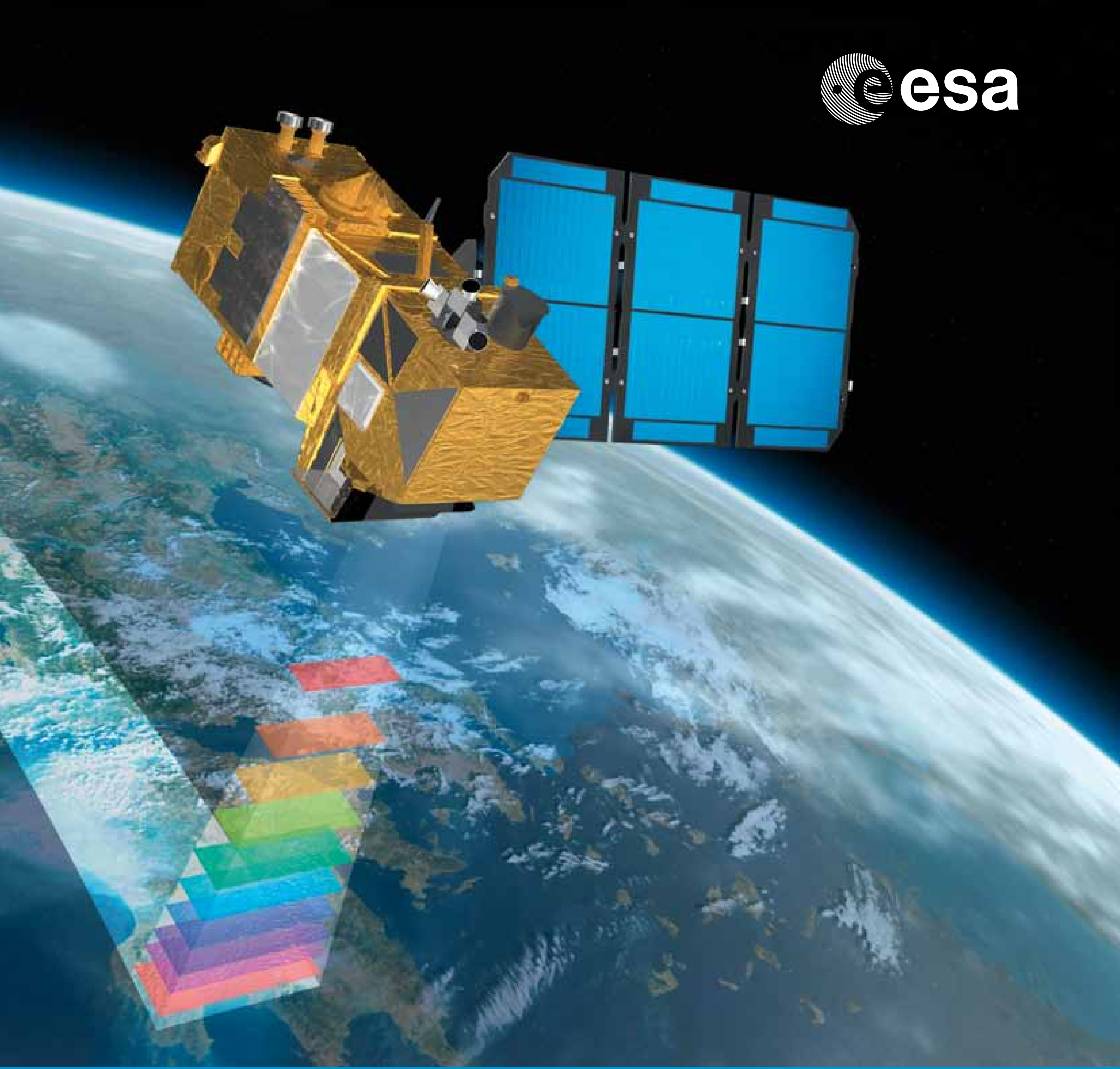

→ SENTINEL-2

ESA's Optical High-Resolution Mission for GMES Operational Services

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SP-1322/2
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Cover: Artist's impression of one Sentinel-2 satellite operating in orbit.

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Foreword

As part of the Global Monitoring for Environment and Security (GMES) Space Component programme, ESA is undertaking the development of an operational optical high-resolution Earth observation mission. Sentinel-2 is a system of two polar-orbiting satellites that will contribute to the continuity and improvement of the SPOT and Landsat series of multispectral missions, and ensure the delivery of high-quality data and applications for operational land monitoring, emergency response and security services.

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1. Introduction

The Global Monitoring for Environment and Security (GMES) programme is a joint initiative of the European Commission (EC) and the European Space Agency (ESA) to establish a European capacity for the provision and use of monitoring information for environmental and security applications. ESA's role in GMES is to provide the definition and the development of the space- and ground-based system elements.

The GMES Sentinel-2 mission will ensure the continuity of services that rely on multispectral high-resolution optical observations over global terrestrial surfaces. The mission objectives are to provide systematic acquisitions of high-resolution multispectral imagery with a high revisit frequency, to ensure the continuity of multispectral imagery provided by the SPOT series of satellites, and to provide observations for the next generation of operational products such as land-cover maps, land-use change detection maps and geophysical variables. Consequently, Sentinel-2 will contribute directly to land monitoring, emergency response and security services.

The corresponding user requirements have driven the design towards a dependable multispectral Earth observation system featuring a MultiSpectral Instrument (MSI) with 13 spectral bands ranging from the visible and near-infrared to the short-wave infrared. The spatial resolution varies from 10 m to 60 m, depending on the spectral band, with a 290 km field of view. This unique combination of high spatial resolution, wide field of view and broad spectral coverage represents a major step forward compared with other multispectral missions.

The mission foresees a series of satellites, each with a lifetime of 7.25 years, over a 20-year period. During full operation, two identical satellites will be maintained in the same orbit with a phase delay of 180°, providing a revisit time of five days at the equator.

The first satellite, Sentinel-2A, is expected to be launched in late 2013, and Sentinel-2B, about two years later.

The Contributors

The report is based on inputs from all the ESA Sentinel-2 teams involved in space, ground and mission development activities. Major contributions have also been received from national space agencies working in partnership with ESA, especially the Centre National d'Etudes Spatiales (CNES, France) and the Deutsches Zentrum für Luft und Raumfart (DLR, Germany), as well as from Astrium GmbH and Astrium SAS, the Prime Contractors responsible for developing the satellite system and the MultiSpectral Instrument, respectively. The contributors to this report are listed on page ii of this report.

Structure of this Report

This report provides an overview of the GMES Sentinel-2 mission, including the technical system concept, image quality, Level-1 data processing and operational applications. The report describes all of the system elements on which the Sentinel-2 mission is built.

Chapter 2, 'GMES Programme Context' provides general information on this European flagship operational space programme.

Chapter 3, 'Sentinel-2 Mission Overview', provides an overview of the mission, including products, user services and precursor missions.

Chapter 4, 'Sentinel-2 System Concept Overview', introduces the Sentinel-2 Space Segment – the satellite design, including the platform and payload instrument, predicted performance and Assembly Integration Test and verification programmes – and the Flight Operations and Payload Data Ground Segments.

Chapter 5, ‘Sentinel-2 Launch Campaign and Early In-Orbit Operations’, addresses the critical phase following the separation of the satellite from the launcher until the performance of time-critical activities in orbit.

Chapter 6, ‘Sentinel-2 Image Quality’, depicts the main payload instrument performance that will determine the quality of the mission products and user services.

Chapter 7, ‘Sentinel-2 Level-1 Processing’, describes how Sentinel-2 mission products are produced, archived and made available to users.

Chapter 8, ‘Prototyping of Level-2 Products: Cloud Screening and Atmosphere Corrections’, underlines the innovative capabilities of Sentinel-2 for automatic data product correction using specific instrument spectral channels.

Chapter 9, ‘Sentinel-2 Applications and Products’, describes the main data products and their applications for land and security services promoted by ESA and the European Commission.

Chapter 10, ‘Sentinel-2 Calibration and Validation’, describes the approach that will be used during the in-orbit commissioning phase to ensure optimal mission performance and the delivery of reliable data to user communities.

Chapter 11, ‘Sentinel-2 Pre-Flight Campaign’, presents the planned activities to generate validation data that will be used to optimise data products during the routine operation phase.

Finally, Chapter 12 presents some conclusions.

2. GMES Programme Context

The GMES programme is a European initiative to ensure the availability of information and data products for environmental and security services. It is based on data received from Earth observation satellites and ground-based networks.

Within the GMES programme, the GMES Space Component (GSC) is responsible for delivering the necessary Earth observation data to the GMES Service Component, which in turn is responsible for providing the Earth observation data and value-added products to users.

As part of the GMES Space Component programme, ESA is responsible for developing a fully operational space-based capability to feed the GMES Service Component with satellite data. This capability will be achieved by facilitating access to data from GMES Contributing Missions as well as by developing new GMES dedicated Earth observation missions, the Sentinel missions. The satellite data will be stored in a long-term archive to enable repeated use of long time series (Fig. 2.1).

The Sentinel missions have been designed in accordance with the individual Mission Requirement Documents (e.g. ESA, 2010) with a view to satisfying the evolving requirements of GMES user communities, in particular those identified in the strategic implementation plans prepared by the EC's GMES Core Services implementation groups in 2007, and in the GMES Space Component Programme Declaration approved by the participating ESA Member States.

2.1 GMES Sentinel Missions

The ESA Sentinels constitute the first series of operational satellites that will respond to the Earth observation needs of the GMES initiative. The GMES Space Component relies strongly on complementary developments within ESA, as well as on the existing and planned space assets of the various national space agencies.

As part of the GMES Space Component, ESA is developing five Sentinels mission families. Each Sentinel-1, Sentinel-2, Sentinel-3 and Jason-CS mission

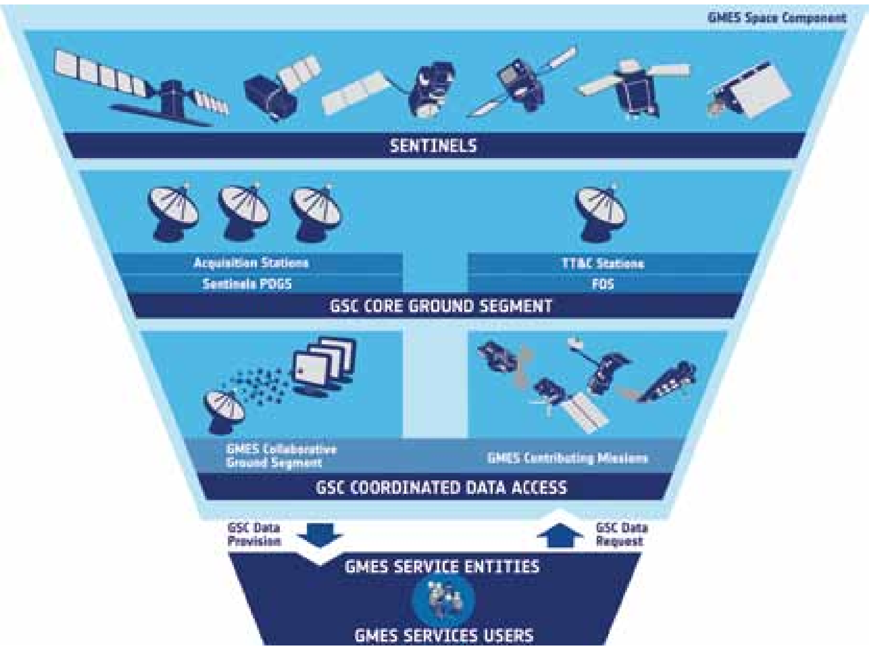


Figure 2.1. The GMES end-to-end system.

is based on a constellation of two satellites in the same orbital plane. With this configuration it will be possible to fulfil the revisit and coverage requirements and provide robust and affordable operational services. Sentinel-5P is conceived as a gap-filler satellite. Sentinel-4 covers the development of two payload instruments to be carried on Meteosat Third Generation. Sentinel-5 covers the development of two instrument payloads to be carried on MetOp Second Generation. The lifetime of the individual satellites is specified as 7.25 years (5 years for Jason-CS), with consumables onboard each satellite allowing for mission extensions of up to 12 years (2 years for Jason-CS). The life cycle of each generation of satellites is planned to be on the order of 15–20 years. The strategy for the procurement and replacement of Sentinel satellites over this period is being elaborated.

The current phase of the GMES Space Component includes the following missions and satellites:

Sentinel-1 – Synthetic Aperture Radar (SAR) imaging for (Davidson et al., 2011):

- monitoring sea-ice zones and the Arctic and Antarctic environment;
- surveillance of marine environments;
- monitoring land surface motion risks;
- mapping of land surfaces: forests, water and soils, agriculture;
- mapping in support of humanitarian aid in crisis situations.

Sentinel-2 – Multispectral imaging for (Drusch et al., 2012):

- land cover, land use and land-use change detection maps;
- maps of biogeophysical variables such as leaf chlorophyll content, leaf water content, leaf area index (LAI);
- risk mapping;
- acquisition and rapid delivery of images to support disaster relief efforts.

Sentinel-3 – Multispectral imaging, radiometry and altimetry for (Donlon et al., 2012):

- sea and land colour data;
- sea and land surface temperatures;
- sea-surface and land-ice topography;
- high-resolution altimetry for synthetic aperture processing;
- land synergy products from optical instrument data.

Sentinel-4, Sentinel-5P and Sentinel-5 – Multispectral imaging and profiling for (Ingman et al., 2011):

- monitoring changes in atmospheric composition at high spatial resolution;
- daily global and regional mapping of ozone, NO_2, SO_2, formaldehyde and aerosols at high temporal resolution;
- daily global mapping of CO and CH_4.

Sentinel-4 is an atmospheric chemistry instrument operating in geostationary orbit, to be flown on the Meteosat Third Generation (MTG) satellites. Sentinel-5P is a precursor atmospheric chemistry mission to be flown in a polar Sun-synchronous orbit (filling the gap between Envisat and MetOp second-generation satellites). Sentinel-5 is an operational atmospheric chemistry instrument to be flown on MetOp second-generation satellites to be operated in a Sun-synchronous polar orbit.

Jason CS – Operational altimetry for monitoring sea-surface height (under Phases A–B1).

2.2 GMES Space Component Ground Segment

The GSC Ground Segment is composed of three segments: the GSC Core Ground Segment, the GSC Collaborative Ground Segment and the GMES Contributing Missions ground segments.

First, the GSC Core Ground Segment, with GSC-funded functions and elements, provides primary access to Sentinel data and coordinates access to GMES Contributing Mission data. The GSC Core Ground Segment consists of the Sentinel Core Ground Segment and the GMES Data Access Layer.

The Sentinel Core Ground Segment comprises:

- The Sentinel Flight Operations Segment (FOS), which provides, for all Sentinels:
  - satellite monitoring and control during all mission phases (i.e. launch and early orbit phases, commissioning, routine and deorbiting);
  - satellite orbit determination and maintenance; and
  - the network of tracking, telemetry and command S-band ground stations.
- The Sentinel Payload Data Ground Segment (PDGS), which provides, for all Sentinel missions:
  - planning, acquisition, processing and dissemination of data products;
  - calibration and validation of the Sentinel missions;
  - user services including cataloguing, data selection, metadata access, user help and documentation;
  - systematic reprocessing of historical Sentinel mission data; and
  - algorithm and product maintenance and upgrading.

The GMES Data Access Layer provides harmonised access to data from the Sentinel missions and the GMES Contributing Missions.

Second, the GSC Collaborative Ground Segment, with non-GSC-funded functions and elements, provides supplementary access to Sentinel mission data, i.e. either through specific data acquisition services, or specific data products.

Finally, the GMES Contributing Mission ground segments allow the acquisition of useful operational data guaranteed by relevant space missions.

2.3 GMES Initiative and Data Access

GMES is a joint initiative of the EC and ESA to establish a European capacity for the provision and use of operational monitoring information for environmental and security applications. This capacity is envisaged to consist of three modules, which together constitute the functional GMES system:

- the production and dissemination of information in support of European Union (EU) policies related to the environment and security;
- the mechanisms needed to ensure permanent dialogue between all stakeholders, and in particular between providers and users; and
- the legal, financial, organisational and institutional frameworks necessary to ensure the functioning of the GMES system and its evolution.

Although elements of these three modules already exist, many have been conceived, designed and managed in isolation, thus limiting their interoperability and the production of relevant information. GMES will provide added value by ensuring the coherence, efficiency and sustainability of a shared information system for Europe. Achieving this goal will involve improving the compatibility of the existing elements, establishing cooperation between the relevant organisations and filling the gaps where necessary.

Within the GMES programme, ESA is responsible for the development of the GMES Space Component, a fully operational space-based capability to supply Earth observation data to support environmental information services across

Europe. These services, implemented in parallel by the European Commission, will then be able to offer added value in terms of the data and services available to users.

The Sentinels are dedicated Earth observation missions that are the essential elements of the GMES Space Component. In the global GMES framework, these missions will complement other satellites made available by third parties or by ESA, and will be coordinated in a synergistic system through the GSC Data Access system (see *http://gmesdata.esa.int*).

