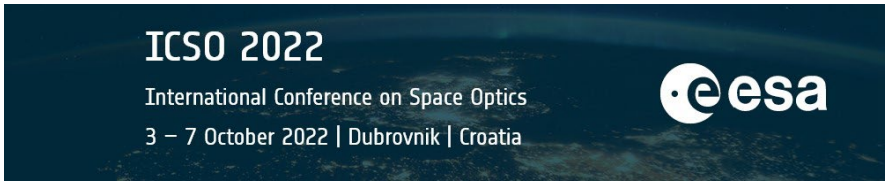
International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,



Optics in ESA's Earth Observation Program

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 127777O · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.3011177

Optics in ESA's Earth Observation Program

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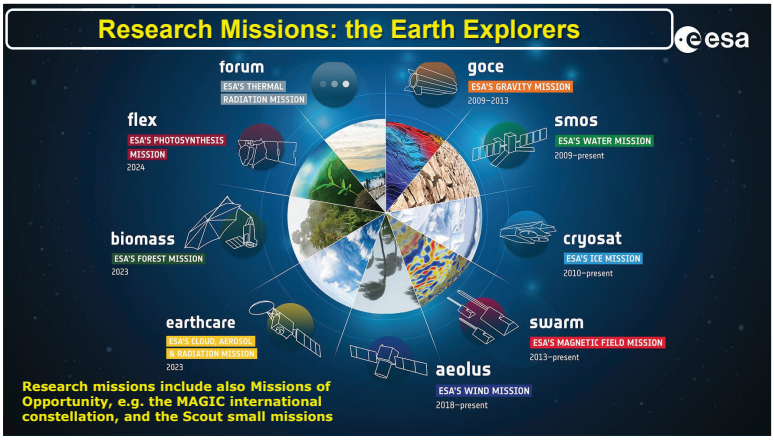
Head of the Optical Instruments section, Directorate of Earth Observation Programmes

International Conference on Space Optics - 3-7 October 2022

ESA-Developed Earth Observation Satellites

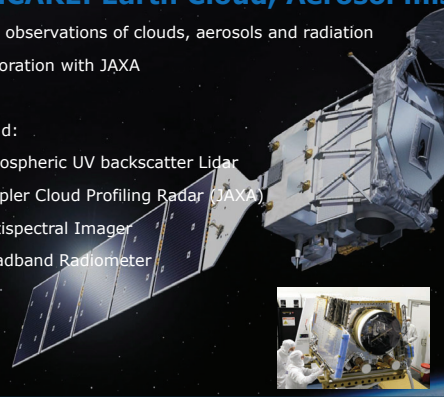
Research Missions: the Earth Explorers



Research missions include also Missions of Opportunity, e.g. the MAGIC international constellation, and the Scout small missions

EarthCARE: Earth Cloud, Aerosol mission

- Global observations of clouds, aerosols and radiation
- Collaboration with JAXA
- Payload:
  - Atmospheric UV backscatter Lidar
  - Doppler Cloud Profiling Radar (JAXA)
  - Multispectral Imager
  - Broadband Radiometer

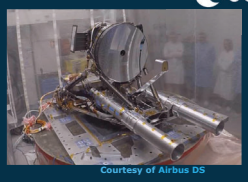


MISSION PARAMETERS
- Orbit: sun-synchronous
- Mean altitude: 393 km
- LTDN: 14:00

Mass: 2300 kg
Power (average): 1.7 kW
Mission life: 3 years
Launch date: 2023-24

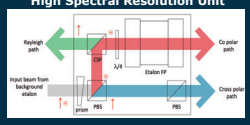
EarthCARE Lidar receiver

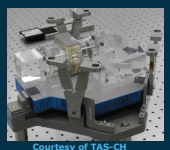
- Afocal 620 mm diameter Cassegrain telescope- All SiC mirrors and mounts
- 3 filtering stages : narrow-band interference filter, spatial filter reducing the receiver FOV to 65microrad and Fabry-Perot etalon with 0.3pm bandwidth
- High spectral resolution filter centred on the laser wavelength: Fabry-Perot etalon
- Separation of the Rayleigh and Mie channels by polarizers
- Low noise detection chain with memory CCD



Courtesy of Airbus DS

High Spectral Resolution Unit

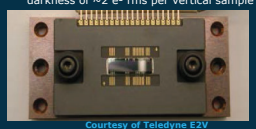




Courtesy of TAS-CH

Memory CCD

quasi photon-counting with a total noise in darkness of ~2 e- rms per vertical sample



