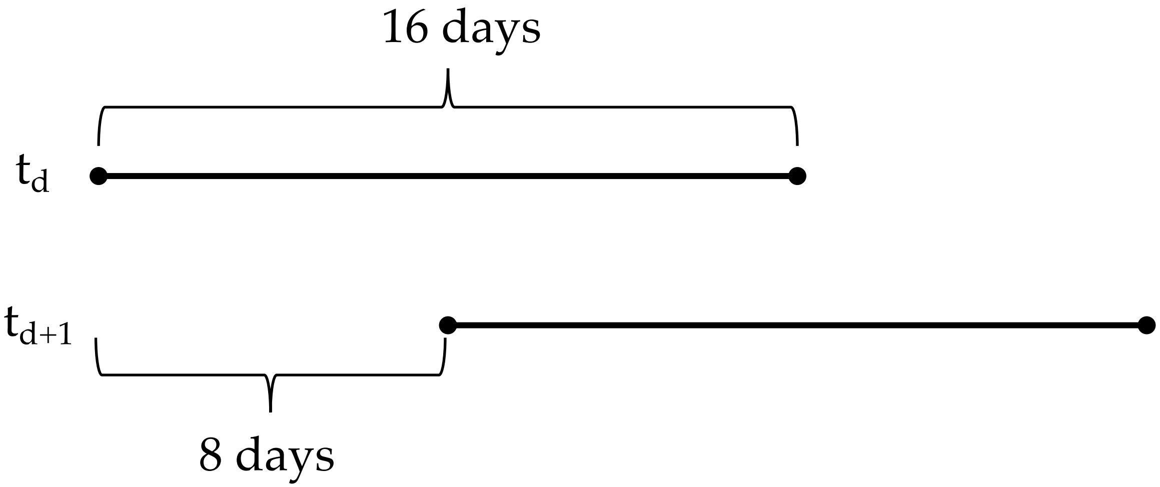
Application to SLSTR - Test Data Set

- For developing purposes, SLSTR observations have been extracted over 11 AERONET station during 1 year.
- The extrated target represent different land cover types.
- If more than 80% of the pixels at 500 m are cloudy (cloud free), only cloudy (cloud free) pixels are aggregated; the observation is discarded otherwise



Application to SLSTR – accumulation period

- SLSTR observations are accumulated during a 16-day period.
- The inversion takes place every 8 days.



Application to SLSTR – Information content

- The information coming from the satellite is measured by the Jacobian, the partial derivative of the TOA BRF with respect to the state variable:

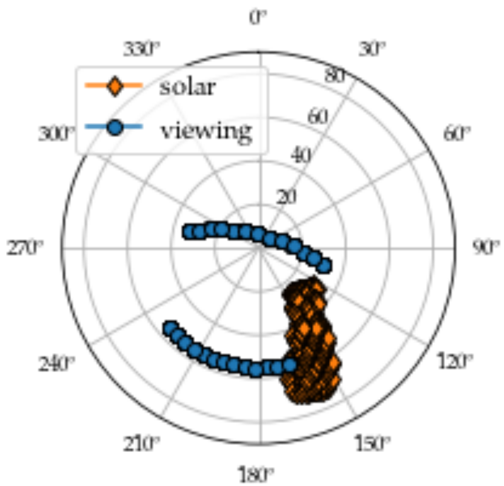
$$K_{x_i} = \frac{\partial y_o}{\partial x_i}$$

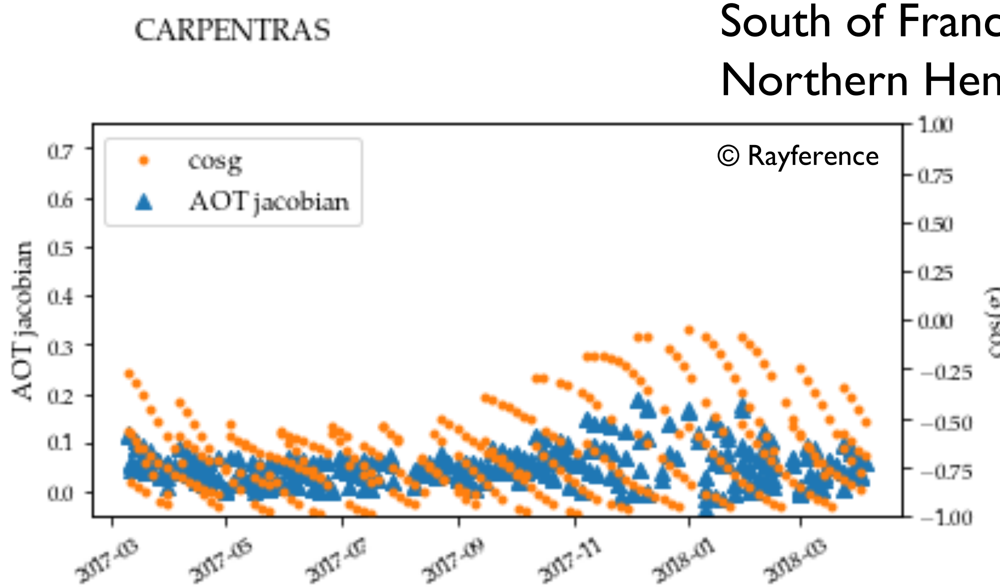
- The magnitude and sign of K_{x_i} are affected by the changes in illumination and viewing geometry both in terms of sign and magnitude (Luffarelli et al., 2016)

Application to SLSTR – Information content

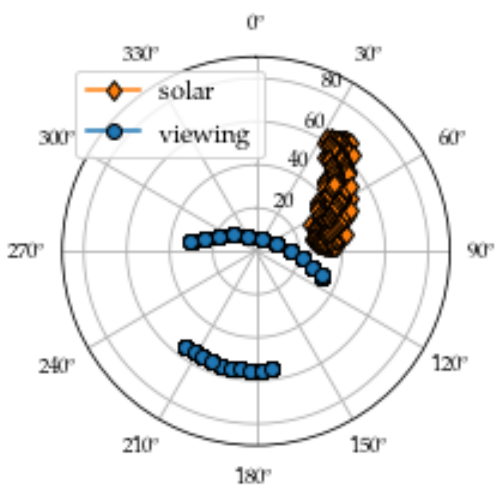
- The maximum information on the aerosols is in the forward direction, while it decreases when approaching the backscattering direction.
- However, in the Northern hemisphere, SLSTR acquires observation almost uniquely in backward scattering direction.

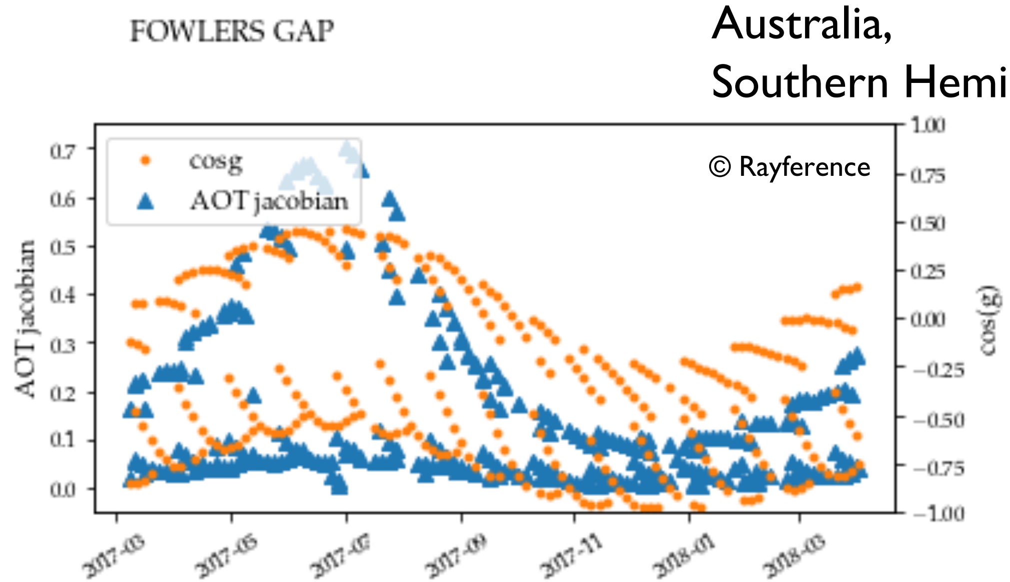
Application to SLSTR – Information content





