Aerosol Remote Sensing in the Context of Operational Missions

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EUMETSAT Remote Sensing & Products / *Cloud & Aerosol* (RSP/CLA)
1) EUMETSAT 2) Rhea Systems GmbH 3) Vision Space Technologies

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Summary

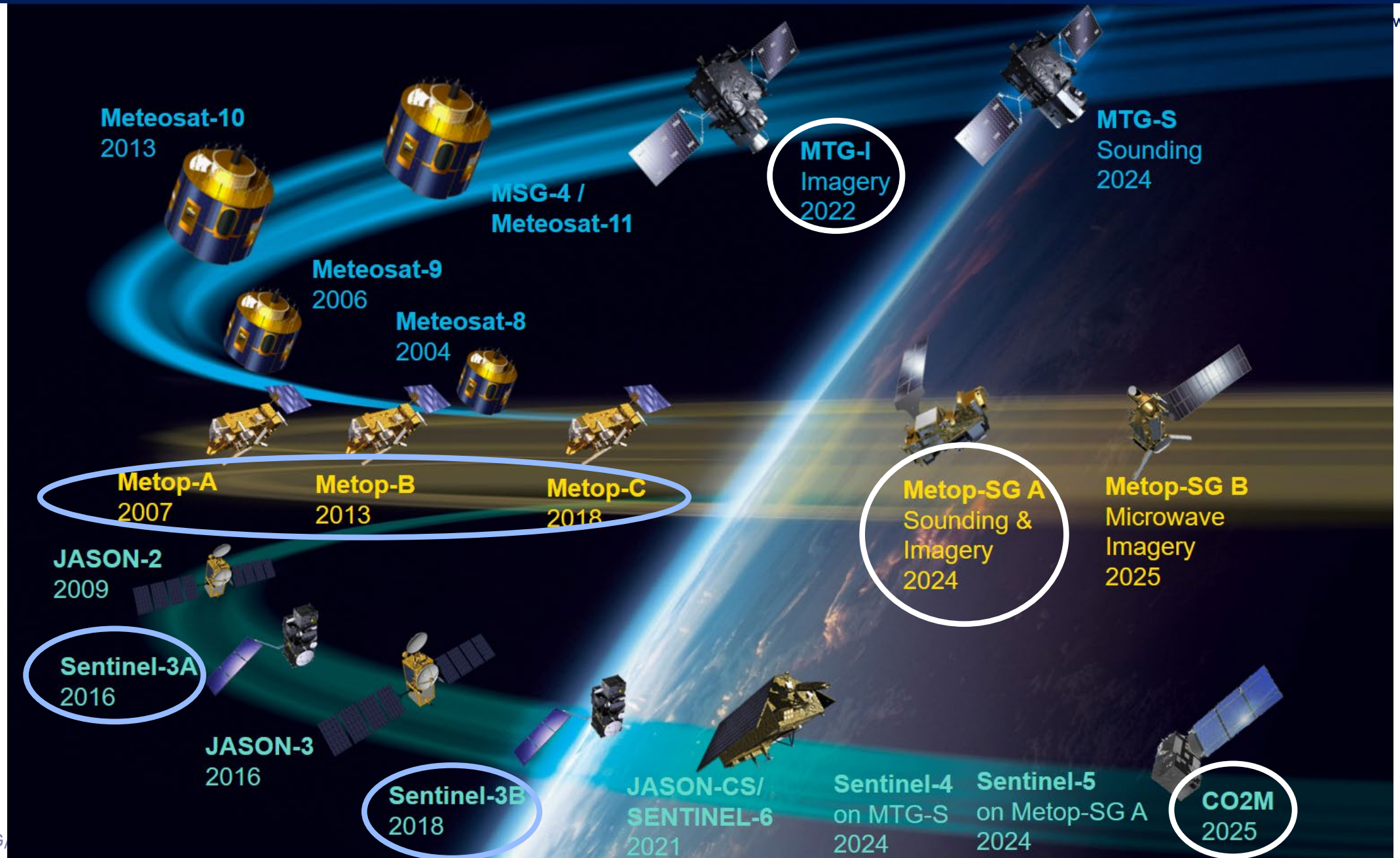
- Aerosol & users in the operational context
- Development of aerosol processor in EUMETSAT
- Operational processors
  - O1: EPS/PMAp
  - O2: S3/OSSAR-CS3
- Processor under preparation & development
  - P1: Polarimetry with EPS-SG/3MI
  - P2: Synergy with EPS-SG/MAP
  - P3: Polarimetry with CO2M/MAP
  - P4: Geostationary orbit
- Strategy wrt Users & Assimilation needs
- Conclusion

Operational Aerosol processors in EUMETSAT

- “Operational product” ?
  - Dissemination to operational users
  - Near real time delivery (<3:00h from sensing time)
  - Robustness (availability)
  - Documented performance (validation report)
  - Stability of the performance
  - Monitoring of the performance
  - In general continuous improvements
  - Product tailored to user needs

- Scientific developments are needed to support these definitions and improvements
  - Some adaptation from the scientific development are needed to convert into an operational processor
  - Tailor the products to user needs (core parameters, performance, additional information…)

EUMETSAT Missions – *Current and Future*



Aerosol algorithm/processor in EUMETSAT

Operational products:

- **O1: EPS/PMAp** : Synergistic combination of instruments
- **O2: S3/SLSTR** : Dual-view radiometer

Under preparation:

- **P1: EPS-SG/3MI**: Multidirectional polarimeter
- **P2: EPS-SG/MAP**: Synergistic use of 4 instruments (inc. 3MI)
- **P3: CO2M/MAP**: Multiview polarimeter
- **P4: S3/SYN and S3-NG**: Synergy with Multispectral Pushbroom
- **P5: MTG/FCI** : Geostationary imagers

Polarisation

→ mono-view, Q/I fraction in 8 bands (414-799nm)

→ 14 views, I/Q/U in 9 bands (410-2200nm)

→ same as 3MI

→ 45 views, I/Q/U in 7 bands (410-865nm)

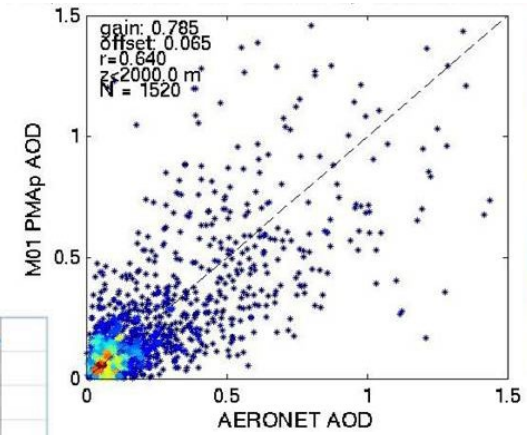
Strategy for the development of Aerosol product

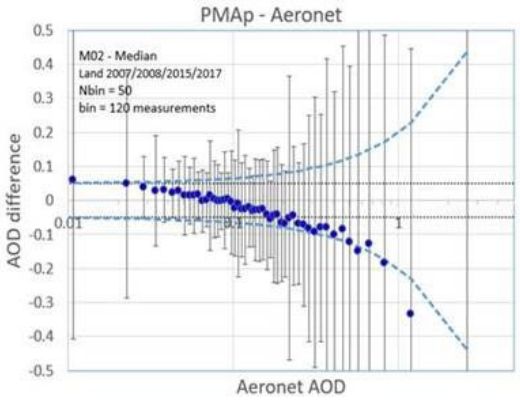
Toward a standardisation of methodology and harmonisation of processes

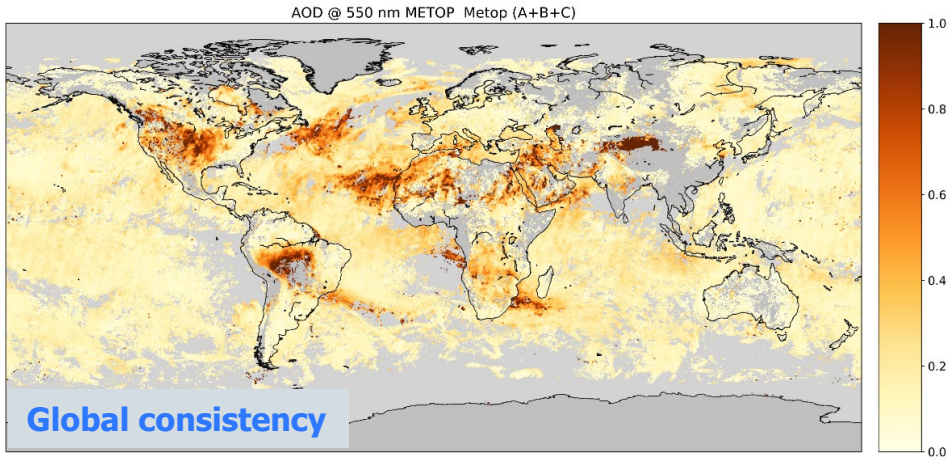
- Information Content Analysis (ICA) for each sensor/system
  - Should identify what can be realistically retrieved
    The larger the IC, the large the number of parameter to be retrieve AND/OR the better the performance
- Simultaneous Surface Aerosol Retrieval (SSAR)
  - Must be adapted & tuned considering the ICA
- Tailor the products to user needs – may impact the algorithm
- Physical description
  - Adopt a common aerosol model definition, vertical distribution definition…
- RTM
- Validation: adopt a consistent 6-step approach
  - Qualitative analysis
  - Matchups with ground measurements (e.g. Aeronet…)
  - Inter-satellite/sensor comparison
  - Consistency with aerosol sources
  - Comparison with alternative algorithms
  - Model-based comparison

