GRASP multi-instrument synergy for advanced aerosol and surface characterisation

Pavel Litvinov and all grasp team

Funded by the European Union

Aerosol and its characterization in remote sensing

Dust outburst

Aerosol from volcano eruptions

Anthropogenic pollution

Biomass burning

Full aerosol characterization

1. Size
2. Aerosol chemistry: absorption and hygroscopic properties
3. Particle structure: morphology, homogeneity, shape etc
4. Vertical distribution

Aerosol remote sensing is based on the models of aerosol and atmosphere

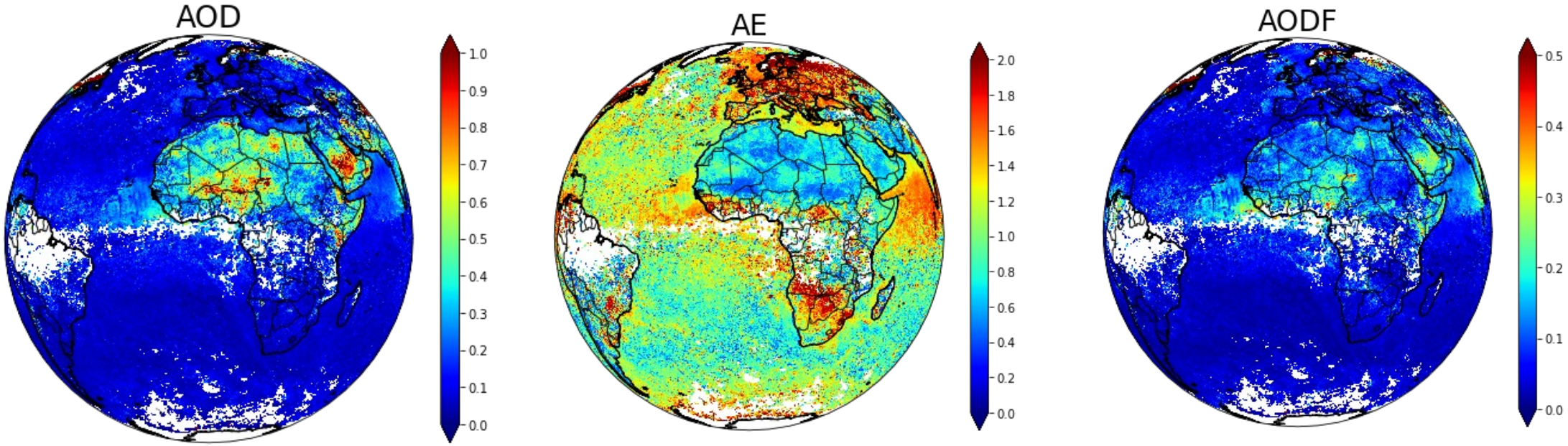
Physical/chemical aerosol characterization

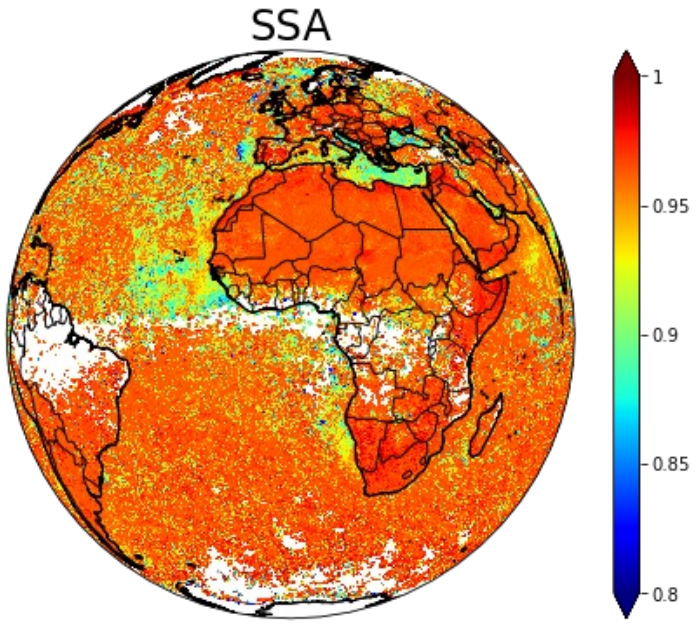
1. Size distribution
2. Aerosol chemistry (complex refractive index)
3. Nonsphericity
4. Concentration vertical profile
5. Atmosphere temperature vertical profile (for TIR)

Aerosol optical characterization

1. **AOD**: aerosol concentration
2. **AE**, Angstrom Exponent (spectral dependence of AOD): aerosol size
3. **SSA**: aerosol absorption
4. **dSSA** (spectral dependence of SSA): size and absorption

Advanced aerosol characterization





Extended TROPOMI/GRASP products

P. Litvinov and C. Chen et al., Part I, RSE, 2024

C. Chen and P. Litvinov et al., Part II, RSE, 2024

1. Spectral AOD, AODF and AODC
2. Angstrom Exponent
3. Spectral AAOD
4. Spectral SSA

https://www.grasp-open.com/products/tropomi-data-release/

Aerosol in different applications

Atmospheric studies and applications	Advanced aerosol characterization						
	1. AOD	2. Extended properties				3. Spatial Resolution/ Coverage	4. Temporal resolution
		SSA	AExp	Vertical profile	Microphysics, Chemistry		
Aerosol ECVs (GCOS-245)	X	X	X	X	-	A few km or more Global	Daily or monthly
Air quality monitoring	X	X	X	X	X	The finer is better (a few meters)	Hourly or better
Aerosol dynamic, aerosol-cloud interaction etc	X	X	X	X	X	Fine and moderate	Hourly or better
Global and regional climate models	X	X	X	X	X	From a few meters to hundred km	Hourly, Daily
Aerosol as auxiliary product for Atmospheric and surface studies	X	X	X	X	-	Global	From Hourly, to Monthly

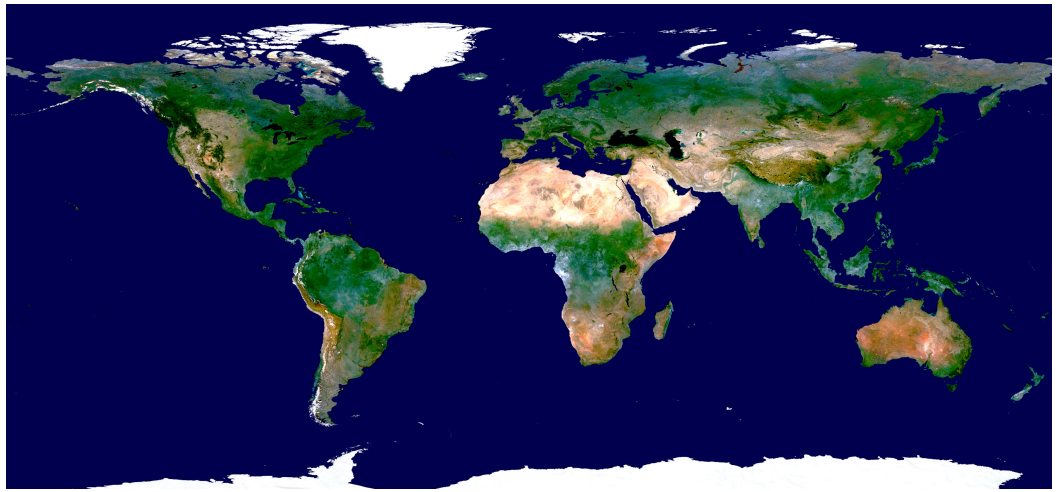
Surface and its characterization in remote sensing

Full Surface characterization

1. Topology
2. Surface structure : morphology, heterogeneity, scatterers distribution etc
3. Surface scatterers chemistry
4. Temperature (TIR)

Too complex!

Surface reflectance



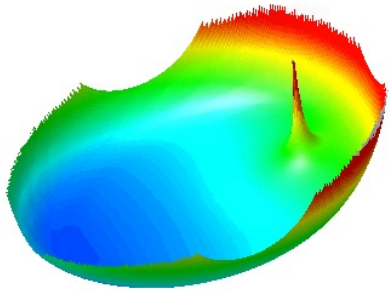
Surface Remote sensing for atmospheric studies is based on

BRDF models: Bi-Directional Reflectance Distribution Function

Land use & Deforestation

Ocean color: sediments and chlorophyll

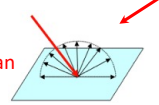
BRDF derived from dessert surface (Banizoumbou)



BRDF parameters to be derived: a_{iso}, a_{vol} , a_{geom}

$$BRDF_{Ross-Li} = a_{iso}(\lambda)\cdot(1 + a_{vol} f_{vol} + a_{geom} f_{geom})$$

Isotropic Lambertian term:



Volumetric turbid medium term (RTT):

Geometric optics shadow driven term term (GO):

A soybean field

backscattering forward scattering

https://www.umb.edu/spectralmass/terra_aqua_modis/modis

Surface in different applications

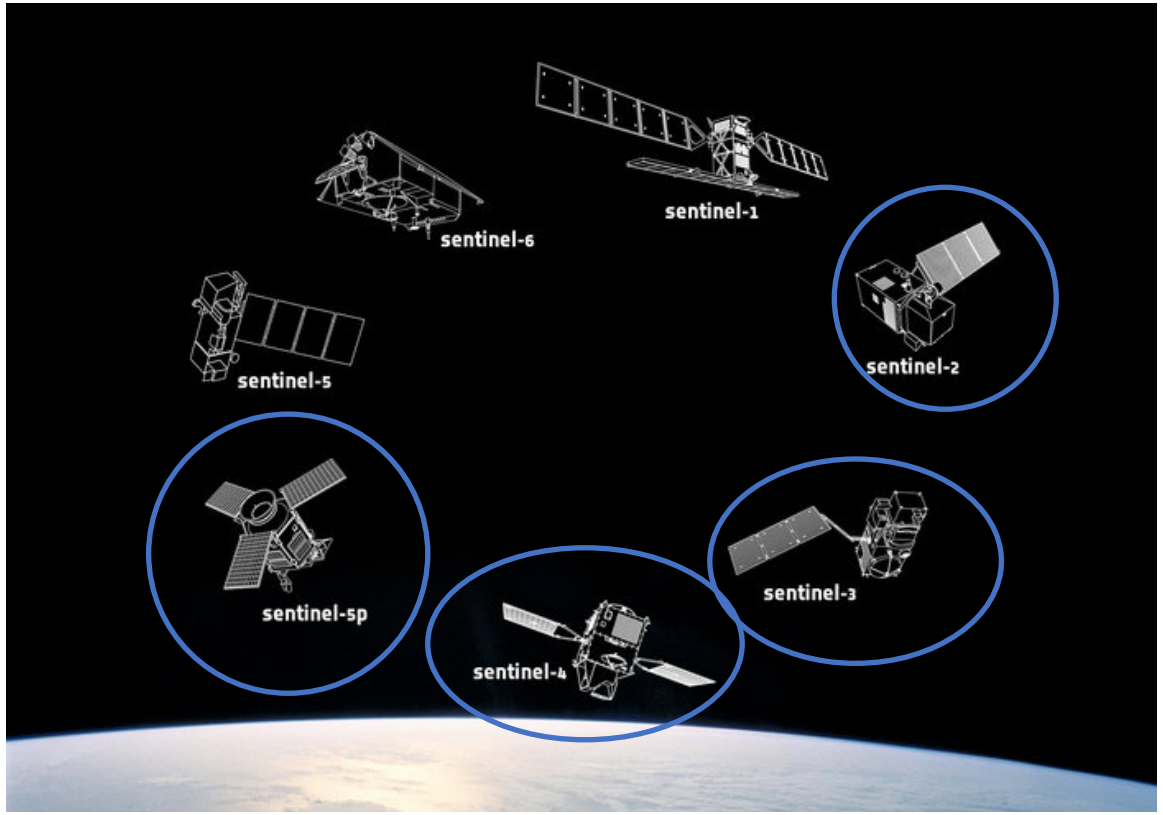
Different applications	Global Surface characteristics				
	BRDF	Albedos	LER/DLER	Temporal coverage	Spatial resolution
ECVs (GCOS-245)	X	X	X	Monthly	Moderate or coarse
L2 atmospheric product	X	X	X	Daily, monthly	From high to coarse
Land cover	X	X	X	Daily, monthly	High or moderate

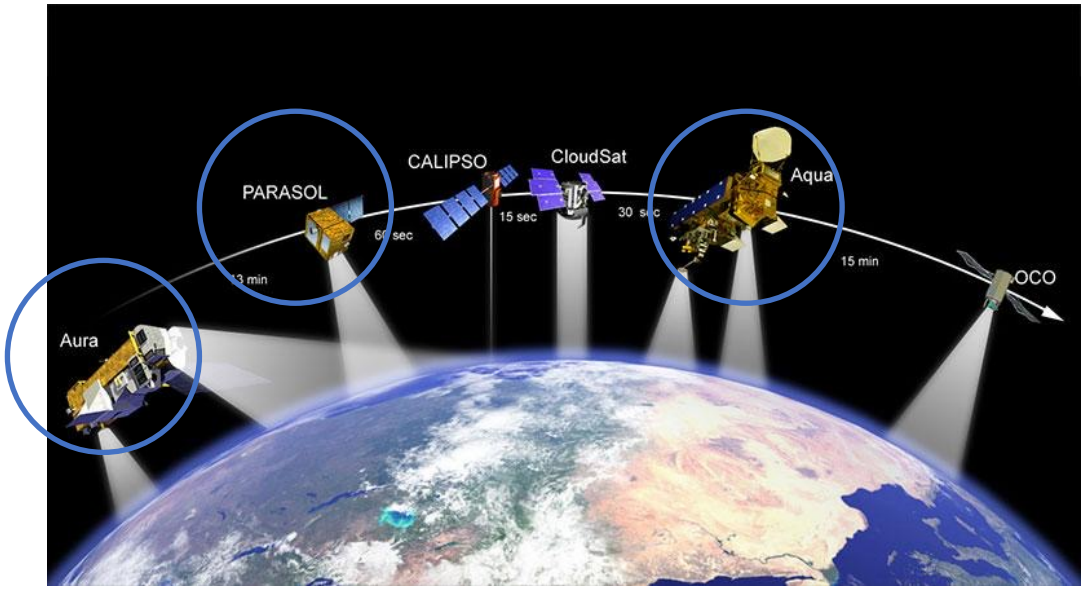
Atmosphere and surface characterisation from remote sensing are closely related topics.

