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The Global Monitoring for Environment and Security (GMES) Sentinel-3 mission

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ABSTRACT

Global Monitoring for Environment and Security (GMES) is the European programme to establish a European capacity for Earth Observation. GMES is designed to provide European policy makers and public authorities with accurate and timely information to better manage the environment, understand and mitigate the effects of climate change and ensure civil security. Sentinel-3 is an Earth observation satellite mission specifically designed for GMES to ensure the long-term collection and operational delivery of high-quality measurements to GMES ocean, land, and atmospheric services, while contributing to the GMES, emergency and security services. Key Sentinel-3 measurement requirements, corresponding to identified GMES user needs, have been derived as follows:

- Sea surface topography (SSH), significant wave height (Hs) and surface wind speed derived over the global ocean to an equivalent accuracy and precision as that presently achieved by ENVISAT Radar Altimeter-2 (RA-2) but with enhanced surface topography measurements in the coastal zone, sea ice regions and over inland rivers, their tributaries and lakes.
- Sea surface temperature (SST) determined for oceanic and coastal waters globally to an equivalent accuracy and precision as that presently achieved by the ENVISAT Advanced Along Track Scanning Radiometer (AATSR) over the ocean (i.e. <0.3 K), at a spatial resolution of 1 km.
- Visible, and Short-Wave Infrared radiances for oceanic, inland and coastal waters at a spatial resolution of 0.3 km (simultaneously and co-registered with SST measurements), determined to an equivalent level of accuracy and precision as ENVISAT Medium Resolution Imaging Spectrometer with complete ocean coverage in 2–3 days.
- Visible and infrared radiances over global land-surfaces in 1–2 days, sea-ice and ice-sheets equivalent to those currently provided from ENVISAT MERIS, AATSR and Système Probatoire d'Observation de la Terre (SPOT) Vegetation.

The Sentinel-3 mission addresses these requirements by implementing and operating:

- A dual frequency, Synthetic Aperture Radar Altimeter (SRAL) instrument supported by a dual frequency passive microwave radiometer (MWR) for wet-tropospheric correction, a Precise Orbit Determination package including a GPS receiver, a DORIS instrument and a laser retro-reflector.
- A highly sensitive Ocean and Land Colour Imager (OLCI) delivering multi-channel wide-swath optical measurements for ocean and land surfaces.
- A dual-view Sea and Land Surface Temperature Radiometer (SLSTR) delivering accurate surface ocean, land, and ice temperature.
- A collaborative ground segment providing management of the mission, management, development, production and access to core data products in an operational near real time delivery context.

The mission foresees a series of satellites, each having 7-year lifetime, over a 20-year period starting with the launch of Sentinel-3A in late 2013 and of Sentinel-3B in late 2014. During full operations two identical satellites will be maintained in the same orbit with a phase delay of 180°.

This paper provides an overview of the GMES Sentinel-3 mission including the mission background and user requirements, a technical description of the space segment, a brief overview of the ground segment concept, and a summary description of Sentinel-3 data products and their anticipated performance.

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1. Introduction and background to the Sentinel-3 mission

Policymakers and public authorities require accurate and timely information to prepare environmental legislation and policies, monitor their implementation and assess their effectiveness (e.g., Meehl et al., 2009). Considering this challenge and, in order to improve its response to ever growing challenges of global safety (e.g., EC, 2000, 2005a, 2005b, 2009a) and climate change (EC, 2009b), Europe requires an independent and sustained Earth observation (EO) capability to monitor the marine and land environment in an operational context. Global Monitoring for Environment and Security (GMES) is a joint initiative of the European Commission (EC) and the European Space Agency (ESA) to establish such a capability (EC, 2005a, 2005b). GMES is designed to generate and deliver environmental information using satellite, in situ and, socio-economic data that is gathered and processed to provide accurate high quality information products and services tailored to decision makers.

In Europe a significant EO measurement capability has been steadily developed beginning with ERS-1/2 (e.g., Francis et al., 1995) and now ENVISAT (e.g., Dubock et al., 2001). Satellite instruments such as the Advanced Along Track Scanning Radiometer (AATSR) provides global coverage climate-quality Sea Surface Temperature (SST) measurements (O'Carroll et al., 2008), the Medium Resolution Imaging Spectrometer (MERIS) instrument (Rast & Bezy, 1999) provides ocean ("colour") and land radiance/reflectance measurements and, the Radar Altimeter-2 (e.g., Roca et al., 2009) provides ocean, ice and hydrologic (river and lake height) topography measurements. These, and other international contemporary instruments, have reached (or are approaching) the end of their operational life and a new capability is required to provide continuity of measurements to address the needs of GMES.

Against this background, the GMES Sentinel-3 (S-3) mission is being developed to satisfy the European needs as expressed through the GMES initiative while providing continuity to ENVISAT capability. The mission consists of:

- The deployment and operation of a European EO Sentinel-3 satellite system for a sustained 20-year period,
- A robust ground segment managing the mission and generating products through a distributed system with near-real-time data distribution capabilities in an operational context,
- Consistent, reliable and accurate validated data products serving GMES (Fig. 1) including uncertainty estimates required by data assimilation systems (e.g., Grünreich, 2007; Ryder, 2007),
- Implementation of long-term calibration, validation and verification activities for all data products throughout the mission lifetime to assure mission quality and performance.

In addition to serving operational GMES services, data from S-3 will provide a significant contribution to a wide variety of scientific research (e.g. Berger et al., 2012-this issue) that underpins the evolution and quality of GMES services.

This paper provides an overview of the GMES S-3 mission. It first describes the key user requirements driving the mission design, and then states the mission aim and objectives. The mission configuration and payload are then reviewed in detail. A summary of the ground segment development and primary data products is then provided. The purpose of the paper is to provide a technical reference for EO practitioners preparing to use S-3 products.

2. GMES Sentinel-3 user requirements

2.1. GMES marine services

Operational ocean services (EuroGOOS, 1996, 2001) are a fundamental component of GMES (Ryder, 2007) with large commercial, economic and social benefits (EuroGOOS, 1996). Marine services provide warnings of hazardous conditions to support safe and efficient marine operations on a daily basis (including those in the marginal ice zone and coastal environment), generate information to define, monitor and forecast the evolution of the ocean state (used by numerical weather prediction systems and for maritime operations), establish baselines for effective marine environmental management, monitor shipping, measure and monitor natural (e.g., harmful algal blooms) and anthropogenic (e.g., oil spill) pollution events and their evolution, support the design of safe marine structures and to determine the impact of European marine policies (e.g., EC, 2000, 2009a). These are all issues of significant European economic importance.

In this context, a pan-European GMES Marine Service (Ryder, 2007) is being implemented. This service is based on the rapid and significant development of operational oceanography over the last decade (e.g., Bell et al., 2009). Stimulated by the application of satellite-derived measurements of ocean surface topography (e.g., Lea et al., 2008), ocean colour (e.g. Hemmings et al., 2008), sea surface temperature (e.g., Donlon et al., 2011; Oke & Schiller, 2007) and sea-ice (e.g., Stark et al., 2008) generated from a combination of scientific and operational meteorological satellite missions (Le Traon et al., 2010), global numerical ocean prediction (NOP) models have developed steadily and significantly (e.g., Dombrowsky et al., 2009; Hurlburt et al., 2009; Le Traon et al., 2010). NOP provides an essential foundation for marine services because it integrates EO and in situ data using data assimilation frameworks that maximise the impact of measurements on hindcast, analysis and forecast products and services. Improved computing facilities, eddy permitting NOP capabilities and ocean data assimilation systems (e.g., Cummings et al., 2009) have all been extremely successful and a critical mass European GMES ocean service (Bahurel et al., 2010; MyOcean, 2010) has now been established. Data assimilation techniques require that accurate uncertainty estimates are available with all measurements (e.g., Cummings et al., 2009). This implies a dedicated and sustained activity across the entire duration of satellite missions to monitor the quality of measurements and assign meaningful uncertainty estimates to all products (Grünreich, 2007; Ryder, 2007).

In anticipation of the GMES Marine Service, the GMES MyOcean project (MyOcean, 2010, http://www.myocean.eu.org) is working towards deploying a strong and reliable capacity for Ocean Monitoring and Forecasting in Europe. MyOcean products include both observational data from satellites and in situ observing systems as well as numerical analysis and forecasting services. The MyOcean objective is to operate a homogeneous and interoperable system for the provision of ocean observations and ocean-state forecast products. Recognising the diversity of oceanographic conditions in the European seas, MyOcean takes a regional approach to production: separate product lines for the Arctic Ocean, the Northwest Shelf seas, the Iberian-Biscay-Ireland region, the Mediterranean Sea, Black Sea and the global ocean are integrated into a uniform, distributed service. MyOcean requires state of the art global coverage measurements of SSH, SST, sea ice parameters, ocean colour and surface wind velocity for use by advanced NOP systems within Model Forecasting Centres (MFC) and EO thematic assembly centres (TAC) tasked with providing a suite of EO and NOP products to downstream marine services.

The primary satellite ocean measurement requirements for the GMES Marine Service (Ryder, 2007) are for:

- Sea surface topography measurements with high accuracy (3 cm or better) and derived topography products (e.g., ocean currents, surface wind speed, significant wave height (Hs)) sampled at mesoscale resolution with global coverage including polar regions,
- Continuity of climate quality (accurate to 0.3 K or better) sea surface temperature (SST) measurements derived from a dual-view AATSR class radiometer at ~1 km spatial resolution with global ocean coverage in 3–4 days,

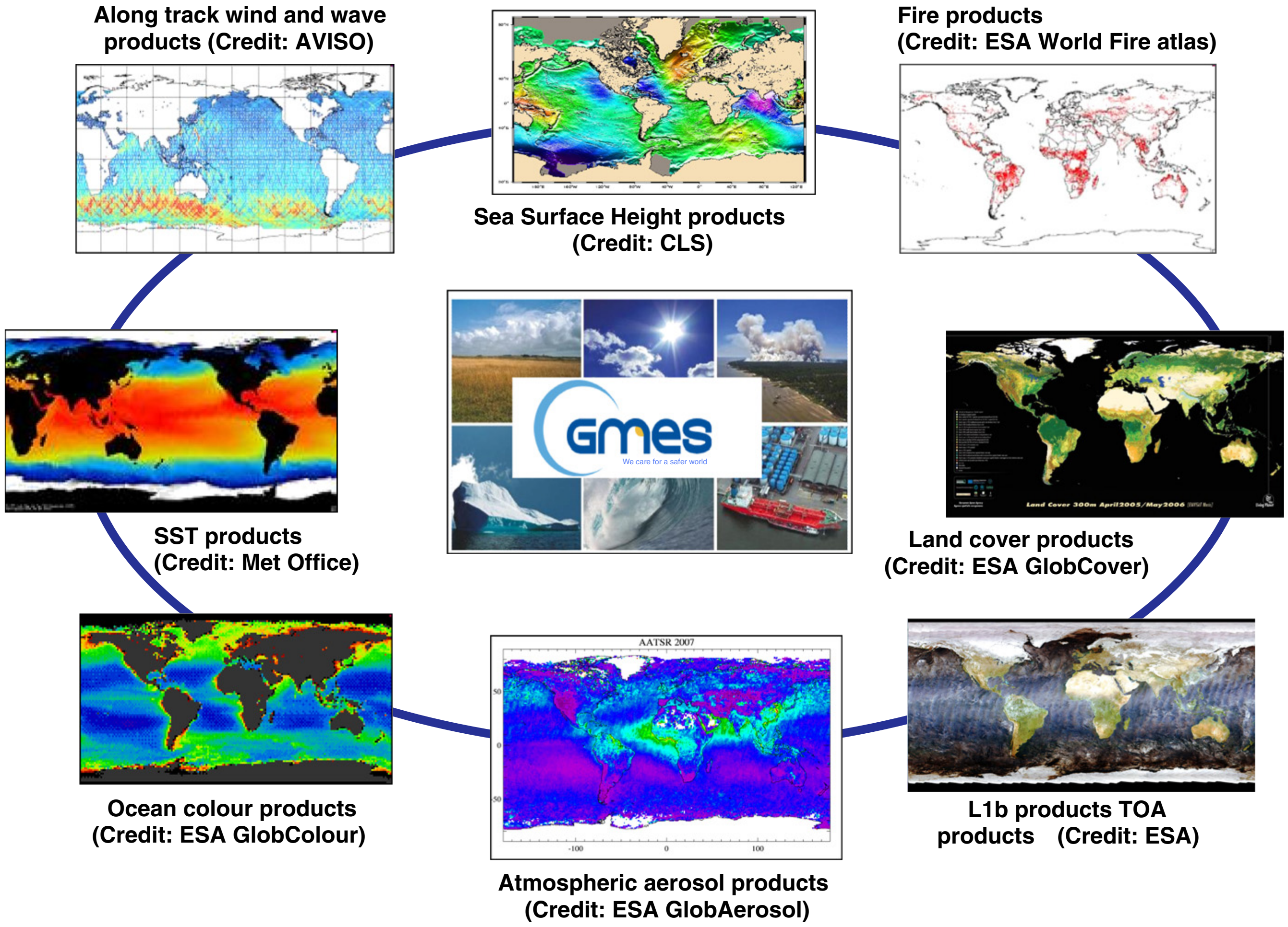

Fig. 1. Example Sentinel-3 data products supporting GMES Services.

- Biological parameters (e.g. total suspended sediment, maps of Harmful Algal Blooms (HAB), chlorophyll-a, water leaving radiance and inherent optical properties) required for ecosystem modelling and forecasts (e.g. HAB evolution, water quality assessment) with high-resolution (300 m) in the coastal zones with global ocean coverage in 2–4 days,
- Sea ice conditions (sea ice concentration, thickness, dynamics, type, and edge).

Continuity of ENVISAT measurement capability is particularly important for NOP, ocean monitoring and climate monitoring applications. The need for accurate measurements delivered in a robust and timely manner underpins the quality of NOP systems (e.g., MyOcean, 2010; Ryder, 2007). Timeliness requirements call for observations to be available to the data assimilation system within ~3 h of measurement at the satellite platform because many operational systems run NOP models at agreed synoptic times of 00:00, 06:00, 12:00 and 18:00 UTC with intermediate model runs between these times.