The different tastes of our validation

Matchups In-situ

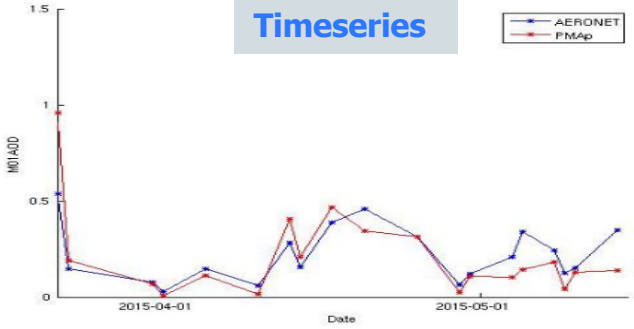




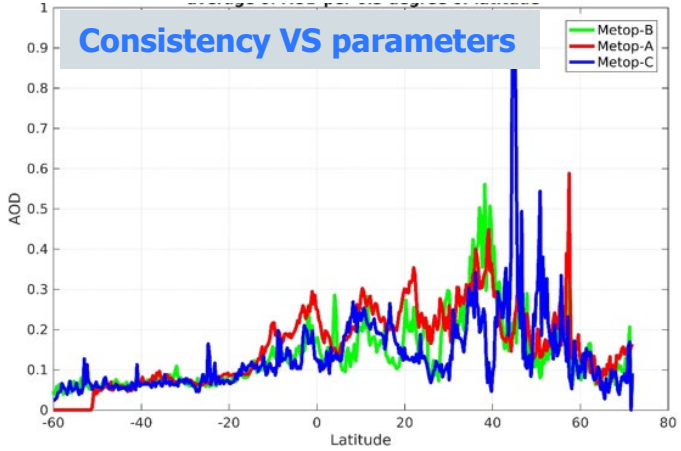


Global consistency

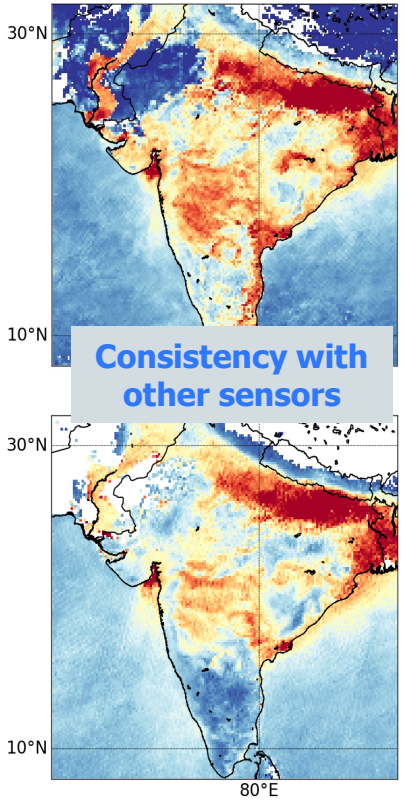
Timeseries



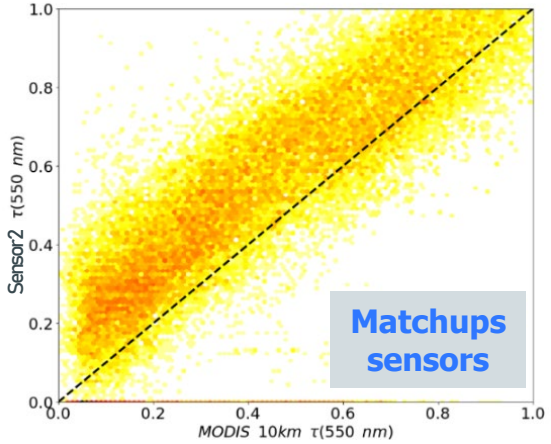
Consistency VS parameters



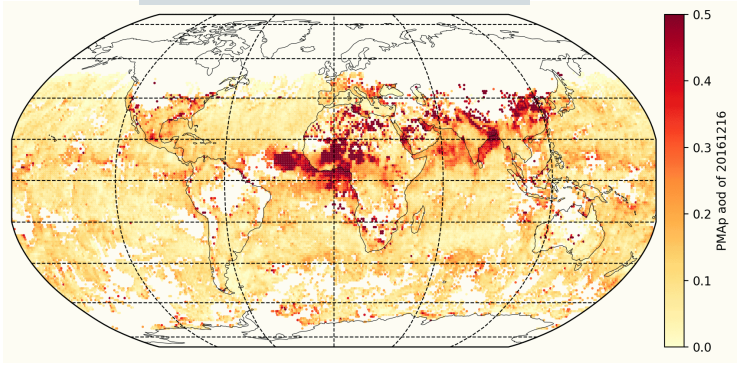
Consistency with other sensors



Matchups sensors



Temporal consistency



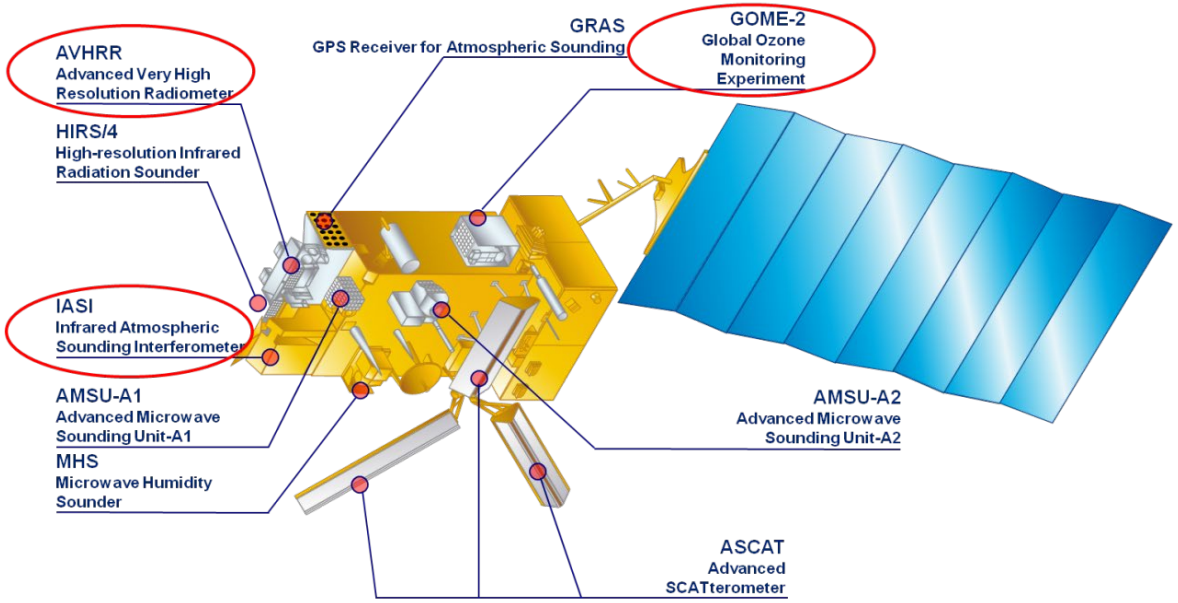
- ➔ Extract signatures
- ➔ "Morphological" description of the performance
- ➔ Try to understand origin

Operational NRT Aerosol processors

01 – EPS/PMAp: Polar Multi-sensor Aerosol Product

PMAp: Polar Multi-sensor Aerosol product from GOME-2, AVHRR and IASI

- EPS EUMETSAT Polar System: 3 Polar platforms, orbit at 09:30 ECT
- 3 redundant platform/instrument → 25 y. of operation
- Metop-A/2006-2021, Metop-B/2012, Metop-C/2018
- 3 instruments for aerosol: GOME-2, AVHRR, IASI



Merging hyper-spectral and high spatial information from GOME-2, AVHRR and IASI

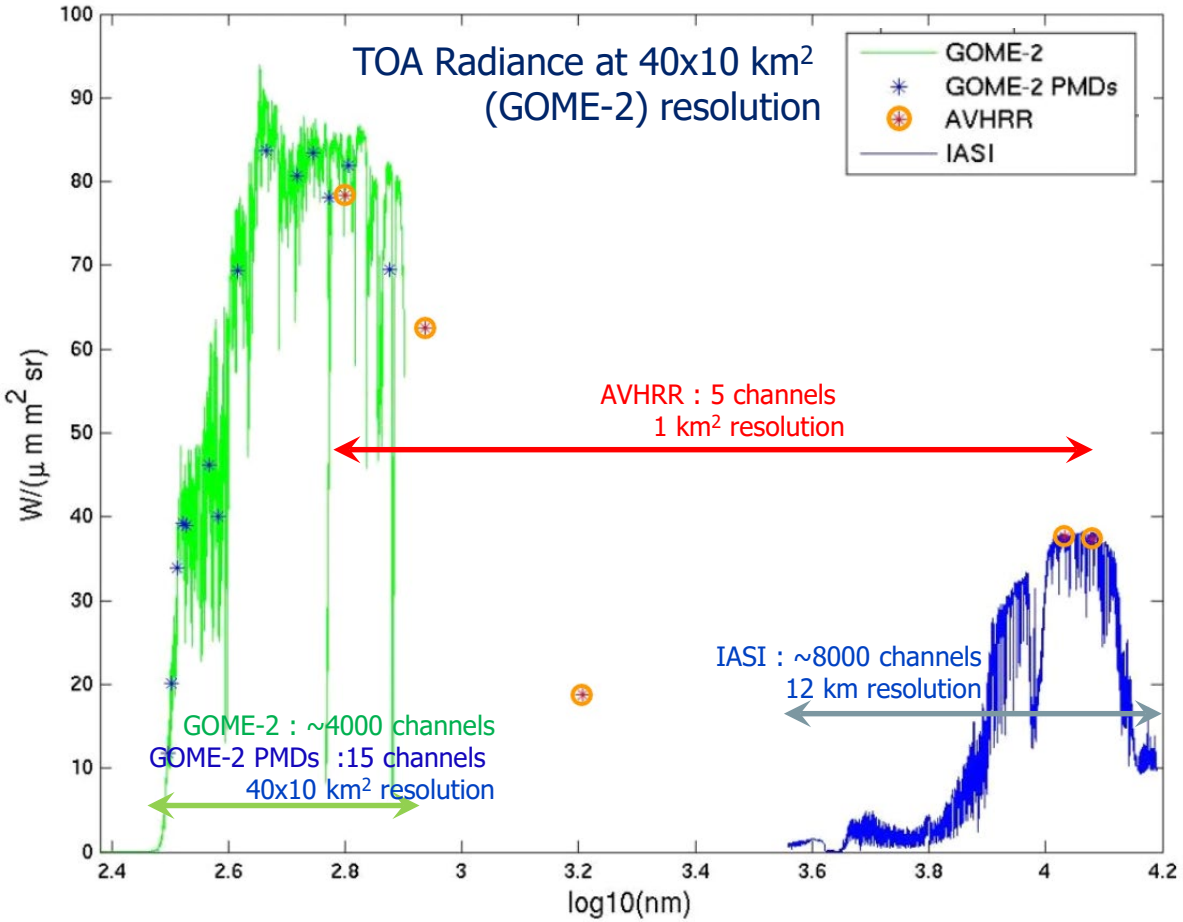
Instruments for L1 data	Spatial resolution	Spectral range
GOME PMD	Metop B and C: 10×40 km^2 Metop A: 5×40 km^2	311 nm – 803 nm (15 band)
AVHRR	1.08 × 1.08 km^2	580 nm – 12500 nm (5 band)
IASI	12 km (circular)	3700 nm – 15500 nm (resolution 0.5 cm^{-1})

01 – EPS/PMAp: Operational Synergistic Aerosol product

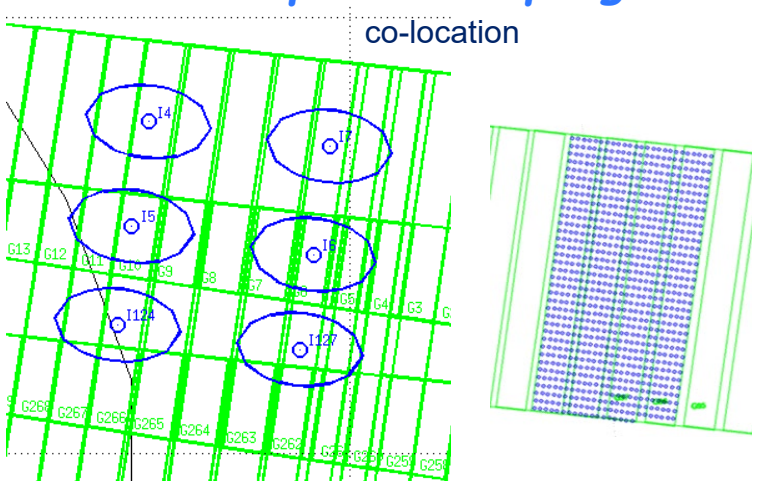
PMAp: Polar Multi-sensor Aerosol product from GOME-2, AVHRR and IASI

- EPS : Polar orbit at 09:30 ECT – A/2006, B/2012, C/2018
- 3 redundant platform/instrument → 25 y. of operation
- GOME-2, AVHRR, IASI

Combined Spectral information



Spatial sampling



- Product = AOD @550nm + aerosol type classification
- Fully operational product since Oct'14 (over ocean)
- Version 2 since Feb'17 (ocean & land)
- Version 2.2.4 released May'21
- Version 2.2.5 released soon

detailed in Grzegorski et al., Remote Sensing, 2022

01 – EPS/PMAp: Algorithm based on synergy

PMAp Synergy retrieval algorithm design - Version 2.2

Cloud / Aerosol Discrimination

- Volcanic Ash Detection
  10 set of thresholds tests **AVHRR + IASI** BTDs tests → Ash presence

- Desert Dust Detection
  IASI dust index → Desert dust presence

- Clouds' Detection & Correction
  clouds detection and cloud fraction calculation (CF)
  cloud free PMD Reflectance .OR. PMD Reflectance Correction (for CF < 0.65; partly cloudy pixels)

- Preliminary Aerosol Type
  if Ash presence → aerosol type = ash
  if Dust presence → aerosol type = dust
  VIS/NIR test for Coarse/Fine mode determination
  } list of preselected aerosol types

Instruments	Purpose
GOME-2 PMD	AOD, Aerosol Type, Absorption, Polarisation
AVHRR	Clouds, Scene heterogeneity, Dust/ash detection
IASI	Volcanic ash detection, Desert dust detection, Aerosol height

Retrieve AODs

- AODs retrieval from **GOME2** for all possible aerosol models in the LUT
  over water PMD 12 (640 nm)
  over land PMD 7 (414 nm) or PMD 8 (463 nm)

best fit selection – model then AOD

- Microphysics fit : $\chi 2$ minimization of AODs and Models
  based on Reflectance and Q fraction for bands in 414 to 799nm
  if cloud free: list of preselected aerosol types
  if partly cloud: all aerosol models
  } → best {AOD, aerosol type}
- Estimation of error on AOD

→ Q/I fraction in 8 bands (414-799nm)

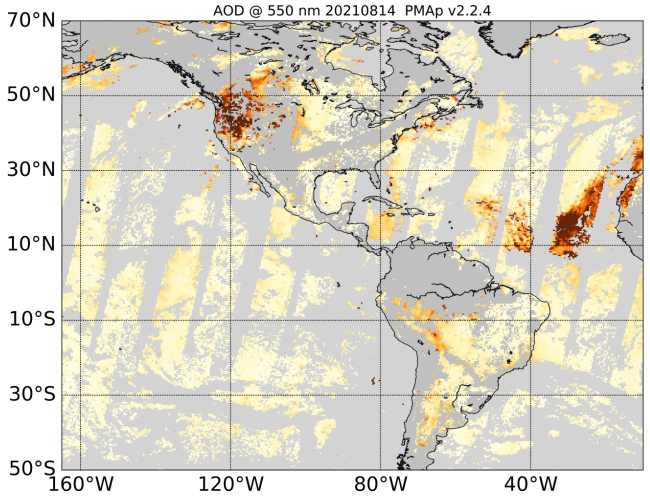
detailed in Grzegorski et al., Remote Sensing, 2022

01 – EPS/PMAp: Consistency with other products

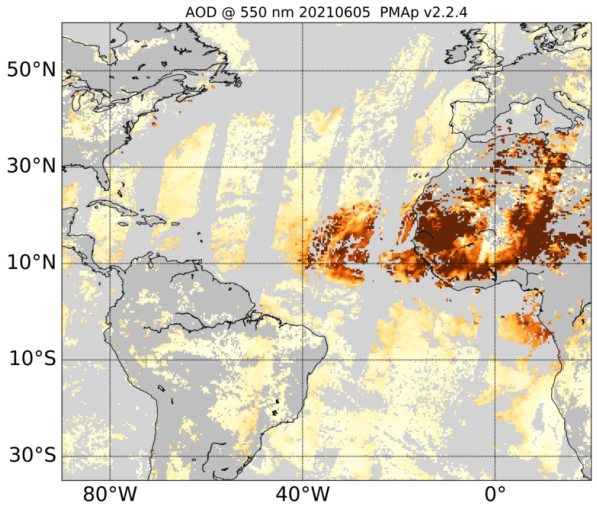
PMAp version 2.2
Metop (A+B+C)

