



Aerosol Measurements from Current and Future EUMETSAT Satellites

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Input from ESA colleagues on Sentinel-3, -4, and -5 gratefully acknowledged



Outline

Products from Current Missions

Metop PMAp product

MSG Aerosol Optical Depth

Products from Future Missions

3MI on EPS-SG

Sentinel-5 on EPS-SG

Sentinel-4 on MTG-S

Sentinel-3 (see presentation by S. Pinnock)



Products from Current Missions

- **PMAp**: Polar Multi-sensor Aerosol product developed at EUMETSAT (M. Grzegorski, G. Poli & A. Holdak)
 - AOD over ocean & cloud products operational in Q1 2014
 - AOD over land (PMAp second generation)
- MSG Aerosol Optical Depth Product



PMAp: Overview

- A few words about GOME-2 PMD measurements
- **PMAp**: **P**olar **M**ulti-sensor **A**erosol **p**roduct developed at EUMETSAT
 - AOD over ocean & cloud products operational in Q1 2014
- Examples and Verifications
- Work in progress & future plans
- First results: AOD over land (PMAp second generation)



PMAp: METOP instruments within the project

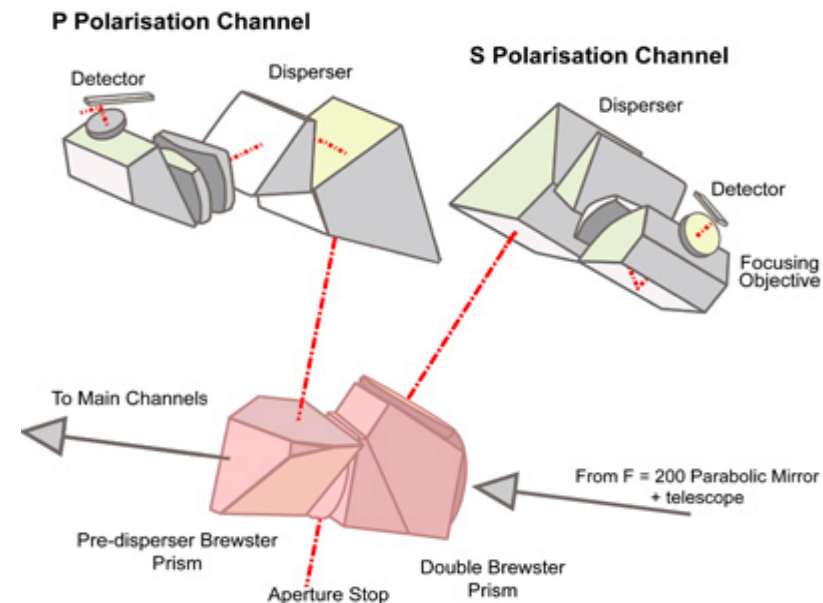
Instrument		Spatial resolution	Spectral range	comments
GOME	Main science channel	80 x 40 km	240nm -800nm, res. 0.25-0.5nm	AAI, poor spatial resolution
	Polarization Monitoring Device	10 x 40 km	311nm-803nm, 15 bands	AOD, aerosol type, AAI
AVHRR	-	1.08 x 1.08 km	580nm-12500nm, 5 bands	Clouds, scene heterogeneity, desert dust
IASI	-	12km (circular)	3700–15500nm, resolution 0.5 cm ⁻¹	Coarse mode aerosols (desert dust, volcanic ash)
Auxiliary data	ECMWF wind speed (forecasting)	Temporal interpolation necessary	-	Required for retrievals over ocean
	Surface albedo, Surface elevation	-	-	Required for land surface retrievals



PMaP: The Polarization Monitoring Devices

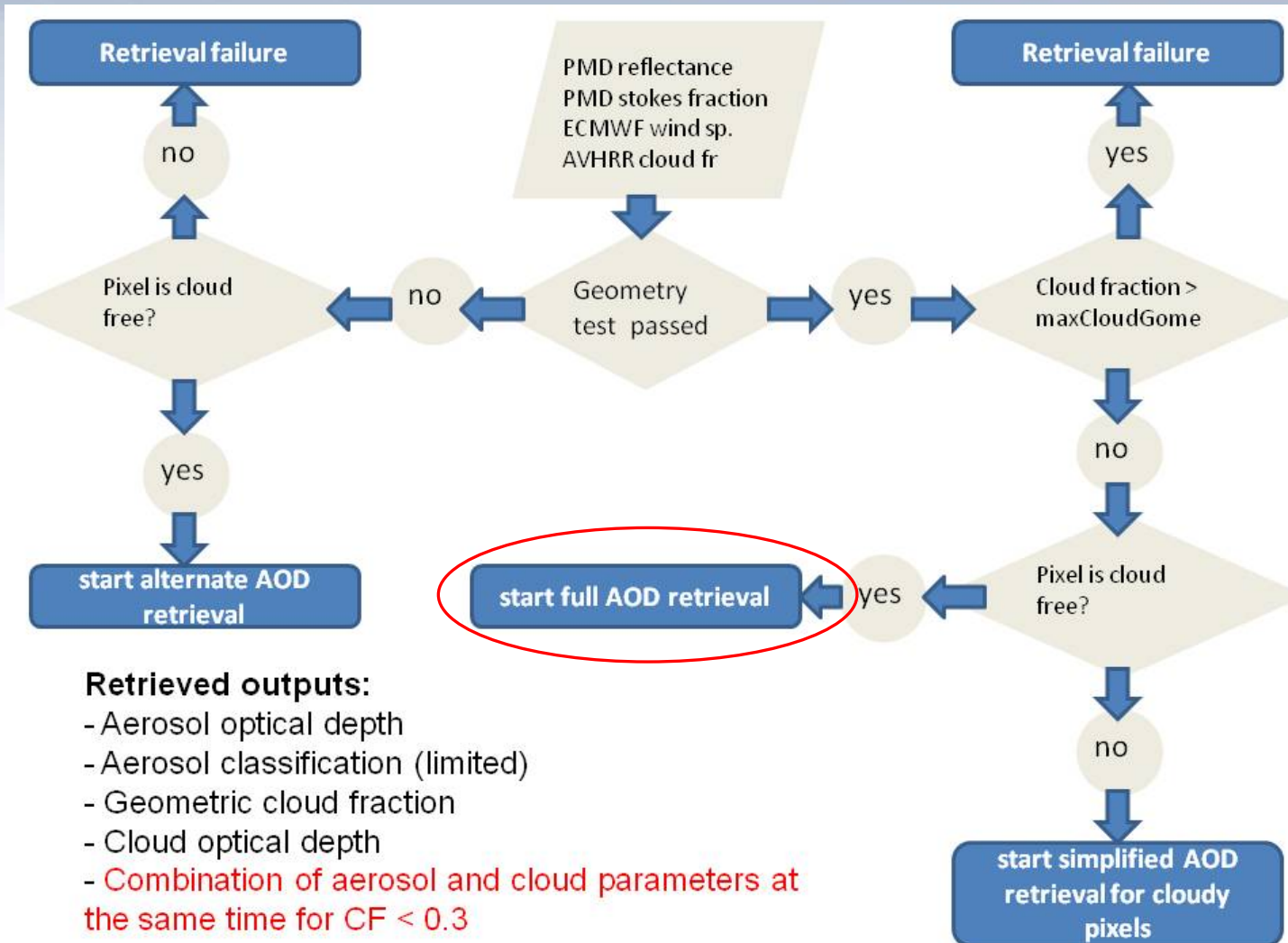
Band-S				
No.	pix1	pixw.	wav1	wav2
1	22	5	311.709	314.207
2	30	4	316.762	318.720
3	37	12	321.389	329.139
4	50	6	330.622	334.443
5	57	6	336.037	340.161
6	84	17	360.703	377.873
7	102	4	380.186	383.753
8	117	19	399.581	428.585
9	138	27	434.083	492.066
10	165	18	494.780	548.756
11	183	2	552.474	556.262
12	187	11	568.070	612.869
13	198	9	617.867	661.893
14	218	4	744.112	768.269
15	224	2	794.080	803.072

- Radiances & stokes fraction
- better spatial resolution
- stokes fraction $s = Q/I$





PMAp: AOD retrieval algorithm



Retrieved outputs:

- Aerosol optical depth
- Aerosol classification (limited)
- Geometric cloud fraction
- Cloud optical depth
- **Combination of aerosol and cloud parameters at the same time for CF < 0.3**

- Geometry dependent test with inter-comparison of:

- calculated surface signal
- calculated wind speed dependence
- calculated aerosol signal

- Cloud filter:

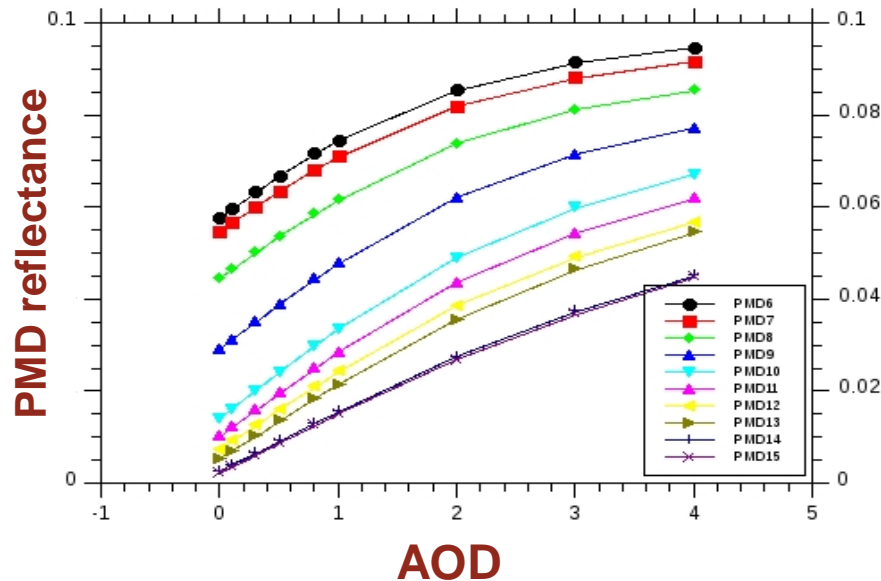
- AVHRR/VIS
- AVHRR/IR



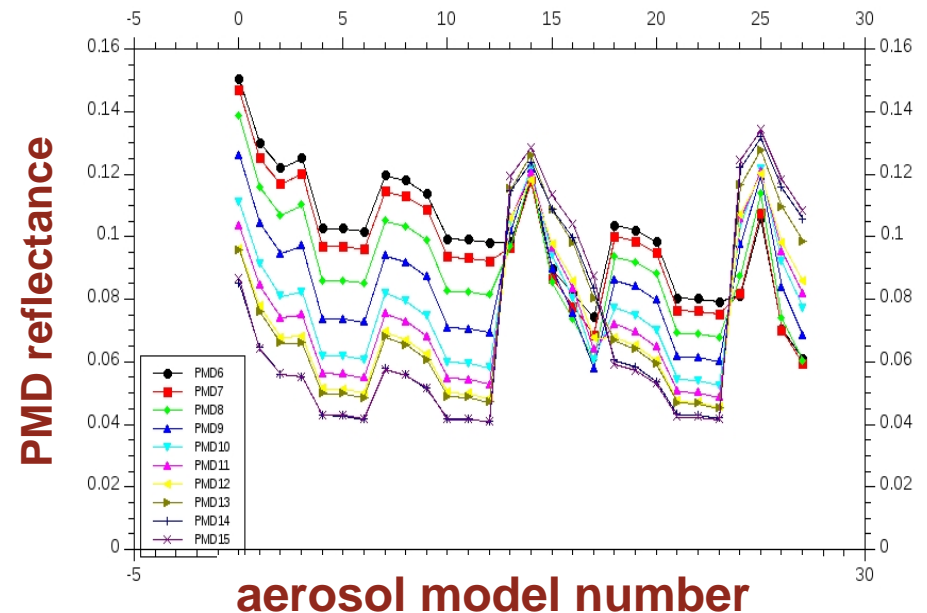
PMAp best case: Retrieval clear sky & dark surface

- **Step 1:** A set of AODs (for 8 selected models) and chlorophyll corrections is estimated using three channels: **UV [380 nm]**, **VIS/green [520 nm]**, **red edge [800 nm]** using least-square minimization. AOD interpolation done at 800nm.
- **Step 2:** Selection of a aerosol type / chlorophyll / AOD set using least-square minimization of measured and modelled reflectances in all PMD channels. **Stokes fractions are used in addition if applicable.**