2.2. GMES land services

GMES land services have matured building on the use of generic optical satellite imaging (e.g., Smith et al., 1997; Maisongrande et al., 2004) complemented by high-resolution (<0.1–0.3 km) land imaging satellite systems (e.g., Durpaire et al., 1995; Grünreich, 2007). Since 1972 LANDSAT (e.g., Loveland et al., 2008) and from 1998 the SPOT Vegetation (e.g., Guyon et al., 2010) missions have offered high-quality moderate-resolution (0.01–0.5 km spatial resolution) global data of the entire terrestrial surface to users. The GMES land service project GEOLAND-2 provides daily monitoring of the terrestrial environment (GEOLAND-2, 2010a) in support of a variety of European Policies and regulations covering water, soil and terrestrial pollution (EC, 2000; EC, 2010; EC, 2006; EC, 1991) amongst others. GEOLAND-2 services include routine wall-to-wall land cover mapping and land cover change, global land productivity, imperviousness, forestry, agriculture, water, wetlands, vegetation status and determination of biophysical vegetation parameters. Scales addressed in the land surface component of General Circulation Models (GCMs) or NWP models or forecasting models are ~1 km (regional) to 100 km (global). Key parameters include surface albedo, surface roughness, resistance to heat exchanges (sensible and latent), active fires, burned areas, lake and rivers and surface temperature identify land cover characteristics and variability. The seasonal and long-term variations of these variables are related to vegetation dynamics, and thus the capability to identify physical characteristics of land cover is important for GMES and EU policies. GMES services require access to land reflectance measurements and derived vegetation/biophysical products (e.g. land use and land cover maps, LAI, FAPAR, crop monitoring and food security, agro-environmental indicators, forestry management and dynamics, snow extent, water resources) in a sustained manner at a moderate spatial resolution (~10–1000 m) with ~2 days global coverage. Hydrologists and hydrology climate modelling groups require a variety of environmental information including lake area, lake height differences from reference height, lake volume change, lake water-quality and surface temperature. River and Lake Height (RLH) products derived from satellite altimetry (e.g., Berry & Benveniste, 2010; Berry & Wheeler,

2009) are also required by GMES to support the implementation of the EC Water Framework Directive (EC, 2000). Such measurements will complement the European Environment Agency's (EEA) Monitoring and Information Network for Inland Water Resources (Eurowaternet) in situ station network.

2.3. Other GMES services and requirements

2.3.1. GMES atmospheric service

The GMES Monitoring Atmospheric Composition and Climate (MACC) project (GMES-GAS, 2009; GMES-MACC, 2010) is developing services to support institutions that are providing advice and warnings related to atmospheric composition. Products derived from satellite optical instruments have the widest range of impacts affecting the forcing of climate, air quality, atmospheric visibility and cloud/precipitation processes. Wild fires also release a variety of chemically-reactive gases through biomass-burning that strongly influence physical and chemical processes within the troposphere. Fire monitoring measurements are required by MACC for trace gas and particulate-emission modelling, climate modelling, atmospheric transport and chemistry models, ecosystem dynamic models and models of land use change. MACC has the capability to make pre-operational volcanic ash plume forecasts using its advanced data assimilation system for atmospheric composition (e.g., Menut & Bessagnet, 2010). Satellite multi-frequency L1b radiance data products from infrared and visible measurements are required for use in NWP and re-analysis model runs in NRT together with uncertainty estimates (GMES-GAS, 2009). Measurements of sea state and surface wind speed over the ocean, soil moisture, atmospheric humidity atmospheric aerosols, SST, land and lake surface temperatures, vegetation state and coverage, and wild fires are all required for NWP/MACC activities with sub-daily revisit, moderate spatial-resolution (0.3–1 km) and global coverage. As NWP systems assimilate data on 3–6 hourly (typical) cycles, frequent revisit and NRT delivery timeliness requirements are particularly challenging.

2.3.2. GMES safety service

Vulnerability to the impact of natural and anthropogenic disasters and management of regional security are some of the greatest obstacles to sustainable economic and social development. Earth observation data provide valuable measurements used by a variety of services including teams managing crises: e.g. those due to storms, volcanic eruption, floods, crop failure, land-slides, pollution (e.g. oil spill), humanitarian crises, wild fires, and large-scale accidents (e.g., explosions) etc. The GMES Services and Applications for Emergency Response (SAFER) project is developing pre-operational GMES emergency management services (GMES-SAFER, 2011) to respond to emergency situations. SAFER requires high-and medium (0.001–1 km) resolution EO products for rapid mapping capability immediately after disaster events together with baseline maps of spatial and socio-economic parameters in areas at high risk. In support of wildfire management, GMES-SAFER requires an effective fire measurement capability (e.g., the ATSR World Fire Atlas; Arino, 2008) to monitor, prevent, detect, control and manage wild fires to safeguard life, property, and resources (e.g., Morgera & TeresaCirelli, 2009). For rapid post-burn assessment of fire impact in ecologically sensitive areas, high-resolution data are required within hours of the fire to assess fire extent, severity and ecosystem and hydrological impact (Townshend et al., 2008). L1b radiance data products from infrared and visible measurements are required at moderate-to-high (<0.1–1 km) with global coverage and rapid revisit and delivery of tailored products to support GMES safety services.

2.3.3. GMES security service

GMES services for Management of Operations, Situation Awareness and Intelligence for regional Crises (G-MOSAIC) is the EU-funded project responsible for the development of the GMES security service (GMES-G-MOSAIC, 2011). G-MOSAIC provides intelligence and early warning services to support root-cause analysis of regional crises, such as weapons proliferation, fighting for natural resources, population pressure, land degradation, and illegal activities in four security domains:

- Natural Resources and Conflicts;
- Migration and Border Monitoring;
- Nuclear and Treaties Monitoring;
- Critical Assets.

Key Earth observation requirements for security applications include: NRT and NTC access to high-resolution (<1 km) multi-channel optical and microwave measurements from which higher-level indicator products tailored to each security domain can be derived, a NRT product dissemination system for derived products, and a suite of baseline maps to monitor time evolution of security issues.

2.3.4. GMES and climate

Climate research has relied heavily on EO data for over the last three decades and in some areas EO measurements (e.g., Sothern Ocean) are the only systematic data available. In the future EO data will play an increasing role in climate research and the provision of climate services. Good examples include the systematic long-term observation of ocean topography and sea-level using sea surface height (SSH) products derived from inter-calibrated altimeter mission data referenced to accurate and precise geoid information (e.g., Leuliette & Miller, 2009), cloud climatologies (Schiffer & Rossow, 1983), SST and sea-ice climatologies (e.g., Hurrell et al., 2008), changes in marine productivity (e.g., Henson et al., 2010), ice mass balance measurements (Rignot, 2006) and monitoring land surface parameters (e.g., Masson et al., 2003). Climate users demand the highest accuracy and stability (over decades) from satellite data products. Full access to L1b and L2 data products is required both in a delayed mode for reanalysis and within ~1 month of measurement for climate monitoring services. Ensemble seasonal (e.g., Buontempo et al., 2010) and decadal forecast systems (Collins et al., 2006; Meehl et al., 2009) are expected to provide significant benefits for climate services addressing societal issues such as improved weather forecasting, heath, energy, water resources, ecosystem management, agricultural production and maintenance of biodiversity. These applications require global coverage accurate time-series of moderate resolution (1–10 km) ocean state information derived from EO data (e.g., SST, SSH, Chla, sea ice parameters etc.), with accompanying uncertainty estimates complemented increasingly by terrestrial measurements.

3. Sentinel-3 mission objectives

In response to S-3 mission requirements (Donlon, 2011; Drinkwater & Rebhan, 2007) and GMES data product requirements (ESA, 2009a), S-3 has been designed to provide measurements to monitor the global environment through measurements that will also be used to constrain and drive global–local numerical prediction models in support of GMES user needs. The aim[1] of the S-3 mission is:

> *To provide continuity of ENVISAT type measurement capability in Europe to determine sea, ice and land surface topography, temperature, ocean and land surface radiance/reflectance, and atmospheric measurements with high accuracy, timely delivery and in a sustained operational manner for GMES users.*

The specific objectives for the mission are presented in Table 1.

S-3 will contribute to climate change activities in several ways. The proposed SST mission shall continue the legacy of the ENVISAT AATSR

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[1] The mission aim is the intended outcome that is desired from the end-to-end mission. The mission aim has a set of objectives that are directly aligned with the aim.

Table 1
Primary and secondary mission objectives for Sentinel-3.

Type	Sentinel-3 objectives
Primary	Sentinel-3 shall provide continuity of an ENVISAT type ocean measurement capability for GMES Services with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users, including: • Ocean, inland sea and coastal zone colour measurements to at least at the level of quality of MERIS on Envisat; • Sea surface temperature measurements to at least at the level of quality of AATSR on Envisat; • Sea surface topography measurements to at least at the level of quality of the Envisat altimetry system, including an along-track SAR capability of CryoSat heritage for improved measurement quality in coastal zones and over sea ice.
Primary	Sentinel-3 shall provide continuity of medium resolution ENVISAT-type land measurement capability in Europe to determine land-surface temperature and land-surface colour with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users.
Primary	Sentinel-3 shall provide, in a NRT operational and timely manner, L1b visible, shortwave and thermal infrared radiances and L1b/L2 topography products for use by GMES Services with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users.
Primary	Sentinel-3 shall provide, in a NRT operational and timely manner, a generalised suite of high-level **primary** geophysical products with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users. Products shall include as priority: • Global coverage Sea Surface Topography (SSH) for ocean and coastal areas, • Enhanced resolution SSH products in the Coastal Zones and sea ice regions, • Global coverage Sea-Surface (SST) and sea ice surface temperature (IST), • Global coverage Ocean Colour and Water Quality products, • Global coverage Ocean Surface Wind Speed measurements, • Global coverage Significant Wave Height measurement, • Global coverage atmospheric aerosol consistent over land and ocean, • Global coverage Vegetation products, • Global coverage Land Ice/Snow Surface Temperature products, • Ice products (e.g., ice surface topography, extent, concentration)
Secondary	Sentinel-3 shall provide continuity of medium resolution SPOT Vegetation P-like products by providing similar products over land and ocean with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users.
Secondary	Sentinel-3 shall provide in an operational and timely manner, a generalised suite of high-level **secondary** geophysical products with a consistent quality, a very high level of availability (>95%), high accuracy and reliability and in a sustained operational manner for GMES users. Products shall include as priority: • Global coverage Fire monitoring products (FRP, burned area, risk maps etc.), • Inland water (lakes and rivers) surface height data.

to provide a 'gold standard' directly addressing the requirements for the GCOS SST ECV (GCOS, 2011). In addition, S-3 will directly contribute to the ocean colour ECV (GCOS, 2011) and the topography mission will make a direct contribution to ice mass balance and sea level ECV (GCOS, 2011). Care must be taken to ensure that high-stability is a feature of each Sentinel-3 instrument design and that long-term stability is maintained and accurately known throughout their entire mission lifetime through careful calibration and validation operations.

4. Sentinel-3 mission configuration

The S-3 mission is based on the heritage of demonstrated European measurement techniques, platform design, instrument design, and data processing systems. There are two primary mission components:

- A Sentinel-3 topography mission providing altimetry measurements.
- A Sentinel-3 optical mission providing visible and infrared measurements simultaneously and contemporaneous with the topography mission.

In order to satisfy the large coverage and high-revisit requirements, the S-3 mission is designed as a constellation of (at least) two identical satellites, S-3A and S3-3B. The S-3 satellite carries the following payload instruments:

- A dual-frequency SAR altimeter, derived from ENVISAT RA-2, CryoSat SIRAL and Jason-2/Poseidon-3 heritage called the SAR Radar ALtimeter (SRAL) instrument.
- A Microwave Radiometer (MWR) instrument, which supports the SRAL to achieve the overall altimeter mission performance by providing the wet atmosphere correction derived from ENVISAT MWR heritage.
- A Precise Orbit Determination (POD) package including a Global Navigation Satellite Systems (GNSS) instrument, a Doppler Orbit determination and Radio-positioning Integrated on Satellite (DORIS) instrument (S3-A only) and a Laser retro-reflector (LRR).
- A push-broom imaging spectrometer instrument building on the heritage of ENVISAT MERIS called the Ocean and Land Colour Instrument (OLCI).
- A dual view (near-nadir and inclined) conical imaging radiometer building on the heritage of ENVISAT AATSR called the Sea and Land Surface Temperature Radiometer (SLSTR) instrument.

Three levels of timeliness are required within GMES depending on the specific application:

- NRT products, delivered to the users in less than 3 h after acquisition of data by the sensor,
- Short time critical (STC) products, delivered to the users in less than 48 h after the acquisition and,
- Non-time critical (NTC) products delivered not later than 1 month after acquisition or from long-term archives.

The following sections provide a functional but technical description of each of the payload instruments to be flown on S-3. The intent is to provide the reader with a baseline technical reference that is required to understand the quality and performance of anticipated data products that are summarised in the final part of the paper.

4.1. The Sentinel-3 spacecraft

S-3 is a low Earth-orbit moderate size satellite compatible with small launchers including Vega[2] and Rokot.[3] The main satellite platform characteristics are given in Table 2. S-3 is designed for a 7-year operational lifetime with 120 kg of hydrazine propellant allowing up to 12 years of continuous operations including de-orbiting at the end of mission. The satellite layout is driven by the need to provide a large face viewing cold-space for thermal control and, a modular design for payload accommodation and simplified management of all on-board interfaces. The satellite mechanical configuration and its flight attitude

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[2] http://www.arianespace.com/launch-services-vega/vega_overview.asp.
[3] http://www.eurockot.com/.

Table 2
Sentinel-3 Spacecraft technical characteristics.

