

Scientific Development for Operational Aerosol Products

Present and Future

Bertrand Fougnie

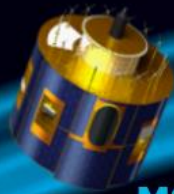
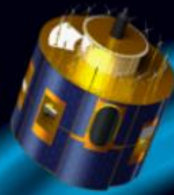
Margarita Vazquez-Navarro, Julien Chimot, Thierry Marbach
and the Cloud & Aerosol Team
Remote Sensing Product Division



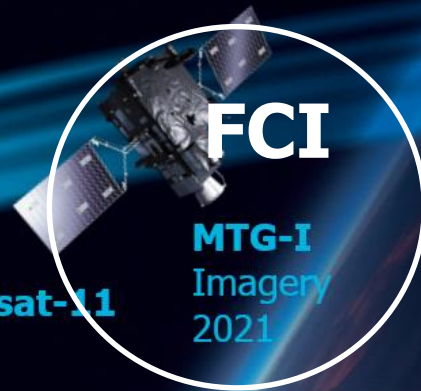
EUMETSAT missions: *current and future*

Geostationary Programmes

Meteosat-10
2013



MSG-4/Meteosat-11
In-orbit storage
2016



FCI

MTG-I
Imagery
2021



MTG-S
Sounding
2023

Mandatory Programmes



Meteosat-9
2006



Meteosat-8
2004

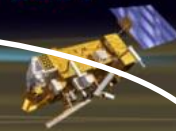
Polar Programmes



Metop-A
2007



Metop-B
2013



Metop-C
2019



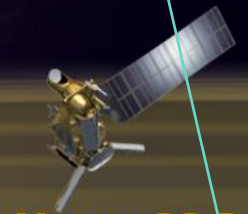
PMAp



MAP

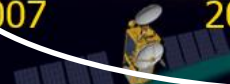
Metop-SG A
Sounding &
Imagery
2022

3MI

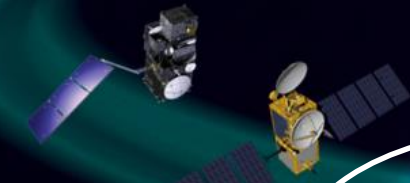


Metop-SG B
Microwave
Imagery
2023

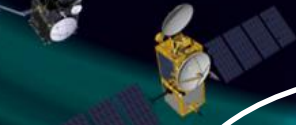
JASON-2
2009



Sentinel-3A
2016



JASON-3
2016



S3

Sentinel-3B
2018



**JASON-CS/
SENTINEL-6**
2021

Sentinel-5 on Metop-SG A
2022

Sentinel-4 on MTG-S
2022

Optional and Third Party Programmes (incl. Copernicus)




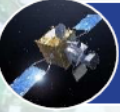



EUMETSAT and Copernicus



EUMETSAT activities in support to Copernicus

- Legal Framework:
 - EUMETSAT: Third Party Programme foreseen by the Convention approved in October 2014
 - EU: Delegation Agreement foreseen by the Copernicus Regulation signed in November 2014
- Focus: ocean and atmospheric composition monitoring
- Cooperation with ESA on development and operations
- Vision : deliver integrated data streams (from Copernicus, EUMETSAT and third party missions)
- Objective : create synergies with EUMETSAT own infrastructures

Third party programmes in support of Copernicus

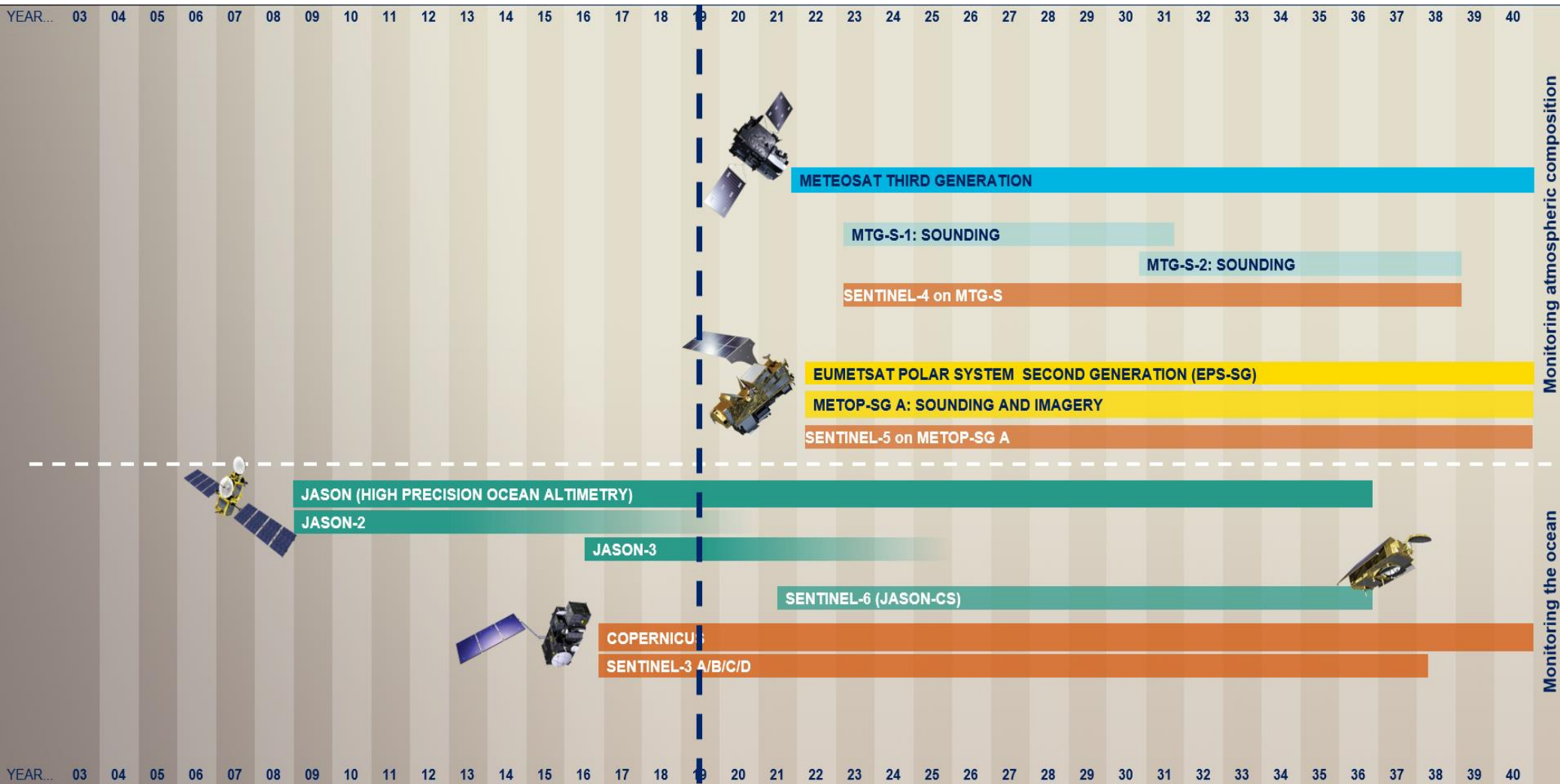
	SENTINEL-1: 4-40m resolution, 3 day revisit at equator	<i>S1A and 1B in orbit</i>	▶ Polar-orbiting, all-weather, day-and-night radar imaging
	SENTINEL-2: 10-60m resolution, 5 days revisit time	<i>S2A and 2B in orbit</i>	▶ Polar-orbiting, multispectral optical, high-resolution imaging
	SENTINEL-3: 300-1200m resolution, <2 days revisit	<i>S3A and S3B in orbit</i>	▶ Optical and altimeter mission monitoring sea and land parameters
	SENTINEL-4: 8km resolution, 60 min revisit time	1st Launch 2022	▶ Payload for atmosphere chemistry monitoring on MTG-S
	SENTINEL-5p: 7-68km resolution, 1 day revisit	<i>S5P in orbit</i>	▶ Mission to reduce data gaps between ENVISAT, and Sentinel 5
	SENTINEL-5: 7.5-50km resolution, 1 day revisit	1st Launch 2023	▶ Payload for atmosphere chemistry monitoring on MetOp 2 nd Gen
	SENTINEL-6: 10 day revisit time	1st Launch 2020	▶ Radar altimeter to measure sea- surface height globally
	Preparing Sentinel-7		▶ CO2 monitoring

Third party programmes in support of Copernicus

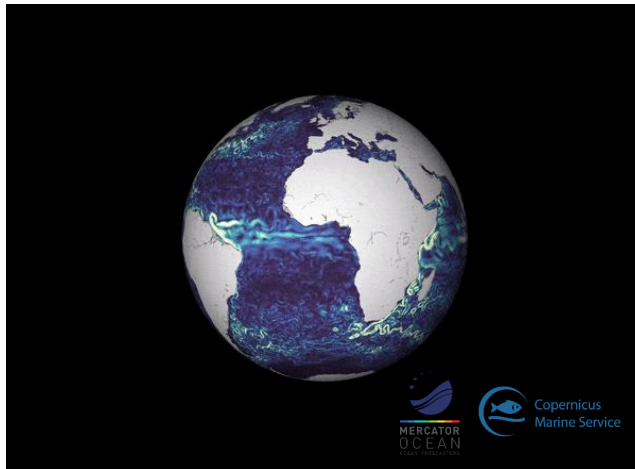
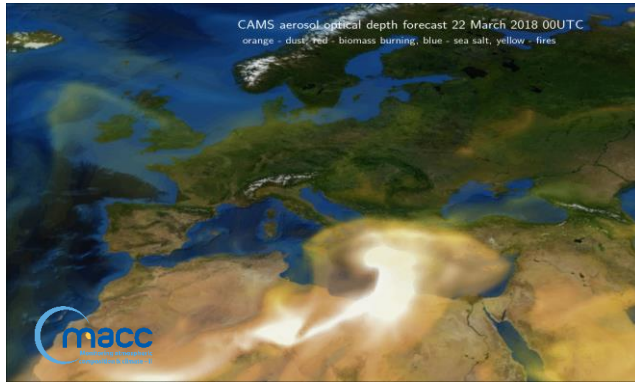
SENTINEL-5/UVNS Level-2 products	Parameter(s)
O3	Ozone (O3) total column, tropospheric column, stratospheric vertical profile
NO2	Nitrogen dioxide (NO2) total column, tropospheric column
SO2	Sulfur dioxide (SO2) total column, layer height (TBC)
HCHO	Formaldehyde (HCHO) total column
CHOCHO	Glyoxal (CHOCHO) total column
CH4	Methane (CH4) total column
CO	Carbon monoxide (CO) total column
Cloud	Cloud effective fraction, effective height, cloud mask
Aerosol	Aerosol UV absorption index, layer height, optical depth (TBC)
Surface	Surface effective albedo, scene heterogeneity
UV	UV spectrally resolved irradiance at surface, UV index

SENTINEL-4 Level-2 products	Parameter(s)
O3	Ozone (O3) total column, tropospheric sub-column,
NO2	Nitrogen dioxide (NO2) total column, tropospheric sub-column
SO2	Sulfur dioxide (SO2) total column
HCHO	Formaldehyde (HCHO) total column
CHOCHO	Glyoxal (CHOCHO) total column
Cloud	Cloud optical thickness, fraction, altitude
Aerosol	Aerosol column optical thickness, type, layer height, absorbing index
Surface	Surface and aerosol characteristics

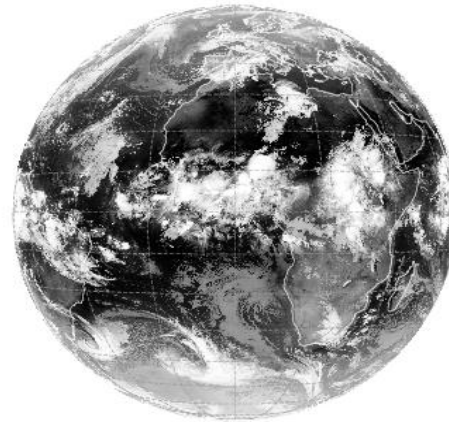
Third party programmes in support of Copernicus



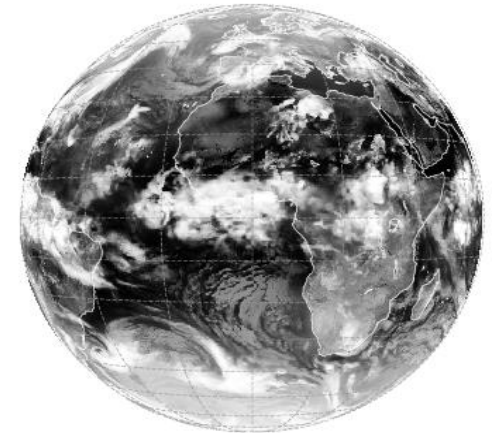
From weather to environmental forecasting







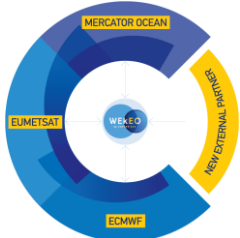

Meteosat 9 IR10.8 20080525 0 UTC



ECMWF Fc 20080525 00 UTC+0h:



Copernicus data access

	<p>EUMETCast <i>eumetcast.com</i></p>	<p>Multi-service push dissemination via satellite or terrestrial networks</p>
	<p>Copernicus Online Data Access (CODA) <i>coda.eumetsat.int</i></p>	<p>Download service offering all Sentinel-3 span up to 12 months of data.</p>
	<p>Data Long-Term Archive <i>archive.eumetsat.int</i></p>	<p>EUMETSAT's long-term archive of products, including Copernicus Sentinel-3</p>
	<p>EUMETView <i>eumetview.eumetsat.int</i></p>	<p>Visualisation service allowing users to view EUMETSAT data and Copernicus Sentinel-3</p>
	<p>New: Copernicus WEkEO DIAS <i>www.wekeo.eu</i></p> 	<p>A federated approach: The most up-to-date Copernicus data and an expanding data offer in the future</p> <p>Distributed open architecture concept, federative and scalable, implemented by European industry.</p>

Aerosol Products



Summary

Heritage and current developments :

- **EPS/PMAp** : Combination of instruments
 - **LUT** retrieval and spectral combination (Grzegorski et al. in prep)
- **S3/SLSTR** : Dual-view radiometer
 - Aerosol retrieval with a physical based surface model from **U. Swansea** (North. et al. 1999)
- **S3/OLCI** : Multispectral Pushbroom
 - Simultaneous aerosol / surface retrieval with **GRASP** (Dubovik et al. 2014)

Next generation of aerosol products :

- **EPS-SG/3MI** : Multi-directional Polarimeter
 - Simultaneous aerosol / surface retrieval with **GRASP** (Dubovik et al. in prep)
- **EPS-SG/MAP**: Multi-sensor
 - Combination of PMAp and 3MI
- **MTG/FCI** : Geostationary imagers
 - Simultaneous aerosol / surface retrieval with **AERUS** (Carrer et al. 2014)

Products from sensors currently in-orbit

- **EPS (EUMETSAT Polar System)**

- 3 LEO satellites : Metop-A (2007), Metop-B (2013), Metop-C (2019)
- 3 instruments for aerosol retrieval
GOME-2, AVHRR, IASI → hyper-instrument