SAZA=40, nadir, aerosol model 3

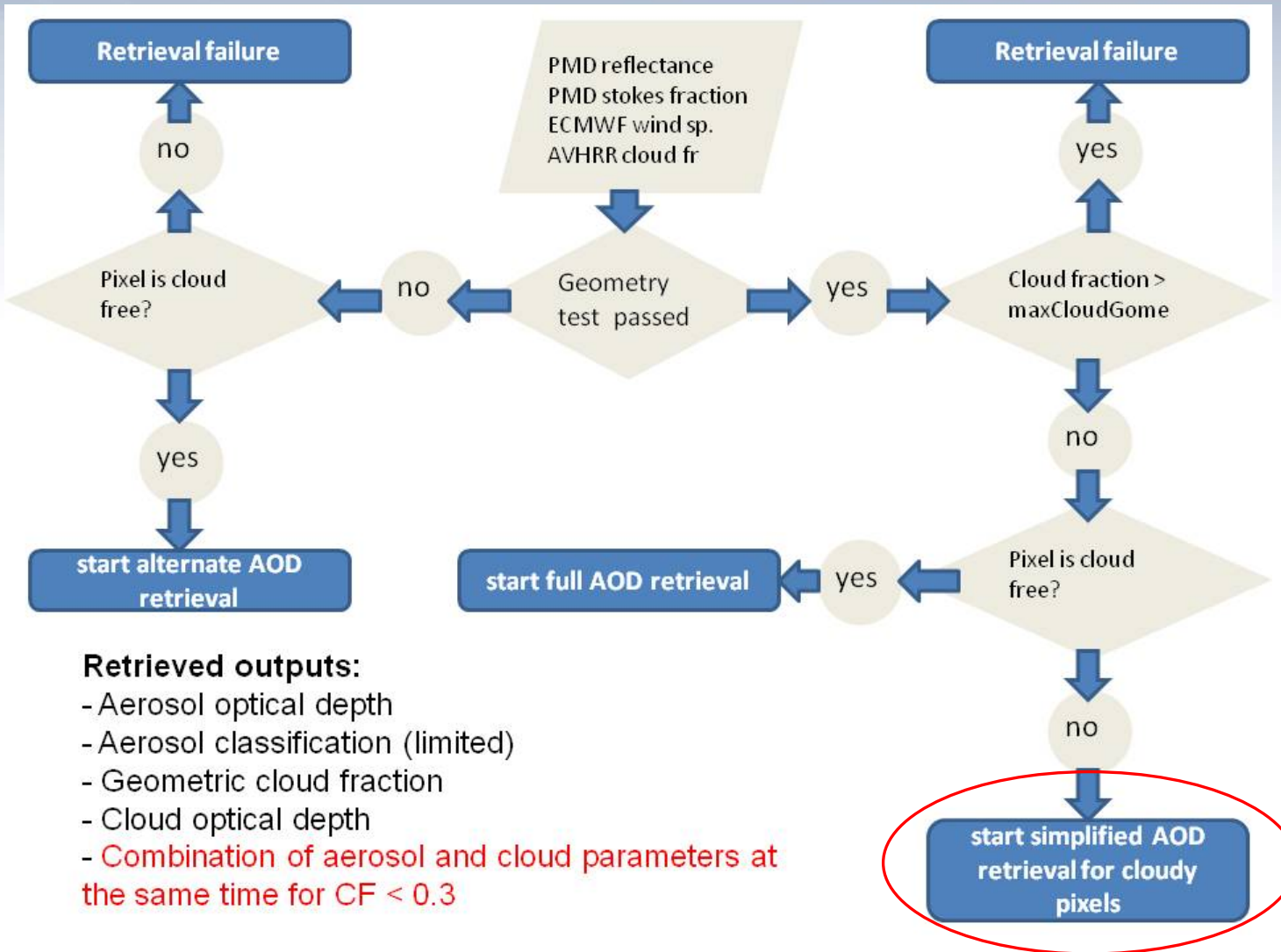


SAZA=40, cos(RAZI)=-1, VZA=45, AOD=4





PMAp: AOD retrieval algorithm



Retrieved outputs:

- Aerosol optical depth
- Aerosol classification (limited)
- Geometric cloud fraction
- Cloud optical depth
- **Combination of aerosol and cloud parameters at the same time for CF < 0.3**

- Geometry dependent test with inter-comparison of:

- calculated surface signal
- calculated wind speed dependence
- calculated aerosol signal

- Cloud filter:

- AVHRR/VIS
- AVHRR/IR



PMAp: Cloud correction by AVHRR



- AVHRR cloud tests:
 - Albedo test
 - T4 test
 - Uniformity test
 - T4T5 test
- Retrieval for partly cloudy pixels:
 - Limitation to PMD 13/15
 - Correct for cloud reflectance

Channel	Central wavelength[μm]	Wavelength range [μm]
1	0.630	0.580 - 0.680
2	0.865	0.725 - 1.000
3A	1.610	1.580 - 1.640
3B	3.740	3.550 - 3.930
4	10.800	10.300- 11.300
5	12.000	11.500- 12.500

Geometric cloud fraction:

$$CF(GOME) = \frac{n_{cloudy}(AVHRR)}{n_{collocated}(AVHRR)}$$

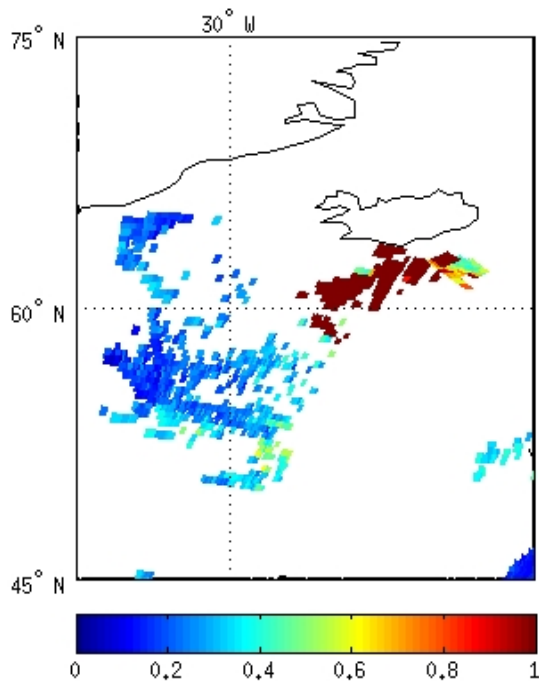
$$R_{cloudfree}(PMD) = R_{all}(PMD) \frac{\tilde{R}_{clearsky}(AVHRR)}{R_{allpixel}(AVHRR)}$$



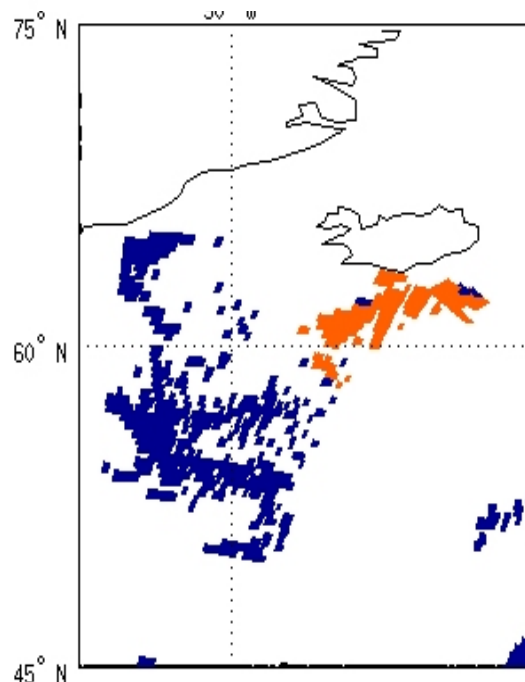
PM_{Ap}: Identify pixels misclassified as cloud Volcanic ash

- Brightness temperature difference T₄-T₅ (10 μm – 12 μm)
- Thresholds in VIS and NIR (e.g. AVHRR CH3A/CH2)

Aerosol optical depth



Volcanic ash flag:



Orange: Strong ash test positive, cloud tests ignored

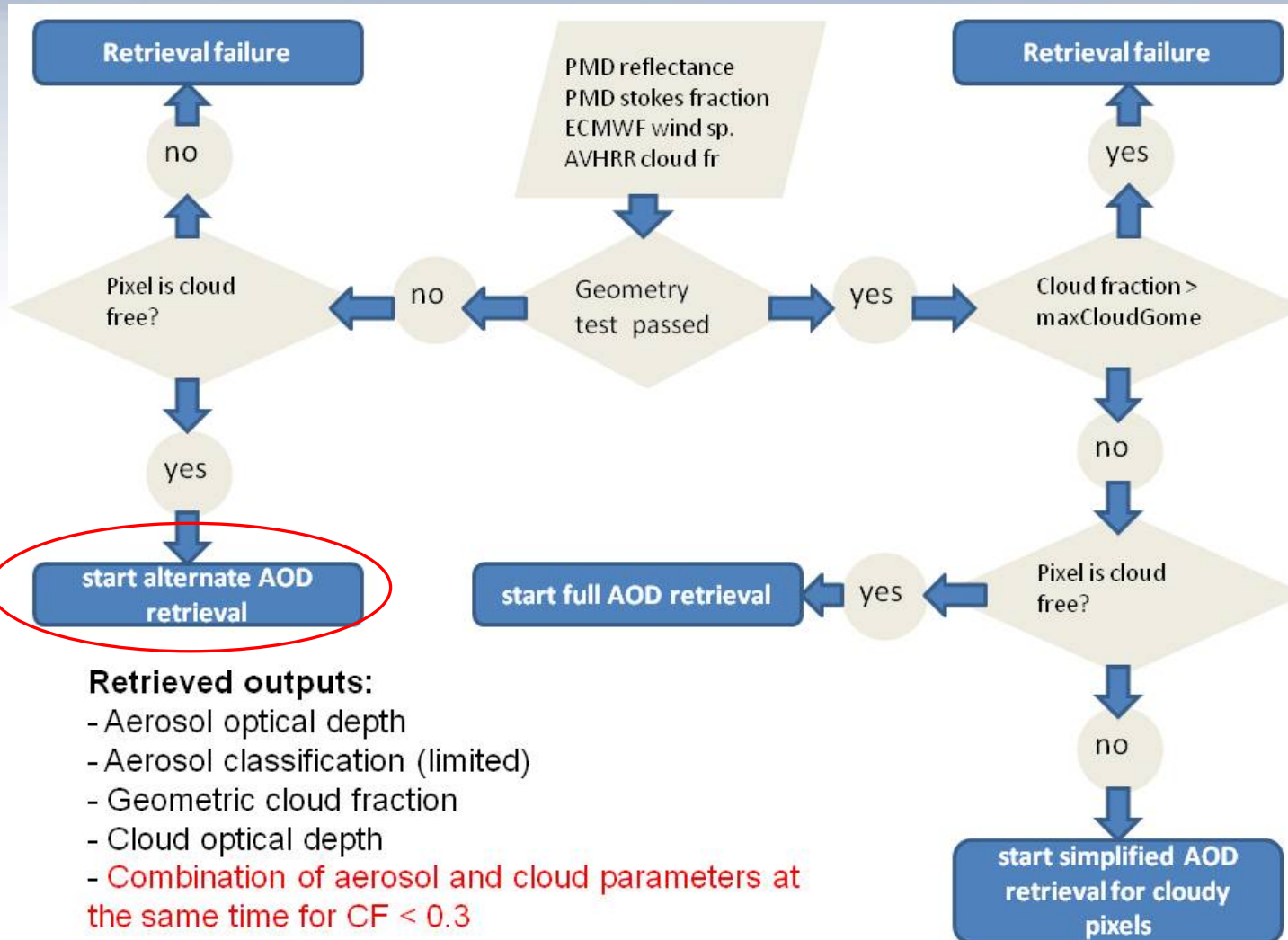
Blue: cloud fraction < 0.3, AOD retrieved

White:

- no retrieval or
- cloud fraction > 0.3 and negative ash test



PMAp: AOD retrieval algorithm



- Geometry dependent test with inter-comparison of:

- calculated surface signal
- calculated wind speed dependence
- calculated aerosol signal

- Cloud filter:

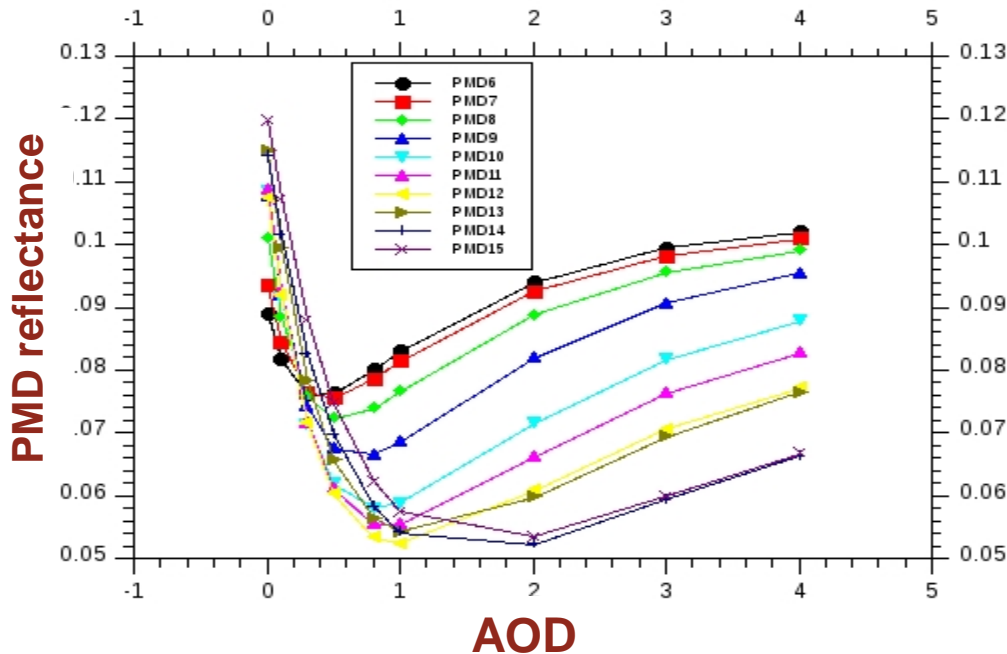
- AVHRR/VIS
- AVHRR/IR

PMAp: Alternate retrieval combining reflectances & stokes fractions

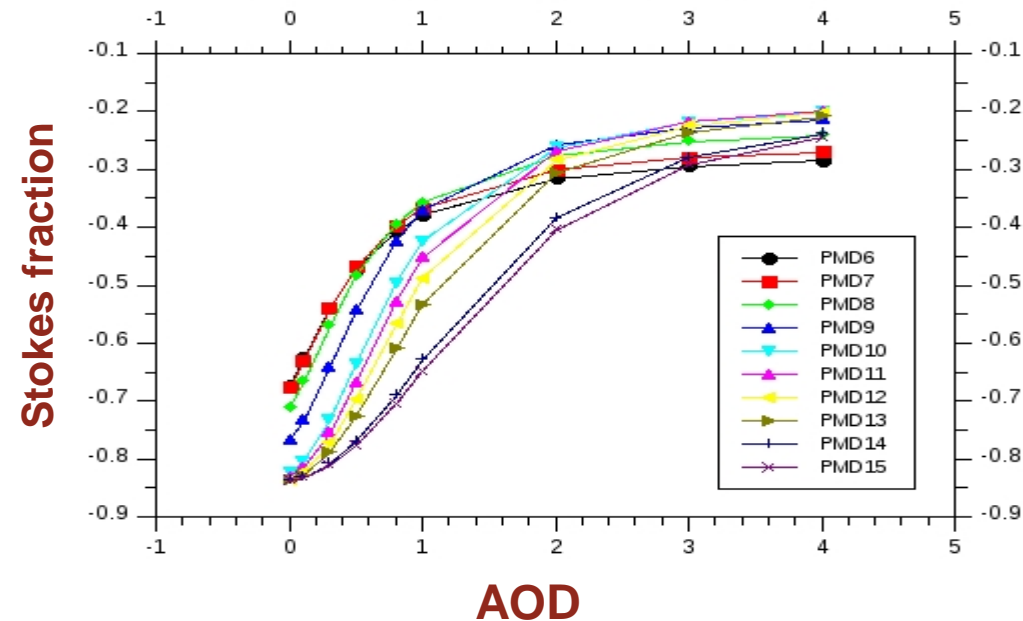
- Guess an AOD using one channel (reflectance or stokes fraction) using different aerosol models and a priori surface

- Check reliability:
$$\chi^2 = \sum_N \frac{(I_{measured} - I_{modelled})^2}{I_{modelled}^2} + \sum_M \frac{(q_{measured} - q_{modelled})^2}{q_{modelled}^2} < MAX$$

Reflectances close to sun glint conditions

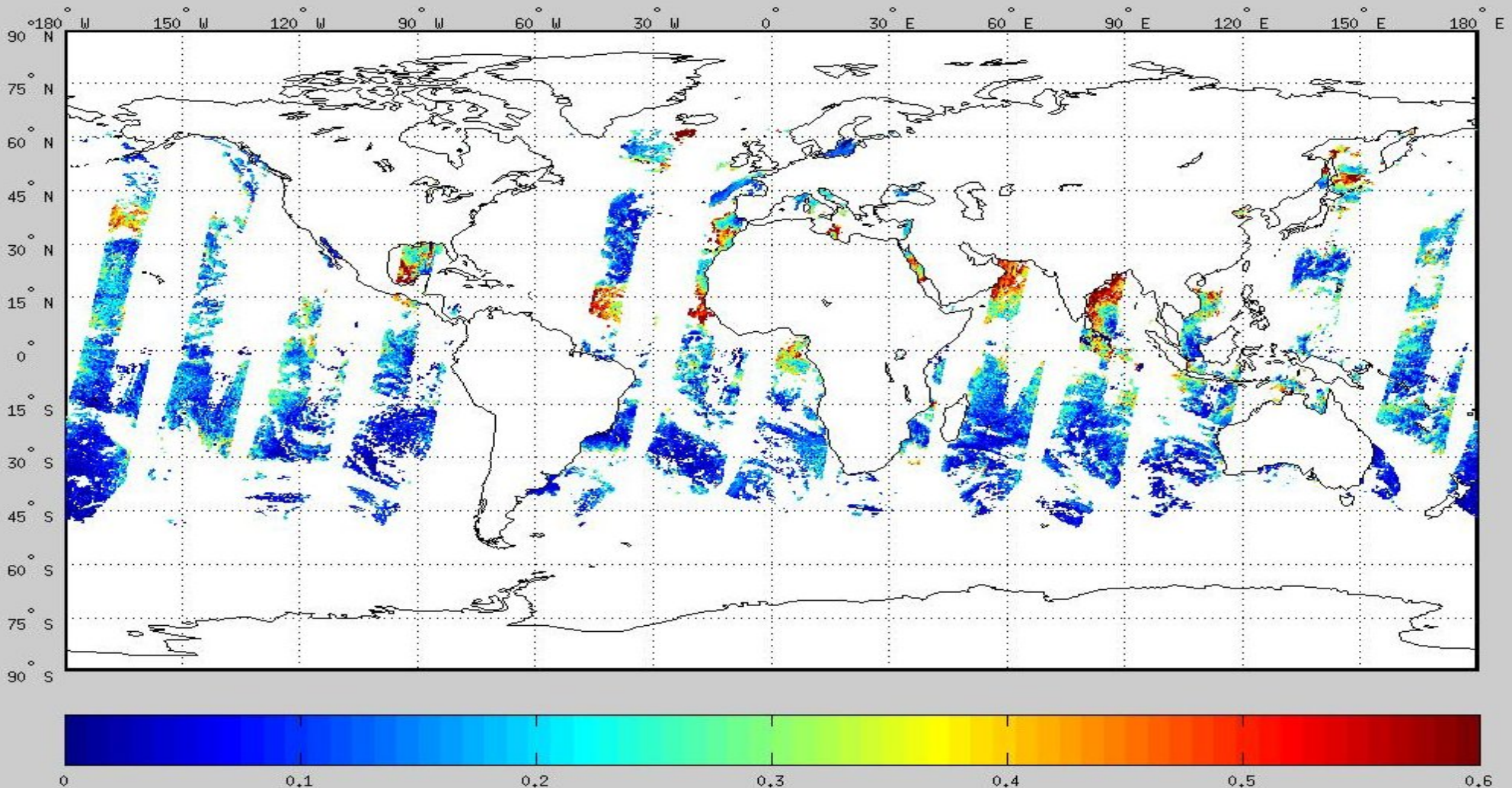


stokes fractions close to sunglint conditions



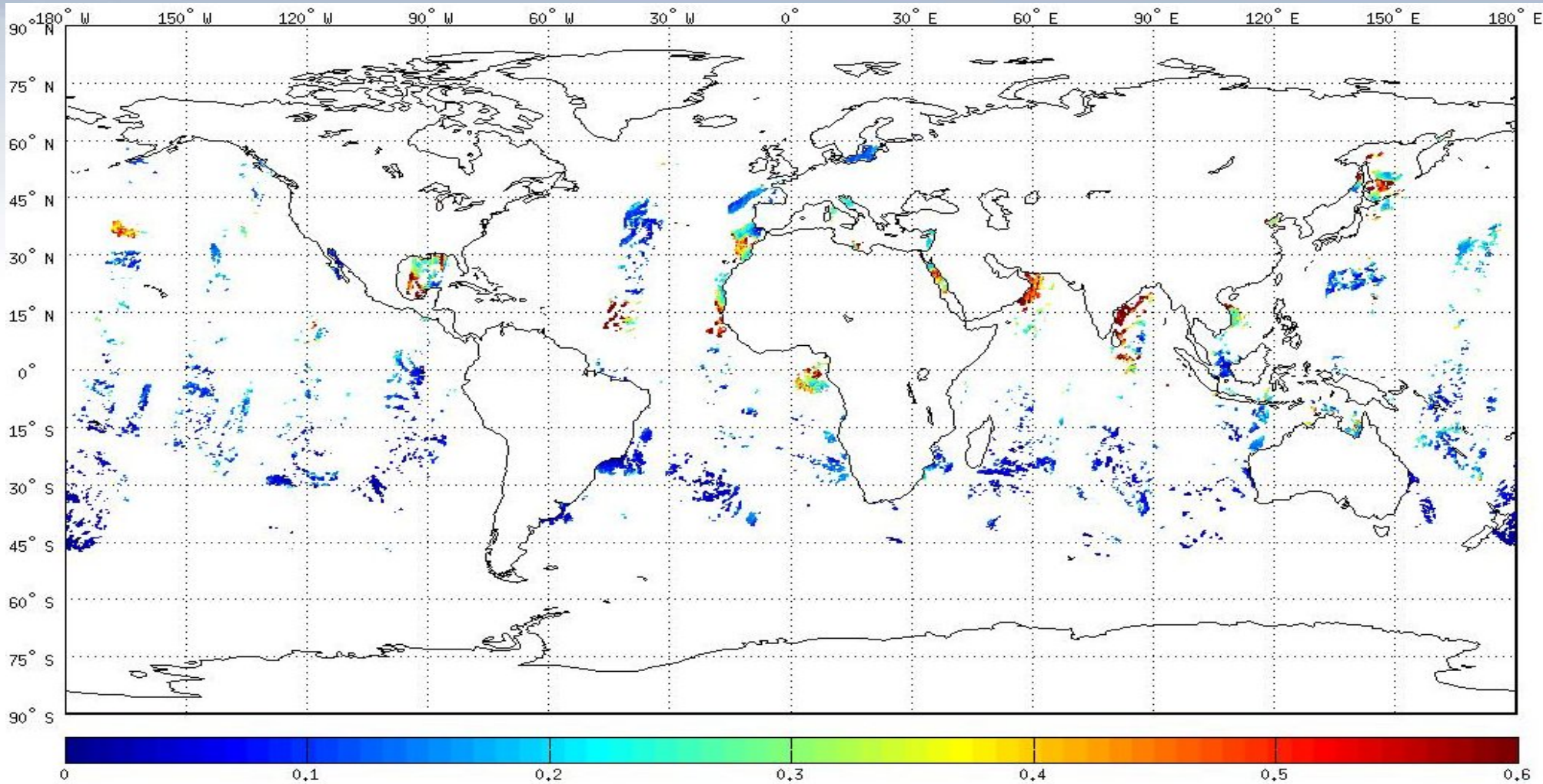


PMAP Results: Aerosol Optical Depth (23/05/2011)





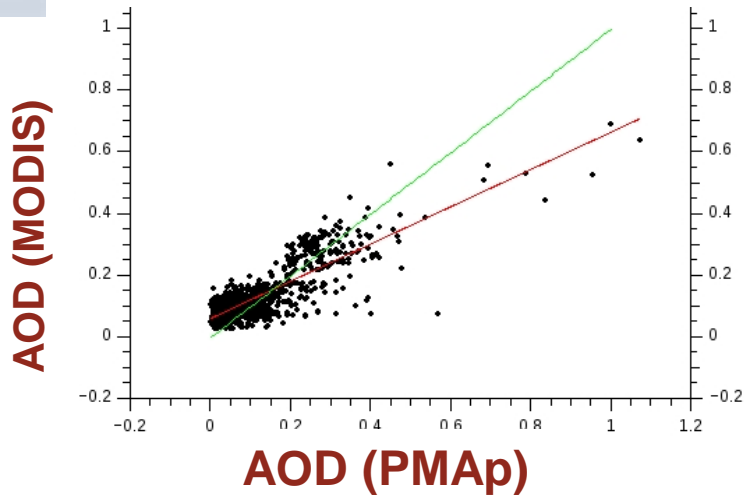
PMAP Results: AOD clear sky cases (23/05/2011)