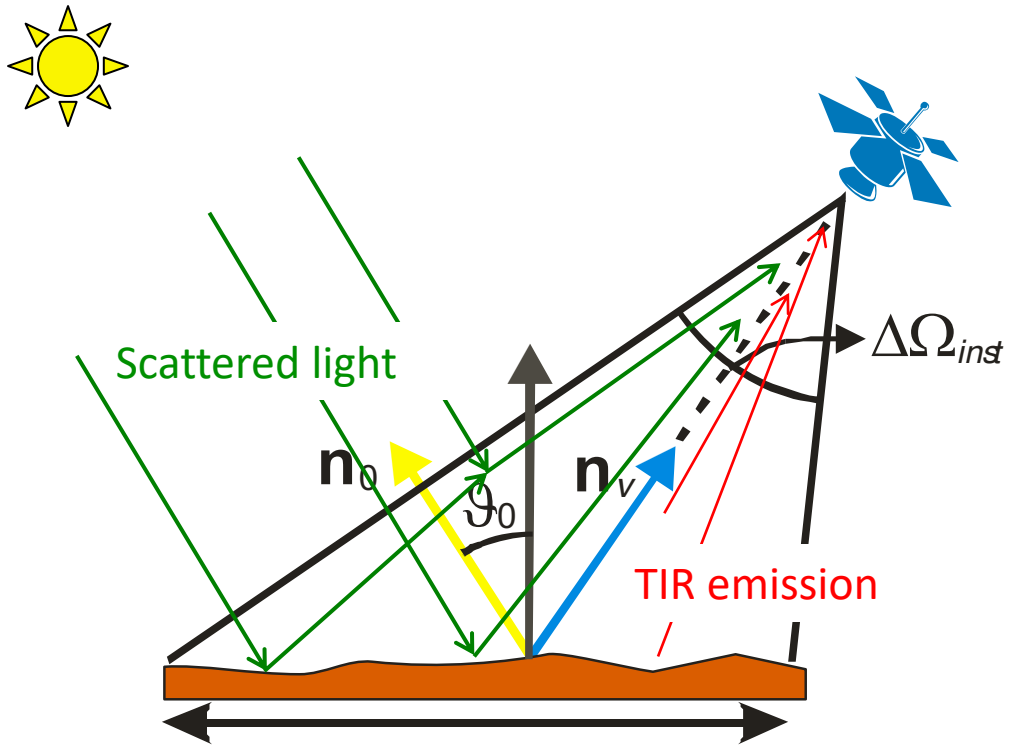
In global scale they can be derived only from satellite measurements!

What are our measurements?

Passive ground based and
space-borne
remote sensing

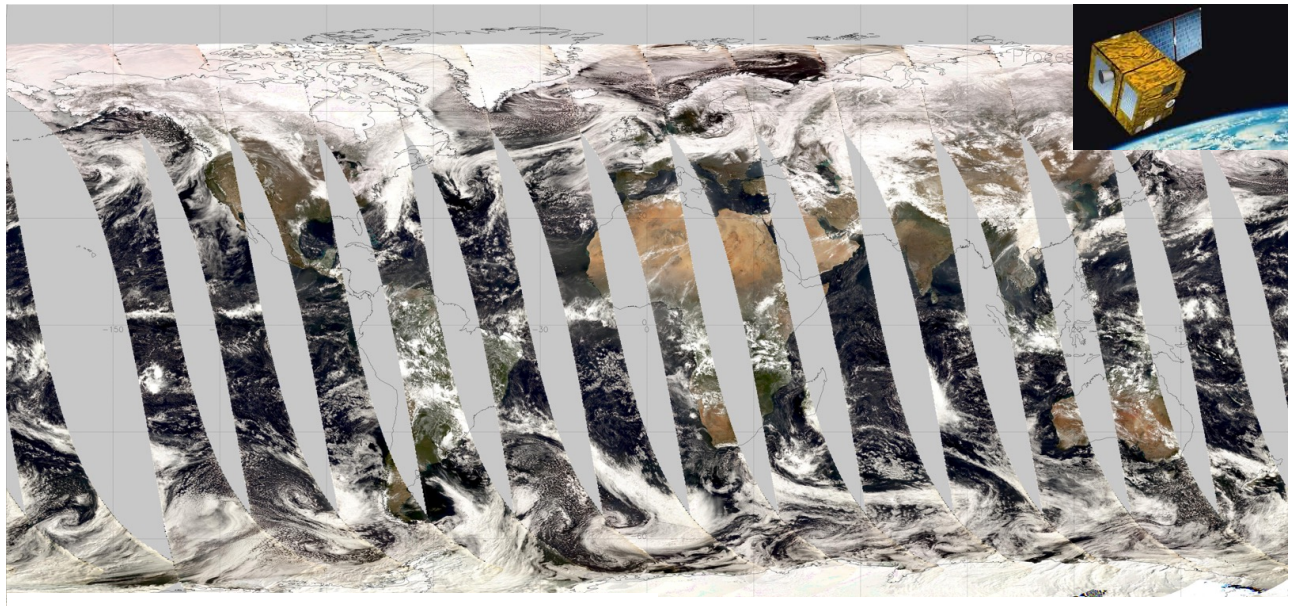






Satellite measurements for aerosol and surface characterization

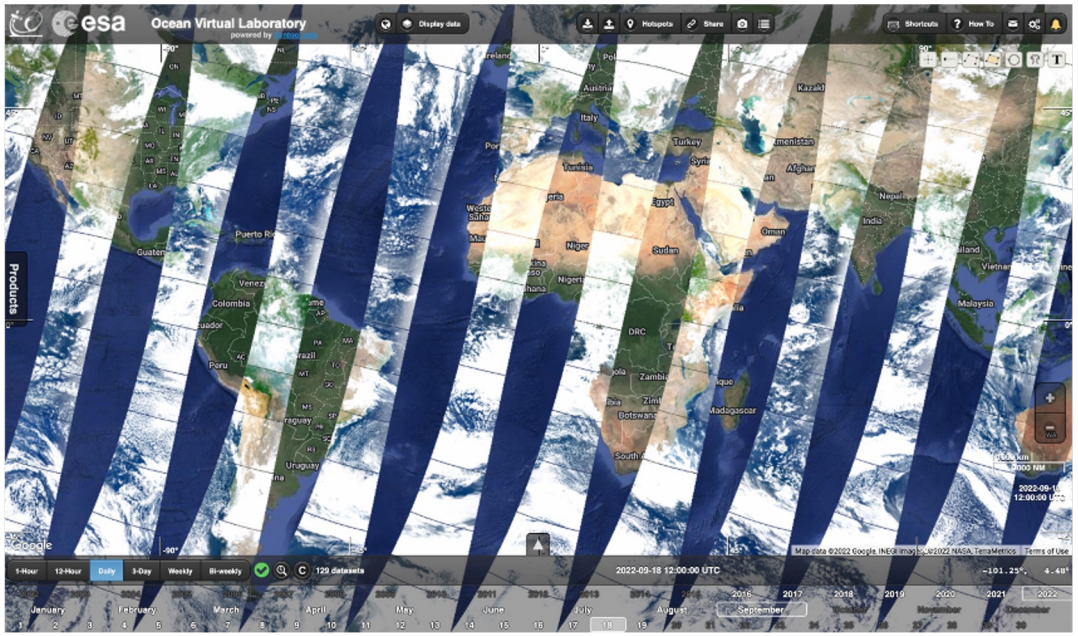
PARASOL daily measurements



INTENSITY (I)
for aerosol: (0.44, 0.49, 0.56, 0.67, 0.865, 1.02 μm)
for gas absorption): (0.763, 0.765, 0.910 μm)
POLARIZATION (Q, U): (0.49, 0.67, 0.865 μm)

Swath: about 1600 km cross-track
Global coverage: every 2 days
1 pixel spatial resolution: 5.3km × 6.2km
Viewing directions: 16: (80^0 – 180^0)

Sentinel-3A/OLCI daily measurements



INTENSITY only (I)
21 spectral bands:
0.4, 0.4125, 0.4425, 0.49, 0.51, 0.56, 0.62, 0.665, 0.67375, 0.68125, 0.70875, 0.75375, 0.76125, 0.764375, 0.7675, 0.77875, 0.865, 0.885, 0.9, 0.94, 1.02

Swath: about 1270 km cross-track
Global coverage: every 2 days
1 pixel spatial resolution ~300m
Viewing directions: 1

Aerosol characterization from space		Advanced aerosol characterization			
		1. AOD	2. Extended properties	3. Spatial resolution	4. Temporal resolution
1. Single angle observation: - **moderate or coarse spatial resolution** - **wide swath**	**MODIS-like**	+	Rather not	Moderate	Daily
	TROPOMI-like (wide spectral range : **UV-SWIR**)	+	Absorption, size, vertical profile with moderate accuracy	Rather coarse	
2. Single angle obs. (Sentinal-2 like): - **high spatial resolution** - **narrow swath (~ 200 km or less)**		+	Rather not	High Spatial	Few days per week
3. Geostationary (Sentinel-4, FCI etc)		+	Limited	Rather coarse	High temporal
4. Multi-angular polarimeters (PARASOL, SPEX, HARP-2, 3MI etc)		+	High accuracy		Daily
5. Active	Space LIDAR	+	Vertical profile	-	-
	TIR sensors	Dust AOD	Dust chemistry	Coarse	Daily

Global aerosol and surface characterization: status

Satellite	i. AOD	ii. Aerosol extended properties SSA, AE, Size etc	iii. Vertical profile	iv. Surface	v. High temporal resolution
MODIS/ VIIRS	Good	poor	poor	good	poor
MISR		good	poor	good	poor
MERIS/ OLCI		poor	poor	good	poor
AATSR/ SLSTR		poor	poor	good	poor
S5p/ TROPOMI		good	good	good	poor
PARASOL		good	poor	good	poor
Geostationary		poor	poor	good	Good

Polarimeters for aerosol studies

	Advanced aerosol characterization								
Satellite	i. Multi-spectral					ii. Multi-angular	iii. Multi-Polarization	iv. Temporal resolution	v. Spatial resolution
	UV	VIS - NIR	SWIR	TIR	Hyper-spectral				
3MI	-	+	+	-	-	+	+	Daily	Coarse
PARASOL, PACE/HARP	-	+	-	-	-	+	+	Daily	Coarse
PACE/SPEX	+	+	-	-	-	+	+	Few days per week	Coarse
S7/MAP	-	+	-	-	-	+	+	Few days per week	Coarse

Polarimeters advance aerosol characterization
but
still have number of limitations.

Global aerosol and surface characterization from space-borne remote sensing

Ideal single instrument has never existed and, probably, will never exist.

Can we do better?