Parameter	Value
Maximum mass	1250 kg
Volume	3.71 m × 2.202 m × 2.207 m in stowed configuration
Power	2.1 kW rotary solar wing 10 m^2 GaAs triple junction solar cells
Battery	Li Ion capacity of 160 Ah
Average power consumption	1100 W
Launch vehicle	Vega or Rokot
Mission lifetime	7 years (consumables for 12 years)
Stabilisation	3-axis stabilised using 4 reaction wheels and 3 star tracker heads
Orbit accuracy	3 m in real-time determination based on GPS and Kalman filtering, 3 cm after processing
Communication links	S-band 64 kbps uplink, 1Mpps downlink for command and control 2 X-band 280 Mbps science downlink
On-board memory	384 Gbit solid state mass memory (~170 Gbit of observation data per orbit)
Autonomy	Position timeframe and onboard sun ephemeris for > 2 weeks for nominal autonomous operations

have been optimised through intensive mission analysis studies and system trade-offs performed during the mission definition that results in significant improvements with respect to ENVISAT.

An extensive instrument payload, together with the need to fit the performance of a "small" class of launchers, has driven the S-3 satellite configuration. The satellite accommodates seven different payloads (seven in the case of S-3A) with specific sizes, interfaces, requirements for Earth and calibration target views, and thermal requirements for cold space-view access by radiators. The resulting satellite architecture is shown schematically in Fig. 2. The main subsystems of the satellite include:

- An Electrical Power System (EPS), comprising one solar array wing providing power to the spacecraft and payload.
- A satellite Attitude and Orbit Control System (AOCS) composed of a Coarse Sun Sensor, Magnetometers, Coarse Rate Sensors, Star Trackers, a GNSS receiver and control actuators including thrusters, magneto-torquers and reaction wheels.
- A Satellite Management Unit for Satellite commanding and monitoring.
- Data Handling and Mass Memory Unit for payload data handling.
- Mass Memory Units for the satellite and its payload.
- Satellite telecommunication subsystems including an S-Band subsystem for both telecommand (TC) uplink and telemetry (TM) downlink, and a dedicated high volume (2 × 280 Mbps) X-Band subsystem for mission data downlink.

All S-3 mission data are stored in dedicated mass memory Packet Stores (PS) within the on-board Payload Data Handling Unit (PDHU). Three memory modules are implemented providing a storage capacity of 576 Gbit (72 Gb) in a configuration where two memory modules provide a net capacity of 384 Gbit (48 Gb) and a third module is used as a redundant spare. The PS downlink sequence will be nominally fixed according to a priority order simplifying S-3 routine operations.

4.2. Mission operations concept

The S-3 operations concept is built around the principle of a quasi-autonomous satellite with minimum human intervention to simplify mission management and operations. Spacecraft and payload operation commands can be stored on-board covering equivalent to the full 27-days Satellite repeat cycle and S-3 instruments can be commanded autonomously on-board the spacecraft using time-tagged commands. Commands are linked to geographic data, orbital time and the selection of a particular measurement mode depending on the surface over which the spacecraft is flying. This approach to operational planning and management does not require any specific request from a user and ground-based routine operation of the spacecraft will be extremely simple. Fig. 3 provides an overview of the main elements of the S-3 operation concept highlighting where and when each instrument is operated around the orbit, preferred spacecraft manoeuvre locations and ground station contacts. The payload instrument duty cycles vary around each orbit: the SRAL, MWR and SLSTR acquisitions

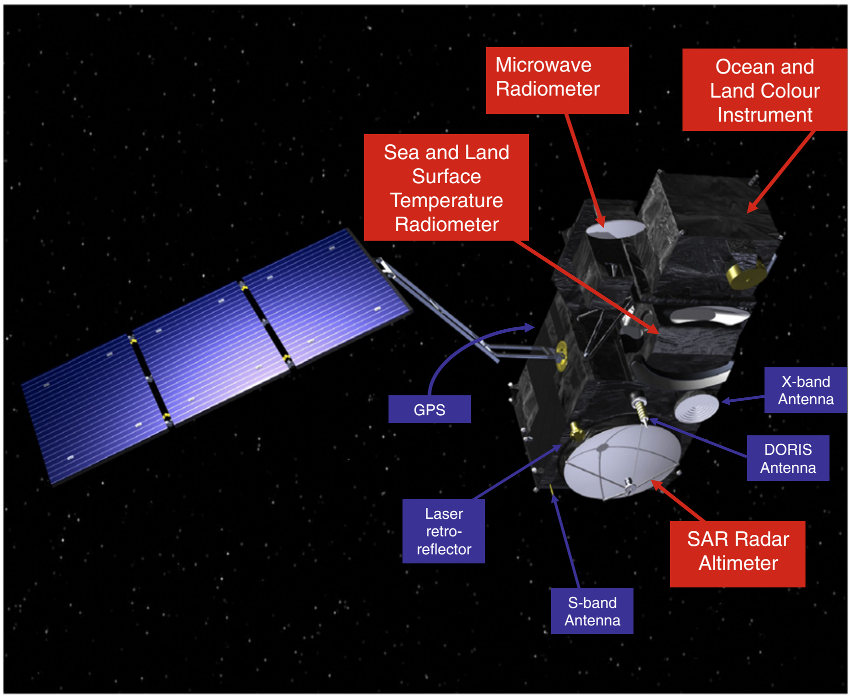

Fig. 2. An artist's impression of Sentinel-3 on orbit. The main features of the satellite are identified.

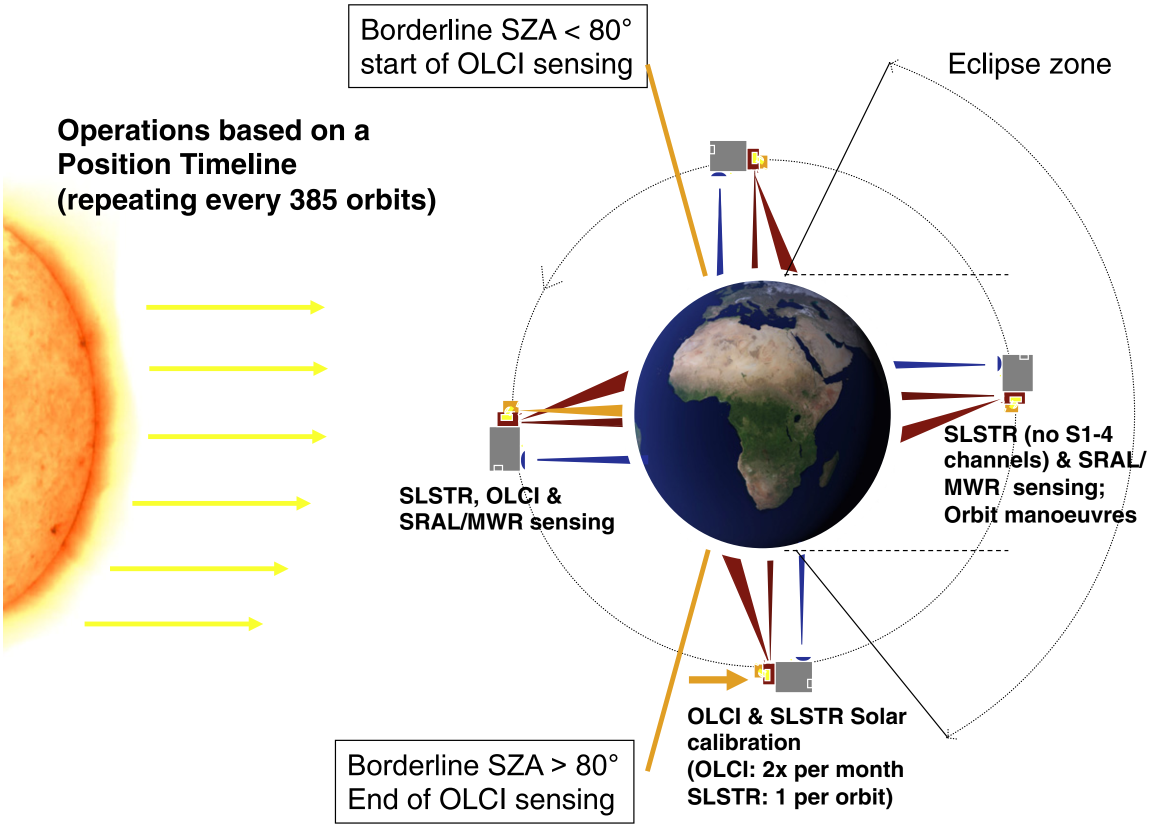

Fig. 3. An overview of Sentinel-3 operations and instrument payload acquisitions for each orbit. Blue indicates SRAL, red SLSTR and orange OLCI.

are performed without interruption over the entire orbit. No SLSTR visible channel data will be acquired during eclipse and OLCI acquisitions are only made when the solar zenith angle >80°. SRAL Low Resolution Mode (LRM) and Synthetic Aperture Radar (SAR) mode will alternate according to requirements managed by mission planning. The projected sensing duty cycle per orbit for each Sentinel-3 instrument is OLCI: 44%, SRAL SAR-mode 75%; SRAL LRM 25%, MWR: 100%, SLSTR: 100%, GNSS/DORIS: 100% and navigation and attitude (NAVATT): 100%.

4.3. Orbit selection and coverage

The choice of orbit for S-3 is a compromise between the requirements of the topography mission and those of the optical mission. The topography mission is optimised to facilitate the description, understanding and forecasting of the mesoscale variability of the ocean while also monitoring globally ocean surface winds and waves, rivers, lakes ice-sheets and sea-ice. The S-3 topography mission, as a single altimeter mission, cannot address these requirements alone and must consider other altimeter systems “in constellation” (e.g., Cotton et al., 2004; Escudier & Fellous, 2006) where synergy provides optimum spatial sampling, cross-calibration and reference (negligible-tidal alias) altimetry (e.g. Ménard et al., 2003). As an altimeter is foreseen in a low-inclination (66°) reference orbit for some time (Escudier & Fellous, 2006), it is appropriate for S-3 to maintain an ENVISAT type high-inclination polar orbit. This choice provides optimal SRAL coverage of the ocean, ice surfaces in high-latitudes and of the European shelf Seas that is fully in line with GMES recommendations (Ryder, 2007).

For the Ocean Colour mission, a polar sun-synchronous orbit is required with a local time of ascending node (LTAN) at the equator ≥10:00 (similar to ENVISAT) to maximise solar elevation (Solar Zenith Angle (SZA)>80°), avoid morning haze and cloud formation. The orbit must also mitigate the negative impact of sun-glint on the ocean colour measurements (e.g., Kay et al., 2009). The SST mission requires a LTAN<11 h to avoid diurnal stratification impacts (e.g., Gentemann et al., 2008), afternoon clouds and morning haze. In addition, an ENVISAT repeat orbit is preferred to maintain continuity with the time-series of ENVISAT AATSR and MERIS measurements.

Following a trade-off analysis between topography and optical mission requirements, a sun-synchronous orbit has been selected for the S-3 mission flying at 814.5 km altitude (14 + 7/27 revolutions per day) with a local equatorial crossing time of 10:00 a.m. (Table 3). The configuration of two S-3 satellites in constellation foresees a 180° in-plane separation between the two spacecraft driven by optical ocean and land coverage requirements. This configuration accommodates operational constraints and guarantees that after each orbit the 2nd satellite ground track is in the middle of the gap left by the track of the first, thus optimising payload coverage while maintaining a balance between topography and optical mission coverage.

This orbit has a revisit time of ~27 days providing global coverage of topography data at mesoscale (inter-track distance at equator 104 km using 1 satellite) with a primary orbit sub-cycle at ~4 days as described in Table 4. In a 2-satellite configuration after one

Table 3
Sentinel-3 satellite orbit parameters for.

Orbit type	Repeating frozen SSO
Repeat cycle	27 days (14 + 7/27 per day)
Local solar time	10:00 at descending node
Average altitude	814.5 km
Inclination	98.65°
S-3B satellite	Identical orbit to S-3A but flown 180° out of phase with S2A

Table 4
Spatial separation of SRAL ground tracks at the equator.

	Constellation configuration	Main 27 day cycle inter-track separation at the equator	4 day sub-cycle day cycle inter-track separation at the equator
Altimetry mission	1 Satellite	104 km	Min = 104 max = 728 km
	2 Satellites	52 km	Min = 57, max = 671 km

Table 5
Global coverage revisit times for Sentinel-3 optical measurements.

	Constellation configuration	Revisit at equator	Revisit for latitude > 30°	Specification
Ocean colour	1 Satellite	<3.8 days	<2.8 days	<2 days
(sun-glint free, day only)	2 Satellites	<1.9 days	<1.4 days	
Land colour (day only)	1 Satellite	<2.2 days	<1.8 days	<2 days
	2 Satellites	<1.1 day	<0.9 day	
SLSTR dual view	1 Satellite	<1.8 days	<1.5 days	<4 days
(day and night)	2 Satellites	<0.9 day	<0.8 day	

complete cycle the inter-track separation is reduced to 52 km at the equator.

Two S-3 satellites support full optical imaging of the oceans within 2 days (even allowing for ocean sun-glint effects), while delivering global land coverage in just over one day (ignoring reduction in coverage due to clouds) at the equator—with coverage improving with increasing latitude (Table 5). The fully overlapping swath of the SLSTR and OLCI instruments together with the nadir pointing SRAL footprint is shown schematically in Fig. 4.

4.4. Sentinel-3 topography mission

The purpose of the S-3 topography payload is to provide continuity to the precise range and normalised backscatter (σ^o) measurements of ENVISAT RA-2 (e.g., Roca et al., 2009) and Cryosat (e.g., Wingham, 1999) altimeters.