In the GMES programme context, the Sentinel-2 mission will ensure the continuity of services that rely on multispectral high-resolution optical observations over global terrestrial surfaces (Martimort et al., 2007a, 2007b). The key objectives of the mission are to:

- provide systematic global acquisitions of high-resolution multispectral imagery with a high revisit frequency;
- ensure the continuity of multispectral imagery provided by the SPOT (Satellite pour l'Observation de la Terre) series of satellites; and
- deliver observations for the next generation of operational products such as land-cover maps, land-cover change detection maps and geophysical variables.

Sentinel-2 will capitalise on the technology and the vast experience acquired in Europe and the United States to maintain the supply of data for operational services such as:

- risk management (floods and forest fires, subsidence and landslides);
- European land use and land cover state and changes;
- forest monitoring;
- food security/early warning systems;
- water management and soil protection;
- urban mapping;
- natural hazards; and
- terrestrial mapping for humanitarian aid and development.

The EC and ESA have agreed to ensure free and open access to all GMES Sentinel data. Conditions of access to and use of data from GMES Contributing Missions will be determined by the respective mission owners, in consultation with ESA.

3. Sentinel-2 Mission Overview

The GMES Sentinel-2 mission will contribute to a variety of services that rely on multispectral high-spatial-resolution optical observations over global terrestrial surfaces. The mission has been designed as a dependable multispectral Earth observation system that will ensure the continuity of Landsat and SPOT observations and improve the availability of data for users (see Fig. 3.1).

The SPOT remote-sensing programme was set up in 1978 by CNES in France, in partnership with Belgium and Sweden. The first satellite, SPOT-1, was launched in 1986, SPOT-2 in 1990, SPOT-3 in 1993, SPOT-4 in 1998 and SPOT-5 in 2002.

Each SPOT payload includes two identical High-Resolution Visible (HRV) imaging instruments that are able to operate in two modes, either simultaneously or individually. The two spectral modes are panchromatic and multispectral. The panchromatic band has a resolution of 10 m on SPOT-4, down to 2.5 m on SPOT-5, and the four multispectral bands – three in the Visible and Near Infrared (VNIR) and one in Short Wave Infrared (SWIR) – have a resolution of 20 m, except for the three VNIR bands with a resolution of 10 m on SPOT-5. The revisit period is 26 days and the coverage is not systematic, but is based on imaging requests received from users. Since the deorbitation of SPOT-2 in 2009, after almost 20 years of service, the SPOT-4 and SPOT-5 satellites together have continued to provide high-resolution SPOT images and global images with the Vegetation instrument.

In a privately financed initiative, Astrium is continuing the SPOT programme with the development of SPOT-6 and SPOT-7 (also called AstroTerra), focusing on commercial applications based on even higher spatial resolution. These satellites are expected to offer 1.5 m resolution in the panchromatic band and 6 m resolution in four VNIR multispectral bands within a 60 km swath. SPOT-6 and SPOT-7 are scheduled for launch in late 2012 and 2014, respectively (*http://eoedu.belspo.be/en/satellites/spot.htm*). The data from the SPOT series of satellites have been used primarily for land-cover classification (Kanellopoulos et al., 1992; Gong et al., 1992) and for detecting changes in land use (e.g. Lu et al., 2004; Jensen et al., 1995).

The Landsat programme started with the launch of the first of six satellites in 1972. Landsat observations have provided key data for monitoring global change and have been a primary source of medium spatial resolution Earth observation data for a wide range of applications (see the special issues of various journals on Landsat published in 1984, 1985, 1997, 2001, 2003, 2004 and 2006).

The Landsat satellites can be classified into three groups, based on their sensor and platform characteristics (Chander et al., 2009). The first group consists of Landsat-1, Landsat-2 and Landsat-3, each of which carries a MultiSpectral Scanner (MSS) sensor and a Return Beam Vidicon (RBV) camera. The second group, comprising Landsat-4 and Landsat-5, carry the MSS and the Thematic Mapper I. The third group, Landsat-6 and Landsat-7, carry the Enhanced Thematic Mapper (ETM) and the Enhanced Thematic Mapper Plus (ETM+).

Currently, Landsat data acquisition is assured by two in-orbit operational satellites, Landsat-5 and Landsat-7. A new satellite, called the Landsat Data Continuity Mission (LDCM), is scheduled for launch in early 2013 and will incorporate some improvements in terms of spatial resolution and spectral coverage. Landsat-5, with the MSS instrument, features six multispectral bands at 30 m resolution – four bands in the VNIR, and one in SWIR. Landsat-7, with the ETM+ instrument, features in addition to Landsat-5 one panchromatic band at 15 m resolution. The LDCM, with the Operational Land Imager (OLI) instrument, features in addition to Landsat-7 a further spectral band in the blue region. Both Landsat-5 and Landsat-7 also feature a thermal infrared spectral band for which continuity will be assured with the Thermal Infrared Sensor (TIRS) instrument on the LDCM.

The US Geological Survey (USGS) currently distributes Landsat data at no charge to users via the Internet. The demand for data seems to be increasing exponentially, with 200 TBytes of data requested by users in 2009. The Landsat data are systematically terrain corrected. Based on the Landsat experience, it is anticipated that users will request a comparable, if not greater volume of Sentinel-2 data under the open access policy.

In comparison with the SPOT and Landsat precursor series of satellites, the Sentinel-2 mission will offer an unprecedented combination of the following capabilities (Figs. 3.1 and 3.2):

- systematic global coverage of land surfaces from 56°S to 84°N, including coastal waters, the Mediterranean and selected calibration sites, e.g. over Antarctica;
- high revisit frequency: every five days at the equator under the same viewing conditions;
- high spatial resolution: 10 m, 20 m and 60 m;
- multispectral information with 13 bands in the VNIR and SWIR parts of the spectrum; and
- a wide field of view: 290 km.

Arising from the need for high revisit frequency and high mission availability, two identical Sentinel-2 satellites will operate simultaneously (Fig. 3.3). Their orbit is Sun-synchronous at an altitude of 786 km (14 + 3/10 revolutions per day) with 10:30 as the local time of the descending node (LTDN). This local time was selected as the best compromise between the need for minimal cloud cover and to ensure suitable solar illumination. It is also close to the Landsat and SPOT local times, allowing the seamless combination of Sentinel-2 data with historical images and the building of long time series. The two satellites will be phased at 180° on opposite sides of the orbit (Fig. 3.4). The first Sentinel-2 satellite is expected to be launched in late 2013.

Sentinel-2's 13 spectral bands extend from the VNIR to the SWIR (Fig. 3.5), featuring:

- four bands at 10 m: the classical blue (490 nm), green (560 nm), red (665 nm) and near-infrared (842 nm);
- six bands at 20 m: four narrow bands in the vegetation red-edge spectral domain (705 nm, 740 nm, 783 nm and 865 nm) and two large SWIR bands (1610 nm and 2190 nm); and

	Landsat	SPOT	Sentinel-2	
Number in series	7+1*	5**	starting with 2	
Launch	1972 to 1999*	1986 to 2002	S2-A launch end 2013	
Measurement principle	scanner	pushbroom	pushbroom	
Earth coverage	16	26	5	days
Swath	185	2 × 60	290	km
Multispectral bands	7(8*)	4+1 (panchromatic)	13	
Spatial sampling distance	30, 60	10, 20, (2.5)	10, 20, 60	m

* LCDM mission targeted early 2013

** SPOT-6 targeted end 2012

Figure 3.1. Comparison of the capabilities of Landsat, SPOT and Sentinel-2. (Astrium GmbH, Germany)

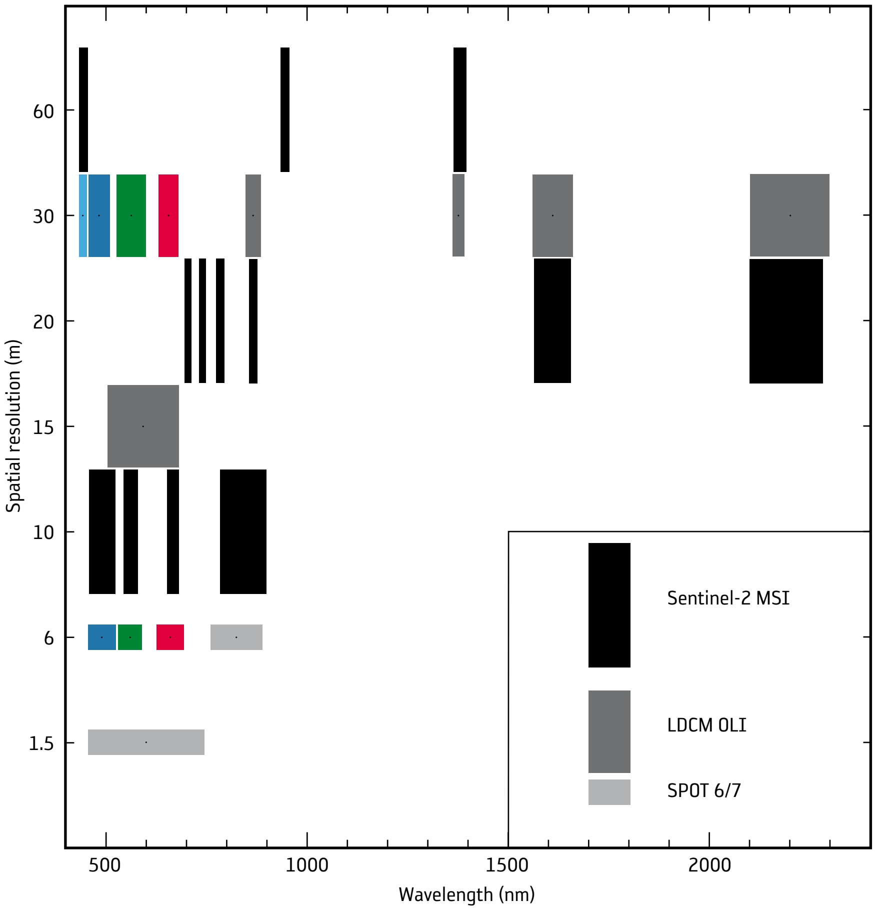


Figure 3.2. Key characteristics of Landsat, SPOT and Sentinel-2 (*main panel*), and the spectral resolution and band settings of the MultiSpectral Instrument (MSI), Operational Land Imager (OLI) and SPOT instruments (*inset, bottom right*).

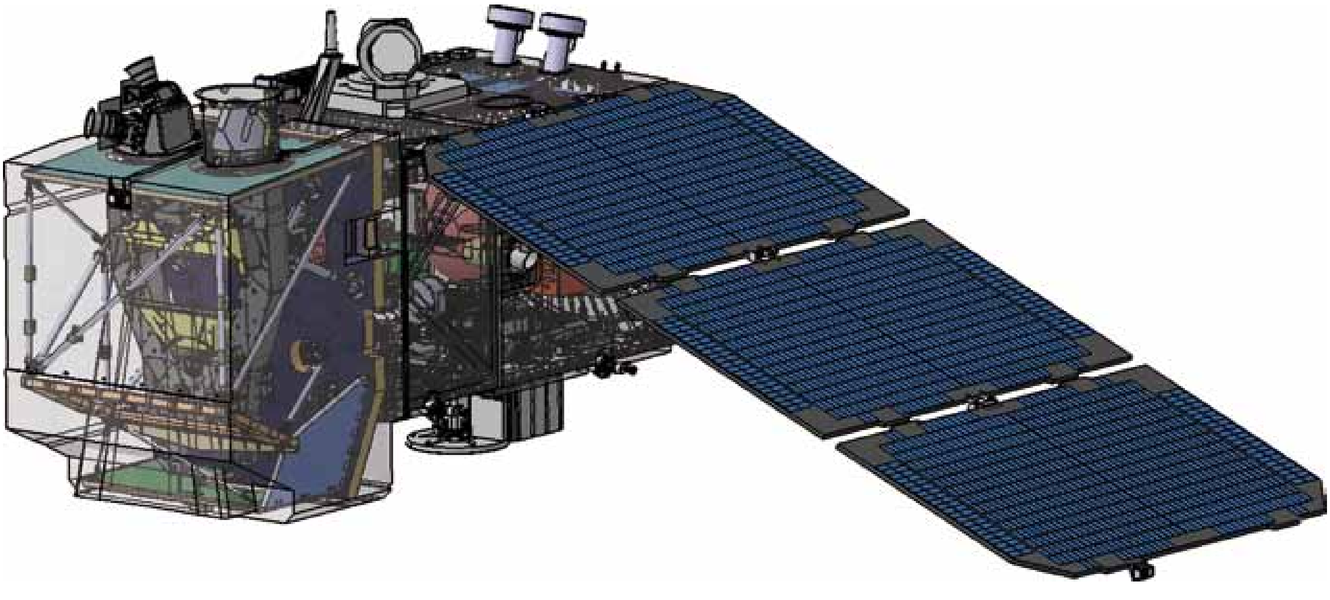


Figure 3.3. Sentinel-2 satellite. (Astrium GmbH, Germany)

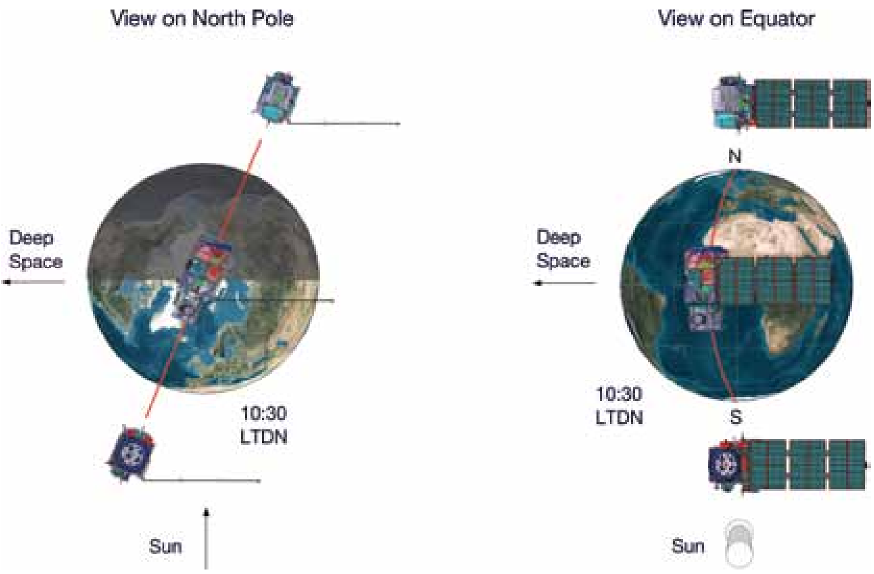


Figure 3.4. Sentinel-2 satellite orbital configuration. (Astrium GmbH, Germany)

Table 3.1. Key features of the Sentinel-2 mission.

Mission features	Data
Mission lifetime	15 years
Number of satellites	2
Nominal in-orbit satellite lifetime	7.25 years with consumables for an additional 5 years
Nominal orbit	Sun-synchronous at 786 km (mean altitude), 10:30 LTDN
Land coverage	–56° to +84°
Global revisit time	<5 days
Global accessibility	<2 days; <1 day above 45° latitude
Global Near-Real Time (NRT) latency	<2 h to reception on ground
Mission phases	LEOP, commissioning, operational, deorbiting phases

— three bands at 60 m, which are mainly dedicated to atmospheric corrections and cloud screening (443 nm for aerosol retrieval, 945 nm for water vapour retrieval and 1375 nm for cirrus cloud detection).

The average observation time per orbit is 17 min, while the peak value is 32 min. The combination of the large swath and broad spectral range, coupled with the requirement for global and continuous acquisition with a high revisit frequency, will lead to the generation of about 1.6 TBytes of compressed raw image data each day from the constellation of satellites. This corresponds to an average continuous raw-data supply rate of 160 Mbit/s.

The key features of the Sentinel-2 mission are summarised in Table 3.1.

