https://doi.org/10.5194/egusphere-2025-1536
Preprint. Discussion started: 14 April 2025

Synergetic Retrieval from Multi-Mission Spaceborne Measurements for Enhancement of Aerosol and Surface Characterization

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Abstract. Atmospheric aerosol is one of the main drivers of climate change. At present time there are a number of different satellites on Earth orbit dedicated to aerosol studies. Due to limited information content, the main aerosol products of the most of satellite missions is AOD (Aerosol Optical Depth) while the accuracy of aerosol size and type retrieval from spaceborne remote sensing still requires essential improvement. The combination of measurements from different satellites essentially increases their information content and, therefore, can provide new possibilities for retrieval of extended set of both aerosol and surface properties.

A generalized synergetic approach for aerosol and surface characterization from diverse spaceborne measurements was developed on the basis of GRASP (Generalized Retrieval of Atmosphere and Surface Properties) algorithm (SYREMIS/GRASP approach). The concept was applied and tested on two types of synergetic measurements: (i) synergy from polar orbiting satellites (LEO+LEO synergy), (ii) synergy from polar orbiting and geostationary satellites (LEO+GEO synergy). On one hand such synergetic constellation extends the spectral range of the measurements. On the other hand, it provides unprecedented global spatial coverage with high temporal resolution, which is crucial for number of climate studies.

In this paper we discuss the physical basis and concept of the LEO+LEO and LEO+GEO synergies used in GRASP retrieval and demonstrate that SYREMIS/GRASP approach allows the transition of information content from the instruments with the

richest information content to the instruments with lower one. This results in the substantial enhancements in aerosol and surface characterizations for all instruments from the synergy.

1 Introduction

Number of climate studies require the extended aerosol and surface characteristics on the global scale, including such properties as Aerosol Optical Depth (AOD) and size distribution, Single Scattering Albedo (SSA), full surface Bi-Directional reflectance Distribution Function (BRDF), etc. This is particularly relevant for the generation of the high-quality aerosol and surface Essential Climate Variables (ECVs), characterizing the Earth climate system, for air-quality monitoring, aerosol emission and transport studies, etc. (Dubovik et al., 2008, 2021b; Martin, 2008; Hollmann et al., 2013; IPCC, 2021; Chen et al., 2019, 2022a). In addition to the global scale, the high temporal resolution of the extended aerosol properties is required for such important but challenging studies as aerosol-cloud interactions, gas-to-particle transformation, atmospheric aerosol dynamics, etc. (Pöschl, 2005; Rosenfeld et al., 2023; Vehkamäki and Riipinen, 2012).

The global information about aerosol can be obtained from spaceborne measurements. Therefore, climate studies are becoming more and more relying on the high-quality aerosol characterization from space. At present time there are many different satellites on Earth orbit dedicated to aerosol characterization. Nevertheless, due to the limited information content, the main aerosol product of most satellite missions is AOD (Remer et al., 2005; Levy et al., 2013; Sayer, 2018b; Sogacheva et al., 2020) while the accuracy of the extended properties with high temporal resolution requires essential improvements. To address this problem, several main requirements on the satellite measurements have been formulated from the general principles of light scattering theory and atmospheric dynamics studies (Van der Hulst, 1957; Tsang et al., 1985; Bohren and Huffman, 1998; King et al., 1999; Mishchenko et al., 2002; 2004; Hasekamp and Landgraf, 2007; Hasekamp et al., 2011, 2024; Lenoble et al., 2013; Dubovik et al., 2011, 2019; Remer et al., 2024). In particular, such measurements should include:

(i) multi-angular measurements in a wide range of scattering angles where the differences between angular dependence of aerosol and surface signals can be observed and the angular sampling is enough for aerosol characterization;

(ii) measurements in a wide spectral range (preferably from Ultra Violet (UV) to Short Wave Infrared (SWIR) ranges) to take advantage of different spectral dependence of aerosol and surface signals and to observe spectral features of different aerosol species;

(iii) polarimetric measurements to gain advantages of differences in the polarization signatures of aerosol and surface signals and strong dependence of such measurements on microphysical properties of aerosol.

(iv) frequent temporal measurements to account for the temporal variability of aerosol properties as well as differences in aerosol and surface conditions.

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The conditions (i)-(iii) are substantially covered by Multi-Angular Polarimetric (MAP) spaceborne missions such as, for example, POLDER-3/PARASOL mission, ended in 2013 (Deschamps et al., 1994; Tanré et al., 2011), or the new missions like PACE (with HARP-2 and SPEX instruments onboard), MetOp-SG 3MI, CO2M MAP, etc. (Dubovik et al., 2019; Hasekamp et al., 2019; Fu et al., 2025). Nevertheless, each of the spaceborne instruments alone, including MAP, still has a number of limitations related to the spectral coverage, spectral and spatial resolutions, etc. Moreover, most of the low-orbiting satellites have a relatively low frequency of the revisiting time (a few times per day or less), which is not enough to study physical and chemical dynamic processes in the atmosphere with a required temporal resolution of one hour or even better.

Strictly speaking, none of the currently operating and future aerosol-oriented satellite instruments alone meets completely all the above-mentioned requirements (i)-(iv). The solution to this problem has been discussed for a long time and is based on the synergetic retrieval of the combined measurements from different sensors (Aires et al., 2012; Holzer-Popp et al., 2008; Vanhellemont et al., 2014; Wang et al., 2014; Lee and Ahn, 2021). Indeed, the different satellites dedicated to atmospheric studies may have different spectral coverage and resolution, overpass the same certain area on Earth's surface during the same day but at different times or different relative positions. As a result, being properly collocated and combined, such measurements can provide multi-angular, multi-temporal measurements in an extended spectral range, satisfying the requirements (i)-(iv).

Despite the known recipe, the generalized synergetic retrieval approach applicable to diverse multi-instrument L1 measurements (L1 synergy) has not been developed yet. The problem is rather algorithmic than engineering since to gain advantages of the combined L1 synergetic measurements the retrieval algorithm must satisfy the following conditions:
(v) retrieval should be based on an advanced inversion approach and flexible forward models adaptable to the information content of the measurements;
(vi) retrieval should be able to account for diverse measurements with, possibly, different calibration accuracy, different spectral and spatial resolution;
(vii) algorithm should be able to account for the multi-temporal (not collocated in time) measurements.

A number of advanced retrieval algorithms can fit the requirements (v) and (vi) resulting in the synergetic approaches for collocated in time satellite measurements, for example, synergy of MERIS and AATSR from ENVISAT platform (North et al., 2008), synergy of OCLI and SLSTR from Sentinel-3 platform (Henocq et al., 2018), PMAP synergetic algorithm for GOME-2, AVHRR, and IASI on MetOp platform (Grzegorski et al., 2021). Nevertheless, the correct treatment of the observations which are not collocated in time is still beyond the capacity for most of the existing algorithms. Since the properties of aerosol do not change randomly in time and space but rather show temporal and spatial correlations due to atmospheric dynamic processes, accounting for such temporal dependencies is crucial in the synergetic retrieval.

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The temporal (as well as spatial) dependences between the characteristics of aerosol or surface are accounted for in the GRASP (Generalized Retrieval of Atmosphere and Surface Properties) algorithm with multi-temporal and multi-spatial smoothness constraints (Dubovik et al. 2011, 2014; 2021a). The algorithm has already been successfully applied to the observations from different spaceborne instruments. Extended aerosol characterization with GRASP algorithm was demonstrated on PARASOL measurements (Popp et al., 2016; Chen et al., 2020; Schutgens et al., 2021). Application of the GRASP to the Sentinel-3A/OLCI instrument showed a performance in AOD retrieval comparable to MODIS dark target (DT) product (Chen et al., 2022b). Nevertheless, the studies also showed strong dependence of the quality of OLCI/GRASP retrieval on a priori information about surface BRDF and reduced quality of retrieval of the extended properties like Angstrom Exponent (AExp) and Single Scattering Albedo (SSA) (Chen et al., 2022b). Applying GRASP to Sentinel-5P/TROPOMI measurements, it was shown that the quality of the extended aerosol and surface characterization can be significantly enhanced even from single viewing instrument if the presented above conditions (ii), (iii)- (v) and (vii) are fulfilled for the sensor and the retrieval algorithm (Litvinov et al., 2024; Chen et al., 2024a).

The GRASP multi-pixel retrieval strategy has already been used in the different synergetic approaches. In particular, the synergetic approach from ground-based observations was developed for the sun-photometer and LIDAR measurements (Lopatin et al., 2013, 2021; Dubovik et al, 2021a). The synergetic retrieval from combined ground-based and satellite measurements was introduced and used to generate surface reference database for validation of the satellite surface retrieval (GROSAT/GRASP approach (Litvinov et al., 2020, 2022, 2024)). In (Litvinov et al., 2021) and (Chen et al., 2024b), the hybrid synergy with the GRASP algorithm gains advantages of the rich information content of the TROPOMI measurements and high spatial resolution of the PRISMA instrument (L2 to L1 hybrid synergy).

In this paper we present a novel generalized synergetic approach with the GRASP algorithm for retrieval of multi-mission spaceborne measurements (hereinafter SYREMIS/GRASP approach), which can be robustly applied to present and future satellite observations. The concept was developed for the two types of synergetic measurements: (i) synergy from Low Earth Orbiting (LEO) (polar-orbiting) satellites (LEO+LEO) and (ii) synergy of LEO and geostationary (GEO) satellites (LEO+GEO). The LEO+LEO synergy was implemented and tested on the combined measurements from Sentinel-5P/TROPOMI, Sentinel-3A/OLCI and Sentinel-3B/OLCI instruments (hereinafter referred to also as S5P/TROPOMI, S3A/OLCI, S3B/OLCI). LEO+GEO synergy concept was applied to S5P/TROPOMI, S3A/OLCI, S3B/OLCI and Himawari-8/AHI sensors.

In this paper, first, we describe the main principles of the SYREMIS/GRASP synergetic approach. Then, based on the validation results, the enhanced possibilities of the synergetic approach will be demonstrated, and the main drivers of the SYREMIS/GRASP synergetic approach be discussed.

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2. SYREMIS/GRASP synergetic concept

SYREMIS/GRASP synergetic approach was developed for the currently operating polar-orbiting and geostationary satellites: S3A/OLCI, S3B/OLCI, S5P/TROPOMI, Himawari-8/AHI. On one hand, such multi-mission measurements allowed testing the approach on the actual aerosol events and considering the enhancement in aerosol characterization relatively to already validated GRASP retrieval from S3A/OLCI and S5P/TROPOMI sensors alone (Chen et al., 2022, 2024a; Litvinov et al., 2024). On the other hand, it allowed filling the gaps in the detailed extended aerosol characterization, existing since the end of the POLDER-3/PARASOL mission in 2013 till the beginning of the new polarimetric missions (HARP-2 and SPEX onboard of PACE, MetOp-SG 3MI, etc.).