- **Sentinel-3 (Copernicus)**

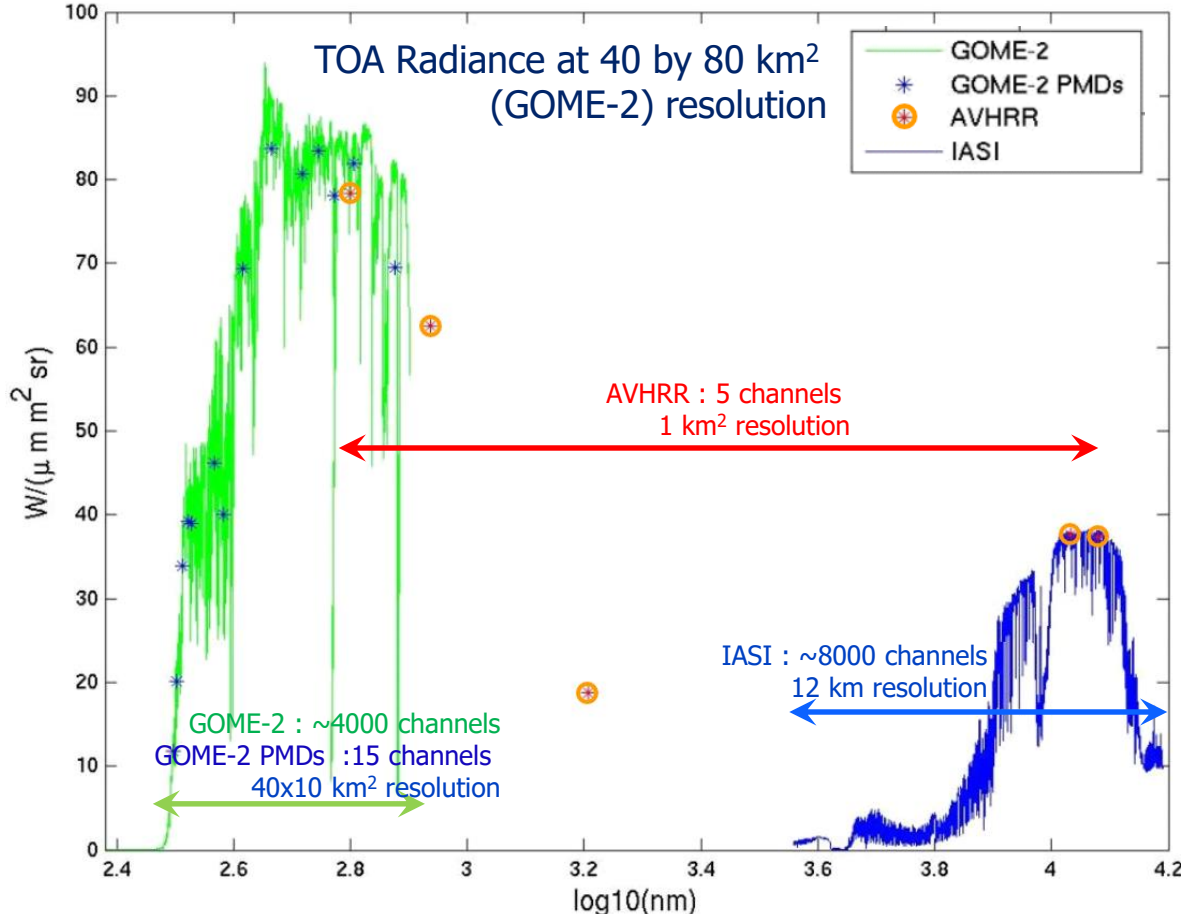
- 2 LEO satellites : S3-A (2016) and S3-B (2018)
- 2 instruments for aerosol retrieval
SLSTR, and OLCI

EPS sensors – creating a hyper-instrument

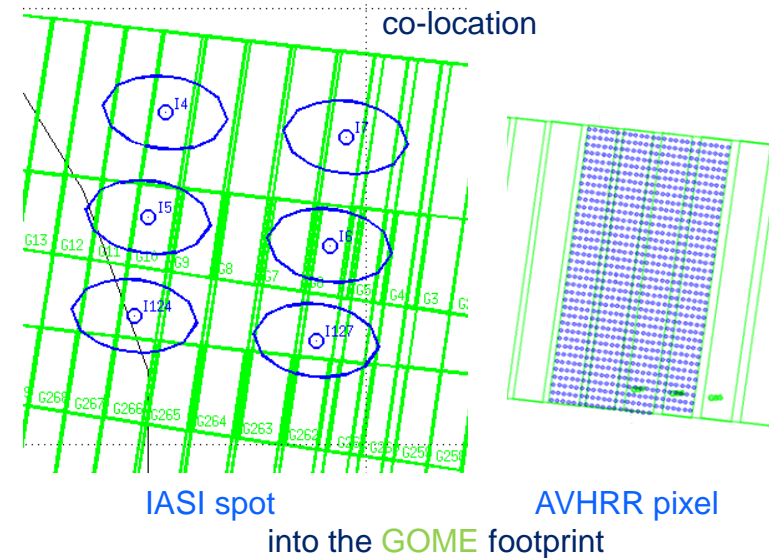
PMAp : Polar Multi-sensor Aerosol product from GOME-2, AVHRR and IASI

- 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 released soon

PMAp Main Updates

- **Operational product, Currently Version 2.1.0 (Feb 2017)**

- Surface homogeneity test
- Surface elevation correction function for Rayleigh scattering calculation
- Surface reflectance database (LER v1.6) statically masked for more accurate land/water areas partition
- Volcanic Ash/SO₂ class using thermal IR IASI measurement

- **Next Release 2.2 - coming mid-2019**

- GOME-2 PMDs L1 radiance correction for degradation (degradation + offset)
- Surface reflectance database (LER) now based on MetopA & B
- Improved detection and AOD quality for thick desert dust -in particular over bright surfaces and discrimination w.r.t. to water clouds (IASI spectrum)

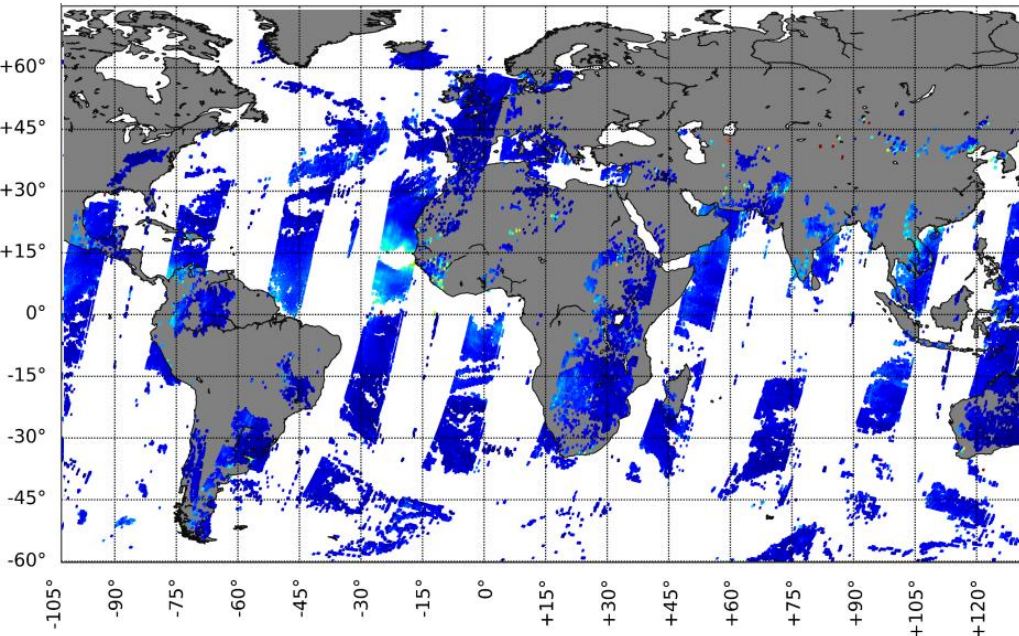
→ Under refinement by EUMETSAT and evaluation by CAMS

- Very good consistency between Metop-A, -B, and -C
- The specific case of dust over clouds creates “hotspots” on AOD retrieval : to be discarded or flagged

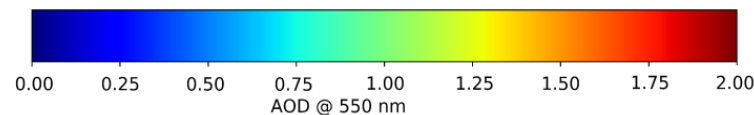
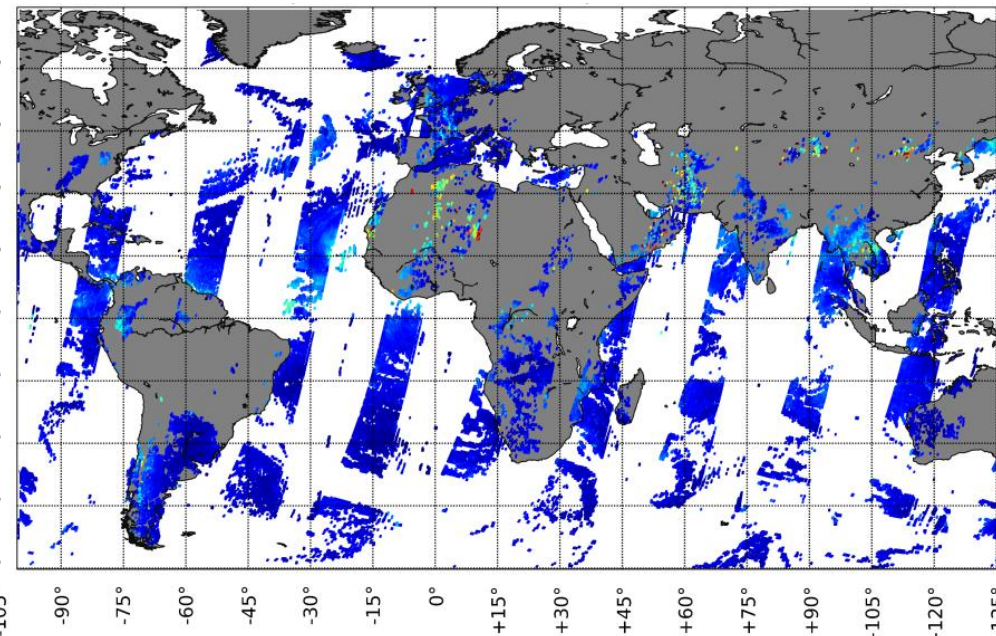
- **PMAp-C V2.1**

- PMAp-C activated after the L1 in-flight calibration update of GOME
- Product quality very similar to PMAp-B
- Currently in GS1. Pre-operational status : released for Trial dissemination (to Cal/Val partners)

V2.1 AOD(550) : MetopC 20190227



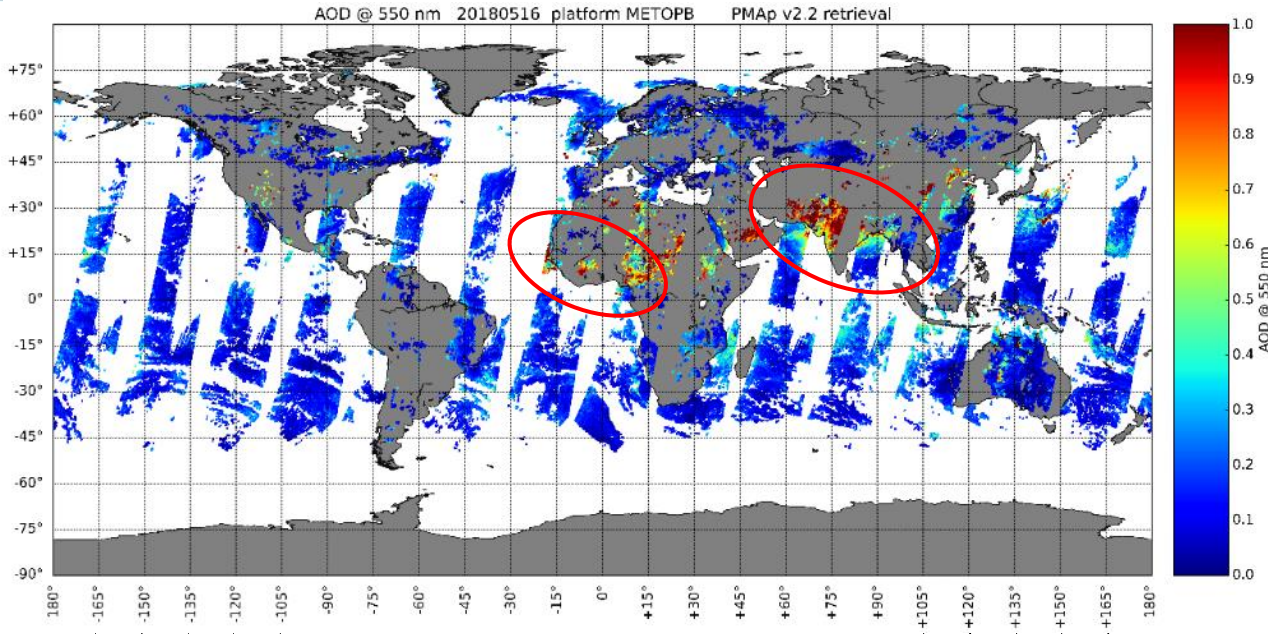
V2.1 AOD(550) : MetopB 20190227



The Polar Multi-sensor Aerosol Product

Operational near-real time products from EPS/Metop

PMAp V2.1 → V2.2

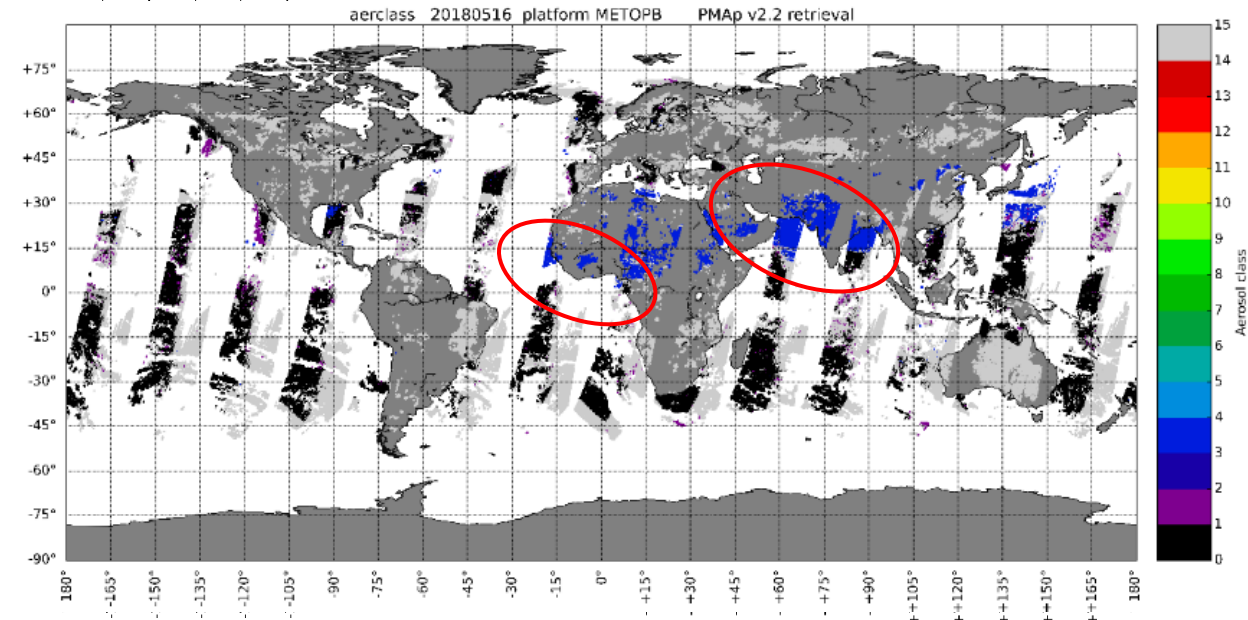


AOD @ 550 nm

PMAp v2.2
Adding information for enhancing the capabilities of desert dust detection and tracking