4.4.1. Synthetic Aperture Radar Altimeter (SRAL) Instrument

The S-3 SRAL instrument (Le Roy et al., 2010) is a fully redundant dual-frequency (Ku and C-band) nadir-looking radar altimeter that employs SAR altimetry technologies inherited from the CryoSat (Wingham, 1999) and Jason altimeter missions. The SAR altimeter approach increases the measurement accuracy and along track resolution when compared to conventional altimetry products. SRAL will acquire topography data over all types of surfaces covered by the Sentinel-3 mission (sea, coastal areas, sea ice, ice sheets, ice margins, in-land waters). SRAL will provide measurements with a high spatial resolution (~300 m along-track) over specific dynamic ocean regions, coastal regions (up to 300 km offshore), sea-ice and inland areas. The SRAL design includes the following sub-systems:

- A Satellite Management Unit for Satellite commanding and monitoring.
- Data Handling and Mass Memory Unit for payload data handling.
- A Radio Frequency Unit (RFU) comprised of Solid State Power Amplifiers in Ku and C bands, diplexers used to route signals in the transmit or receive chains, a signal demodulation and "deramp" system, and gain controlled amplifiers to slave the echo level.
- A Digital Processing Unit (DPU) that manages all communication interfaces between the satellite platform (telemetry and telecommands), a chirp generator, full sequencing of the instrument, received signal sampling and all elements of the required for tracking.

Two identical DPU and RFU systems mounted inside the satellite platform as shown in Fig. 5 provide cold redundancy. Key design elements of the SRAL instrument are provided in Table 6.

The SRAL antenna is a parabolic reflector with a C/Ku dual frequency feed horn supported by 3 struts separated by a 120° angle placed centrally at a focal length of about 430 mm. The antenna provides a minimum gain of 41.5 dB in Ku-band and 31.6 dB in C-band at bore-sight in the signal bandwidths. In order to minimise the Ku Band Range Ambiguity Ratio, the side-lobe level is less than − 18 dB. SRAL transmits pulses alternatively at Ku-Band (13.575 GHz, bandwidth = 350 MHz) main frequency for altimeter range measurements complemented by a C-Band frequency (5.41 GHz, bandwidth = 320 MHz) that is used to correct range delay errors due to the varying density of electrons in the ionosphere (e.g., Lorell et al., 1982). The dry troposphere range delay can be determined with sufficient accuracy using meteorological data and models (e.g., Fu & Cazenave, 2001). However, wet troposphere range delay is more challenging and must be corrected using dedicated microwave radiometer measurements (described in Section 4.4.2) to achieve the required altimetry accuracy.

SRAL uses a linearly frequency-modulated pulse (chirp) with pulse compression carried out on-board using the deramp technique (MacArthur, 1976). The instrument requires a 10 MHz input signal

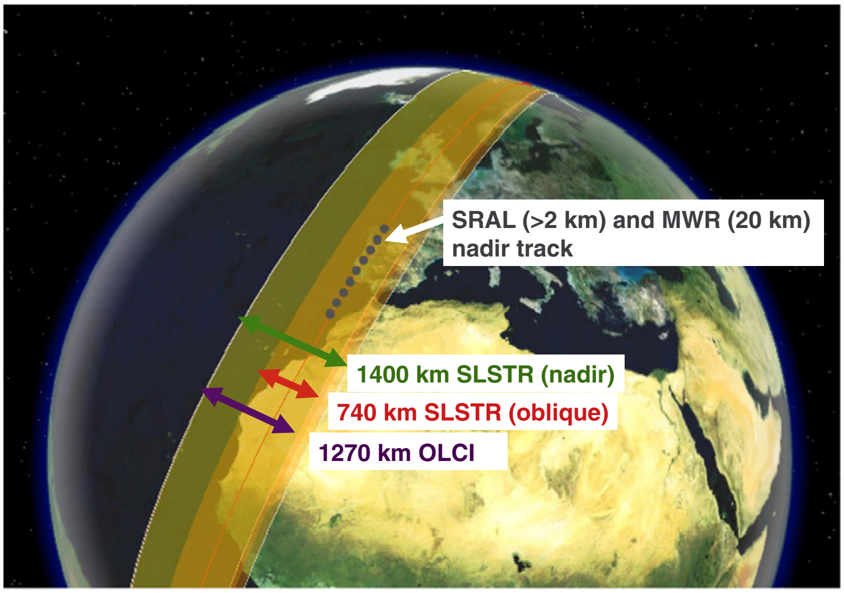

Fig. 4. Ground swath of OLCI and SLSTR showing the centrally located footprint of the SRAL and MWR and overlapping SLSTR and OLCI swaths offset to the west of the nadir point.

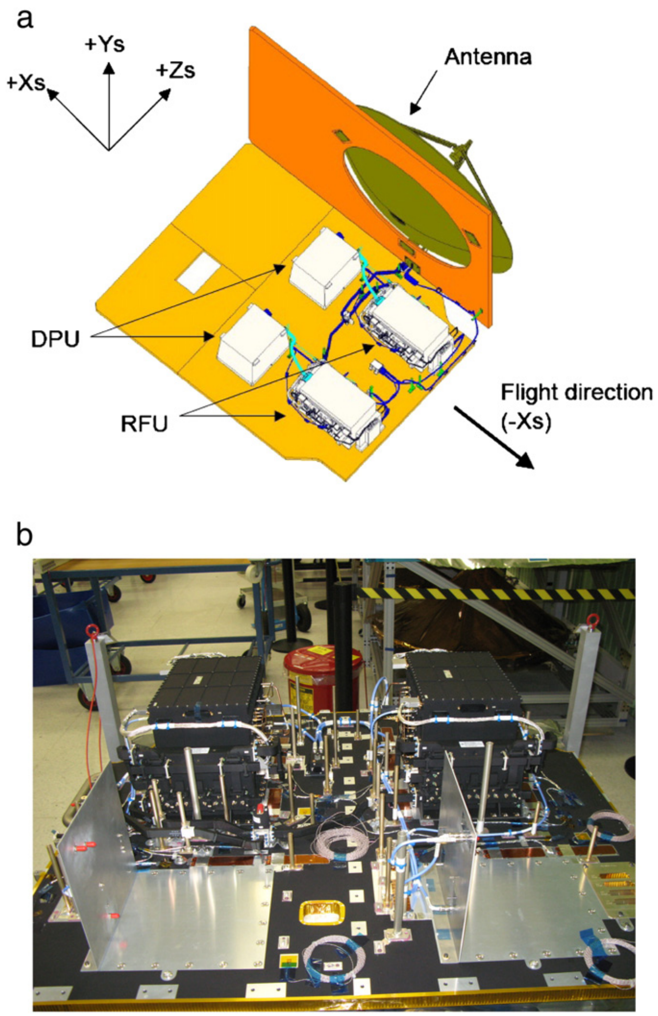

Fig. 5. (a) Schematic layout of the Sentinel-3 Synthetic aperture Radar Altimeter (SRAL) instrument showing the redundant electronics chains located inside the satellite platform and antenna accommodation arrangement. (b) Integrated SRAL-RFU showing Side-A and Side-B pre-flight units. (Credit: Thales Alenia)

Table 7
Estimated Sea Surface Height (SSH) error budget for the Sentinel-3 topography mission.

Source	ENVISAT error [cm]	S-3 error [cm]	Contributor
Altimeter noise	1.8	1.4	SRAL
Sea state bias	2	2	SRAL
Ionosphere	0.5	0.5	SRAL
Dry troposphere	0.7	0.7	SRAL
Wet troposphere	1.4	1.4	MWR
Total range error	3.1	2.9	
Radial orbit error	1.9	1.9	POD
Sea Surface height error	3.6	3.4	

delivered by an USO (Ultra-Stable Oscillator). The signal of the USO also serves the on-board navigation tracking system that tracks orbit and attitude drifts required to derive appropriate corrections and maintain the accuracy of SRAL measurements.

Two radar modes are provided by the SRAL design to facilitate autonomous operations. Low Resolution Mode (LRM) is the primary mode when observing level surfaces with homogeneous and smooth topography including open-ocean and smooth ice-sheet plateaux. In this mode, SRAL operates as a conventional pulse limited altimeter with regular Tx/Rx sequences at a Pulse Repetition Frequency (PRF) of 1920 Hz. Patterns of 6 Ku-Band pulses surrounded by 1 C-Band pulse are used to ensure sufficient ionospheric bias correction. After deramping and digital processing, the echo received from each pulse is sampled on 128 points corresponding to a 60-m range window. C and Ku-Band echoes are accumulated separately over a 50-ms cycle (i.e., 84 Ku-Band pulses and 14 C-Band pulses accumulated over that cycle). Further ground processing produces 20-Hz Ku-band and C-band waveforms and associated parameters for user applications.

SRAL provides a SAR Mode (SAR) to generate high-resolution (~300 m) along-track measurements to maximise information retrieval over more variable terrain surfaces sea/ice and sea/land transitions in coastal areas or over inland water areas that are challenging for conventional pulse limited altimeter systems. In this mode, patterns of 64 coherent Ku-band pulses are emitted in a burst (PRF of 18 kHz) surrounded by 2 C-Band pulses to provide ionospheric bias correction. After deramping and digital filtering, the echo received from each pulse is sampled on 128 complex points and sent directly to ground without any on-board processing or further accumulation. SAR processing on-ground then enhances the azimuth (along-track) resolution of the altimeter for each burst of pulses.

To facilitate autonomous operations, LRM and SAR modes use one of two on-board tracking modes. Traditional, autonomous closed-loop tracking of range and gain may be used where the altimeter range window is autonomously positioned based on-board NRT analysis of previous SRAL waveforms (Le Roy et al., 2010). Alternatively, an open-loop tracking mode is available where the altimeter range window is positioned using a-priori knowledge of the surface height stored on-board the instrument in a one-dimensional along-track Digital Elevation Model (DEM). This mode facilitates acquisition over rough terrain and ensures continuous acquisitions across sea/land sea/ice transition zones. A key advantage of open-loop tracking is that data loss typical of conventional closed-loop tracking due to

Table 6
Technical characteristics of the Sentinel-3 SAR Radar Altimeter (SRAL) instrument.

Parameter	Ku band	C band
Frequency	13.575 GHz	5.41 GHz
Bandwidth	350 MHz (320 used)	320 MHz (290 used)
Antenna footprint	18.2 km	48.4 km
Radius of 1st resolution cell	823 m	865 m
Low Resolution Mode (LRM) Pulse repetition frequency (PRF)	1924 Hz	274.8 Hz
LRM Tracking Modes	Closed loop and open loop	
Synthetic Aperture Radar (SAR) mode		
SAR (PRF)	17,825 Hz	
SAR along track resolution	291 m (Orbit height 795 km)–306 m (Orbit height 833 km)	
SAR across track resolution	>2 km depending on Hs	
Doppler bandwidth	15,055 Hz	
Tracking modes	Closed loop and open loop	
Antenna size	1.2 m diameter, focal length 0.43 m	

Table 8
Technical characteristics of the Sentinel-3 MicroWave noise-injection Radiometer (MWR) instrument specification.

Centre frequency	23.8 GHz	36.5 GHz
Bandwidth	200 MHz	200 MHz
Integration time (typical)	152.88 ms	152.88 ms
Polarization	Linear	Linear
Main antenna (reflector) size (projected diameter)	0.6	
Calibration	Noise injection Dicke radiometer configuration with a separate sky horn viewing deep space (cold reference at 50% and 100% noise injection). Dedicated instrument calibration temperature sensors.	
Noise figure (at 25 °C)	<4.4 dB (main path)	<5.1 dB (main path)
Radiometric sensitivity	0.29 K (main path, NIR mode)	0.34 K (main path, NIR mode)
Radiometric accuracy	<3 K	<3 K
Radiometric stability	0.6 K	0.6 K

mode switching and loss of track during transitions or over variable terrain are minimised.

Two SRAL calibration modes are available that are used to monitor the flight configuration of the instrument and in ground processing. One mode calibrates the internal range and azimuth impulse responses in C and Ku Band and a second mode calibrates the gain profile of the range window by averaging thermal noise measured at each C and Ku-Band antenna port.

An estimated SSH error budget for the Sentinel-3 topography mission compared to ENVISAT RA-2 is shown in Table 7. The range noise (accuracy) of SRAL in LRM mode is ~1.2 cm (1-second average with Hs = 2 m) in Ku-band. An improved accuracy of <1 cm is expected when operating in SAR mode (Le Roy et al., 2010) due to the higher number of looks that are integrated in 1 s.

The S-3 ground segment will produce a set of standard core topography data products that are summarised in Table 13.