SYREMIS/GRASP synergetic satellites constellation extends the spectral range of the measurements and provides unprecedented spatial and temporal coverage which is crucial for global climate studies and air-quality monitoring (Table 1). Moreover, the single-view measurements from all instruments in Table 1 are obtained at different illumination and observation geometry (solar and viewing zenith angles, azimuthal angles). As a result, the combined synergetic measurements can be considered as a multi-angular one or, strictly speaking, pseudo-multi-angular, taking into account different times of the measurements for each observation angle.

Table 1. Multi-mission constellation for prototyped synergetic retrieval

Platform / Instrument	**Description**	**Level**	**Reference**
S3A/OLCI and 3B/OLCI	- Near-Polar orbiting - Swath: ~1270 km - One observation angle per pixel - Equatorial crossing: ~10.00 a.m. local time - Revisiting time: ~2 days near equator - Spatial resolution: ~300m - Radiance measurements in VIS and NIR spectral range	Level 1B S3A/OL_1_ERR S3B/OL_1_ERR	1*
S5P/TROPOMI	- Near-Polar orbiting - Swath: ~2600 km - One observation angle per pixel - Equatorial crossing: ~13.30 local time	Level 1B	2*

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	- Revisiting time: 1 day near equator - Spatial resolution: 5.5 x 3.5 km (UV, VIS, NIR range), 5.5 x 7 km (SWIR range) - Hyperspectral measurements in UV, VIS, NIR, SWIR spectral range		
Himawari-8/AHI	- Geostationary. - Coverage area: Asia - One observation angle per pixel - Spatial resolution: 2-5 km - Temporal resolution: every 10 min - Radiance measurements in VIS, NIR and SWIR spectral range	L1 Gridded data (3*)	3*,4*

1*: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-3-olci/data-formats

2*: https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-5p/products-algorithms

3*: https://www.eorc.jaxa.jp/ptree/userguide.html

4*: https://www.data.jma.go.jp/mscweb/en/himawari89/space_segment/sample_netcdf.html

Figure 1 demonstrates schematically the general concept of combining the multi-instrument spaceborne measurements in SYREMIS/GRASP synergy.

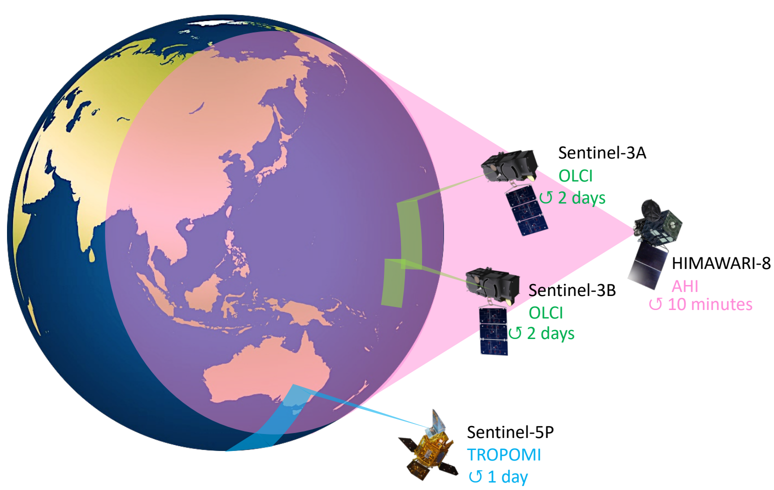

Figure 1: Schematic representation of the SYREMIS/GRASP multi-instrument measurements.

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Overall, the SYREMIS/GRASP synergetic concept is based on three main principles: (i) harmonization of data from different instruments; (ii) "weighting" the measurements according to their information content and measurements accuracies; (iii) optimization of GRASP forward models and retrieval setup.

2.1 SYREMIS/GRASP synergetic measurements harmonization

All satellites from Table 1 are very different in their measurement capabilities, including spectral range and spatial coverage, spatial resolution, revisiting time etc. To gain advantages of the extended information content of the synergy, the measurements from each instrument should be properly harmonized and merged. In particular, this includes (i) spectral measurements harmonization; (ii) harmonization on spatial resolution and gridding; (iii) cloud masking merging etc.

As a first step of the harmonization, the spectral bands which are more optimal for aerosol characterization were selected for LEO+LEO and LEO+GEO synergy (Table 2). The independent retrieval with GRASP algorithm has been already applied to each of the instruments using 9 spectral bands for OLCI sensor, 10 for TROPOMI, and 6 bands for AHI instrument (Chen et al., 2022, 2024a; Litvinov et al., 2024; Table 1). These bands were also considered in the SYREMIS/GRASP synergy. In particular, 19 spectral measurements were included in polar orbiting LEO+LEO synergetic retrieval and 21 bands in LEO+GEO one (Table 2).

All instruments from the synergetic satellite constellation have different spatial resolution (Table 1). To apply properly the multi-pixels constraints in the GRASP algorithm, all measurements were re-gridded to the same spatial grid. Following the approach used in TROPOMI/GRASP retrieval (Litvinov et al., 2024; Chen et al., 2024a), the equidistant cylindrical projection and WGS84 coordinate system with the same spatial pixel resolution of 0.09° was used for all selected spectral bands, using bilinear regridding method (https://gdal.org/programs/gdalwarp.html) (Tables 2).

Table 2. Harmonized measurements from SYREMIS synergy

	S3A/OLCI and S3B/OLCI	S5P/TROPOMI	Himawari-8/AHI
Wavelength selection	9 spectral bands: 412.5, 442.5, 490, 510, 560, 665, 753, 865, 1020 nm	10 spectral bands: 340, 367, 380, 416, 440, 494, 670, 747, 772, 2313 nm	6 spectral bands: 470.6, 510, 639.1, 856.7, 1610.1, 2256.8 nm
LEO+LEO synergy	19 spectral bands		-
LEO+GEO synergy	24 spectral bands		
L1C Regridding method	0.09°, WGS84 coordinate system		

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Cloud masking	IDEPIX	S5P NPP-VIIRS	Level 2 JAXA cloud product

Since the measurements in the SYREMIS synergy are not collocated in time, the cloud masking was applied independently for each instrument. In particular, the cloud screening for TROPOMI in SYREMIS/GRASP processing is based on the S5P NPP-VIIRS cloud product with about 500 m spatial resolution like it was done for TROPOMI/GRASP processing (Litvinov et al., 2024; Chen et al., 2024a). Similarly to OLCI/GRASP retrieval (Chen et al., 2022), IDEPIX cloud masking was applied to OLCI instrument. Himawari-8/AHI cloud screening is based on Level 2 cloud products (Letu et al., 2018, 2020).

2.2 "Weighting" the multi-instrument measurements in the synergy

The multi-instrument measurements for the synergetic retrieval can be prepared in many possible combinations. A number of extensive case studies were performed to identify the most optimal retrieval setup for the synergy.

First of all, it was found out that merging close spectral measurements (for example, OLCI 442.5 nm and TROPOMI 440 nm, or OLCI 665 nm and TROPOMI 670 nm etc.) does not provide the best results. This can be explained by different accuracy of radiometric calibration and different bandwidth of the measurements in the synergy. Therefore, the final SYREMIS/GRASP synergetic data were prepared for 19 spectral measurements in LEO+LEO synergy and for 24 bands in LEO+GEO ones (Table 2). Accounting for the differences in the calibration and spectral bandwidth in GRASP algorithm is realized with application of the different requirements on the standard deviation of measurements fitting for the different spectral bands.

Second, extended standard deviation tests showed that proper "weighting" the multi-instrument measurements is crucial part of the SYREMIS/GRASP synergetic approach. In particular, it was found out that the "weight" of the TROPOMI measurements in the synergetic LEO+LEO and LEO+GEO retrieval should be stronger than the "weight" of the OLCI and AHI instruments. This can be explained by higher information content and better radiometric accuracy of TROPOMI measurements in comparison to other instruments in the synergy. Specifically, whenever close values of the standard deviation were applied to all instruments and all spectral bands, validation versus AERONET showed reduced performance in comparison with the single instrument retrieval (for example, in comparison with TROPOMI/GRASP results (Litvinov et al., 2024; Chen et al., 2024a). Application of the stronger requirements on the measurements fitting for the TROPOMI bands in the synergy resulted in much better validation results versus AERONET (Figs. 2 and 3). In the SYREMIS/GRASP synergetic approach a few "weighting" groups with different requirements on the standard deviation of measurement fitting were associated with different instruments from the synergy (Tables 3 and 4).

In addition, it was discovered that exchanging of the a few measurements between the "weighting" groups provided better retrieval results vs AERONET. In particular, over land, the same standard deviation 0.001 as for the most of TROPOMI

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channels (Table 3) was assigned to OLCI bands 490 nm and 560 nm, whereas one TROPOMI band 494 nm was allocated to the OLCI bands "weighting" group with required standard deviation 0.05 (Table 3). Such bands inter-exchange was found to be useful to improve OLCI retrieval in the LEO+LEO synergy without loss in accuracy for SYREMIS/TROPOMI retrieval. It allows transferring information content from TROPOMI to OLCI and vice versa. The inter-exchange of selected bands between OLCI and AHI measurements also improved the consistency of the retrieval for all instruments in the LEO+GEO synergy (Table 4). The optimal "weighting" of the different measurements in LEO+LEO and LEO+GEO SYREMIS synergy, according to the applied requirements on the standard deviation, is presented in Tables 3 and 4.

Table 3. SYREMIS LEO+LEO synergy setup.

		Land	Ocean
SYREMIS/GRASP measurements "weighting" groups based on the requirement on the standard deviation of measurements fitting		0.001 (highest "weight"): - for 9 TROPOMI bands (340, 367, 380, 416, 440, 670, 747, 772, 2313 nm) - for 2 OLCI bands (490 , *560* nm) 0.05 (lower "weight"): - for 1 TROPOMI band (494nm) - for 7 OLCI bands (412.5, 442.5, 510, 665, 753, 865, 1020 nm)	0.01 (highest "weight"): - for 9 TROPOMI bands (340, 367, 380, 416, 440, 670, 747, 772, 2313 nm) - for 1 OLCI band (490 nm) 0.02 (lower "weight"): - for 6 OLCI bands (510, 560, 665, 753, 865, 1020 nm) 0.1 (lower "weight"): - for 1 TROPOMI band (494nm) - for 2 OLCI bands (412.5, 442.5nm)
Temporal thresholds	Surface variability	+/- 6 h	+/- 0.5h
	Aerosol scale height variability	+/- 3h	+/- 0.5h
Temporal smoothness constraints	Aerosol concentration	0.0001 (relaxed constraints)	0.0001 (relaxed constraints)
	Aerosol models fractions	0.01	0.01
	Surface BRDF isotropic parameter	0.01	5.0
	Surface BRDF other parameters	0.005	A priori information from ECMWF

Table 4. SYREMIS GEO+LEO synergy setup.