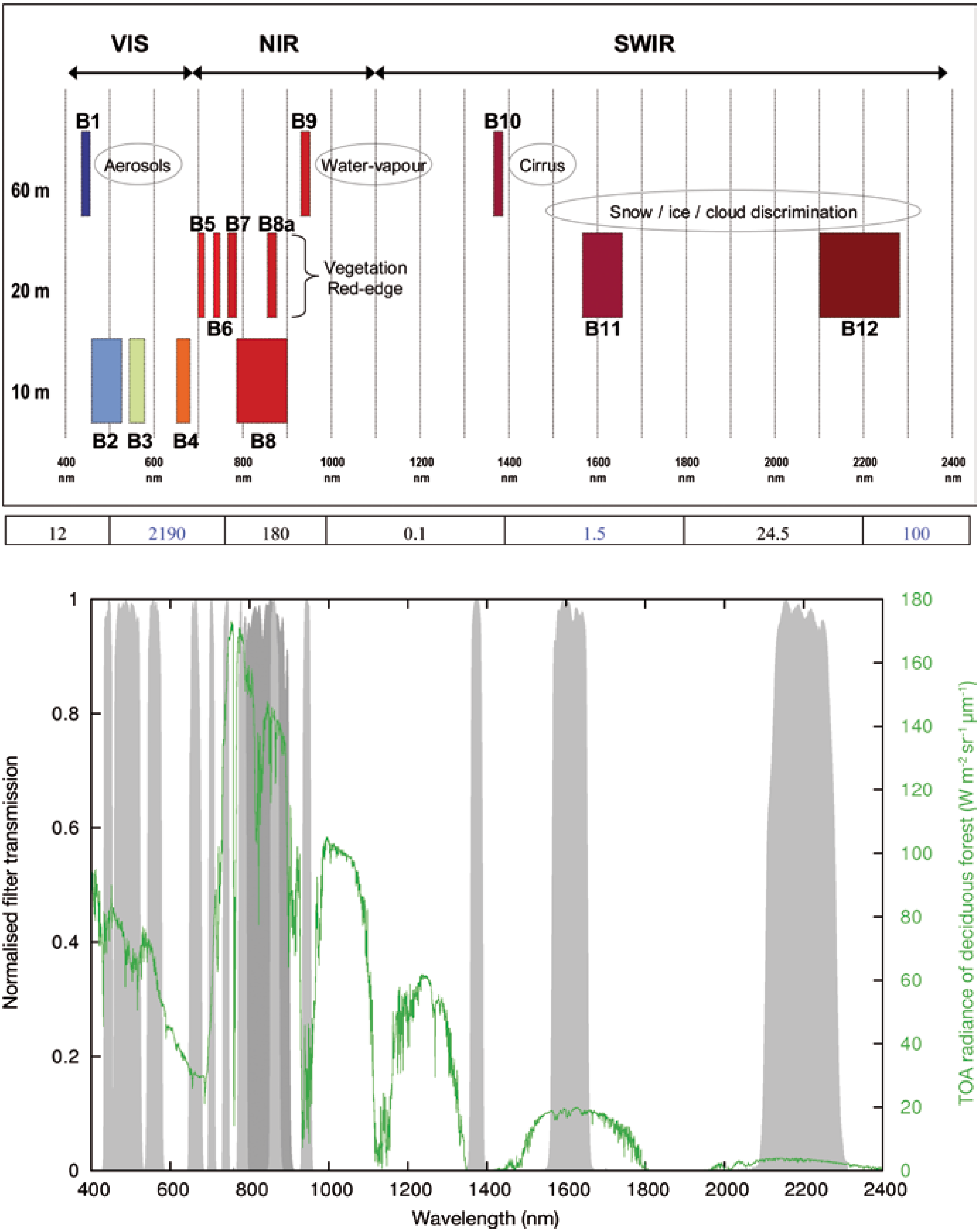


Figure 3.5. Spectral bands versus spatial resolution (*upper panel*), and MSI normalised filter transmission functions and the modelled top-of-atmosphere (TOA) radiance spectrum of deciduous forest (*bottom panel*).

4. Sentinel-2 System Concept Overview

The Sentinel-2 end-to-end system will comprise two segments:

— the Sentinel-2 Space Segment, i.e. the two orbiting satellites including their payload instruments; and
— the Sentinel-2 Ground Segment, which will acquire the data transmitted by the Space Segment, perform data processing (Level-0 to -1c; -2a), archiving and dissemination, control the mission as a whole, and command and control the satellites in orbit.

The main features of the Sentinel-2 system are summarised in Appendix C.

4.1 Sentinel-2 Space Segment

4.1.1 Satellite and Platform Design

The Sentinel-2 satellite system is being developed by an industrial consortium led by Astrium GmbH (Germany) as the Prime Contractor, while Astrium SAS (France) is responsible for the MultiSpectral Instrument. The satellite is based on a new platform developed for Sentinel-2 that is conceived as a generic product that will be compatible with the pointing accuracy and stability requirements of some very demanding Earth observation missions. The design of the satellite has benefited from the experience gained by EADS-Astrium on previous ESA missions such as the European Remote Sensing (ERS) satellites, Envisat, MetOp, CryoSat and the Earth Explorer Atmospheric Dynamics Mission (ADM-Aeolus), as well as national missions such as the German TerraSAR-X.

Each Sentinel-2 satellite weighs about 1.2 tonnes and features a rather compact design that ensures compatibility with small launchers like Vega and Rockot (Fig. 4.1). The satellite lifetime is specified as 7.25 years, including a three-month in-orbit commissioning phase. Batteries and propellants are sized for 12 years, including provision for deorbiting manoeuvres at end-of-life.

Each satellite is 3-axis stabilised and will be placed directly in circular polar orbit by the launcher. The satellite attitude is measured by an advanced multihead startracker and an Inertial Measurement Unit (IMU) using a fibre-optic gyroscope (Fig. 4.2) and controlled by a set of four reaction wheels (Fig. 4.3) and three magnetic torque rods. The startracker heads and the fibre-optic gyro unit are mounted on the MultiSpectral Instrument structure for better pointing accuracy and stability. The reaction wheels are damper-mounted and the Solar Array Drive Mechanism (SADM) employs a microstepping motor in order to reduce microvibrations that could adversely affect image quality and performance (Fig. 4.4).

The position of each Sentinel-2 satellite in orbit will be measured by a dual-frequency GNSS (Global Navigation Satellite System) receiver and its orbit is accurately maintained by a dedicated propulsion system using hydrazine propellant and catalytic reaction thrusters. Coarse Earth and Sun Sensors (CESS) are used to maintain a coarse pointing in the event that an anomaly affects the fine pointing system (Fig. 4.5). The power subsystem relies on highly efficient solar cells (GaAs triple junction) and lithium ion batteries.

The Sentinel-2 satellite design is characterised by a modular configuration enabling parallel development and integration of its main assemblies for schedule optimisation (Fig. 4.6). Its main components are as follows:

— An aluminium frame divides the satellite into a lower propulsion module and platform equipment compartment, and an upper instrument and sensor compartment (Fig. 4.7). This frame interfaces with a cylindrical launcher

Figure 4.1. The Sentinel-2 satellite enclosed within the launcher fairing. (Astrium GmbH, Germany)

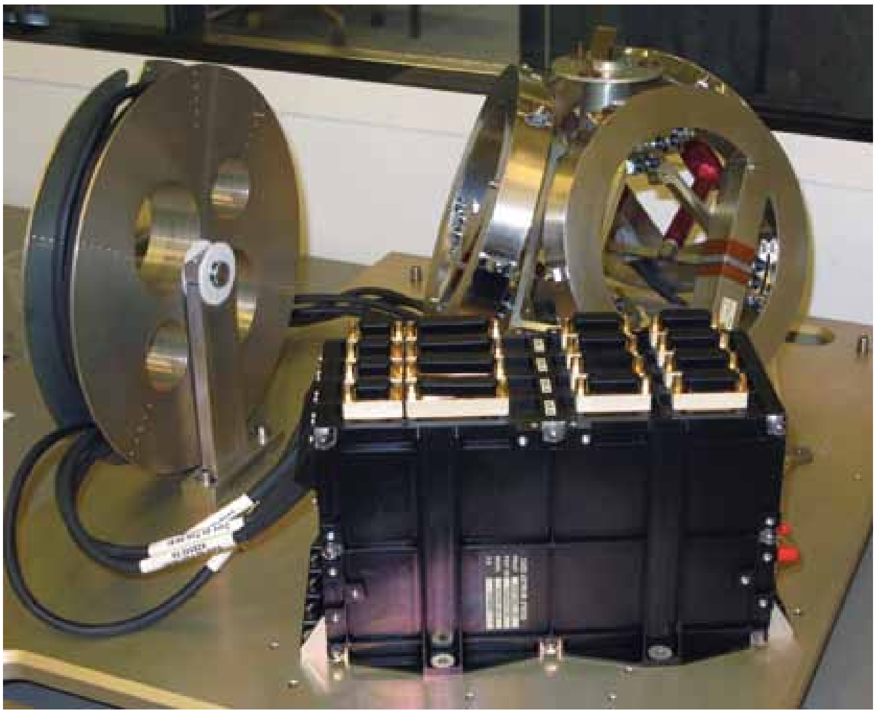


Figure 4.2. Inertial Measurement Unit. (Astrium SAS, France)

adapter. The instrument and sensor plate compartment is stiffened by an aluminium frame and closed by four access and radiator panels and a top floor. The top floor provides accommodation for the MultiSpectral Instrument optical assembly in SiC technology mounted isostatically through six Carbon-fibre Reinforced Polymer (CFRP) struts on top of a CFRP panel. The critical Attitude and Orbit Control System (AOCS) sensor assembly carrying the three startrackers and the fibre-optic gyroscope package is isostatically accommodated directly on the instrument's telescope structure (Fig. 4.8).

- The satellite configuration provides nadir pointing to the instrument and unobstructed fields of view for the startracker optical heads and for the X-band/S-band communication and GNSS antennas. The Optical Communication Payload (Fig. 4.9) is located on the side of the satellite facing away from Earth in order to ensure optimal visibility to a geostationary data relay satellite (Alphasat, and later EDRS). The Coarse Earth and Sun Sensors are positioned such that there is an unobstructed field of view of a deployed and rotating solar array.
- The platform equipment compartment accommodates all the electronic equipment on four sandwich panels and an intermediate floor. The batteries are mounted outside the compartment for late integration.
- The various units have been located so as to optimise thermal heat dissipation and to maintain the satellite's centre of gravity. Optical alignment cubes are integrated into all sensitive equipment for the derivation of accurate alignment vectors and transfer matrices with the satellite reference frame.
- The single-wing solar array has been designed so as to limit in-orbit mechanical disturbances in its deployed and rotating configuration.
- The propulsion system has been designed as an independent module that can be tested prior to its integration within the platform compartment. Thruster plume impingement and thruster obstruction are avoided by a mechanical accommodation within the launcher adapter ring.

The satellite has been designed to operate autonomously in the event of a nominal or single failure without updating its mission commands for up to 15 days. Retrieval and analysis of the satellite housekeeping telemetry data are, however, scheduled to take place twice a day. Satellite command and control

Figure 4.3. Reaction wheels. (Bradford Engineering, the Netherlands)

Figure 4.4. Qualification model of the Sentinel-2 Solar Array Drive Mechanism. (RUAG, Switzerland)

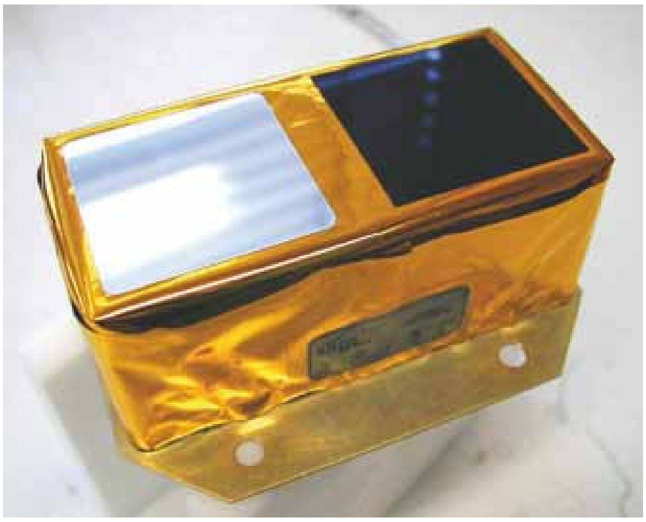


Figure 4.5. Coarse Earth and Sun Sensors. (Astrium GmbH, Germany)

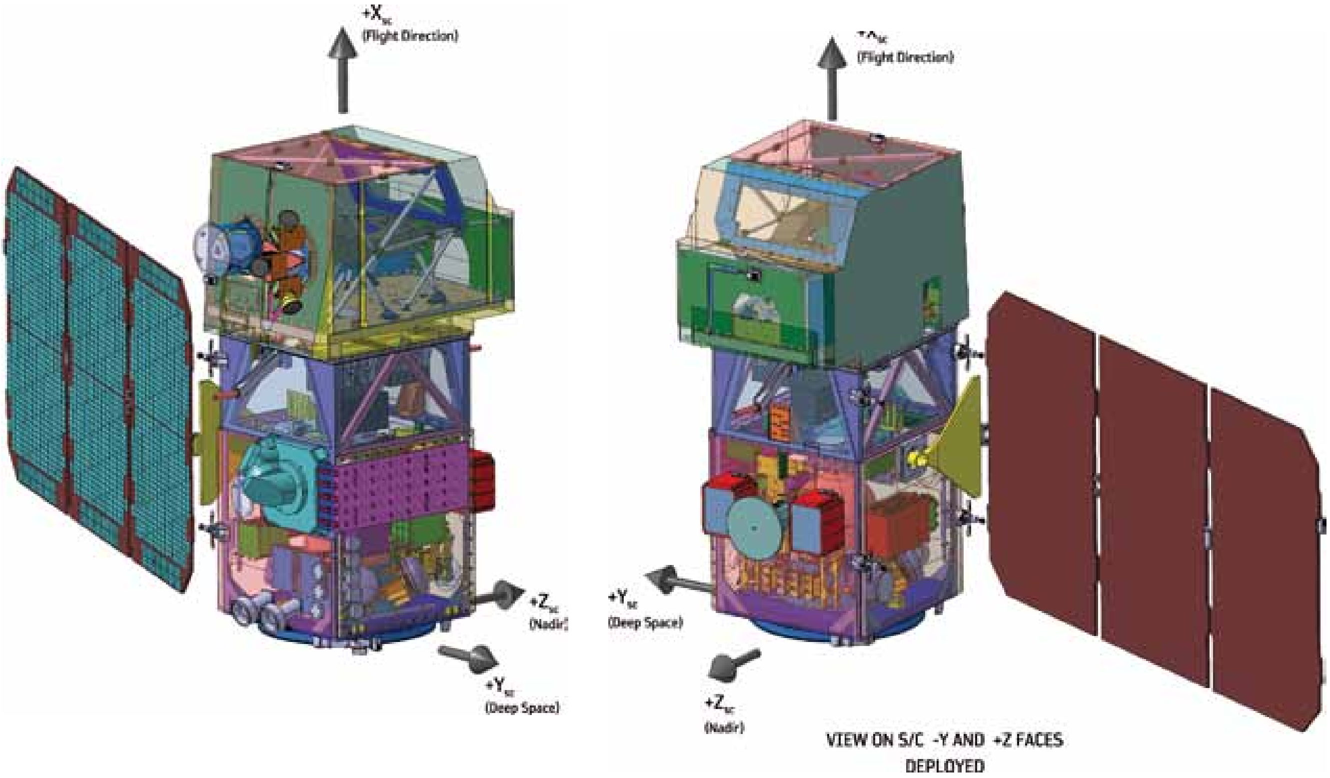


Figure 4.6. Sentinel-2 configuration with the solar array deployed. (Astrium GmbH, Germany)

and thermal control functions are implemented by the satellite Onboard Computer (OBC). The Atmel ERC-32 processing module performs the core processing of the unit via patchable software. The computer also drives two redundant MIL-STD-1553B buses (one for the payload, one for the platform). The payload data handling is based on a 2.4 Tbit solid state mass memory based on NAND flash technology, and the payload data downlink is performed at a rate of 560 Mbit/s in the X-band with 8-PSK modulation and an isoflux antenna (Fig. 4.10) compliant with the spectrum bandwidth allocated by the International Telecommunication Union (ITU).

The OCP complements the payload data handling and telecommunication system for optical data transmission of mission data through a geostationary satellite (e.g. Alphasat, a forerunner of the European Data Relay System, EDRS). Redundant S-band telemetry/telecommand (TM/TC) chains, compliant with ECSS/CCSDS communications standards, provide authenticated command and secure satellite telemetry links with the Ground Control segment (Fig. 4.11). Most satellite functions are redundant and can be autonomously reconfigured by the OBC to maximise the reliability and availability of the system. Furthermore, extensive internal cross-coupling within the OBC permits maximum operational flexibility during the mission.

Figure 4.12 provides an overview of the satellite's operational modes, while Fig. 4.13 sketches the Sentinel-2 data communication system. Figure 4.14 shows the system and equipment-level onboard software functions embedded in the satellite design.

The main platform functions are as follows:

- attitude and orbit control, including precise attitude measurements, stable and precise 3-axis pointing and precise orbit determination;
- propulsion, including correction of orbit injection errors, orbit maintenance and attitude control during ultimate safe mode and end-of-life disposal (Fig. 4.15);
- satellite data handling, including telecommand reception, deciphering, handling and distribution, telemetry collection, packetisation and forwarding to ground by telemetry, tracking and command (TT&C) communication equipment, and time and synchronisation signals management also in support of the payload;
- satellite autonomy and failure detection identification and recovery, including payload and satellite status monitoring, management and recovery, satellite operations planning support (mission timeline and sub-schedules);
- power generation (Fig. 4.16) and energy balance management, including power generation and energy storage, power conditioning, protection, distribution and switching, and pyrotechnic device actuation;
- thermal control, including temperature monitoring, heat generation and dissipation;
- structure, including primary structural support and interface with the launch vehicle, and appendage tie-down points and release mechanisms; and
- telemetry data communication with the ground, with satellite telemetry transmission and telecommand reception via the S-band transponder, instrument telemetry downlink via the X-band transmitter or via the OCP using an intermediate geostationary data relay satellite.