PMAp AOD compared to MODIS/Terra and Sentinel-3

August 2021



June 2021



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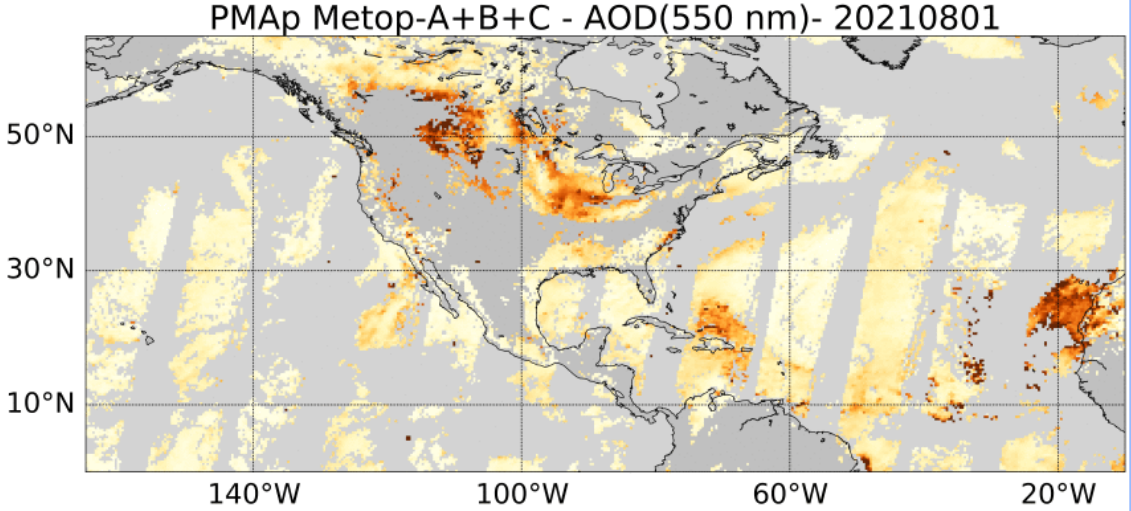
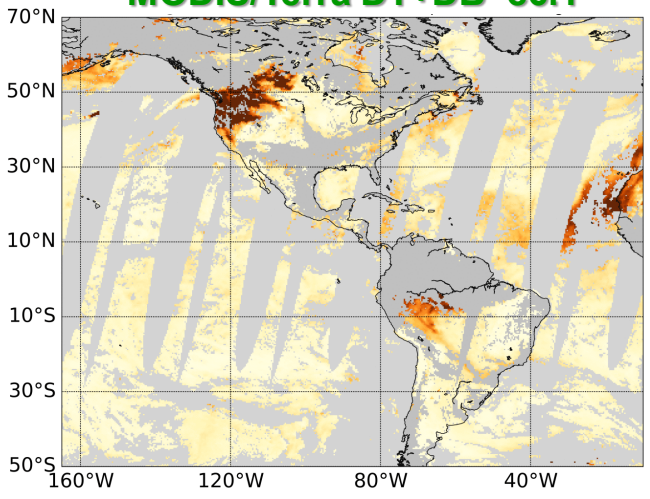


MODIS/Terra DT+DB c6.1



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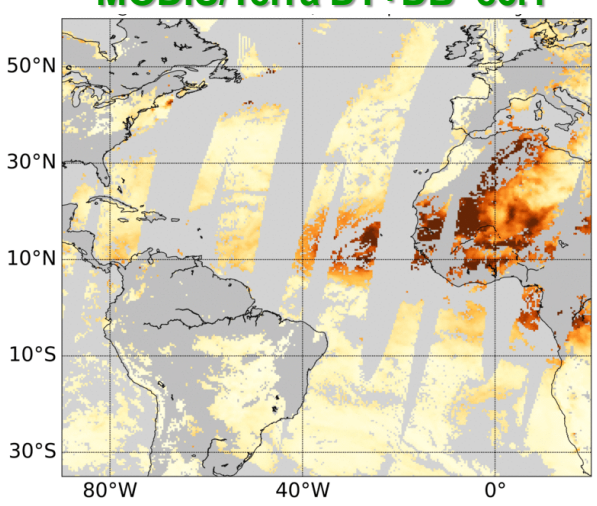
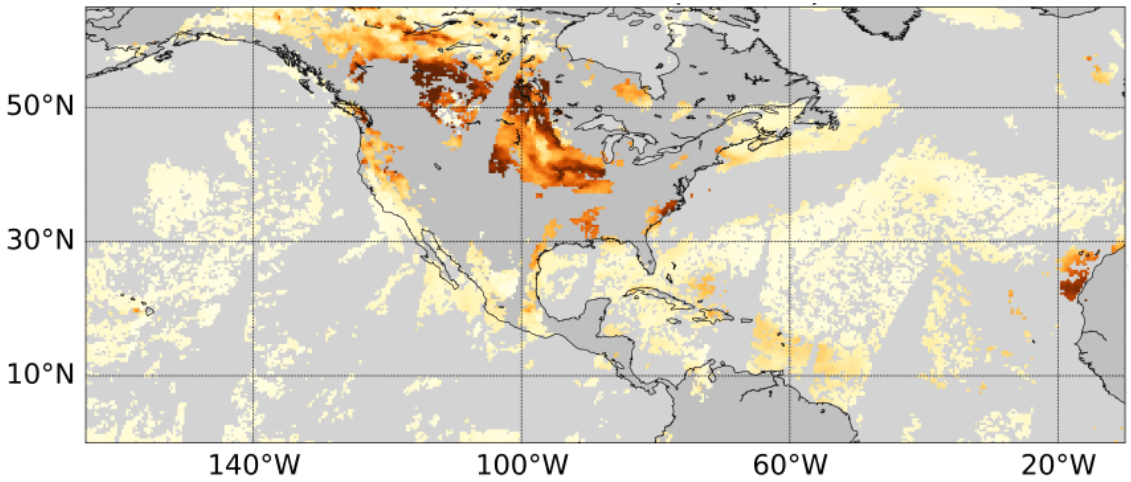


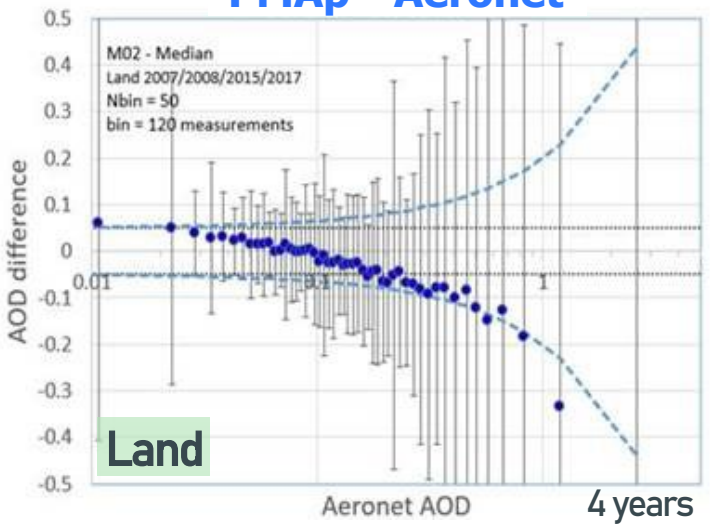
SLSTR/Sentinel-3 A+B OSSAR-CS3



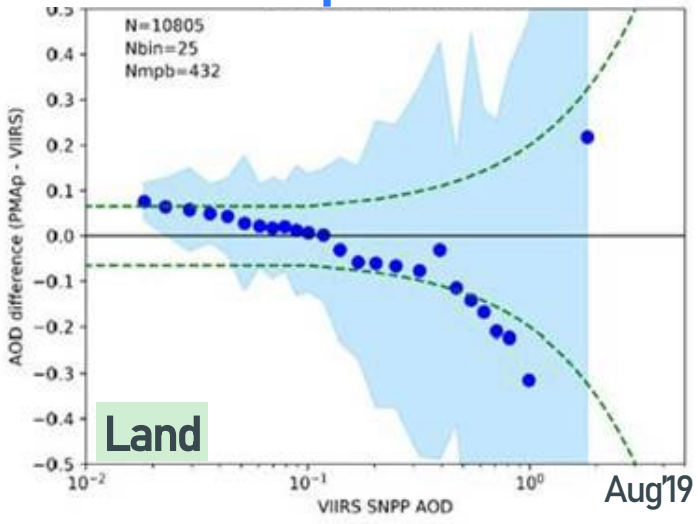
01 – EPS/PMAp: Validation and Performance

- Performance compared to Aeronet, VIIRS and MODIS
  - "weighted bins" analysis

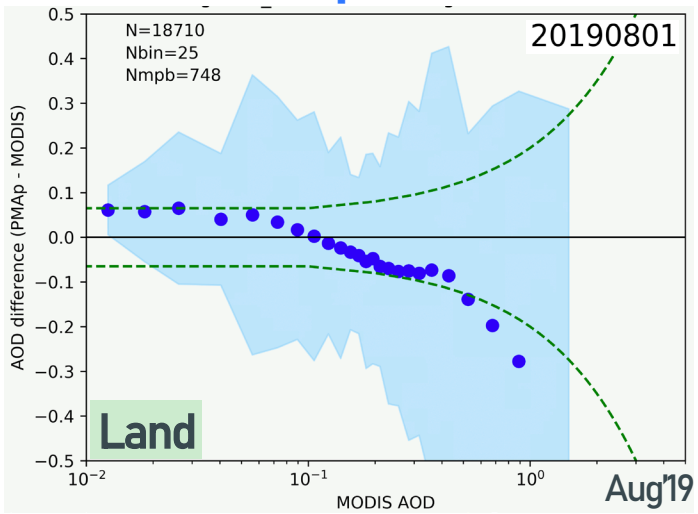
PMAp - Aeronet



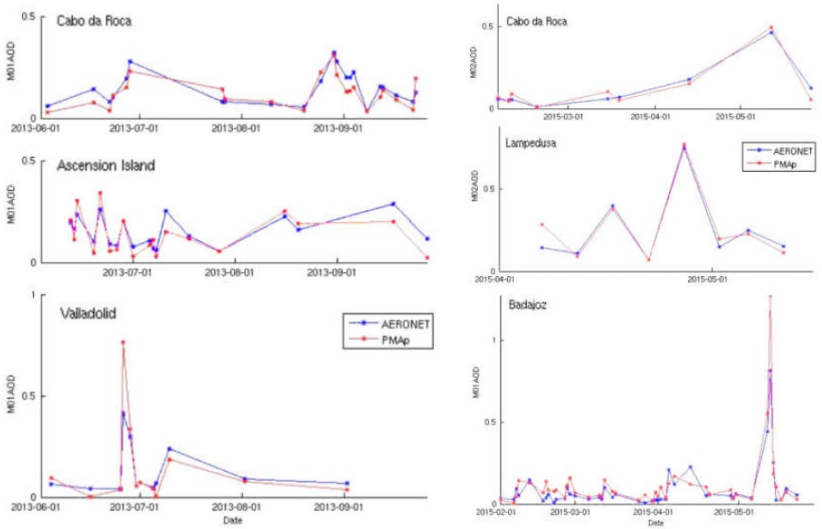
PMAp - VIIRS

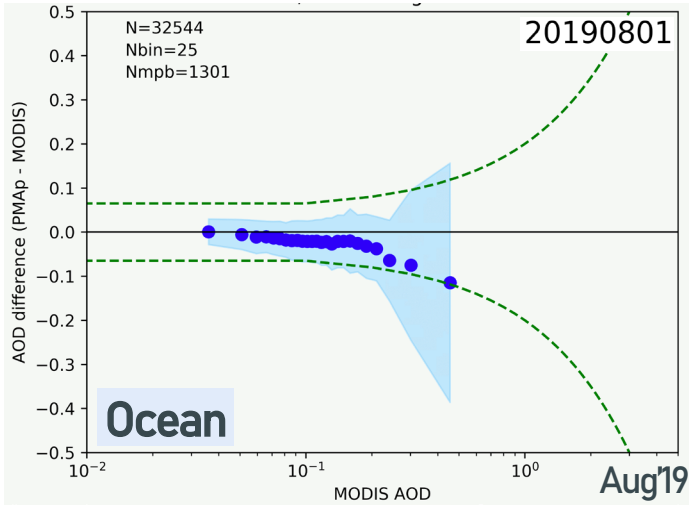


PMAp - MODIS



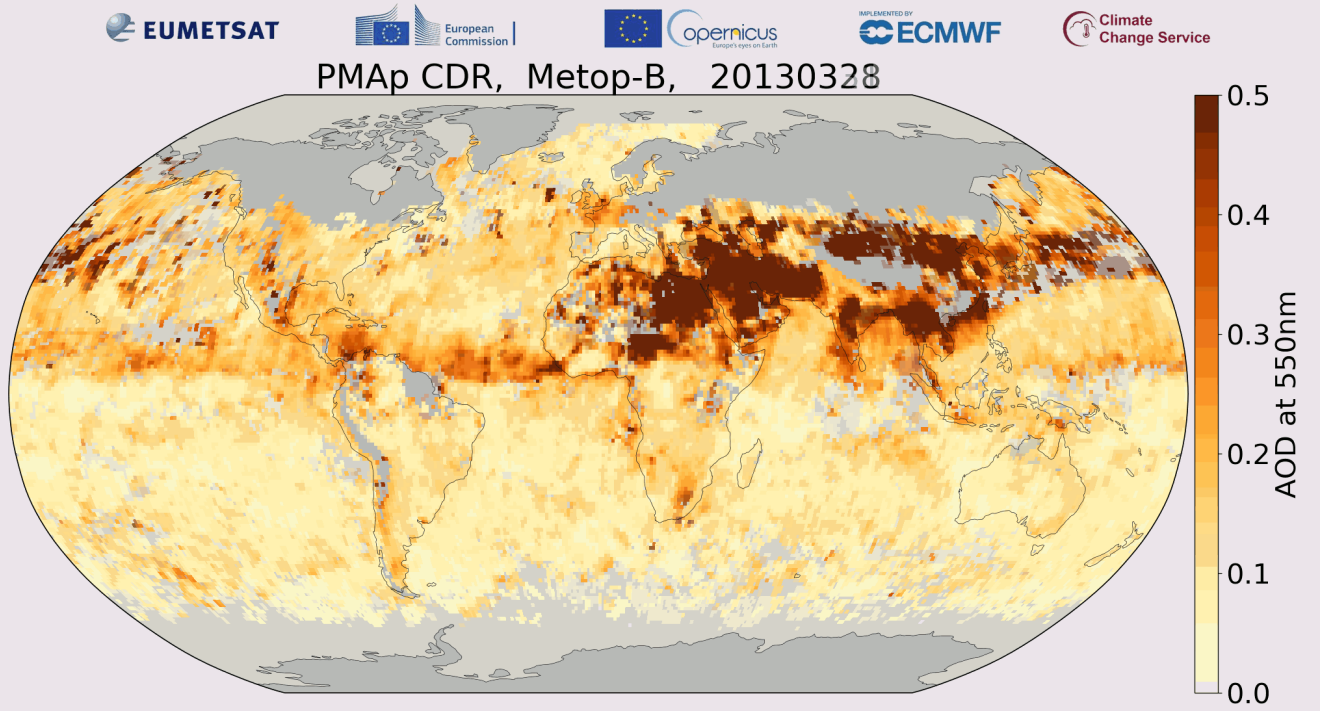
Comparative time-series with Aeronet





01 – EPS/PMAp: Climate Data Record

- Context of the Copernicus Climate Change Service (C3S)
- Strategy = use the up-to-date version of PMAp to reprocess a consistent archive
  - PMAp Version 2.2
  - Create a well-calibrated, homogeneous, consistent, long-term AOD dataset
  - Also instrumental to support a more extensive validation of the PMAp product