	Land

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SYREMIS/GRASP measurements "weighting" groups based on the requirement on the standard deviation of measurements fitting		0.001 (highest "weight"): for 9 TROPOMI bands (340, 367, 380, 416, 440, 670, 747, 772, 2313 nm) for 2 OLCI bands (490,560 nm) 0.05 (lower "weight"): for 1 TROPOMI band (494nm) for 6 OLCI bands (412.5, 442.5, 665, 753, 865, 1020 nm) 0.01 (lower "weight"): for 4 AHI bands (471, 510, 639, 856.7nm) for 1 OLCI band (510 nm) 0.05 (lower "weight"): for 2 AHI bands (1610, 2256.8 nm)
Temporal thresholds	Surface variability	+/- 1h
	Aerosol scale height variability	+/- 3h
Temporal smoothness constraints	Aerosol concentration	0.1
	Aerosol models fractions	0.1
	Surface BRDF	1.0

2.3 Forward models and retrieval setup for multi-instrument synergy

Application of the GRASP retrieval algorithm independently to OLCI, TROPOMI and AHI single view instruments as well as to the multi-angular polarimetric PARASOL measurements showed good performance of the so-called aerosol "models" approach (Chen et al., 2020, 2022, 2024a; Dubovik et al., 2021a, Hasekamp et al., 2024; Litvinov et al., 2024). In such approach the total single scattering characteristics of aerosol are represented as the linear combinations of the scattering characteristics of the preselected aerosol components i.e. assuming an external mixture of different aerosol models (Lopatin et al., 2021; Litvinov et al., 2024).

The surface reflectance in the GRASP retrieval is, usually, described by the spectrally constrained renormalized Ross-Li BRDF model over land (Litvinov et al., 2010, 2011a, 2011b, 2024) and modified Cox and Munk with accounting for water leaving reflectance (Cox and Munk, 1954; Litvinov et al., 2024). These aerosol and surface reflectance forward approaches were found to be optimal also in SYREMIS/GRASP synergetic retrieval for the satellite constellation from Table 1.

In SYREMIS LEO+LEO and LEO+ GEO synergies the temporal difference between S3A/OLCI, S3B/OLCI, S5P/TROPOMI and Himawari-8/AHI measurements can vary from several minutes to several hours within one day. During this time aerosol

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properties (in particular, aerosol concentration) can change essentially. At the same time, the changes in aerosol microphysics (size, chemistry/complex refractive index, non-sphericity etc.) or surface BRDF parameters may not be as fast.

The temporal correlations of aerosol properties as well as surface BRDF parameters are accounted with the temporal constraints in the GRASP algorithm (Dubovik et al., 2011, 2021a). Correct selection of these constraints is one of the crucial elements of the synergy from the multi-instrument measurements when they are not coincident. To account for such temporal variability, different temporal thresholds and smoothness constraints were applied to different retrieval parameters. In particular, in the SYREMIS/GRASP processing the surface properties are considered to be the constant within +/-6h over land and +/-0.5h over ocean (“Temporal threshold on surface variability” in Tables 3 and 4). For the vertical distribution of aerosol concentration, the temporal threshold +/- 3h over land +/-0.5h over ocean was applied (“Aerosol scale height variability” in Tables 3 and 4).

The temporal variability of aerosol and surface properties from day to day is controlled in SYREMIS/GRASP by adequately selected temporal smoothness constraints. Since the combined measurements from S3A/OLCI, S3B/OLCI, S5P/TROPOMI and Himawari-8/AHI contain more information about temporal variability than for each separated instrument, the temporal smoothness constraints were relaxed for the synergetic retrieval in comparison to those were used for the single instrument, for example, TROPOMI/GRASP and OLCI/GRASP (Tables 3, 4, (Litvinov et al., 2024; Cheng et al., 2022). They are also more relaxed for LEO+GEO synergy than for LEO+LEO (Tables 3, 4).

Figures 2 and 3 show SYREMIS LEO+LEO retrieval results obtained before and after harmonization, instrument “weighting” and retrieval setup optimization. One can observe essential improvement in the retrieval relatively to AERONET after proper accounting for the information content of the instruments, measurements accuracy and adjustment of the retrieval approach to the synergetic multi-instruments’ constellation.

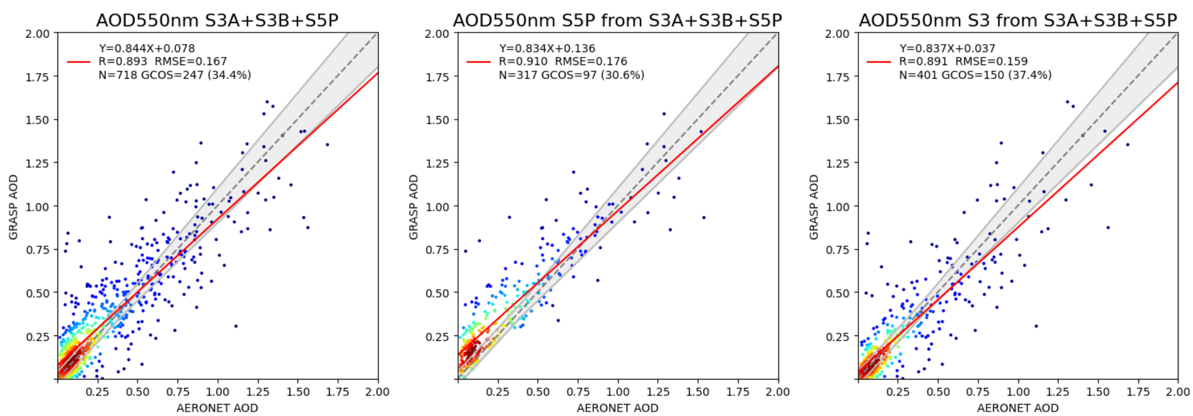

Figure 2: SYREMIS AOD retrieval before harmonization, instrument “weighting” and retrieval setup optimization: SYREMIS all instruments (left), SYREMIS/TROPOMI AOD extract (middle), SYREMIS/OLCI AOD extract (right).

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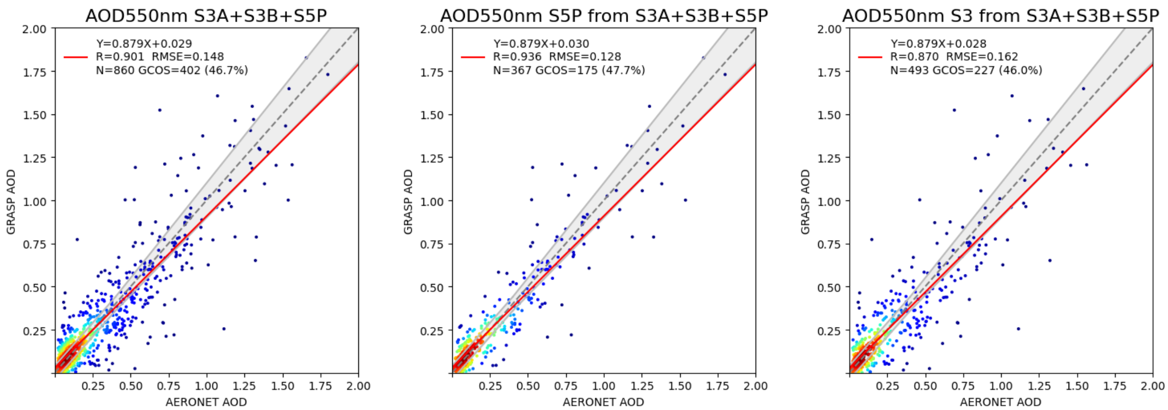

Figure 3: The same as in Fig.2 but after harmonization, instrument "weighting" and retrieval setup optimization (Table 3).

3 Validation and inter-comparison of the synergetic product

The validation of the SYREMIS/GRASP processing for LEO+LEO and LEO+GEO synergies was performed against AERONET and intercompared with VIIRS and MODIS aerosol and surface products (Schaaf et al., 2002; Schaaf and Wang, 2015; Hsu et al., 203, 2019; Sayer et al., 2018a, 2018b). The validation criteria are the same as was used for TROPOMI/GRASP retrieval evaluation (Litvinov et al., 2024; Chen et al., 2024a).

3.1 SYREMIS/GRASP LEO+LEO synergetic performance versus AERONET

Validation results from the synergetic SYREMIS/GRASP retrieval versus AERONET for March, April and May 2019 are presented in Figs. 4-7 separately for (i) all instruments in the synergy (SYREMIS/GRASP); (ii) for TROPOMI instrument extracted from the synergy (SYREMIS/TROPOMI) and (iii) for OLCI instrument extracted from the synergy (SYREMIS/OLCI). To remove the outliers of the retrieval, the filtering similar to TROPOMI/GRASP quality assurance flag was applied (Litvinov et al., 2024). In particular, over land the validation was done for the pixels satisfying the following conditions: (i) relative residual of fitting is less than 0.03 (3%); (ii) standard deviation (σ_{AOD}) of AOD(865nm) within the 3x3 pixels window is less than 0.05 or relative standard deviation σ_{AOD}(865)/AOD(865) is less than 0.15. Over ocean the filtering conditions were relaxed taking into account overall smaller the total reflectance and global AOD values in comparison to the pixels over land: (i) relative residual is less than 0.1; (ii) σ_{AOD}(865 nm)<0.05. For Angstrom Exponent (AExp) and SSA the additional filter was applied when only pixels with AOD(550 nm)> 0.2 and AOD(550 nm)> 0.3, respectively, were used in the validation.

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In general, the synergetic SYREMIS/GRASP retrieval shows good correspondence to AERONET with high percentage of fulfilments of GCOS (Global Climate Observation System, (GCOS-245, 2022)) requirements and the value of the statistical characteristics (Pearson correlation coefficient, Root Mean Square Error (RMSE), bias etc.) indicates the high quality of the retrieval (Figs. 4-7). All extended characteristics (AOD, AExp, SSA) are consistent for all instruments in the synergy.