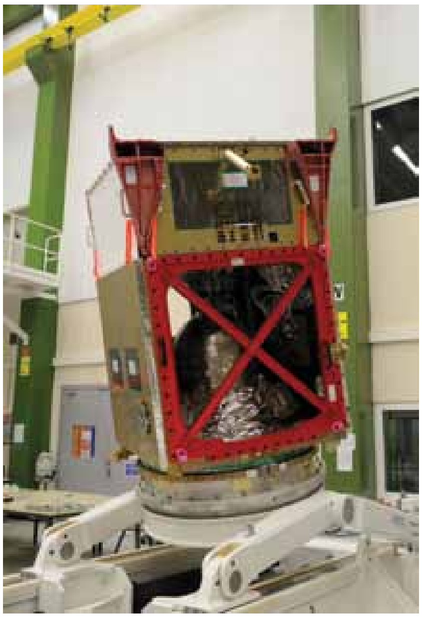


Figure 4.7. Sentinel-2 Protoflight Model (PFM) platform integrating the structure, propulsion module, thermal hardware and harness. (CASA, Spain, and Astrium GmbH, Germany)

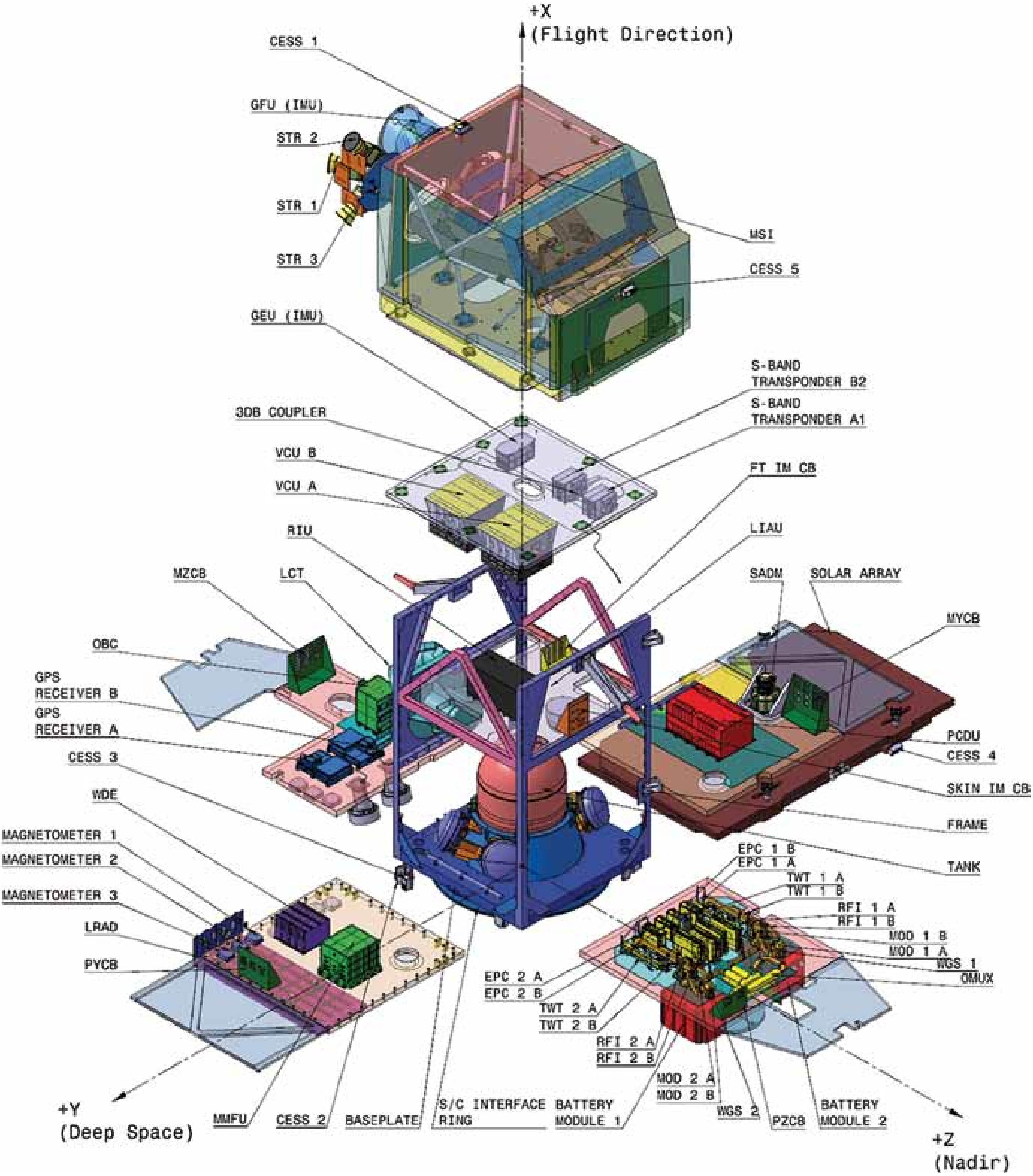


Figure 4.8. Sentinel-2 satellite architecture. (Astrium GmbH, Germany)

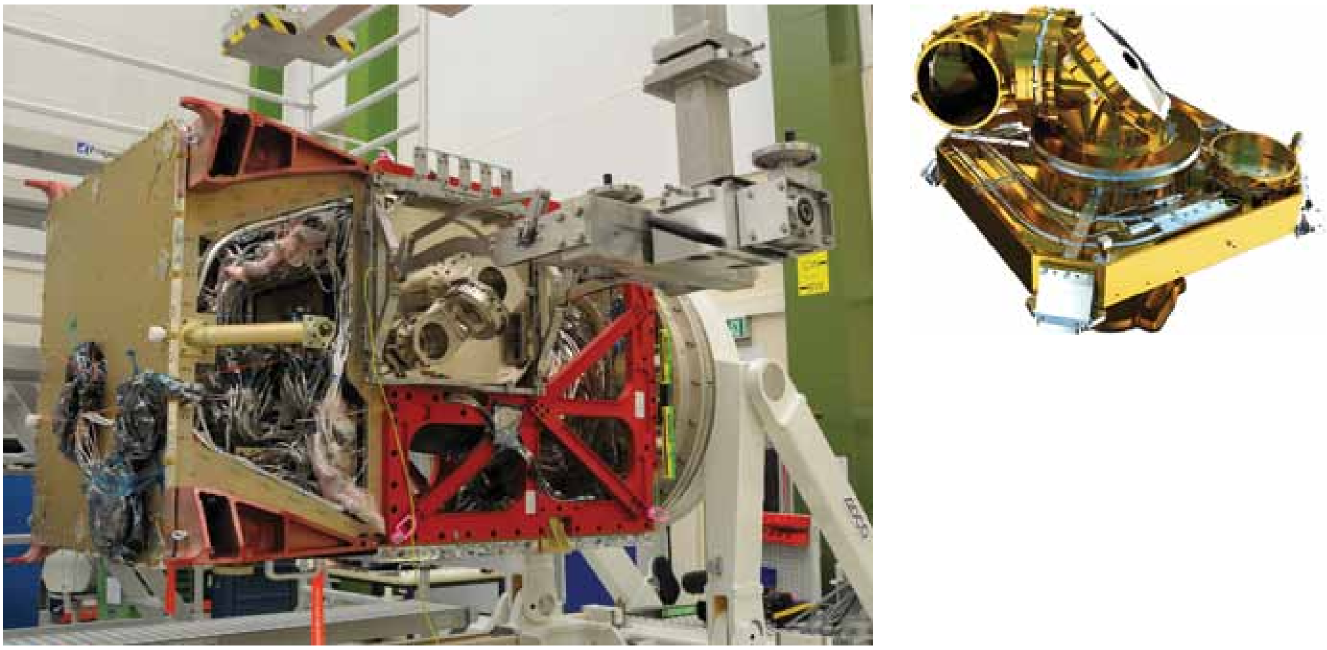


Figure 4.9. *Left:* OCP integration rehearsal on the PFM satellite. (Astrium GmbH, Germany) *Right:* Sentinel-2 Optical Communication Payload (DLR and Tesat GmbH, Germany).

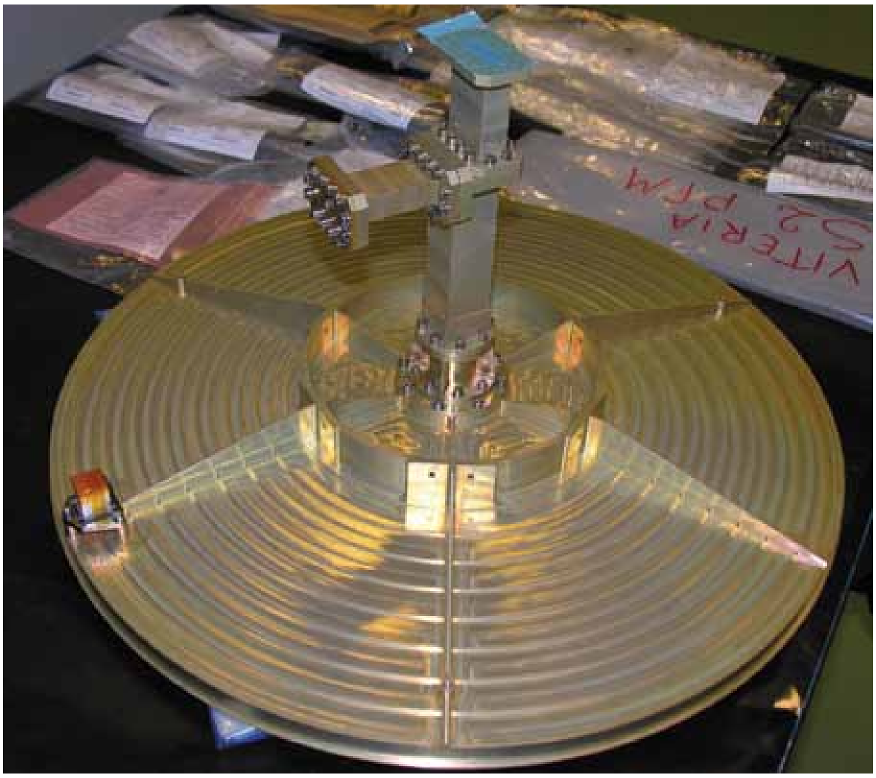
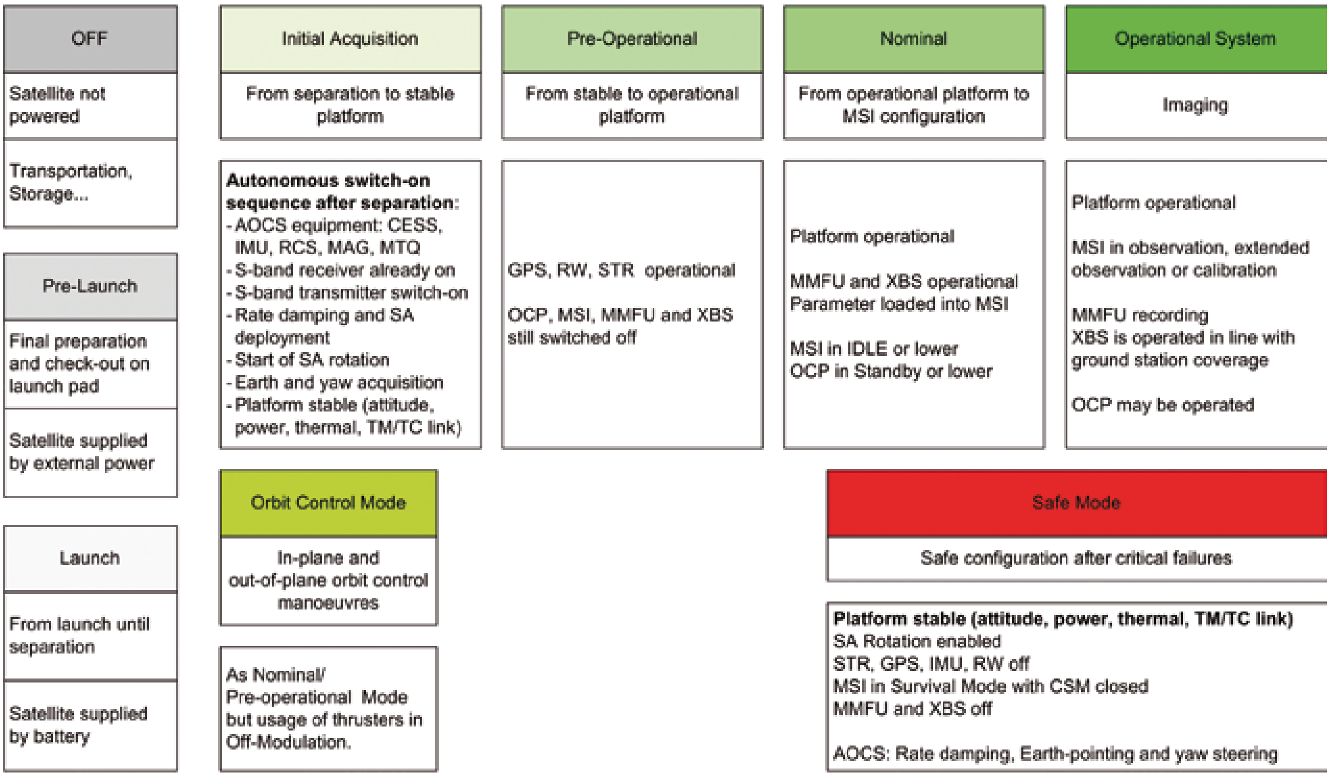


Figure 4.10. X-band antenna. (Thales, Italy)

Figure 4.11. S-band transponder. (Thales Spain)

Figure 4.12. Sentinel-2 operational modes. (Astrium GmbH, Germany)



OFF

Satellite not powered

Transportation, Storage...

Pre-Launch

Final preparation and check-out on launch pad

Satellite supplied by external power

Launch

From launch until separation

Satellite supplied by battery

Initial Acquisition

From separation to stable platform

Autonomous switch-on sequence after separation:
- AOCS equipment: CESS, IMU, RCS, MAG, MTQ
- S-band receiver already on
- S-band transmitter switch-on
- Rate damping and SA deployment
- Start of SA rotation
- Earth and yaw acquisition
- Platform stable (attitude, power, thermal, TM/TC link)

Orbit Control Mode

In-plane and out-of-plane orbit control manoeuvres

As Nominal/ Pre-operational Mode but usage of thrusters in Off-Modulation.

Pre-Operational

From stable to operational platform

GPS, RW, STR operational

OCP, MSI, MMFU and XBS still switched off

Nominal

From operational platform to MSI configuration

Platform operational

MMFU and XBS operational
Parameter loaded into MSI

MSI in IDLE or lower
OCP in Standby or lower

Operational System

Imaging

Platform operational

MSI in observation, extended observation or calibration

MMFU recording
XBS is operated in line with ground station coverage

OCP may be operated

Safe Mode

Safe configuration after critical failures

Platform stable (attitude, power, thermal, TM/TC link)
SA Rotation enabled
STR, GPS, IMU, RW off
MSI in Survival Mode with CSM closed
MMFU and XBS off

AOCS: Rate damping, Earth-pointing and yaw steering

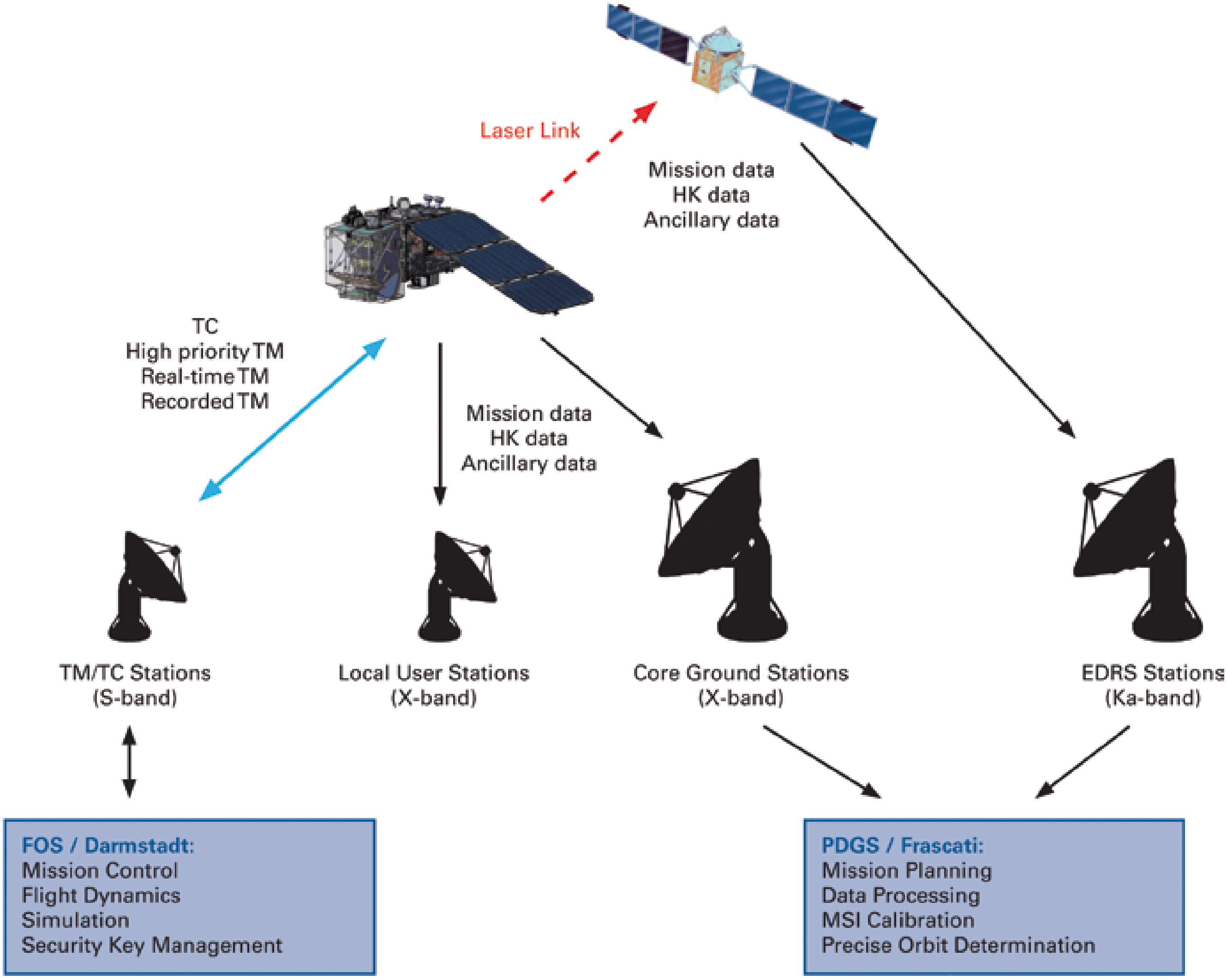


Figure 4.13. Sentinel-2 data communication system. HK – housekeeping; TM/TC – telemetry/telecommand; FOS, Darmstadt, Germany; PDGS, Frascati, Italy.