Jafariserajehlou and Fougnie, 2021

Satellite	Coverage	Reprocessing period
Metop-A	global	01/07/2007 – 29/01/2018
Metop-B	global	20/02/2013 – 31/08/2019

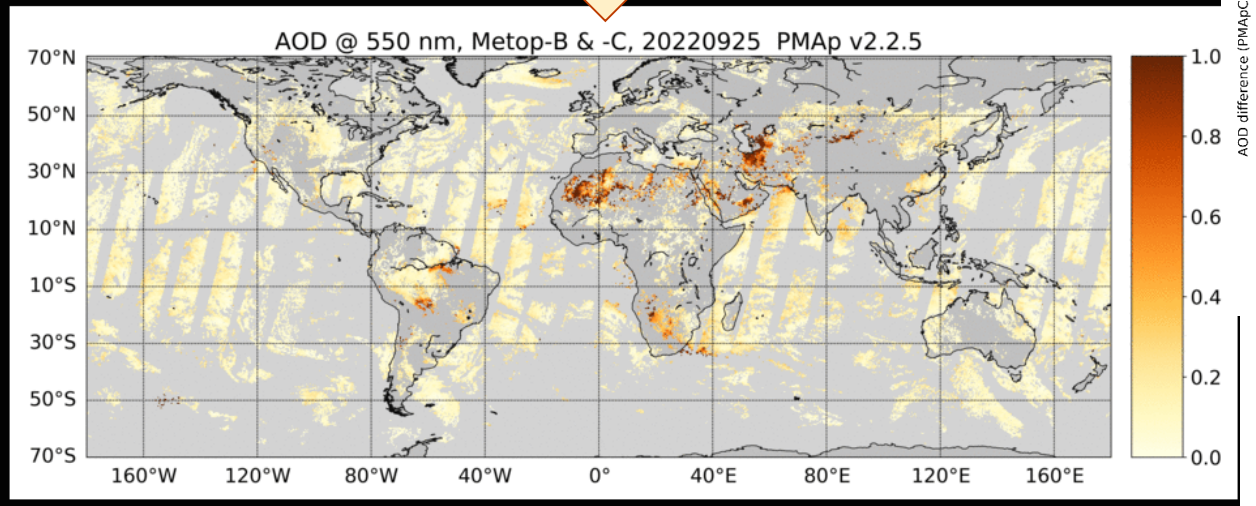
→ Can be used for extensive reanalysis

01 – EPS/PMAp: Last revision

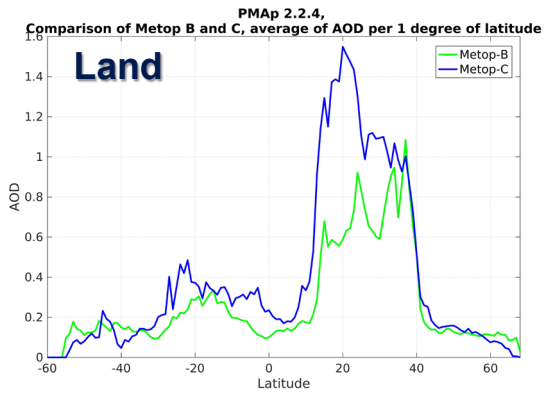
t.int

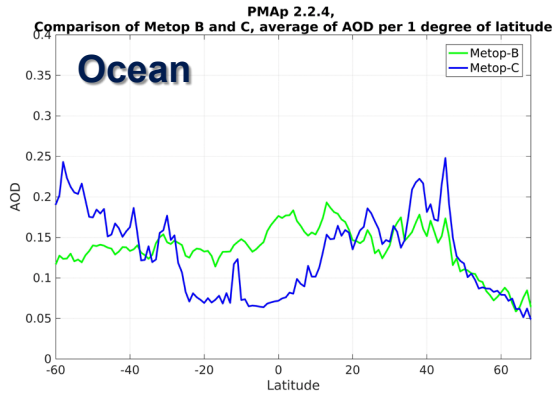
To address the known limitations of PMAp 2.2.4:

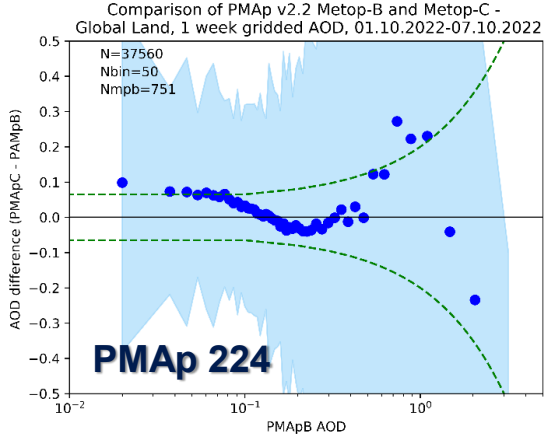
1) Update of degradation correction to account for the aging of GOME-2 sensor;
1) Calculation of Radiometric adjustment for Metop-C;
2) Update of the radiometric adjustment for Metop-B;
3) Use of Mode-LER instead of Min-LER (ongoing analysis).

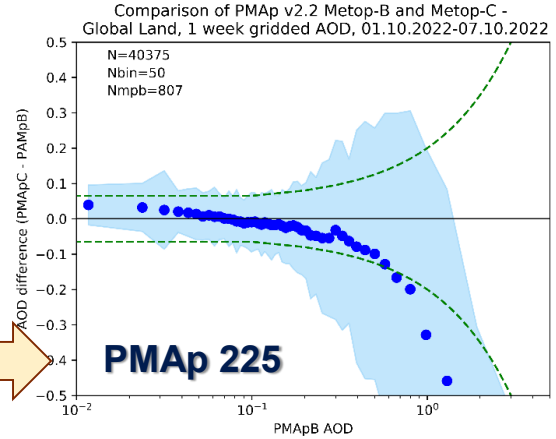


- Increasing the consistency between PMAp-B & -C
- Overall performance of PMAp-C improved.

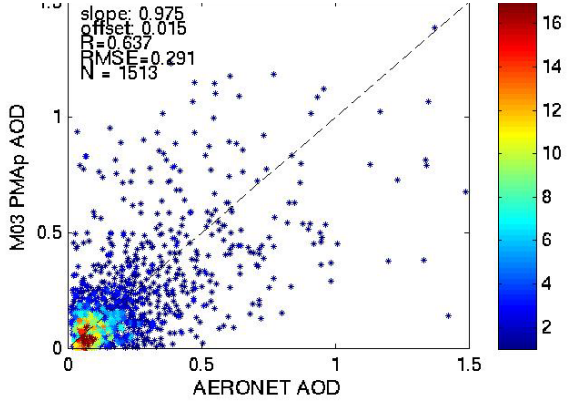


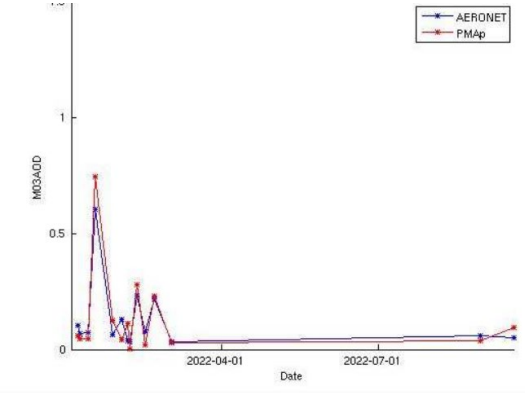






Validation vs AERONET





01 – EPS/PMAp: Polar Multi-sensor Aerosol Product

- PMAp v2.2:
  - operational since 6th May 2021: (https://www.eumetsat.int/new-version-metop-pmap-product-released-soon)
  - significant improvements compared to the previous operational version in terms of aerosol loading, spatial and temporal distribution, especially over land.
  - known limitations of PMAp 2.2.4 being addressed in PMAp 2.2.5.
  - High consistency between the two Metops (-B & -C) is achieved in PMAp 2.2.5

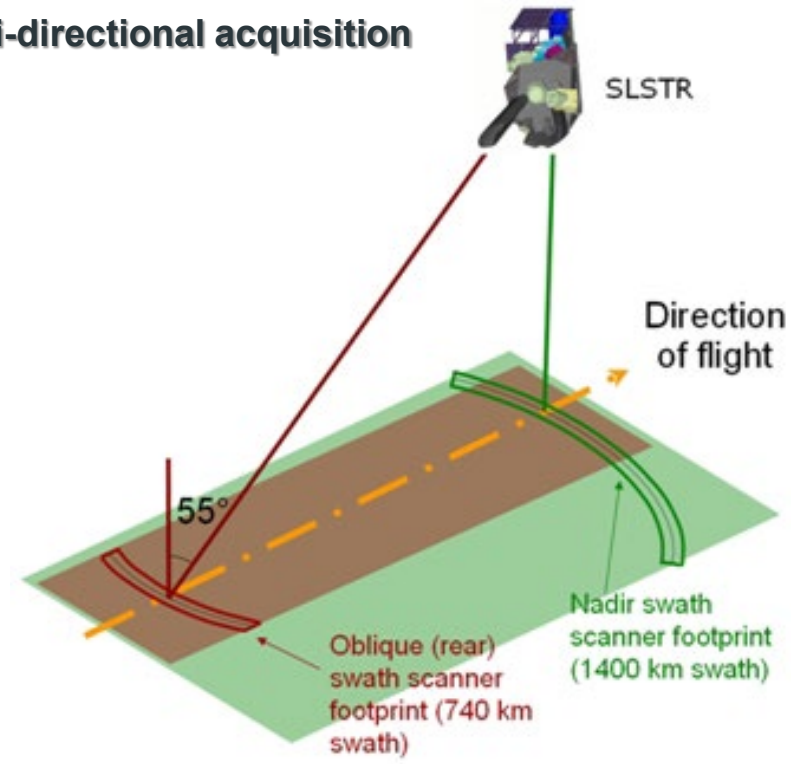
  - Now published in Grzegorski et al., Multi-sensor Retrieval of Aerosol Optical Properties for Near-Real-Time Applications Using the Metop Series of Satellites: Concept, Detailed Description and First Validation, *Remote Sensing*, 2022

  - Unless request from users to improve PMAp (test over Land needed), the development will mostly be done on the follow-on synergistic product EPS-SG/MAP

02 – OSSAR-CS3 from Sentinel-3/SLSTR

- **OSSAR-CS3 = Optimised Simultaneous Surface Aerosol Retrieval from Copernicus Sentinel-3**
- First operational aerosol product from Sentinel-3
  - ➔ SLSTR instrument: spectral combined with dual-view
    - Nadir view with spectral VIS to SWIR
    - A second oblique view (rear) with the same spectral bands

Bi-directional acquisition



Spectral acquisition

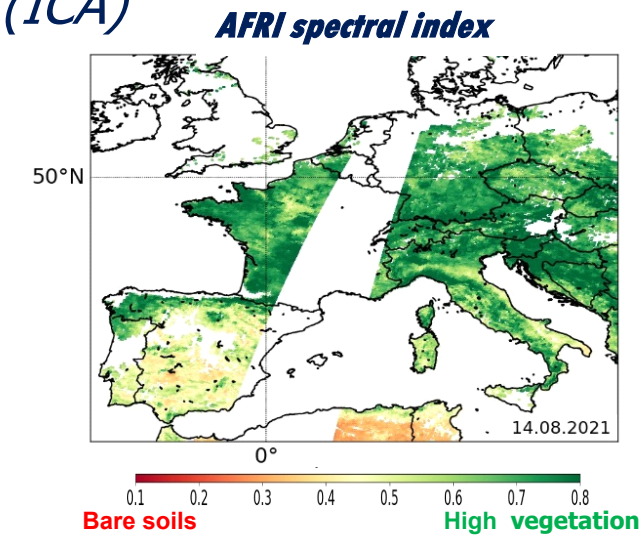
Sensor	Channel	CWL (µm)
SLSTR	S-1	0.555
SLSTR	S-2	0.659
SLSTR	S-3	0.868
SLSTR	S-4	1.375
SLSTR	S-5	1.613
SLSTR	S-6	2.250
SLSTR	S-7	3.742
SLSTR	S-8	10.854
SLSTR	S-9	12.022

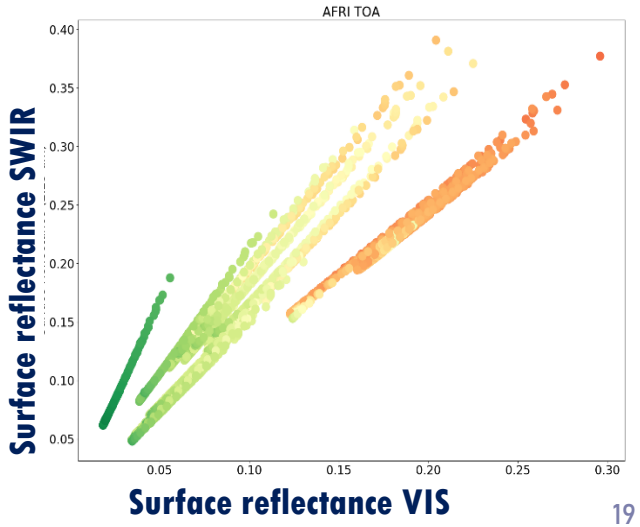
O2 – OSSAR-CS3 from Sentinel-3/SLSTR

Joint surface & aerosol retrieval weighted by the actual Information Content (ICA)