South of France,
Northern Hemisphere

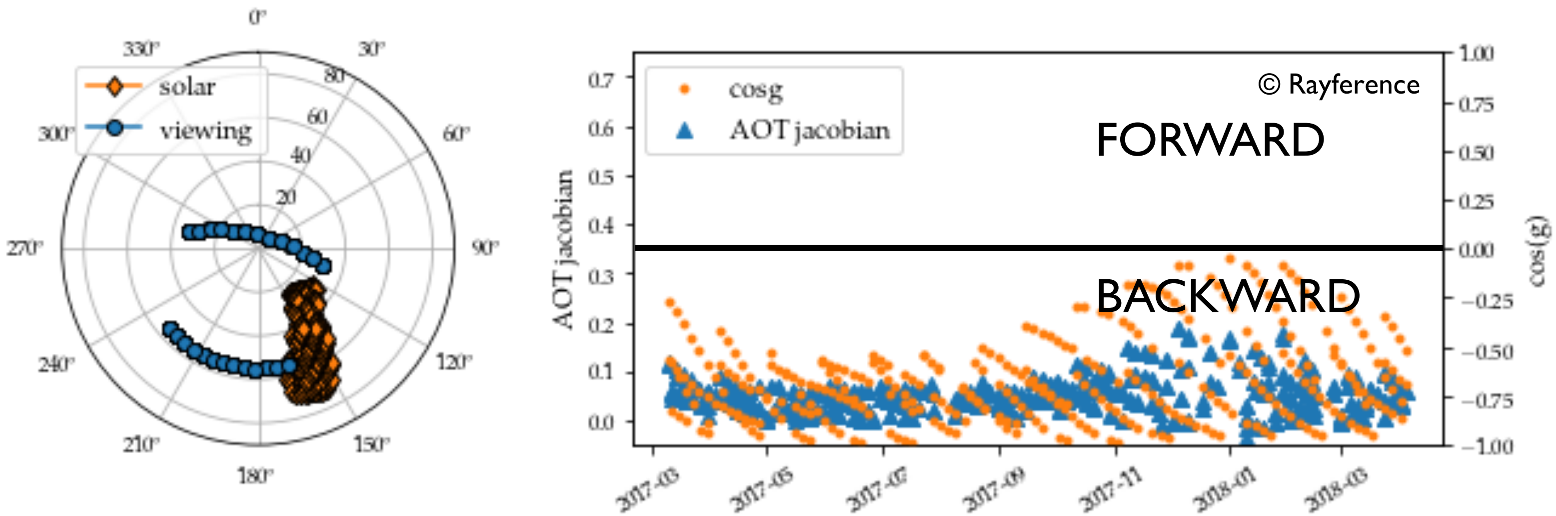




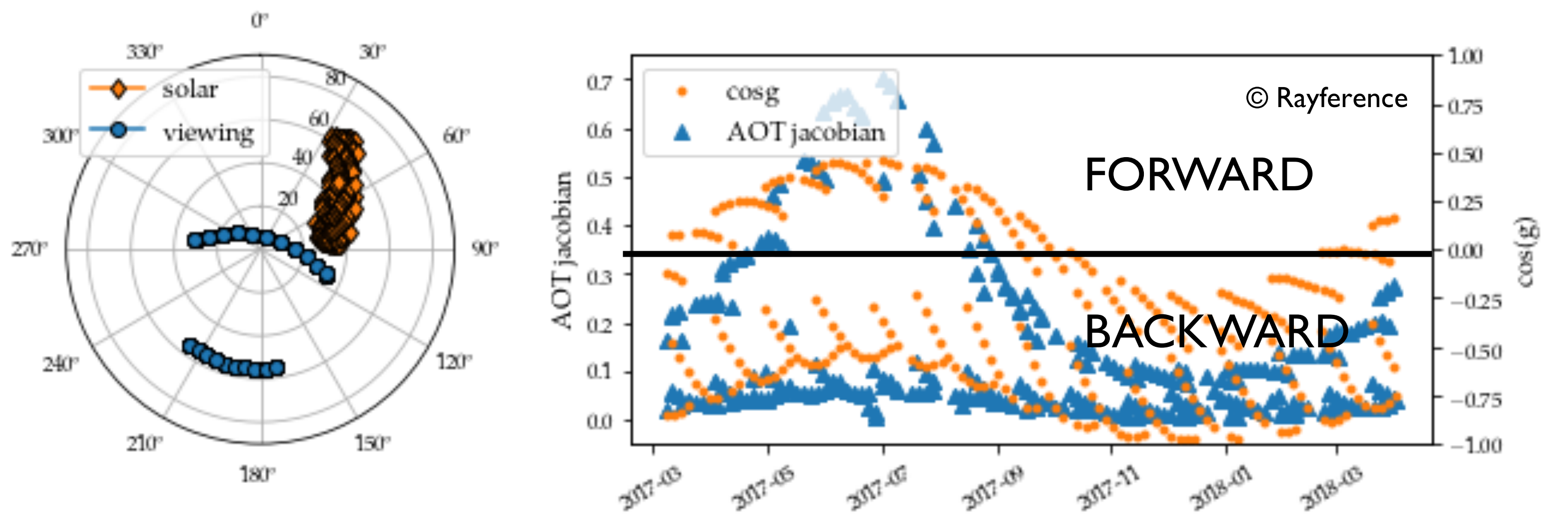
Australia,
Southern Hemisphere

Application to SLSTR – Information content

CARPENTRAS



FOWLERS GAP

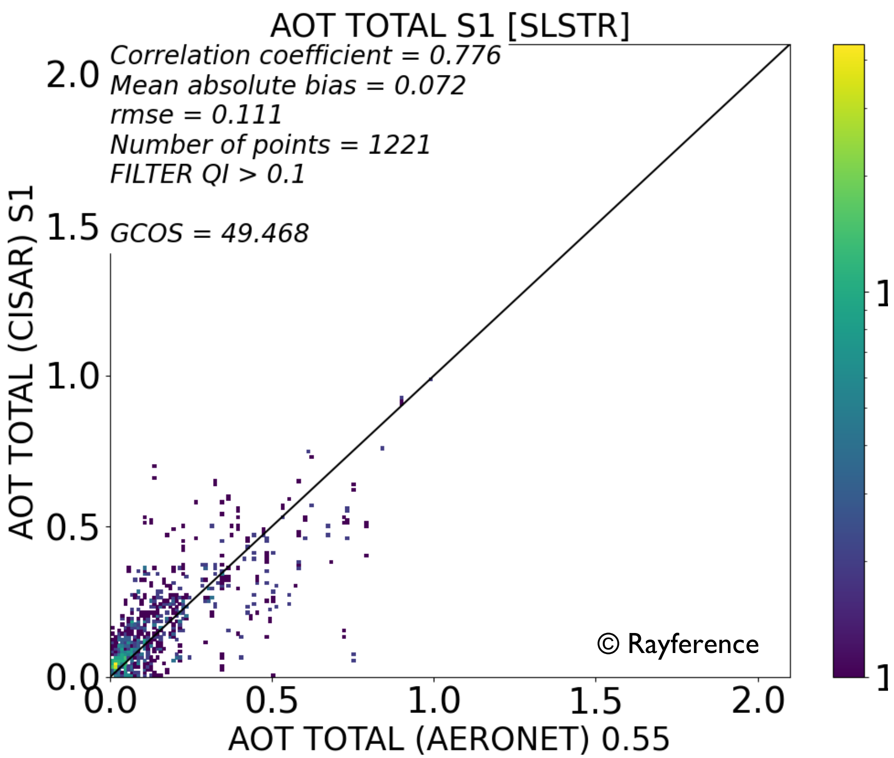


Results

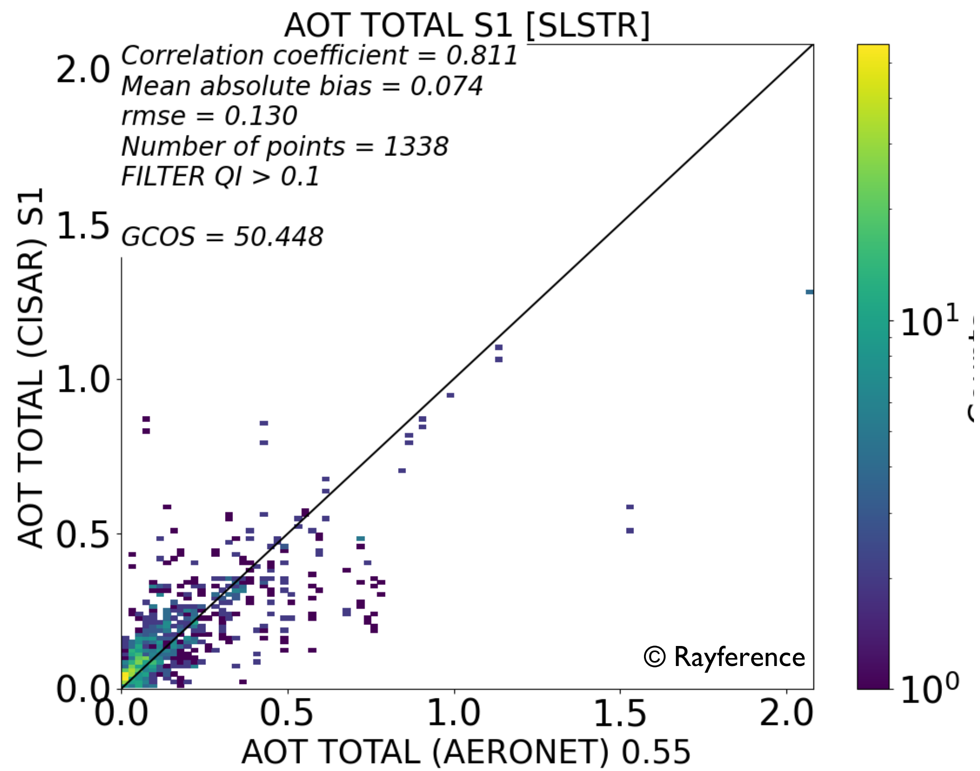
- CISAR has been applied to 5 km superpixels over the selected AERONET stations twice:
  1. Only on cloud free observations
  2. On both cloudy and cloud free observations
- CISAR AOT retrievals with QI>0. have been evaluated against AERONET data within ±30 minutes.
- The performances are evaluated in terms of correlation, Root Mean Square Error (RMSE), mean absolute bias and percentage of retrievals satisfying the GCOS requirements.