Aerosol Class

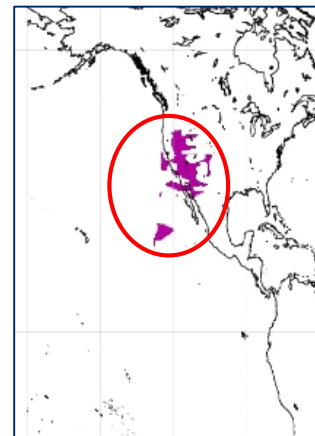
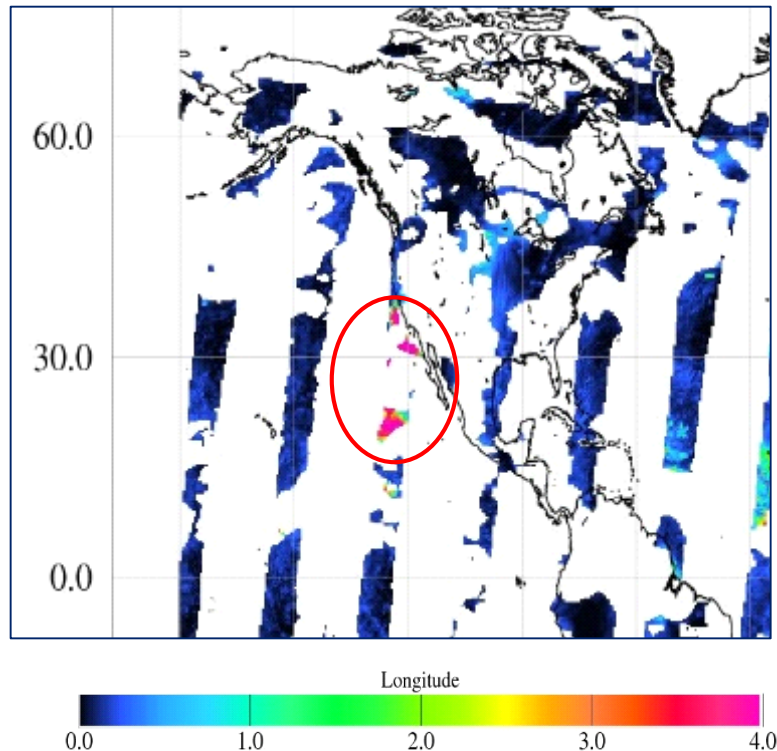
- fine mode
- coarse mode
- volcanic ash / thick dust
- volcanic ash with SO₂



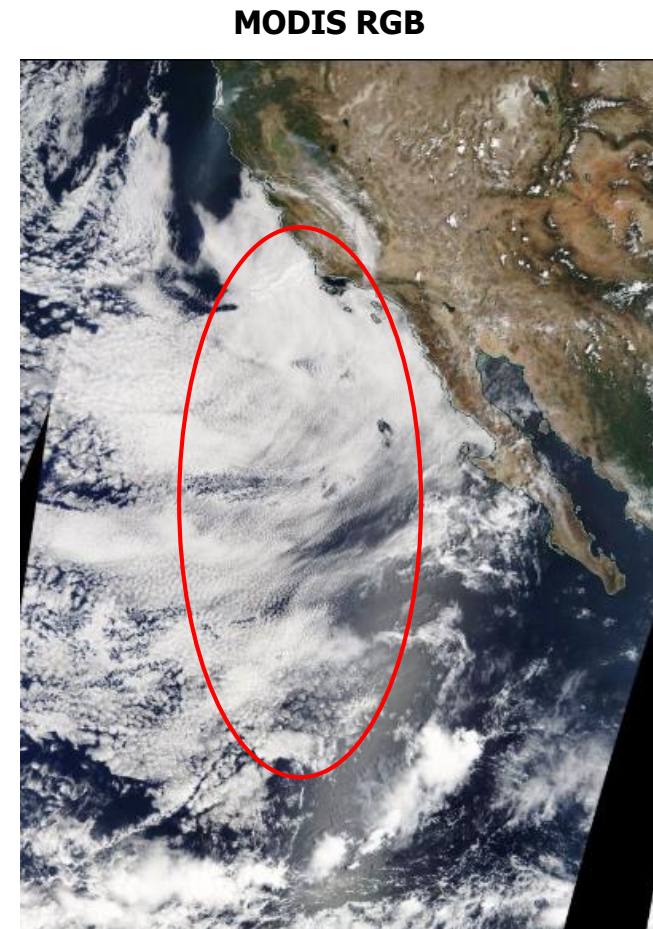
• Investigation on the HotSpots

- IASI detection of dust over ocean
- This corresponds also to cloudy situations – in V2.2 cloud test skipped because dust event is supposed to be non-cloudy
- Impact not only hot-spot (saturation of AOD)
- Update = to force the cloud-test even if dust

PMAp Aerosol Optical Depth 2013081800000 2013081900000



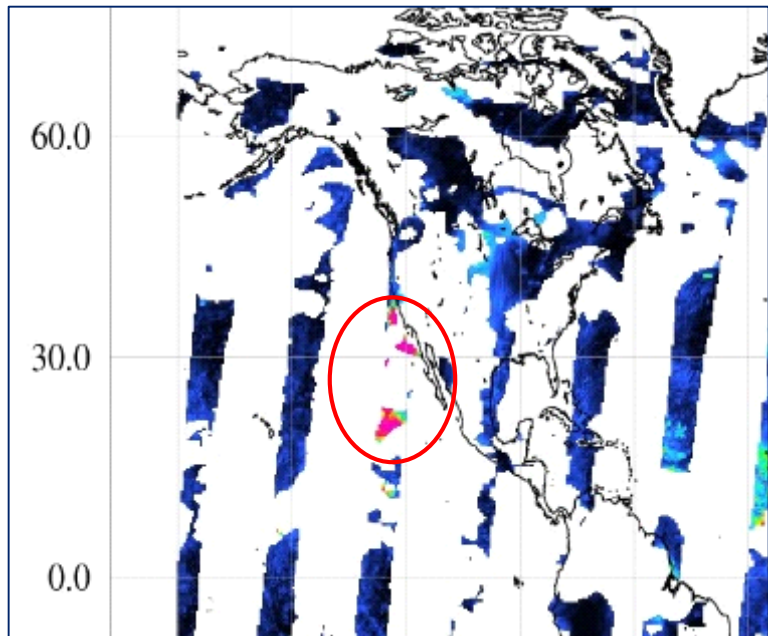
PMAp Dust type



• Investigation on the HotSpots

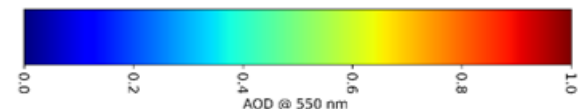
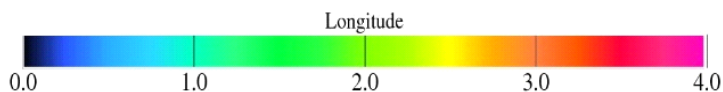
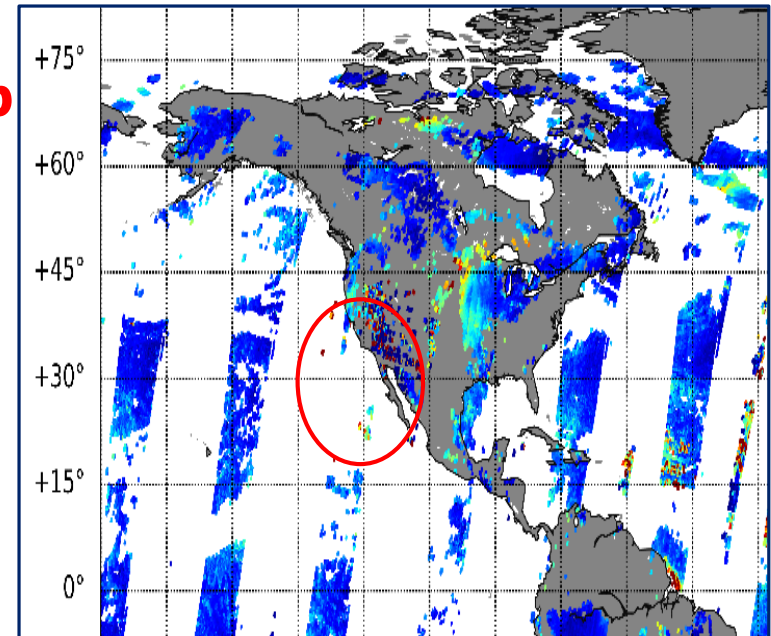
- IASI detection of dust over ocean : corresponds sometimes to cloudy situations – in V2.2 cloud test skipped because dust event is supposed to be non-cloudy
- Impact not only hot-spot (saturation of AOD)
- Update in V2.2b = to force the cloud-test even if dust
 - Now identified as cloudy pixel + the aerosol contaminated flag raised (no more AOD value)

PMAp Aerosol Optical Depth 2013081800000 2013081900000



V2.2

V2.2b



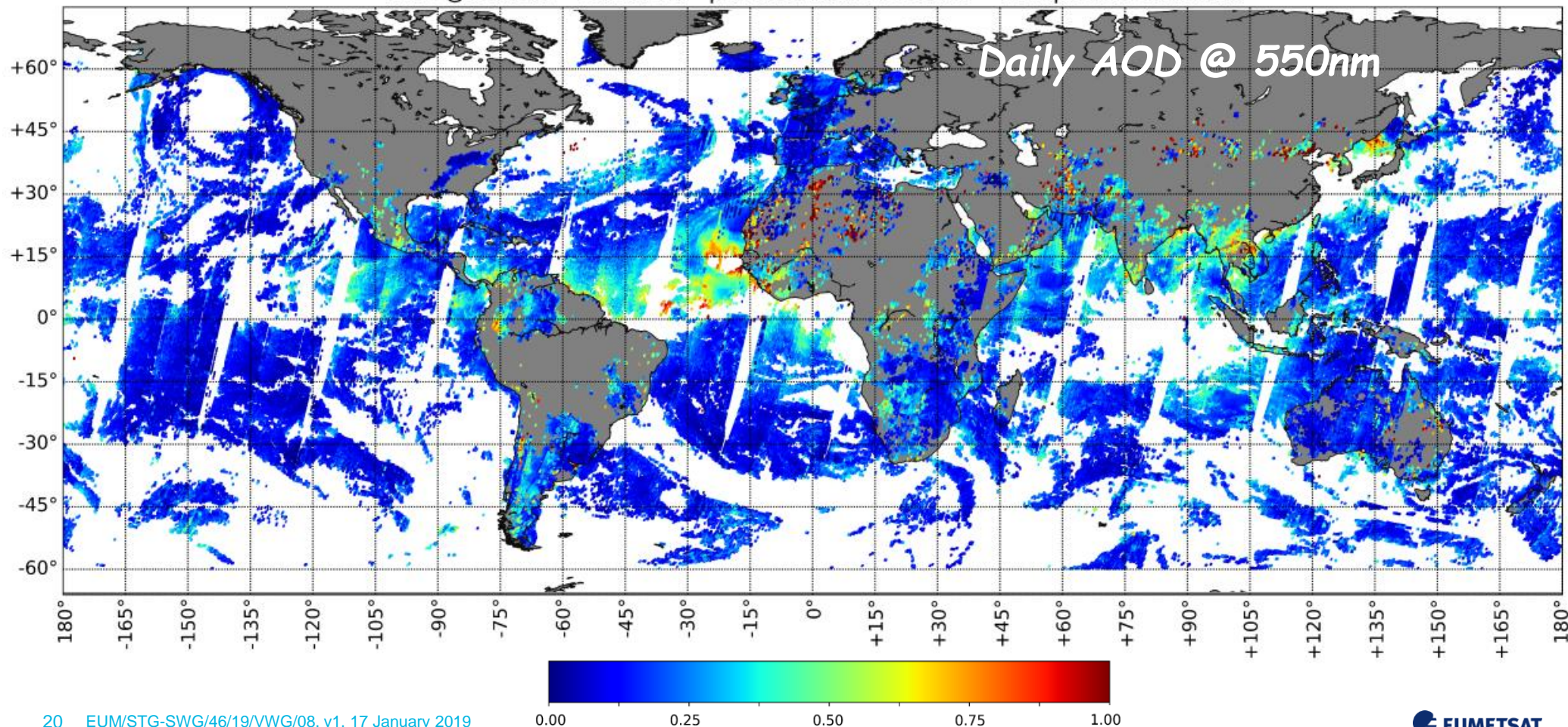
The Polar Multi-sensor Aerosol Product

Operational near-real time products from EPS/Metop

PMAp-A/B/C = PMAp-D

- **Tristar MetOp configuration → very good complementarity of PMAp A/B/C products**
 - Remarkable global daily coverage : complementarity of the ground tracks (low loss due to sunglint)
 - Efficiency of the cloud decontamination, especially over ocean
 - Good consistency over dust events & Better identification of the inter-track residues