- **Level-1 radiance correction** (e.g. vicarious calibration, drift, inter-band, dual-view)
- **Internal cloud & aerosol mask** (Land since coll. 2, ocean since coll. 3)
- **Ocean:**
  - Dual-view retrieval
  - Ocean surface pre-computed (not retrieved)
    - Wind speed from forecast (ECMWF), whitecaps (Koepke et al.), ocean colour with Chl=0.1 mg/m3
- **Land:**
  - Dynamic ICA per L2 pixel = f(dual scattering angle, land cover type)
  - Land surface reflectance 1st guess: spectral model built upon AFRI vegetation index & Red-SWIR spectral matching
  - Weighted joint aerosol-land surface: high weight for unfavourable dual-view geometry & vegetation
- **Aerosol types:** 35 mixtures interpolated between dust, sea salt, weakly & strongly absorbing (Kinne et al., 2006)
- **Log(AOD) retrieved**
- **A posteriori diagnostic Quality Indicators:** AOD spatial uniformity, spectral residuals (sediments, melted ice, missed polar stratospheric clouds), bright deserts

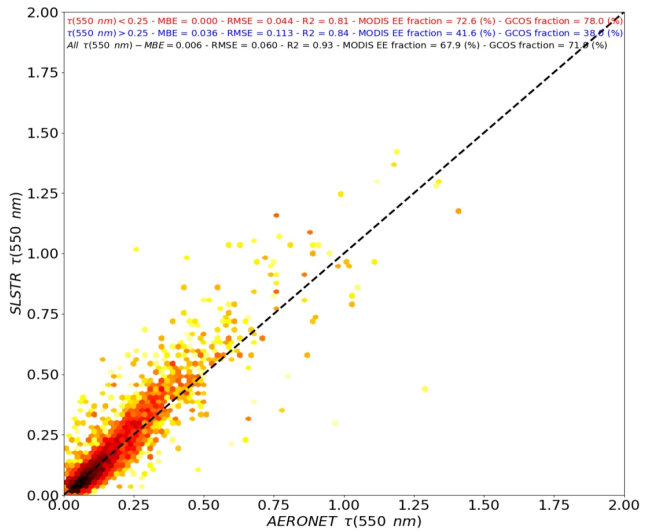
- **History of a recent development**
  - Version 1.0 – not released: Initial version from ESA/University Swansea
  - Version 2.0 – EUMETSAT development disseminated since August 2020
  - Version 3.0 – dissemination since October 2021



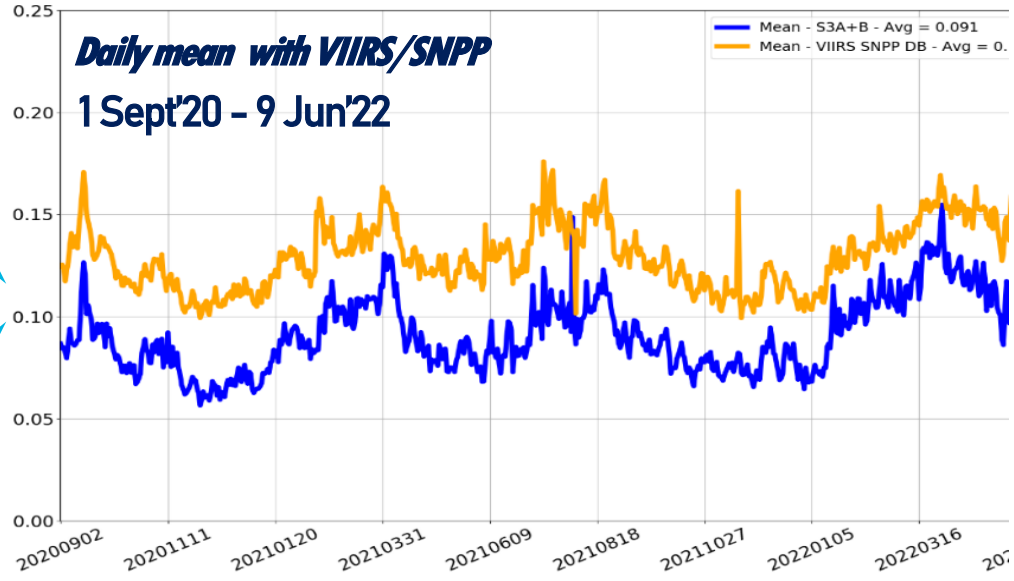


02 – OSSAR-CS3: validation

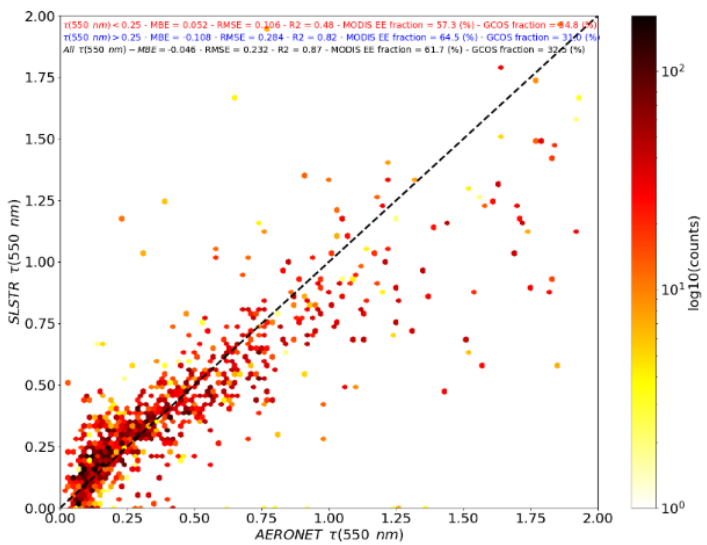
Ocean



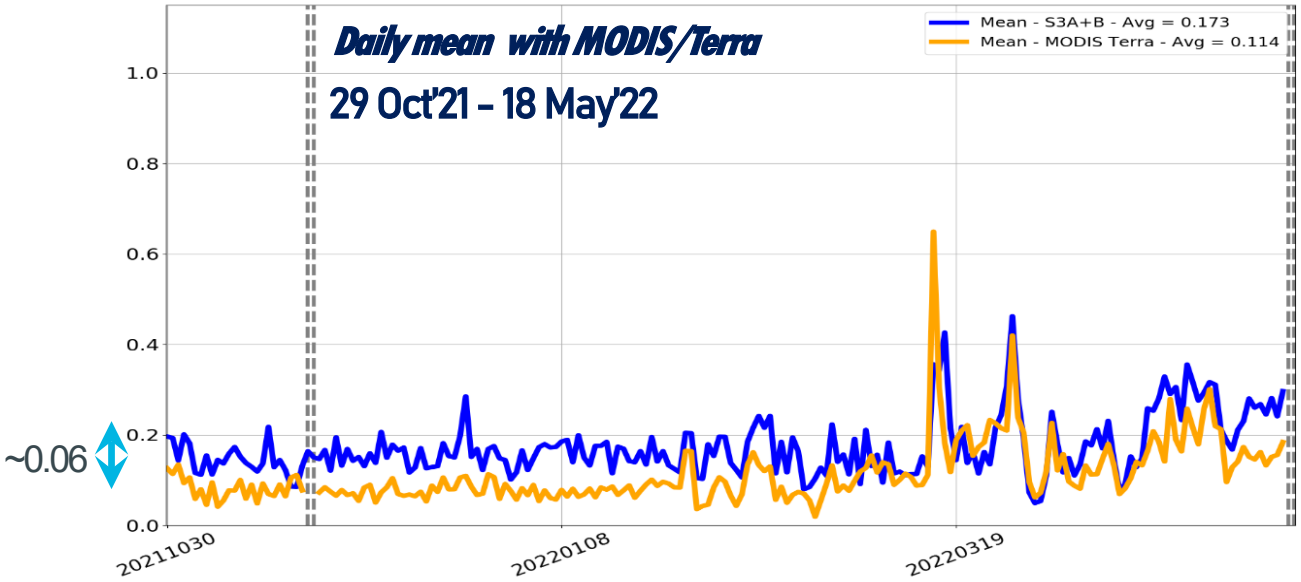
OSSAR-CS3 vs. AERONET



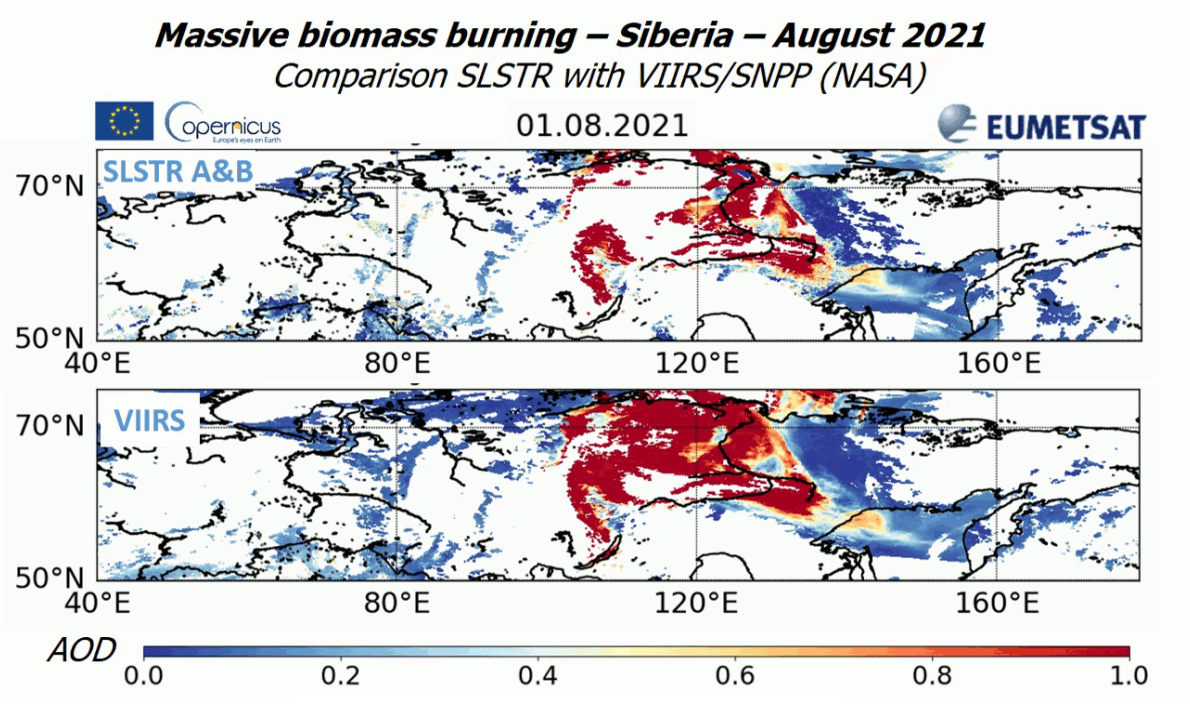
Land

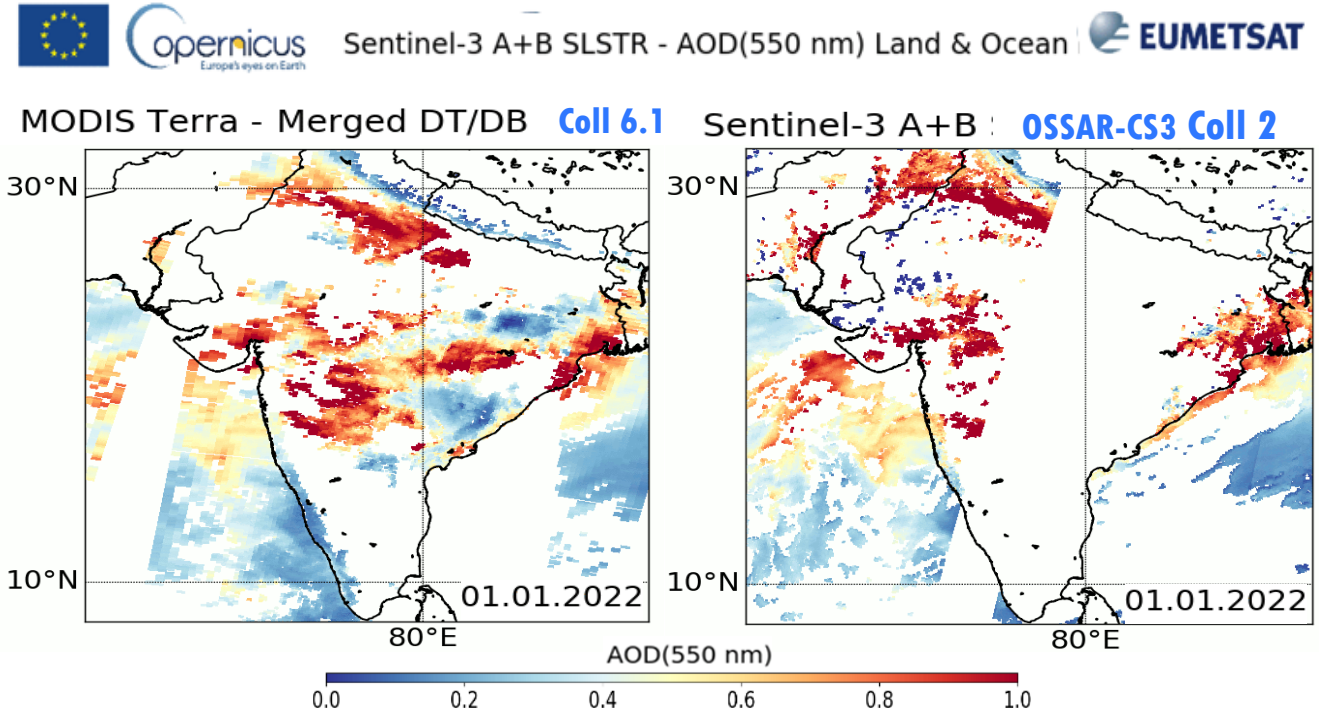


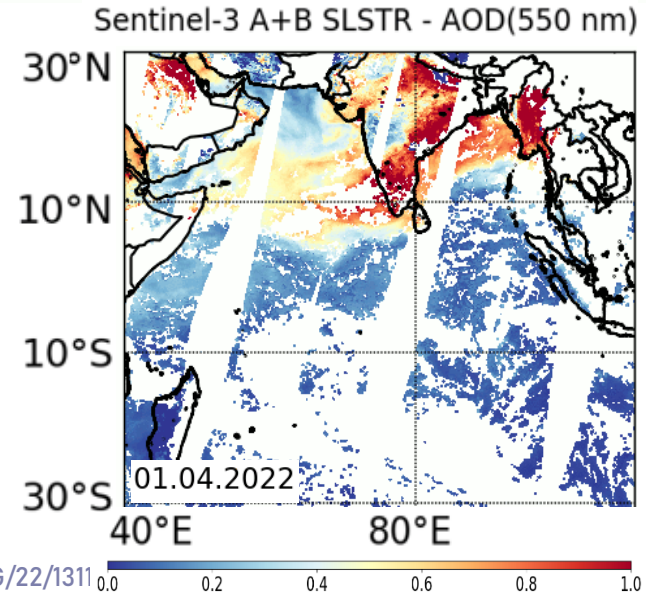
OSSAR-CS3 vs. AERONET (North America)