Solution: Multi-instrument synergy

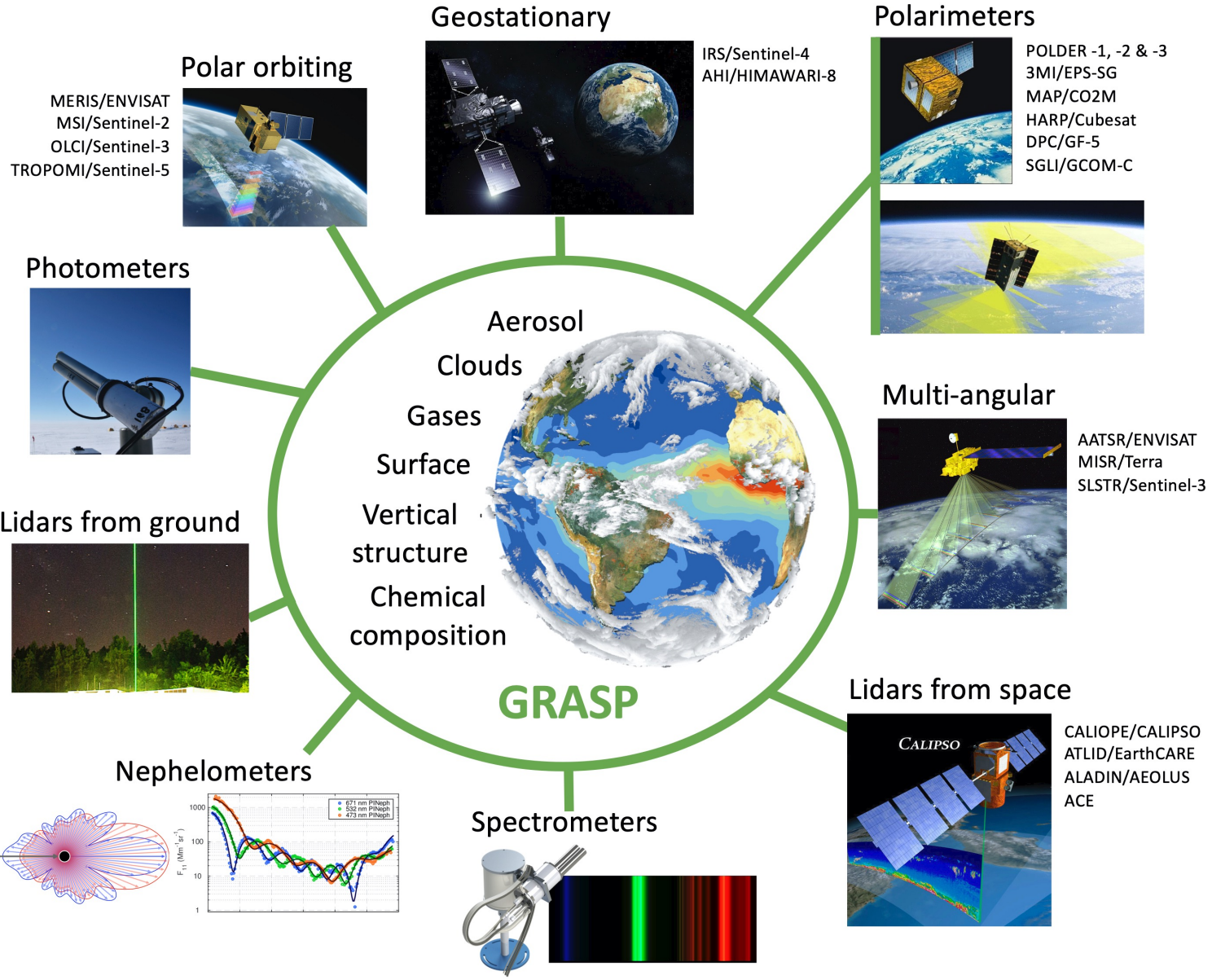
Aerosol characterization from multi-instrument synergy	Extended aerosol characterization				
	i. Multi-spectral	ii. Multi-angular	iii. Multi-Polarization	**iv. Temporal resolution**	v. Spatial resolution
LEO + GEO + High spatial resolution + Polarimeters + etc	+	+	+	+	+

Requirements on the retrieval algorithms for synergy:

1. Algorithm should be based on advanced inversion approach and adaptable flexible forward models.
2. Algorithm should be able to account diverse measurements from different instruments.
3. Algorithm should be able account for multi-temporal and multi-spatial measurements (multi-pixel retrieval approach).

GRASP: Generalized Retrieval of Atmosphere and Surface Properties

1. Full synergetic retrieval from different space-borne instruments is impossible without accounting for **multi-temporal diverse** measurements!
2. GRASP algorithm multi-pixel (in particular, multi-temporal) approach is very suitable for synergetic purposes



Dubovik et al. "A Comprehensive Description of Multi-Term LSM for Applying Multiple a Priori Constraints in Problems of Atmospheric Remote Sensing: GRASP Algorithm, Concept, and Applications", Front. Remote Sens., 2021

Synergetic retrieval with GRASP algorithm

1. Coarse and fine spatial resolution (L2-L1 synergy):

PRISMA + S5P demonstration for COVID-19 studies
GRASP-SAS (FR)

Cheng Chen and Pavel Litvinov et al. JGR, 2024.

eo science for society

SENTINEL-5P+ INNOVATION – THEME 5, AEROSOL OPTICAL DEPTH (AOD) + BRDF
GRASP-SAS (FR)

Pavel Litvinov and Cheng Chen et al. RSE, 2024

2. Synergetic retrieval from satellite and ground-based measurements (L1 synergy):

eo science for society

Pavel Litvinov et al. FR, 2022

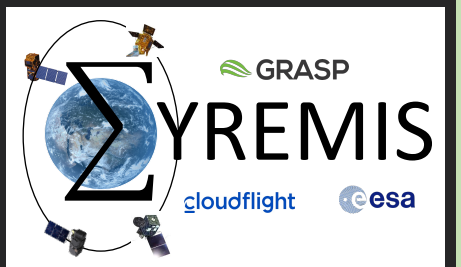
Synergetic Retrieval from GROund based and SATellite measurements for surface characterization and validation (GROSAT)
GRASP-SAS (FR)

3. Synergetic retrieval from multi-mission space-borne instruments (L1 synergy):

eo science for society

Pavel Litvinov et al. FR, 2023

Synergetic retrieval from multi-mission space-borne measurements for enhancement of aerosol characterization (SYREMIS)
GRASP-SAS (FR)



GRASP algorithm multi-pixel (in particular, multi-temporal) approach is very suitable for synergetic purposes

1. **Coarse and fine spatial resolution (L2-L1 synergy):** Application of GRASP Algorithm To S5p/TROPOMI and PRISMA Measurements

1: GRASP

2: Laboratoire d'Optique Atmosphérique

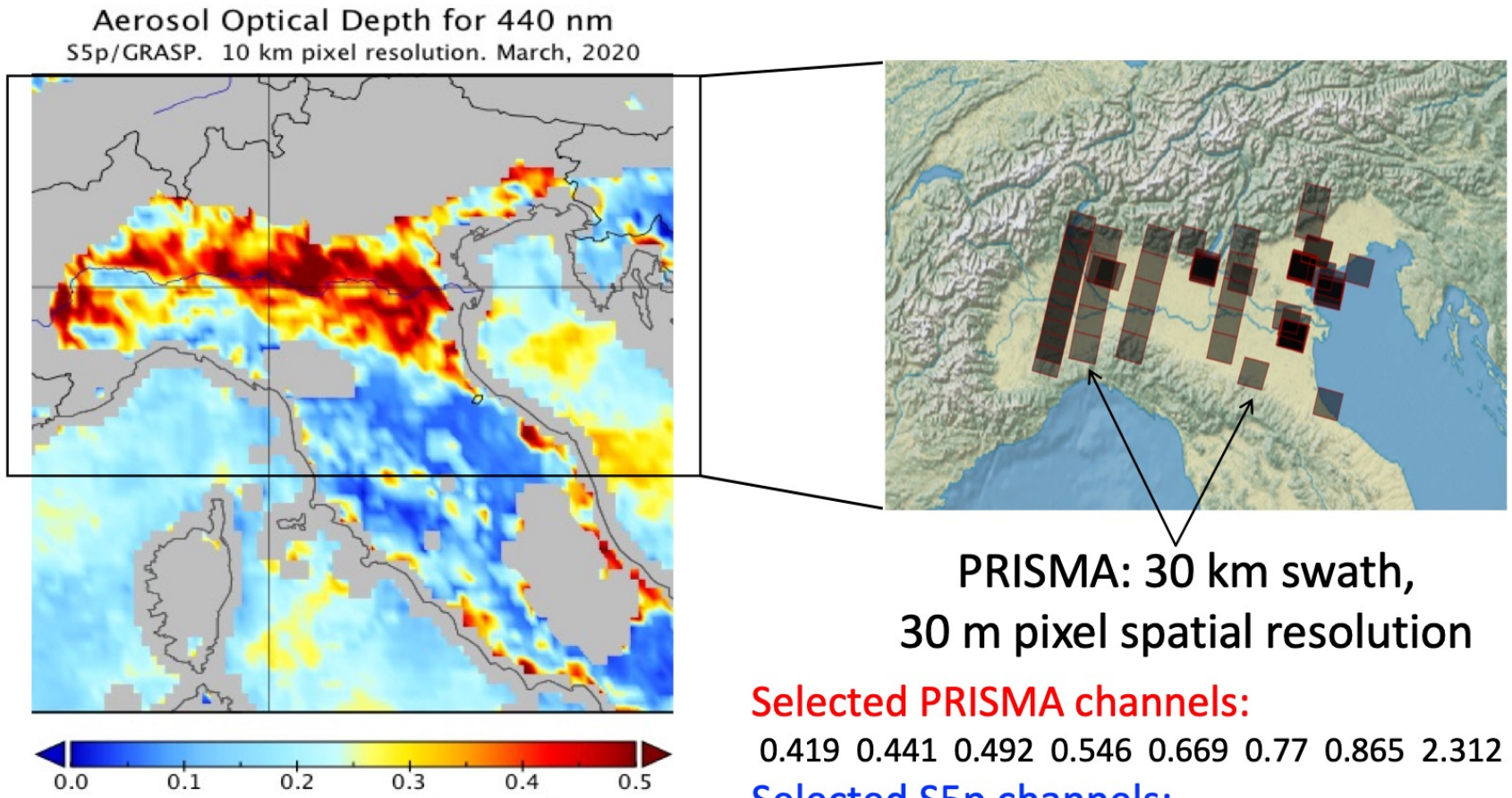
3: Consiglio Nazionale delle Ricerche, Istituto per la BioEconomia

4: istituto per il rilevamento elettromagnetico dell'ambiente

5: cloudflight

6: Koninklijk Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Waterstaat

7: esa



S5p/TROPOMI: 2600 km swath,
about 7 km pixel spatial resolution

PRISMA: 30 km swath,
30 m pixel spatial resolution

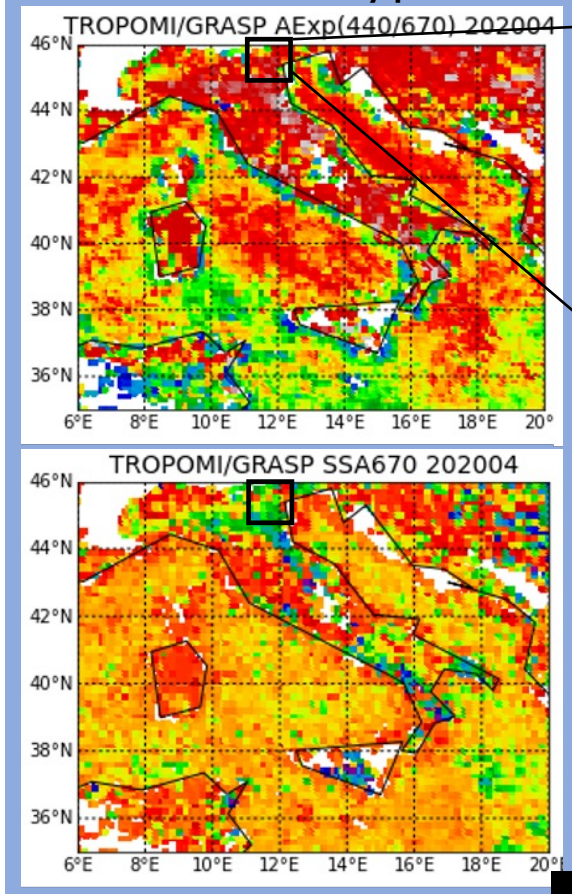
Selected PRISMA channels:
0.419 0.441 0.492 0.546 0.669 0.77 0.865 2.312

Selected S5p channels:
0.340 0.367 0.380 0.416 0.440 0.494 0.670 0.747 0.772 2.313

Pavel Litvinov and Cheng Chen et al. RSE, 2024.