Figs. 8-11 demonstrate the added value of the synergetic retrieval by comparing SYREMIS/TROPOMI and SYREMIS/OLCI-A validation with the one obtained from GRASP single-instrument retrieval (GRASP/TROPOMI and GRASP/OLCI (Litvinov et al., 2024; Chen et al., 2024a). Overall, one can see slightly better performance of SYREMIS/TROPOMI data extract in comparison with TROPOMI/GRASP: SYREMIS/TROPOMI AOD is better than the one derived from TROPOMI/GRASP retrieval, whereas AExp and SSA from the synergy are quite comparable with quality of TROPOMI/GRASP retrieval (Figs. 8-12 in (Litvinov et al., 2024)).

The biggest improvement is observed for the OLCI instrument where the performance of all retrieved parameters in SYREMIS/OLCI data extract is essentially improved in comparison to the independent GRASP/OLCI retrieval (Figs. 6, 10, 11): AOD, AExp, SSA from the synergy are much better than from single OLCI/GRASP retrieval. Moreover, SYREMIS/OLCI SSA retrieval reaches the same quality as for SYREMIS/TROPOMI and GRASP/TROPOMI with RMSE less than 0.05 (Litvinov et al., 2024; Chen et al., 2024a).

The presented results clearly show that properly combining measurements from S3A/OLCI, S3B/OLCI and S5P/TROPOMI according to the information content and accuracy, the synergetic SYREMIS/GRASP approach essentially improves the retrieval of the extended aerosol characterization in comparison to the single instrument retrieval. Overall, the quality of the retrieval for all instruments in SYREMIS/GRASP LEO+LEO synergy is comparable to or better than the quality from TROPOMI/GRASP retrieval and much better than OLCI/GRASP retrieval. This can be explained by the fact that S5P/TROPOMI measurements provide a richer information content than S3/OLCI (bigger spectral coverage, wider swath) and is known for its high radiometric accuracy (Ludewig et al., 2020; Tilstra et al., 2020). Therefore, the synergetic retrieval allows the transition of the information content from one instrument to another. In addition, such synergy allows consistent aerosol characterization from non-coincident diverse satellite measurements. In particular, SYREMIS/GRASP approach provides diurnal variability of the extended aerosol properties from S3A/OLCI, S3B/OLCI and S5P/TROPOMI multiple overpasses over the same geolocation.

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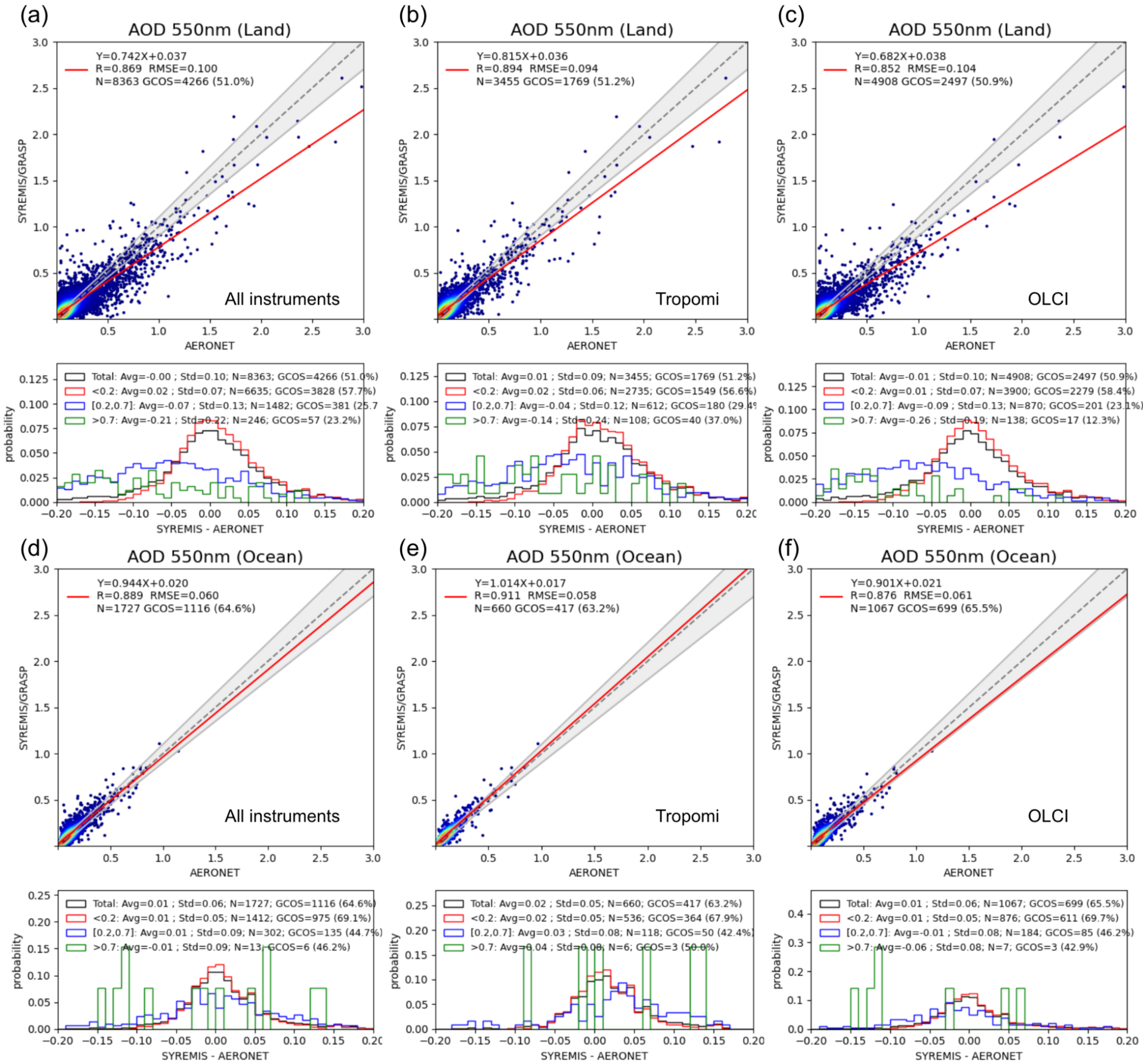

Figure 4: AOD550 validation vs global AERONET sites over land and ocean for SYREMIS/GRASP LEO+LEO synergy. 2019 March, April, May. Left: All instrument in the SYREMIS/GRASP synergy; middle: SYREMIS/TROPOMI extract; right: SYREMIS/OLCI extract.

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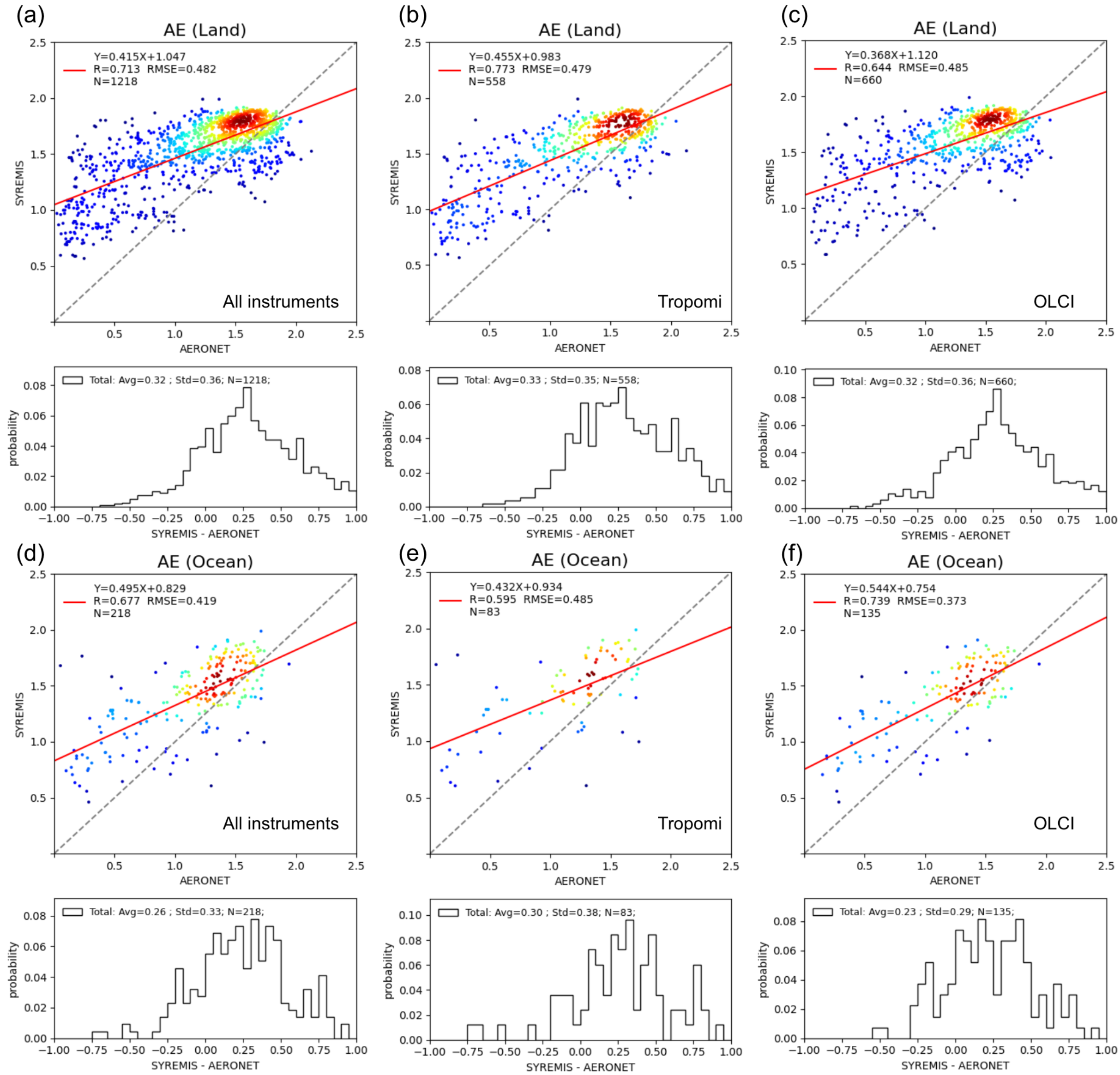

Figure 5: The same as in Fig. 4 but for AExp validation vs AERONET.