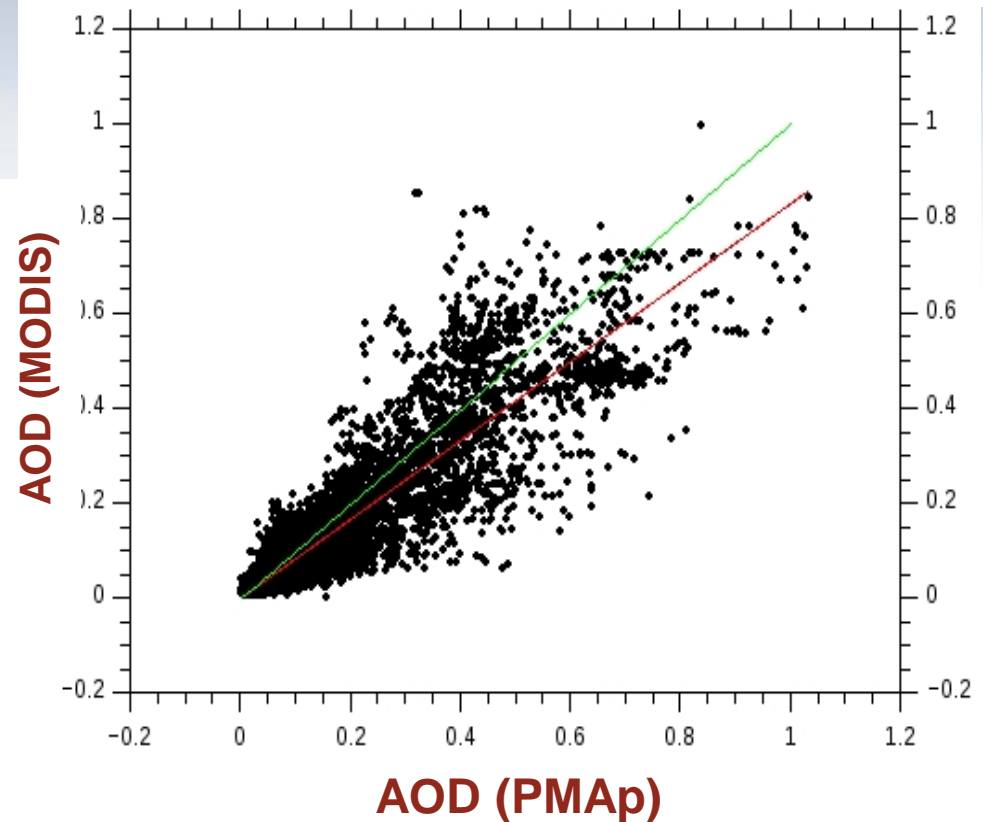


Verification of PMAp: Comparison to MODIS

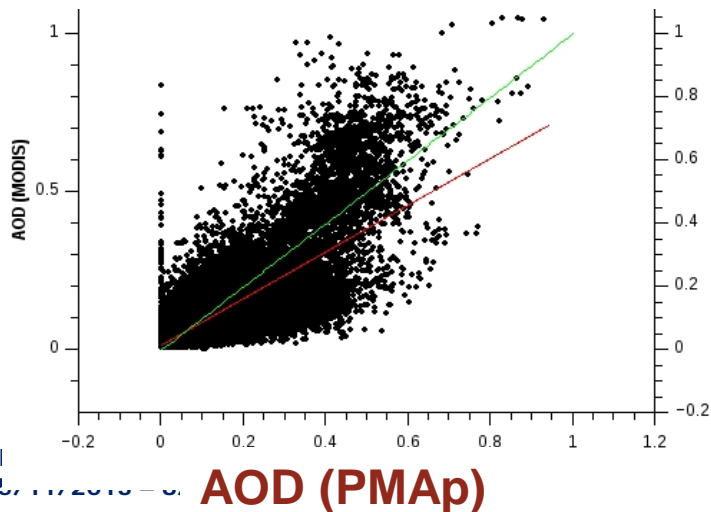
Alternate retrieval R = 0.83



Main retrieval R = 0.89



Cloudy pixels R = 0.71

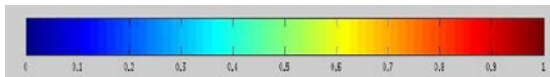
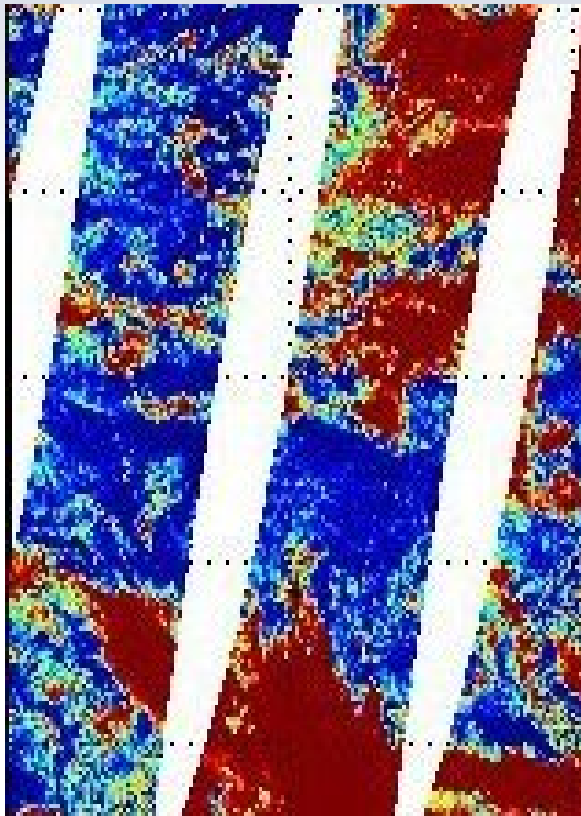


Overpass difference: 1.0h MODIS / Terra and METOP

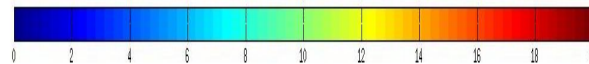
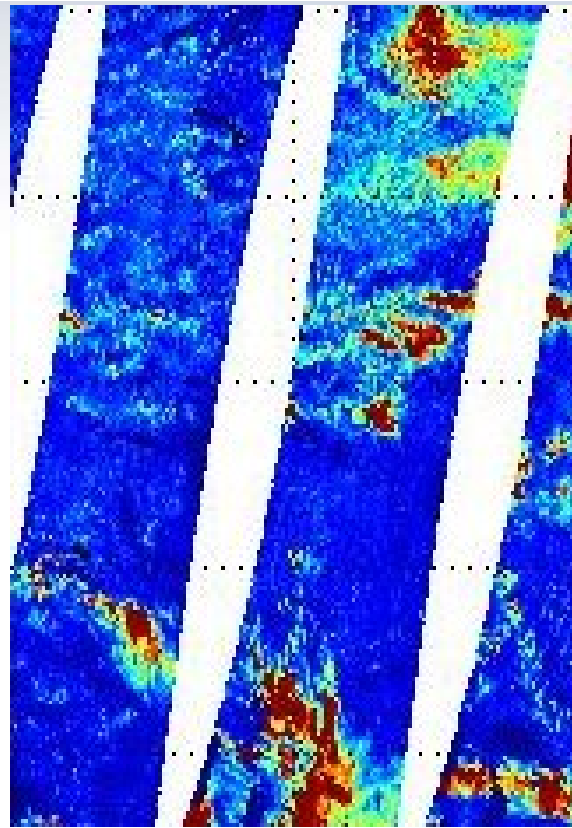


PMaP: Cloud products

PMaP: cloud fraction

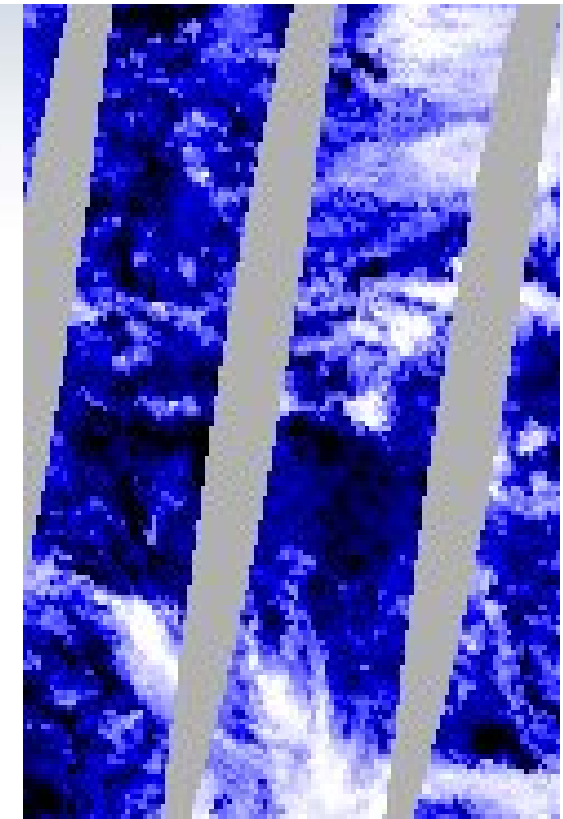


PMaP: cloud optical depth



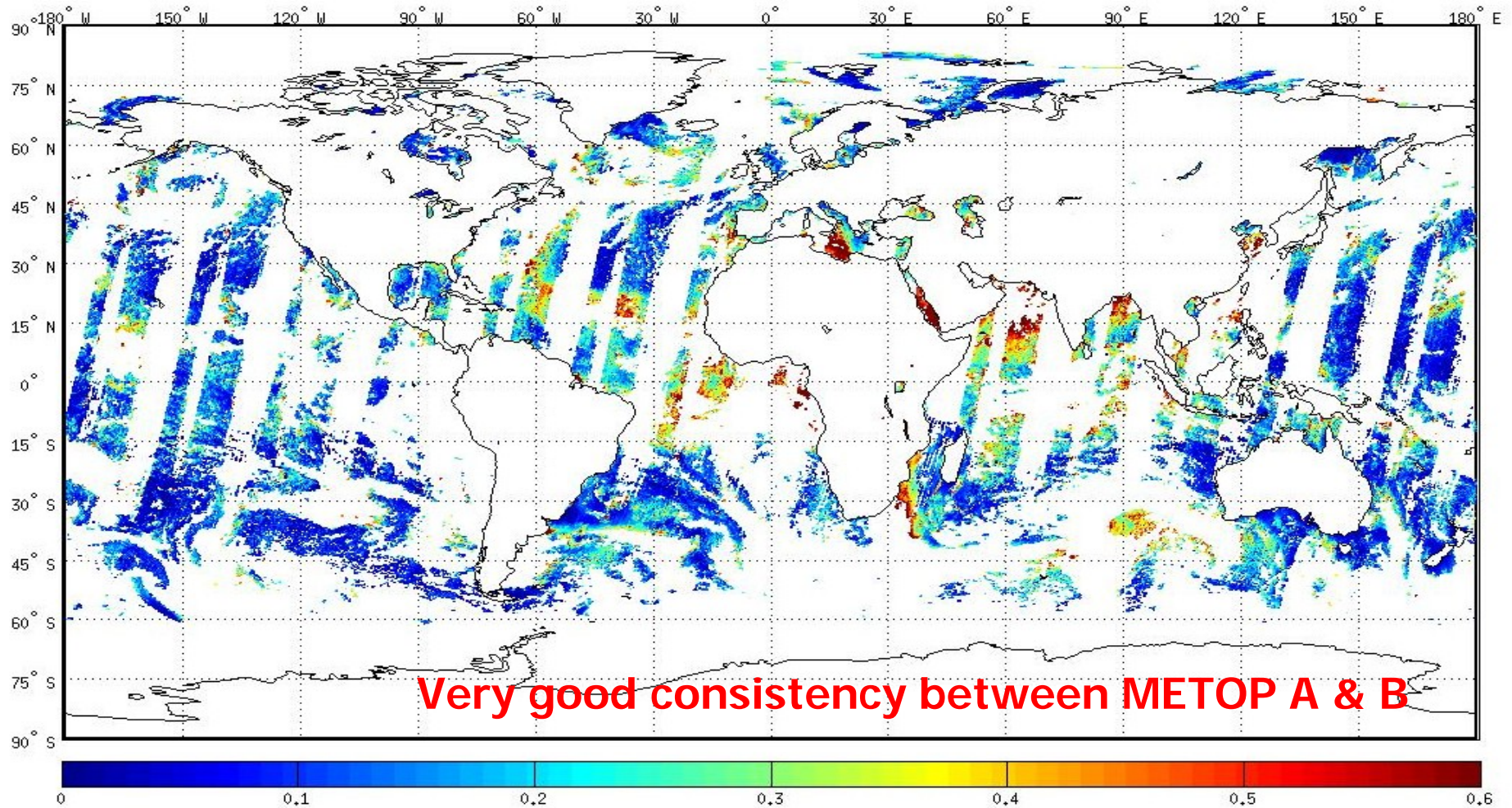
FRESCO (www.temis.nl)

Effective cloud fraction





PMAp Tandem Operations: AOD Metop A & Metop B



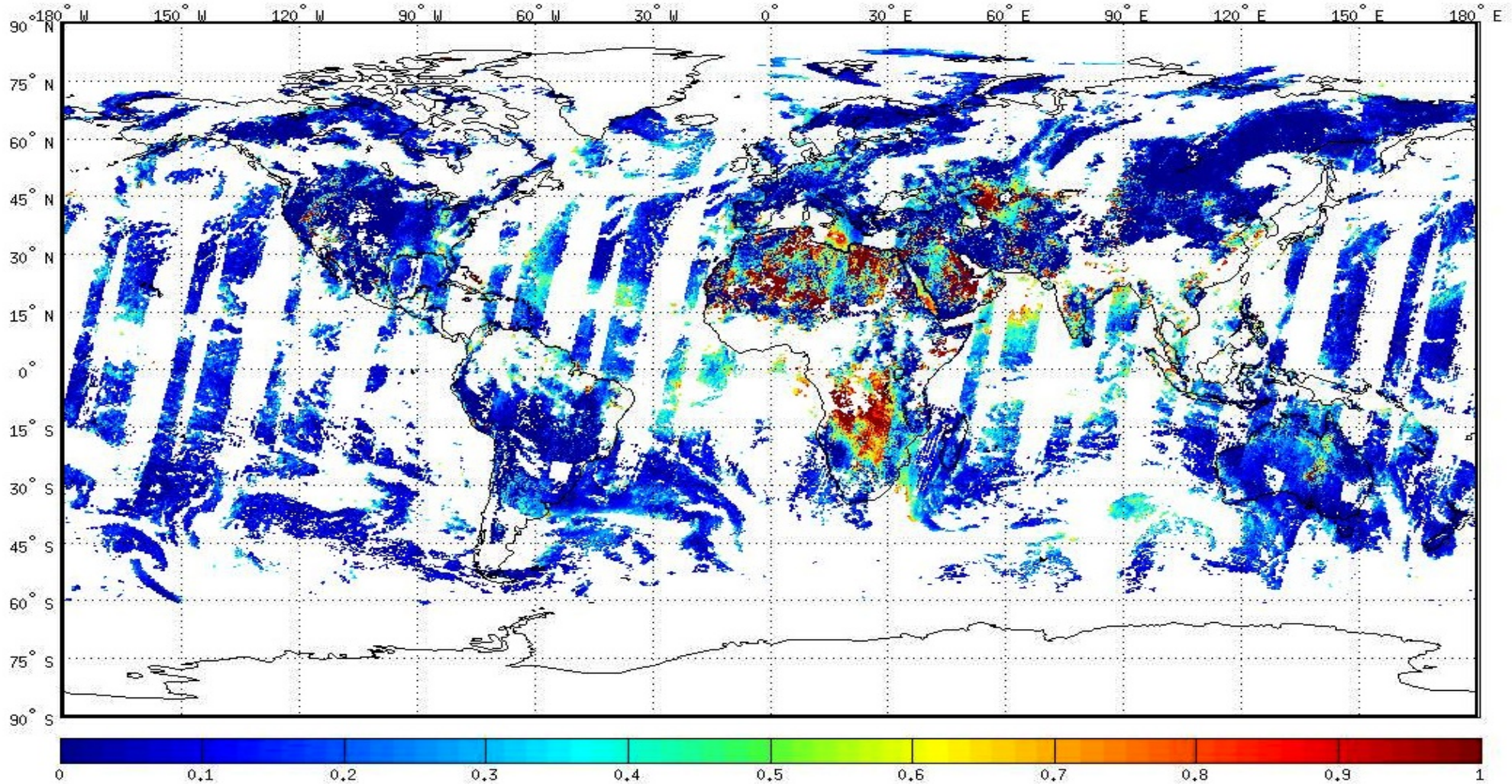


PMAP Looking forward: Algorithms in development

- Extension of the AOD retrieval to pixels over land (preliminary land retrieval available on prototype level)
 - AOD interpolation for different aerosol types at 460nm
 - AOD type selection using different aerosol indices between 370-460nm
 - Corrections for partly cloudy pixels combining GOME and AVHRR around 630nm
- A dedicated volcanic ash retrieval is currently being developed using the same framework:
 - Temperature differences & NDVI (AVHRR)
 - Shape of the IASI spectra (e.g. concept of Lieven Clarisse)
 - GOME-2 UV ratio