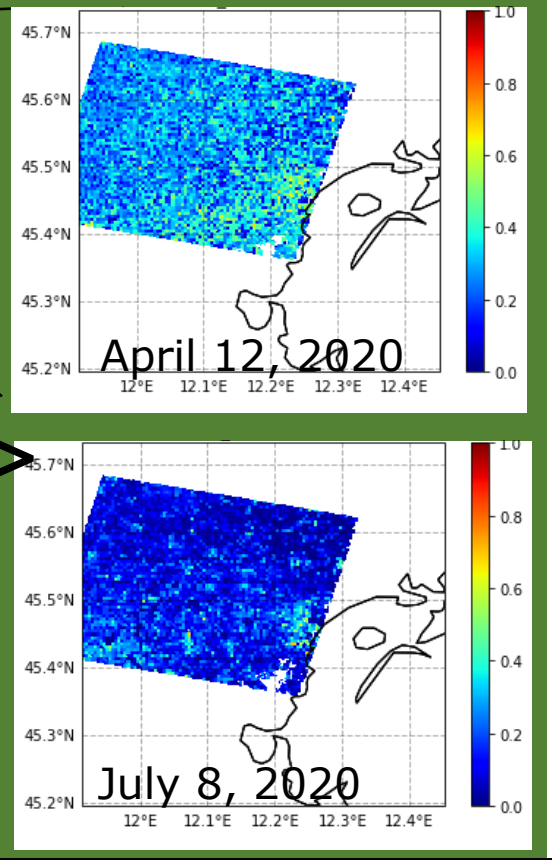
Cheng Chen and Pavel Litvinov et al., JGR 2024

GRASP/TROPOMI Aerosol Type



=>

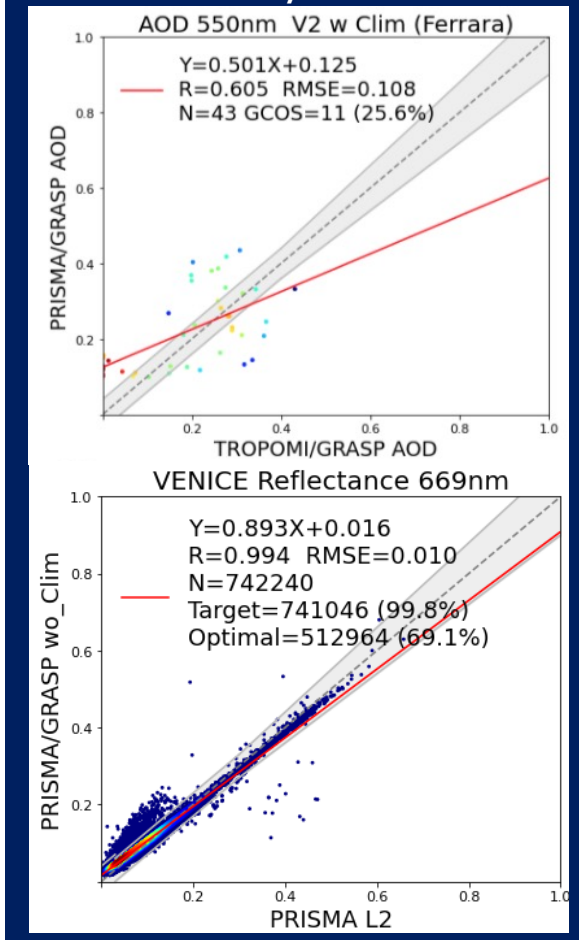
GRASP/PRISMA AOD, 100 m resolution



+

GRASP/PRISMA Surface Reflectance, 100 m

GRASP/PRISMA



Cheng Chen and Pavel Litvinov et al. JGR, 2024

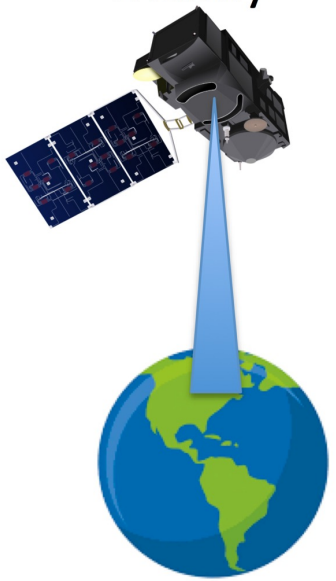
Conclusions and outlook

1. Combination of the instruments with coarse and fine spatial resolution (for example, S5p/TROPOMI and PRISMA) opens new possibilities for aerosol sources identifications at high spatial resolution and aerosol emission/pollution monitoring.
2. The retrieval from the instrument with coarse resolution and global coverage can provide information about aerosol type and aerosol background.
3. The retrieval from the sensor with fine spatial resolution can use this information to get AOD at high spatial resolution for identification of local aerosol sources and air quality monitoring.
4. The combined retrieval provides enhanced surface reflectance characterization at high spatial resolution.
5. Developed GRASP methodology for the combination PRISMA+S5p can potentially incorporate other satellites like S5p+S2 or S5p+OLCI+S2 etc.

2. Synergetic Satellite + AERONET retrieval with GRASP algorithm

Satellite + Nearest AERONET TOD + Almucantar (or Combined Almucantar and Principal plane) measurements

Surface properties mainly



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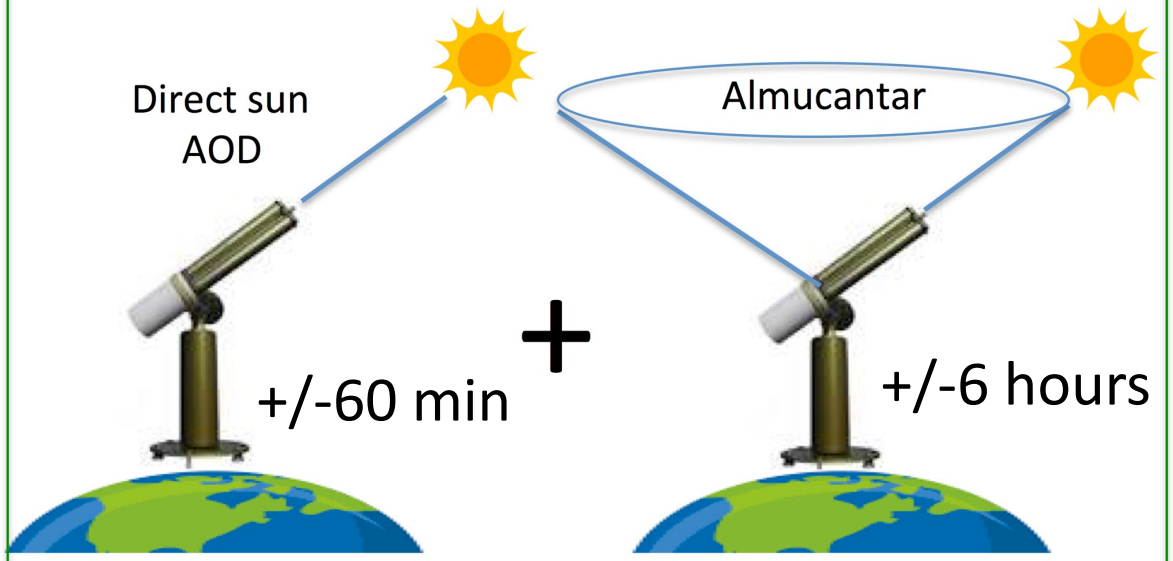
Aerosol properties mainly



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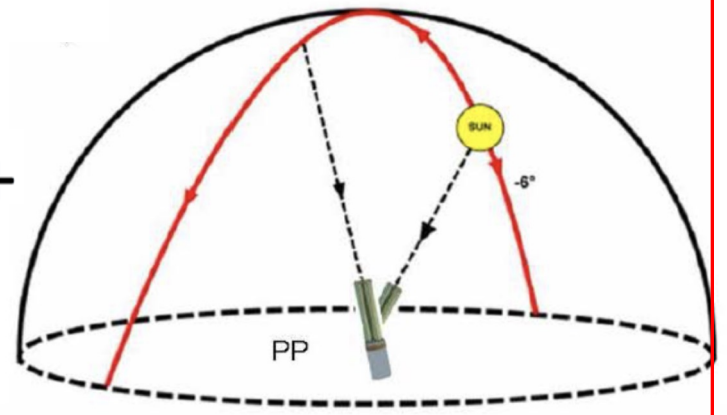
Principal Plane



Input:

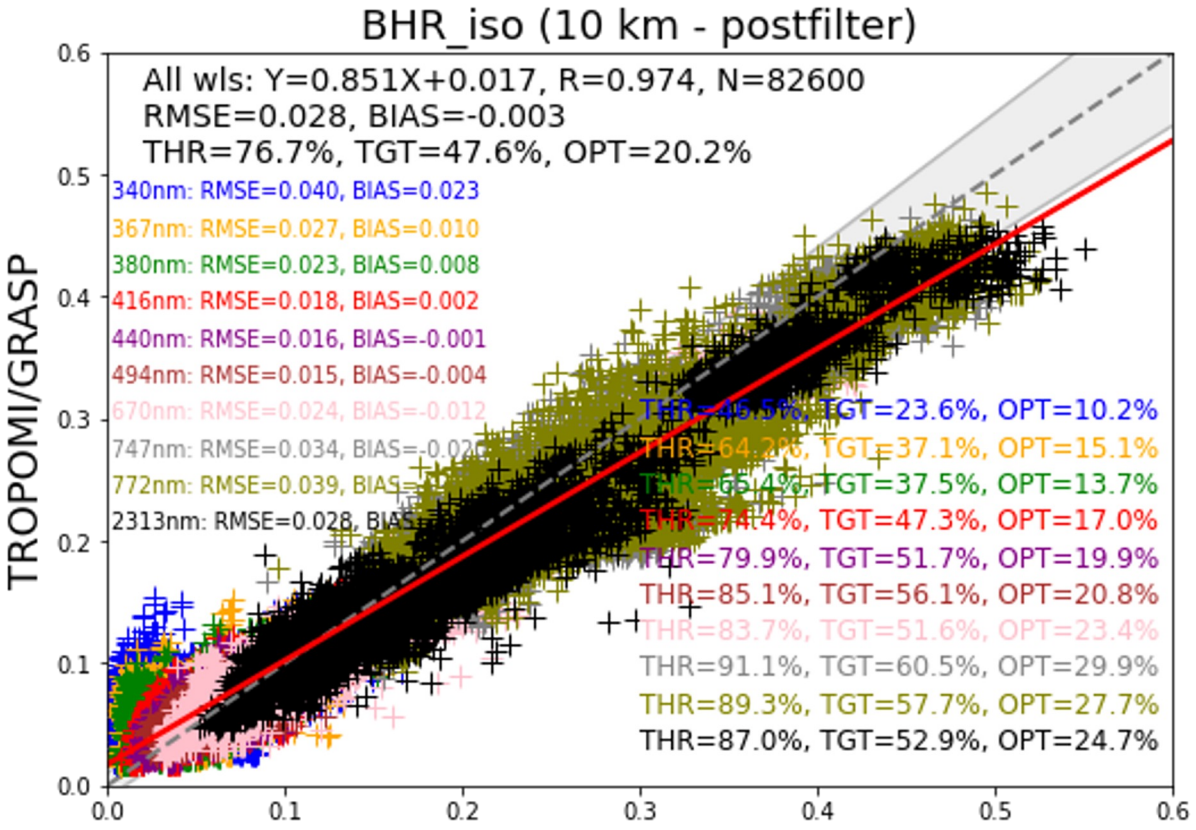
- Nearest AERONET TOD (direct sun) + Almucantar (Scattering plane) measurements
- **Satellite measurements**

Synergetic Satellite + AERONET retrieval.
New possibilities

1. Validation tool for forward models of aerosol and surface
2. Surface Reference Database for surface validation at the satellite spectral bands and spatial resolution
3. Instrument inter-calibration.

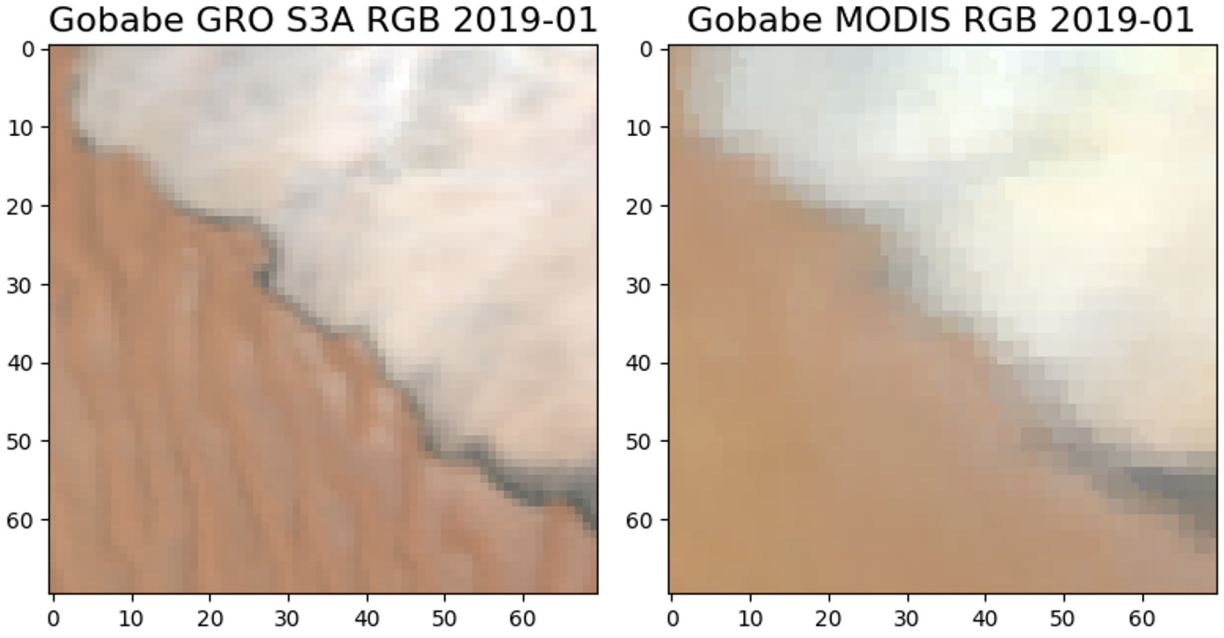
GROSAT surface retrieval as reference for **satellite**