AOD @ 550 nm 20190227 platform M01 M02 M03 PMAp v2.10 retrieval

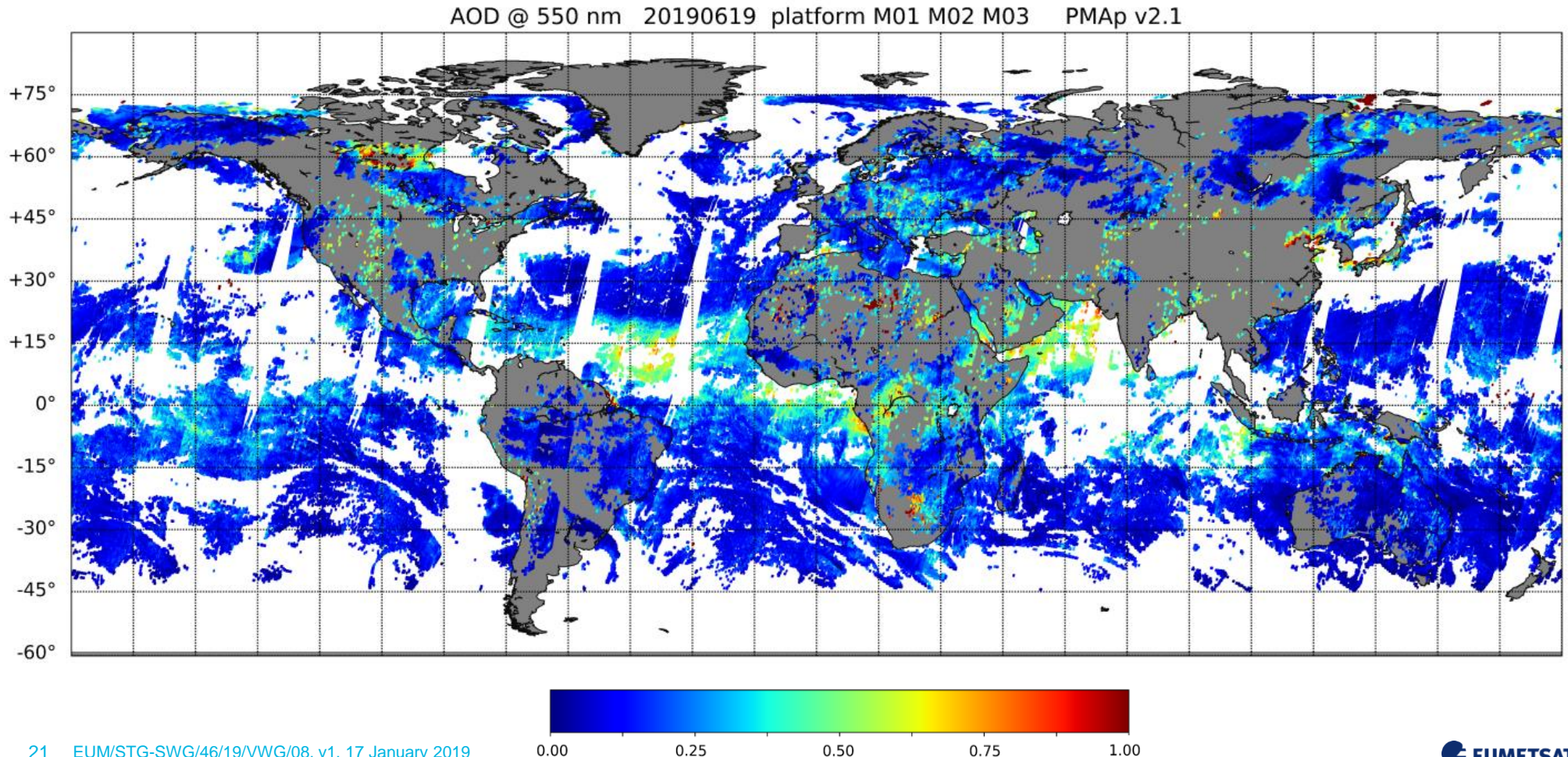


The Polar Multi-sensor Aerosol Product

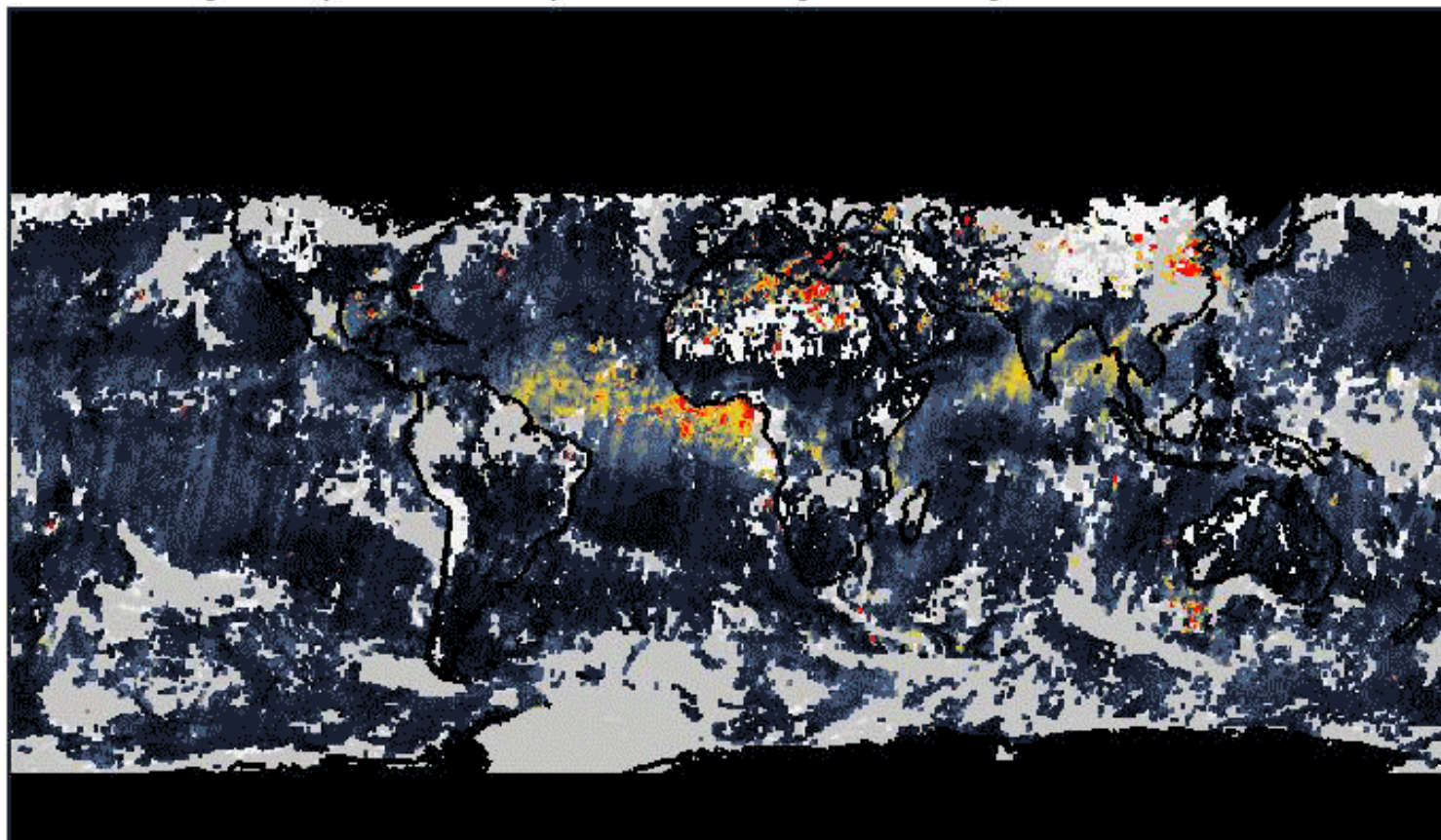
Operational near-real time products from EPS/Metop

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 - Remarkable global daily coverage : complementarity of the ground tracks (low loss due to sunglint)
 - Efficiency of the cloud decontamination, especially over ocean
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PMAp L3 (0.50x0.50) Aerosol Optical Depth 01-Feb-2015



**Feb-May 2015
&
Jun-Sep 2013**

**3-day averaging
Binning 3x3**

**Version 2.2
(not yet released)**



0.00 0.21 0.41 0.61 0.82

Courtesy R. Lang

Products from sensors currently in-orbit

- **EPS (EUMETSAT Polar System)**

- 3 LEO satellites : Metop-A (2007), Metop-B (2013), Metop-C (2019)
- 3 instruments for aerosol retrieval
GOME-2, AVHRR, IASI → hyper-instrument

- **Sentinel-3 (Copernicus)**

- 2 LEO satellites : S3-A (2016) and S3-B (2018)
- 2 instruments for aerosol retrieval
SLSTR, and OLCI

Actual Aerosol Mission: Sentinel-3 sensors

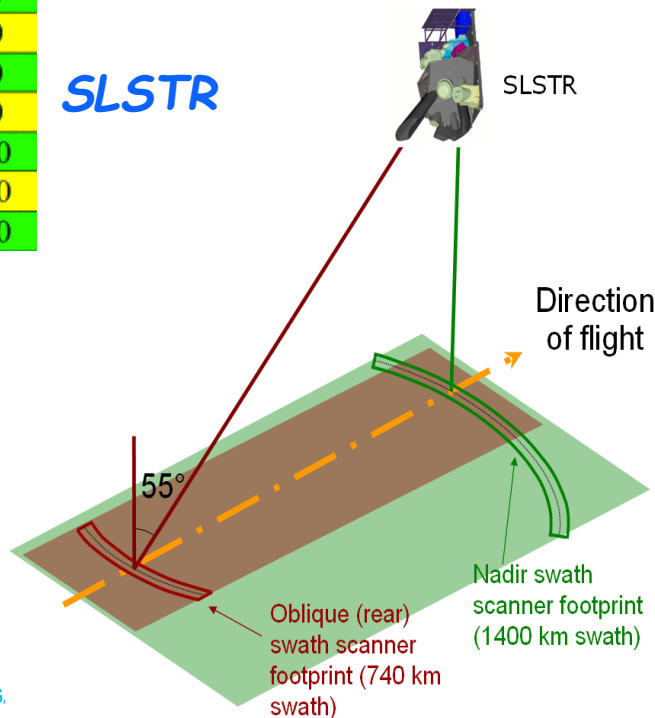
Sentinel-3 : Copernicus Mission

- Polar orbit at 10:00 ECT – A in Feb. 2016, B in Apr. 2018
- 2 complementary instruments : OLCI and SLSTR

	λ center (μm)
Band 1	0.555
Band 2	0.659
Band 3	0.865
Band 4	1.375
Band 5	1.610
Band 6	2.250
Band 7	3.740
Band F1	3.740
Band 8	10.850
Band F2	10.850
Band 9	12.000

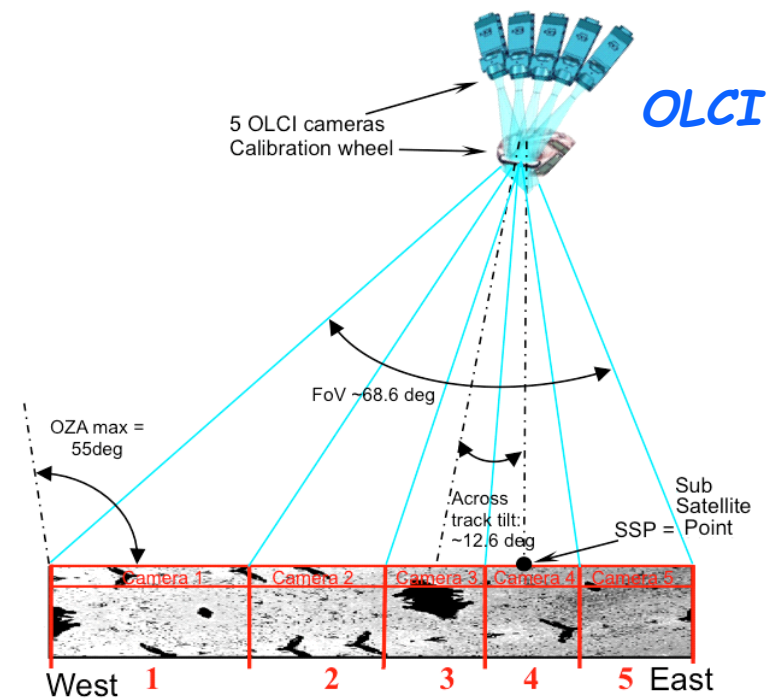
Sea Land Surface Temperature Radiometer

dual view conic scanner, 500m @nadir
(1km @nadir for TIR)
9 spectral bands



Ocean Land Colour Imager

pushbroom,
Fine resolution 300m@nadir
Reduced Resolution 1.2 km@nadir
21 spectral bands



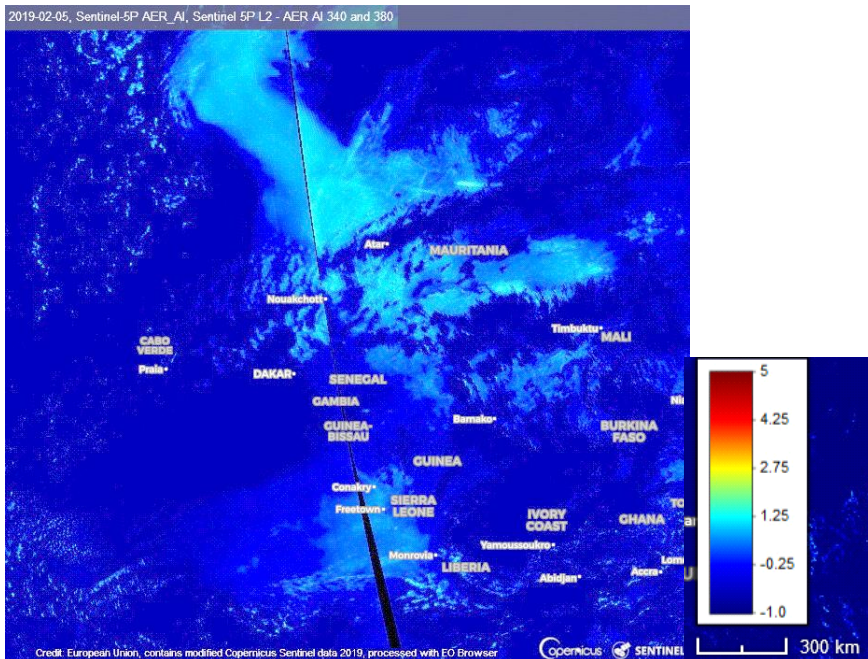
λ center nm	Width nm
400	15
412.5	10
442.5	10
490	10
510	10
560	10
620	10
665	10
673.75	7.5
681.25	7.5
708.75	10
753.75	7.5
761.25	2.5
764.375	3.75
767.5	2.5
778.75	15
865	20
885	10
900	10
940	20
1020	40