4.4.2. Microwave radiometer (MWR)

Significant altimeter range-delay errors of several cm due to wet tropospheric attenuation must be corrected (e.g., Tapley et al., 1982) to provide accurate topography data products. Wet-tropospheric corrections are even more challenging in the coastal zones where strong

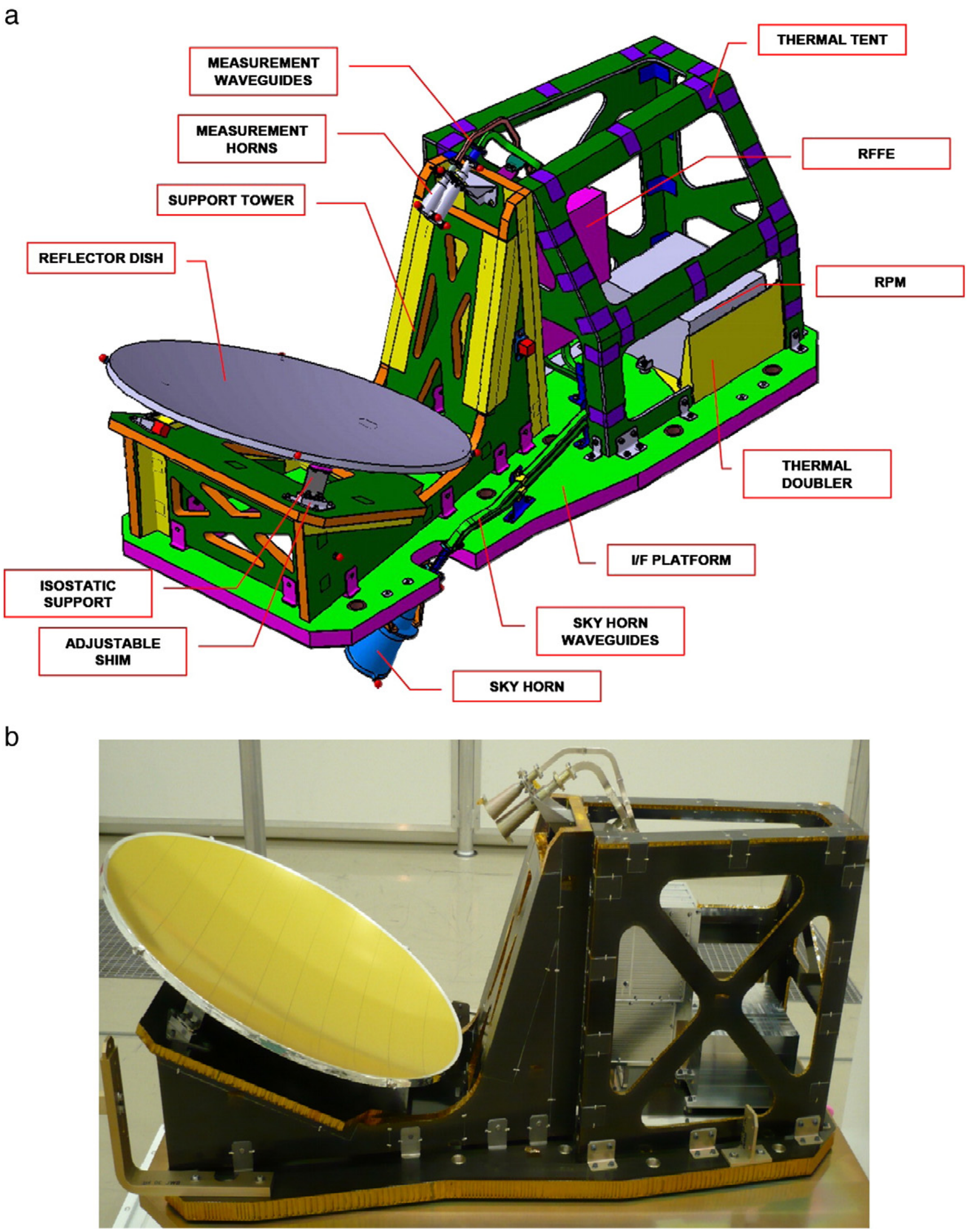

Fig. 6. (a) An overview of the Sentienel-3 Microwave Radiometer (MWR) instrument highlighting principal components of the instrument design. (b) Photograph of the Sentinel-3 MWR Structural and Test Model. (Credit: EADS-CASA)

Table 9
Technical characteristics of the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR).

Swath	Nadir view 1400 km Dual view 740 km
SSI at SSP (km)	Visible channels: 0.5 km SWIR, IR and fire: 1 km
Calibration	Two on-board calibration reference black bodies and 1× Visible calibration unit (VISCAL) viewed once per orbit at the South Pole ecliptic
Detectors	VIS: Silicon diode at 260 K SWIR and MIR: HgCdTe photovoltaic (PV) elements actively cooled to 80 K, TIR: HgCdTe photoconductive (PC) elements actively cooled to 80 K.
Optical scanning design	Along-track scanning based on two earth view scanning mirrors viewing two scan lined per revolution led to one recombination mirror with focusing optics to the detector array (field stop on the detector elements)
Radiometric resolution	VIS(a = 0.5%): SNR > 10 SWIR(a = 0.5%): SNR > 20 MWIR(T = 270 K): NeΔT < 80 mK TIR(T = 270 K): NeΔT < 50 mK Fire1 (< 500 K): NeΔT < 1 K Fire2 (< 400 K): NeΔT < 0.5 K
Radiometric accuracy	VIS-SWIR (a = 2–100%): < 2% (BOL) < 5% (EOL) MWIR-TIR (265–310 K): < 0.1 K (goal) Fire1 and fire2 (< 500 K): < 3 K
Mass	150 kg
Size	2.116 m^3
Design Lifetime	7.5 years

SSI is the spatial sampling interval at sub-satellite point (SSP), a is top of atmosphere albedo, T is top of atmosphere brightness temperature, SNR is signal-to-noise ratio, and NEΔT is noise equivalent difference temperature.

water vapour gradients across land–sea transition regions (e.g., Cipollini et al., 2010) require specialised on-ground processing. Progress is being made using NWP model outputs but current systems do not yet provide the required accuracy or horizontal resolution for robust wet-tropospheric range-delay corrections (e.g., Desportes et al., 2010). Instead, precision altimetry relies on measurements of atmospheric water vapour and liquid water content derived from dedicated multichannel passive microwave radiometer (MWR) measurements (e.g., Eymard et al., 1994; Keihm & Ruf, 1995). This approach was considered mandatory for S-3 (e.g., Donlon, 2011; Drinkwater & Rebhan, 2007) to achieve the required altimetry product accuracy at spatial scales < 100 km. In addition, MWR measurements can also be used to determine surface emissivity, "soil moisture" over land, and in support of studies on surface energy budget, atmosphere and ice characterization (e.g., Drinkwater et al., 2005).

The S-3 MWR is a dual frequency Noise Injection Radiometer (NIR) developed from the CryoSat and Jason MWR instruments (Bergadà et al., 2010). The main specifications of the MWR are provided in Table 8. The design aim is to determine a wet troposphere correction for SRAL with typical accuracy of 1.4 cm. Key elements of the MWR mechanical design are shown in Fig. 6.

The MWR is sensitive to the amount of water vapour and liquid water content in the atmosphere over a ~20 km footprint coincident with the SRAL nadir point. A channel at 23.8 GHz is used for tropospheric water vapour determination and a channel at 36.5 GHz provides information on non-precipitating clouds. The instrument consists of antenna assembly and a Radiometer Electronics Unit (REU). The REU includes a Radiofrequency Front-End (RFFE) and Radiometric Processing Module (RPM). The supporting interface platform is made of Carbon Fibre Reinforced Plastic (CFRP) skin with an aluminium core to achieve required stiffness and strength with low mass. The MWR has an independent thermal control system to optimise the instrument performance. Careful thermal design maintains the REU at a stable temperature using a thermal tent construction based on a CFRP frame with Multilayer Insulation (MLI) covering and thermal doublers.

The antenna subsystem includes two independent antennas: a 600 mm-diameter parabolic main antenna and a Sky Feed Assembly (SFA). The main antenna is made of CFRP with an aluminised kapton surface to minimise its dissipative loss having an antenna beam efficiency > 90% with low side-lobe levels. Signal feeds are offset to minimise the distance to receivers and provide high RF performance with a simple and reliable design. The Sky Feed Assembly measures deep space radiation in both channels as part of the instrument calibration system using a corrugated feed horn with a narrow-beam to minimise stray radiance from the spacecraft and sun. Except for the antenna sub-systems, the MWR instrument includes full cold redundancy of all subsystems.

During normal operations, the measured target signals are balanced against a very stable Dicke noise source. The Dicke load produces a precisely known noise power equivalent to its physical temperature and signal balancing is performed by injecting noise pulses of variable length from a noise diode into the measurement path. The scene brightness temperature is then derived from the duration of the injected noise pulses. The NIR principle reduces the effect of receiver gain and offset instabilities. For scene temperatures that are higher than the Dicke load temperature the balanced condition can no longer be achieved and the instrument operates in an equivalent manner to a classical un-balanced Dicke radiometer.

During in-orbit calibration, the MWR uses well characterised cold space noise measured using the SFA and the Dicke load. Fixed amounts (50% and 100%) of noise are injected on top of the cold space signal to calibrate the power of the noise diode and the receiver gain. In addition, periodic short SFA views are made between calibration measurements using the standard NIR operation to monitor the stability of the instrument. To avoid possible electro-magnetic interference from SRAL, the MWR design includes a blanking signal to synchronise its measurement cycle to SRAL and optimise the measurement integration time. The

Table 10
Band characteristics of the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR). F1 and F2 are dedicated active fire monitoring bands.

SLSTR band	L centre [μm]	ΔL [μm]	SNR [−]/ NeΔT [mK]	SSD [km]	Function
S1	0.555	0.02	20	0.5	Cloud screening, vegetation monitoring, aerosol
S2	0.659	0.02	20	0.5	NDVI, vegetation monitoring, aerosol
S-3	0.865	0.02	20	0.5	NDVI, cloud flagging, Pixel co-registration
S4	1.375	0.015	20	0.5	Cirrus detection over land
S5	1.61	0.06	20	0.5	Cloud clearing, ice and snow, vegetation monitoring,
S6	2.25	0.05	20	0.5	Vegetation state and cloud clearing
S7	3.74	0.38	80 mK	1.0	SST, LST, Active Fire
S8	10.95	0.9	50 mK	1.0	SST, LST, active fire
S9	12	1.0	50 mK	1.0	SST, LST
F1	3.74	0.38	< 1 K	1.0	Active fire
F2	10.95	0.9	< 0.5 K	1.0	Active fire

anticipated radiometric sensitivity of the MWR is <0.4 K with a stability <0.6 K, and absolute accuracy <3 K over a brightness temperature range of 150–313 K (Bergadà et al., 2010).

4.4.3. Precise orbit determination (POD)

High accuracy (2–3 cm) radial orbit data are required by SRAL in ≤2 days (goal) and <5 days (threshold) to meet altimetry product accuracy requirements. A geodetic-quality GNSS Global Positioning System (GPS) receiver, complemented by a passive laser retro-reflector, and a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) system (on S3-A) are flown for this purpose.

The S-3A GNSS receiver is designed to operate using existing GPS satellites and the S3-B receiver will use both GPS and European Galileo satellite systems (e.g., Hein & Pany, 2002). The S-3 GNSS tracker provides the following functions:

- Sensor and data for the S-3 Attitude and Orbit Control Sub-system,
- Data for POD required for the topography mission,
- Real time orbit information support to SRAL tracking.

Two GNSS units are included in a redundant configuration on S-3 and each can track up to 8 GNSS satellites at the same time. L1 and L2P (Y) GPS signals are exploited by the GNSS instrument (and additionally L2C-M by the S-3B GPS receiver). Ionospheric attenuation of GPS signals is corrected using a differential technique based on two signals at different frequencies (between 1160 and 1590 MHz). The GNSS receiver produces a real-time on-board position to ~3 m accuracy in satellite altitude. This is required to control both SRAL open-

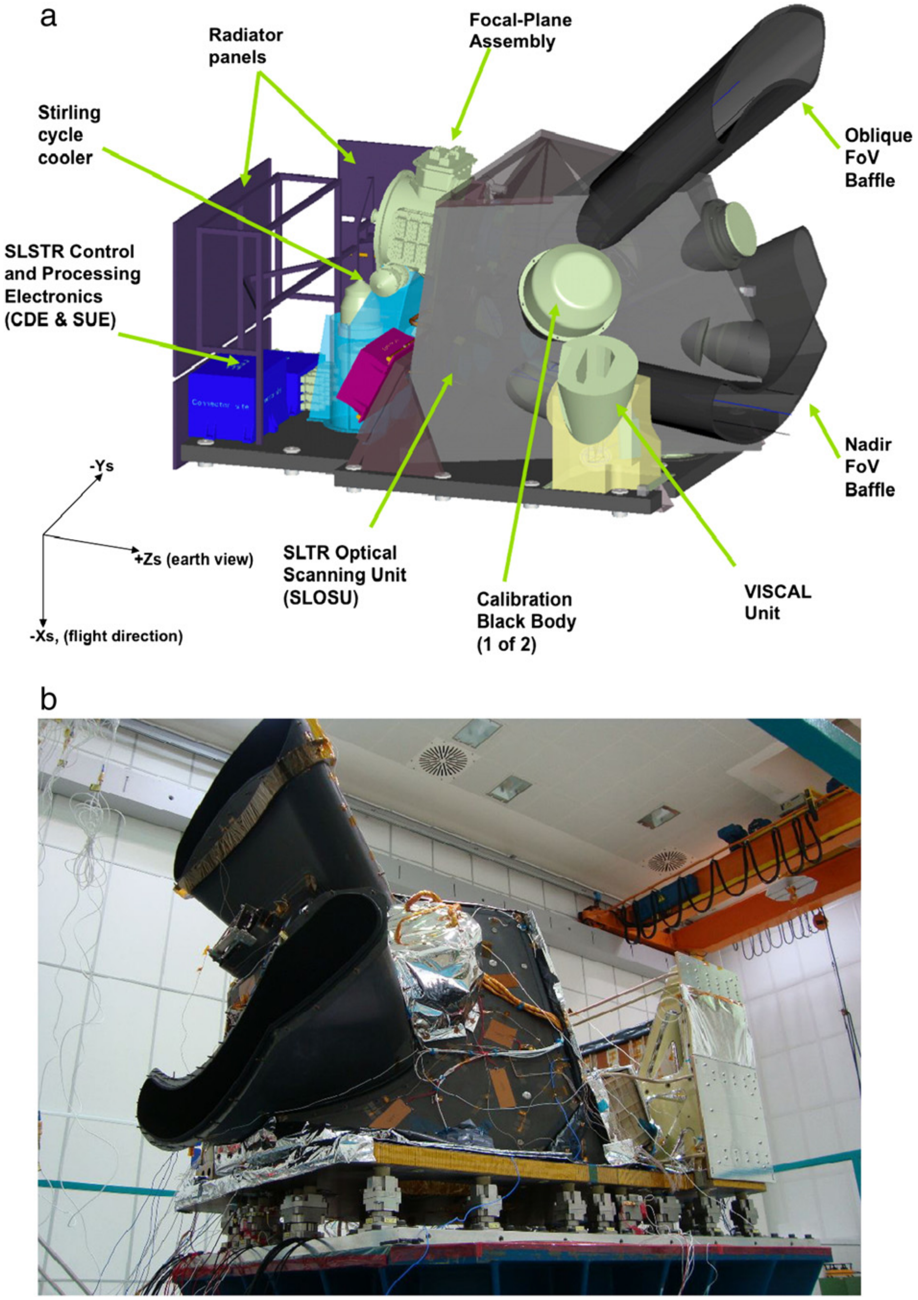

Fig. 7. (a) An overview of the Sentienel-3 Sea and Land Surface Temperature Radiometer (SLSTR) instrument highlighting principal components of the instrument design. (b) Photograph of the SLSTR Structural and Test Model (STM). (Credit: Selex-Galileo & Jena-Optronik)

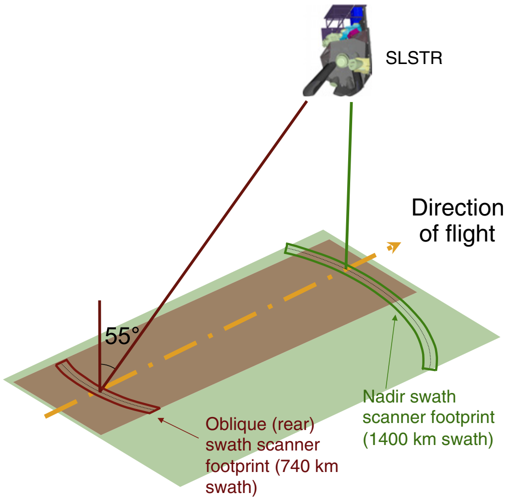

Fig. 8. Outline sketch of the Sentinel-3 SLSTR instrument viewing geometry highlighting the asymmetric nadir swath with respect to the nadir point.