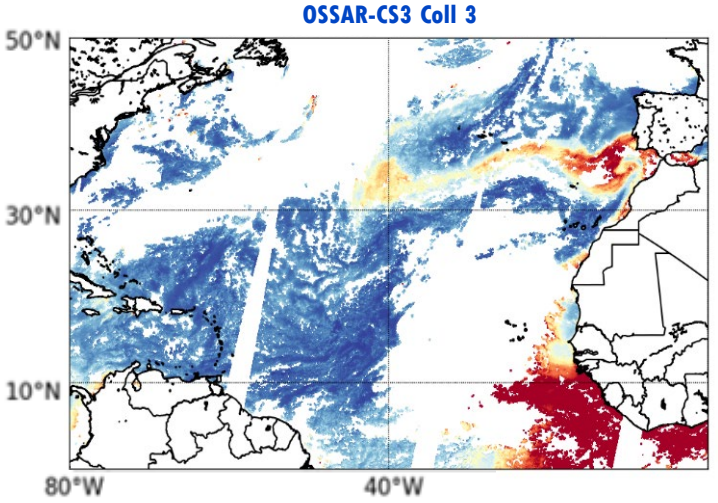


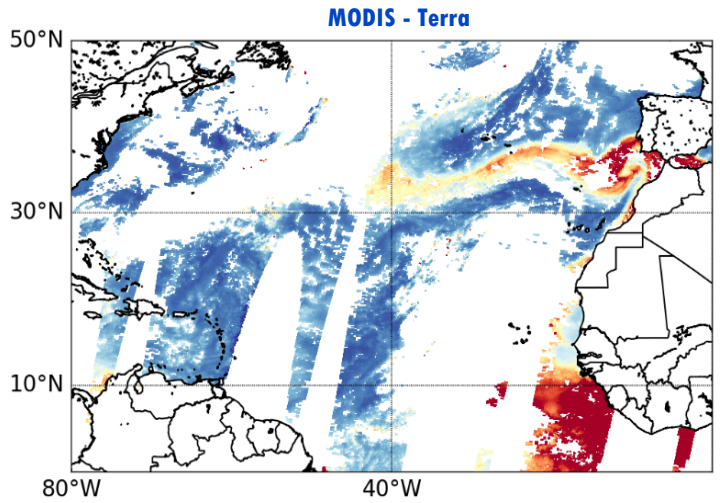
02 – OSSAR-CS3: comparison with other products