PMAp AOD over Land: First results (30/08/2013)





PMAp: Conclusions

- A new aerosol product over ocean from METOP instruments (PMAp) will be provided to users (operational in Q1/2014)
- The aerosol product is developed using a multi-instrument approach combining GOME, AVHRR and IASI
- AOD will be retrieved for clear-sky and partly cloudy scenes
- Cloud fraction, cloud optical depth and limited information on aerosol type like volcanic ash is provided in addition
- Verifications of the algorithms show promising results

- The second generation will provide AOD over land and an improved multi-sensor retrieval of volcanic ash



PMAP: Conclusions

Test Users Welcomed

For test data please contact

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Rosemary.Munro@eumetsat.int

For scientific collaboration please contact

Michael.Grzegorski@eumetsat.int



MSG Aerosol Optical Depth Product

- The MSG Aerosol product development will initially focus on an evaluation of the ATBD and prototype processor which have been provided by Météo-France
 - “Daily Estimate of Aerosol Optical Thickness Over Land Surface based on a Directional and Temporal Analysis of SEVIRI MSG Visible Observations”, JGR, Vol. 115, D10208, 2010.”
- Potential for extension to a three hourly product is under evaluation



Products from Future Missions

EPS-SG

- 3MI
- Sentinel-5 (UV/Vis/NIR/SWIR spectrometer)
- *IASI-NG (infrared spectrometer)*
- *METimage (imager)*

EPS-SG EUMETSAT Polar System - Second Generation (I)

- Follows the EUMETSAT Polar System (EPS)
- 2020-2040 timeframe
- Contributes to the Joint Polar System being jointly set up with NOAA
- Two-satellite configuration: Metop-SG-A and -B flying in the same orbit, separated by 180°
- Metop-like orbit:
 - sun synchronous
 - low earth orbit at 832 km mean altitude
 - 09:30 local time of the descending node

More information:

<http://www.eumetsat.int/Home/Main/Satellites/EPS-SG>



EPS-SG

 **EUMETSAT**



EPS-SG EUMETSAT Polar System - Second Generation (II)

- EPS-SG will carry a dedicated multi-angle, multi-polarisation, multi-spectral aerosol mission, **3MI** also the **Copernicus Sentinel 5** (provided by ESA)
- Sentinel-5, in addition to the species measured by GOME-2, will also measure CO and CH₄, all at significantly higher spatial resolution.
- In addition there will be an improved infrared sounder **IASI-NG** with enhanced capabilities for measuring atmospheric trace gases
- This will be complemented by an improved imaging instrument **MetImage** that can detect aerosol optical thickness and size distribution.



3MI on EPS-SG

*The Multi-Viewing, -Channel, -Polarisation Imaging (3MI) Mission of the EUMETSAT Polar System - Second Generation (EPS-SG)
- dedicated to aerosol characterisation*

Dedicated to aerosol characterisation for:

- Climate monitoring
- Air quality monitoring and forecasting
- Numerical Weather Prediction

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

Provide 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)

POLDER heritage

Synergy with METimage, Sentinel-5 and IASI-NG (satellite-A)



3MI: Geophysical Products

Primary objectives: HQ imagery of aerosol variables over ocean and land

- AODs for accumulation, coarse and total modes at high horizontal resolution
- Aerosol particle size for accumulation, coarse and total modes.
- Aerosol type through Ångström exponent, refractive index, non-sphericity index
- Aerosol height index
- Aerosol absorption

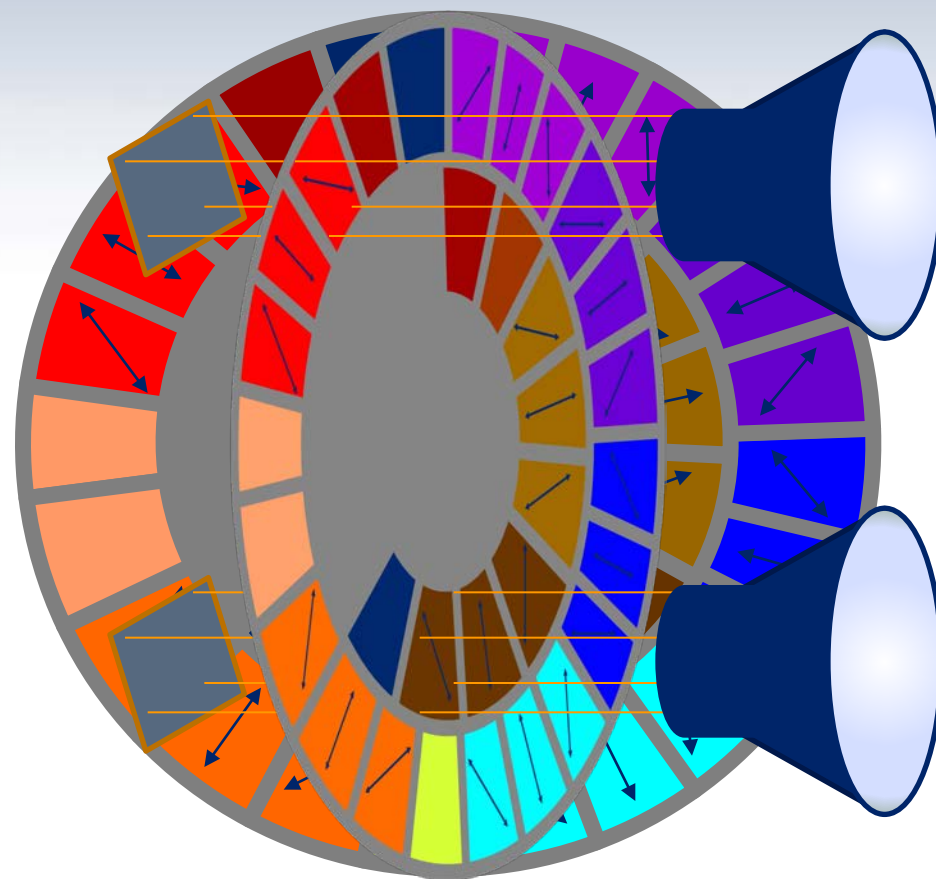
Secondary objectives:

- Improved cloud characterisation through cloud imagery, COD, CTH, and cloud microphysics (phase and effective particle size)
- Land surfaces (surface albedo, BRDFs)
- Vegetation (e.g. Leaf area index, Vegetation type, Fraction of vegetated land)

3MI: Channels

Channel centre and width Polarisation Optical head

410 nm 20 nm	Yes	VNIR Optical head
443 nm 20 nm	Yes	
490 nm 20 nm	Yes	
555 nm 20 nm	Yes	
670 nm 20 nm	Yes	
763 nm 10 nm	No	
754 nm 20 nm	No	
865 nm 40 nm	Yes	
910 nm VNIR 20 nm	No	SWIR Optical head
910 nm SWIR 20 nm	No	
1370 nm 40 nm	Yes	
1650 nm 40 nm	Yes	
2130 nm 40 nm	Yes	



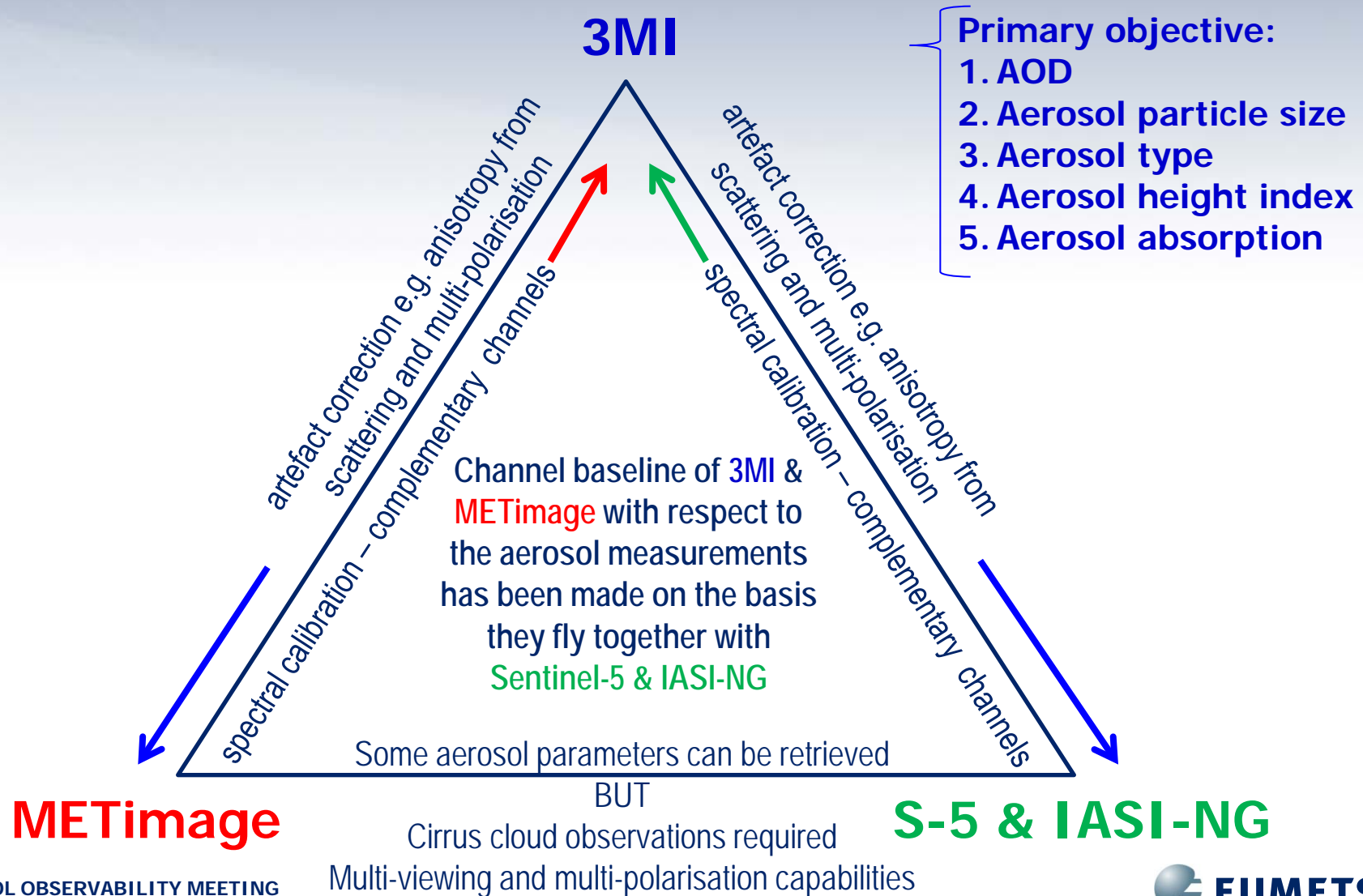


3MI: Channels

Channel centre and width		Polarisation	Optical head	Primary Use
410 nm	20 nm	Yes	VNIR Optical head	Absorbing aerosol and ash cloud monitoring
443 nm	20 nm	Yes		Aerosols absorption and height indicators
490 nm	20 nm	Yes		Aerosol, surface albedo, cloud reflectance, cloud optical depth
555 nm	20 nm	Yes		Surface albedo
670 nm	20 nm	Yes		Aerosols properties
763 nm	10 nm	No		Cloud and aerosols height
754 nm	20 nm	No		Cloud and aerosols height
865 nm	40 nm	Yes		Vegetation, aerosol, clouds, surface features
910 nm	VNIR 20 nm	No		Water vapour , atmospheric correction
910 nm	SWIR 20 nm	No		SWIR Optical head
1370 nm	40 nm	Yes	Cirrus clouds, water vapour imagery	
1650 nm	40 nm	Yes	Ground characterisation for aerosol inversion	
2130 nm	40 nm	Yes	Ground characterisation for aerosol inversion, Cloud microphysics at cloud top, Vegetation, fire (effects)	