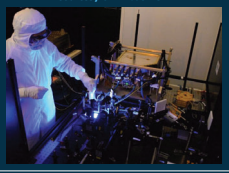
Courtesy of Teledyne E2V

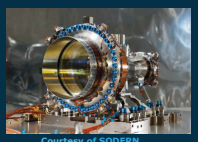
EarthCARE Lidar transmitter

- Diode-pumped Nd:YAG laser (1064 nm), with frequency tripling stage to generate the third harmonic of 355 nm
- LIC mitigation
  - Complete separation of the emission path from the rest of the instrument to avoid cross-contamination (Bi-static architecture)
  - Pressurised and sealed canister over the whole emission path (both power Laser Head and Emission Beam expanding optics)
  - Reduction of laser fluence

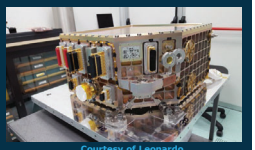
Laser main requirements	
Pulse energy	38 mJ UV
PRF	51 Hz
Divergence	<200 µrad
Linewidth	< 50 MHz
Frequency stability	< 50 MHz over 1 month
Total number of shots	>5 Gshots

Courtesy of Airbus DS





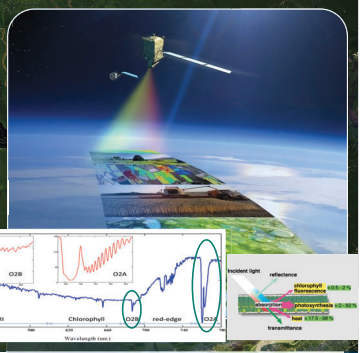
Courtesy of SODERN



Courtesy of Leonardo

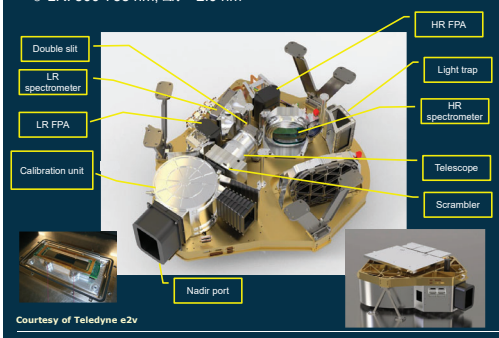
FLEX: The Vegetation Fluorescence Mission

Mission	Measurement of vegetation fluorescence signal to quantify actual photosynthetic activity of terrestrial ecosystems and provide physiological indicators for vegetation health status
Swath/ resolution	150 km / 300 m
Payload	FLORIS, 2 channels spectrometers (O_2 lines)
Orbit	SSO, alt: 814 km; LTDN: 10h00, flying in formation with Sentinel-3
Satellite	470 Kg
Planned Launch date	2025
Lifetime	3.5 years



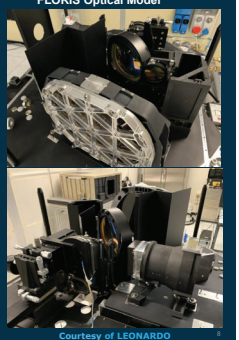
FLORIS Instrument : Hyperspectral imager with two spectrometers

- HR: 677-697 nm, 740-780 nm, $\Delta\lambda$ = 0.3 nm
- LR: 500-758 nm, $\Delta\lambda$ = 2.0 nm



Courtesy of Teledyne e2v

FLORIS Optical Model



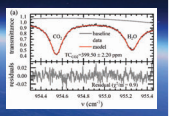
Courtesy of LEONARDO

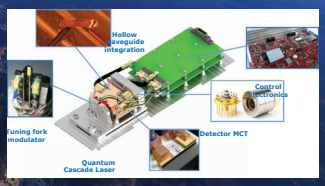
Scout Missions

Innovative smallsats, demonstrating EO techniques and/or enabling valuable science

CubeMAP

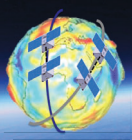
Earth System Processes Monitored in the Atmosphere based on Sun occultation.
Three 12U cubesats with
HIROS (Heterodyne TIR Spectrometer)
+ HSDI (VIS NIR Hyperspectral Solar Disk Imager)

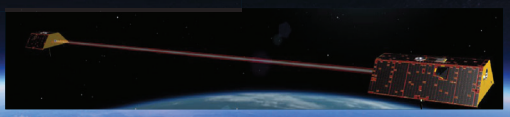




Courtesy of RAL Space

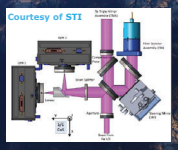
Next Generation Gravity Mission





- Mission objective to measure the geoid with 1 mm accuracy at 3-day intervals at <500 km spatial resolution, with ~220-km inter-satellite distance, over a time span of 10 years
- Cooperation with NASA and DLR
- Accurate instruments (laser metrology, accelerometers), satellite drag free control

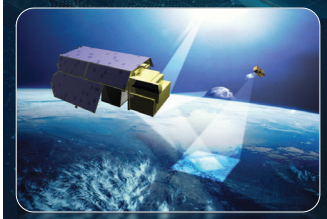
Courtesy of TESAT



Courtesy of STI

Courtesy of Airbus DS and NPL

TRUTHS – An operational climate mission



- **Climate benchmarking:** enhance by up to an order-of-magnitude our ability to estimate the **Earth Radiation Budget** through direct measurements of incoming & outgoing energy,
- **Satellites cross-calibration:** establish a 'metrology laboratory in space' to create a fiducial reference data set to cross-calibrate other sensors and improve the quality of their data (essential for New Space constellations)
- **SI-traceable measurements** of the **solar spectrum** to address direct science questions.