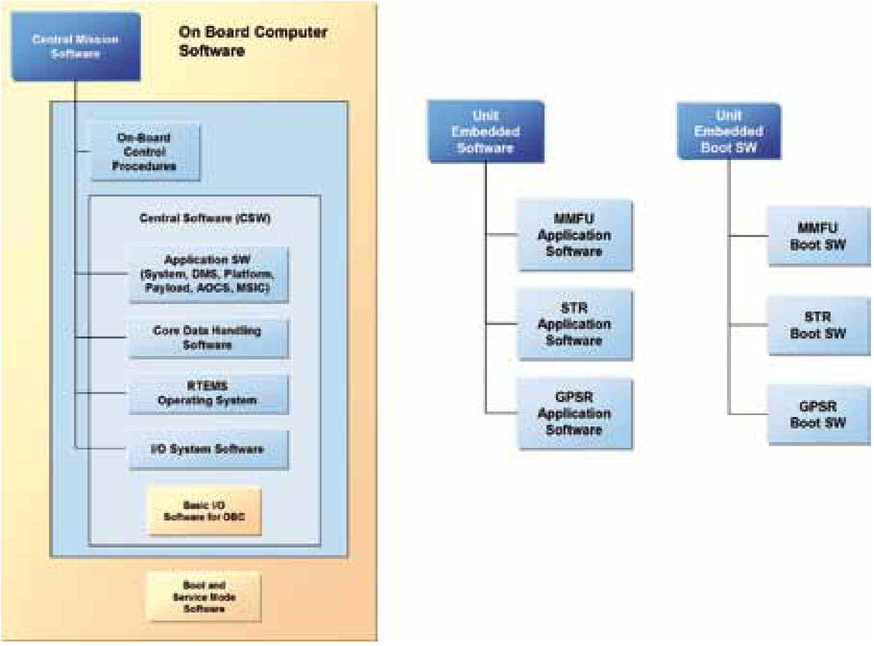


Figure 4.14. Sentinel-2 software. (Astrium GmbH, Germany)

Figure 4.15. The propulsion module. (Astrium GmbH, Germany)

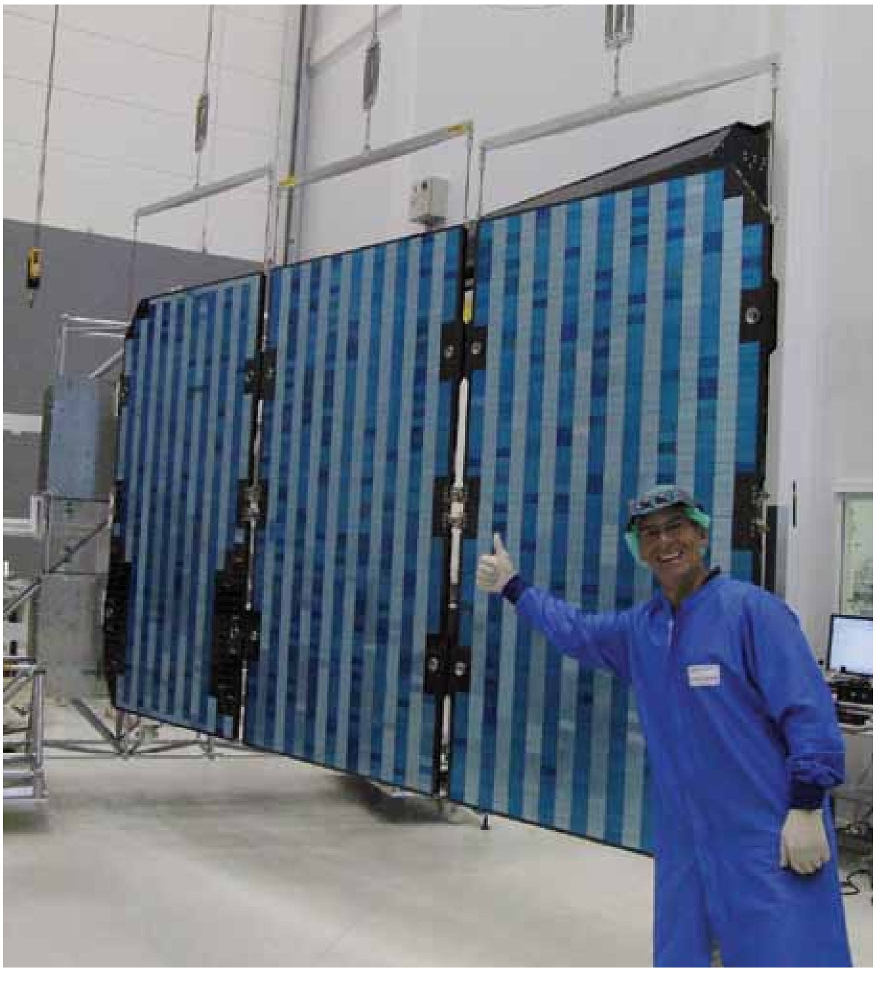


Figure 4.16. Qualification model of the Sentinel-2 solar array. (Dutch Space, the Netherlands)

Table 4.1. Sentinel-2 system characteristics.

System features	Data
Evolution	Four satellites needed for 15 years of operation
Ground station scenario (for payload data recovery via the X-band)	Matera (Italy), Svalbard (Norway), Maspalomas (Spain), Prudhoe Bay (Alaska, USA), plus local user stations
Security	Authentication of commands
Reliability	>0.7
Availability	>97%
Geolocation (2σ) without ground control points (GCPs)	<20 m
Swath	290 km
Modes of operation	Nominal mode, extended mode, support modes, safe mode
Maximum imaging	32 min per 100 min orbit
Launcher for Sentinel-2A	Rockot (Eurockot, Germany)
Launcher for Sentinel-2B	Vega (Arianespace, France)
Satellite launch mass	1225 kg (with 70 kg margin included)
Satellite dimensions (stowed)	3390 × 1630 × 2350 mm

The main characteristics of the Sentinel-2 satellite system are presented in Table 4.1.

4.1.2 The MultiSpectral Instrument Design

The MultiSpectral Instrument has a mass of 290 kg (Fig. 4.17) and is based on the push-broom concept. It features a Three-Mirror Anastigmatic (TMA) telescope with a pupil diameter equivalent to 150 mm, which is isostatically mounted on the platform in order to minimise thermoelastic distortions. The optical design has been optimised to achieve state-of-the-art imaging quality across its very wide field of view: its 290 km swath width is significantly larger than the 120 km swath of SPOT-5 (using two instruments), or the 185 km of the OLI included in the Landsat Continuity Mission. The telescope structure and the mirrors are made of silicon carbide, which provides a very high optical stability to mass ratio and minimises the thermoelastic deformation (Fig. 4.18).

Figure 4.17. The MultiSpectral Instrument. (Astrium SAS, France)

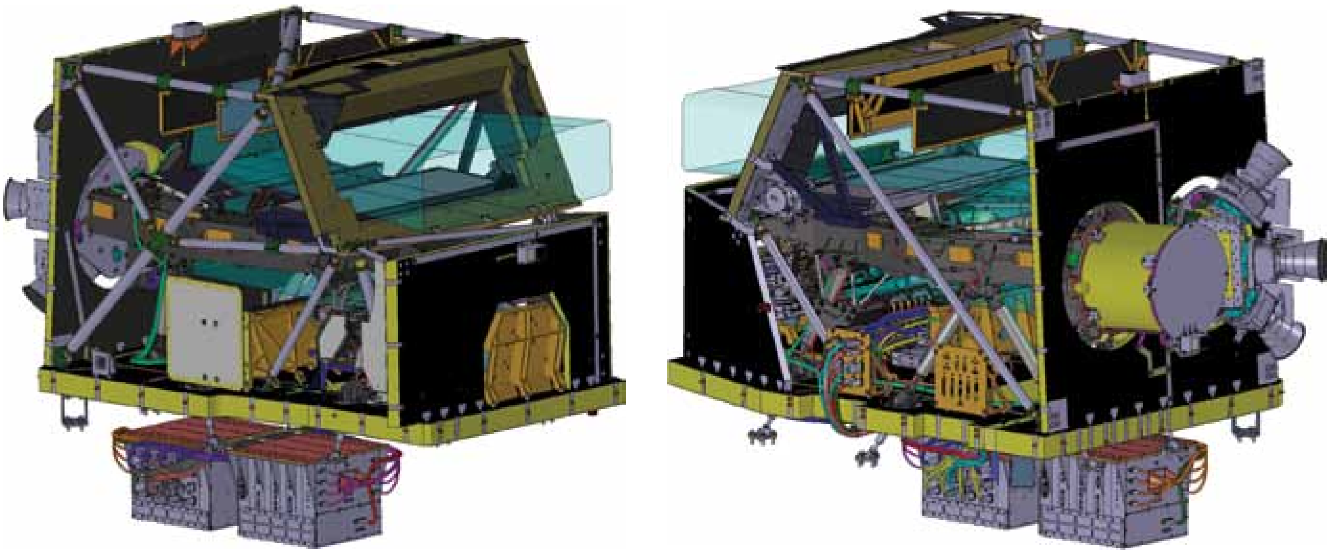
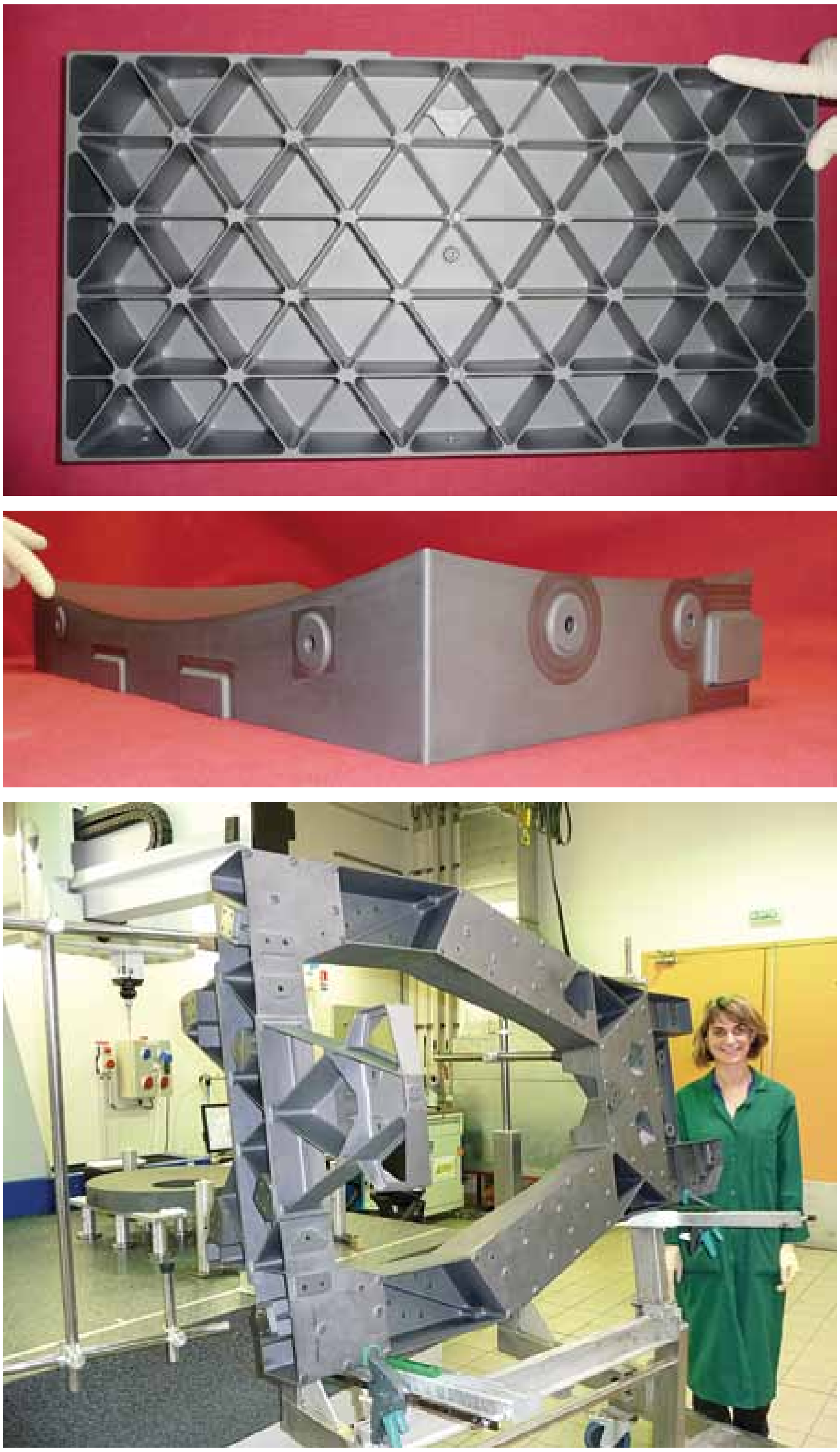


Figure 4.18. Sentinel-2 MultiSpectral Instrument SiC mirrors after polishing and coating (AMOS, Belgium) and the monolithic telescope base plate (Boostec, France).



The VNIR focal plane is based on monolithic complementary metal oxide semiconductor (CMOS) detectors, while the SWIR focal plane (see Fig. 4.19) is based on mercury–cadmium–telluride (MCT) detectors hybridised on a CMOS readout circuit. Twelve VNIR and SWIR detectors are employed in a staggered configuration to cover the field of view. The SWIR focal plane is passively thermo-controlled at temperatures below 195K. A dichroic beam splitter provides the spectral separation of the VNIR and SWIR channels. Spectral separation in the various bands is provided by stripe filters (see Fig. 4.20) mounted on top of the detectors.

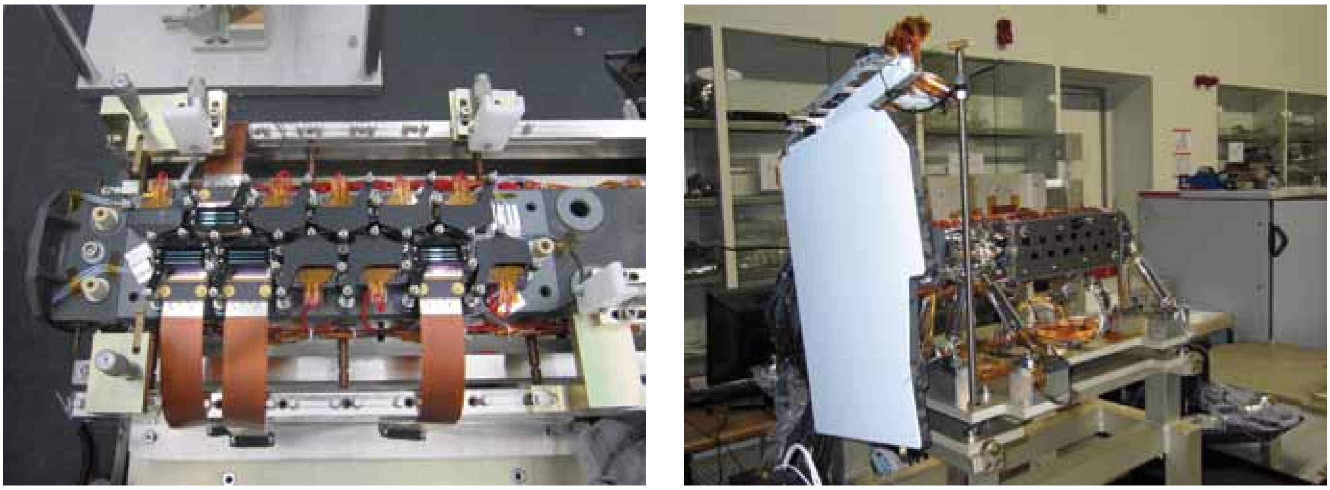


Figure 4.19. Two views of the Engineering Model (EM) of the SWIR focal plane, equipped with detectors and thermal hardware. (Astrium SAS, France)

Figure 4.20. VNIR filter assemblies positioned on top of the detectors on the FPA. The assembly design and materials have been optimised to minimise straylight. (Jena-Optronik, Germany)

A full-field and full-pupil onboard diffuser will be employed for radiometric calibration to guarantee high-quality radiometric performance. The observation data are digitised into 12 bits. State-of-the-art lossy compression based on a wavelet transform is applied to reduce the data volume. The compression ratio of between 2 and 3 has been fine-tuned for each spectral band to ensure that there is no significant impact on image quality. A shutter mechanism is implemented to prevent the instrument from direct illumination by the Sun in orbit and to avoid contamination during launch. The same mechanism will also function as a calibration device by collecting the sunlight after reflection by a diffuser (Fig. 4.21).