Surface BRDF/albedos	Uncertainties
Threshold	Max (0.02 or 20%)
Target	Max (0.01 or 10%)
GCOS (Optimal)	Max (0.0025 or 5%)



Surface from synergetic retrieval

Gobabeb validation site

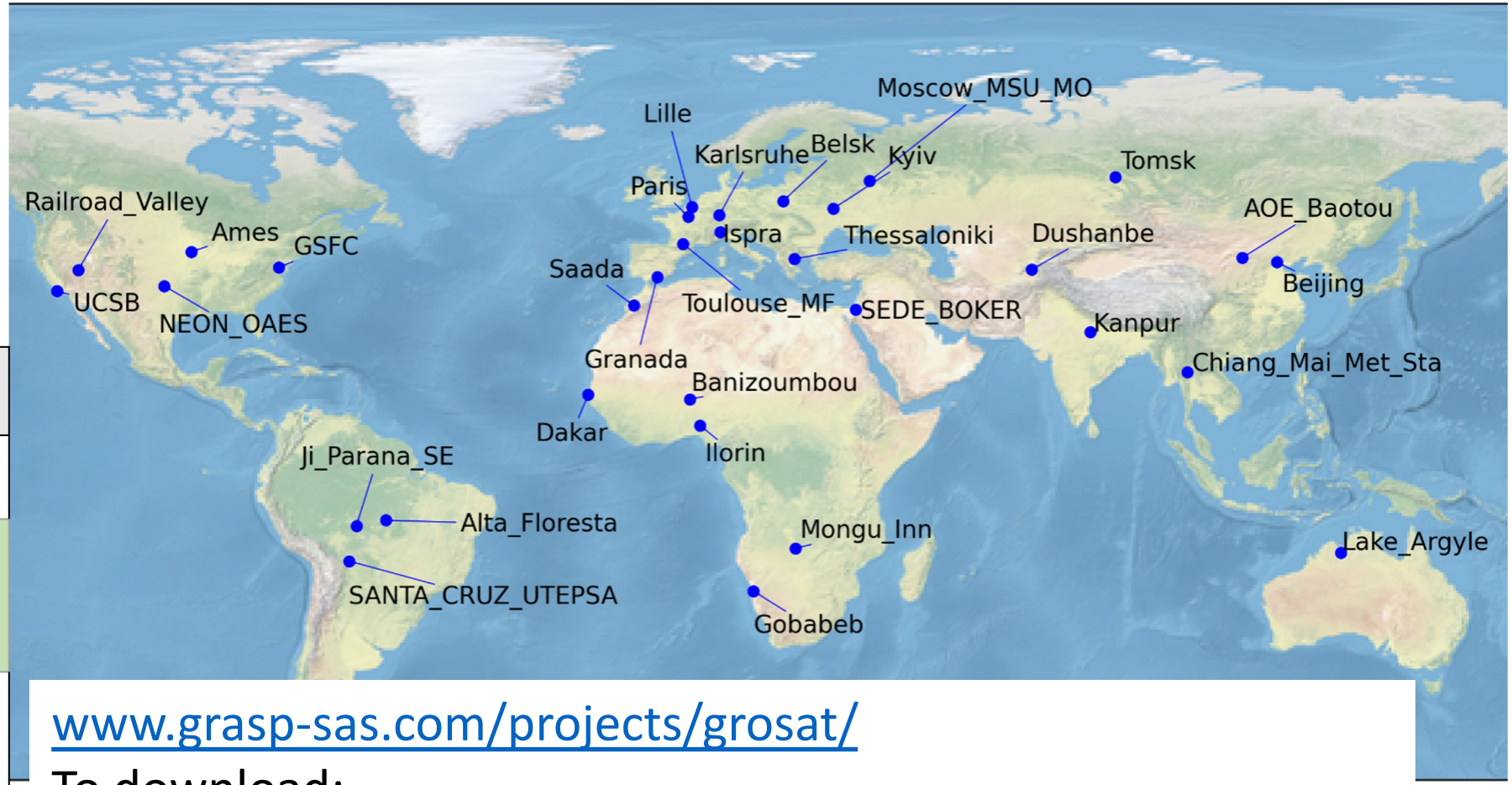


GROSAT/OLCI, 300m

MODIS, 500m

GRASP: surface reference site

Satellites	Resolution	Product
S2/MSI	20 m	BRDF, albedos
S3/OLCI	300m, 700 m; 10 km	BRDF, albedos
PARASOL/ POLDER	6 km	BRDF, BPDF, albedos
S5p/ TROPOMI	0.1 deg (~10 km)	BRDF, albedos

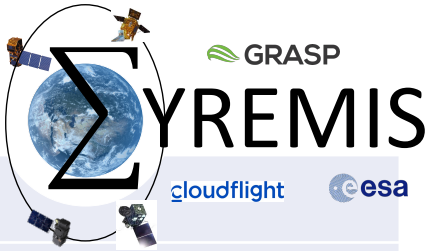


www.grasp-sas.com/projects/grosat/

To download:

www.grasp-open.com/products/grosat-data-release/

3. GRASP multi-instrument synergetic retrieval:



Satellites	Description
Sentinel-3A /OLCI and Sentinel-3B/OLCI	- Polar-orbiting, global coverage - One observation per pixel - Moderate spatial resolution - Radiance measurements in VIS and NIR spectral range
Sentinel-5p/TROPOMI	- Polar-orbiting, global coverage, from 1 to a few observations per day - Hyperspectral measurements in UV, VIS, NIR, SWIR spectral range
Himawari/AHI	- Geostationary. Coverage area: Asia - Every 15 min daily measurements - Radiance measurements in VIS, NIR and SWIR spectral range

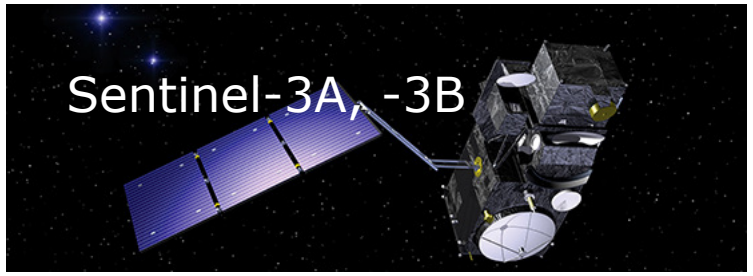
SYREMIS Synergy	i. Multi-spectral			ii. Multi-angular	iii. Multi-Polarization	iv. Multi - Temporal
	UV	VIS - NIR	SWIR			
S3A/OLCI + S3B/OLCI + TROPOMI + HIMAWARI	+	+	+	+ Quasi multi-angular	-	+

Filling gaps with GRASP SYREMIS synergy

cloudflight esa

PARASOL

2016, 2018



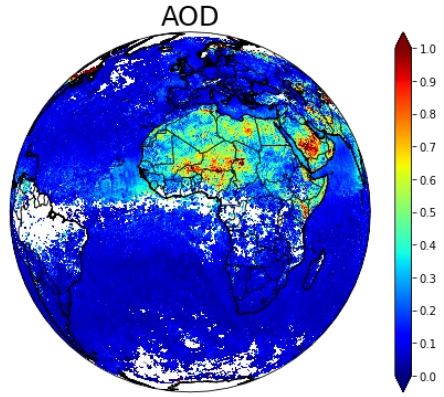
2017

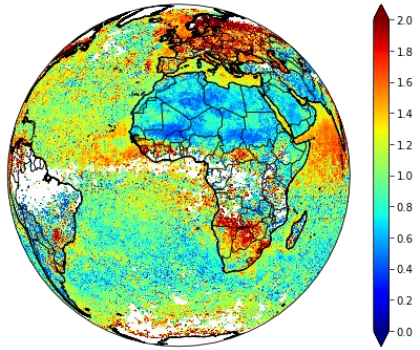
2013

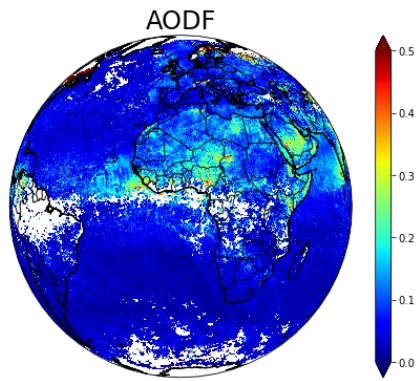
11-12 years gap

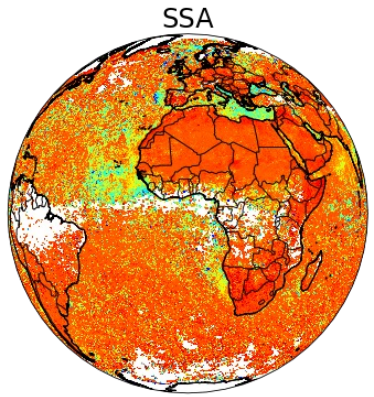
2024

2025 ?









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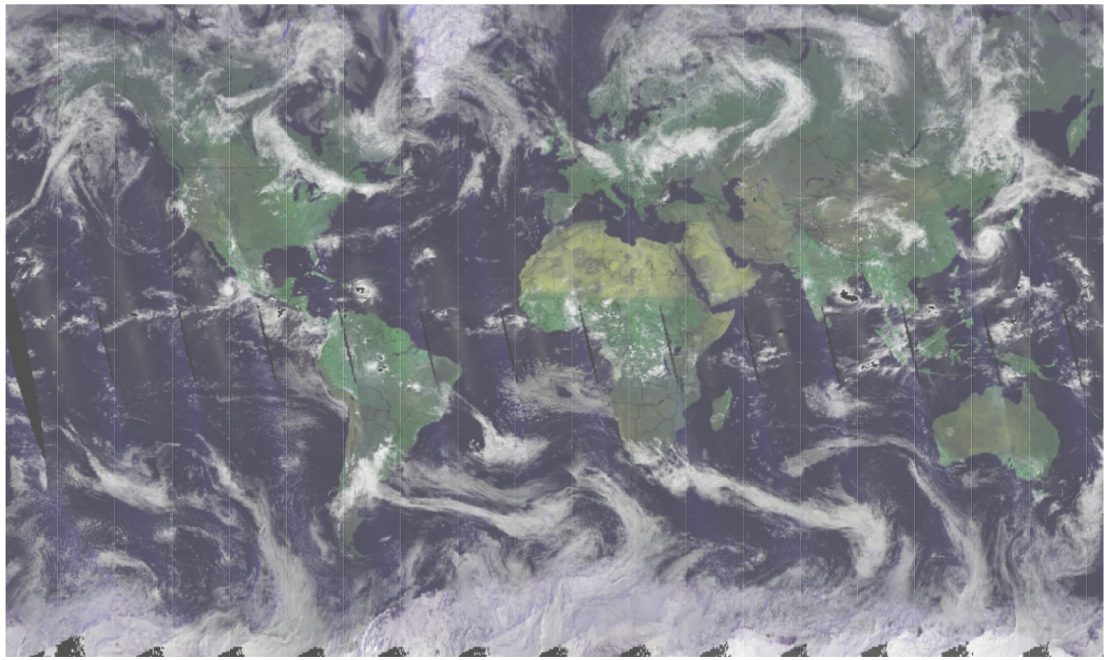
https://www.grasp-open.com/products/tropomi-data-release/

Satellite measurements for SYREMIS synergy

Sentinel-5p/TROPOMI



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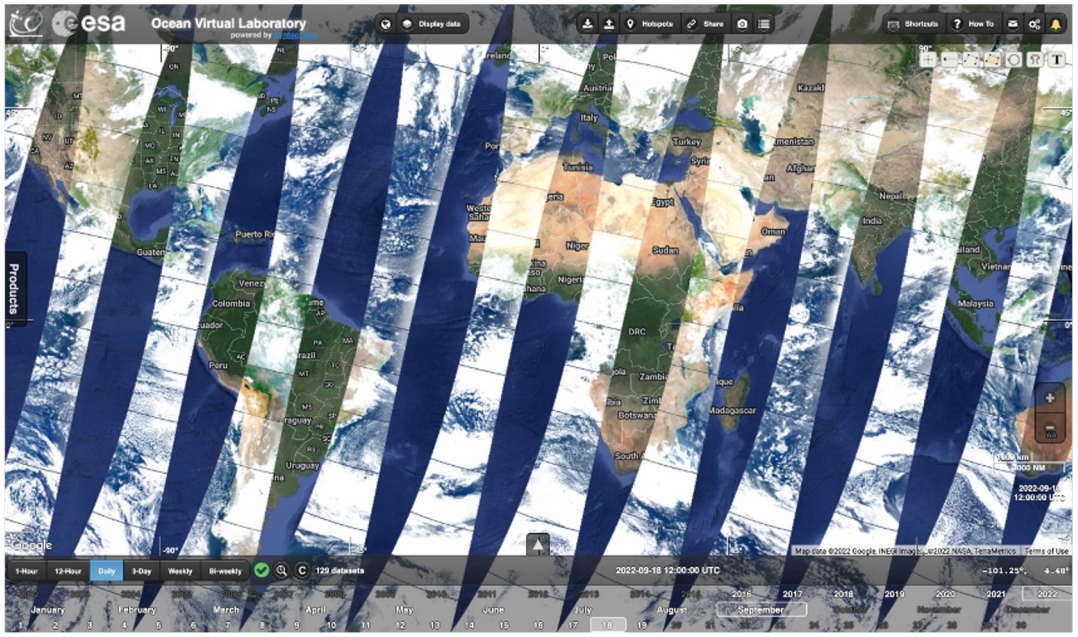
Hyperspectral:
UV,VIS,NIR,SWIR
10 spectral bands for aerosol retrieval:
0.34, 0.367, 0.38, 0.416, 0.44, 0.494, 0.67, 0.747, 0.772, 2.3130