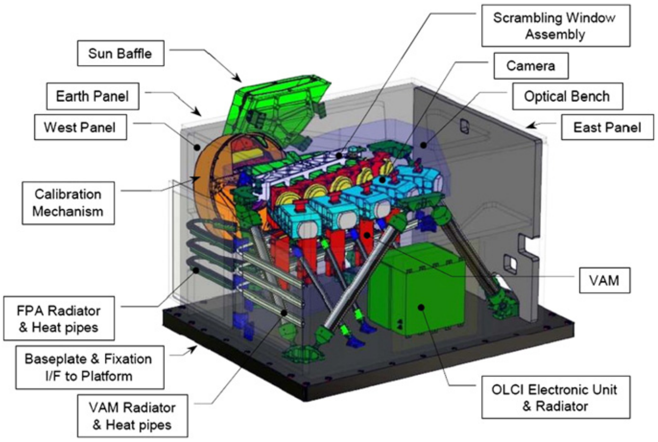

Fig. 9. Schematic overview of the Sentinel-3 Ocean and Land Colour Imager (OLCI) instrument. (Credit: TAS-France)

loop tracking operations and platform navigation. Ground processing computes satellite altitude to <8 cm accuracy within 3 h for NRT and ~2 cm for STC altimetry products.

The S-3 laser retro reflector (LRR) is a small passive optical device consisting of corner cube mirrors designed to directly reflect an incident laser beam compatible with Satellite Laser Ranging stations operating at for wavelengths of 532 nm and/or 694 nm (Pearlman et al., 2002). Laser tracking calculates the distance between the spacecraft and a laser ranging station using high-power pulsed lasers by measuring the round-trip time of laser pulses reflected from the LRR. Corner-cubes are mounted symmetrically on a hemispherical housing, with one nadir-looking corner-cube in the centre, surrounded by an angled ring of corner-cubes to allow laser ranging when the spacecraft is at all elevations above the horizon and for all azimuths. The LRR is mounted on the Earth-facing panel of S-3 close to the SRAL antenna to support satellite ranging for POD and SRAL range measurement calibration. Laser tracking provides ranging to an accuracy of <2 cm and will be used throughout the S-3 commissioning phase and operationally during the mission for SLR-based POD solutions.

A DORIS (e.g. Jayles et al., 2006; Nouël et al., 1988) instrument is flown on S-3 contributing to the POD accuracy and robustness, essential for the Topography mission performance. This instrument also provides a very stable oscillator signal, permanently monitored from the ground, as required for the SRAL operation. In addition, DORIS could provide a backup for the GPS function in case of failure or outage of the GPS system. Since 1990, the DORIS system has evolved to deliver real-time products and retrieved satellite orbits with an accuracy of ~1 cm (e.g., Auriol & Tourain, 2010).

4.5. Sea and Land Surface Temperature Radiometer (SLSTR)

The aim of the Sentinel-3 SLSTR instrument is to maintain continuity with the ENVISAT (A)ATSR series of instruments (e.g., Edwards et al., 1990; Llewellyn-Jones et al., 1984) that provide a reference SST data set for other satellite missions (Donlon et al., 2009; Donlon et al., 2010). Consequently, wherever possible, the SLSTR design is based on the reuse of AATSR concepts using existing and qualified technologies (Coppo et al., 2010). SLSTR will retrieve global coverage sea surface skin temperature (SSTskin) with zero bias and an uncertainty of ±0.3 K (1σ) for a 5×5° latitude longitude area, having a temporal stability of 0.1 K/decade in support of GMES climate monitoring, NOP, and NWP applications. In addition, SLSTR using a suite of visible and infrared radiance measurements, will provide land surface temperature, active fire monitoring, ice surface temperature cloud, atmospheric aerosol, land surface, forestry and hydrology products in support of GMES services.

Following ENVISAT AATSR, the SLSTR instrument is a conical scanning imaging radiometer employing the along-track-scanning dual view technique (Edwards et al., 1990) to provide robust atmospheric correction over a dual-view swath. Key technical details of the SLSTR instrument are provided in Table 9 and a full instrument description can be found in Coppo et al. (2010). The instrument includes channels in the visible (VIS), thermal (TIR) and short wave (SWIR) infrared spectrum as described in Table 10. The main improvements over the heritage (A)ATSR instruments include wider swath coverage, more spectral bands, and a spatial resolution of 0.5 km for visible and

Table 11
Technical characteristics of the Sentinel-3 Ocean and Land Colour Imager instrument.

Swath	1440 km
SSI at SSP (km)	300 m
Calibration	MERIS type calibration arrangement with spectral calibration using a doped Erbium diffuser plate, PTFE diffuser plate and dark current plate viewed ~every 2 weeks at the South Pole ecliptic. Spare diffuser plate viewed ~periodically for calibration degradation monitoring.
Detectors	ENVISAT MERIS heritage back illuminated CCD55-20 frame-transfer imaging device (780 columns by 576 row array of 22.5 µm square active elements).
Optical scanning design	Push-broom sensor. 5 cameras recurrent from MERIS dedicated Scrambling Widow Assembly supporting 5 Video Acquisition Modules (VAM) for analogue to digital conversion.
Spectral resolution	1.25 nm (MERIS heritage), 21 bands.
Radiometric accuracy	<2% with reference to the sun for the 400–900 nm waveband and <5% with reference to the sun for wavebands >900 nm 0.1% stability for radiometric accuracy over each orbit and 0.5% relative accuracy for the calibration diffuser BRDF.
Radiometric resolution	$<0.03\ \mathrm{W\ m^{-2}\ sr^{-1}\ mm^{-1}}$ (MERIS baseline)
Mass	150 kg
Size	1.3 $\mathrm{m^3}$
Design lifetime	7.5 years

SWIR bands. Both the SLSTR and OLCI instruments (Section 4.6) require a clear view to the sun for calibration purposes and accommodating both on the same platform resulted in the SLSTR oblique view pointing backwards. This configuration is different to the ENVISAT AATSR configuration.

To maintain continuity, the complete suite of AATSR and ATSR-2 spectral channels (0.55, 0.66, 0.85, 1.6, 3.7, 10.8 and 12 μm) are included in the SLSTR design. Additional channels at 1.378 μm and 2.25 μm have been included to enhance thin cirrus cloud detection (e.g., Gao et al., 1993). The design also includes the capability to measure active wild fires (e.g., Wooster et al., 2005) although this capability is secondary to the primary SST retrieval capability. This is achieved by extending the dynamic range of the 3.7 μm channel and including dedicated detectors at 10.8 μm that are capable of detecting fires at ~650 K without saturation.

A sketch of the SLSTR instrument general layout is provided in Fig. 7 which identifies the location of key instrument features and components. Thermal control radiators and aperture baffles to reduce stray light are visible. SLSTR is separated into two physical units that are integrated on a single platform plate: the SLSTR Optical Scanning Unit (SLOSU) housing an Opto-Mechanical Enclosure (OME) and Detection Assembly (DA) and, an SLSTR Control and Processor Electronics (SLCPE) unit.

The SLSTR uses two independent scan chains each including a separate scan mirror (scanning at a constant velocity of 200 rpm), an off-axis paraboloid mirror, and a fold mirror to focus measured radiance into the instrument DA. An innovative recombination “flip” mirror alternately relays each of the scanned optical beams into a common field plane at the entrance of the DA where there is a cold baffle. While more complex than the single scan system employed by the ATSR instrument, this configuration increases the instrument oblique view swath to ~740 km (centred at the SLSTR nadir point) and the nadir swath to ~1400 km (offset in a westerly direction). The nadir swath is asymmetrical with respect to the nadir point (Fig. 8) to provide identical and contemporaneous coverage with OLCI ocean/land colour measurements.

The SLSTR Focal Plane Assembly (FPA) is a box composed of a base-plate and an aluminium dome containing the IR and visible optical benches. Two-element photo-conductive detectors are used for the TIR channels that are actively cooled to ~80 K using a Stirling cycle cooler (e.g., Matra Marconi Space, 1996). Small multi-element arrays of Photo Voltaic (PV) detectors are used for the other channels. The Ground Sampling Distance (GSD) at nadir for the TIR channels is ~1 km, and ~0.5 km for visible and SWIR channels. The scan rate is half that of AATSR so that each mirror-scan will measure simultaneously 2 along-track pixels of 1 km (and 8 pixels at 0.5 km resolution). Each scanner views alternatively one of two identical calibration black body cavities every second scan. SLSTR also includes a PTFE sun diffuser (VISCAL) for visible channel gain calibration that is viewed once per orbit. The SLSTR design ensures the spectral and radiometric integrity of all measurements because both oblique and nadir measurements are made through common focal plane optics and detectors that also viewing the target scene, share the same calibration blackbodies and VISCAL unit. Each visible (VIS) channel pixel sample achieves a high signal-to-noise ratio (SNR≈Δ600) at 30% Earth albedo signals and each IR pixel sample a low noise-equivalent temperature difference (NEΔT) <80 mK. SLSTR will provide SST and other products to GMES services as shown in Table 13.

4.6. The Ocean and Land Colour Instrument (OLCI)

The key mission driver for the Sentinel-3 OLCI instrument is continuity of the ENVISAT MERIS instrument capability. OLCI, in synergy with the SLSTR instrument, will also provide continuity to the SPOT Vegetation capability. Ocean colour sensors are designed to retrieve the spectral distribution of upwelling radiance just above the sea surface (the water-leaving radiance) that is then used to estimate a number of geophysical parameters through the application of specific bio-optical algorithms. Atmospheric correction for ocean colour data is challenging (International Ocean Colour Coordinating Group (IOCCG)), 2010) as only about 4% of the radiation measured by a satellite instrument originates from the water surface and sensors require high signal to noise ratio (SNR), particularly for the ‘blue’ bands (~400 nm). Ocean colour instrument design must therefore incorporate extremely sensitive and stable radiometry, dedicated on-board calibration and a large number of spectral channels.

The S-3 OLCI instrument is based on the opto-mechanical and imaging design of ENVISAT MERIS with key characteristics described in

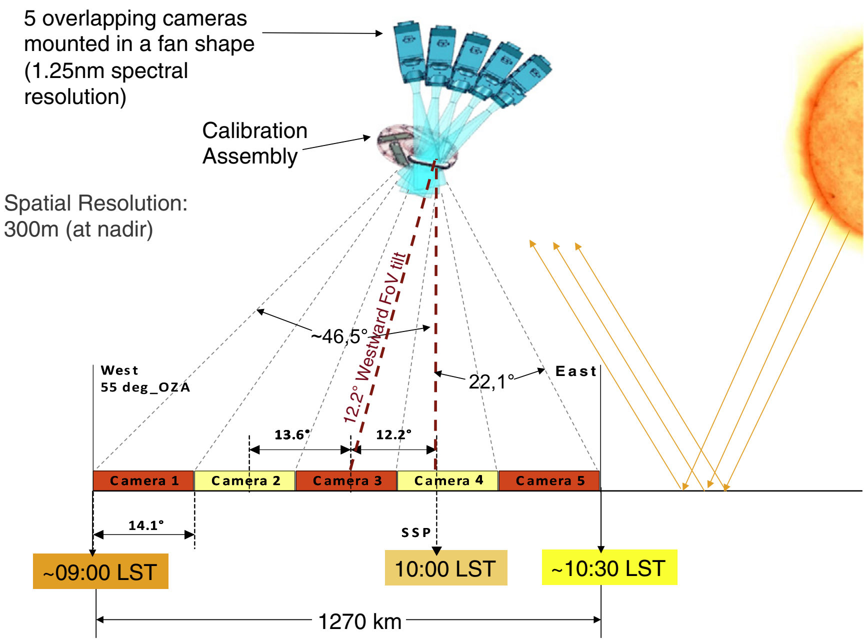

Fig. 10. Details of the Sentinel-3 OLCI instrument viewing geometry showing the fan arrangement of 5 cameras viewing the earth through the calibration assembly and the off-nadir pointing of the instrument swath. Note that the solar zenith angle is limited to a 55° limit. The swath is 1270 km.

Table 12
Band characteristics of the Sentinel-3 Ocean and Land Colour Instrument (OLCI).