3MI: Synergy with other EPS-SG Instruments





Sentinel-5: Overview

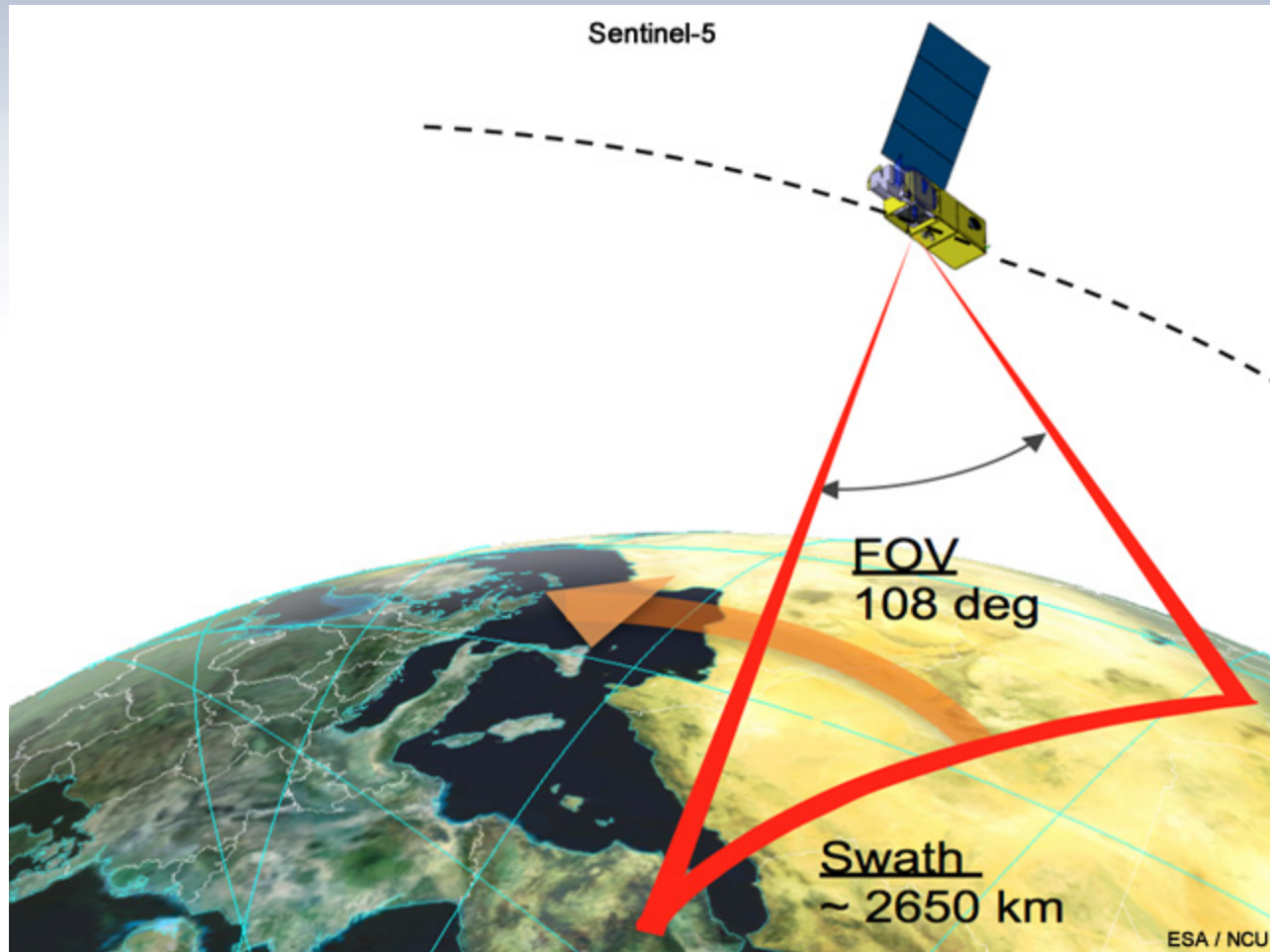
Sentinel 5 Mission Objectives

- Monitoring of the composition of the atmosphere for Copernicus Atmosphere Services
 - Sources of trace gases and aerosols impacting air quality and climate
 - Major target trace gases are O₃, NO₂, CO, SO₂, CH₂O and CH₄
 - Services proposed will cover air quality near real-time applications, air quality protocol monitoring, and climate protocol monitoring
- Will take advantage of collocated measurements taken at the same time by METimage, IASI-NG and 3MI which will provide more information on clouds and deliver improved understanding of atmospheric composition, most notably in the troposphere
- The high spatial resolution will enable more accurate detection of emission sources and provide an increased number of cloud-free ground pixels.



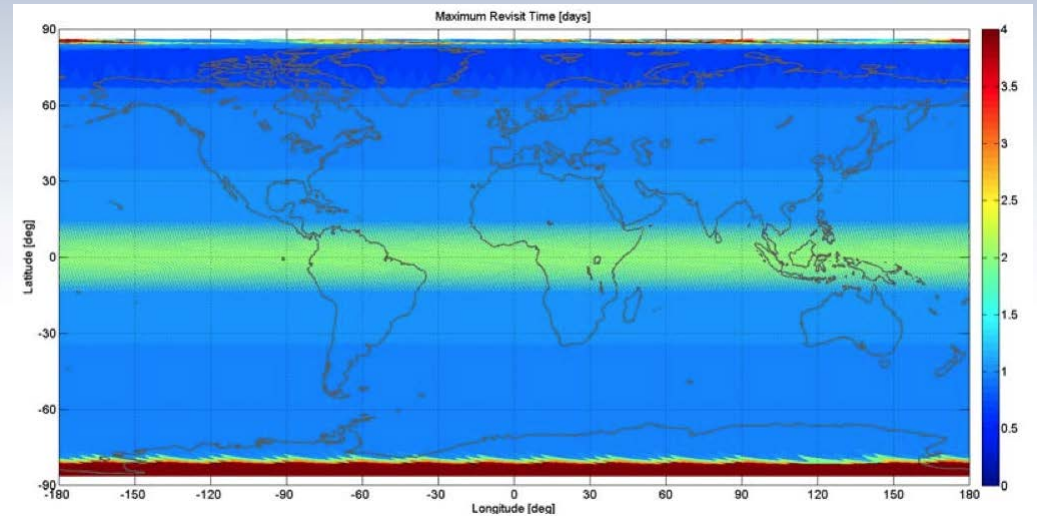
Sentinel-5: Key Features (I)

- Sentinel-5 will build on the heritage from the GOME/SCIAMACHY/GOME-2/OMI series of instruments and will provide continuity with these instruments.
- The spatial resolution will be significantly improved as compared to previous missions, which is important to support development of air quality applications.

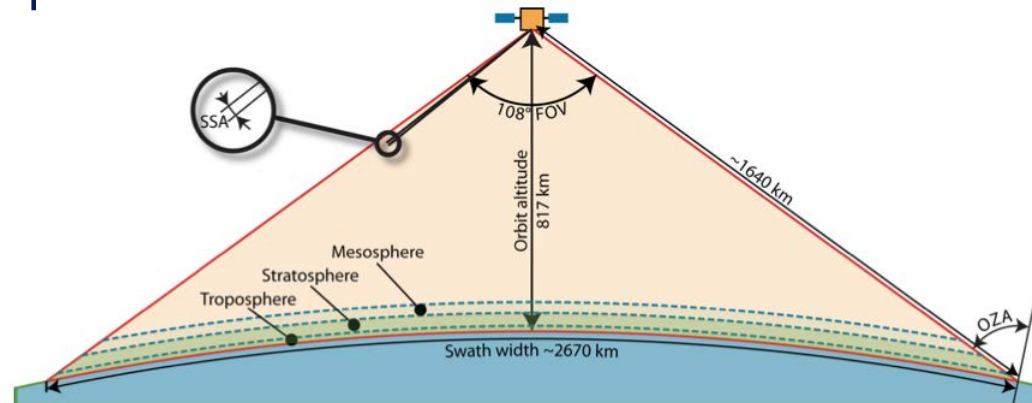


Sentinel-5: Key Features (II)

Daily Global Coverage
(at latitude beyond 20 deg)



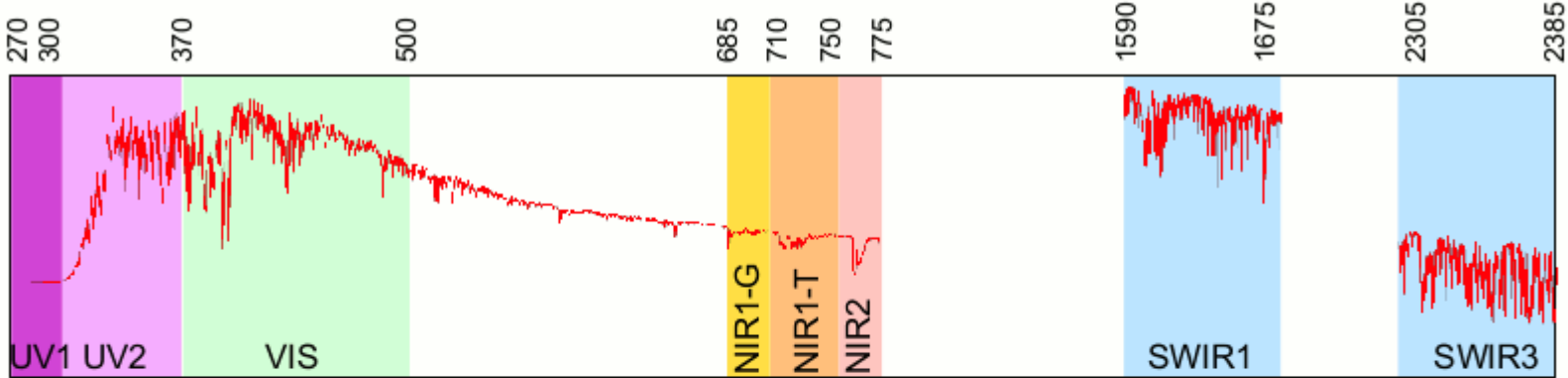
Large field of view required = 108.4°



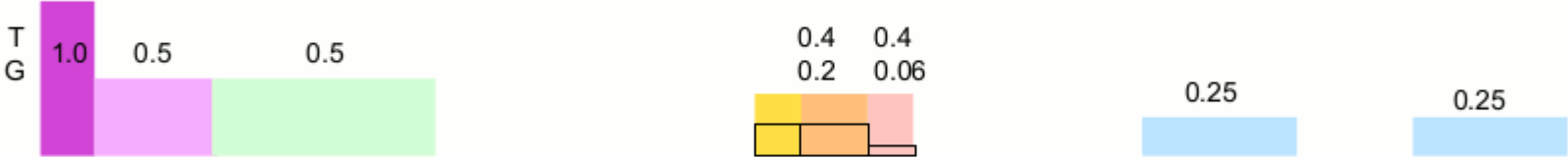


Sentinel-5: Key Features (III)

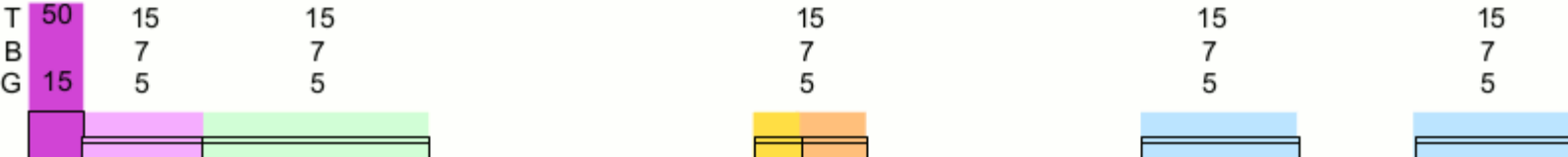
Spectral bands



Spectral resolution (nm)



Spatial Sampling Distance (km)





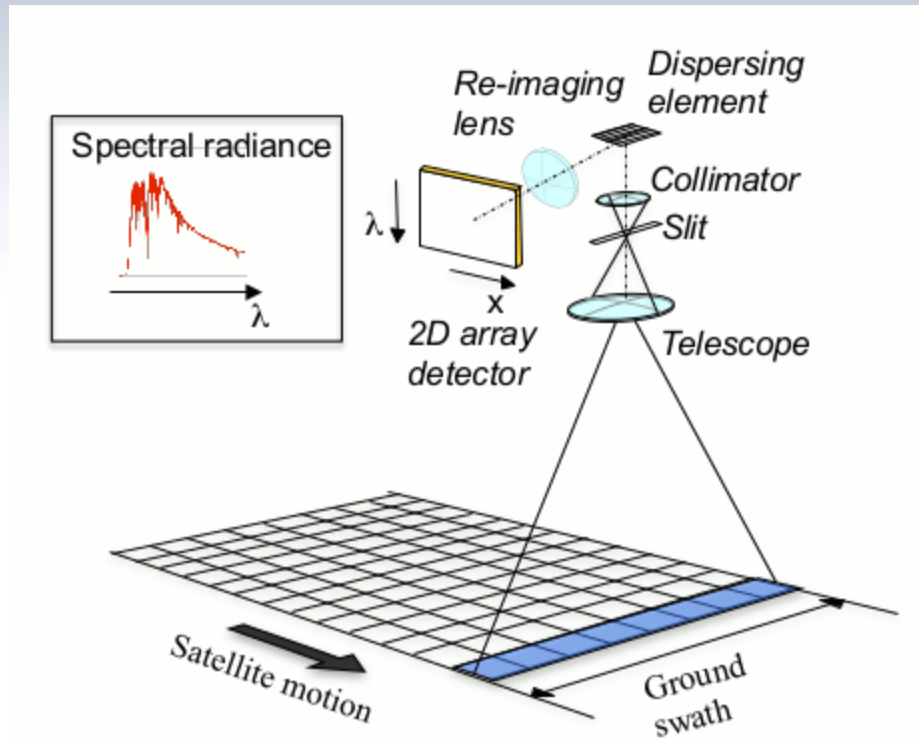
Sentinel-5: Instrument Concept

Pushbroom Imaging Spectrometer

- UV1 spectrometer
- UV2/VIS spectrometer
- NIR spectrometer
- SWIR1 spectrometer
- SWIR3 spectrometer
- Polarisation scrambler located in the telescope