Swath*:* about 2600 km cross-track
Global coverage: every day
1 pixel spatial resolution ~10km
Viewing directions: 1

Sentinel-3A/OLCI



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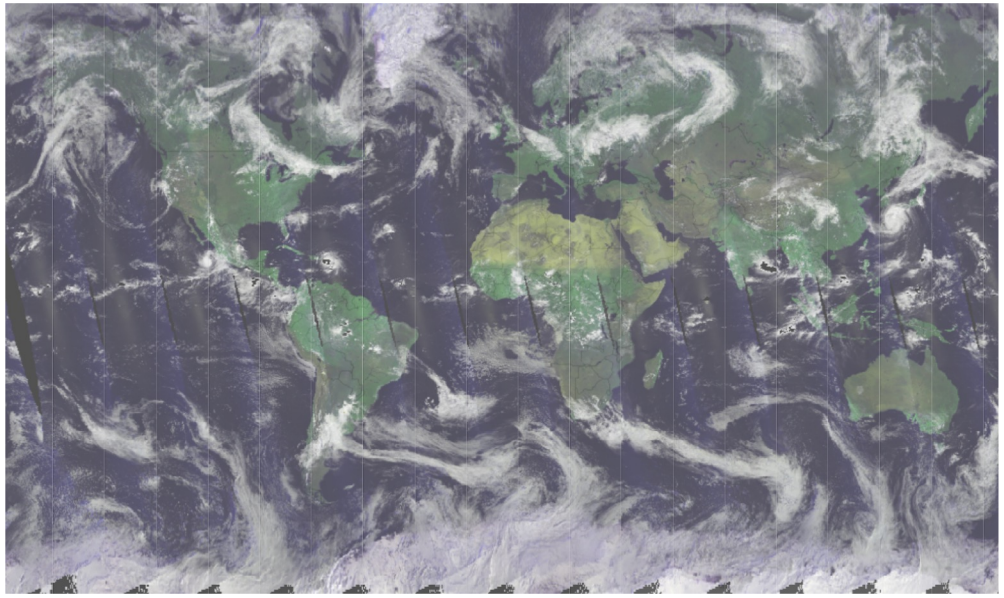
0.4, **0.4125**, **0.4425, 0.49, 0.51, 0.56,** 0.62, **0.665,** 0.67375, 0.68125, 0.70875, **0.75375**, 0.76125, 0.764375, 0.7675, 0.77875, **0.865**, 0.885, 0.9, 0.94, **1.02**

Swath*:* about 1270 km cross-track
Global coverage: every 2 days
1 pixel spatial resolution ~300m
Viewing directions: 1

Main principles of the L1 synergy

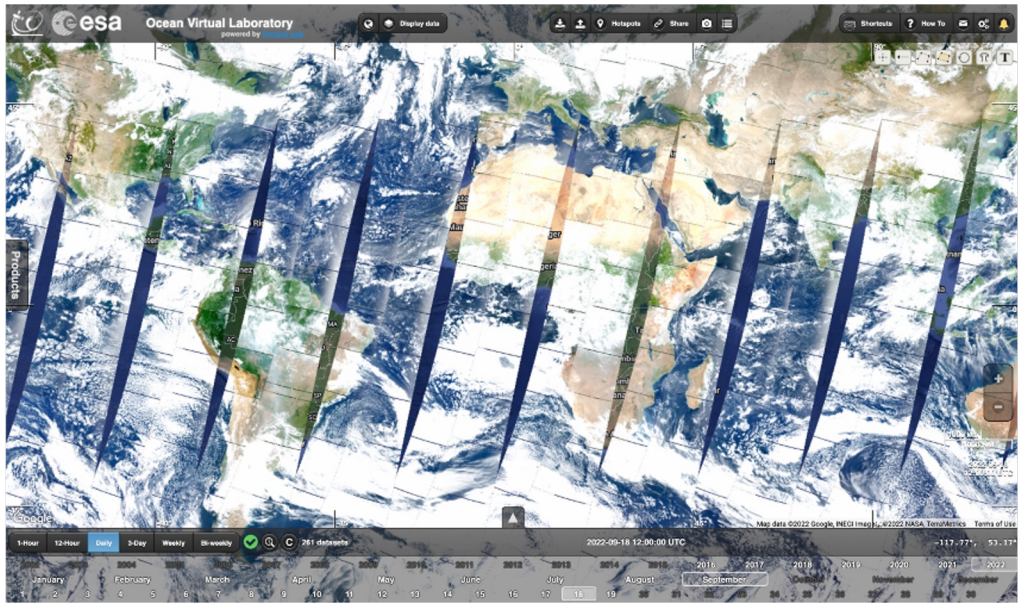
i. Harmonization of data from different instruments
ii. “Weighting” of the measurements according to their information content and measurements accuracies
iii. Optimization of forward models and retrieval setup.

1. Polar-orbiting LEO+LEO synergy

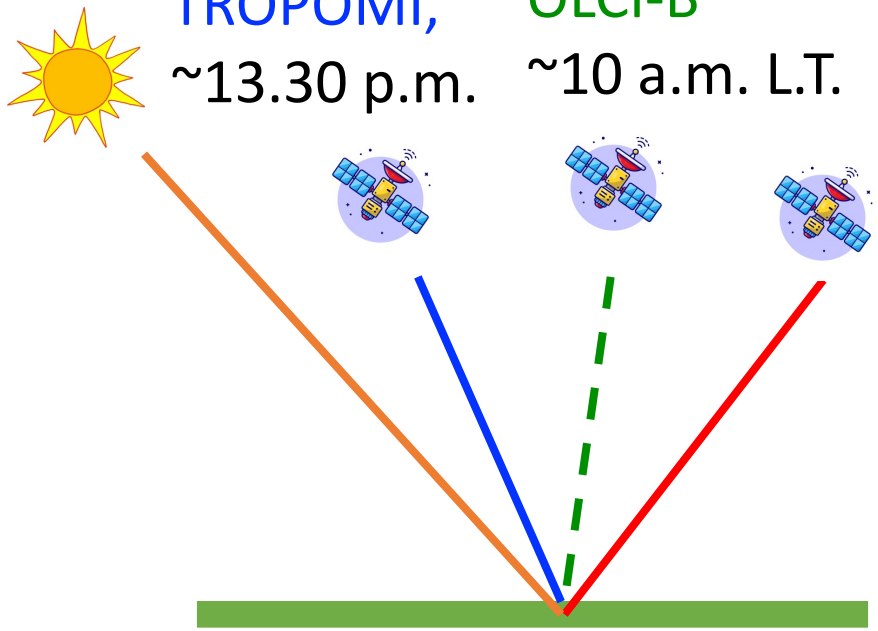


TROPOMI

+



OLCI-A + OLCI-B



- Pseudo-multi-angular measurements
- Few measurements per day!
- Extended spectral range

1. Better surface BRDF sampling and surface/atmosphere signal separation
2. Better temporal resolution!

Multi-temporal measurements should be accounted for !

LEO+LEO SYREMIS synergy

vs

Single instrument retrieval.

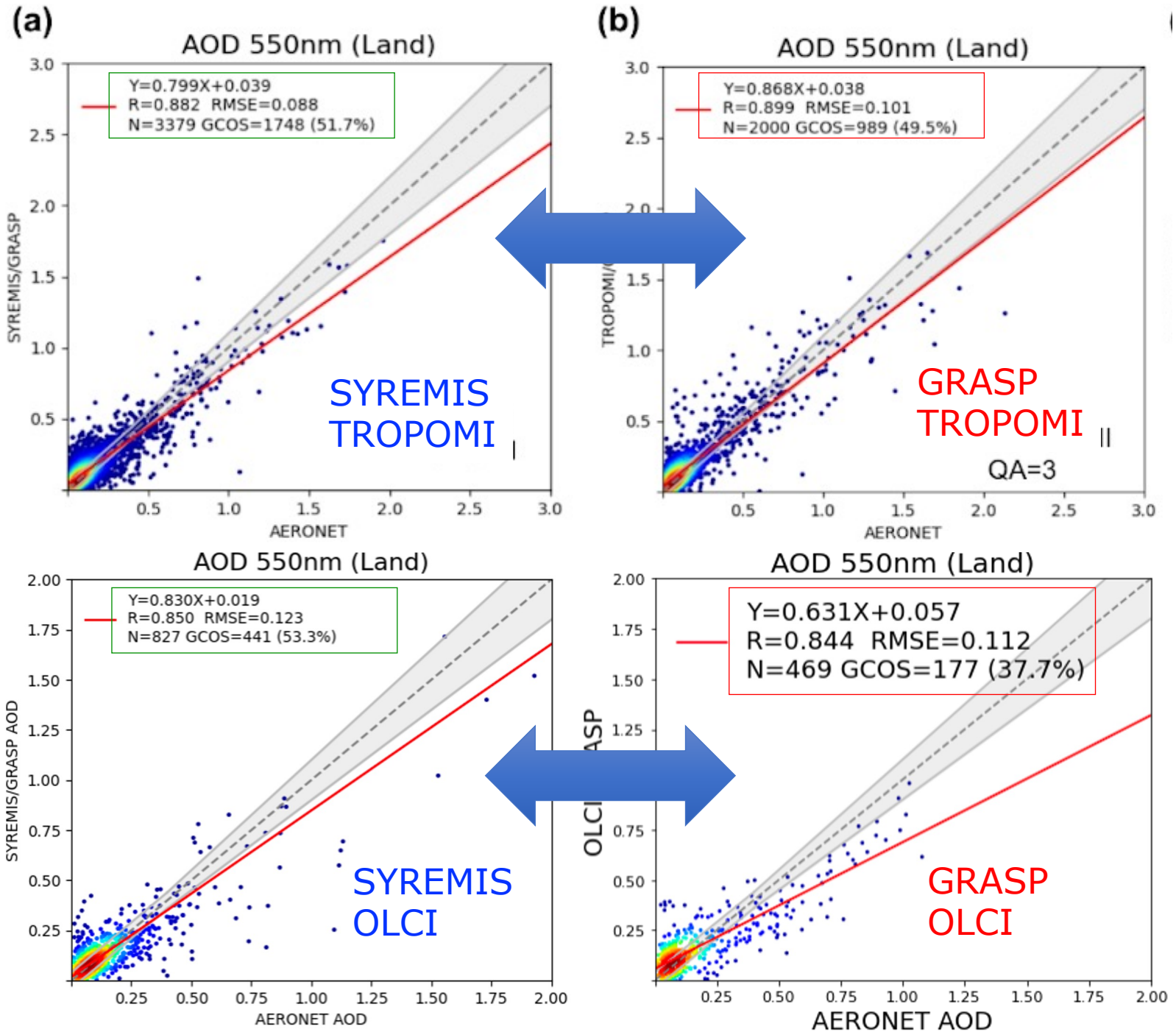
AOD.

Global. March-May, 2019

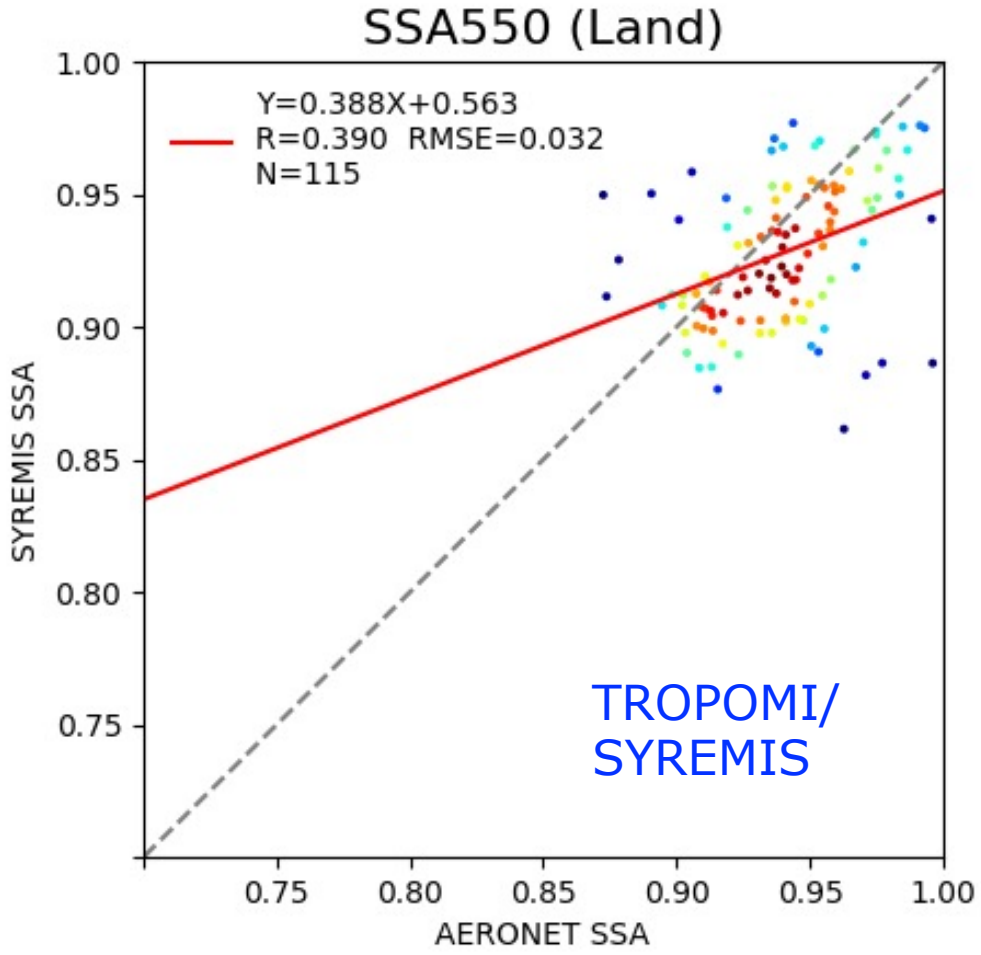
Synergy effect on AOD:

- Clear improvements in TROPOMI AOD!