Band	λ centre nm	Width Nm	Lmin W/(m^2 sr μm)	Lref W/(m^2 sr μm)	Lsat W/(m^2 sr μm)	SNR @ Lref	Function
Oa1	400	15	21.60	62.95	413.5	2188	Aerosol correction, improved water constituent retrieval
Oa2	412.5	10	25.93	74.14	501.3	2061	Yellow substance and detrital pigments (Turbidity).
Oa3	442.5	10	23.96	65.61	466.1	1811	Chl absorption max., Biogeochemistry, vegetation
Oa4	442	10	19.78	51.21	483.3	1541	High Chl, other pigments
Oa5	510	10	17.45	44.39	449.6	1488	Chl, sediment, turbidity, red tide.
Oa6	560	10	12.73	31.49	524.5	1280	Chlorophyll reference (Chl minimum)
Oa7	620	10	8.86	21.14	397.9	997	Sediment loading
Oa8	665	10	7.12	16.38	364.9	883	Chl (2nd Chl abs. max.), sediment, yellow substance/vegetation
Oa9	673.75	7.5	6.87	15.70	443.1	707	For improved fluorescence retrieval and to better account for smile together with the bands 665 and 680 nm
Oa10	681.25	7.5	6.65	15.11	350.3	745	Chl fluorescence peak, red edge
Oa11	708.75	10	5.66	12.73	332.4	785	Chl fluorescence baseline, red edge transition.
Oa12	753.75	7.5	4.70	10.33	377.7	605	O2 absorption/clouds, vegetation
Oa13	761.25	2.5	2.53	6.09	369.5	232	O2 absorption band/aerosol corr.
Oa14	764.375	3.75	3.00	7.13	373.4	305	Atmospheric correction
Oa15	767.5	2.5	3.27	7.58	250.0	330	O2A used for cloud top pressure, fluorescence over land.
Oa16	778.75	15	4.22	9.18	277.5	812	Atmos. corr./aerosol corr.
Oa17	865	20	2.88	6.17	229.5	666	Atmos. corr./aerosol corr., clouds, pixel co-registration.
Oa18	885	10	2.80	6.00	281.0	395	Water vapour absorption reference band. Common reference band with SLST instrument. Vegetation monitoring.
Oa19	900	10	2.05	4.73	237.6	308	Water vapour absorption/vegetation monitoring (max. reflectance)
Oa20	940	20	0.94	2.39	171.7	203	Water vapour absorption, atmos./aerosol corr.
Oa21	1020	40	1.81	3.86	163.7	152	Atmos./aerosol corr.

Table 11. The instrument is a quasi-autonomous, self contained, visible push-broom imaging spectrometer and incorporates the following significant improvements when compared to MERIS:

- An increase in the number of spectral bands (from 15 to 21),
- Improved SNR and a 14-bit analogue to digital converter,
- Improved long-term radiometric stability,
- Mitigation of sun-glint contamination by tilting cameras in westerly direction,
- Complete coverage over both land and ocean at 300 m Full-Resolution (FR),
- Improved instrument characterization including stray light, camera overlap, and calibration diffusers.
- Improved coverage global ocean<4 days, land<3 days with 1 satellite (ignoring the effect of clouds) MERIS is effectively ~15 days,
- Improved data delivery timeliness of 3 h for L1b and L2 products,
- 100% overlap with SLSTR instrument swath and simultaneous acquisitions facilitating the use of OLCI and SLSTR in synergy.

To simplify OLCI operations, maximise instrument autonomy and, offer maximum flexibility for data processing and re-analysis, OLCI will always operate in a full resolution (FR) mode providing data at ~300 m spatial resolution. In addition, all instrument calibration will be performed in the ground segment.

The main OLCI structure, shown schematically in Fig. 9, is composed of a base plate, supporting truss structure and a temperature controlled optical bench. An OLCI Electronics Unit (OEU) is mounted on the base plate that includes a power conditioning and distribution module, an instrument control module and a digital processing module responsible for real time on-board processing of instrument measurement data. Heaters, radiators and heat pipe networks are configured in a similar way to MERIS providing separate thermal control to the electronics unit, the Video Acquisition Module (VAM) and Focal Plane Array (FPA). OLCI is located on top of the Sentinel-3 satellite (Fig. 2) providing easy access to the sun (via the sun baffle assembly) during calibration views with minimum stray light. In this configuration instrument radiators can be located away from the sun on the cold face of the spacecraft.

Radiance passes via a calibration assembly to one of five “cameras” each with a 14.1° FoV that are mounted in a fan arrangement on a common optical bench. The cameras are arranged to slightly overlap with each other to cover a wide 68.5° across-track field of view as shown in Fig. 10. The OLCI swath is not centred at nadir (as in the MERIS design) but is tilted 12.6° westwards to mitigate the negative impact of sun-glint contamination that affects almost half of the MERIS observations at sub-tropical latitudes (e.g., Kay et al., 2009). In addition, the OLCI instrument is mounted on the satellite to allow a direct view of the Earth, removing the need for an additional fold mirror used by MERIS.

Each OLCI “camera” includes a scrambling window unit (SWU) mounted on the optical bench using a common support structure. The SWU forms the camera entrance pupil, includes a diaphragm structure to reduce stray light, reduces incoming radiance polarization sensitivity (depending on the scene, the atmosphere and the illumination geometry), blocks UV radiance using a UV cut-off filter and optimises the incoming signal to the CCD response using an inverse filter. The inverse filter has a high transmission in the blue and IR spectral region but attenuates the signal between these spectral limits. Radiance then passes to a Camera Optic Sub Assembly (COSA) that includes a ground imager and a spectrometer. The ground imager collects incoming radiance from the SWU and forms an image of the Earth in the plane of the spectrometer entrance slit. The spectrometer disperses the radiance using a concave grating and forms a dispersed image of the entrance slit on a CCD array mounted on an FPA. The resulting entrance slit image is bi-dimensional: one dimension corresponds to the spatial extension of the slit, and the other one corresponds to the decomposition of radiance into spectral components from 390 nm to 1040 nm as shown in Table 12.

OLCI bands are optimised to measure ocean colour over the open-ocean and coastal zones. A new channel at 1.02 μm has been included to improve atmospheric and aerosol correction capabilities, additional channels in the O2A spectral region are included for improved cloud top pressure (height) and water vapour retrieval, and a channel at 673 nm has been added for improved chlorophyll fluorescence measurement. In principle, the OLCI programmable acquisition design allows spectral bands to be redefined in both location and width during commissioning of the instrument after which time they will be fixed for the mission duration.

The CCD assembly is derived from MERIS heritage and is actively cooled to an operating temperature of ~251 K using a Peltier cooler. It operates with a sampling period of 44 ms that corresponds to ~300 m spatial ground resolution in the satellite flight direction. A VAM (one for each camera) then converts the output of the CCD

Table 13
List of “core” products to be produced from the Sentinel-3 mission.

Name	Description	Units	Resolution	Delivery
SLSTR surface TOA radiances L1b	Top of atmosphere brightness temperatures and radiances, calibrated to geophysical units, and their associated uncertainty estimates. Measurements are geo-referenced onto the Earth surface, spatially re-sampled onto an evenly spaced grid—common to the Nadir and Inclined Views—and annotated. Annotations include: Illumination and Observation geometry, environment data (meteorological data), and quality and classification flags.	–	VIS: 0.5 km TIR: 1 km	NRT/NTC
OLCI TOA radiances L1b	Top of atmosphere radiances, calibrated to geophysical units, and their associated uncertainty estimates. Measurements are geo-referenced onto the Earth surface, spatially re-sampled onto an evenly spaced grid and annotated. Annotations include: Illumination and Observation geometry, environment data (meteorological data), and quality and classification flags.	–	0.3 km	NRT/NTC
SRAL waveforms	1 Hz and 20 Hz Ku and C band parameters (LRM/SAR), the waveforms and the associated parameters necessary to reprocess the data. Access to lower level (e.g. so called SGDR product containing the full radar-echo waveforms/L1b) data on request for regional RLH and coastal altimetry applications.	–	~300 m along track (SAR) >2 km along track (LRM)	NRT/STC/NTC
Water leaving reflectance (R)	Surface directional reflectance, corrected for atmosphere and Sun specular reflection.	–	0.3–1.2 km	NRT/NTC
Photosynthetically Active Radiation (PAR)	Quantum energy flux from the Sun in the spectral range 400–700 nm and associated error estimates.	μmol quanta/m^2/s	0.3–1.2 km	NRT/NTC
Diffuse attenuation coefficient (Kd)	Diffuse attenuation coefficient for down-welling irradiance, and associated error estimates	m^{-1}	0.3–1.2 km	NRT/NTC
Chlorophyll (Chl)	Chlorophyll-a concentration, and associated error estimates in coastal and open ocean waters.	mg/m^3	0.3–1.2 km	NRT/NTC
Total Suspended Matter (TSM)	Total suspended matter concentration, and associated error estimates	g/m^3	0.3–1.2 km	NRT/NTC
Coloured Dissolved Organic Material (CDOM)	Absorption of Coloured Detrital and Dissolved Material, and associated error estimates, at 443 nm.	m^{-1}	0.3–1.2 km	NRT/NTC
Altimeter backscatter (Sigma-0)	SRAL sigma-0 backscatter	dB	~300 m along track (SAR) for coastal waters >2 km along track (LRM) for open ocean	NRT/STC/NTC
Sea Surface Height Anomaly (SSHA)	Variations of the SSH with respect to a mean sea surface.	m	~300 m along track (SAR) for coastal waters >2 km along track (LRM) for open ocean	NRT/STC/NTC
Significant wave height (Hs)	The average wave height (trough to crest) of the one-third largest waves in a given sample period	m	~300 m along track (SAR) for coastal waters >2 km along track (LRM) for open ocean	NRT/STC/NTC
Surface wind speed over ocean	SRAL derived surface wind speed modulus	m/s	~300 m along track (SAR) for coastal waters >2 km along track (LRM)	NRT/STC/NTC
Sea surface temperature (SSTskin)	Sea surface skin temperature and associated error estimates	K	1 km	NRT/NTC
TOA surface reflectances over land	Ratio between the irradiance (flux per unit surface area) in all the upward directions at wavelength λ; and the irradiance in all the downward directions, at the same wavelength and depth.	mW/cm2/μm/Sr	0.3 km	
TOA Reflectance product provided for the continuity of the SPOT VGT P-like product	Top-Of-Atmosphere Reflectance in the bands similar to SPOT/Vegetation with a spatial sampling of 1 km in Plate-Carrée projection. SPOT/Vegetation L1P bands are: Band B0: blue (0.43–0.47 μm), Band B2: red (0.61–0.68 μm), Band B3: near-infrared (NIR, 0.78–0.89 μm) band MIR: shortwave infrared (SWIR, 1.58–1.74 μm).	–	1 km	NTC
1 day synthesis Surface Reflectance product provided for the continuity of the SPOT VGT S1-like product	1 day surface reflectance in the bands similar to SPOT/Vegetation (derived from OLCI and SLSTR bands) with a spatial sampling of 1 km m in Plate-Carrée projection. SPOT/Vegetation L1P bands are: Band B0: blue (0.43–0.47 μm), Band B2: red (0.61–0.68 μm), Band B3: near-infrared (NIR, 0.78–0.89 μm) band MIR: shortwave infrared (SWIR, 1.58–1.74 μm).	–	1 km	NTC
10 days synthesis Surface Reflectance product provided for the continuity of the SPOT VGT S10-like product	10-day surface reflectance in the bands similar to SPOT/Vegetation with a spatial sampling of 1 km m in Plate-Carrée projection. SPOT/Vegetation L1P bands are: Band B0: blue (0.43–0.47 μm), Band B2: red (0.61–0.68 μm), Band B3: near-infrared (NIR, 0.78–0.89 μm) band MIR: shortwave infrared (SWIR, 1.58–1.74 μm).	–	1 km	NTC

Table 13 (*continued*)

Name	Description	Units	Resolution	Delivery
Daily Normalised Difference Vegetation Index (SPOT VGT S1-like)	Daily Normalised Difference Vegetation Index (NDVI) derived from for the four SPOT channels synthesised from OLCI and SLSTR channels (nadir view only). In Plate-Carrée projection. This is a SPOT VGT continuation product.	–	1 km	NTC
10-days Normalised Difference Vegetation Index (SPOT VGT S10-like)	10-day Normalised Difference Vegetation Index derived from for the four SPOT channels synthesised from OLCI and SLSTR channels (nadir view only). In Plate-Carrée projection. This is a SPOT VGT continuation product.	–	1 km	NTC
OLCI global Vegetation Index:(OGVI)	Fraction of Available Photosynthetically Active Radiation (FAPAR)	–	1 km	NRT
OLCI chlorophyll terrestrial Index (OCTI)	Monitoring vegetation condition based on terrestrial chlorophyll content	–	1 km	NRT
Land Surface Temperature (LST)	Land surface temperature, associated error estimates and exception flags, and contextual information.	K	1 km	NRT/NTC
Integrated Water vapour column (IWV)	Global coverage of total amount of water vapour integrated over an atmosphere column, and associated error estimates.	kg m^{-2}	0.3–1.2 km	NRT/NTC
Aerosol Optical Depth (AOD (τ)) over water at 865 nm	Global coverage over water of aerosol load, expressed in optical depth at 865 nm, and associated error estimates.	–	0.3–1.2 km	NRT/NTC
Aerosol Angstrom exponent (Å) over water at 865 nm	Global coverage over water of spectral dependency of the Aerosol Optical Depth with associated error estimates.	–	0.3–1.2 km	NRT/NTC
Aerosol Optical Depth (AOD (τ)) over land at 550 nm	Global coverage over land of aerosol load, expressed in optical depth at a given wavelength and associated error estimates.	–	0.3 km	NTC
Aerosol Angstrom exponent (Å) over land at 550 nm	Global coverage over land of spectral dependency of the Aerosol Optical Depth with associated error estimates.	–	0.3 km	NTC
Sea ice thickness	Thickness of sea ice (freeboard): accuracy 20–50 cm	cm	~300 m along track (SAR) for coastal waters	NRT/STC/NTC
Sea ice surface height	Height of the sea ice surface with respect to a reference datum (reference ellipsoid).	m	~300 m along track (SAR) for coastal waters	NRT/STC/NTC
Sea ice surface height anomaly	Variations of the Sea Ice Surface Height with respect to a mean sea surface.	m	~300 m along track (SAR) for coastal waters	NRT/STC/NTC

into an analogue signal and passes 46 micro-bands (including the smeared data during frame transfer from the CCD) to the OEU for digital processing. Two imaging modes are possible: a raw mode used during instrument calibration when all 46 micro-bands are available (including all MERIS bands and those required to produce SPOT Vegetation legacy products in synergy with SLSTR) and a nominal operating mode in which on-board spectral relaxation processing delivers 22 micro-bands (including 1 smear band) providing measurements with high absolute radiometric accuracy.