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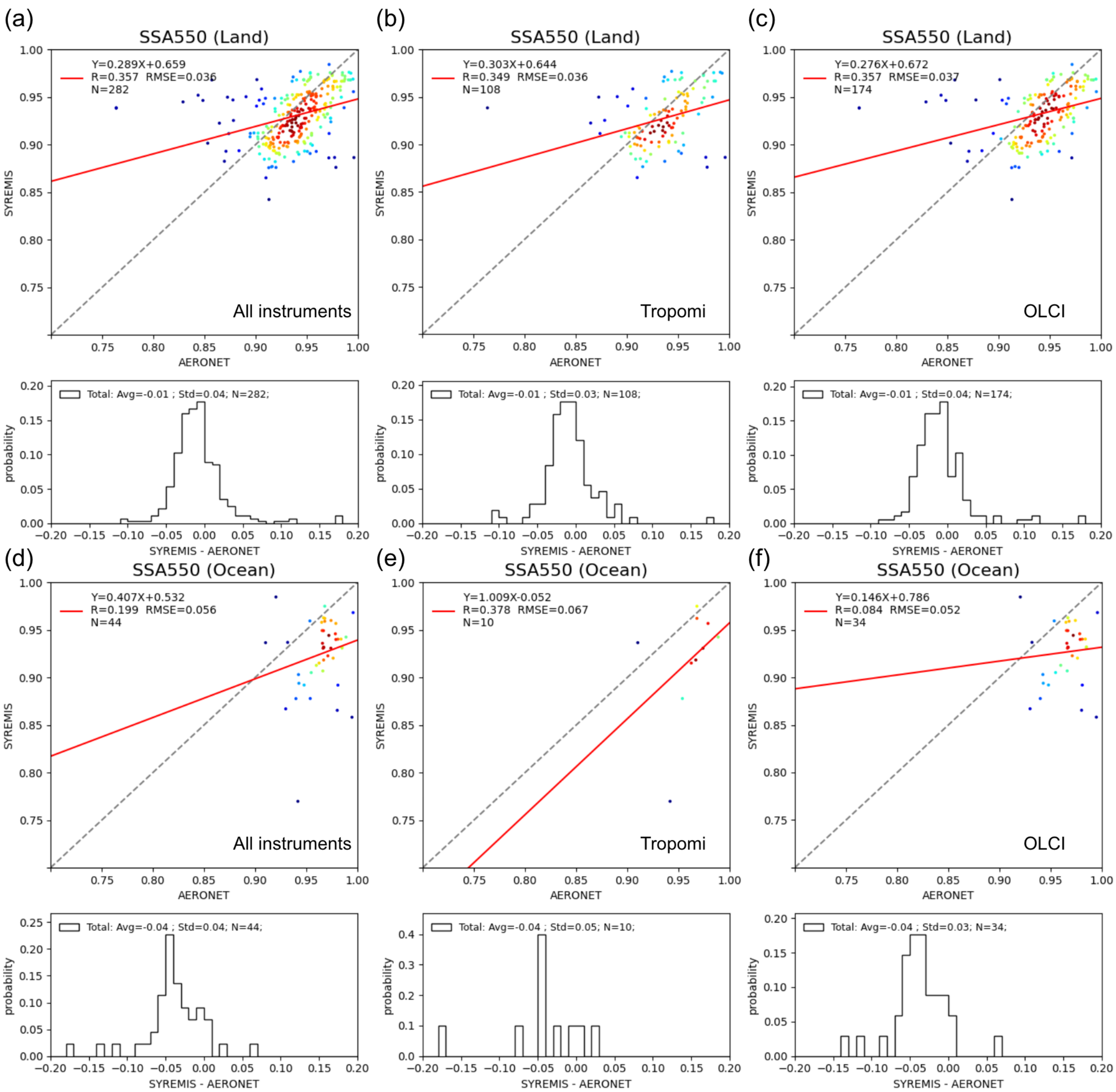

330 **Figure 6: The same as in Fig. 4 but for SSA validation vs AERONET.**

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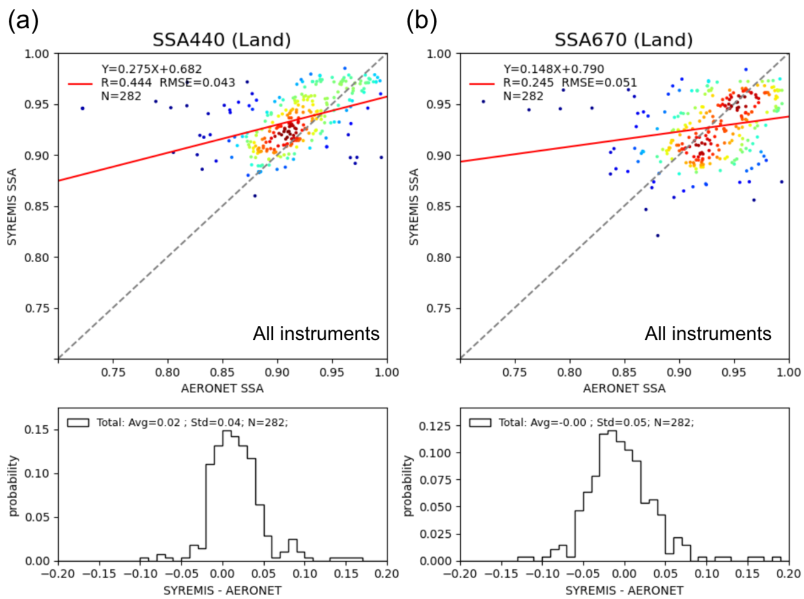

Figure 7: SSA 440 and 670nm validation vs AERONET over land for SYREMIS/GRASP LEO+LEO synergy. March, April, May 2019.

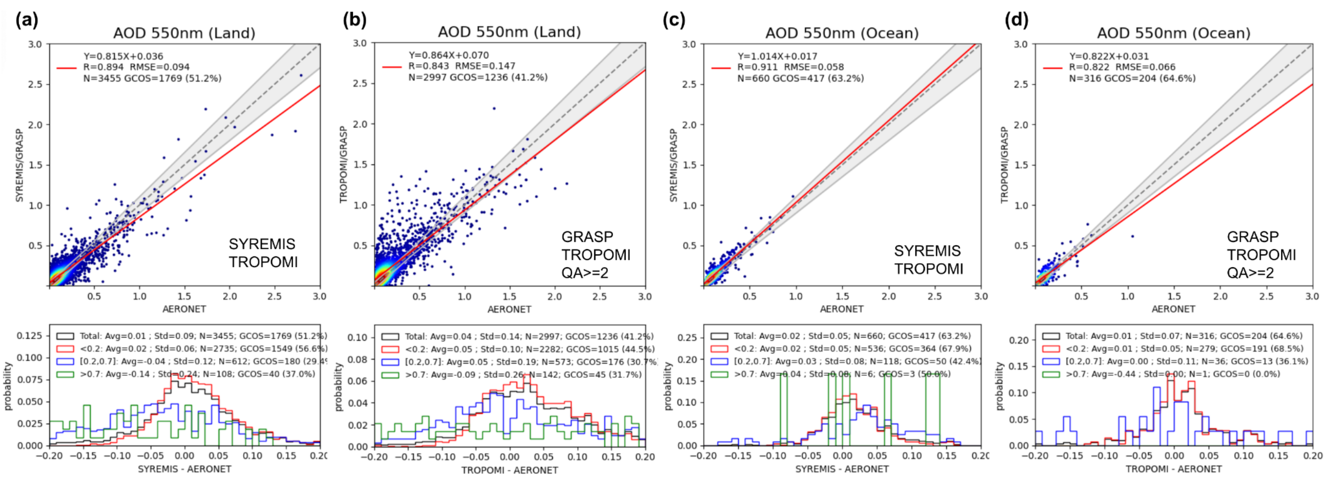

Figure 8: AOD (550) validation vs AERONET over land and ocean for SYREMIS/TROPOMI and TROPOMI/GRASP (QA>=2) products. March, April, May 2019.

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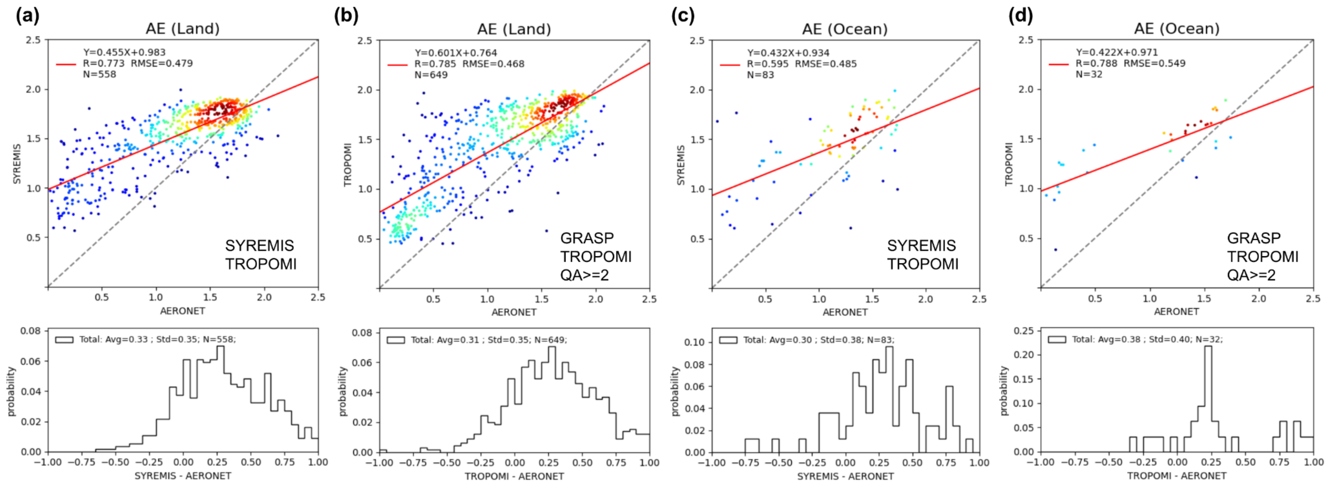

Figure 9: The same as in Fig. 8 but for AExp.