Mission/System Drivers:

- Climate application drives the stringent Radiometric accuracy (0.3% G÷1% T) ➔ Payload & calibration design
- Cross-calibration application leads to a non-SSO orbit ➔ Satellite design (CRISTAL P/F recurrent)
- Solar/Earth samples in a large spectral range: UV to SWIR (320-2400 nm). SSD 50 m , 100 km swath

TRUTHS – An operational climate mission

- **Platform**, recurrent from CRISTAL, polar non-SSO at 614 km.
- **Satellite**, ~1500kg / 1kW, compatible with Vega-C.
- **Payload**, ~400kg, composed of three elements:

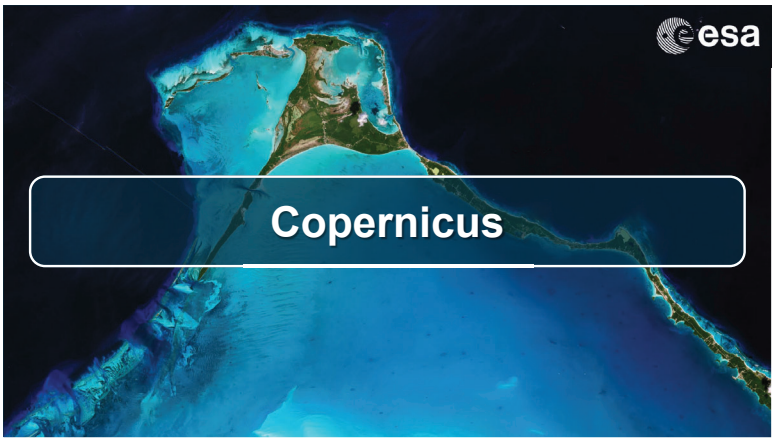
- **HIS** (Hyperspectral Imaging Spectrometer) – based on a single passively cooled detector operating from UV to SWIR

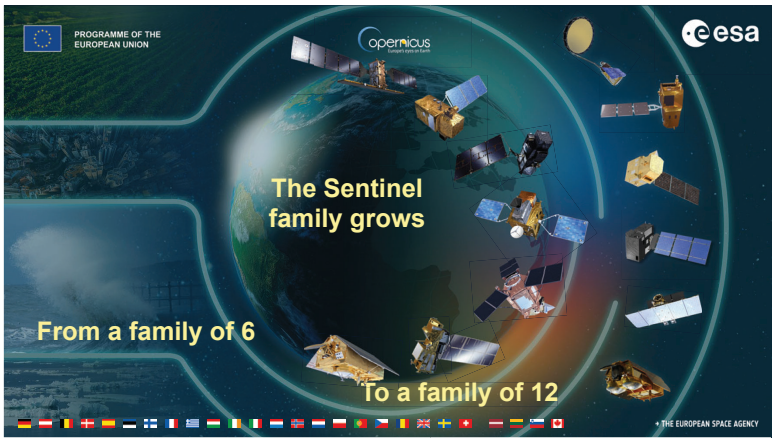
- **CSAR** (Cryogenic Solar Absolute Radiometer) – Primary metrology standard operated at 60 K with cryo-cooler, delivering the "absolute radiometric reference"

- **OBCS** (On-Board Calibration System) – traceable set of absolute wavelength anchors transferring the CSAR solar absolute measurement to the HIS
- Pre-developments running for all critical items (detector, coating, CSAR, mirror, calibration sources…) with intense interactions with MAG to optimize operational benefit and development risks.
- Completed Phase B1 (preliminary definition) and passed independent technical, science and program reviews in July 2022.
- Implementation phase will be proposed to next ESA Ministerial Council in Nov-22