Aerosol Product from Sentinel-3 : SLSTR

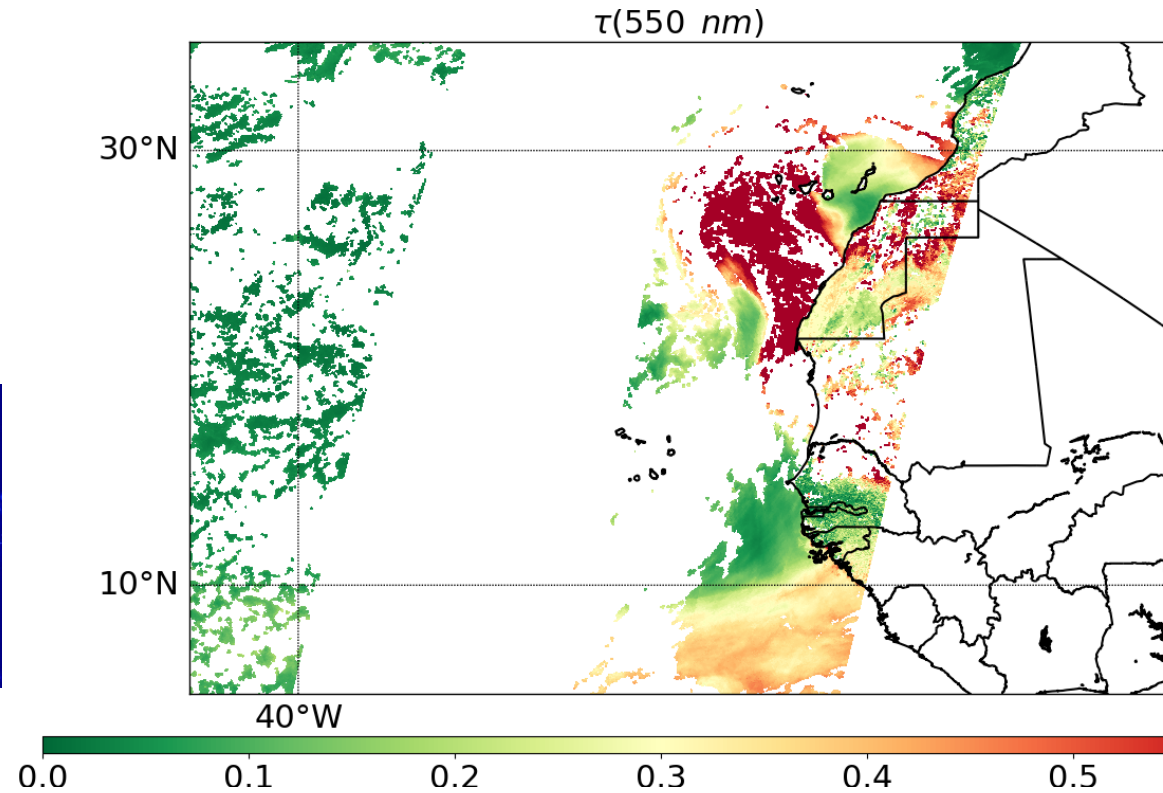
- Sentinel-3 / SLSTR
 - 5 spectral channels at 554, 659, and 868 nm, and 1.613, 2.255 μm – 4.5km resolution
 - dual-view instruments nadir + 50° oblique (ATSR 1&2, AATSR)
 - Retrieval of AOD + model
- Scientific approach (Univ. Swansea; North. et al. 1999)
 - Historically applied to dual-view instruments ATSR 1&2, AATSR (ESA CCI_aerosol project)
 - Aerosol retrieval with a physical based surface model - Iterative optimization of AOD, aerosol model & surface reflectance
 - Viewing constraints: multi-angular – dual-view over land, nadir view over ocean
- Initial algorithm & Processor
 - Developed in the framework of S3 Mission Performance Centre (ESA contract)
 - Delivered to EUMETSAT (Oct. 2018), now fully in charge of maintenance, long-term evaluation, validation monitoring, evolution, deployment.
- On-going analyses / validation by EUMETSAT - necessary evolutions before operational release:
 - Optimal adaptation based on up-to-date knowledge of SLSTR sensor specificities (e.g. geometry, radiometry calibration, etc..)
 - Note : parallel study with Finnish Met. Inst. to consolidate the SLSTR specificities and the expected product performance

Aerosol Product from Sentinel-3 : SLSTR

*S5P-Tropomi
over Middle Atlantic*

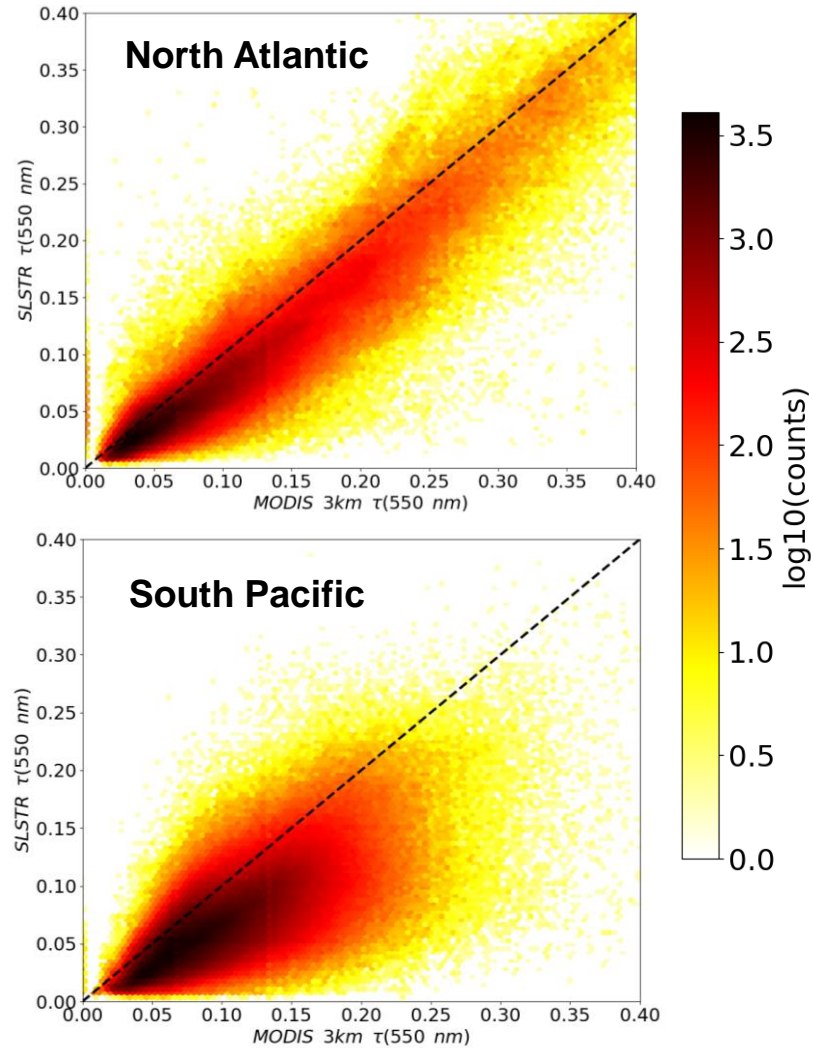


*SLSTR retrieval
over Middle Atlantic*

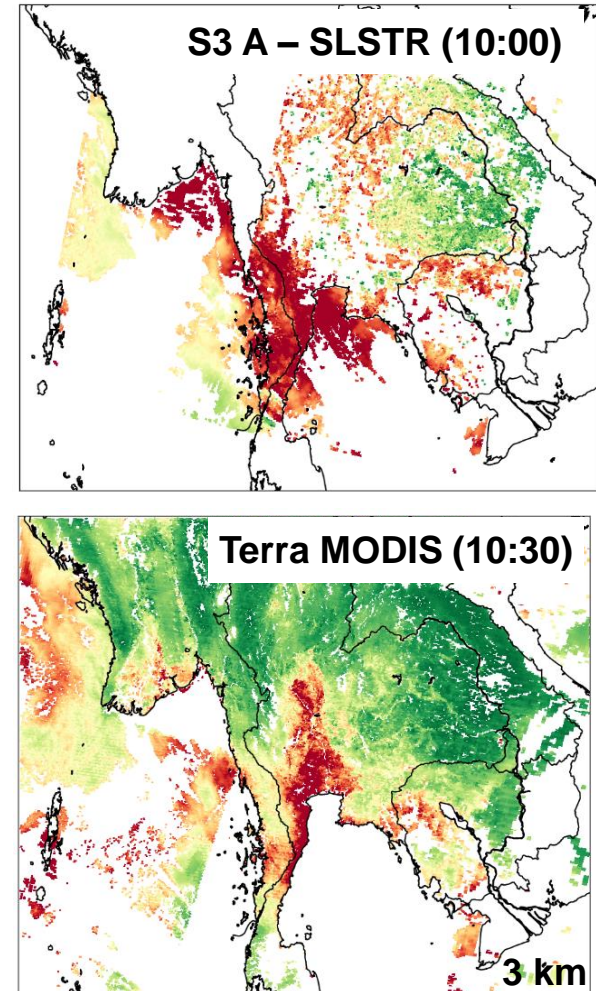


Aerosol Product from Sentinel-3 : SLSTR

Validation over Ocean

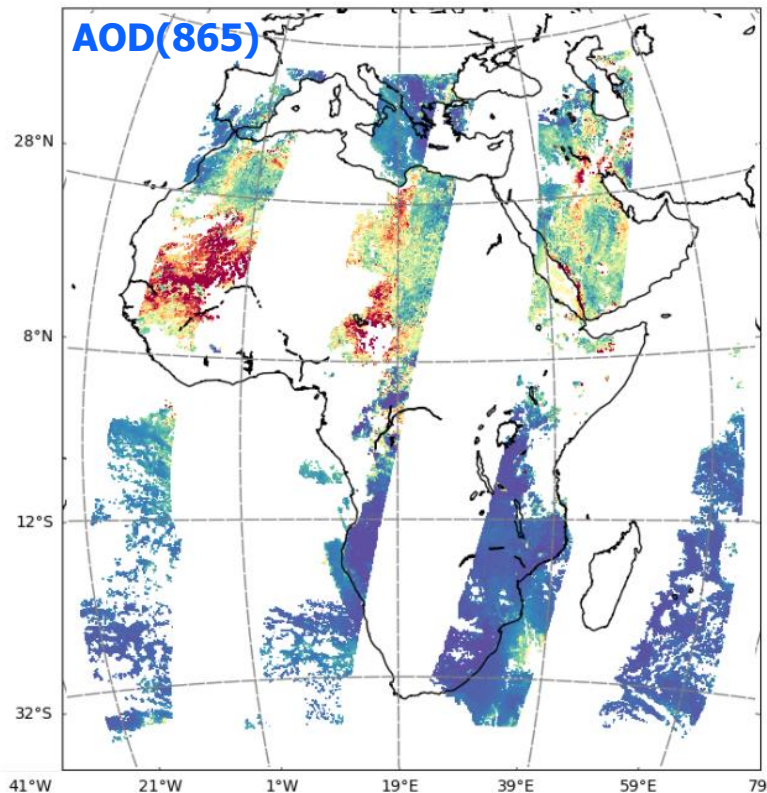


Validation over Land



Aerosol Product from Sentinel-3 : OLCI

- Sentinel-3 / OLCI
 - 21 bands from 400 to 1020nm for 1700 km nadir swath
 - Retrieval of AOD
- OLCI : on-going demonstration of GRASP performance for OLCI
 - Simultaneous surface aerosol retrieval (Dubovik et al. 2014)

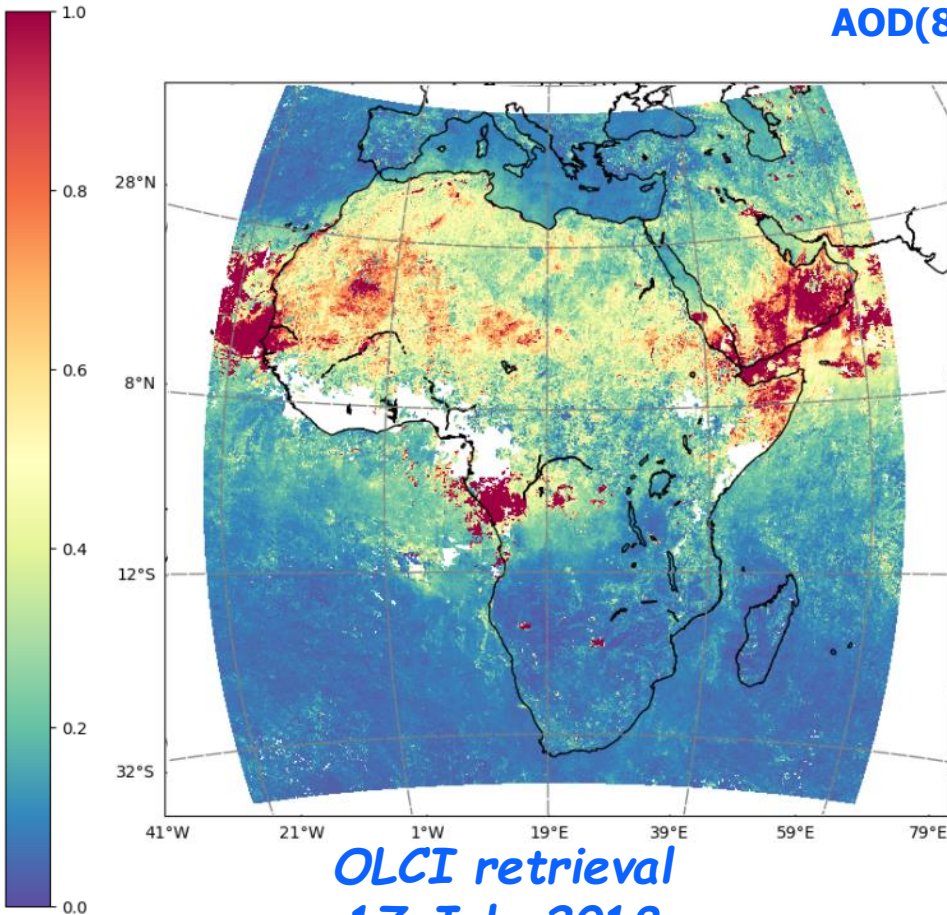


*OLCI retrieval
1st June 2018*

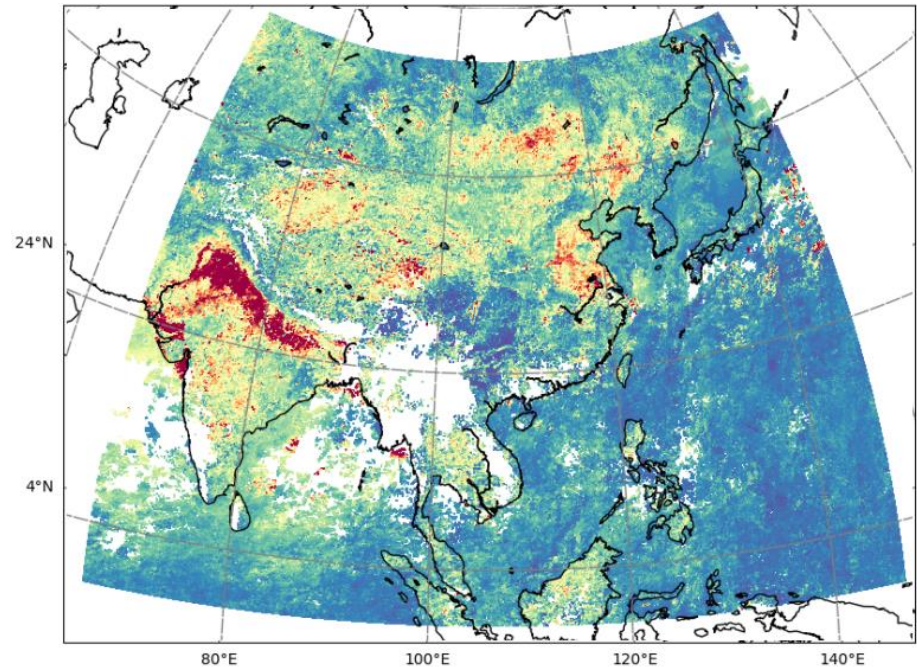
Aerosol Product from Sentinel-3 : OLCI

- OLCI : on-going demonstration of GRASP performance for OLCI
 - Simultaneous surface aerosol retrieval (Dubovik et al. 2014)