Results – Evaluation against AERONET

Only cloud free

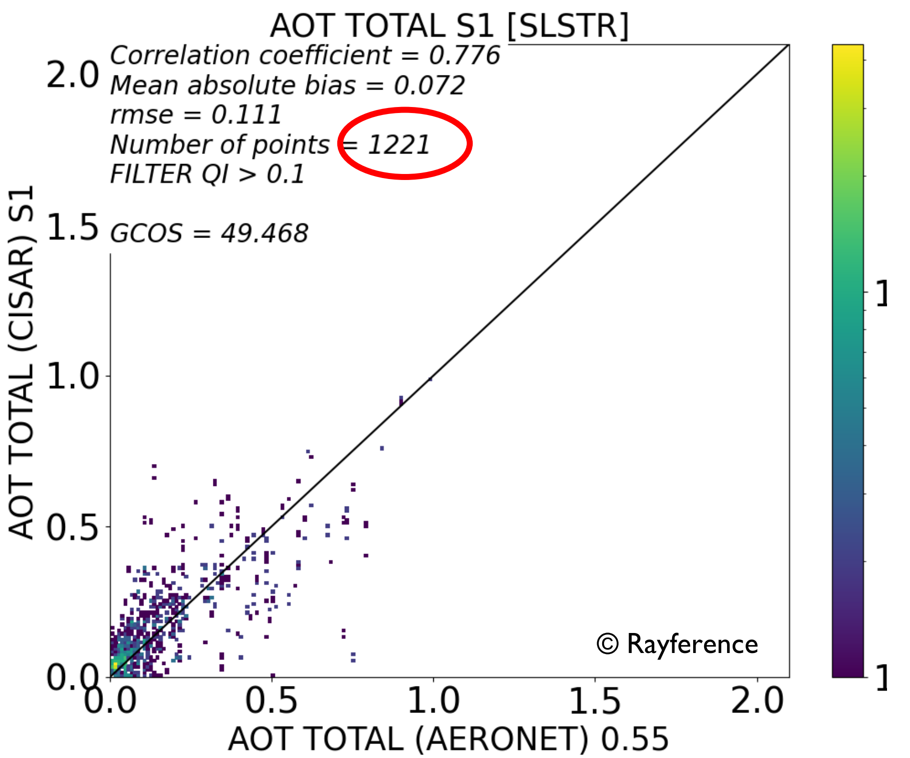


Both cloudy and cloud free

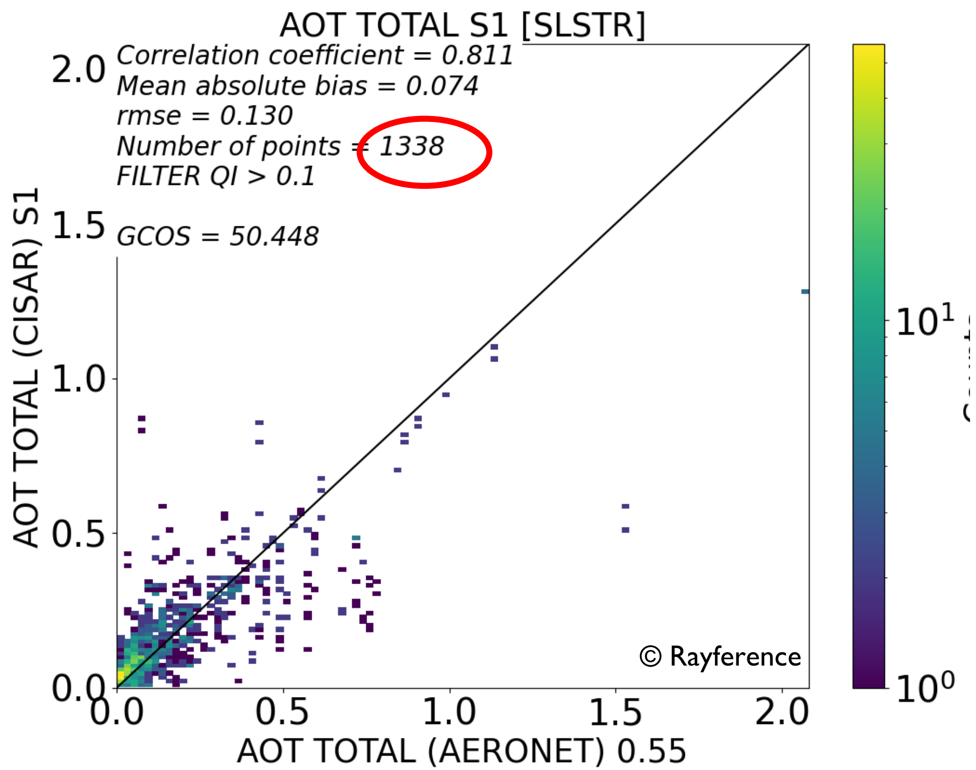


Results – Evaluation against AERONET

Only cloud free

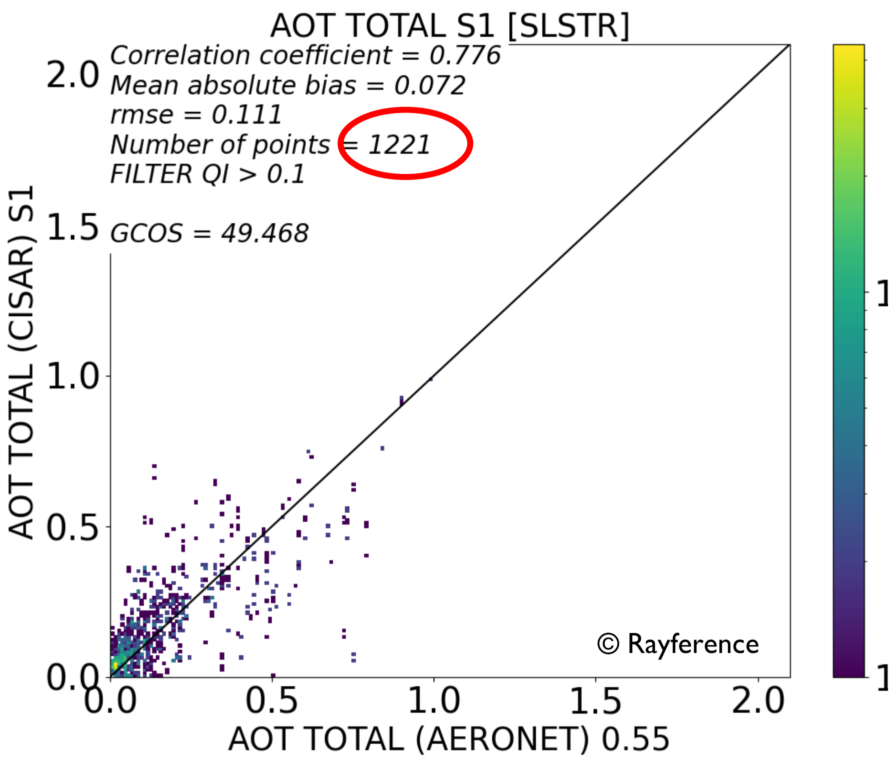


Both cloudy and cloud free

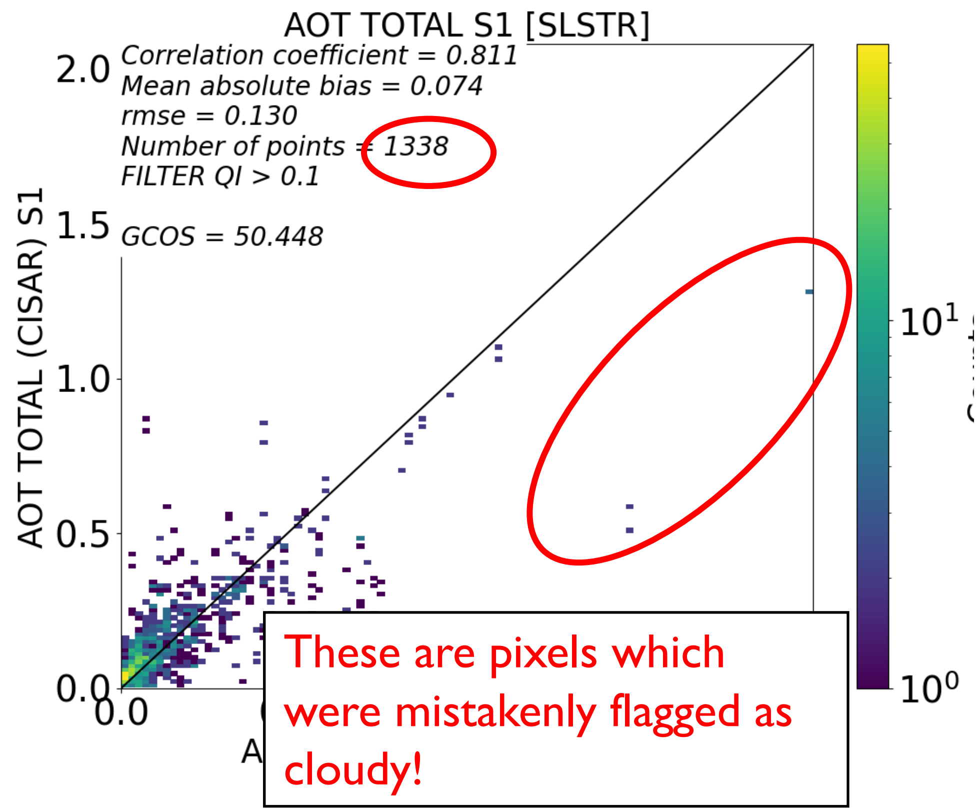