TRUTHS satellite

TRUTHS Payload


esa
Copernicus


PROGRAMME OF THE EUROPEAN UNION
opernicus
esa
The Sentinel family grows
From a family of 6
To a family of 12
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PROGRAMME OF THE EUROPEAN UNION
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Food Security and Water Management
Monitoring Land and Natural Resources
CHIME
ROSE-L
LSTM
CIMR
Combatting Climate Change
Safeguarding the Arctic
CO2M
CRISTAL
Strengthening Copernicus Space with the Sentinel Expansion Mission observations
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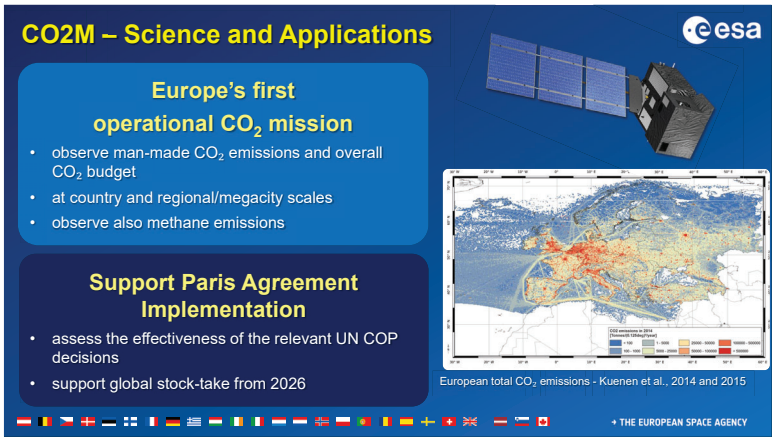
CO2M – Science and Applications
esa
Europe's first operational CO_2 mission
observe man-made CO_2 emissions and overall CO_2 budget
at country and regional/megacity scales
observe also methane emissions
Support Paris Agreement Implementation
assess the effectiveness of the relevant UN COP decisions
support global stock-take from 2026
European total CO_2 emissions - Kuenen et al., 2014 and 2015
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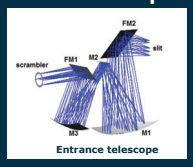
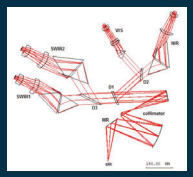
CO2M: Concept and design of CO2I/NO2I

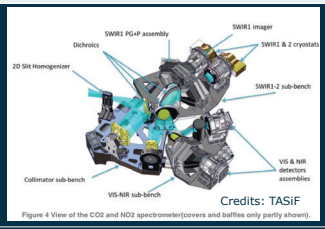


Entrance telescope



3+1 band spectrometer

Telescope	Common telescope with polarisation scrambler and entrance slit homogeniser
Collimator	One reflective collimator, common for all bands
Band separation	3 Dichroic plates split used in collimated beam
Diffraction grating	4 Prism-Grating-Prism assemblies
Imagers	Glass (VIS/NIR) and silicon (SWIR-1/SWIR-2); band-pass filters
Detectors	Mercury-Cadmium-Telluride CMOS detectors in SWIR; Si CMOS in VIS-NIR



Credits: TASiF

Figure 4 View of the CO2 and NO2 spectrometer(covers and baffles only partly shown).

17

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CO2M technological key items: 2D Slit homogeniser

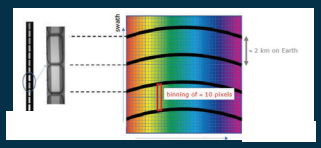
Fiber-based entrance slit made of stacked rectangular multi-mode fibers (TASiCH/Optec)

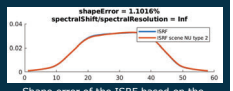
- Each fiber defines instantaneous FOV and slit width (core dimensions: 320 µm x 120 µm)
- Assembly of 110 rectangular fibers -> 250 km swath
- Excellent homogenization performance in both ALT and ACT directions
- Stable ISRF (slit function) independent of ground scene contrast

Credits: OPTEC

- Alignment, Focal Ratio Degradation (FRD) and transmission measured
- Straylight measured below 10^{-5} (limited by camera sensitivity)
- Homogenization measurements (ACT & ALT) confirmed the design is compatible with the need and highlighted sensitivity to several parameters (fiber section, wavelength, length)
- Qualification Model under manufacturing.


Homogenisation ACT measurements with Knife Edge at 3 positions in the fiber





Shape error of the ISRF based on the ISRF reconstructed for a non-uniform source from the measured KEF responses

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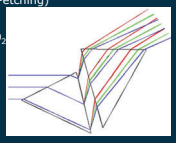
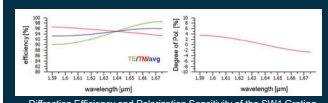
CO2M technological key items: Diffraction gratings

Diffraction gratings based on Prism-Grating-Prism assemblies (Fraunhofer IOF for NIR & SWIR)