AOD(865) : OLCI-A



**OLCI retrieval
17 July 2018**



**OLCI retrieval
June 2018**

Products from future sensors

- **EPS-SG (EPS Second Generation)**

- 3 LEO satellites : Metop-SG on LEO at 9:30
- core instrument for aerosol : 3MI polarimeter
- 4 instruments for aerosol retrieval

3MI, Metimage, S5, IASI-NG → hyper-instrument MAP

- **MTG (Meteosat Third Generation)**

- 3 GEO satellites
- 1 instrument for aerosol retrieval

FCI imager

Future Aerosol Mission: EPS-SG - 3MI

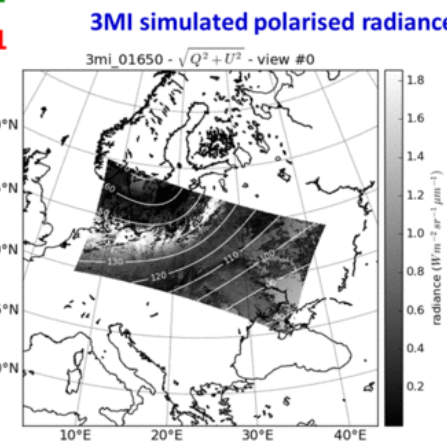
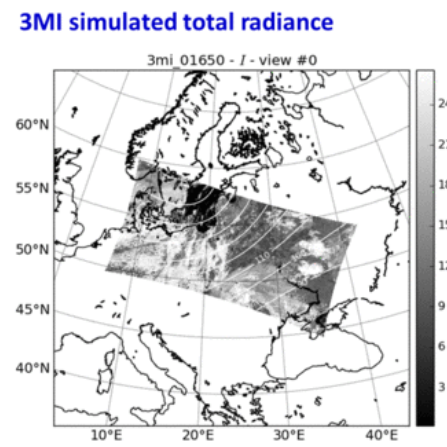
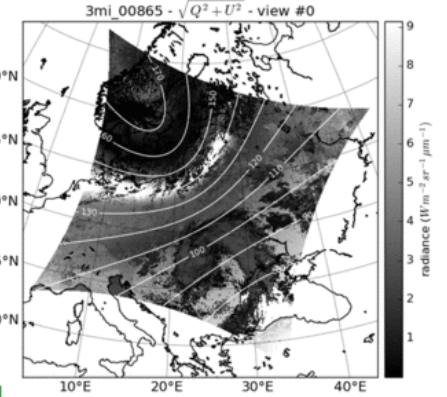
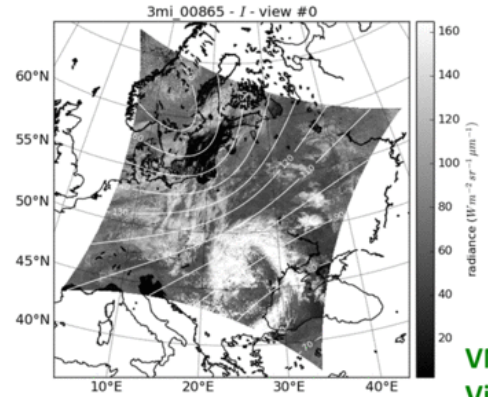
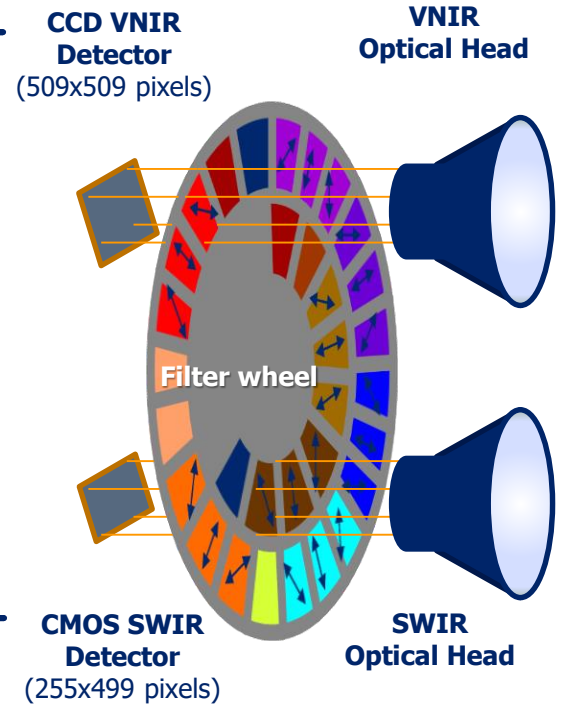
2D Push-broom radiometer (2200 km swath, 4 km pixel at nadir)

Provides images of the Earth TOA outgoing radiance using:

- Multi-view (10 to 14 views; angular sampling in the order of 10°)
- Multi-channel (12 channels from 410 to 2130 nm)
- Multi-polarisation (9 channels with -60° , 0° , $+60^\circ$ polarisers)

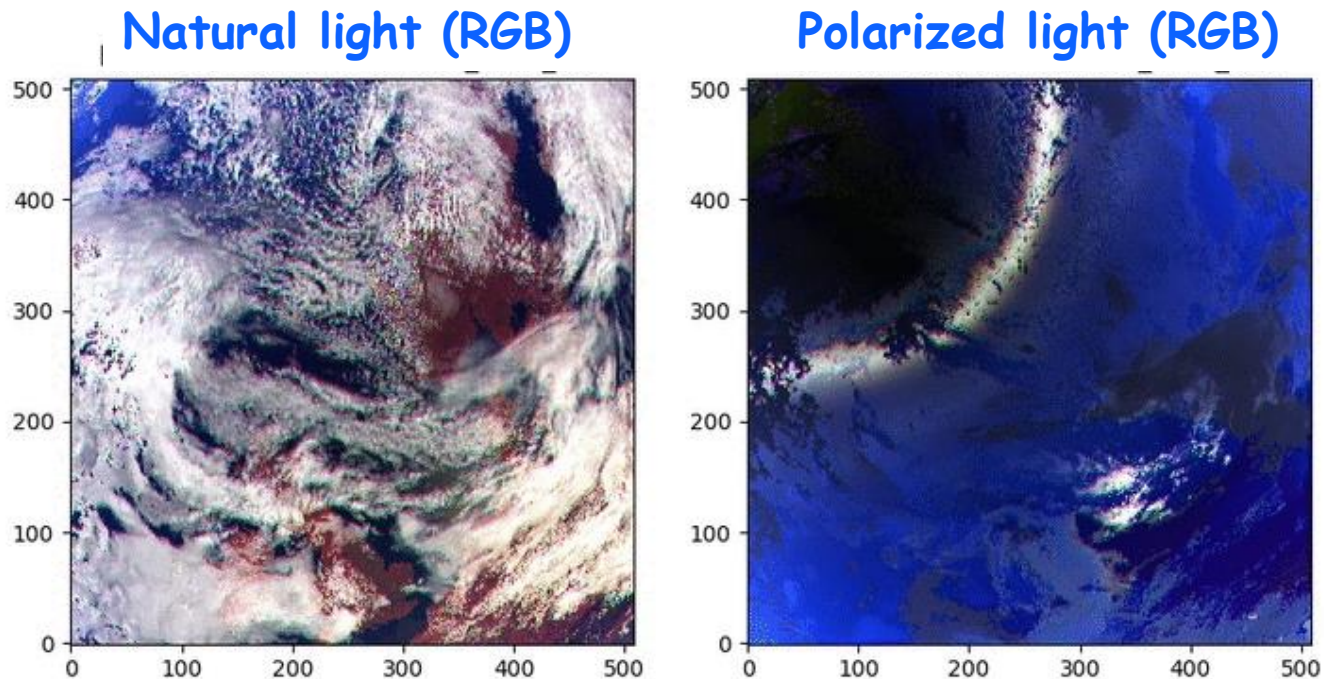
3MI channels	
410-P	± 10 nm
443-P	± 10 nm
490-P	± 10 nm
555-P	± 10 nm
670-P	± 10 nm
763	± 5 nm
765	± 20 nm
865-P	± 20 nm
910	± 10 nm

1370-P	± 20 nm
1650-P	± 20 nm
2130-P	± 20 nm



Aerosol Product from EPS-SG : 3MI

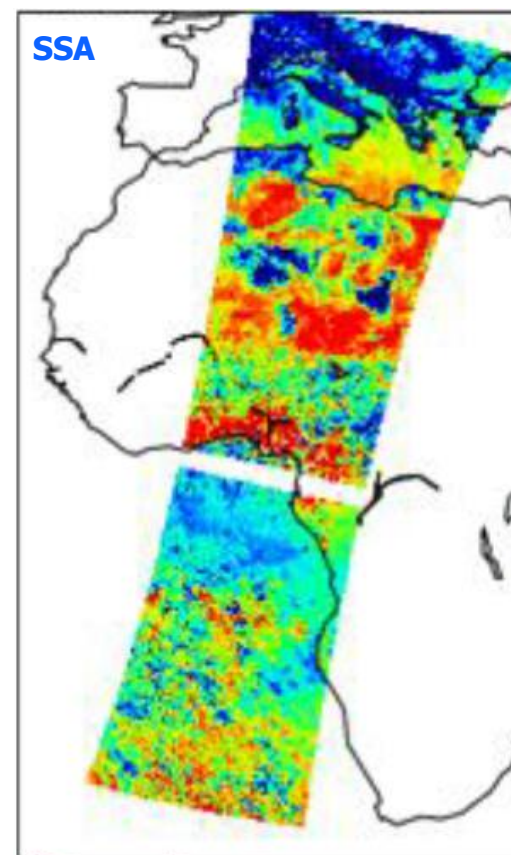
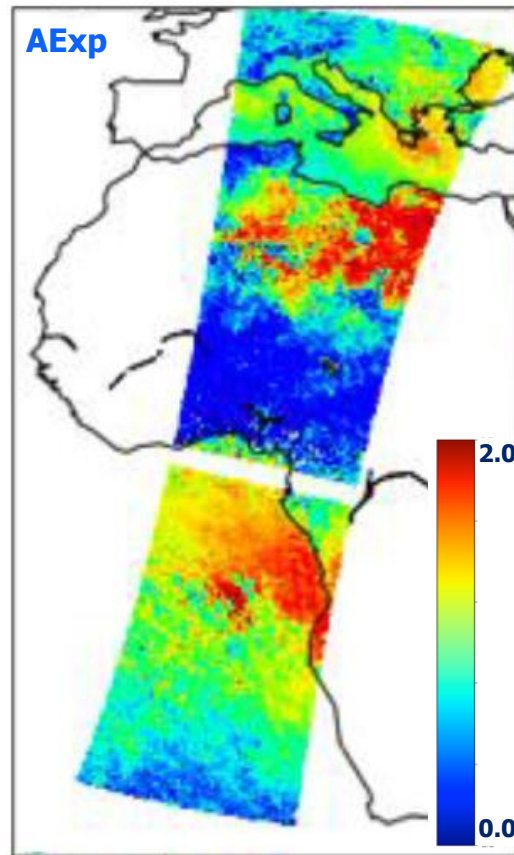
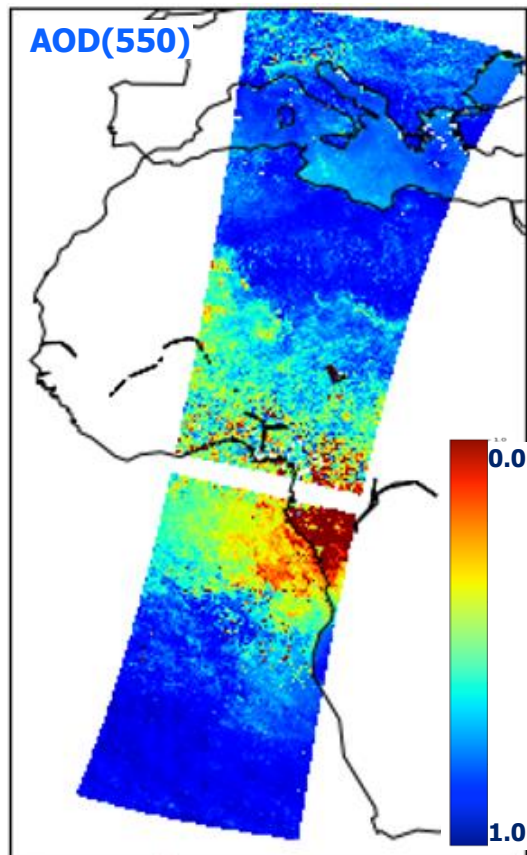
- 3MI = Multi-directional polarimeter
- Added-value information content for aerosol retrieval : 14 views, polarisation, and 12 bands from 410 to 2130nm



Based on simulated 3MI "ideal" dataset

Aerosol Product from EPS-SG : 3MI

- Simultaneous aerosol / surface retrieval with GRASP
- Approach according Dubovik et al., 2014 using all the information content
- Already tested for various sensors (PARASOL, MISR, MODIS, OLCI...)
- Under adaptation for an operational use in EUMETSAT (Near Real Time)

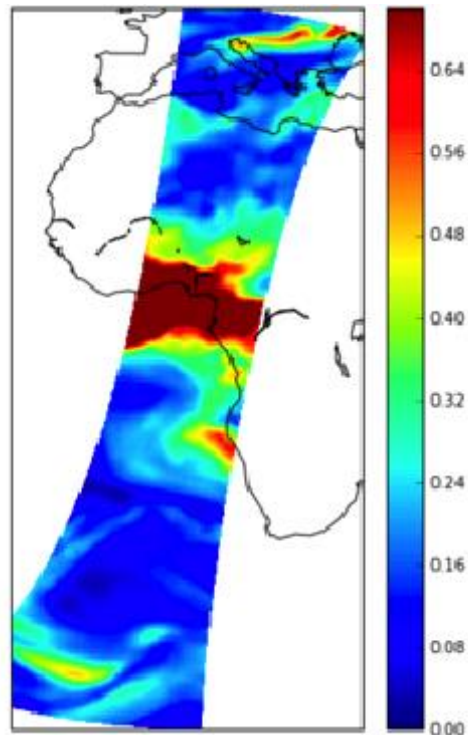


Based on simulated
3MI "ideal" dataset

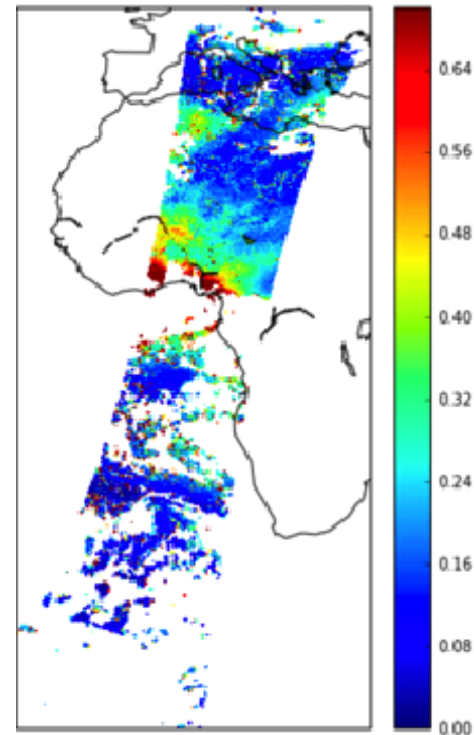
Aerosol Product from EPS-SG : 3MI

- Simultaneous aerosol / surface retrieval with GRASP
- Already tested for various sensors (PARASOL, MISR, MODIS, OLCI...)
- Under adaptation & evaluation for an operational use in EUMETSAT (Near Real Time)