Results – Evaluation against AERONET

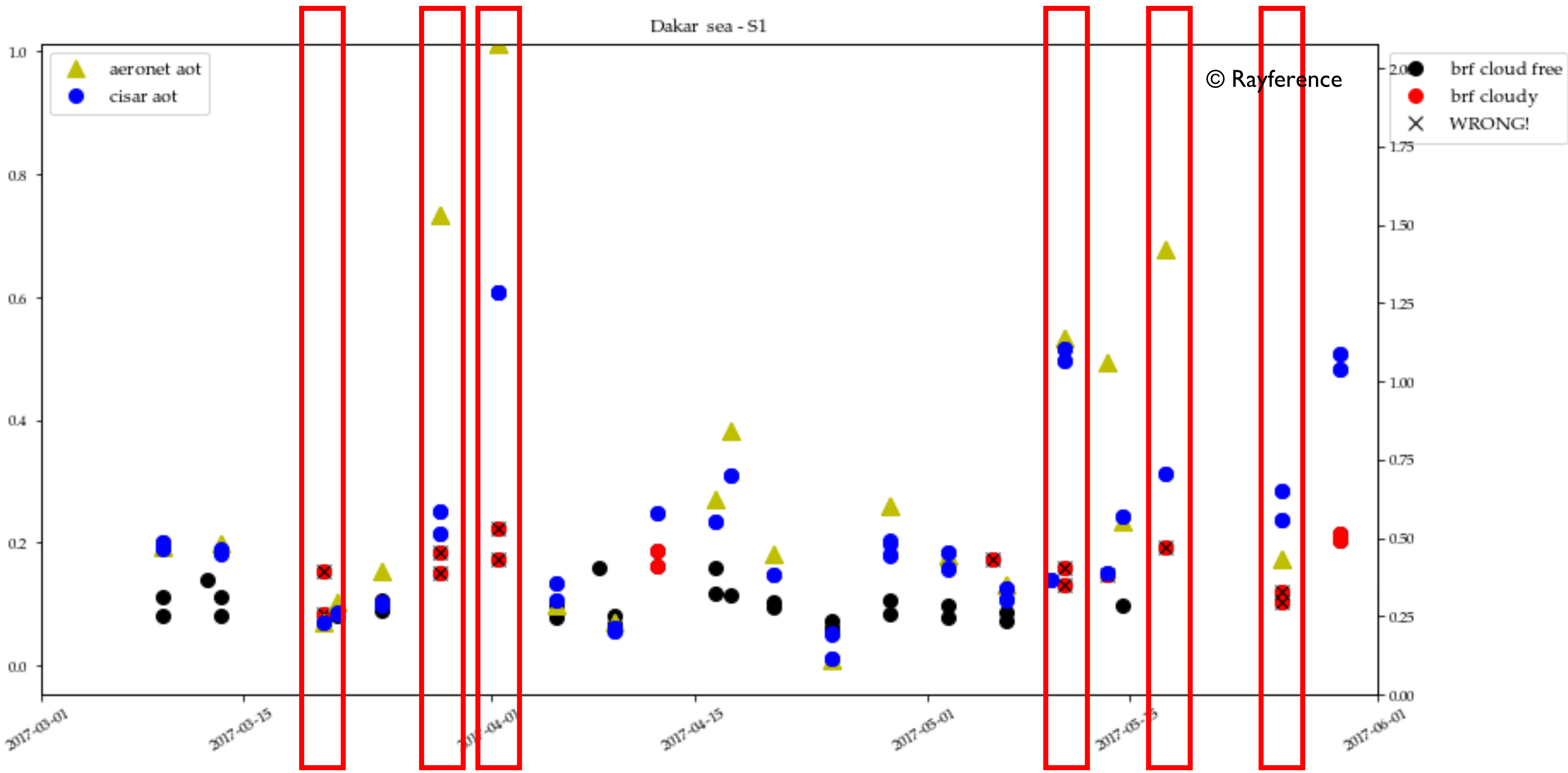
Only cloud free



Both cloudy and cloud free

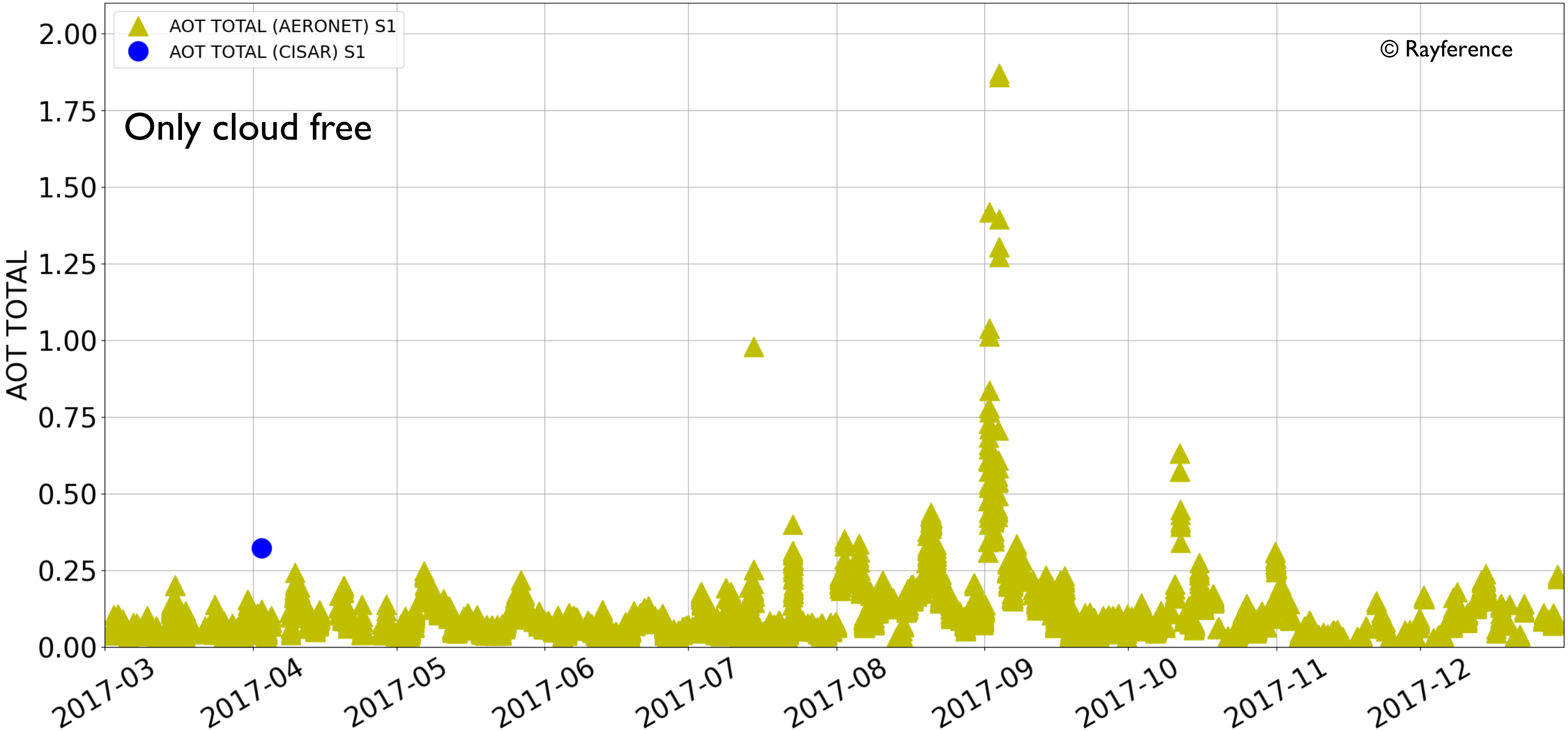


Results – Evaluation against AERONET



Results – timeseries continuity

- The new CISAR version allows more continuous timeseries as shown, for instance, over Modesto.