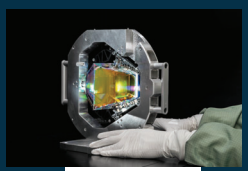
- Photonic sub-wavelength structures (e-beam lithography and reactive ion-etching)
- NIR: TiO_2 over-coating applied by Atomic Layer Deposition
- SWIR: Nano-laminate multi-layer coating (alternating stack of Al_2O_3 + TiO_2)
- Grooves completely filled by multi-layer coating, enclosed in SiO_2
- Measured performance
  - Diffraction efficiency > 90%
  - Polarisation Sensitivity < 10%
  - Low wavefront error and straylight
- Optical & STM manufacturing in progress
- First flight prisms received and flight grating started
- Bonding qualification on-going

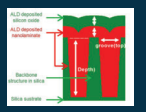



Credits: IOF



Diffraction Efficiency and Polarization Sensitivity of the SW1 Grating


Credits: IOF



19

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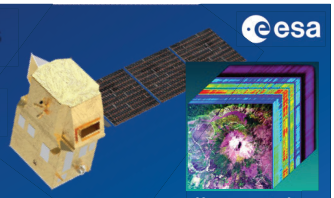
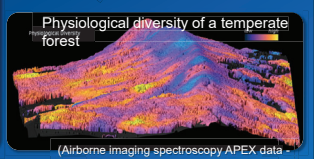
CHIME – Science and Applications

Provides routine hyperspectral measurements at global scale in support of EU policies for the monitoring and management of natural resources and food security


Hyperspectral data cube

- main application: agriculture, soil and raw materials, and new applications and services
- secondary application: monitoring and management of forests and water resources, biodiversity and cryosphere through
- systematic (12.5 day revisit) hyperspectral measurements in VNIR and SWIR (0.4 - 2.5 µm) with <10 nm spectral and <30 m spatial resolution



(Airborne imaging spectroscopy APEX data - Schaepman, Jehle et al. 2015)

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CHIME Technology developments

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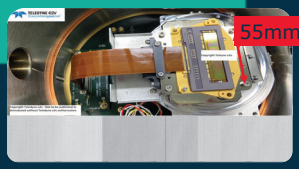
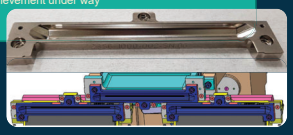
Detector and packaging
- 3072x512 pixel detector
- Provision of first ROIC noise images T_room
- TRL6 achievement provisioned in October



Slit
- 3-slit arrangement for wide swath
- First 90mm spectrometer slit with 60µm aperture machined at AMOS
- TRL6 achievement under way



Order sorting filter
- High rejection capability for diffraction noise
- TRL6 achievement under way in the next month

21

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CHIME Technology developments (TRL6 achieved)

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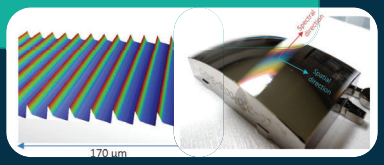
Grating
- Dual-blazed groove shape for high throughput broad band diffraction with 8.4nm spectral sampling distance
- low roughness <3.5nm minimizes straylight
- 47 grooves/mm on spherical AlSi443 alloy NiP plated surface via single point diamond turning
- 28x32 mm2 aperture



Optical Bench Torus
- CFRP base structure for star trackers and spectrometers
- Adequate thermo-and hydroelastic behavior proven by test and model correlation of optical bench equipment breadboard

22

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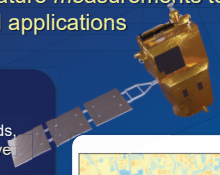
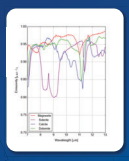
LSTM

esa

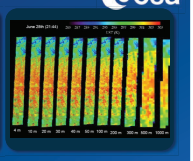
Land surface temperature measurements to support research and applications



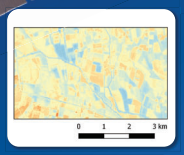
- TIR observations (5 bands, from 8.5 to 12 micron) over land & coastal regions
- complement current S-2 and S-3 observations with high spatial and temporal resolution (50 m, 3 days)



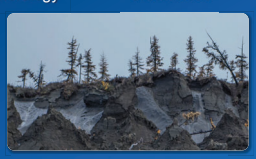
mineralogy



urban heat



water stress (from evapotranspiration)



permafrost thaw monitoring

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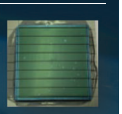
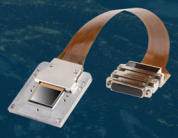
LSTM MISSION SUMARY

esa

- 2 satellites, 4 days geometric revisit time each
  → **two days geometric revisit globally**
- **50 meters resolution** (37 meters nadir)
- Mean Local Solar Time over **Europe at 13:00** descending
- Spectral bands: 5 TIR, 4 VISNIR, 2 SWIR
- Nominal **swath 687 km**
- Maximum **OZA 30.3** degrees
- TIR observations **day and night**
- VNIR/SWIR observations when SZA < 82 deg.
- **651 km** average geodetic altitude, (643km to 665km)
- 7 years lifetime following 6 months commissioning. Consumables for 12 years.