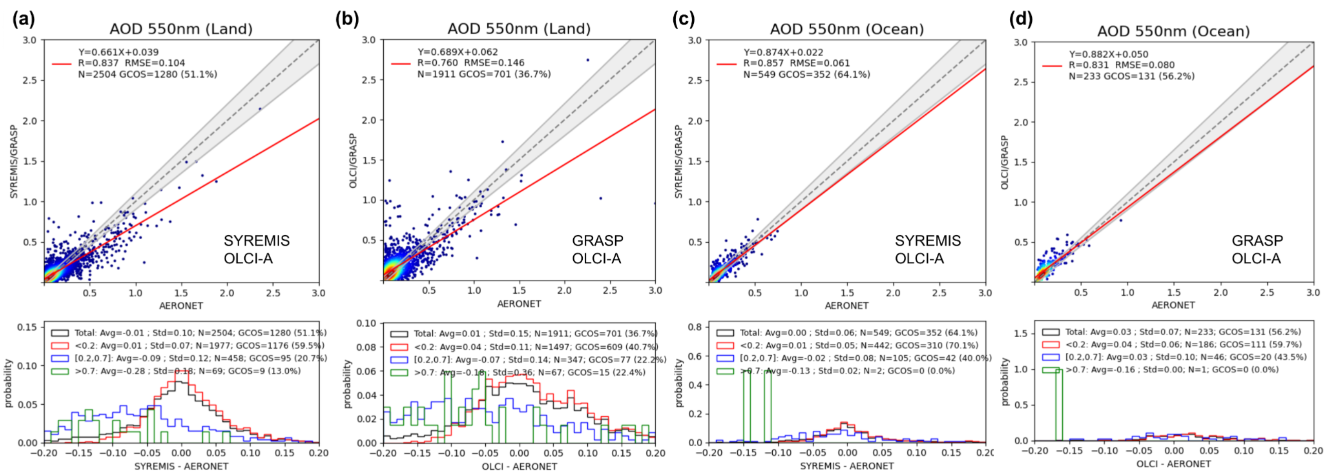

Figure 10: AOD(550) validation vs AERONET over land and ocean for SYREMIS/OLCI-A and OLCI-A/GRASP products. March, April, May 2019.

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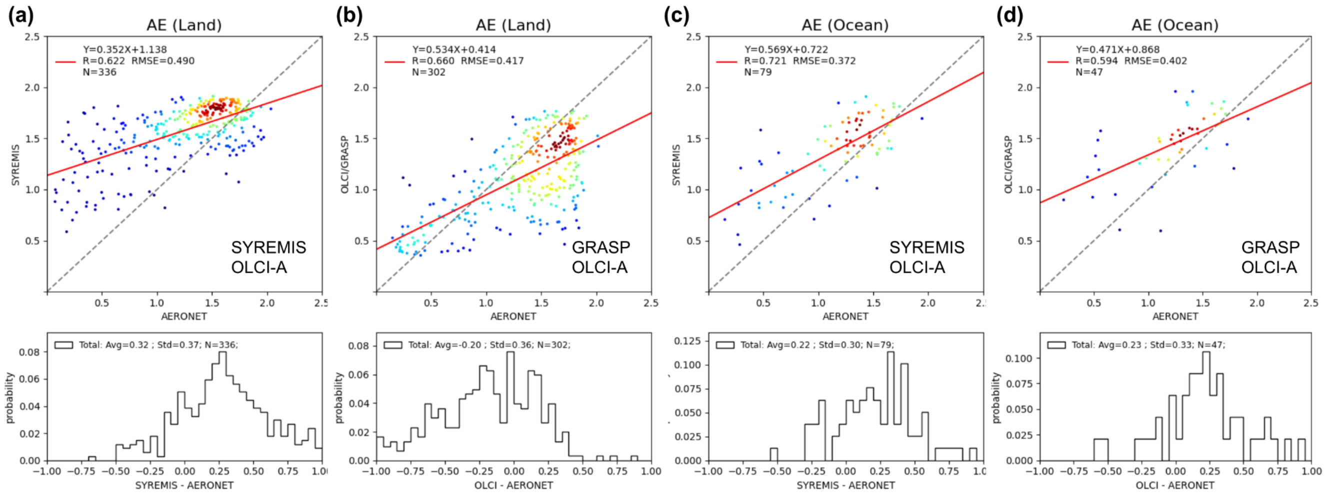

Figure 11: The same as in Fig. 10 but for AExp.

3.2 SYREMIS/GRASP LEO+GEO synergetic performance versus AERONET and intercomparison with LEO+LEO synergy

Validation of AOD, AExp, and SSA from SYREMIS LEO+GEO synergy over all AERONET stations within Himawari-8/AHI full scan is presented in Figs. 12-14. Similarly to LEO+LEO synergy, the results are presented for all instruments involved in the SYREMIS/GRASP synergy, as well as for the data extracted for each specific instrument: SYREMIS/TROPOMI, SYREMIS/S3 (OLCI-A and OLCI-B) and SYREMIS/AHI. One can see very consistent, harmonized retrieval for different spectral bands and for all instruments. In particular, AOD, AExp and SSA retrievals are quite comparable for all instruments in the synergy. Moreover, for all instruments AExp with RMSE~0.3 and SSA with RMSE<0.5 are of the same quality as AExp and SSA retrieved from GRASP/TROPOMI (Litvinov et al., 2024) and SYREMIS LEO+LEO synergy (Figs. 5, 6). Being compared with SYREMIS LEO+LEO over the same AERONET stations, LEO+GEO synergy shows further improvement in AOD characterization (Fig. 5).

In general, the validation and inter-comparison results show that, similarly to the LEO+LEO synergy, richer information content from S5P/TROPOMI “propagate” to other instruments of the SYREMIS LEO+GEO synergy (S3A/OLCI, S3B/OLCI and Himawari-8/AHI) improving extended aerosol characteristics, for example, AExp and spectral SSA. At the same time AOD is improved for all instruments in LEO+GEO synergy including S5P/TROPOMI due to additional spatial, temporal and spectral information content in the synergetic measurements. Moreover, one of the crucial advantages of LEO+GEO synergy is the high temporal resolution of the extended aerosol characterization (AOD, AExp, SSA etc.). In particular, the considered SYREMIS LEO+GEO synergy provides diurnal variability of aerosol with it is about ~1 hour temporal resolution, which allows monitoring aerosol transport, air quality and atmosphere dynamics.

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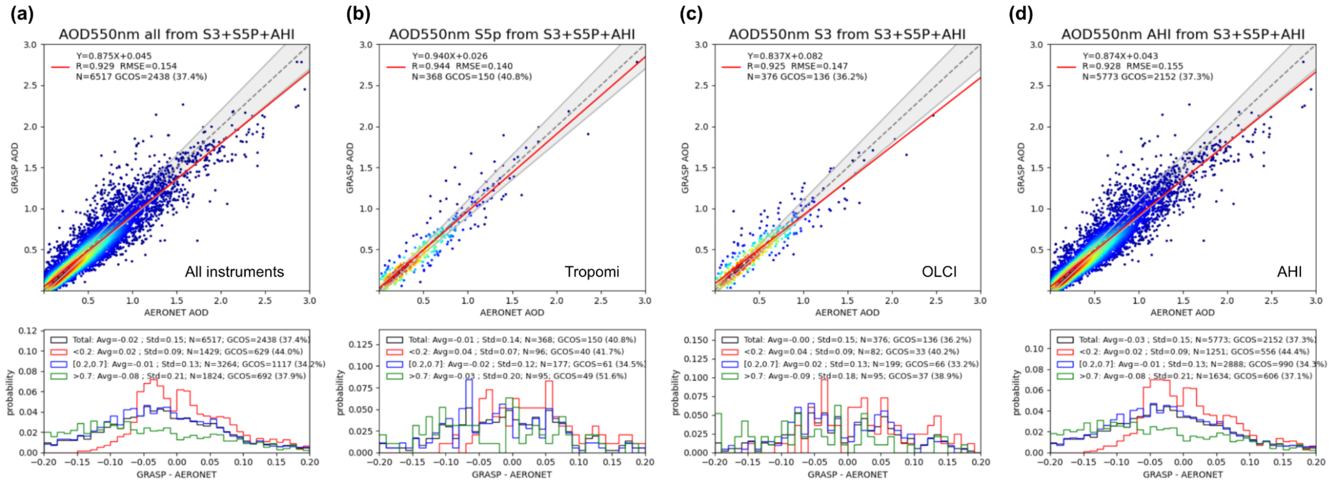

Figure 12: AOD550 validation against AERONET sites over land for SYREMIS/GRASP LEO+GEO synergy. March, April, May 2019.

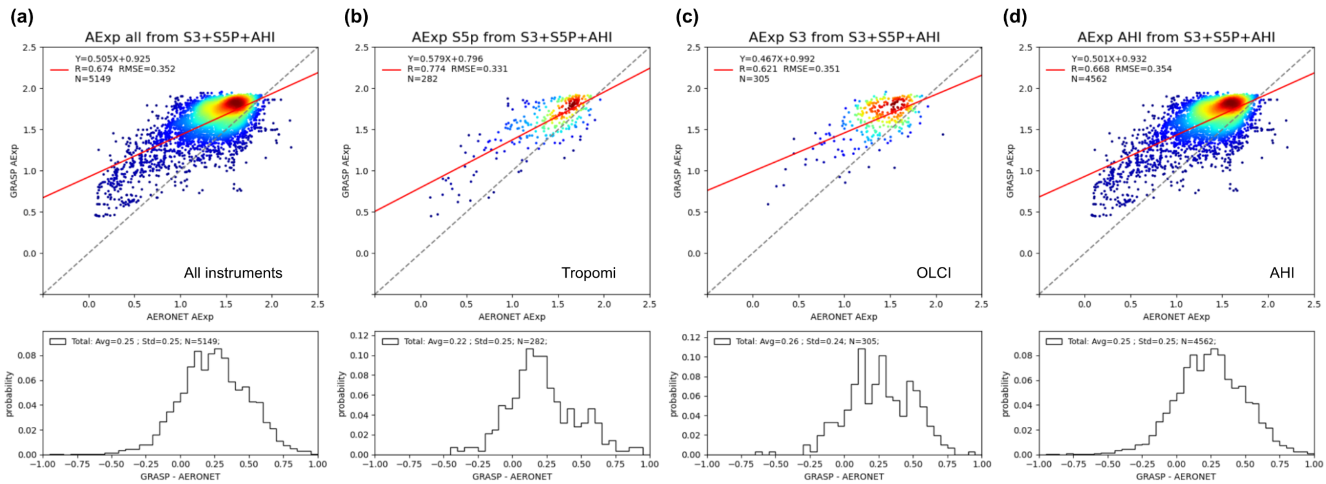

Figure 13: AExp validation against AERONET sites over land for SYREMIS/GRASP LEO+GEO synergy. March, April, May 2019.