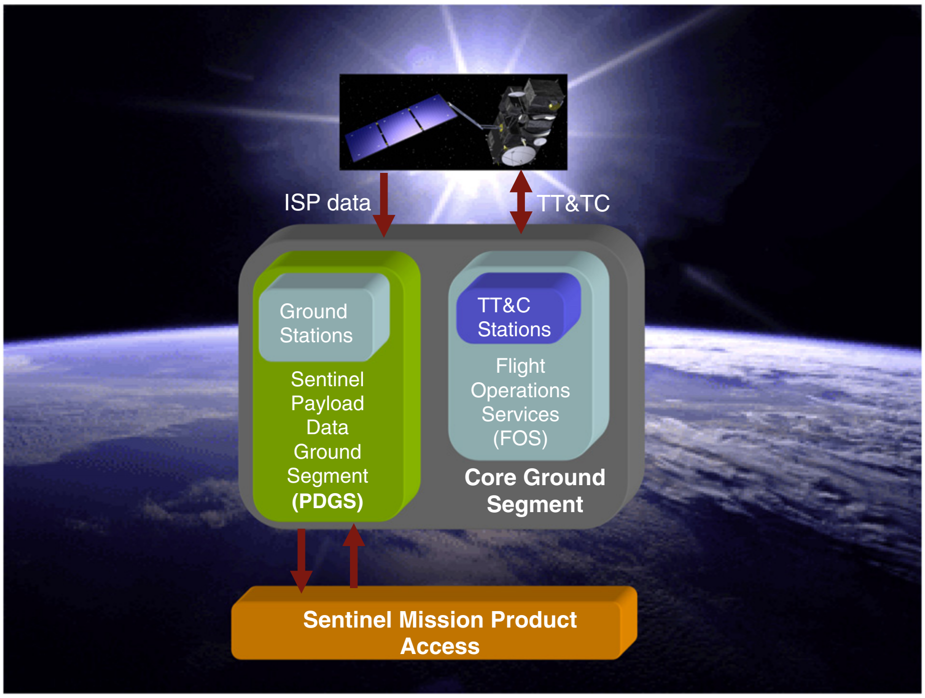

Fig. 11. Schematic overview of the Sentinel-3 Core Ground Segment now in development.

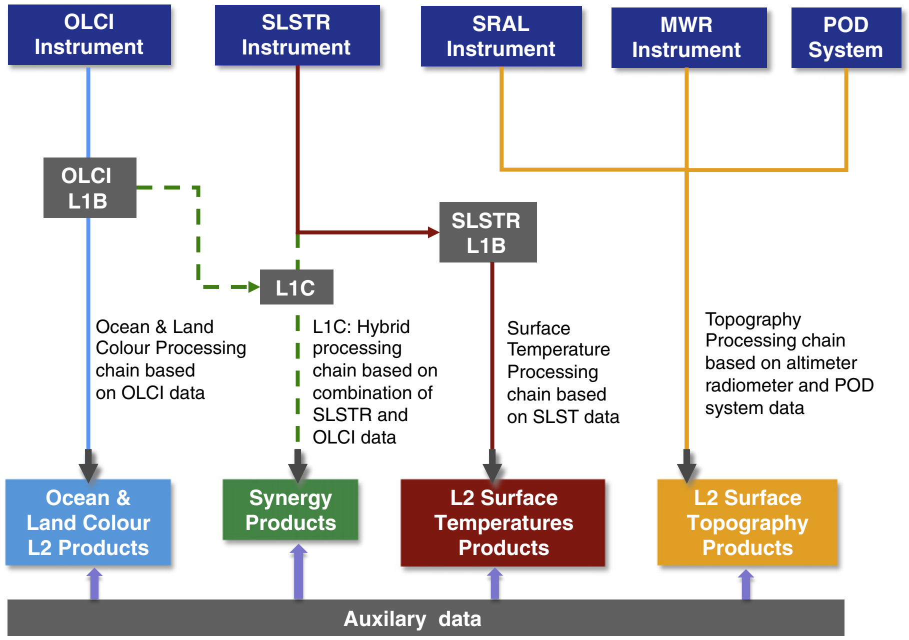

Fig. 12. A schematic overview of Sentinel-3 generic data processing chains.

In-flight calibration of OLCI is a fundamental component of the instrument design. All OLCI measurements are made via a calibration assembly of a similar design to MERIS that includes a mechanical rotating table. Either a direct view of the Earth (for imaging mode) or one of several calibration targets may be selected by rotating the table: a dark shutter plate (for dark current calibration), a primary PTFE calibration diffuser (viewed every 2 weeks for radiometric calibration), a redundant PTFE calibration diffuser (viewed every 3 months to determinate degradation of the primary diffuser due to solar exposure) or an erbium doped 'pink' diffuser plate for spectral calibration. During the calibration sequence, a selected diffuser plate is moved into the instrument FoV and illuminated by the sun so that all five cameras can be calibrated at the same time. Characterisation of diffuser ageing is determined through on-ground processing using the two OLCI diffusers in synergy.

The OLCI calibration sequence is carried out before the terminator crossing over the southern hemisphere to maintain a stable internal instrument temperature in a similar manner to that of MERIS. Two successive orbits are required; the first for radiometric calibration and the second performs a spectral calibration. Each calibration sequence begins with a dark current evaluation. This sequence lasts 45 s and acquires 1024 measurement frames that are averaged on-ground to reduce noise and used to accurately derive the signal produced under dark conditions.

OLCI will provide primary products to GMES services as shown in Table 13. Working in synergy with the SLSTR, OLCI will also provide continuity of SPOT Vegetation products.

5. The Sentinel-3 ground segment concept

The S-3 mission ground segment is planned as a distributed system and is shown schematically in Fig. 11. The Ground Segment includes:

- Satellite Ground Stations with dedicated S-band stations used for satellite command, control and management and X-band stations for science data downlink.
- A Flight Operations Segment (FOS) to perform Sentinel-3 command and control tasks including the uplink and downlink of tele-command and telemetry (S-band link) as well as satellite maintenance support (e.g., on-board software maintenance, collision avoidance etc.).
- A Payload Data Ground Segment (PDGS) to perform all NRT, STC and NTC payload data processing for Sentinel-3 instruments, data dissemination, instrument calibration management, data archival, long-term preservation and reprocessing of all mission data (e.g., to address data anomalies, new algorithm developments etc.), mission planning, mission performance and data product monitoring. The PDGS architecture is based on a set of distributed and specialised centres working on different aspects of the mission connected through high performance network links. The S-3 PDGS operational and architectural concepts are at a preliminary development phase at the time of writing and will be consolidated before the launch of S3-A.
- A Precise Orbit Determination service that will make optimal use of all data derived from S-3 POD systems as well as the generation of information for FOS operations and PDGS ground processing.
- A product distribution framework that will make available products to users in the most appropriate manner with flexibility to extract specific information as required.

The Sentinel-3 PDGS will implement complete processing chains for generating ocean colour and land reflectances, land and sea temperature and ocean and land topography products as shown in Fig. 12. Processing systems are based on state-of-the art geophysical algorithms developed in collaboration with the Sentinel-3 industrial and scientific communities. Table 13 describes the core products that will be produced by the Sentinel-3 system. Additional products may be produced as required by GMES services either in the core PDGS or as a collaborative component of the PDGS system.

Level-1b optical products will be produced as Top-Of-Atmosphere (TOA) radiometric measurements, radiometrically corrected, calibrated and spectrally characterised. Products will be quality controlled and ortho-geo-located (with latitude and longitude coordinates and altitude), accurate inter-channel co-registration, annotated with satellite position and pointing, landmarks and preliminary pixel classification (e.g. land/water/cloud masks). Level 1B Topography products will include altimeter geo-located and calibrated radar echoes (i.e. Ku and C-band waveforms) with all ancillary information annotated. MWR L1b products will include geo-located, radiometrically and geometrically corrected brightness temperature measurements (at each of the antenna frequencies).

Level-2 core geophysical products will also be provided by the PDGS for the parameters set out in Table 13. Level 2 optical products include a range of geophysical quantities derived from more fundamental L1b products making use of auxiliary data (as required by L2 algorithms). Level 2 topography products include the altimeter range, (1 Hz and 20 Hz waveform data) orbital altitude, time, water vapour from the MWR and geophysical corrections, along with significant wave height and wind-speed information. A dedicated L2-pre-processed (L2P) SST data product, with the addition of a quantitative confidence value attached to every data point will also be generated according to the specifications of the Group for High-Resolution Sea Surface Temperature (GHRSST, 2010).

Generic L1b data sets will be used at a variety of different centres and institutions to develop higher level products and applications. For example, the Sentinel-5 mission concept (Ingmann et al., 2011) includes a dedicated instrument for atmospheric aerosol measurements, which is an imager with multi-angle polarimetric hyper-spectral capabilities. The atmospheric trace gas retrievals from Sentinel 4 and Sentinel 5 Precursor missions will profit from a synergetic aerosol product from the S-3 optical data in the O_2A band (Siddans et al., 2007), while observations in the UV spectral band are suitable to constrain the aerosol absorption also over bright surfaces including clouds (de Graaf et al., 2004).

6. Calibration and validation

S-3 calibration and validation (cal/val) activities are essential to the quality of the S-3 Mission. Data quality will be assessed through determination of the radiometric, spatial, spectral and geometric fidelity of the satellite sensor and the accuracy of geophysical products. Three phases of cal/val are foreseen for S-3:

- Pre-Launch Phase instrument characterization and on-ground calibration.

A commissioning Phase (E1) lasting ~5 months will be performed for S-3A where all instrument operation aspects will be verified and in-orbit calibration and validation activities will be initiated. Instrument data should be available from ~1 month after launch for initial tests and engineering commissioning verification, calibration and validation activities. Once complete, a final validation review authorises data dissemination to end-users. Building on the experience of S-3A, a slightly shorter E1 phase (~3 months) is planned for S-3B.

- An exploitation Phase (E2) will then commence extending for the duration of the mission in which calibration and validation activities will continue for geophysical data products.

Dedicated sentinel-3 calibration tasks include:Full pre-launch characterisation and calibration of all instruments, Full in-flight calibration and (re)characterisation of all instruments, Comprehensive verification of Level 1 data processors (tuning of all relevant processing parameters, regeneration of all L1 auxiliary products), Preparation and advice for necessary Level 1 processor updates, Routine calibration monitoring and assessment after the end of the Commissioning Phase).

Dedicated Sentinel-3 validation tasks include:In Commissioning phase Level 2 algorithm verification for all L2 “baseline” products (Table 13), Level 2 algorithm validation starting during Commissioning Phase and continued throughout Phase E2. Quantification of L1 and L2 product error estimates. Long term monitoring for consistency and constant quality of geophysical products.

In addition, the cal/val component of the Sentinel-3 mission will include maintenance and evolution of prototype ground processors, generation of all pre-launch auxiliary data sets needed for L1 and L2 processing, convening and managing dedicated cal/val teams, detailed Commissioning Phase planning with definition of interfaces to all processing and support centres, and the definition and planning of in-situ campaigns to be conducted during Commissioning Phase. On-going operations will include monitoring and maintenance of all uncertainty estimates and may require additional activities to maintain the quality of Sentinel-3 data products. Sentinel-3 Cal/val plans and activities will be consolidated prior to launch and will be reviewed and updated on a regular basis as required by the Mission. In particular, a PDGS re-processing capability will support calibration and validation activities as well as potential tuning of algorithms and product evolution.

In terms of data access policy, joint EC/ESA Principles of Sentinel data policy have been approved by ESA in Sep 2009 and call for an open access to Sentinel data free of charge. This will significantly enhance the utility of Sentinel-3 data products by the operational and scientific community working together to generate the best products for GMES. The data policy is currently under review by the EC and it is expected that a final data policy will be agreed in 2012.

7. Conclusions

Sentinel-3 is a European Earth Observation satellite mission to support GMES Ocean, Land, Atmospheric, Emergency, Security and Cryospheric applications and will enable the development, operation and sustainability of an effective portfolio of GMES services. Sentinel-3 measurements are essential to maintain and improve operational ocean state analysis, forecasting and service prevision in the context of GMES serving applications in the domains of open ocean and ice monitoring, global land monitoring, coastal zone monitoring, NOP and NWP and global climate change monitoring. The mission foresees a series of satellites for a 20-year period starting with the launch of Sentinel-3a in 2013 that will ensure the long-term collection of uniform quality data products generated and delivered in an operational manner to GMES services. The Sentinel-3 mission addresses these requirements by implementing and operating the following components:

- A SAR Radar Altimeter (SRAL) instrument, a passive microwave radiometer (MWR) a GPS receiver and laser retro-reflector for accurate/precise orbit determination (i.e. 3-d position) continuing the legacy of ENVISAT RA-2 and CryoSat.
- An Ocean and Land Colour Imager (OLCI) delivering multi-channel optical measurements for ocean and land providing continuity to ENVISAT MERIS.
- A Sea and Land Surface Temperature Radiometer (SLSTR) delivering accurate surface ocean, land and ice surface temperature providing continuity of ENVISAT AATSR.
- A ground segment providing access to core data product in a near real time mode and a collaborative ground segment providing additional data products for specific users and purposes in collaboration with other entities.

Sentinel-3 has been designed to provide EO data products in routine, long-term and continuous fashion with a consistent quality and a very high level of availability primarily supporting GMES operational oceanography and global land applications. In order to meet GMES user needs, the Sentinel-3 satellite data shall also support the operational generation of high-level geophysical products with a consistent quality. The mission is also designed provide continuity to SPOT Vegetation-like products to meet GMES user needs.

Considering a long-term perspective, the sustained measurement systems of Sentinel-3 within the GMES framework may ultimately lead to improved long range ocean, biogeochemical and atmospheric forecasts and land monitoring capability based on new technology and new understanding of the marine, land, atmospheric and cryospheric environments. GMES is providing the foundations for such a framework in which environmental information is gathered and processed into accurate high quality information products and services tailored to decision makers. In an operationally robust and sustained near-real-time system, Sentinel-3 will provide policymakers and public authorities within GMES state-of-the-art Earth Observation information to take decisions with confidence, prepare environmental legislation and policies, monitor their implementation and assess their socio-economic impacts and benefits.

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