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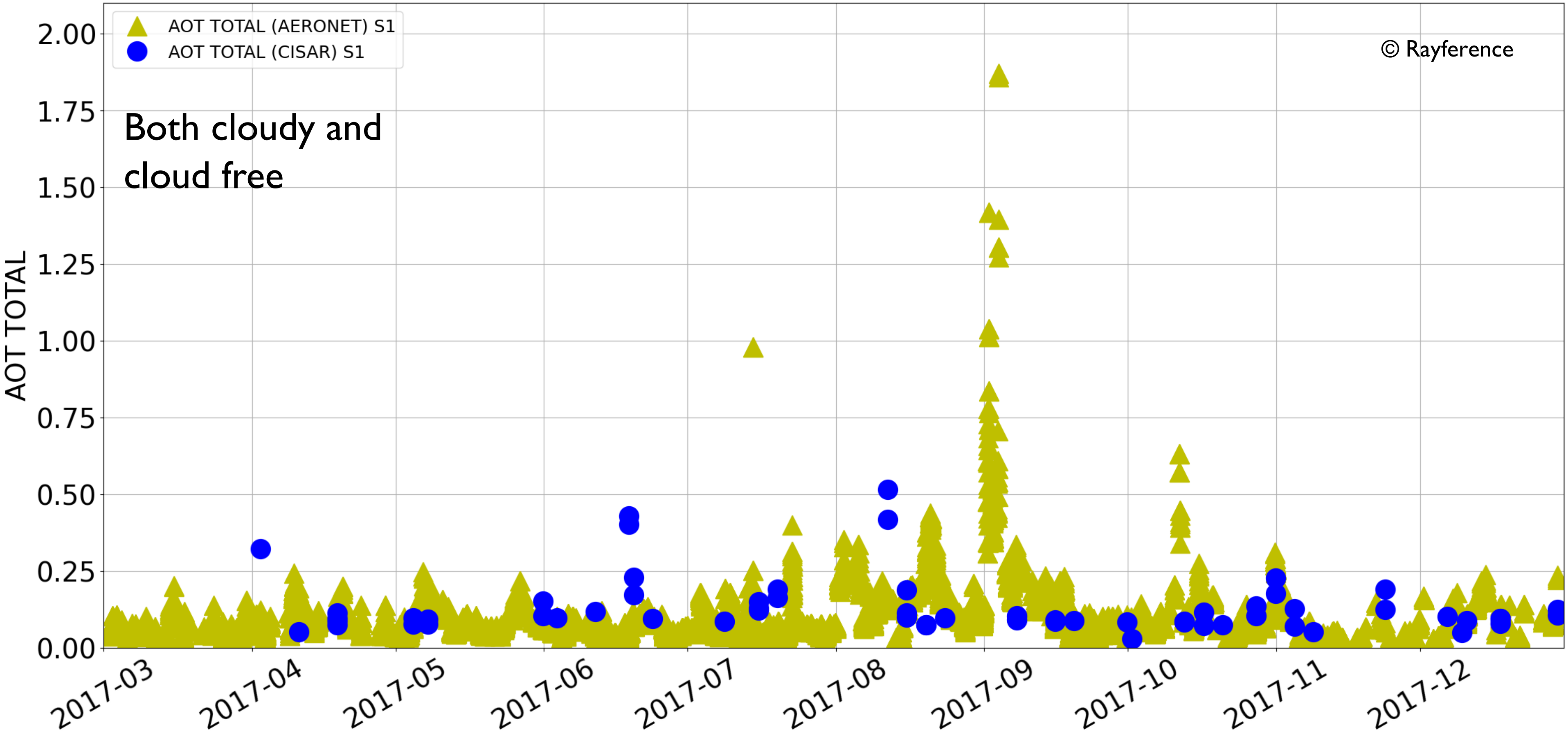
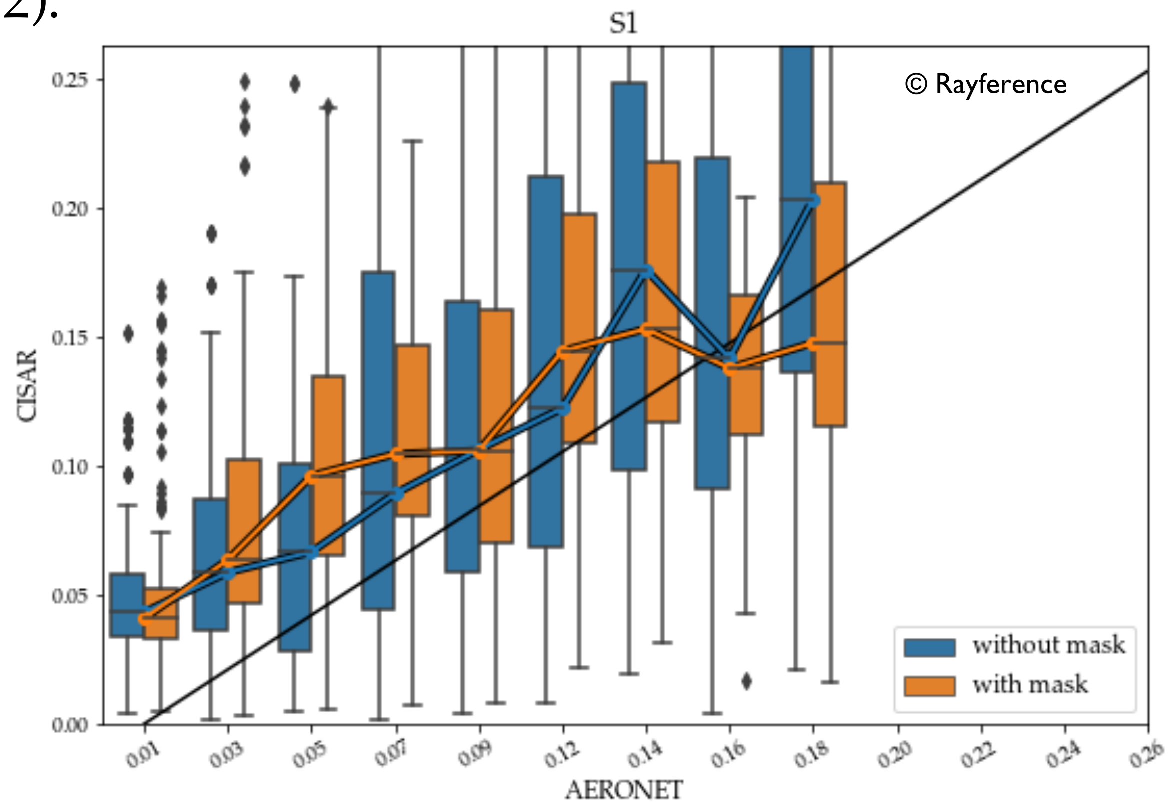


Results – reduced overestimation

- One of the reason that lead to the CIRCAS project is the overestimation for low AOT, partially due to cloud contamination (Remer et al, 2012)
- The new version of the CISAR version, without relying on the external cloud mask, reduces the overestimation for low AOT (AOT<0.2).