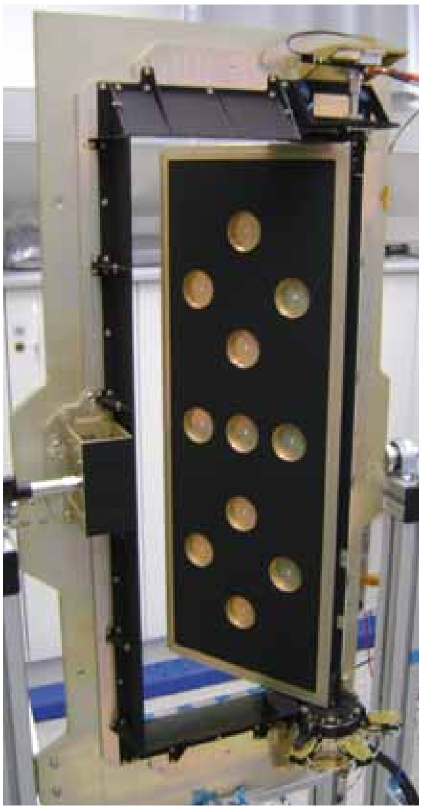


Figure 4.21. Calibration and shutter mechanism showing the fixation points for the Sun calibration diffuser. (SENER, Spain)

4.1.3 Assembly, Integration and Test Programmes

Platform and Satellite AIT programme

The Sentinel-2 satellite Assembly, Integration and Test (AIT) programme encompasses:

- functional test activities;
- integration and qualification of the Sentinel-2A satellite; and
- integration and acceptance of the Sentinel-2B satellite.

In line with the Sentinel-2 development model philosophy, three test facilities are used to support the functional tests on the development models and on the Sentinel-2 satellites: the Software Test Bench (STB); the Electrical Functional Model (EFM) and the Protoflight Model (PFM).

The STB includes an Elegant Breadboard of the Onboard Computer (Fig. 4.22) and is dedicated to executing the satellite Central Software (CSW) in representative target hardware and to simulate in real time its command and control interfaces with the other platform and payload units. The STB constitutes an operational facility capable of supporting the development of the different CSW versions in synergy with the other CSW verification facilities and performance analysis benches. This allows the preparation and debugging of automated test sequences that can be reused on the other development models and to prepare the flight operation sequences.

Figure 4.22. Sentinel-2 Software Test Bench with the OBC Elegant Breadboard and simulation front-end. (Astrium GmbH, Germany)

The EFM includes the engineering qualification model of the OBC and engineering models of the main platform and payload units, complemented by a simulation of the remaining units. It constitutes an electrical model representative of the whole satellite, including fully representative hardware and software of all the critical units operating on the MIL-bus and with high-fidelity electrical and functional simulation models of the missing units. The EFM provides all the features needed to perform early validation of the electrical interfaces, verification of the AOCS functionalities by real-time closed-loop testing, including failure detection, isolation and recovery, and the development of the flight operational procedures. It allows also early electrical and functional verification of the interfaces between the platform and all payload units.

The PFM test environment is designed to support the functional verification of the Sentinel-2 satellites throughout their assembly and integration phases and during the respective environmental qualification and acceptance test campaigns. The design of the satellite and of the PFM Electrical Ground Support Equipment (EGSE) has been conceived to provide the capability to stimulate and test in closed-loop the AOCS sensors and actuators. This encompasses the utilisation of sophisticated external optical and electrical real-time stimuli to the sensors, including the simulation of the GNSS constellation of satellites (Fig. 4.23). It also includes the capability to fully stimulate and monitor the power subsystem, S-band and X-band subsystems, and allows the execution of System Functional Tests (SFTs) and Operations System Tests (OSTs) using the same TM/TC command and control databases used for the flight operations. The above features allow the execution of functional tests of the satellite with its hardware and software in flight configuration until the late stages of the AIT programme.

The EFM and PFM test environments support the preparation and execution of the System Validation Tests (SVTs). During these tests, executed in four sessions during the satellite AIT programme, the control of the satellite is transferred to the Flight Operations Segment at ESA's ESOC (European Space Operations Centre), and the S-band TM/TC and X-band downlink data are exchanged and acquired by dedicated EGSE.

It is planned to conduct environmental tests of the Sentinel-2 satellites at the ESTEC Test Centre over a period of about six months. For the PFM satellite, the following tests are foreseen:

— mass property measurements;
— sine and acoustic vibration tests;
— adapter fit check and separation shock tests, with the Vega and Rockot 1194 mm launcher adapters;
— thermal vacuum and thermal balance, including solar simulation;
— electromagnetic compatibility tests;
— operations system tests; and
— functional, alignment tests, including payload end-to-end optical stability checks, propulsion leak and solar array deployment tests, which will be executed at the beginning and the end of the environmental test campaign.

For the second and recurring models of the satellite, a standard environmental acceptance test sequence is foreseen, allowing the duration of the test to be reduced to 8 weeks.

Figure 4.24 shows the arrival of the first Sentinel-2 protoflight platform at Astrium within its transport container.

Figure 4.23. Sentinel-2 GPS constellation simulator. (Astrium GmbH, Germany)

MultiSpectral Instrument AIT Programme

The Sentinel-2 MultiSpectral Instrument is undergoing a thorough integration and test programme based on a two-step approach. The MSI verification programme starts with an EM programme dedicated to the early verification of the VNIR and SWIR focal plane opto-mechanical integration, and an electrical coupling allowing a first end-to-end characterisation of the performance of the MSI detection chains. To complete the MSI verification, the flight hardware will undergo a protoflight (PFM) qualification programme, including a full characterisation of geometric, optical and radiometric performance at instrument level.

The instrument EM AIT programme uses sophisticated test and verification techniques specific to each focal plane. For the VNIR Focal Plane Assembly (FPA), composed of ten bands with strip filters mounted on top of the detectors, the alignment procedure requires fine-tuned positioning with micrometre accuracy in order to achieve planarity without vignetting and to minimise straylight parasitic effects. For the SWIR FPA, the challenge lies in achieving accurate control of the detectors and strip filter alignment under flight-representative thermal conditions (195K) in order to reach the specified signal-to-noise ratio (SNR) performance. The alignment and radiometric performance will be characterised during a dedicated thermal balance test.

The EM test programme also couples the detectors to the front-end electronics module (Fig. 4.25) and to the Video and Compression Unit (VCU), allowing the verification of the instrument data sequencing of the onboard data compression performance and of the data handling for the VNIR and SWIR detection chains.

The instrument EM test programme is completed by a performance characterisation of all the detection chains, including optical Modulation

Figure 4.24. The Sentinel-2 protoflight platform arriving at Astrium in Friedrichshafen. (Astrium GmbH, Germany)

Figure 4.25. Front-end electronics module. (CRISA, Spain)

Transfer Function (MTF, for stray light effects) and radiometric performance such as cross-talk, SNR and linearity.

The instrument PFM test programme is based on a sequential integration approach. In particular, geometric, radiometric and optical tests will be run at Focal Plane Assembly level with additional geometric and optical tests done after alignment with the telescope structure and before the complete set of performance tests run at instrument level. Following the instrument equipment integration, a qualification programme is conducted including vibration, electromagnetic compatibility (EMC), and thermal vacuum tests completed by initial and final functional and performance tests. Note that the SWIR detections chains have been designed to allow functional and radiometric health checks at ambient by specific adjustment of integration time under controlled ambient conditions.

The MSI qualification programme will be run at Intespace in Toulouse, France, for the vibration and EMC tests, while the thermal tests will be conducted in the Focal-5 vacuum chamber at the Centre Spatial de Liège (CSL), Belgium. The PFM instrument test sequence includes a complete calibration test sequence and verification of all nominal and redundant instrument functions, telecommands, all mission and ancillary data, and verification of the housekeeping telemetry content.

The calibration test is based on an end-to-end verification using a fully characterised onboard diffuser. A determination of on-ground coefficients will be performed and further computed to define calibration laws to be used during the Sentinel-2 mission. Based on these laws, a table of non-uniformity coefficients (NUCs) will be determined and uploaded to perform the onboard correction prior to data compression. The first cross-validation of the calibrated data will be done during the in-orbit commissioning phase to validate or update the onboard NUC table. During the lifetime of the MSI, the NUC table will be cross-checked on a monthly calibration basis.

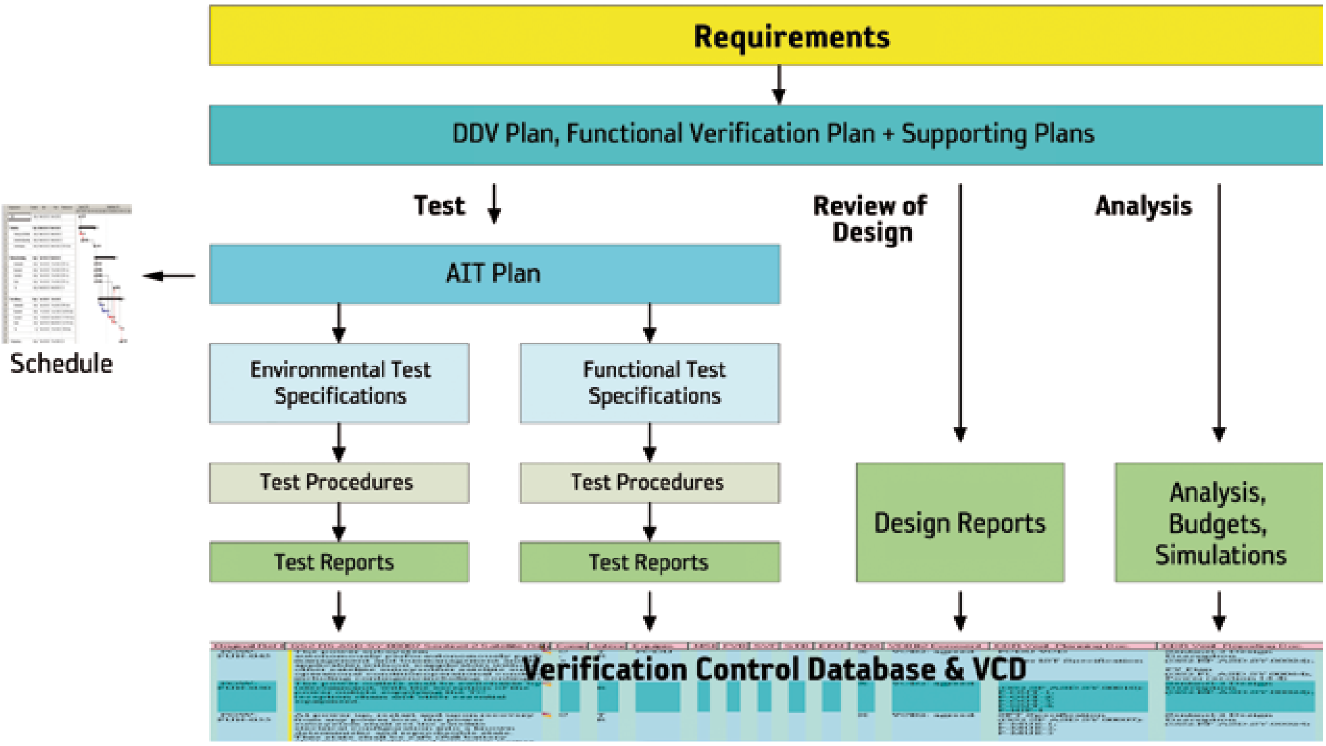


Figure 4.26. Sentinel-2 requirements verification logic.

4.1.4 Satellite System Verification

ESA's technical requirements are expressed in the System Requirements Document that specifies the satellites' functions, performance and external interfaces, and in the Operational Interface Requirements Document specifying satellite operability. These system level requirements have been broken down into a consistent tree of specifications, interface control documents and test and verification plans.

At all levels of the satellite, product requirement verification methods have been defined with the relevant industries and ESA teams (i.e. tests, analyses and design reviews, and combinations of all three methods), and each verification process is tracked throughout the development phase to certify its adequate close-out. The Satellite Flight Acceptance Review will check the adequate completion of the verification process, including the acceptability of requests for deviations or waivers agreed between ESA and the relevant industries.

The satellite system verification is configured and controlled using the DOORS software tool. The definition of a structured and complete verification process has in turn allowed the definition of a sound analysis campaign completed at the Satellite Critical Design Review by an optimised AIT programme that permits the derivation of a consistent schedule for all activities. Figure 4.26 illustrates the tight links maintained between the system requirements, AIT programme definition, verification methods and close-out, and finally the Sentinel-2 programme schedule (see Fig. 4.27).

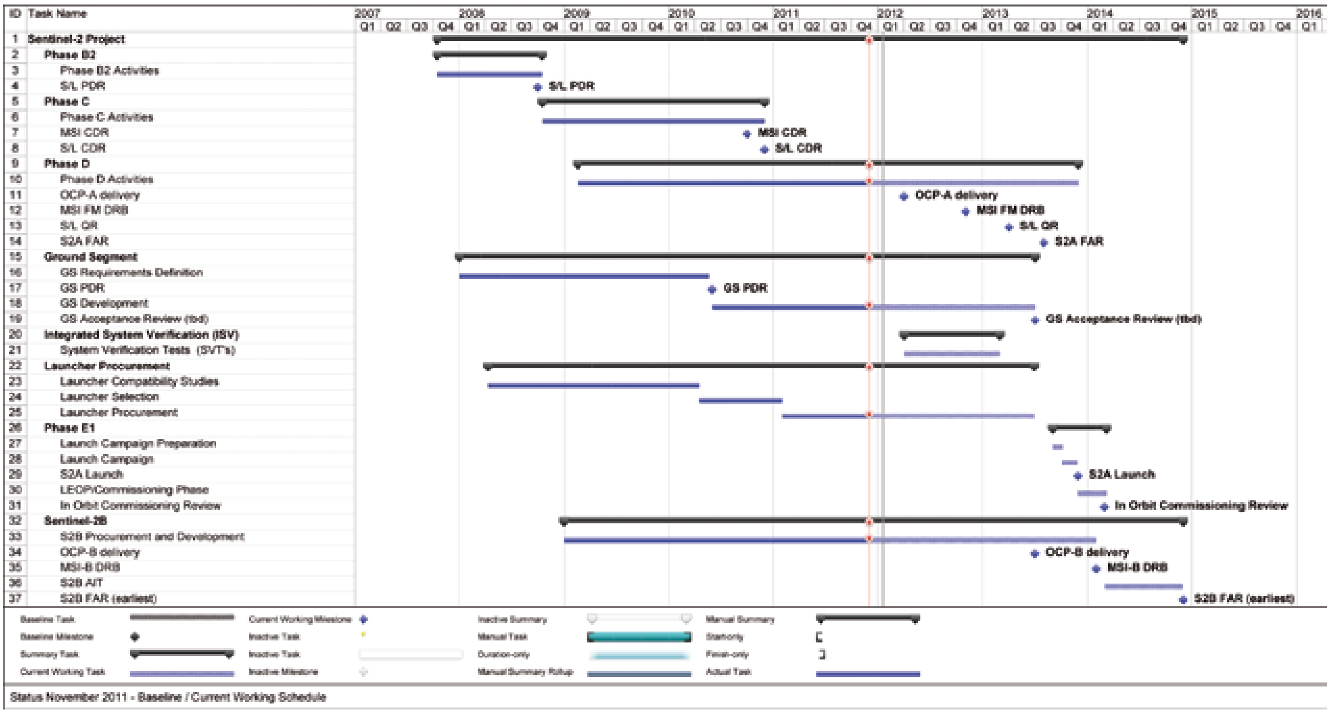


Figure 4.27. Sentinel-2 programme schedule.

4.2 Sentinel-2 Ground Segment

The Sentinel-2 Ground Segment is composed of the Flight Operations Segment and the Payload Data Ground Segment.