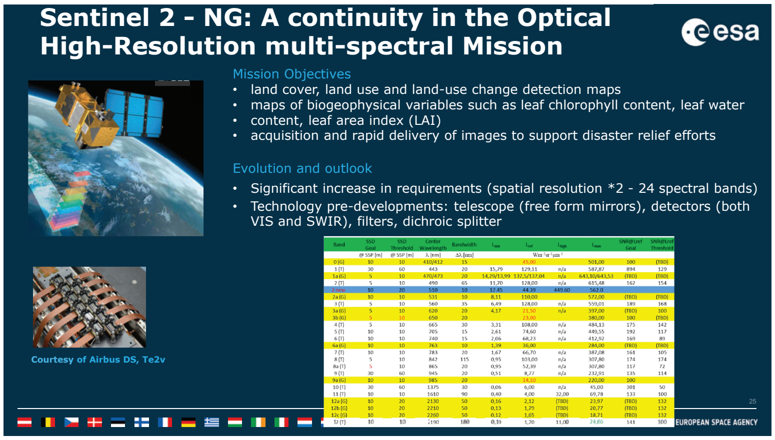


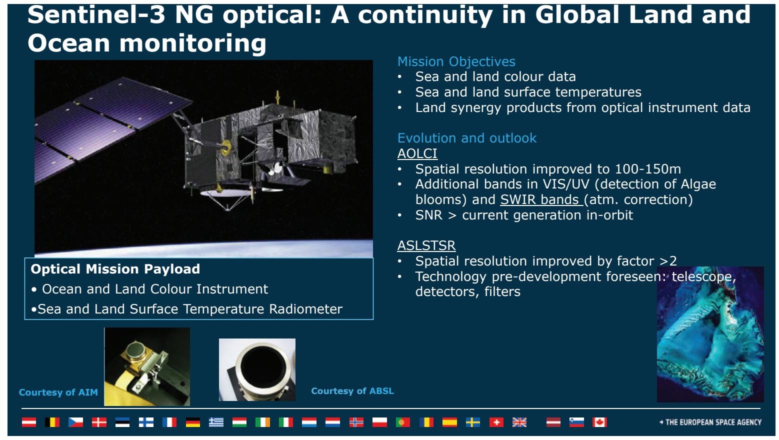


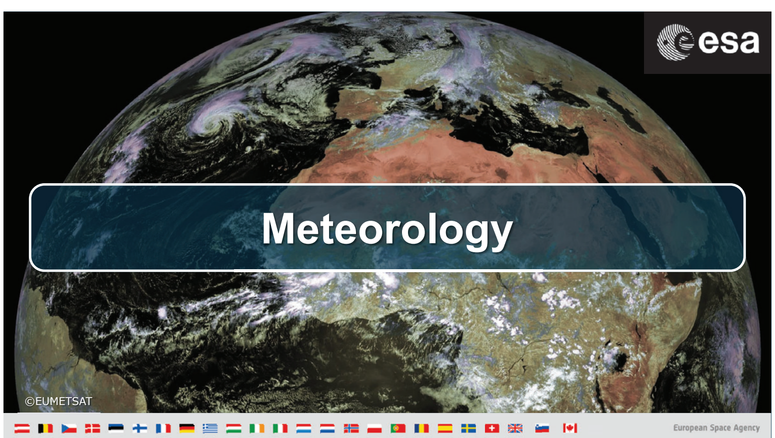
MTF 0.15 to 0.3
NeDT < 0.1 K @ 300 K
ARA < 0.3 K @ 300 K

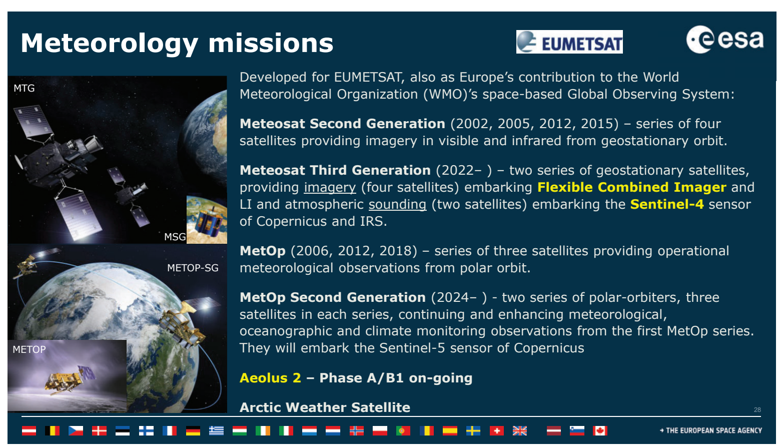
24

THE EUROPEAN SPACE AGENCY


Sentinel 2 - NG: A continuity in the Optical High-Resolution multi-spectral Mission
esa
Mission Objectives
• land cover, land use and land-use change detection maps
• maps of biogeophysical variables such as leaf chlorophyll content, leaf water content, leaf area index (LAI)
• acquisition and rapid delivery of images to support disaster relief efforts
Evolution and outlook
• Significant increase in requirements (spatial resolution *2 - 24 spectral bands)
• Technology pre-developments: telescope (free form mirrors), detectors (both VIS and SWIR), filters, dichroic splitter
Courtesy of Airbus DS, Te2v
EUROPEAN SPACE AGENCY