Compatibility with satellite demonstrated

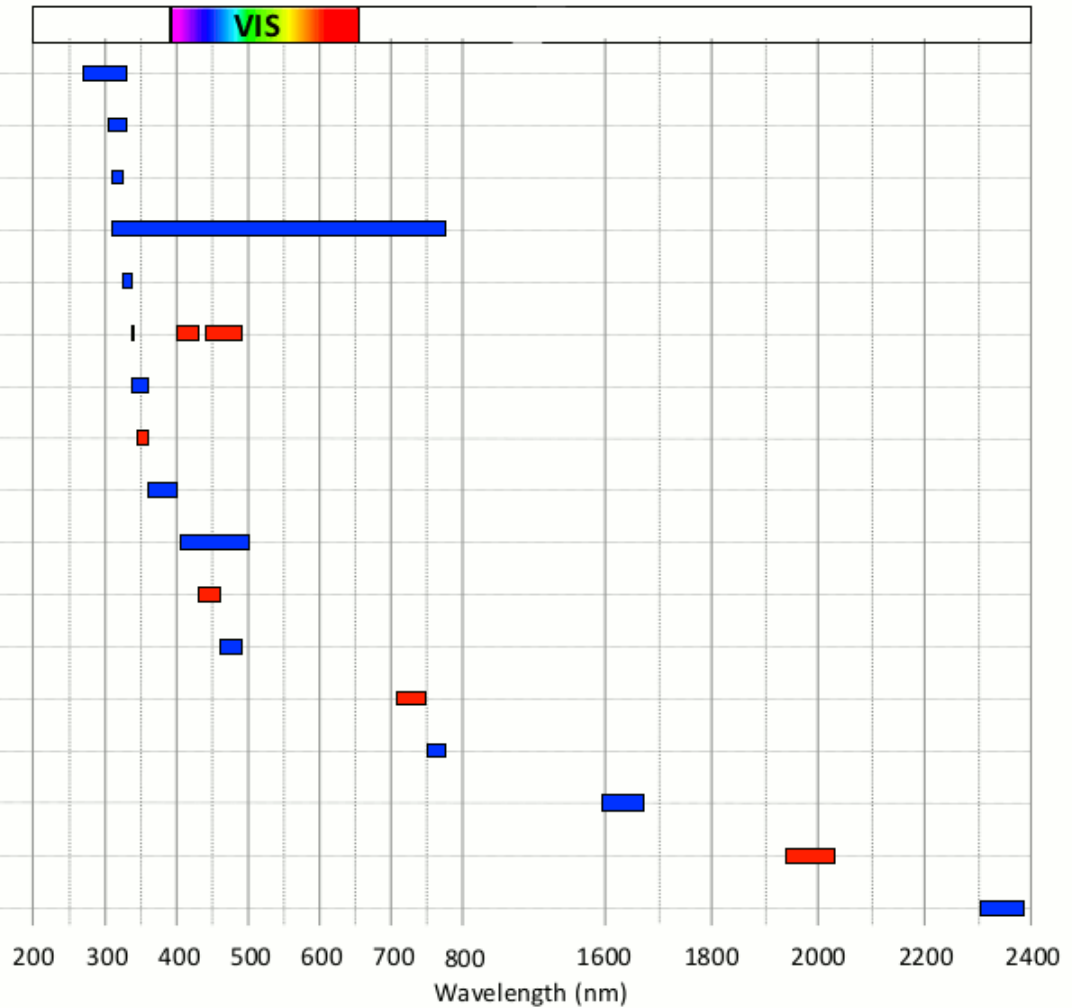
- Mass: 250 ...260 kg (incl. 20% margin)
- Power: 220 ...250 W
- Data rate: 20 Mbits/s
 - All co-addition performed on board
 - All binning performed on-board





Sentinel-5: Envisaged Product List

- Ozone vertical profile (O_3)
- Tropospheric ozone (O_3)
- Sulphur dioxide (SO_2)
- Albedo
- Total ozone (O_3)
- Aerosol
- Formaldehyde (HCHO)
- Bromine monoxide (BrO)
- Rayleigh scat. (cloud), aerosol abs.
- Nitrogen dioxide (NO_2)
- Glyoxal (CHOCHO)
- O₂-O₂ (cloud)
- Water vapour and cloud (eff. scatt. height)
- O-A (cloud, aerosol)
- Methane (CH₄)
- Aerosol profile
- Carbone monoxide (CO)

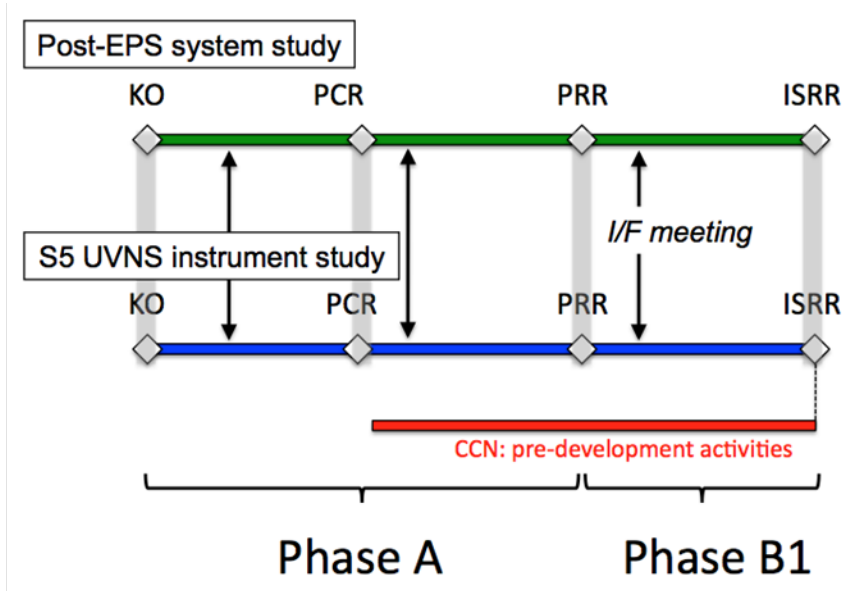


Priority A Priority B



Sentinel-5: Mission Implementation Status

- Two competitive feasibility (phase A/B1) studies were run in parallel led by Astrium GmbH and Kayser-Threde in the period 2011 – 2013
- Study synchronised with the system Metop-SG phase A/B1 studies
- PRR successfully completed in May-June 2012
- ISRR near completion
- ITT B2CDE1 planned in summer 2013 (ongoing)



Other activities started (ESA):

- S5 Requirements Consolidation - NIR
- S5 Requirements Consolidation – SWIR

Other activities in preparation (ESA):

- S5 Synergy UVN + VII, IRS, 3MI
- S5 Performance Model



Sentinel-5: Ground Segment Development

Share of Responsibility

EUMETSAT	EPS-SG Ground Segment
ESA	S5 Level 1 Prototype Processor
EUMETSAT	S5 Level 1 Operational Processor
ESA	Sentinel 5 Level 2 Prototype Processors for an agreed list of products
EUMETSAT	Sentinel 5 Level 2 Operational Processors for an agreed list of products



Products from Future Missions

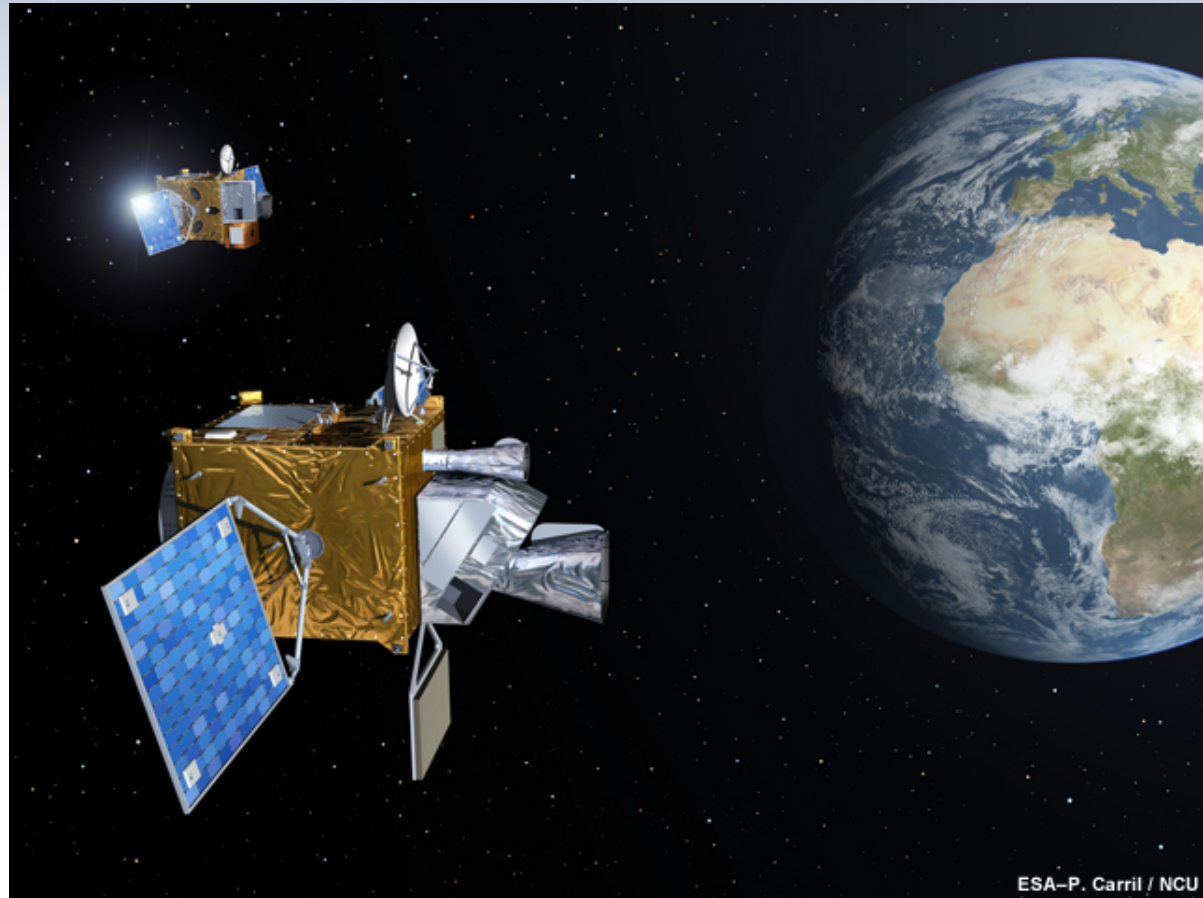
MTG-I & MTG-S

- Sentinel-4 (UV/Vis/NIR spectrometer)
- *IRS (infrared spectrometer)*
- *FCI (imager)*



MTG and Sentinel 4: Overview (I)

- The Meteosat Third Generation (MTG) system is a two-platform system.
- The MTG Imaging platform will be launched end 2018.
- This platform will carry the Flexible Combined Imager, which will, in addition to other products, provide improved information on aerosol and volcanic ash as compared to the current generation of geostationary imagers.
- The Lightning Imager will also fly on the MTG-I platform