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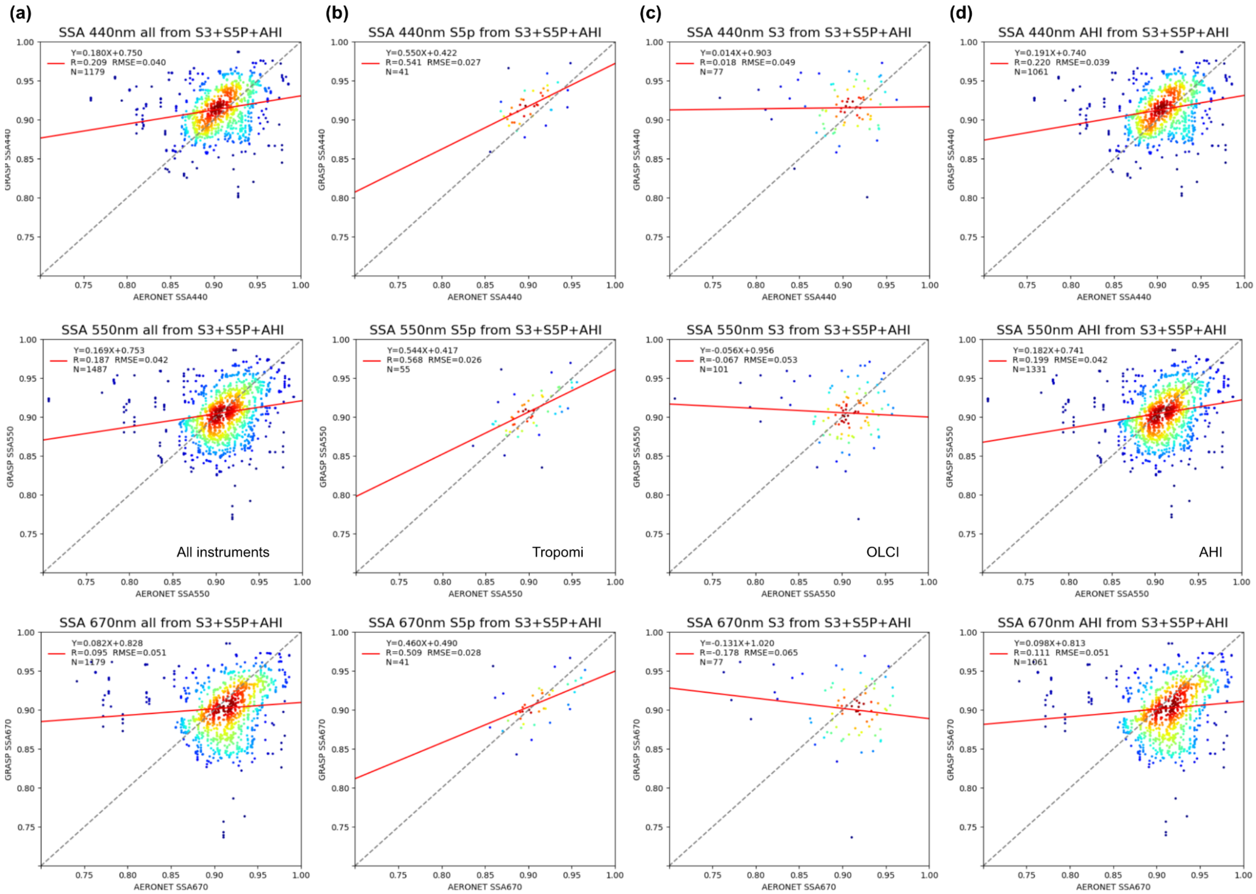

Figure 14: SSA validation against AERONET over land for SYREMIS/GRASP LEO+GEO synergy. March, April, May 2019.

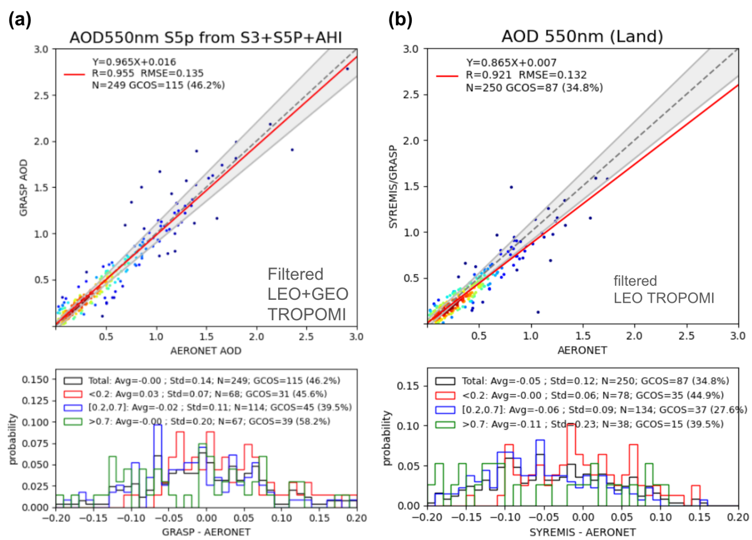

Figure 15: AOD550 validation against the same AERONET sites over land: SYREMIS/TROPOMI LEO+GEO vs SYREMIS/ TROPOMI LEO+LEO. March, April, 2019.

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3.3 SYREMIS/GRASP aerosol and surface products global intercomparison.

Figures 16-18 show comparison of the SYREMIS/GRASP retrieval with GRASP results from S5P/TROPOMI, S3A/OLCI as well as with VIIRS and MODIS aerosol and surface products (Hsu et al., 2013; 2019; Sayer et al., 2018; Schaaf et al. 2015a, 2015b; Chen et al., 2022; Litvinov et al., 2024). The comparison was performed within 1 month (March, 2019) on the pixel level collocated in time (pixel-by-pixel comparison). To do this, the SYREMIS/TROPOMI and SYREMIS/OCLI pixels were extracted from SYREMIS LEO+LEO synergetic retrieval and then compared with corresponding pixels collocated in space and time from independent TROPOMI/GRASP, OLCI/GRASP, VIIRS and MODIS retrieval.

One can see from Fig. 16 that, overall, SYREMIS/GRASP AOD retrieval corresponds well to VIIRS, MODIS, TROPOMI/GRASP and OLCI/GRASP products. The SYREMIS/TROPOMI provides AOD values lower than VIIRS over Saharan and Arabian Peninsula, North Indian Subcontinent, East coast of China and South polar regions. In comparison to the TROPOMI/GRASP results, the SYREMIS/TROPOMI shows a little bit smaller AOD globally.

Figure 17 shows a very similar retrieval of the first (isotropic) BRDF parameter from SYREMIS/TROPOMI relatively to MODIS product. Depending on the region, the SYREMIS/GRASP can provide brighter or darker surface in comparison to MODIS. The biggest difference in the surface retrieval emerging from the synergetic approach can be found in the second (volumetric) and third (geometric) Ross-Li BRDF parameters, describing the angular profile of the surface reflectance. As can be seen from Fig. 18 the values of these parameters derived by the SYREMIS/GRASP over bright surfaces (for example, over Sahara) are essentially higher than those ones from MODIS BRDF product. This can be well seen from the pixel-by-pixel comparison in Fig. 19. The stronger variability of the second and third BRDF parameters can be explained by the pseudo multi-angular measurements in the synergetic retrieval with much more angular information than from any of the single instruments with observation angle per measurements (MODIS, S5P/TROPOMI, S3A/OLCI or S3B/OLCI etc.). Due to this fact, SYREMIS synergy measurements provides much more information about the surface angular reflectance properties which results in better characterization of BRDF parameters representing surface angular dependence.

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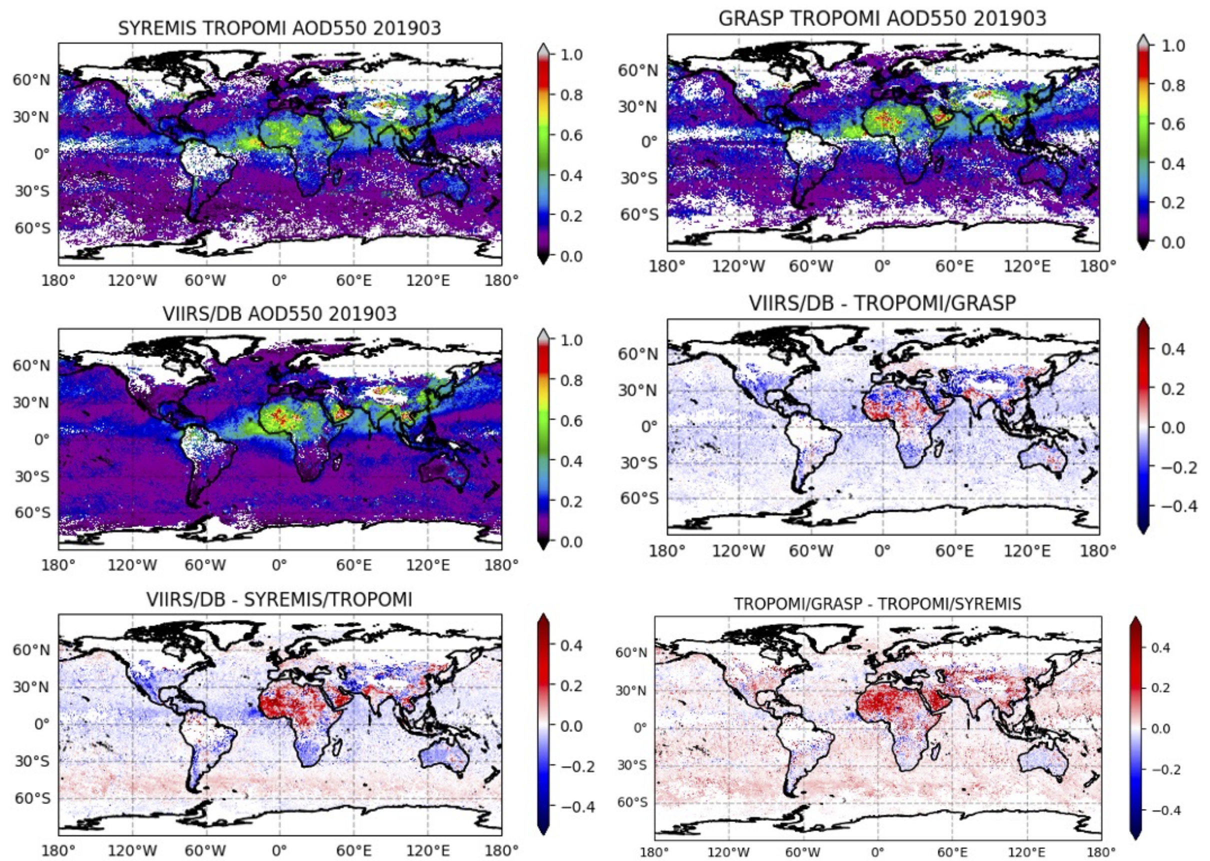