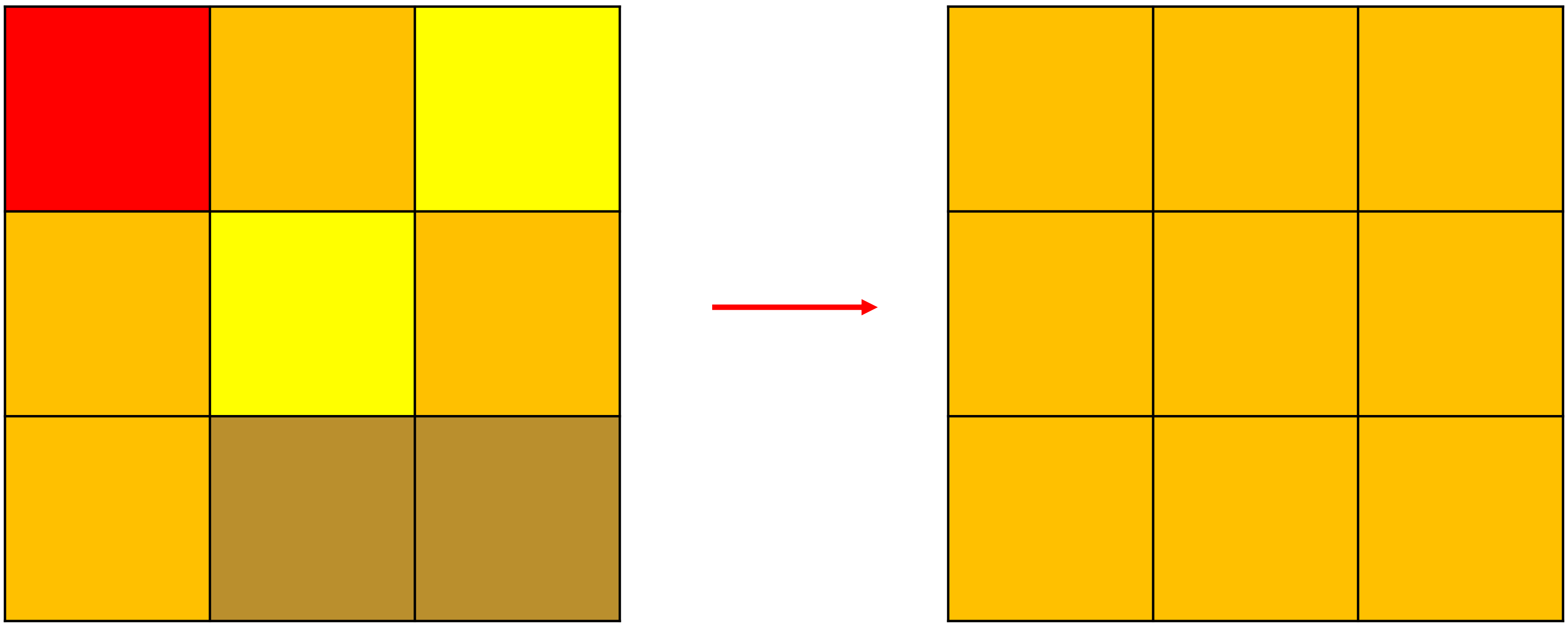
Conclusions

- The new developed CISAR version consistently retrieves surface reflectance, aerosol and cloud single scattering properties.
- After 2 cloud-free accumulation periods training, the CISAR retrieval is not based anymore on the external cloud mask.
- Pixels that are mistakenly flagged as cloudy by the cloud mask are now processed.
- The overestimation due to cloud contamination is reduced.

Way forward – spatial smoothing

- At the moment no spatial smoothing is applied within CISAR.
- This allows the parallelisation of the algorithm at pixel level.
- However, the temporal overlap between two consecutive accumulation periods could be exploited to implement spatial smoothing on the prior information.
- This spatial smoothing would still keep the inversion pixel-independent.

Way forward – spatial smoothing



Retrieval @ period i

PRIOR @ period i+1

Way forward – non diagonal matrices

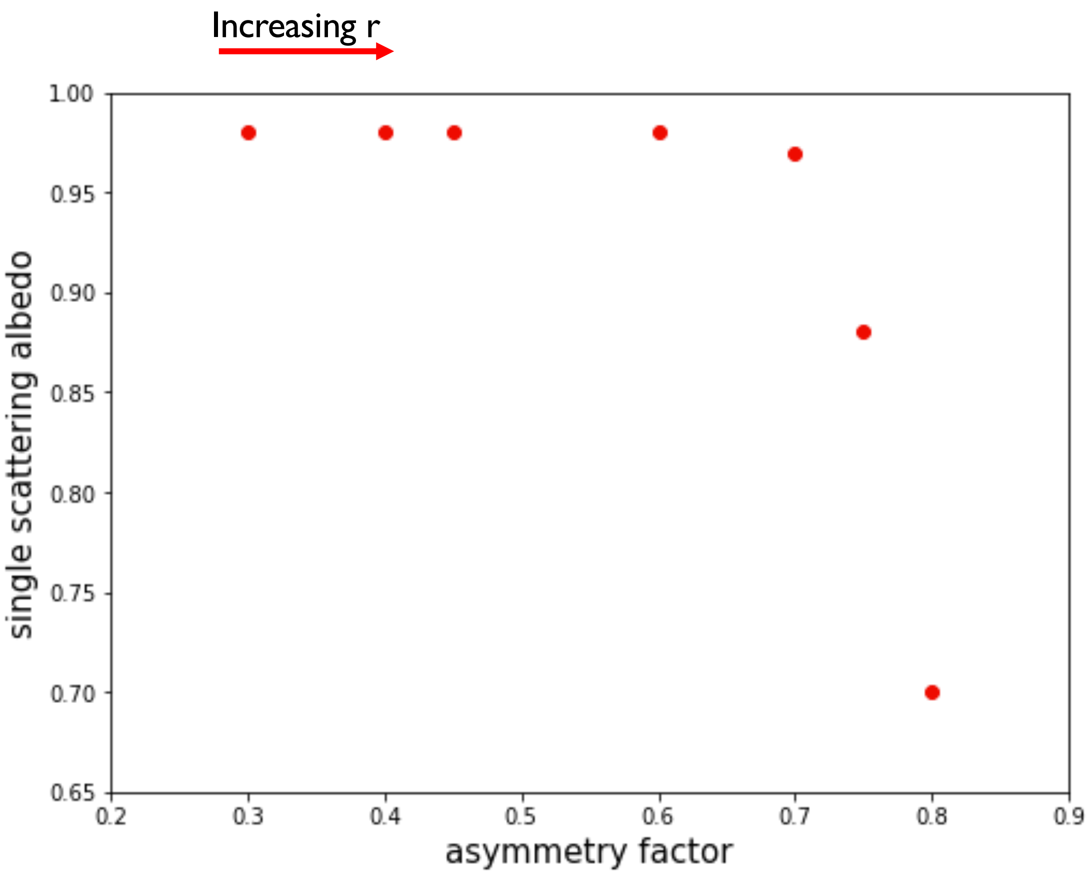
- At the moment, all the input covariance matrices are considered diagonal, i.e. any correlation information is lost.
- Considering the off-diagonal elements will certainly increasing the computational effort but it might improve the quality of the retrieval.
- More effort is needed to implement non-diagonal covariance matrices and quantify the associated computational cost.

Way forward – non linearity

- The CISAR retrieval within the same pixel has been limited to either AOT or COT because of the linearity assumption in the solution space.
- It hasn't been demonstrated yet that the linear combination of single scattering albedo and asymmetry factor is still valid for large particles.

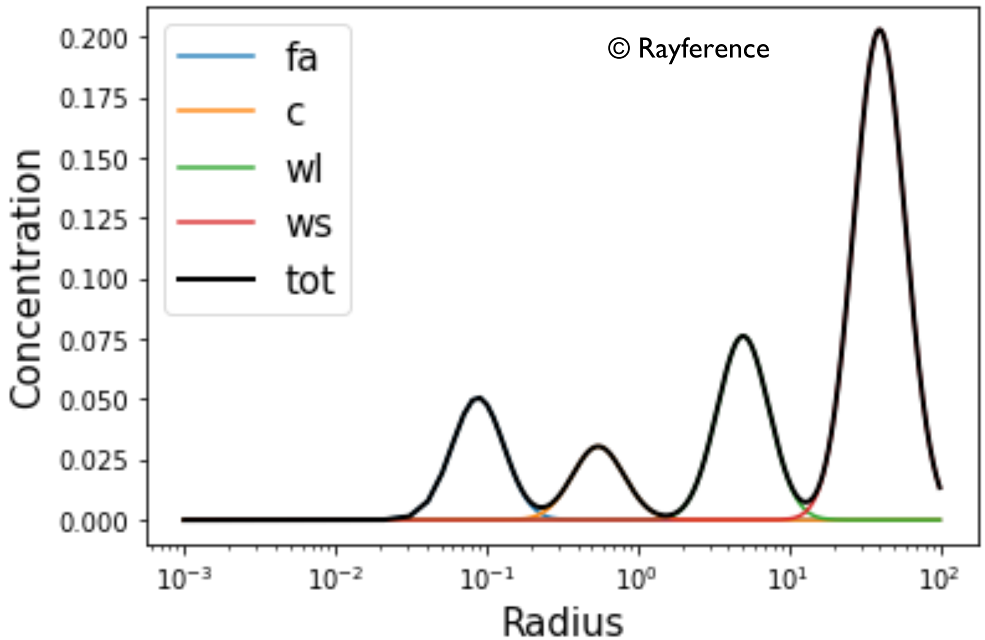
Way forward – non linearity

- The $\boldsymbol{\omega}$-g space is non – linear moving towards coarser particles.