4.2.1 Flight Operations Segment

The FOS is responsible for all flight operations of the Sentinel-2 satellites, including monitoring and control, the execution of all platform activities and commanding of the payload schedules. Based at ESOC in Darmstadt, Germany, the principal components of the FOS are as follows (see Fig. 4.28):

- The Ground Station and Communications Network, which will perform telemetry, tracking and command operations using the S-band telecommunication subsystem of the satellites. The S-band ground station used throughout all mission phases will be ESA's Kiruna station (complemented by Svalbard and Troll as backup stations).
- The Flight Operations Control Centre (FOCC) at ESOC, including:
  - the Sentinel Mission Control System, which will support hardware and software telecommand coding and transfer, housekeeping telemetry (HKTM) data archiving, and processing tasks essential for controlling the mission, as well as all FOCC external interfaces;
  - the Sentinel Mission Scheduling System (part of the Mission Control system), which will support command request handling and the planning and scheduling of satellite/payload operations;
  - specific Sentinel-1/-2/-3 satellite simulators, which will support procedure validation, operator training and simulation campaigns before each major phase of the mission; and
  - the Sentinel Flight Dynamics System (FDS), which will support all activities related to attitude and orbit determination and prediction,

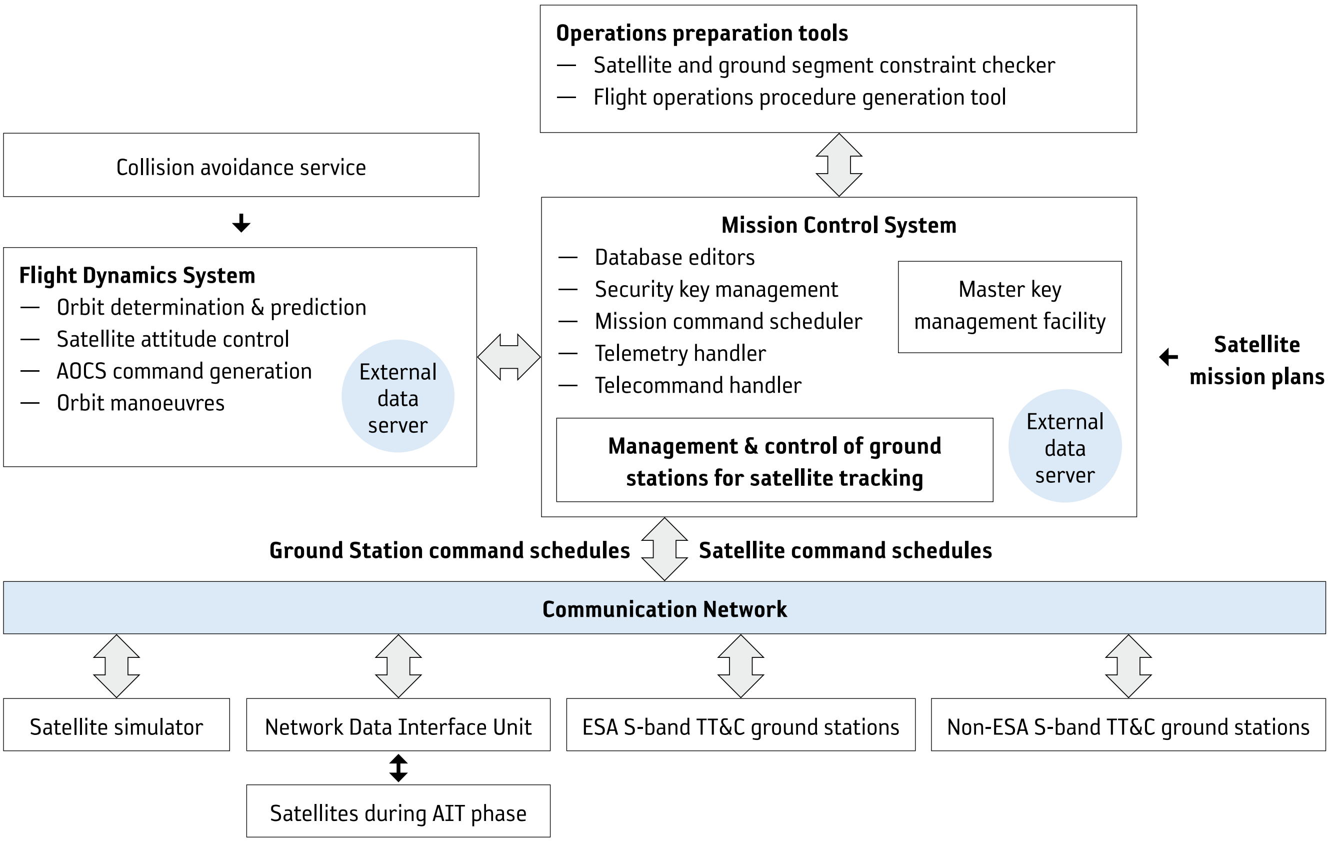


Figure 4.28. Sentinel-2 Flight Operations Segment.

preparation of slew and orbit manoeuvres, evaluation of satellite dynamics and navigation.
- A general purpose communication network, which will provide services for exchanging data with any other external system during all phases of the mission.

In order to improve the cost effectiveness of running routine operations, a single satellite operator for the three Sentinels will be on shift during working hours, seven days a week. Also, the number of TT&C ground station passes scheduled for each satellite will be minimised to only two per day thanks to the high autonomy of the satellites.

The housekeeping telemetry from the satellites will be downlinked every orbit using dedicated X-band stations and retrieved by the FOS for offline processing. Once a day and during special operations (e.g. LEOP, commissioning activities) the data will also be retrieved at the S-band via a 2 Mbit/s link.

The satellite design foresees not only traditional onboard scheduling based on time-tag commands, but also another one based on orbit position tags (a combination of orbit number and angle from the ascending node). The FOS Mission Planning System supports both schedules, allowing the different activities to be planned either by time (e.g. platform maintenance) or by orbit position (e.g. payload operations). The system also supports re-planning based on plan increments starting from synchronisation points identified in advance.

4.2.2 Payload Data Ground Segment

The Sentinel-2 Payload Data Ground Segment (see Fig. 4.29) is responsible for payload and downlink planning, data acquisition, processing, archiving and downstream distribution of satellite data, while contributing to the overall monitoring of the payload and platform in coordination with the FOS.

The systematic activities of the PDGS include the coordinated planning of the mission subsystems and all processes cascading from the data acquired from the Sentinel-2 constellation, including:

- the automated and recurrent planning of satellite observations and their transmission to a network of distributed X-band ground stations;
- the systematic acquisition and safeguarding of all satellite-acquired data, and their processing to higher-level products ensuring quality and timeliness targets;
- the recurrent calibration of the instrument as triggered by quality control processes;
- the automated circulation of data products across the PDGS distributed archives to ensure the required reliability of the data and their availability to users; and
- the long-term archiving of all mission data with embedded redundancy over the mission lifetime and beyond.

Vis-à-vis its users, the PDGS features:

- a scalable data access and distribution system to cope with the large volumes of data and the anticipated high level of demand from users; and
- user services, including providing automated user-registration facilities, online access to data, tools, user manuals, and up-to-date news on the main events of the mission and performance.

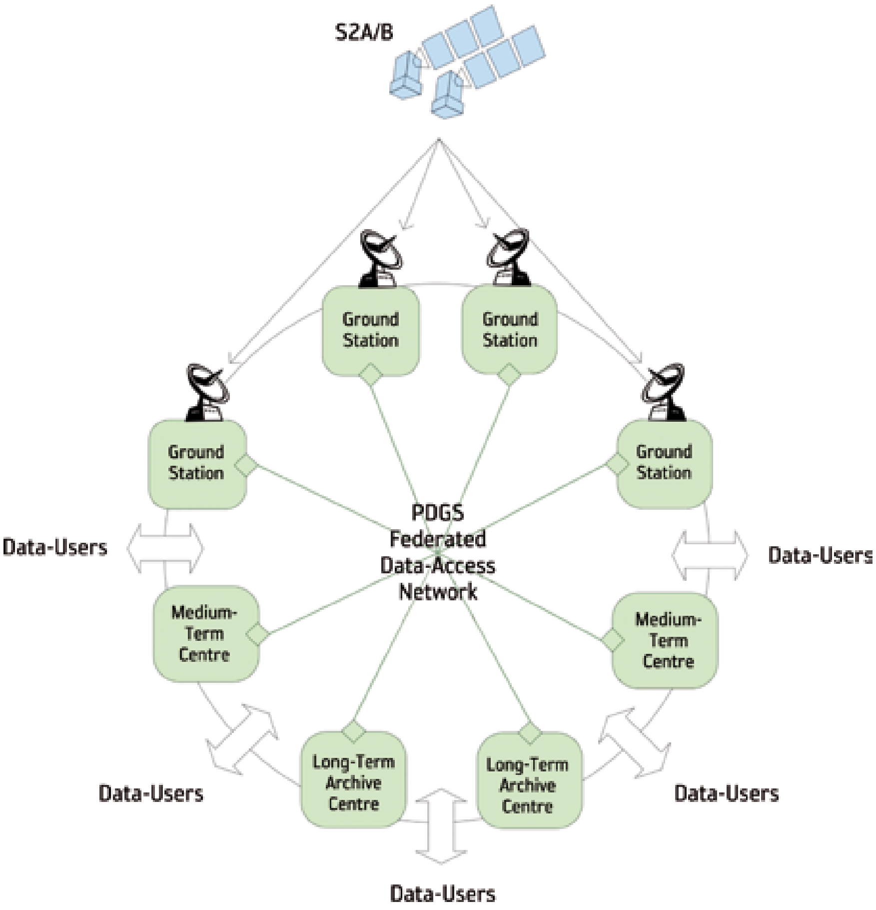


Figure 4.29. Sentinel-2 Payload Data Ground Segment architecture.

Table 4.2. Sentinel-2 data product dissemination strategies.

Sentinel-2 product type	Online product retention	Offline product retention	Product storage strategy
Housekeeping telemetry data	1 week	Mission lifetime	Data available online at the station for 1 week, then stored in the long-term archive
Level-0 data products	3 months	Mission lifetime	Data available online at the station for 1 week, and stored in the medium-term archive for 3 months (swift data reprocessing, e.g. during commissioning), in parallel storage in the long-term archive
Level-1a data products	1 month	No	Products available online from the medium-term archive for 1 month
Level-1b data products	1 month	Mission lifetime	Products maintained online for 1 month, then accessible from the long-term archive
Level-1c data products	1 month global 1 year global cloud free 1 year over Europe	Mission lifetime	All products with cloudiness below a threshold (e.g. 80%) archived offline for 1 year. Over Europe, all products are archived regardless of cloud cover. All data are kept online for at least 1 month, after which all products can be retrieved from the long-term archive offline

The PDGS has been designed as a distributed ground system that includes ground stations, processing and archiving centres, and a control centre. The PDGS links all remote archives, although physically located at various sites, offering users a single virtual access point for locating and downloading products.

All Sentinel-2 data will be processed by the Sentinel-2 PDGS, which will offer users three levels of data product timeliness:

- Real Time (RT), corresponding to product availability online not later than 100 min after data sensing;
- Near-Real Time (NRT), corresponding to product availability online between 100 min and 3 h after data sensing; and
- Non-Time-Critical (NTC) for all other data products, available within 3–24 h following data take.

Considering the very high data generation profile of the Sentinel-2 mission, and depending on the product type and age of the data, different data dissemination and archiving strategies will be followed. Two complementary means of archiving are foreseen:

- a rolling medium-term archive will provide optimised access to the latest products generated for a period of up to typically four months following data take; and
- a long-term archive will provide access to older data, with retrieval capabilities covering the entire historical archive.

An analysis of the Sentinel-2 data supply has concluded that about a quarter of the overall data will be required by users under RT or NRT constraints, leaving the remaining data as NTC. Table 4.2 shows the dissemination strategies for each of these product types.

5. Sentinel-2 Launch Campaign and Early In-Orbit Operations

5.1 Launch Campaign

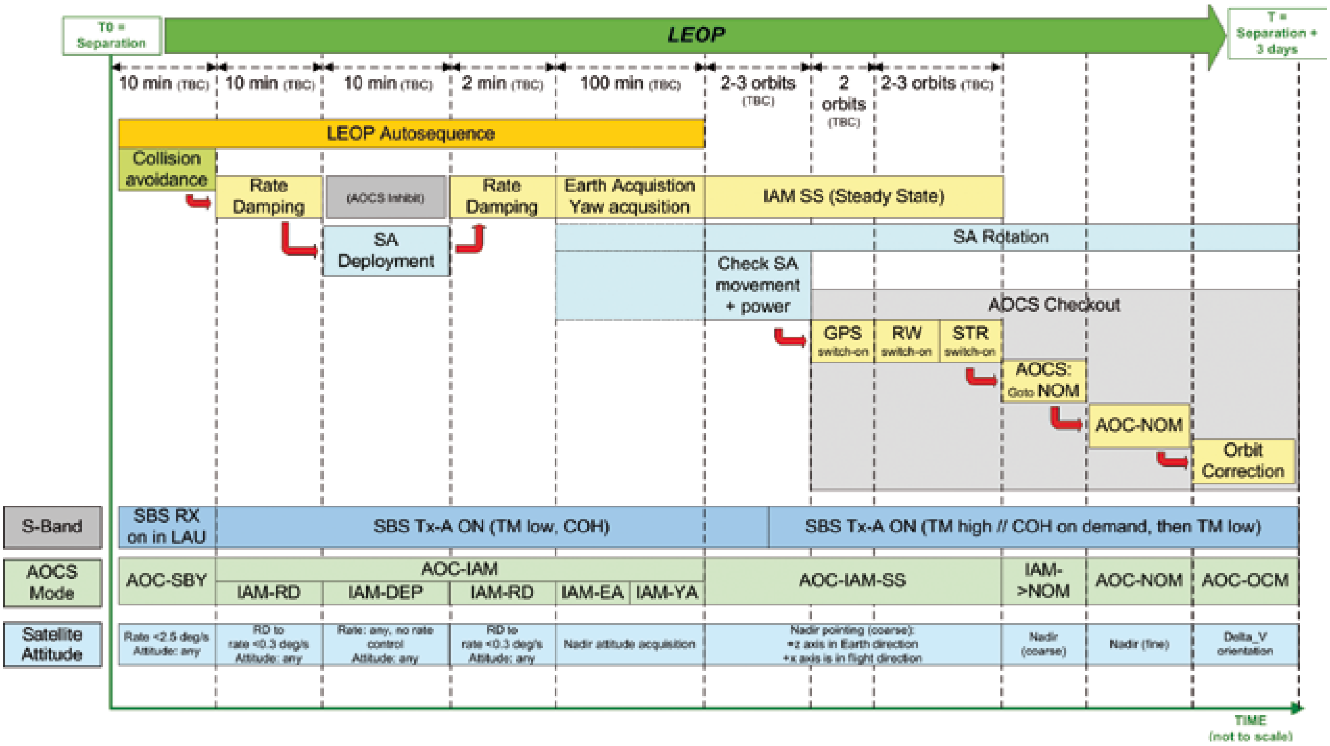
Following a successful Flight Acceptance Review, and pending the readiness of the Ground Segment to conduct system operations and mission exploitation, each Sentinel-2 satellite will be transported to the launch site for final integration, validation and preparations for launch, including fuelling. These activities will be performed by a joint team led by ESA and involving the industrial Prime Contractor and core team partners and will last about two months. Following lift-off, the launcher will inject the satellite into its operational orbit.

5.2 Early Orbit Phase

Following separation of the satellite from the launcher upper stage, an automatic sequence piloted by the onboard software will deploy the three panels of the solar array, initiate the rotation of the solar array drive mechanism, and initialise the acquisition of the satellite local normal pointing so that the satellite can be operated by the Flight Operations Segment at ESOC. The S-band transponder will also implement a ranging function to determine the satellite orbit precisely prior to the full operation of the onboard GPS receiver. This critical phase will only last a few orbits prior to initiating the satellite switch-on and in-orbit verification phase.

Figure 5.1 provides a timeline for the Launch and Early Orbit Phase (LEOP).

Figure 5.1. Sentinel-2 satellite LEOP timeline.



5.3 Switch-on and Verification

Following a successful LEOP, the satellite functions will be incrementally switched on and functionally verified. The satellite attitude and orbit control, telecommunication links, and the thermal equilibrium of the satellite will be characterised. After the payload instrument switch-on and health characterisation, the first images will be acquired and processed simultaneously by the Level-1c Ground Prototype Processor (GPP) and by the PDGS Operational Processor. Data performance and quality indicators will be derived from these measurements and performance comparisons between the PDGS and the GPP will be carried out to confirm their compliance with mission requirements and to derive a strategy for periodic instrument in-orbit and ground processing characterisation.

Following the satellite and ground segment functional verification, calibration and performance characterisation, the In-orbit Commissioning Review will decide whether to release operationally the Sentinel-2 system. From that moment, the Sentinel-2 Mission Manager will be responsible for the operational phase of the mission.