Sentinel-3 NG optical: A continuity in Global Land and Ocean monitoring
Mission Objectives
• Sea and land colour data
• Sea and land surface temperatures
• Land synergy products from optical instrument data
Evolution and outlook
AOLCI
• Spatial resolution improved to 100-150m
• Additional bands in VIS/UV (detection of Algae blooms) and SWIR bands (atm. correction)
• SNR > current generation in-orbit
ASLSTSR
• Spatial resolution improved by factor >2
• Technology pre-development foreseen: telescope, detectors, filters
Optical Mission Payload
• Ocean and Land Colour Instrument
•Sea and Land Surface Temperature Radiometer
Courtesy of AIM
Courtesy of ABSL
THE EUROPEAN SPACE AGENCY


esa
Meteorology
©EUMETSAT
European Space Agency


Meteorology missions
EUMETSAT
esa
MTG
MSG
METOP-SG
METOP
Developed for EUMETSAT, also as Europe's contribution to the World Meteorological Organization (WMO)'s space-based Global Observing System:
Meteosat Second Generation (2002, 2005, 2012, 2015) – series of four satellites providing imagery in visible and infrared from geostationary orbit.
Meteosat Third Generation (2022–) – two series of geostationary satellites, providing imagery (four satellites) embarking Flexible Combined Imager and LI and atmospheric sounding (two satellites) embarking the Sentinel-4 sensor of Copernicus and IRS.
MetOp (2006, 2012, 2018) – series of three satellites providing operational meteorological observations from polar orbit.
MetOp Second Generation (2024–) - two series of polar-orbiters, three satellites in each series, continuing and enhancing meteorological, oceanographic and climate monitoring observations from the first MetOp series. They will embark the Sentinel-5 sensor of Copernicus
Aeolus 2 – Phase A/B1 on-going
Arctic Weather Satellite
THE EUROPEAN SPACE AGENCY

Flexible Combined Imager (FCI)

- Full disc imagery every 10 minutes in 16 bands
- Fast imagery of Europe every 2.5 minutes
- Sampling Distance
  - VNIR/SWIR: 0.5 / 1.0 km
  - MWIR/TIR: 1.0 / 2.0 km
- TMA telescope with a pupil diameter of 300 mm

Channel	Centre (µm)	Width (µm)	SSD (km)	
VIS 0.4	0.444	0.06	1.0	new
VIS 0.5	0.510	0.04	1.0	new
VIS 0.6	0.640	0.05	1.0/0.5	
VIS 0.8	0.865	0.05	1.0	
VIS 0.9	0.914	0.02	1.0	new
NIR 1.3	1.38	0.03	1.0	new
NIR 1.6	1.61	0.05	1.0	
NIR 2.2	2.25	0.05	1.0/0.5	new
IR1 3.8	3.8	0.4	2.0/1.0	
IR1 6.3	6.3	1.0	2.0	
IR1 7.3	7.35	0.5	2.0	
IR2 8.7	8.7	0.4	2.0	
IR2 9.7	9.66	0.3	2.0	
IR3 10.5	10.5	0.7	2.0/1.0	
IR3 12.3	12.3	0.5	2.0	
IR3 13.3	13.3	0.6	2.0	

FCI PFM

VIS Detection Assembly

Courtesy of Teledyne e2v/JOP

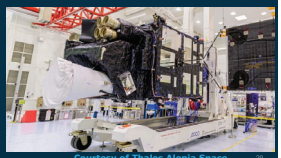
Telescope M1 mirror

Courtesy of Thales SESO

LPTC Cooler Assembly

Courtesy of Air Liquide Advanced Technology

Courtesy of LYNRED



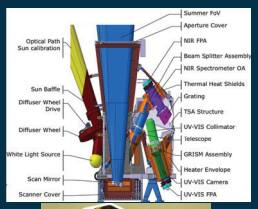
Courtesy of Thales Alenia Space

Sentinel-4 Spectrometer targeting air quality (O3, NO2, SO2, HCHO and aerosols)

UV-Visible and NIR infrared spectrometer- 8km spatial resolution- 60 minutes repeat cycle