- Crucial improvement in OLCI AOD!

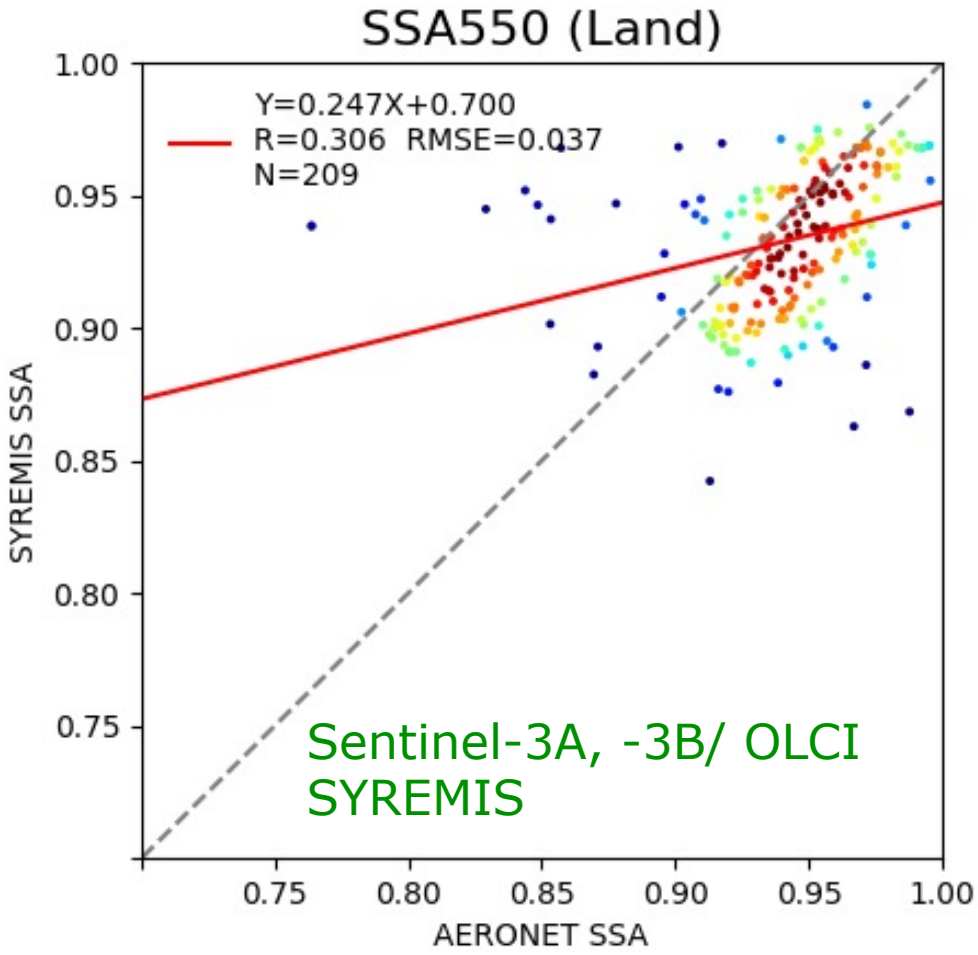


SSA from LEO+LEO SYREMIS/GRASP

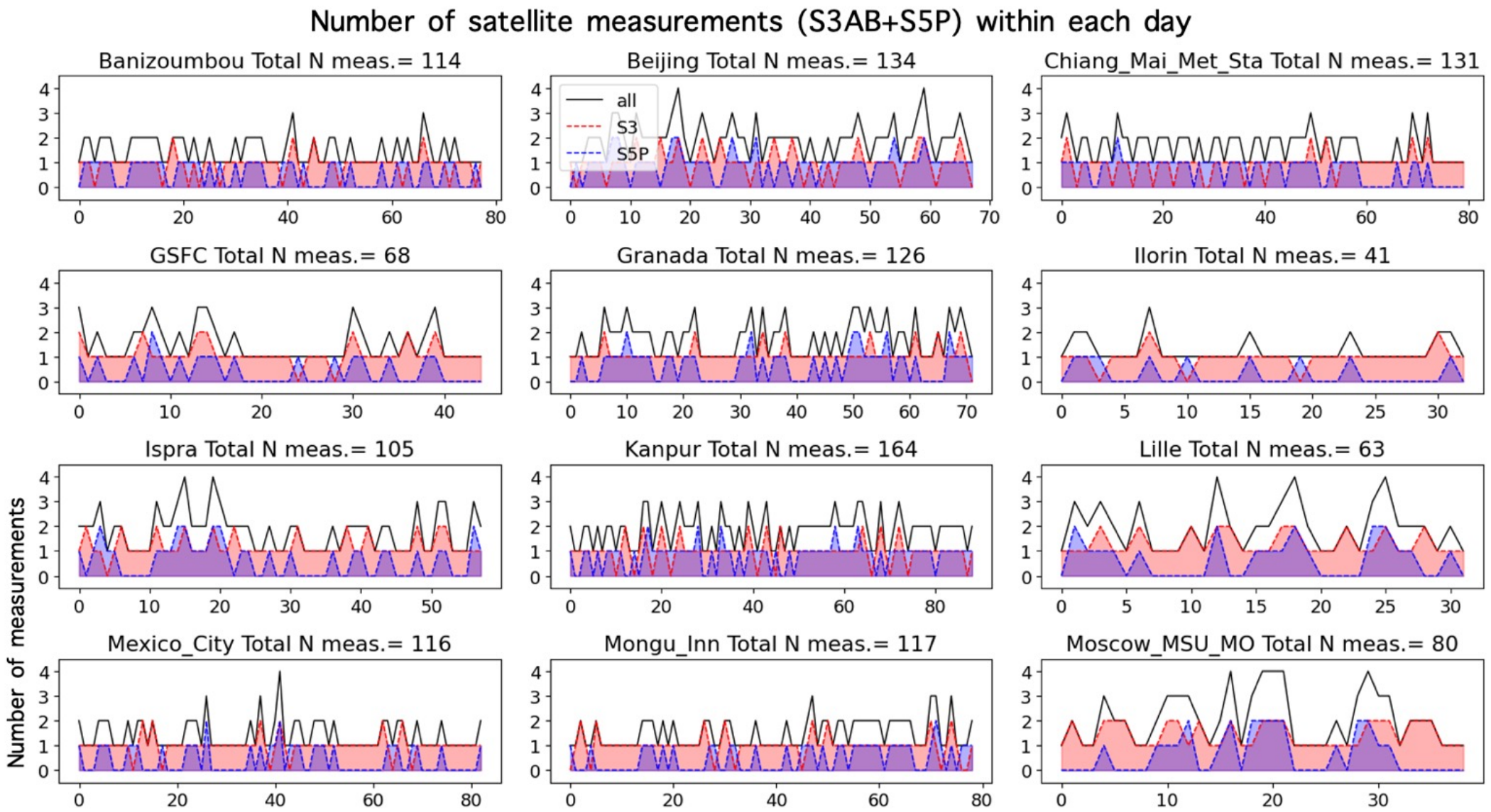


Synergy effect on SSA:

Transition of TROPOMI information content to OLCI results in essential improvements in SSA characterization!



Multi-temporal measurements in S3AB+S5P synergy

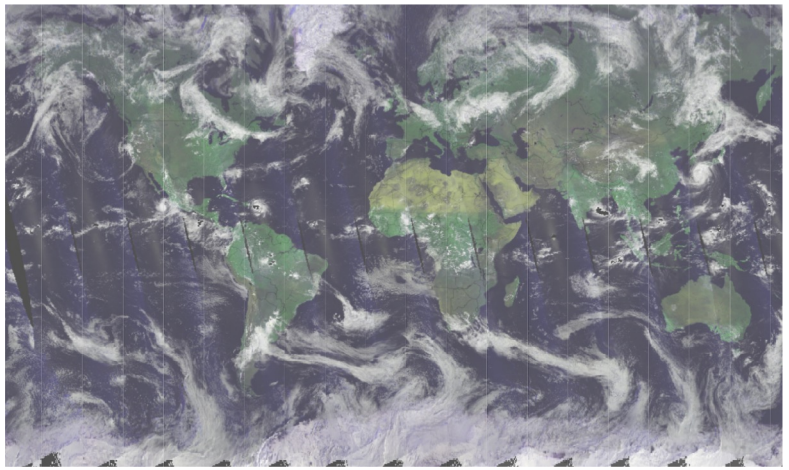


Several measurements per day from the synergy !

S. Zhai and P. Litvinov et al. (publication is under preparation)

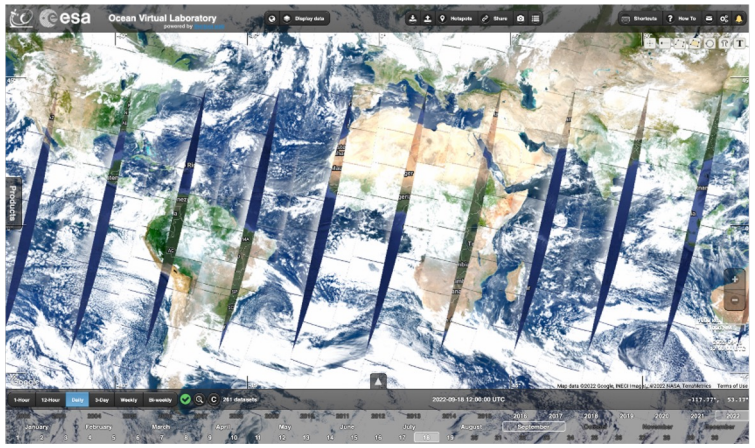
2. LEO+GEO synergy

TROPOMI



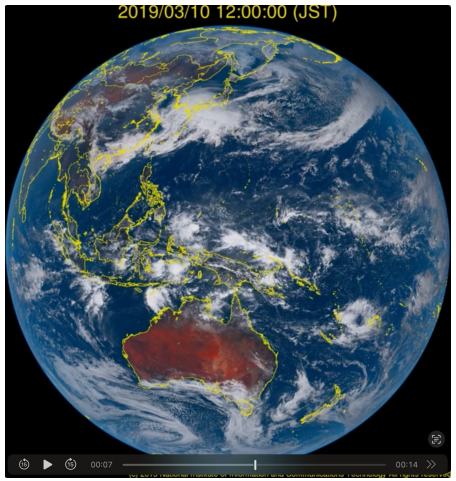
+

OLCI-A + OLCI-B



+

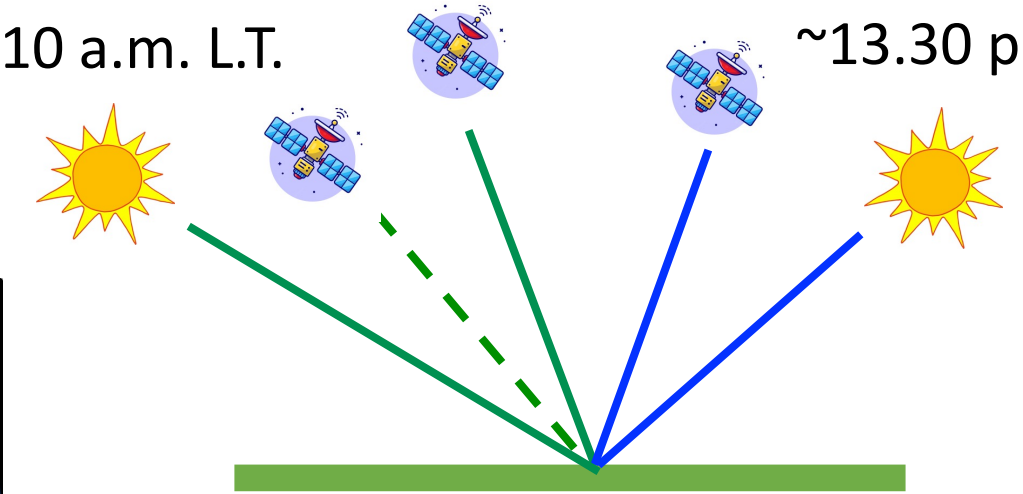
HIMAWARI



OLCI-A
~10 a.m. L.T.