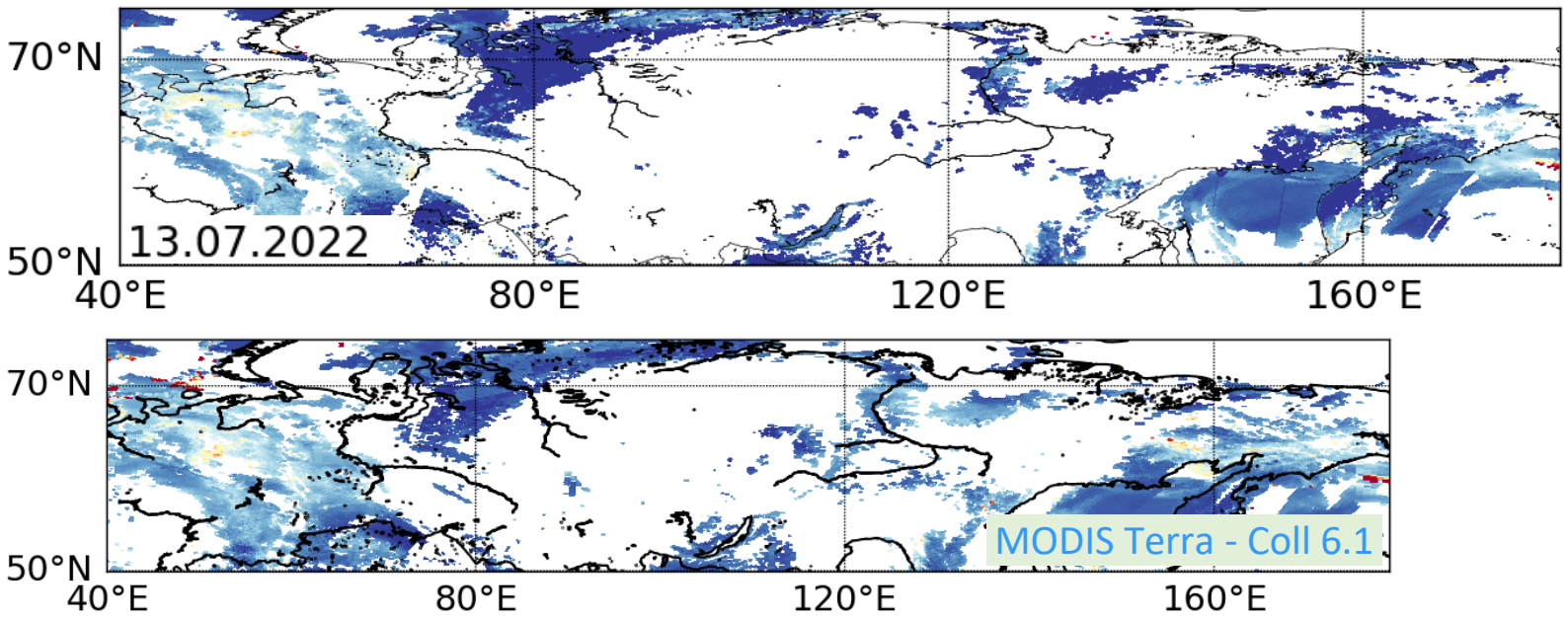


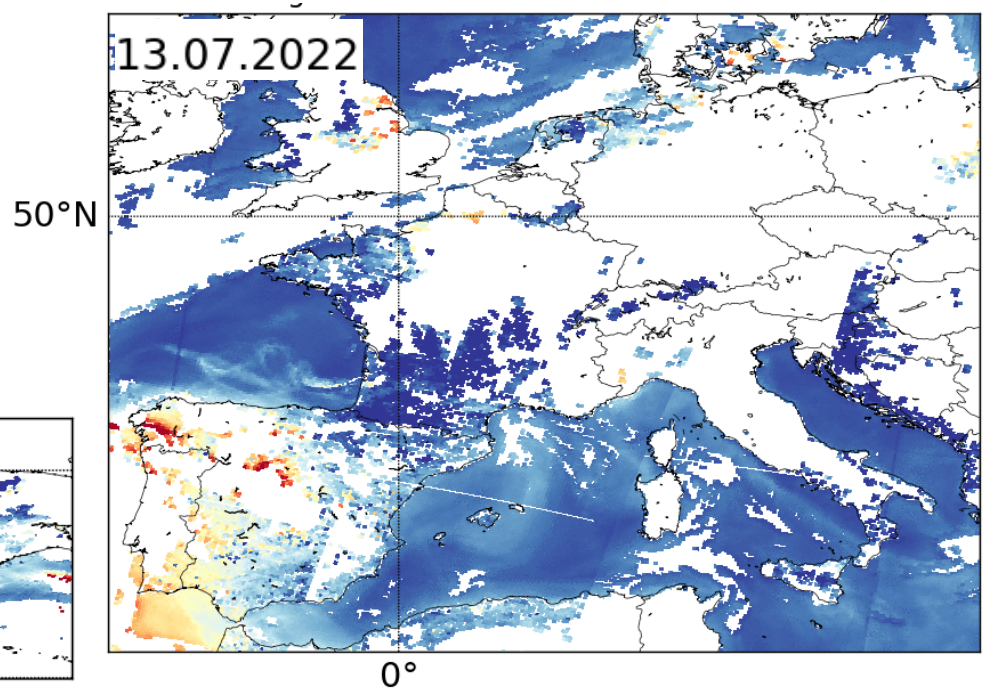


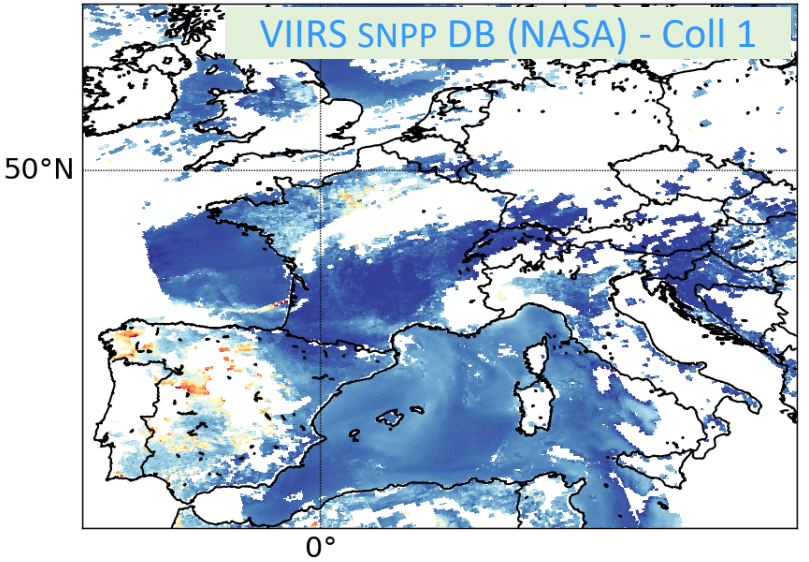


02 – OSSAR-CS3: comparison with other products

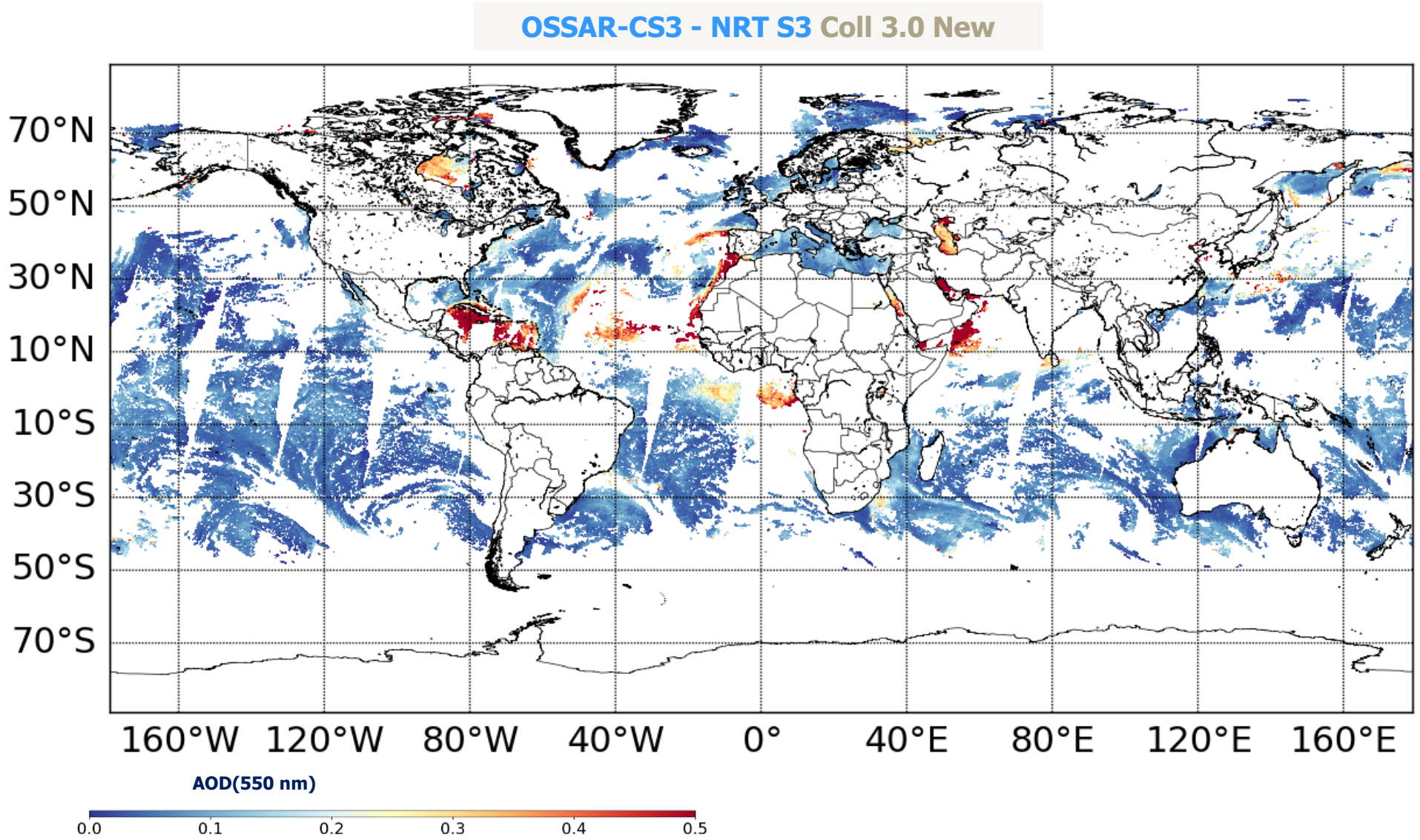
OSSAR-CS3 - NRT S3
Coll 3.0 New

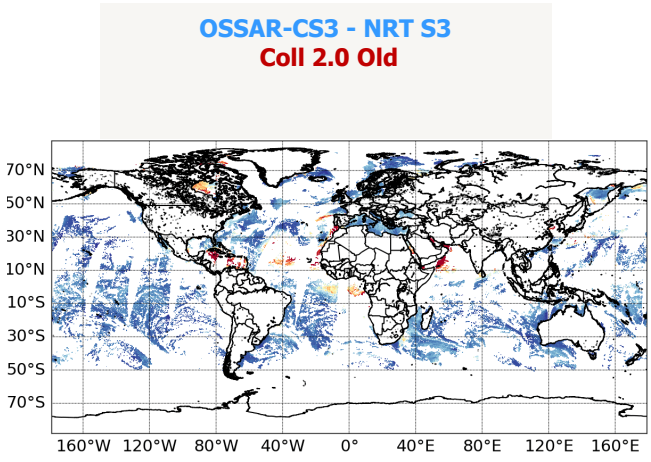






02 – OSSAR-CS3 improvement over oceans & waters



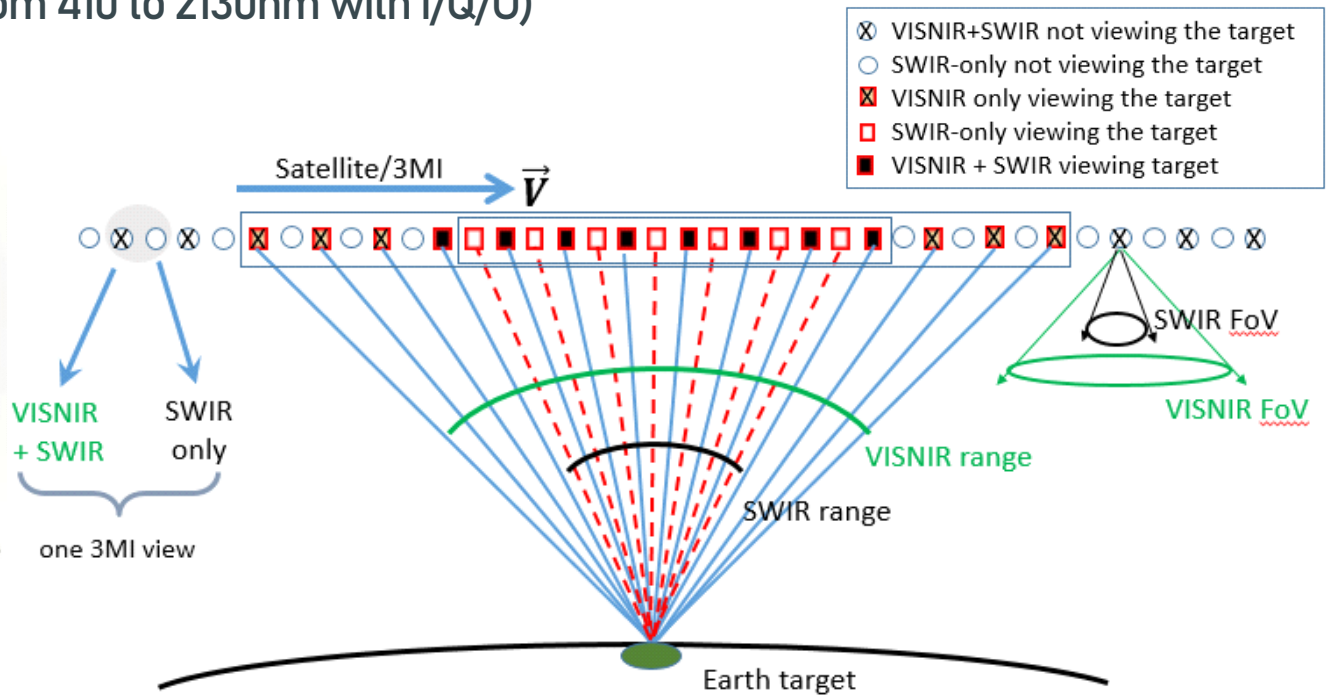


Under Development Aerosol Processors

P1 - EPS-SG/3MI in a nutshell

- Multi-angle polarimeter
- The instrument relies on a very simple concept
  - 2 wide field-of-view optics (VISNIR + SWIR)
  - 2D detectors at focal planes (CCD for VISNIR, and CMOS for SWIR)
  - 1 filter wheel inc. polarizer (12 bands from 410 to 2130nm with I/Q/U)

→ 14 views, I/Q/U in 9 bands (410/2200nm)

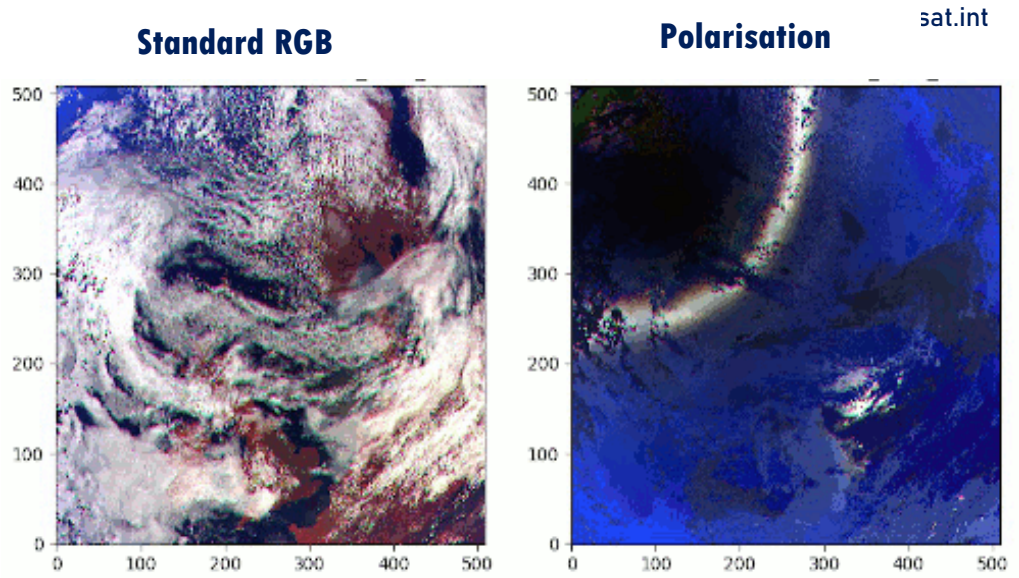


➔ See APOLO talk by Thierry Marbach

detailed in Fougnie et al., JQSRT, 2018

P1- EPS-SG/3MI: polarimetry

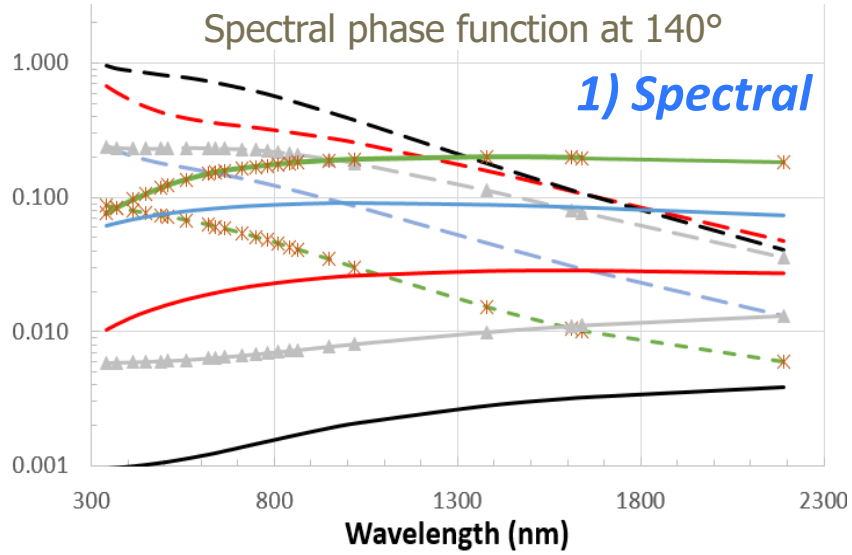
- Large information content:
  - 14 views : from -50° backward to 50° forward
  - 12 spectral bands: from 410 to 2130nm
  - 3 polarisations providing I, Q, and U (exc. absorption bands)
  - → Potentially 420 information per pixel to feed the retrieval

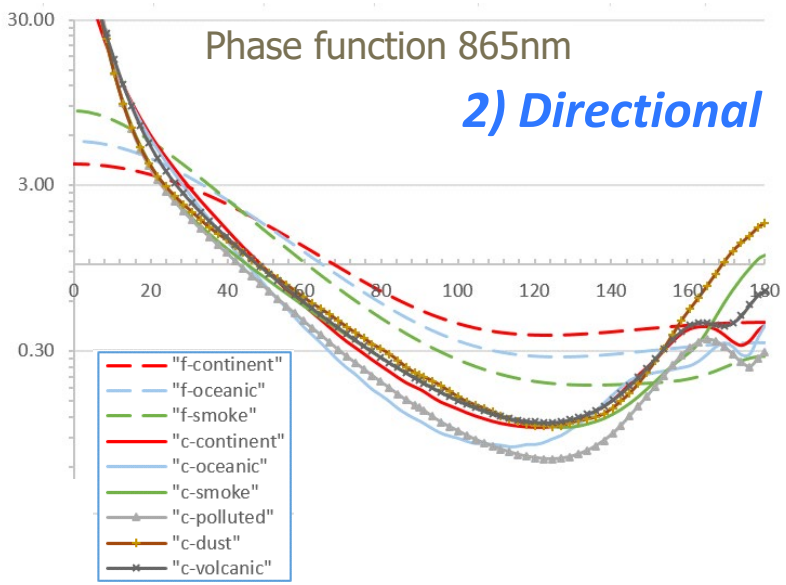


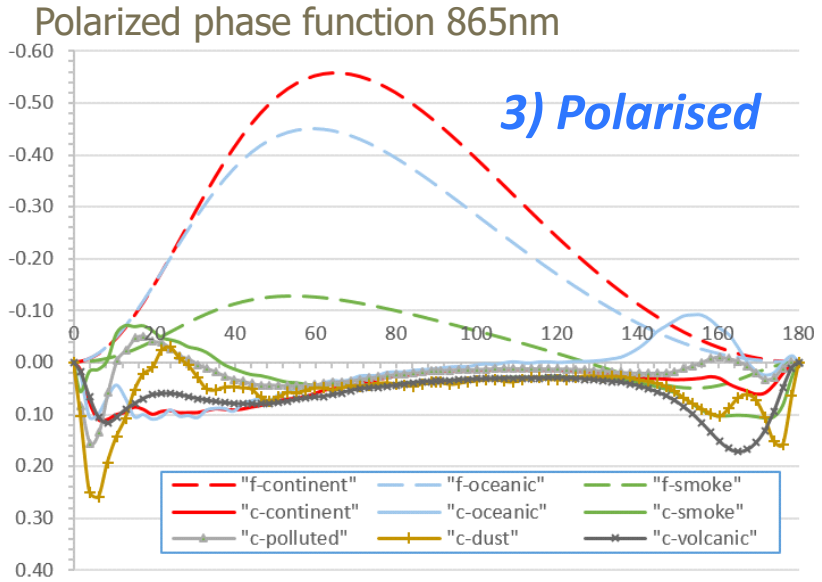
- The aerosol retrieval is based on an optimal simultaneous retrieval of the surface and aerosol
  - **GRASP** was adopted as the best solver for this specific information content
  - To be configured to an Operational processor (product available 1:30 after sensing)
  - The simultaneous retrieval will be adjusted to optimise the performance of the aerosol retrieval
  - Multi-view polarimetry potentially allows distinction of fine & coarse particles + characterization of their properties:
    - aerosol optical thickness, angstrom coefficient, fine/coarse fraction, single scattering albedo, absorbing aerosol optical thickness, refractive indexes, sphericity fraction, aerosol height…

P1 – EPS-SG/3MI: polarimetry

The ability to measure a part of the phase function

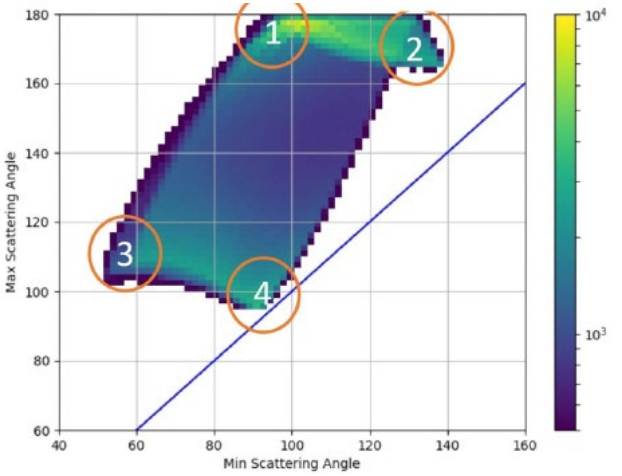






- **Aerosol model (type f/c, microphysics, size distribution, shape, absorption…)**
- **Aerosol load (optical thickness)**
- But it is unrealistic to retrieve all of them and everywhere
  - Geometry of acquisition and/or the surface type strongly influence the performance of the retrieval
  - Wrt our user needs, the retrieval will be optimised to derive properly for AOD and Aerosol model
  - Other parameters will be retrieved when/if possible