Way forward – non linearity

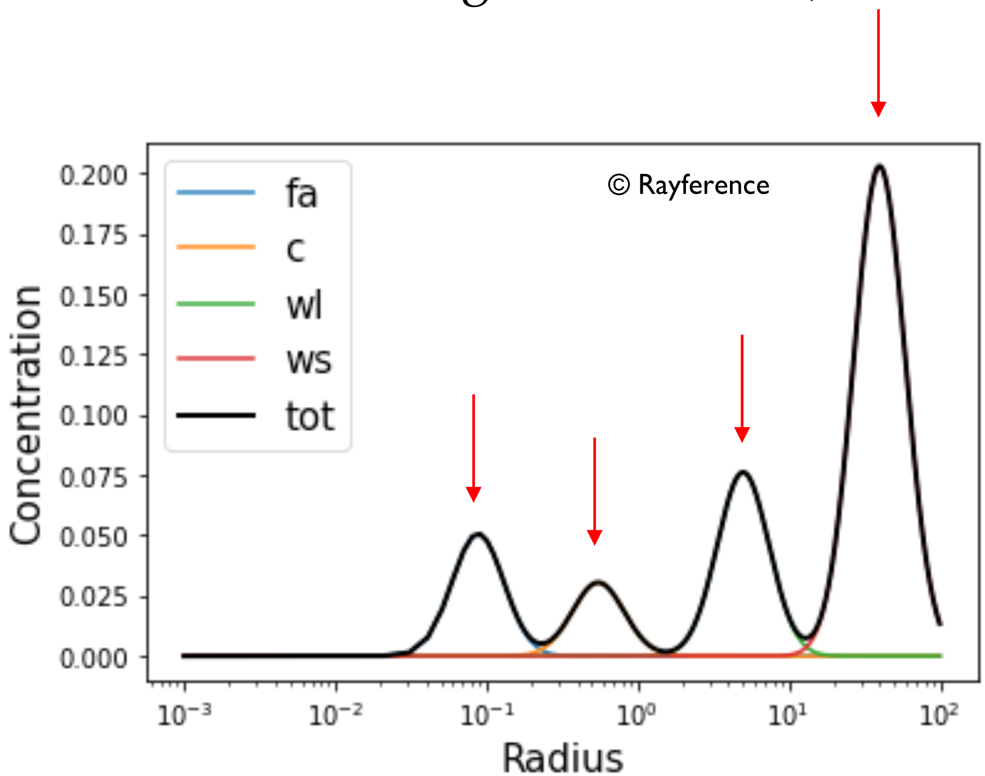
- To study this non linearity, simulations with the libradtran model have been made.
- The tool to apply the Mie theory does not allow to mix different refractive index → simulations are limited to particles with different radius.



r_{fa} = 0.088 μm
r_c = 0.55 μm
r_{ws} = 5. μm
r_{wl} = 40. μm

Way forward – non linearity

- Mie is applied twice:
  1. On each distribution separately, combining the resulting properties as it is done within CISAR (as a linear combination)
  2. On the resulting distribution (black line)



r_{fa} = 0.088 µm
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r_{ws} = 5. µm
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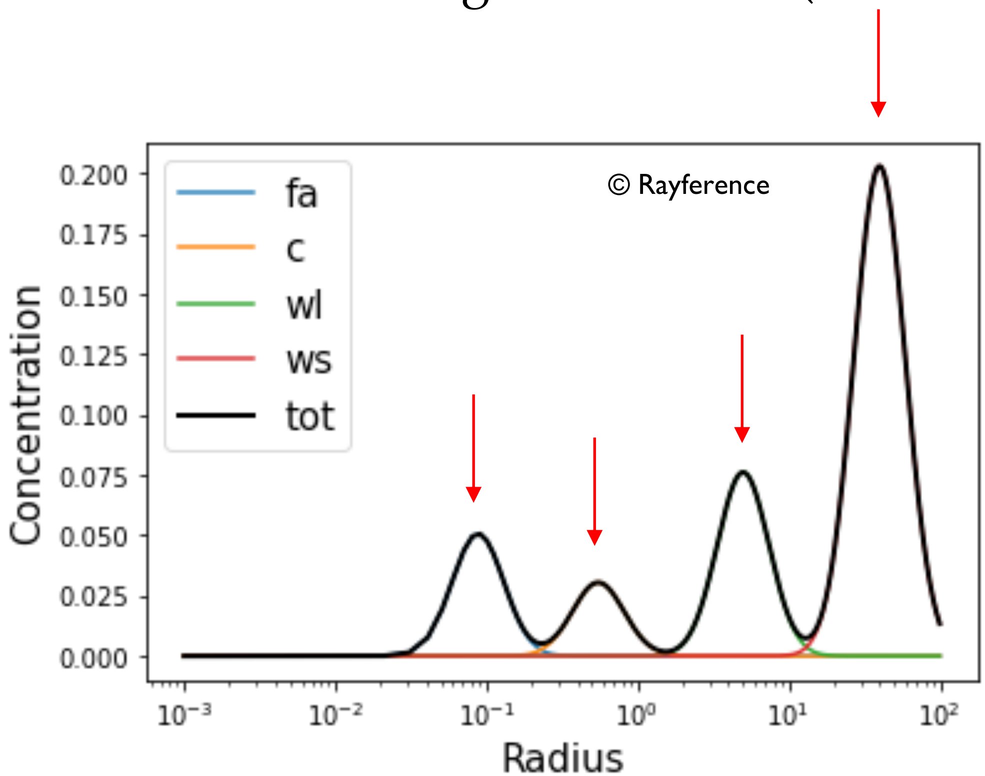
Way forward – non linearity

- Mie is applied twice:
  1. On each distribution separately, combining the resulting properties as it is done within CISAR (as a linear combination) → LINEAR COMBINATION
  2. On the resulting distribution (black line) → MIE



r_{fa} = 0.088 µm
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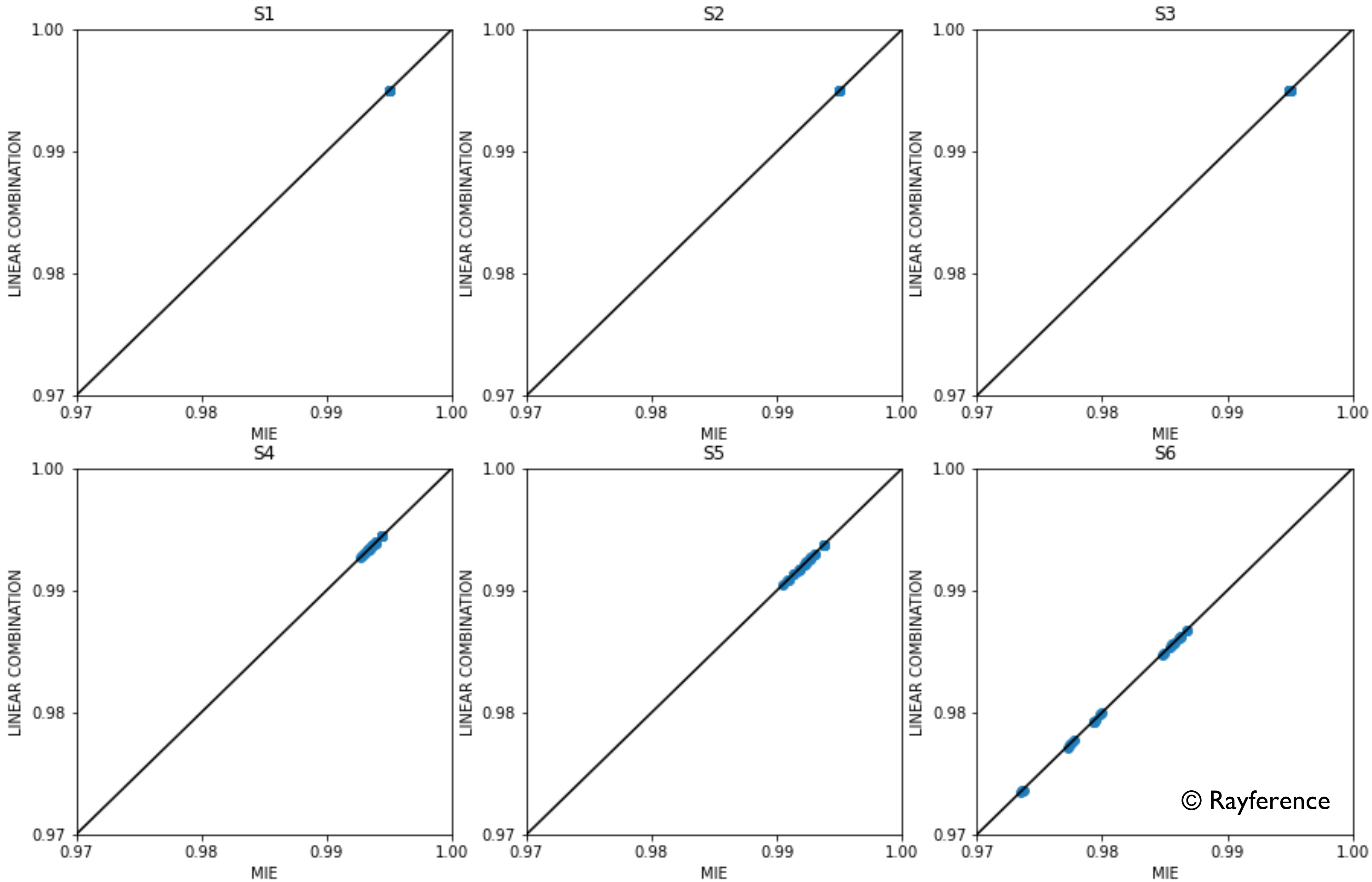
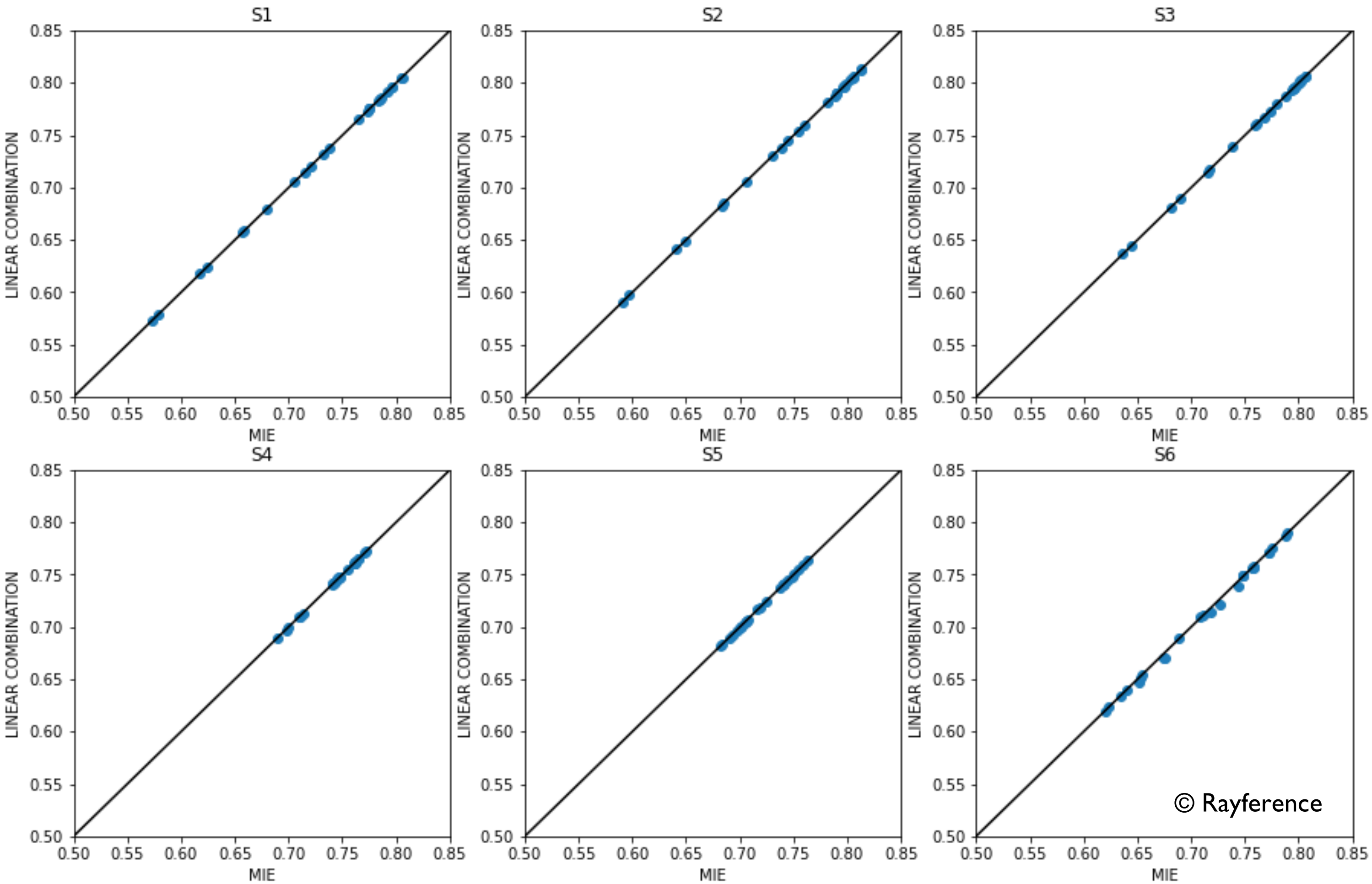
Way forward – non linearity