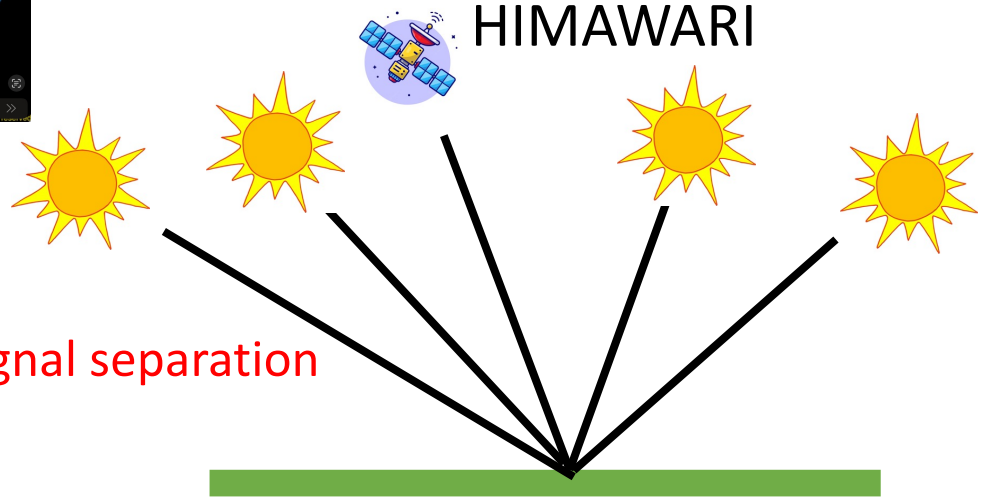
OLCI-B
~10.20 a.m. L.T.

TROPOMI
~13.30 p.m.



+

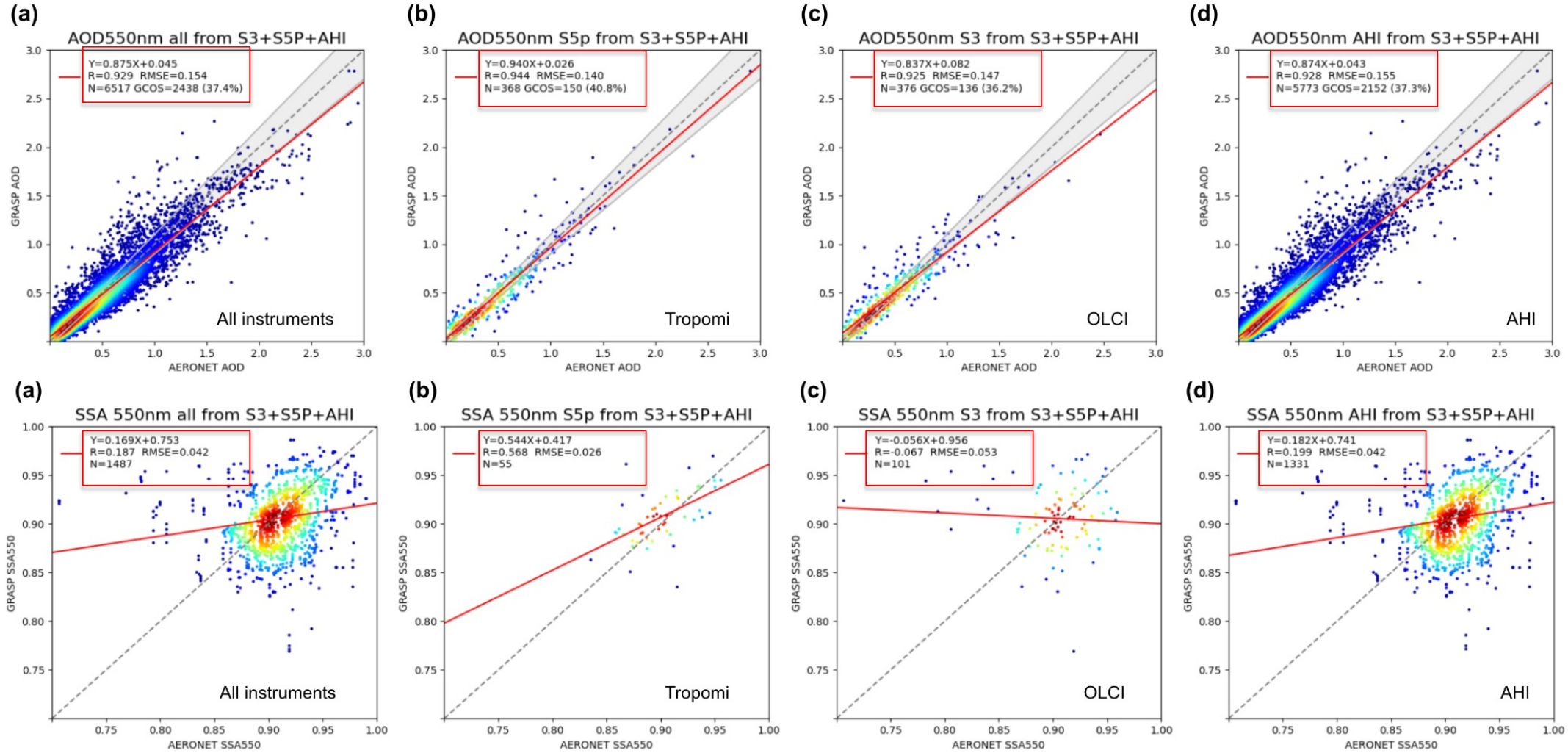
HIMAWARI



- Pseudo-multi-angular measurements
- Hourly measurements!
- Extended spectral range

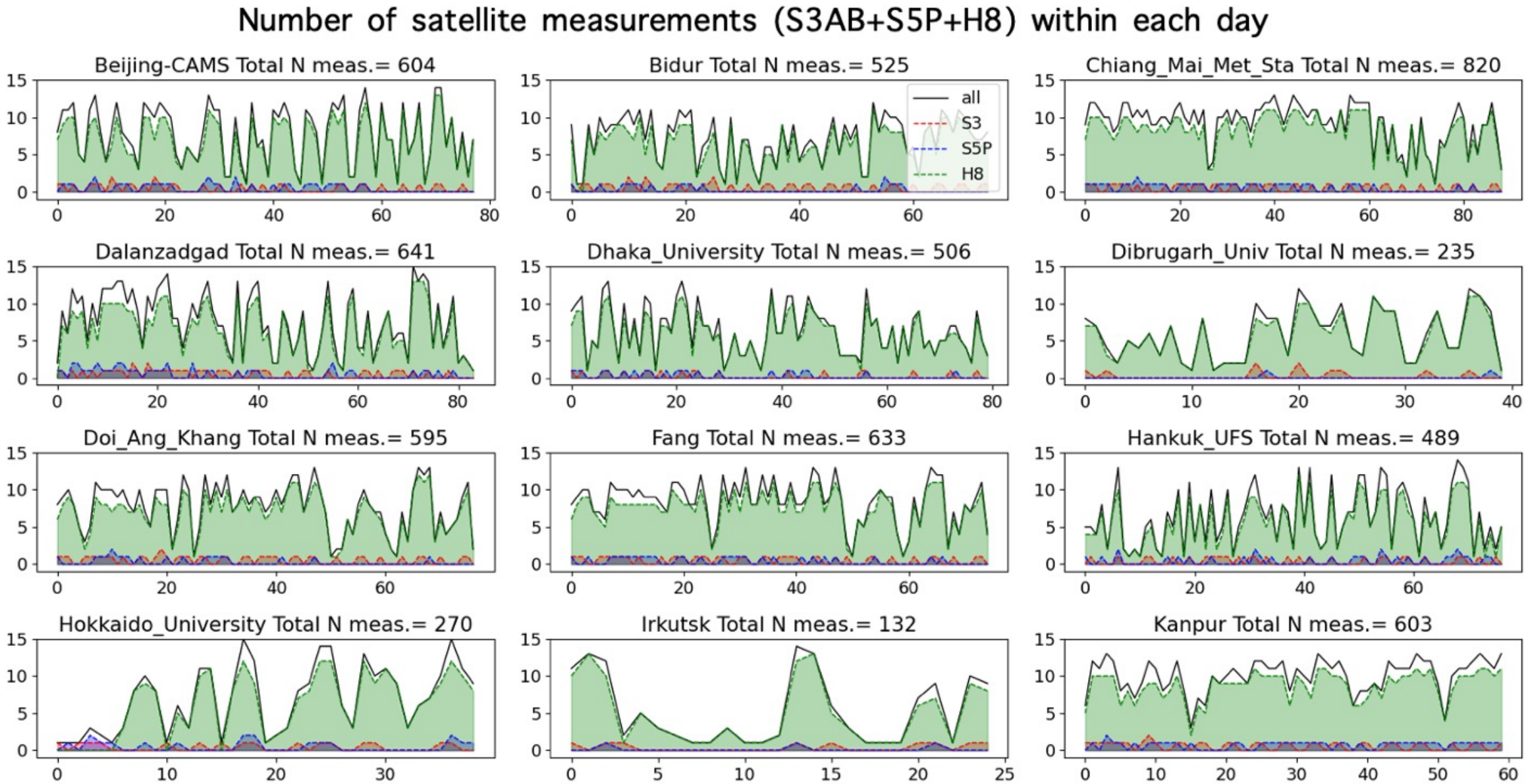
1. Better surface BRDF sampling and surface/atmosphere signal separation
2. **Hourly extended aerosol properties variability!**
3. Aerosol transport!

SYREMIS /GRASP LEO+GEO synergy and extended aerosol characterization



1. Extended aerosol properties (AOD, AExp, SSA etc) are improved for all instruments
2. The biggest improvements are for the instruments with smaller information content (OLCI, AHI)
3. TROPOMI is a driver of the considered synergy
4. Consistent retrieval for all instruments in the synergy!

Multi-temporal measurements in S3AB+S5P+ HIMAWARI synergy



Diurnal aerosol variability from the synergy !

S. Zhai and P. Litvinov et al. (publication is under preparation)

Benefits of the synergetic retrieval

1. Enhanced characterization of such aerosol parameters as spectral AOD but also SSA and aerosol size characteristics etc
2. Improved global coverage and temporal resolution of the aerosol dataset.
3. Consistent retrieval from all satellites from synergetic constalation
4. New possibility for global aerosol emission and transport monitoring, aerosol dynamic and aerosol-cloud-nteraction, air-quality and global climate changes ...

The instrument with richest information content is a "driver" of synergetic retrieval

Upcoming space-borne missions

Instrument/ Platform	Orbit	Spectral Range	Resolution		Specific sensitivity to dedicated products
			Spatial	Timporal	
S-5/EPS-SG	LEO	UV,VIS, NIR, SWIR	7 km	~1-2 days	AOD, ALH, Surface albedo
3MI/EPS-SG		VIS, NIR, SWIR	4 km		AOD, AODF, AODC, AE, SSA, ALH, Aerosol type and composition, BRDF, BPDF, Surface albedo
IASI-NG/ EPS-SG		TIR	12 km		DOD, DLH, Surface TIR emissivity, Surface temperature
OLCI/S 3A&B/		VIS, NIR	300 m	~1 day	AOD, Surface albedo
FCI/MTG-I Sentinel-4 etc	GEO	VIS,NIR, SWIR	1 km	10 min	AOD, Surface albedo

From current synergy to future

<table>
<tr><th rowspan="2">Synergy</th><th rowspan="2">Instrument/ Platform</th><th rowspan="2">Spectral Range</th><th colspan="2">Resolution</th><th rowspan="2">Specific sensitivity to dedicated products and added value</th></tr>
<tr><th>Spatial</th><th>Timporal</th></tr>
<tr><td rowspan="3">LEO+LEO</td><td rowspan="2">S5 + 3MI + OLCIA&B</td><td>UV + VIS + NIR + SWIR</td><td rowspan="2">4-10 km</td><td rowspan="3">a few hours</td><td>AOD, AODF, AODC, AE, SSA, Aerosol type and composition, DOD, DLH, BRDF, BPDF, Surface albedo</td></tr>
<tr><td>UV + VIS + NIR + SWIR + Hyperspectral (S5)</td><td>+ Aerosol layer hight</td></tr>
<tr><td>S5 + 3MI + OLCIA&B +IASI-NG</td><td>UV + VIS + NIR + SWIR + TIR</td><td>12 km</td><td>+ DLH + Dust Chemistry + Surface TIR emissivity + Surface Temperature</td></tr>
<tr><td>LEO + GEO</td><td>LEO+LEO+FCI

LEO+LEO+TIR+ FCI</td><td>UV + VIS + NIR + SWIR
UV + VIS + NIR + SWIR + TIR</td><td>1-12 km</td><td>10 min</td><td>LEO + LEO +
+ high temporal resolution of the product</td></tr>
</table>

Welcome to contribute!

Questions?