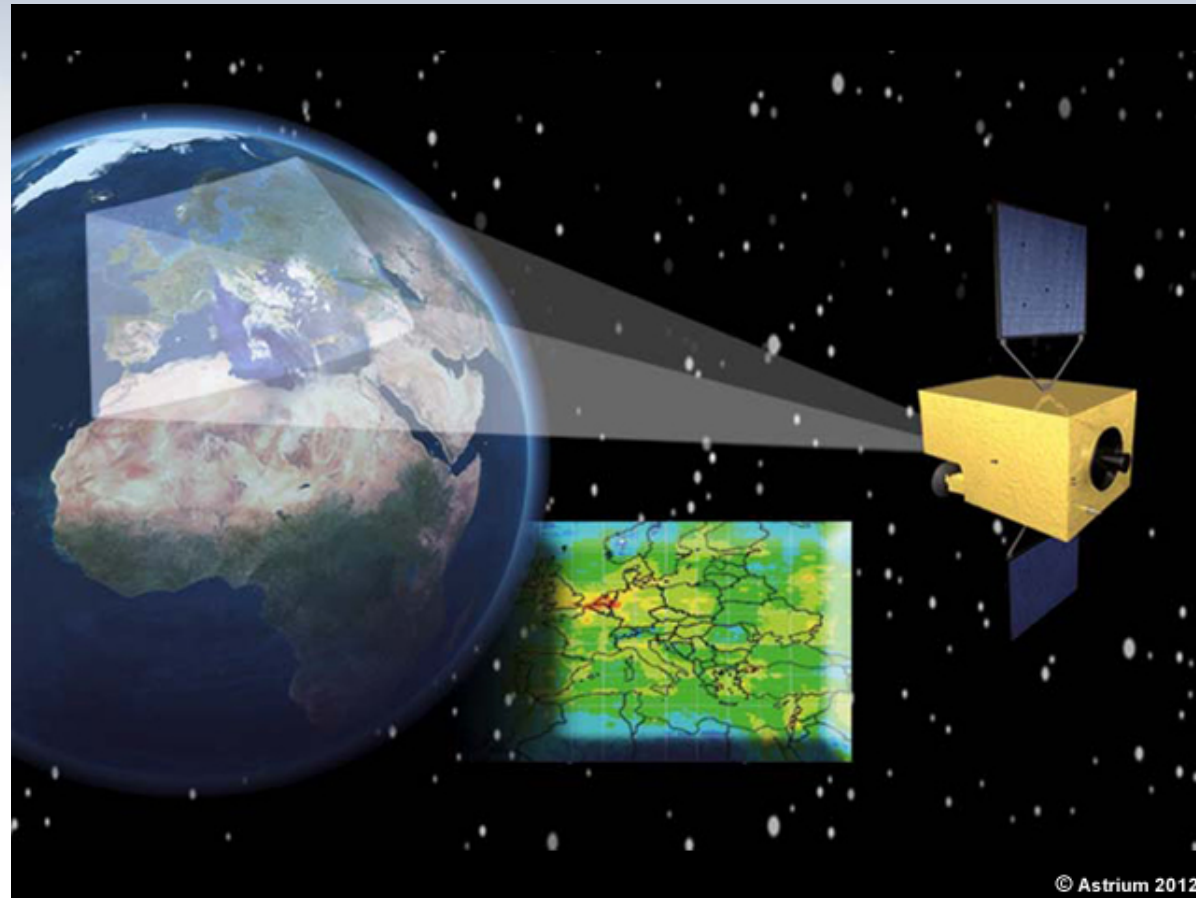


ESA-P. Carril / NCU



MTG and Sentinel 4: Overview (II)

- The MTG Sounding platform is planned for launch by end 2020.
- It will carry the Copernicus Sentinel-4 mission, which will focus exclusively on monitoring European air quality and will be the first UV/Visible spectrometer flown in geostationary orbit.
- It will fly alongside the MTG/Infrared sounder, the first hyperspectral sounder flown in geostationary orbit.
- The MTG/IRS is not optimised for atmospheric composition applications, but it is hoped that under favourable conditions it will provide information on ozone and carbon monoxide.

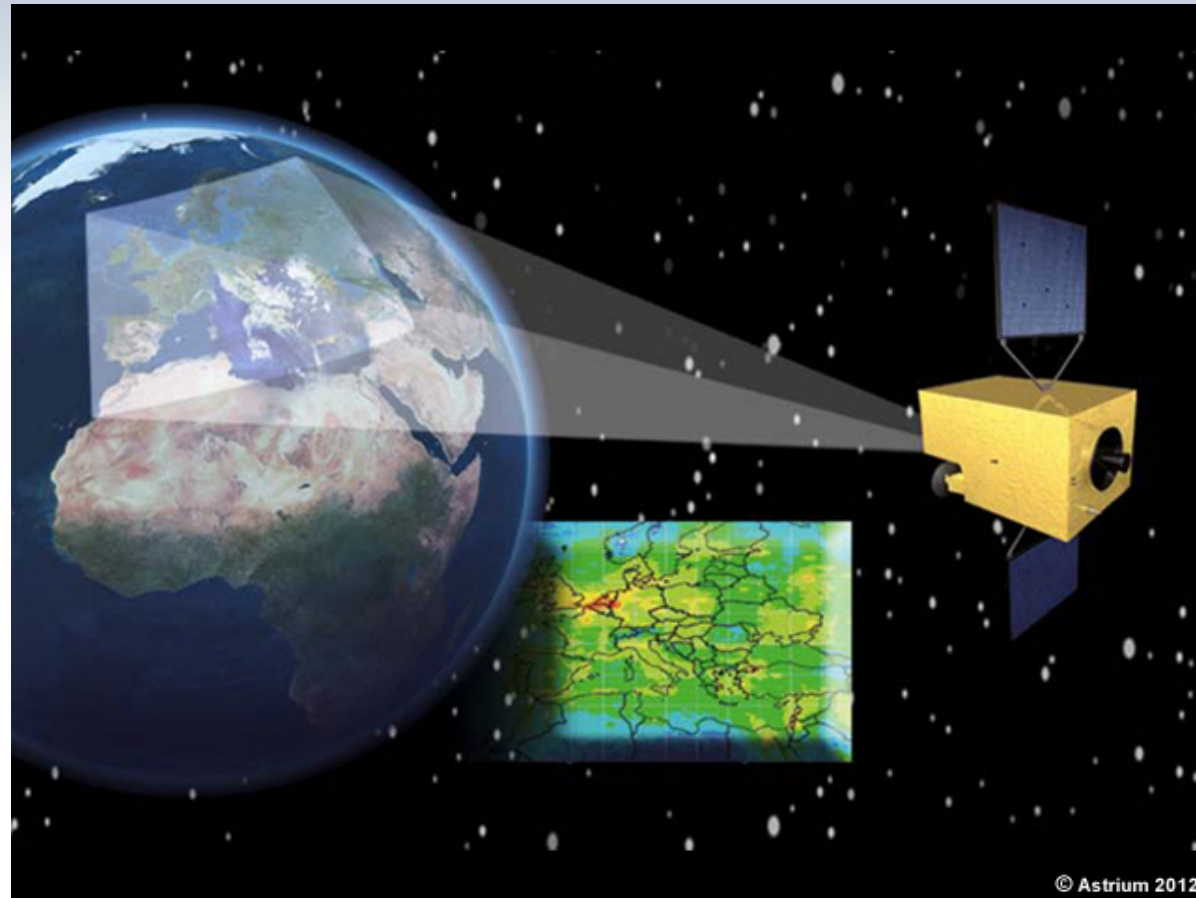


© Astrium 2012



Sentinel-4: Key Features (I)

- Sentinel-4 has heritage from the GOME/SCIAMACHY/GOME-2/OMI series of instruments.
- Its primary focus will be on the monitoring of air quality in the European domain with high spatial and temporal resolution.
- Like other nadir instruments measuring in the UV, it will make measurements of O_3 , NO_2 , BrO, SO_2 , HCHO, CHOCHO etc.
- The spatial resolution will be $\sim 8 \times 8$ km with hourly temporal resolution.

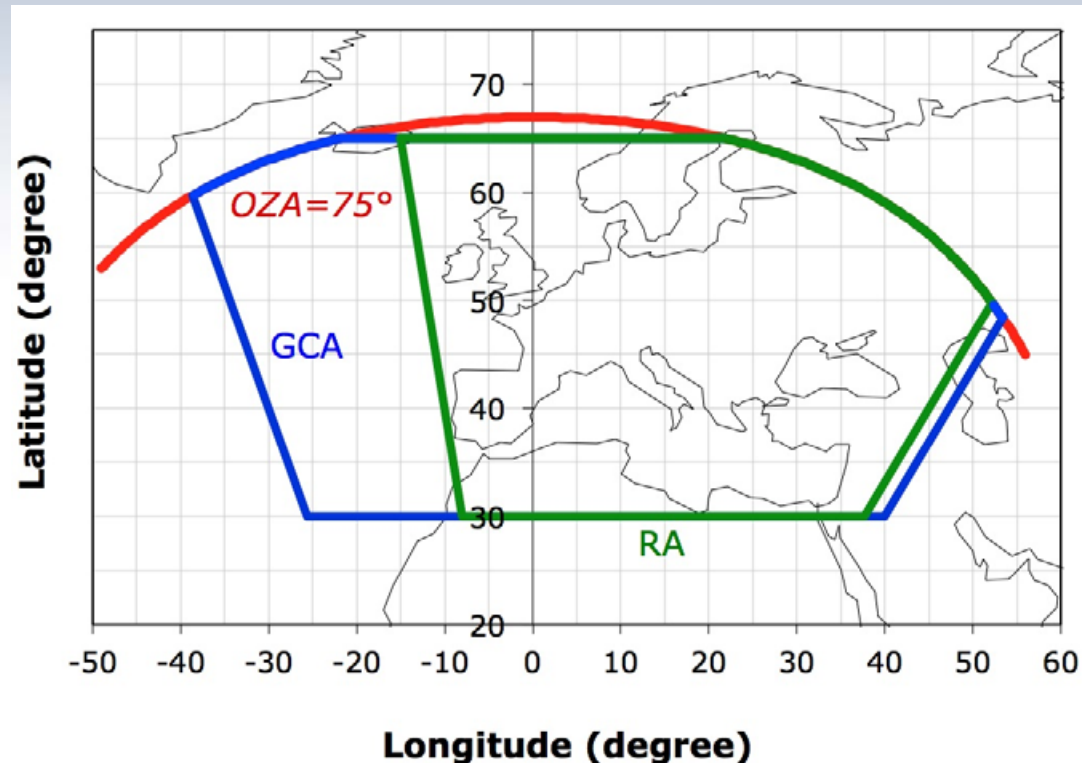


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Sentinel-4: Key Features (II)

- Spatial Sampling: 8 km at 45°N
- Coverage: Europe + Sahara
- Repeat Cycle: 1 hr
- UV-VIS: 305 – 500 nm with 0.5 nm spectral resolution, 3 x oversampling
- NIR: 750 – 775 nm with 0.12 nm spectral resolution, 3 x oversampling
- Polarisation sensitivity: 0.6% (<315 nm), 0.7% (315-500 nm), 0.4% (NIR)
- Radiometric accuracy: 2.3% (<315 nm), 1.8% (315-500 nm), 2.3% (NIR)
- Low level of spectral features (0.05%)





Sentinel-4: Instrument Concept

Imaging Spectrometer

- Pushbroom in E/W direction
- N/S FOV: 3.85°
- E/W FOR: 11.2°
- 2 grating spectrometers
 - UV-VIS: 305 – 500 nm
 - NIR: 750 – 775 nm
- CCD detectors cooled at < 215 K

Scan Mirror

- E/W scan
- N/S compensation of MTG yaw flip manoeuvre around equinox
 - seasonal shift in latitude (per steps of 5 deg up to 10 deg)
 - star calibration (at the beginning of every day)
- High performance on board calibration sources (diffusers, lamp, LED)



Sentinel-4: Envisaged Product List

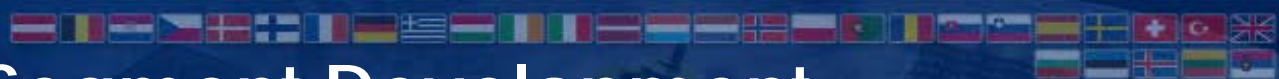
Product	Application			Comment
	Air Quality	Climate	Surface UV	
O ₃ total & trop. column	X		X	
O ₃ profile	X		X	Synergy with data from the IRS
NO ₂ total & trop. column	X			
SO ₂ total column	X			Also for volcanic eruption monitoring
CHOCHO total column	X			By-product
CH ₂ O total column	X			
Aerosol extinction coeff. Profile, column optical depth/type/index	X	X		Also for volcanic eruption monitoring Also auxiliary for other S4 products Synergy with imager data from FCI
Cloud optical thickness, fraction, altitude			X	Mainly auxiliary for other S4 products Synergy with imager data from FCI
Surface reflectance daily map			X	Mainly auxiliary for other S4 products



Sentinel-4: Mission Implementation Status

Instrument Preliminary Design Review completed → Phase C/D

- L1 processor development in preparation
- L2 pre-development ongoing (ESA responsibility)
 - aerosol profile retrieval from O2A-band (AEROPRO study with KNMI)
 - surface reflectance map from temporally aggregated S4 data (SURMACED study with BIRA, GC, LOA, IM)
- L2 operational processor development in preparation (ESA responsibility)
 - ITT end 2013
 - Kick-off early 2014



Sentinel-4: Ground Segment Development

Share of Responsibility

EUMETSAT	MTG Ground Segment
ESA	S4 Level 1 Prototype Processor
EUMETSAT	S4 Level 1 Operational Processor (part of MTG IDPF)
ESA	S4 Level 2 Prototype & <i>CFI L2 Operational Processor S4L2 CFI (under discussion)</i>
EUMETSAT	Integration of S4L2 CFI into MTG L2 Processing Facility



Sentinel-4 & -5: Aerosol Profile Scientific Points of Interest

- The aerosol profile product will be sensitive to uncertainties in the Instrument Spectral Response Function (ISRF) at the level of 1% in FWHM, which is the requirement level ->important requirement for aerosol retrievals
- Current spectroscopy in the O2A-band is not considered sufficiently accurate for aerosol retrieval, in particular regarding line mixing and collision induced absorption data.
- There has been a recommendation to initiate a study on the spectroscopy needs in the O2A-band in particular for applications exploiting high spectral resolution data.



Products from Future Missions

Synergistic Products

MTG-I & MTG-S:

Possibility for synergistic products from Sentinel-4 (UV/Vis/NIR spectrometer) & IRS (infrared spectrometer) and also FCI (imager)

EPS-SG:

Possibility for synergistic products from Sentinel-5 (UV/Vis/NIR/SWIR spectrometer), IASI-NG (infrared spectrometer), METImage (imager) and 3MI -> PMAp heritage



Products from Future Missions

Sentinel-3

See presentation from Simon Pinnock ESA/ESRIN



Thank You & Questions?