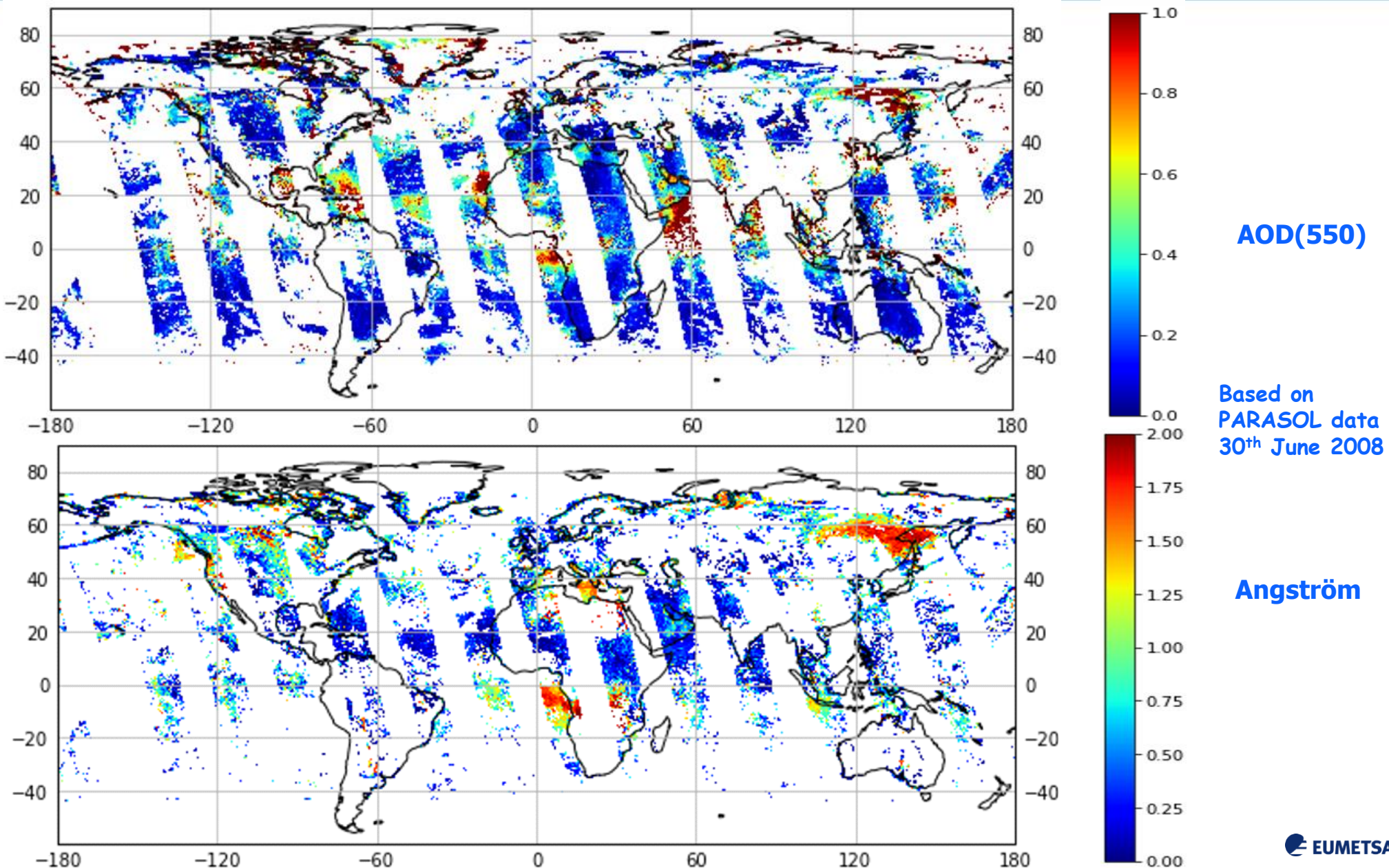
Input AOD to generate
3MI simulated dataset



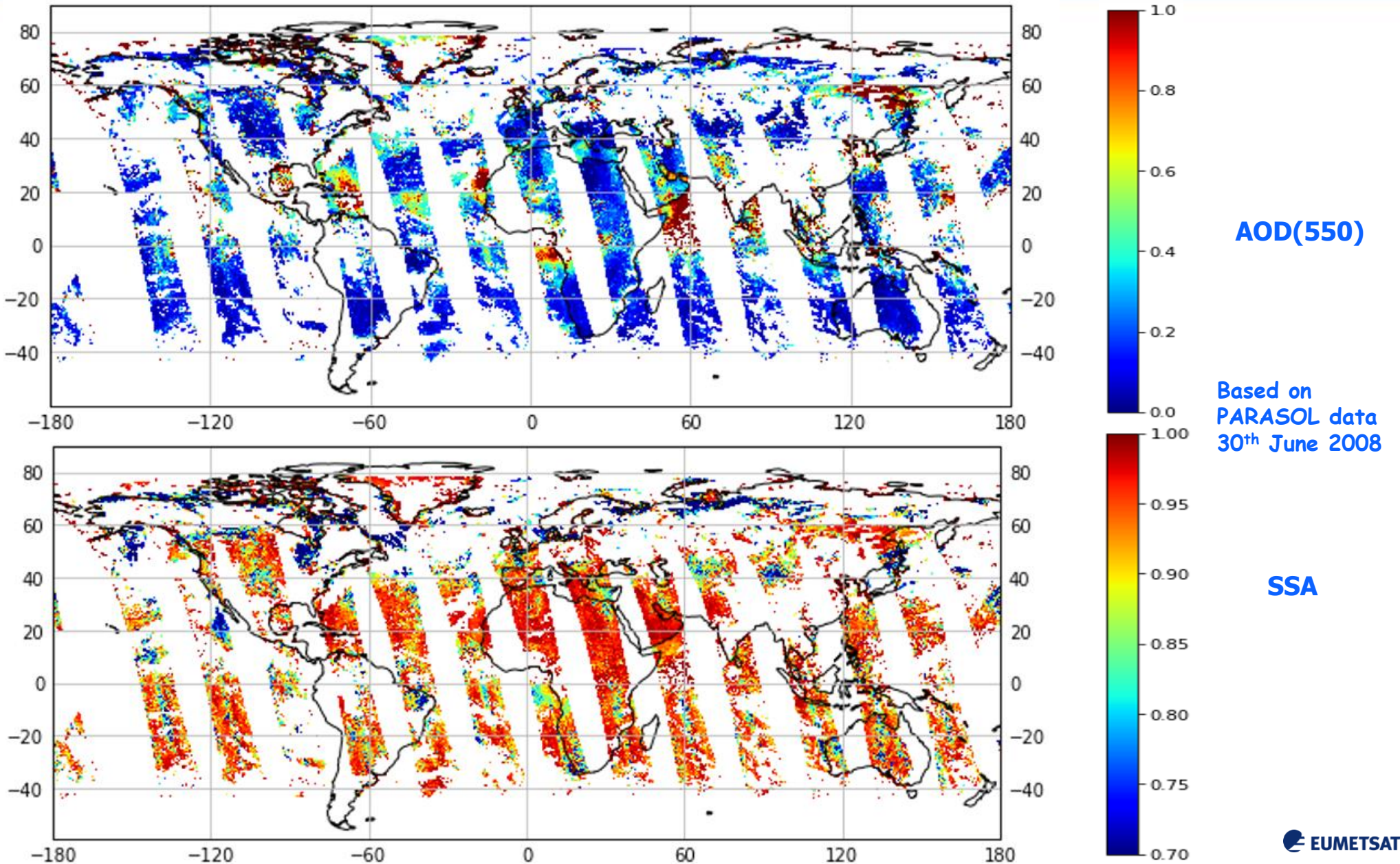
AOD retrieved from
3MI simulated dataset



Aerosol Product from EPS-SG : 3MI



Aerosol Product from EPS-SG : 3MI



Aerosol Product from EPS-SG : toward MAP

- Multi-sensor Aerosol Product (follow-on PMAp)
- All sensors available on the same platform → Hyper-instrument
 - Spectral range (from 270nm to 15 micron)
 - Spectral resolution
 - Spatial resolution (from 500m to 20km)
 - Polarisation and multi-directionality
- Core product based on 3MI
- Additional information content from METImage (sub-pixel information), Sentinel-5 (extension to UV), IASI-NG (TIR sounding)
- Improvement of the accuracy or more parameter retrieved :
 - Aerosol type
 - Aerosol height
 - AOD, SSA, refractive index, fine mode fraction
- Potentiality for PM2.5 estimation
- AOD over clouds

Products from future sensors

- **EPS-SG (EPS Second Generation)**

- 3 LEO satellites : Metop-SG on LEO at 9:30
- core instrument for aerosol : 3MI polarimeter
- 4 instruments for aerosol retrieval

3MI, Metimage, S5, IASI-NG → hyper-instrument MAP

- **MTG (Meteosat Third Generation)**

- 3 GEO satellites
- 1 instrument for aerosol retrieval

FCI imager

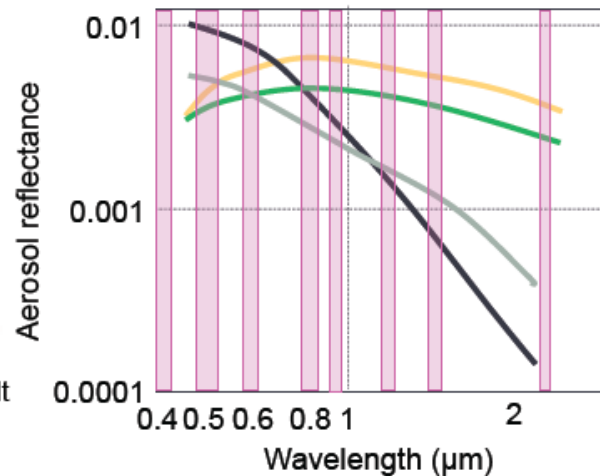
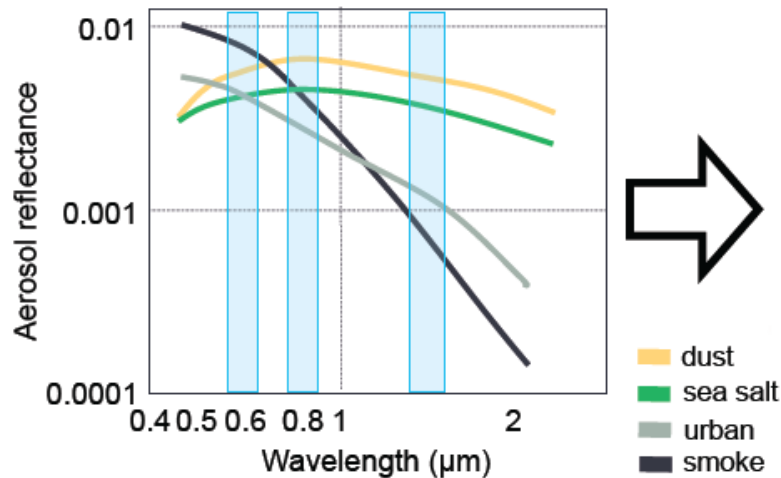
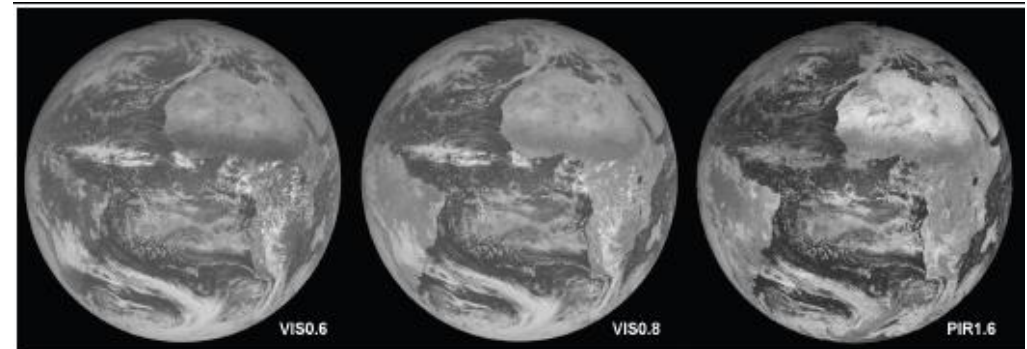
Geostationary sensors – SEVIRI and FCI

MSG/SEVIRI :

- full disk every 15'
- 3 reflective solar bands
- 3km@nadir

MTG/FCI :

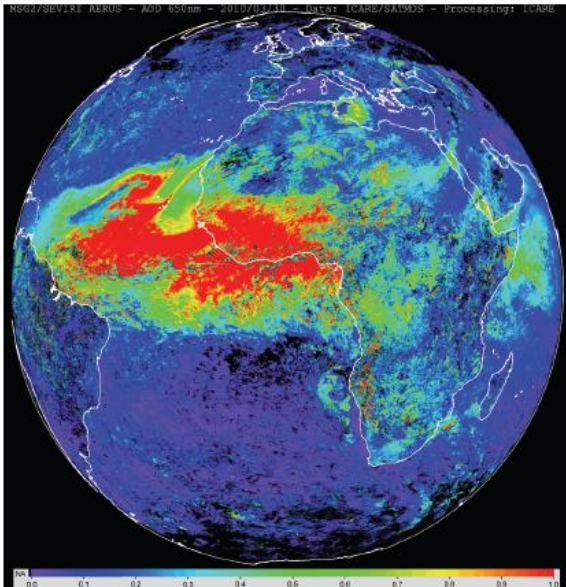
- full disk every 10'
- Rapid scan service (1/4th of full disk every 2.5')
- 8 reflective solar bands
- 1km@nadir