FM Telescope and UVVIS spectrometer

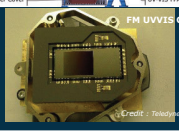
Jena-Optronik (DE) courtesy



2-axis FM scanning mechanism and scan mirror

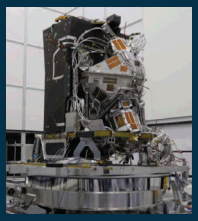
Credit : RUAG

FM UVVIS CCD



Credit : Teledyne e2v

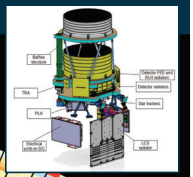
Sentinel 4 Flight Model instrument in RAL facilities

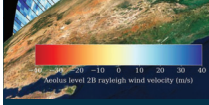


Credit: Airbus DS GmbH

Aeolus 2 : Securing the long-term observation and improving NWP models

esa





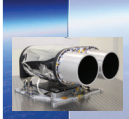
	required Laser performance
Pulse energy	>125 mJ at 355nm
PRF	> 50 Hz
Divergence and stability	<300 µrad with <40 µrad stability
Linewidth	< 50 MHz
Frequency stability	< 50 MHz over 1 month
Total number of shots	>8 Gshots (corresponding to a lifetime > 5 years)

Incubed: some examples of upstream projects with payload development

esa

mantis

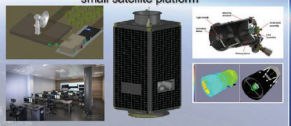
Mission and Agile Nanosatellite for Terrestrial Imagery Services



Specific focus on Oil and Gas applications
3m GSD (SR)
12U Cubesat with
VIS-NIR Push broom Multispectral 4 bands Dual Telescope - Onboard Super Resolution and Cloud Detection

SAT4EO

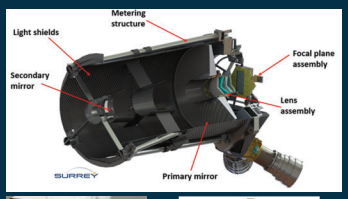
AOCS and Instrument for Very High Resolution imagery from state of the art small satellite platform



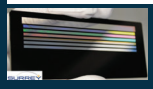
VHR System, 0.6 m native GSD with Super Resolution capabilities (0.3 m), Enhanced AOCS
100-200 Kg S/C AOCS Suite – Compact VIS-NIR VHR Telescope (new Sensor Development) – Dedicated ground Exploitation Platform

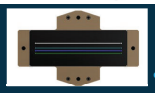
Incubed: SAT4 EO Precision payload

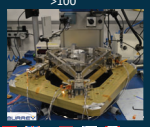
Precision is a very high resolution multispectral imager which utilizes a novel CCD-in-CMOS time delay and integration (TDI) line scan detector and innovative opto-mechanical techniques to achieve cutting edge performance at a market-leading size, weight and power.



Parameter	Specification
GSD	0.6 m PAN (< 0.5 m with ½ pixel shift) 1.2 m multispectral
Swath	9.5 km
Bands	PAN, R, G, B, NIR
Sensor Type	CCD-in-CMOS TDI detector
SNR	>100



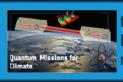




Courtesy of Teledyne e2v

Quantum Missions for Climate

monitor climate changes with constellation of enhanced quantum sensors



to provide, enhance and enable new Essential Climate Variables for a more sustainable Earth

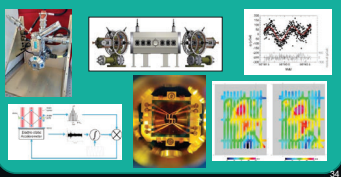
monitor and prevent in time major hazards due to climate change

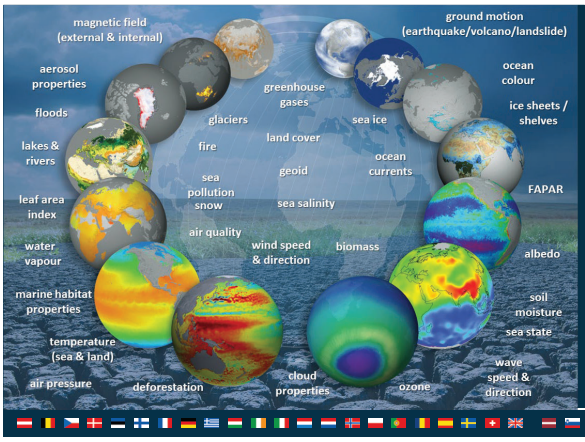
ECVs

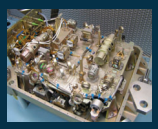
User needs

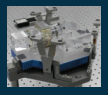
Opening new application and services

Enter Quantum Technological Breakthrough for new generation of enhanced sensors









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