Single scattering albedo



Way forward – non linearity

Asymmetry factor

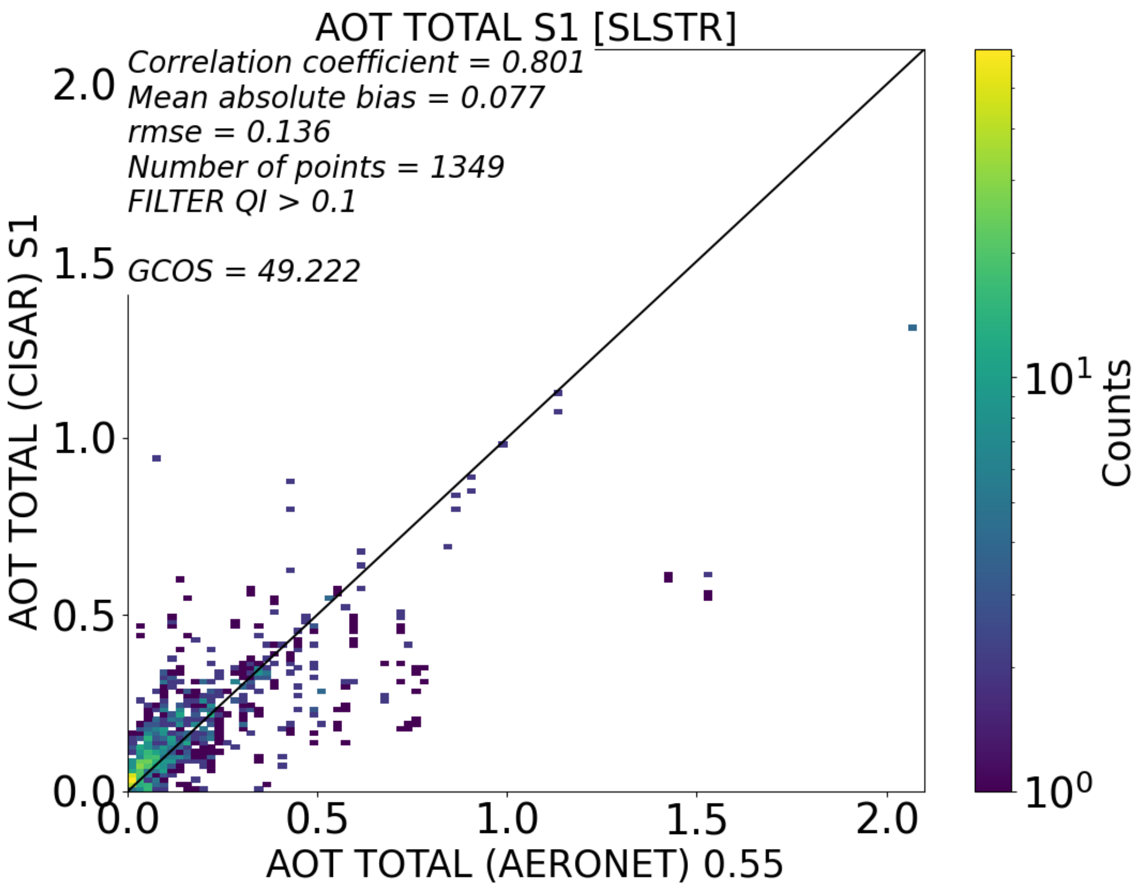


Way forward – aggregating all observations

- Given these findings on the linearity of the solution space for large particles, it has been decided to remove the limitation of retrieveing either AOT or COT within a pixel.

- The SLSTR data aggregation is now performed as follows:
  - If more than 80% of the pixels at 500 m are cloudy (cloud free), only cloudy (cloud free) pixels are aggregated
  - Otherwise, all pixels are aggregated.

Way forward – aggregating all observations



Performance are similar to what was obtain discarding mixed (cloudy and cloud free) pixels!

Way forward - Maps

- To actually verify the advantage of the latest CISAR version performing the inversion on mixed pixels, it is necessary to produce maps.
- Only looking at the maps it will be possible to verify the retrieval in the twilight zone.
- CISAR is currently being deployed at Brockmann Consult on Calvalus for the processing of satellite images.

Thank you!

For any question:
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http://www.rayference.eu/1/

Useful links

- CIRCAS project: http://circas.eu/
- CISAR:
  - Part 1: theoretical concepts - https://www.atmos-meas-tech.net/11/6589/2018/
  - Part 2: application to geostationary and polar orbiting satellites: https://www.atmos-meas-tech.net/12/791/2019/
  - Jacobians: https://www.researchgate.net/publication/304040041_ASSESSING_HOURLY_AEROSOL_PROPERTY_RETRIEVAL_FROM_MSGSEVIRI_OBSERVATIONS_IN_THE_FRAMEWORK_OF_AEROSOL_CCI2
- SLSTR: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-3-slstr/instrument
- The Aerosol-CCI project: http://cci.esa.int/aerosol
- On the twilight zone: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007GL029253
- Aerosol retrieval in cloudy environment: https://www.atmos-meas-tech.net/5/1823/2012/amt-5-1823-2012.pdf
- RTMOM: Govaerts, Y. M. 2006. "RTMOM V0B.10 User's Manual." EUMETSAT