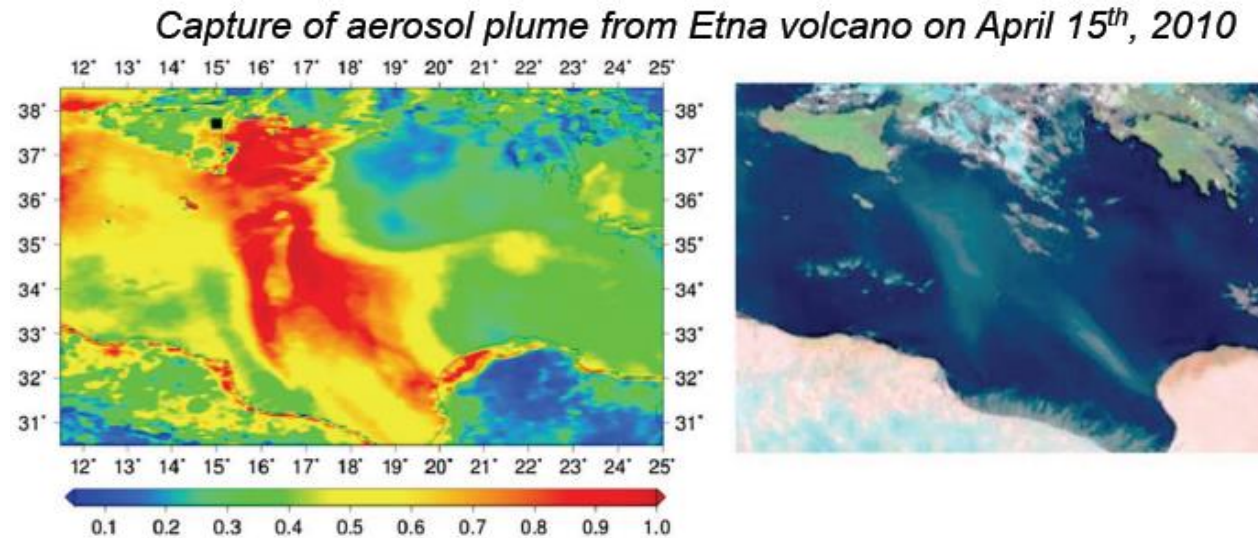
(courtesy Météo-France/CNRM)

Aerosol Product from MSG : SEVIRI

- Simultaneous aerosol / surface retrieval with AERUS-GEO
- Approach according Carrer et al., 2010; 2014
- Daily retrieval for MSG/SEVIRI available in ICARE
- Instantaneous retrieval (up to 96/day) under development
- Planned to be operationally implemented in EUMETSAT for MTG/FCI



Daily AOD at $0.64\mu\text{m}$ on March 30th, 2010



(Ceamanos et al. 2018)

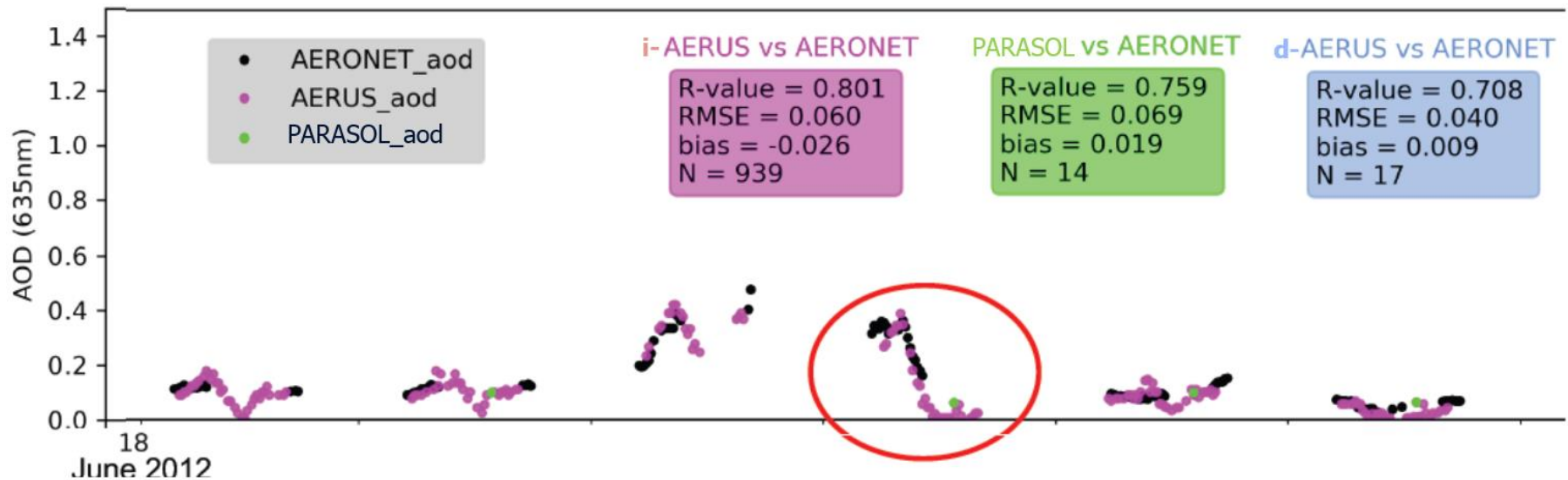
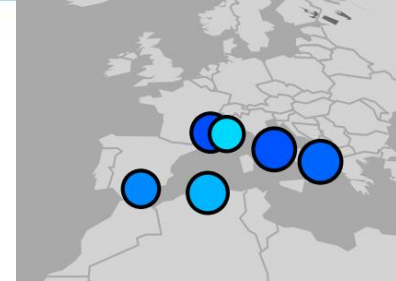
Aerosol Product from MSG : SEVIRI

- Instantaneous retrieval with i-AERUS

- good estimation of the AOD
- reveal the diurnal cycle that may be large

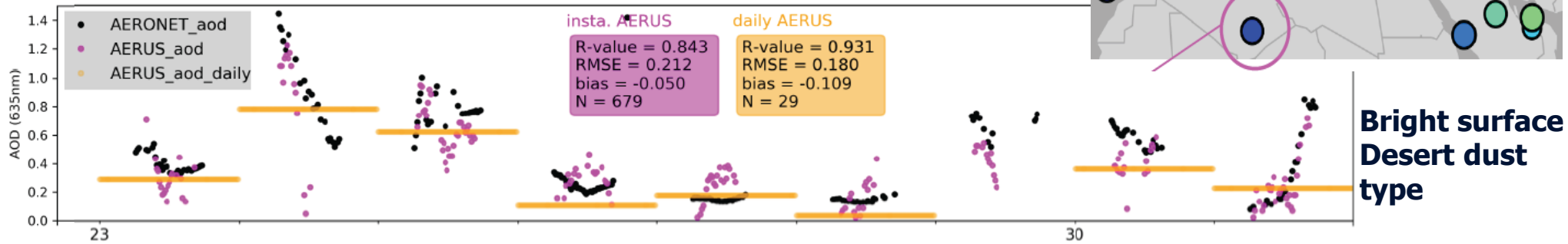
→ comparison to Aeronet and PARASOL (GRASP)

- artefacts : identified limitation in backscattering geometry with the aerosol model (phase function)

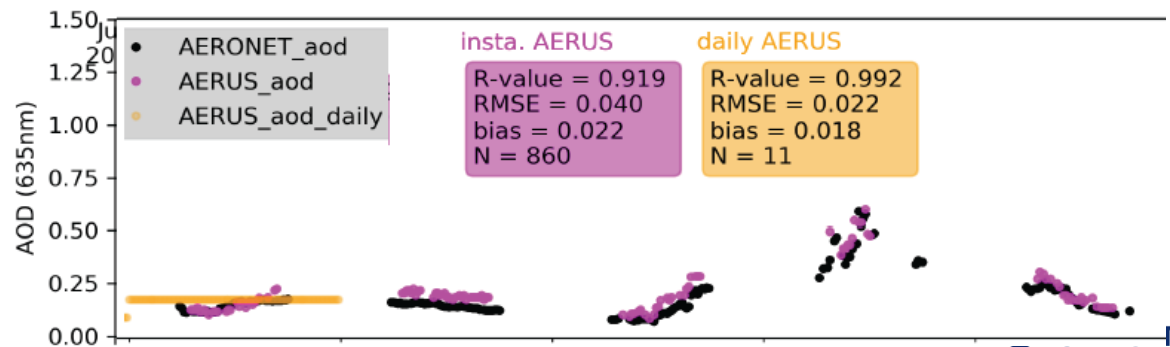
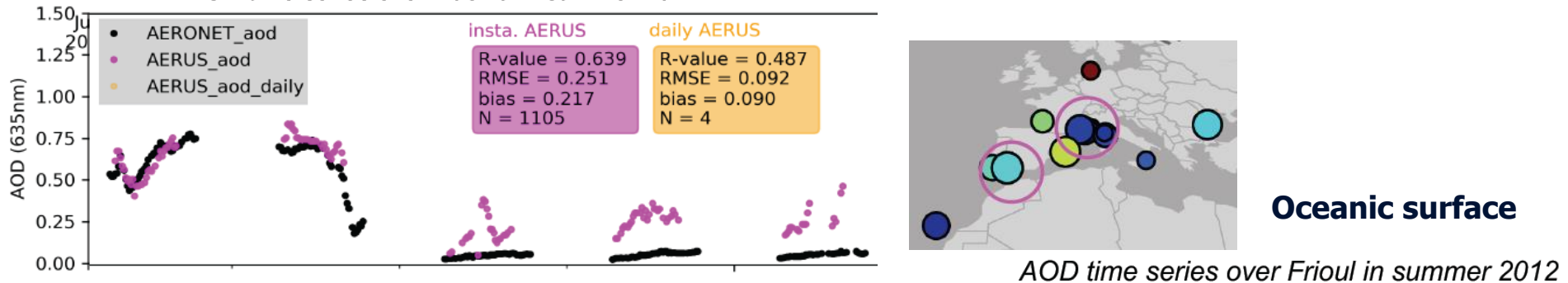


Aerosol Product from MSG : SEVIRI

- Instantaneous retrieval with i-AERUS
 - Various types of behaviour



AOD time series over Huelva in summer 2012

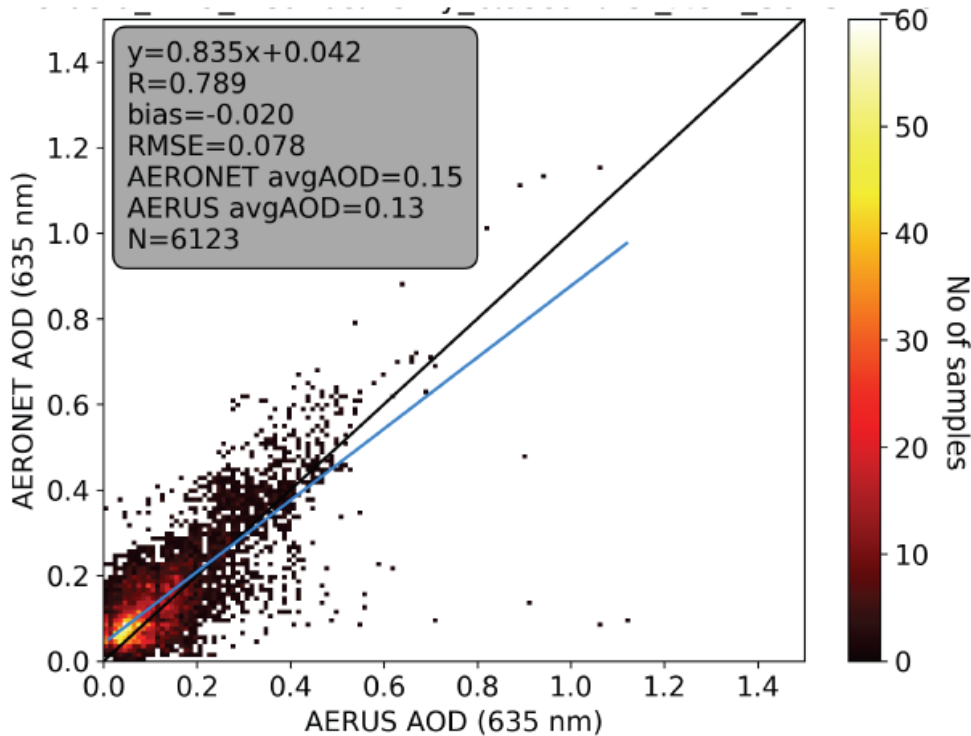


Aerosol Product from MSG : SEVIRI

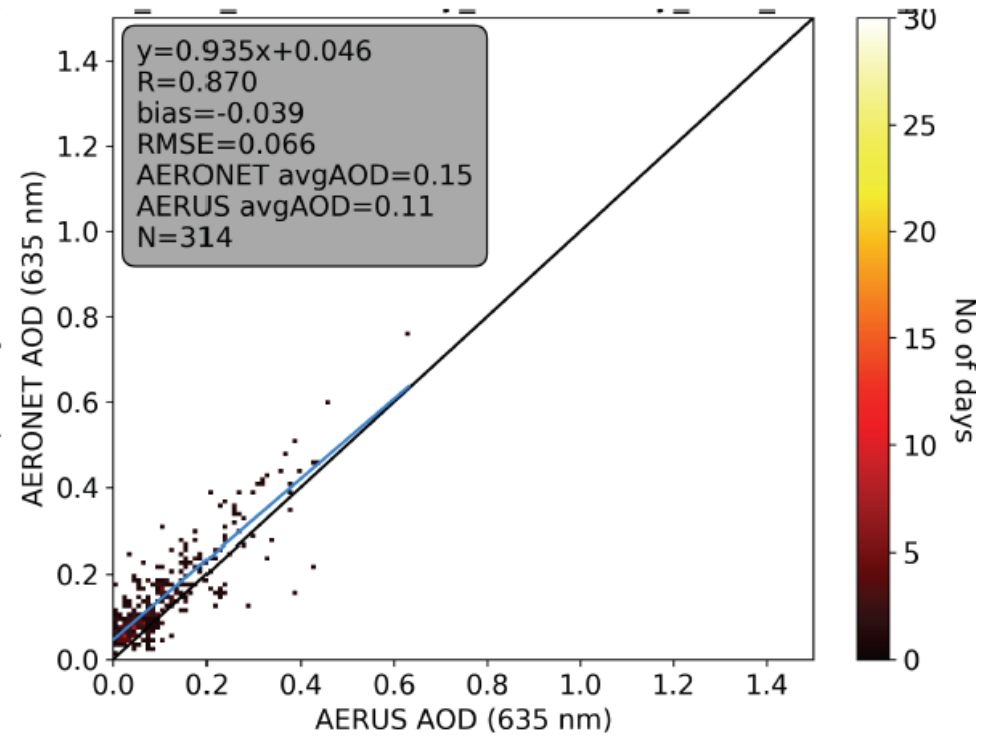
- Instantaneous retrieval with i-AERUS

- Mediterranean basin

i-AOD retrieved by *i*-AERUS-GEO



d-AOD retrieved by *d*-AERUS-GEO



Scores are similar to those of the operational *d*-AERUS-GEO

Aerosol Product from MSG to MTG

- Instantaneous retrieval with i-AERUS
 - The i-AERUS product is already at a good level of maturity
 - Good assessment of the AOD and its diurnal variation
- Clear improvements are identified for :
 - A better consideration of the aerosol type
 - A better consideration of the surface (especially for ocean)
- MTG/FCI will provide more spectral information expected to contribute to a better constrain of the retrieval

Development of Operational Aerosol Products

- Several developments on-going
- EPS PMAp already operational – improvements coming very soon
- Sentinel-3 : current development and operational product is expected to arrive soon
- Operational product under preparation for MTG - based on development with MSG
 - Assessment of the diurnal cycle for AOD
- Follow-on MAP based on the core aerosol mission 3MI and other sensors
 - Robust and accurate aerosol characterisation (AOD + other parameters)

Development of Operational Aerosol Products

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