Figure 16: AOD global map. TROPOMI/SYREMIS, TROPOMI/GRASP and VIIRS/DB. March 2019

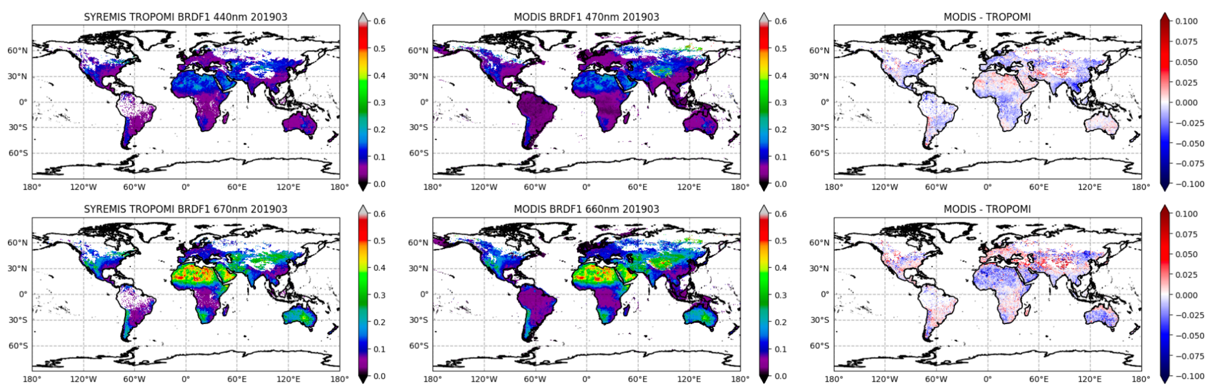

Figure 17: BRDF first parameter. SYREMIS: 440, 670. MODIS: 470, 660. March 2019

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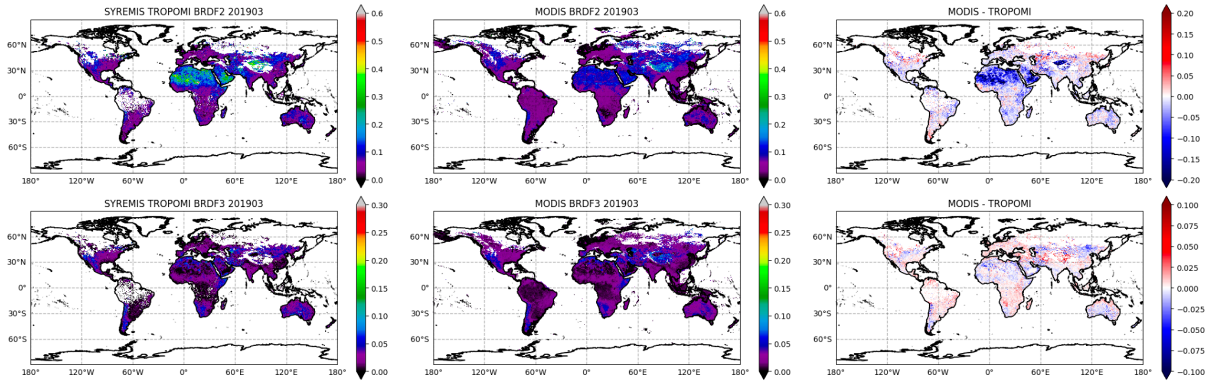

Figure 18: BRDF second and third parameters from TROPOMI/SYREMIS and MODIS. March 2019.

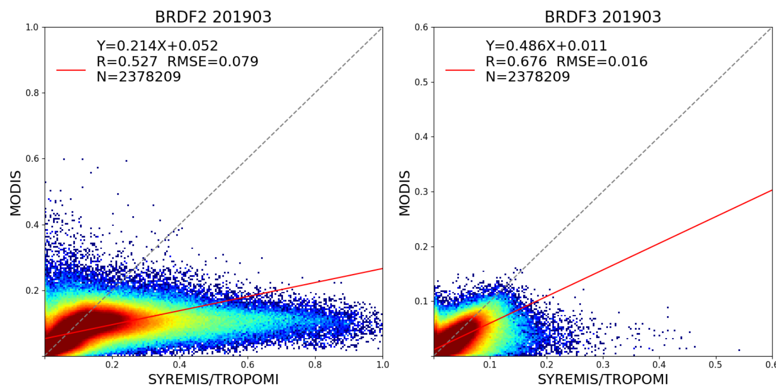

Figure 19: BRDF first, second and third parameters: SYREMIS/TROPOMI vs MODIS. March 2019.

4 Conclusions

The SYREMIS/GRASP multi-instrument synergetic approach was developed for the retrieval of aerosol and surface properties from the combined spaceborne instruments. It was tested on (i) synergy from polar-orbiting satellites (LEO+LEO synergy of S5P/TROPOMI, S3A/OLCI and S3B/OLCI instruments) and (ii) synergy of polar-orbiting and geostationary satellites (LEO+GEO synergy of S5P/TROPOMI, S3A/OLCI, S3B/OLCI and Himawari-8/AHI sensors). The SYREMIS/GRASP synergy is based on three main principles: (i) harmonization of the multi-instruments L1 measurements, (ii) "weighting" the multi-instruments measurements, and (iii) optimization of the forward models and the retrieval setups.

After number of retrieval experiments with "weighting" the measurements from different sensors it was found out that the best SYREMIS/GRASP retrieval can be achieved when the "weight" of TROPOMI measurements in both LEO+LEO and LEO+GEO synergy is requested to be higher than the "weight" of OLCI and AHI instruments. TROPOMI is known by its good calibration and rich information content in terms of spectral measurements (from UV to SWIR spectral range) and wide swath. In particular, UV measurements provide sensitivity to the absorption properties of aerosol, wide spectral range are

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crucial for aerosol size and type characterization as well as for aerosol and surface signals differentiation (Litvinov et al., 2024). In the considered synergetic satellite constellation, TROPOMI has a richest information content and serves as a "driver" of the SYREMIS/GRASP retrieval. Nevertheless, it was demonstrated that the contribution of the other satellites in SYREMIS LEO+LEO and LEO+GEO synergy is not negligible since they essentially extend spectral, temporal and spatial coverage of TROPOMI instrument. Such synergetic multi-spectral and pseudo-multi-angular measurements are crucial for distinguishing between atmosphere and surface signals and improve essentially aerosol and surface BRDF characterization.

Overall, it was demonstrated that harmonizing multi-instrument measurements and properly balancing "weights" of measurements from different sensors, the SYREMIS/GRASP approach allows transition of the information between all instruments in the synergy. In combination with adjusted forward models and retrieval setups (spectral, spatial, and temporal constraints on the aerosol/surface variability), this results in increased performance of AOD, aerosol size and absorption properties retrieval and more consistent surface BRDF characterization.

In particular, for all instruments from the LEO+LEO and LEO+GEO synergies, AOD performance against AERONET was increased essentially. AExp and SSA from the synergies were found to be comparable with TROPOMI/GRASP single instrument retrieval and essentially better than from previous OLCI/GRASP and AHI/GRASP retrievals, supporting the conclusion that the information about aerosol size and absorption/scattering comes from S5P/TROPOMI measurements mainly.

SYREMIS/GRASP AOD inter-comparison with VIIRS and TROPOMI/GRASP shows similar global features though the noticeable regional differences that requires further analysis. Global inter-comparison of the retrieved surface properties showed good consistency of SYREMIS/GRASP first BRDF parameter (isotropic Ross-Li parameter) with MODIS one, though, depending on the region, the brighter or darker surface can be retrieved. The SYREMIS/GRASP shows essential difference of the volumetric and geometric Ross-Li BRDF parameters in comparison to MODIS surface product. This can be explained by the fact that SYREMIS multi-instrument pseudo-multi-angular measurements provide more information about surface reflectance angular dependence in comparison to the single instrument with one-angle observations.

With properly applied temporal smoothness constraints, the SYREMIS/GRASP retrieval allows deriving consistent temporal variation of aerosol properties with enhanced temporal resolution. In particular, LEO+LEO synergy can provide consistent variability of aerosol properties several time per day, whereas LEO+GEO synergy can essentially improve the temporal resolution to one hour or better. Such extended aerosol characterization with high temporal resolution is required in air quality studies, for monitoring aerosol transport, aerosol-cloud interaction etc.

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Developed SYREMIS/GRASP synergetic concept with formulated three main principles is quite universal and can be extended to future spaceborne missions, including synergy with multi-angular, multi-spectral, polarimetric measurements. In such advanced synergy with spaceborne polarimeters, more complex aerosol model can be used, allowing further enhancement of the aerosol microphysical and chemical properties retrieval at very fine temporal resolution.

Code availability

The retrieval results presented in this paper were obtained with GRASP-OPEN software (https://www.grasp-open.com).

Data availability

SYREMIS/GRASP datasets are available on request

Author contribution

PL provided the original concept of the multi-instrument synergetic approach and together with CC performed original research, developments, and prepared the manuscript. OD provided consultancy on GRASP algorithm adaptation to the synergetic retrieval and edited the manuscript. SZ provided validation results and visualization, contributed to writing the manuscript. CM, LB, MD and AL prepared satellite data for SYREMIS/GRASP synergy, generated retrieval output. CL and AL provided consultancy on GRASP algorithm application to HIMAWARI/AHI instrument, edited the manuscript. DF and TL provided support and developments of GRASP algorithm for the synergetic approach. CR together with AD and DG supervised ESA SYREMIS project, discussed SYREMIS/GRASP results and edited the manuscript.

Competing interests

Some authors are members of the editorial board of journal AMT.

Acknowledgments

The studies presented in this paper were performed in the framework of ESA (European Space Agency) SYREMIS project (Future EO-1 Science for society, ESA Contract No. 4000138902/22/I-DT-bgh, https://eo4society.esa.int/projects/syremis/). Authors would like to gratefully acknowledge AERONET network for freely available data used for validation purposes in these studies. The retrieval results presented in this paper were obtained with GRASP-OPEN software (https://www.grasp-open.com).

Financial support

The financial support of these studies was provided in the framework of ESA (European Space Agency) SYREMIS project (Future EO-1 Science for society, ESA Contract No. 4000138902/22/I-DT-bgh).

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