Scattering Angle Range Distribution for 3MI



detailed in Fougnie et al., JQSRT, 2020

P2 – EPS-SG Multi-sensor Aerosol Product MAP

Next generation of synergy aerosol product from EPS-SG: MAP *(follow-on EPS/PMAp)*

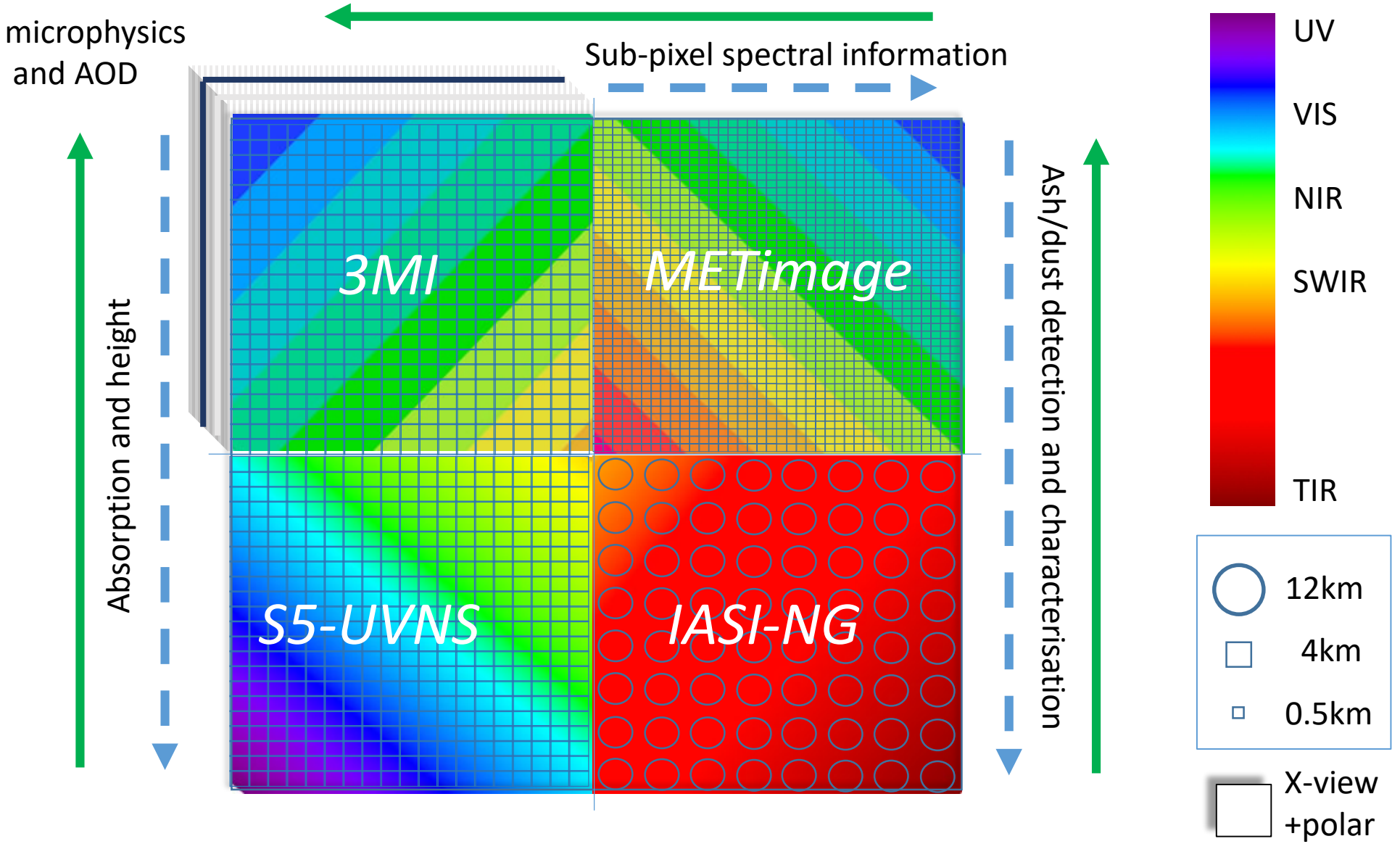
- Retrieval of aerosol properties using a hyper-instrument synergy of instruments on-board the platform
  - 3MI - Multi-View, Polarisation, -Spectral Imager;
  - UVNS - UV/Near- and Shortwave Infrared Sentinel-5 spectrometer (Sentinel 5);
  - METimage - Visible Infrared Imager (VII);
  - IASI-NG - Infrared Atmospheric Sounding Interferometer.

Sensor	Spatial resolution	Swath	Spectral type	Spectral bands	Spectral range	Additional capabilities
3MI	4x4 km²	2200 x 2200 km²	VIS/NIR/SWIR	12 bands	410 to 2130nm	14 views Polarisation (I/Q/U)
METimage	0.5x0.5 km²	2670 km	VIS/NIR/SWIR TIR	11 bands 9 bands	443 to 2250nm 3.3 to 13.3µm	
S5-UVN	7.5x7.5 km² 50x50 km² (<300nm)	2670 km	UV/VIS/NIR/SWIR	1669 bands (0.25nm in SWIR to 1nm in UV)	270-300nm 300-370-500nm 685-710nm 755-773nm 1590-1675nm 2305-2385nm	
IASI-NG	12km spot	2000 km	TIR	16921 bands (0.25cm-1)	645 to 2760cm-1	

Instrument	Main use
3MI	Retrieval of aerosol properties (> 10 parameters)
VII	Cloud, scene homogeneity, volcanic ash, thick dust
S5	Retrieval of aerosol properties, Clouds, scene homogeneity
IASI-NG	Volcanic ash, desert dust, aerosol height

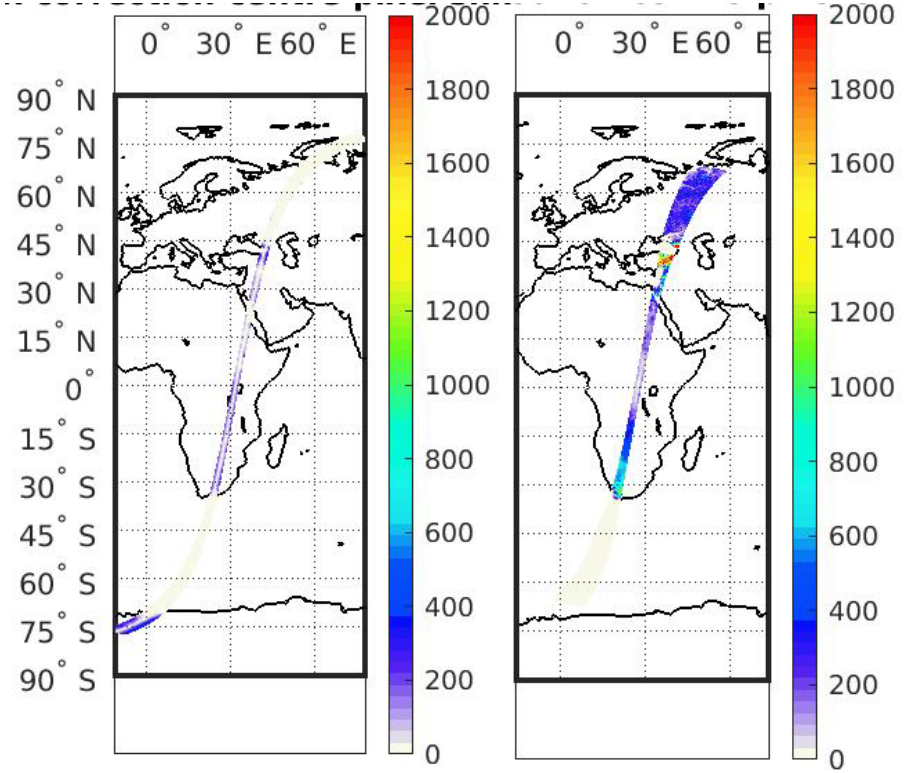
- Baseline for the design of MAP version 1:
  - PMAP synergy adapted to EPS-SG: colocation, cloud masking, pre-classification, ash/dust detection…
  - AOD and model retrieval from 3MI/GRASP
- Extension to other parameters: improve ash & dust, aerosol height, SSA, PM25…
- Revisions could consider feeding GRASP directly with some inputs from UVNS/Metimage/IASI-NG – to be developed

P2 – The Aerosol Observatory from EPS-SG sensors



P3 – CO2M project

- MAP Multi-Angle Polarimeter in VIS-NIR → 45 views, I/Q/U in 7 bands (410-865nm)
- Aerosol correction is needed to reach the performance for CO2 & CH4
- Optimisation for atmospheric correction
- Challenge: aerosol contribution is needed in SWIR
- Similarly as for 3MI, GRASP to be optimised for MAP
- Influence of the geometry
- Synergy with CLIM and CO2IS



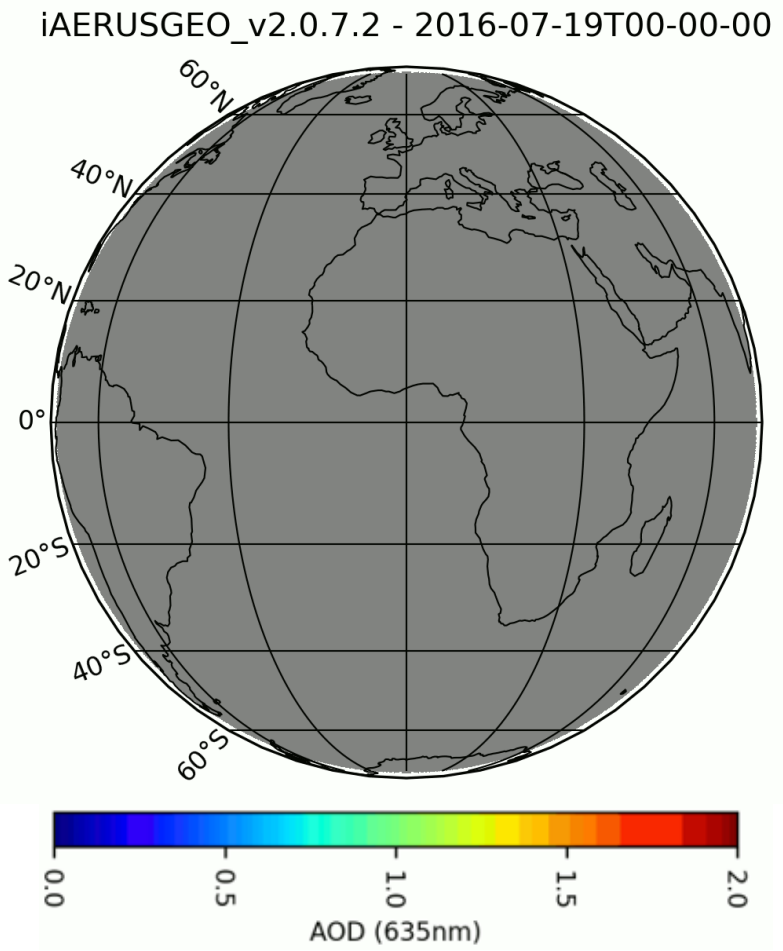
P4 – S3/SYN and S3-NG

- S3/SYN with SLSTR and OLCI
  - Current OSSAR-CS3 based on SLSTR to be “extended” with new information content from the imager OLCI (21 bands between 410 and 1020nm)
  - At least:
    - “Blue” part of the spectrum to improve AOD retrieval over surface
    - “O2 bands” to support the assessment of Aerosol Layer Height
  - Should rely on an optimised L1C/SYN product

- S3-NG
  - Currently under definition
  - Feedback from S3 + additional user needs are being considered for the MRD
  - The development will initiated accordingly

P5 – On-going development with GEO (MTG)

- GEO – for a given lat/lon:
  - Very high number of observation per day
  - fix viewing geometry, but wide range of solar geometry
- i-AERUS based on MSG/SEVIRI observations
  - Previous EUMETSAT study, continued by Meteo-France
  - Improvements on aerosol model (7 models), surface contribution, uncertainty estimation (Jacobian)…
  - Operated in ICARE
- Demonstrate the potential for i-AERUS with MTG/FCI
  - More spectral bands → better assessment of the aerosol model
  - Tests on FCI (MTG launch end'22) and/or ABI-AHI
  - Test for assimilation – Framework with Météo-France
- Exploratory:
  - Synergy with UVN/S4 and IRS would serve AQ/PM25
  - GEO-ring : Explore the possibility i-AERUS applied to FCI/AHI/ABI – demonstrational in ICARE



Strategy wrt Users & Assimilation Needs

- On-going developments in current (01, 02) and future (P1, P2, P3, P4, P5) processors
  - Workflow of improvements and developments (inc. harmonisation, consistency…)
- Can be & Need to be tailored to user needs
- Prepare assimilation
  - Feedback for the definition of products (relevant parameters, associated performance)
  - Optimisation of the development driven by priorities expressed by users
- New parameters having impact on the radiative processes for NWP & AQ
  - AOD “dust”
  - Aerosol Models as defined in Assimilation Models
  - Alternatives with Particle Size Distribution or fine mode fraction
  - Aerosol Layer Height
  - Ash/dust characterisation
  - Single Scattering Albedo
  - PM25
- New type of data
  - High-temporal revisit with geostationary data (providing less parameters)
  - Additional information from polarimetric measurements

Thank you for your contribution !

References

- Fougnie, B., T. Marbach, A. Lacan, R. Lang, P. Schlüssel, G. Poli, R. Munro, and A. B. Couto, "The Multi-Viewing Multi-Channel Multi-Polarisation Imager – Overview of the 3MI polarimetric mission for aerosol and cloud characterization," *J. Quant. Spectrosc. Rad. Transf.*, APOLO special issue, No. 219, pp. 23-32, 2018.
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