6. Sentinel-2 Image Quality

The Sentinel-2 products will take advantage of the stringent radiometric and geometric image quality requirements. These requirements constrain the stability of the platform and the instrument, the ground processing and the in-orbit calibration. Table 6.1 shows the spectral band characteristics and the required signal-to-noise ratios for the reference radiances (L_{ref}) defined for the mission. An accurate knowledge of the band equivalent wavelength is very important as an error of 1 nm can induce errors of several percent on the reflectance, especially in the blue part (atmospheric scattering) and the near-infrared part of the spectrum (vegetation red edge). The equivalent wavelength therefore needs to be known with an uncertainty below 1 nm.

Obtaining a physical value (radiance or reflectance) from the numerical output provided by the instrument requires knowledge of the instrument sensitivity. Any error on the absolute calibration measurement will directly affect the accuracy of this physical value. This is why a maximum 5% absolute calibration knowledge uncertainty was required for the mission, with an objective of 3%. In the same way, the cross-band and multitemporal calibration knowledge accuracies were set to 3% as an objective and 1%, respectively. Moreover, the nonlinearity of the instrument response will be known with an accuracy of better than 1% and will have to be stable enough that the detector non-uniformity can be calibrated at two radiance levels in flight.

The system MTF is specified to be higher than 0.15 and lower than 0.3 at the Nyquist frequency for the 10 m and 20 m bands, and lower than 0.45 for the 60 m bands.

The geometric image quality requirements are summarised in Table 6.2. The accuracy of the image location, 20 m without ground control points (GCPs), is very good with regard to the pixel size and should be sufficient for most applications. However, from the Level-1 processing description, most of the Sentinel-2 images will benefit from GCPs and will satisfy the 12.5 m maximum geolocation accuracy.

The main instrument performance specifications are recalled in Table 6.3, with an example representing the spectral performance measured using the EM filter programme shown in Fig. 6.1, and the MultiSpectral Instrument spectral requirements in Table 6.4.

Table 6.1. Spectral bands and signal-to-noise ratio requirements for the Sentinel-2 mission.

Band number	Central wavelength (nm)	Bandwidth (nm)	Spatial resolution (m)	L_{ref} (W m^{-2} sr^{-1} μm^{-1})	SNR @ L_{ref}
1	443	20	60	129	129
2	490	65	10	128	154
3	560	35	10	128	168
4	665	30	10	108	142
5	705	15	20	74.5	117
6	740	15	20	68	89
7	783	20	20	67	105
8	842	115	10	103	174
8b	865	20	20	52.5	72
9	945	20	60	9	114
10	1380	30	60	6	50
11	1610	90	20	4	100
12	2190	180	20	1.5	100

Table 6.2. Sentinel-2 geometric image quality requirements.

Geometric image quality requirements	Ground processing hypothesis
A priori accuracy of image location: 2 km max (3σ)	No processing
Accuracy of image location: 20 m (3σ)	After image processing without GCPs
Accuracy of image location: 12.5 m (3σ)	After image processing with GCPs
Multitemporal registration: 3 m (2σ) for 10 m bands 6 m (2σ) for 20 m bands 18 m (2σ) for 60 m bands	After image processing with GCPs
Multispectral registration for any pair of spectral bands: 3 m (3σ) for 10 m bands 6 m (3σ) for 20 m bands 18 m (3σ) for 60 m bands	After image processing with GCPs

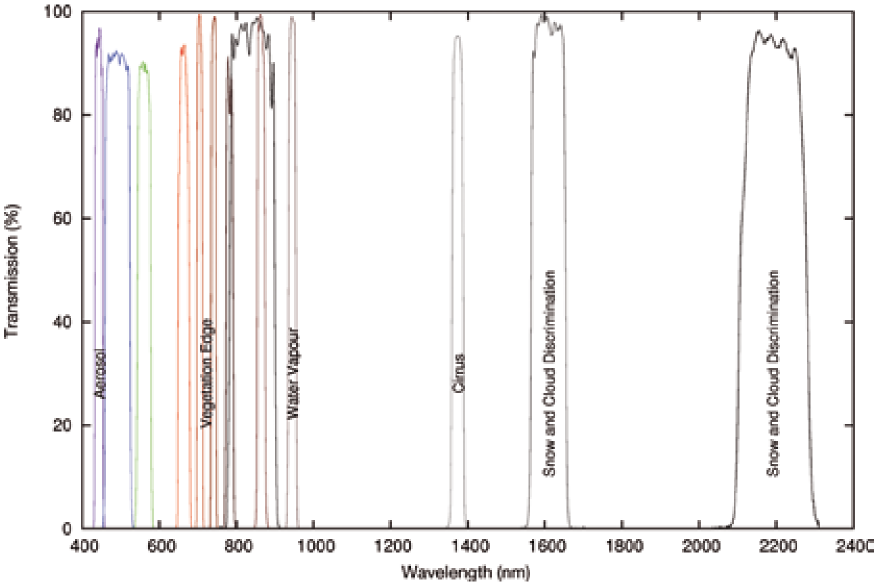


Figure 6.1. Filter transmission of the flight model for Sentinel-2 MSI bands.

Table 6.3. MultiSpectral Instrument performance specifications.

	Specifications
SNR	See Table 6.1
Spectral performance	See Fig. 6.1
Rejection	For any spectral channel and at any radiance level between $L_{\min}$ and $L_{\max}$, the out-of-band integrated energy, as defined by the following equation, shall be less than 1% and 5% at the wavelengths indicated as $\lambda_{\min 1\%}$, λmax1%, and λmin5%, λmax5%, respectively, specified in Table 6.4: $$1-\frac{\int_{\lambda_{\min 1\%}}^{\lambda_{\max 1\%}} L(\lambda)R(\lambda)d\lambda}{\int_{0.3\mu m}^{20\mu m} L(\lambda)R(\lambda)d\lambda} < 0.01 \text{ and } 1-\frac{\int_{\lambda_{\min 5\%}}^{\lambda_{\max 5\%}} L(\lambda)R(\lambda)d\lambda}{\int_{0.3\mu m}^{20\mu m} L(\lambda)R(\lambda)d\lambda} < 0.05$$
Cross-talk	The channel-to-channel cross-talk shall be less than 0.5%.
MTF	The system MTF, at the Nyquist frequency, shall be higher than 0.15 and lower than 0.30, both across-track and along-track, for the spectral bands at 10 m and 20 m SSD (smoothing by spectral dispersion), and not higher than 0.45 for the spectral channels at 60 m SSD. MTF curves over the entire frequency range shall be calculated.
Absolute radiometric accuracy	The absolute radiometric accuracy should be 3% (goal)/5% (threshold).
Inter-band calibration accuracy	The inter-band calibration accuracy shall be 3%.
Geolocation	The geolocation accuracy of Level-1c data with reference to a reference map shall be ≥20 m at 2σ confidence levels without the need for any ground control points.

Table 6.4. MultiSpectral Instrument spectral requirements.

Band	Centre λ_{centre} (nm)	Spectral width, Δλ (nm)	Stability of λ_{centre} (± nm)	Stability of spectral width (± nm)	Knowledge of λ_{centre} (± nm)	Knowledge of spectral width (± nm)	Min 5% $\lambda_{\text{min5\%}}$ (nm)	Max 5% $\lambda_{\text{min5\%}}$ (nm)	Min 1% $\lambda_{\text{min5\%}}$ (nm)	Max 1% $\lambda_{\text{min5\%}}$ (nm)
B 1	443	20	3.0	2.0	0.2	0.2	418.7	467.3	413.7	472.3
B 2	490	65	5.0	2.5	0.5	0.5	430.1	549.9	425.1	554.9
B 3	560	35	5.0	2.0	0.5	0.5	515.2	604.8	510.2	609.8
B 4	665	30	5.0	1.5	0.5	0.5	622.8	702.2	617.7	707.2
B 5	705	15	3.0	1.5	0.2	0.2	680.0	717.0	675.0	722.0
B 6	740	15	3.0	1.5	0.2	0.2	725.0	758.0	720.0	760.0
B 7	783	20	5.0	2.0	0.5	0.5	745.7	807.3	740.7	812.3
B 8	842	115	5.0	5.0	0.5	0.5	764.5	919.5	752.2	926.8
B 8a	865	20	5.0	2.0	0.2	0.2	835.0	895.0	822.7	902.3
B 9	945	20	5.0	2.0	0.2	0.2	907.7	977.3	902.7	982.3
B 10	1375	30	5.0	5.0	0.5	0.5	1342.6	1407.5	1337.6	1412.5
B 11	1610	90	10.0	10.0	1.0	1.0	1546.0	1685.0	1532.0	1704.0
B 12	2190	180	10.0	10.0	1.0	1.0	2045.0	2301.0	2035.0	2311.0

7. Sentinel-2 Level-1 Processing

As the Sentinel-2 mission objectives emphasise the potential of data time series, the basic Level-1 products must be geometrically registered and radiometrically calibrated. This has led to the following product definitions: Level-0 and Level-1a products provide raw compressed and uncompressed data, respectively. Level-1b data are radiometrically corrected radiances. The physical geometric model is refined using available ground control points and appended to the product but not applied.

The Level-1c product provides geocoded top-of-atmosphere TOA reflectance with sub-pixel multispectral and multi-date registration. Cloud and land/water masks are associated with the product. The cloud mask also provides an indication of the presence of cirrus clouds. These masks are based on threshold tests using the spectral information obtained from the MultiSpectral Instrument. The ground sampling distance of Level-1c products is 10 m, 20 m or 60 m, depending on the band (see Table 6.1). The Level-1c unitary product is a tile of 100×100 km. Users will receive as many tiles as necessary to cover their requested area.

Figure 7.1 presents the data processing workflow up to and including Level-1C.

Sentinel-2 data products will follow the recommendations of Quality Assurance Framework for Earth Observation (QA4EO) agreed by the Committee on Earth Observation Satellites (CEOS, 2010). Performance traceability and radiometric and geometric quality indices will be provided with the ancillary product data. A schematic overview of Level-1 processing is shown in Fig. 7.1.

For the SWIR bands, the detector module is made up of three lines for band B10 and four lines for bands B11 and B12. In order to make optimal use of the pixels with the best SNR for the acquisition, for each column we select one pixel over three lines for B10 and two successive pixels over four lines for B11 and B12 as these bands work in Time Delay Integration (TDI) mode. At ground level, a rearrangementof the SWIR pixels is performed by shifting the columns of the

Figure 7.1. Level-1 data processing chart.

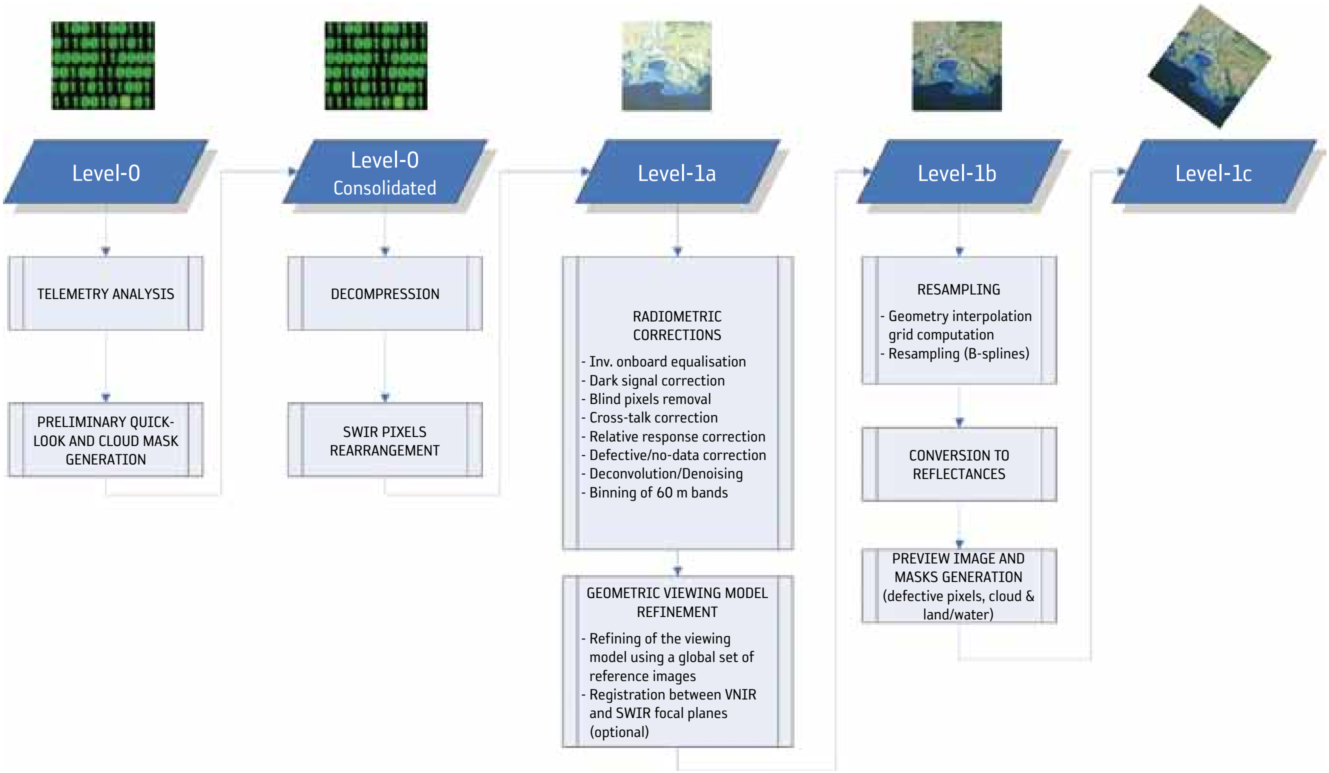


image according to the relative position of the selected pixels. A simple pixel rearrangement along columns in the image is performed thanks to Earth rotation compensation by the satellite yaw steering. For the normalisation a dark signal and photo-response non-uniformity correction is applied, including a dynamic offset correction for each detector module thanks to blind pixels.

Despite a very demanding cross-talk specification, the high radiance dynamics specified for Sentinel-2 may induce defects that need to be corrected. This phenomenon, mainly driven by the electronics, will be completely characterised and modelled before launch. For defective pixels (specified as less than 0.1% of pixels) a correction may have to be applied. The image restoration combines deconvolution to correct the instrument MTF (frequency-domain processing) and denoising based on a wavelet processing. When the denoising is not necessary, it is automatically deactivated through a noise level threshold. For the 60 m bands data are binned as the spatial resolution acquired across the track is 20 m because of the pixel size.

The goal of the geometric correction is to perform the temporal and spectral registration of all the images taken over any target. To achieve this objective, the physical geometric model, which associates a viewing direction to any pixel, has to be refined. This physical geometric model combines position, attitude and date information, transformation matrices between different reference frames – satellite, instrument, focal planes and detectors – and for each pixel of each elementary detector of each band a viewing direction is defined. An automatic correlation processing between a reference band of the image to be refined and a reference image provides ground control points, allowing the calibration online of the viewing model and correcting for variations in attitude or position or thermoelastic deformation. This refined geometrical model is then applied to all the bands and is used to project them onto a cartographic reference frame.

The reference image will be part of a worldwide georeferenced database of Sentinel-2 mono-spectral images that will be gradually built up from cloud-free scenes. The georeferencing of all the images is performed through a global space-triangulation process using tie points between the different images and GCPs. Because of the parallax between odd and even detector modules, and between bands, the registration is sensitive to the Digital Elevation Model (DEM) used for the processing. A Shuttle Radar Topography Mission (SRTM; Farr et al., 2007) class DEM is necessary to reach the required performance. It is planned to use the SRTM DEM, complemented at higher and lower latitudes with DEMs such as the Canadian National DEM, the Greenland Geoscience Laser Altimeter System (GLAS) DEM (Di Marzio et al., 2007), the National Elevation Dataset (NED; Gesch et al., 2009), and corrected in specific areas where the SRTM presents artefacts (e.g. over the Himalayas).

For the resampling two steps are combined. First, a geometric process computes the grid that gives for each point of the output image its location in the focal plane, and second, a radiometric process computes for each point of the grid its radiometry using spline interpolation functions. The inversion of the radiometric model provides the TOA reflectance taking into account the camera sensitivity. Finally, cloud (opaque/cirrus) and land/water masks are computed based on spectral criteria.

8. Prototyping of Level-2 Products: Cloud Screening and Atmospheric Corrections

The Sentinel-2 Payload Data Ground Segment will offer additional data processing options, through a software toolbox to be made available to users, to derive bottom-of-atmosphere (BOA) reflectance (Level-2a) and enhanced cloud masks from the top-of-atmosphere reflectance (Level-1c). The Sentinel-2 atmospheric correction is being developed based on algorithm proposed in the Atmospheric/Topographic Correction for Satellite Imagery (ATCOR; Richter and Schlaepfer, 2011).

The method performs atmospheric correction based on the libRadtran radiative transfer model (Mayer and Kylling, 2005). The model is run once to generate a large look-up table (LUT) that accounts for a wide variety of atmospheric conditions, solar geometries and ground elevations. This LUT is used as a simplified model (running faster than the full model) to invert the radiative transfer equation, and to calculate BOA reflectance. All gaseous and aerosol properties of the atmosphere are either derived by the algorithm itself or fixed to an a priori value. The aerosol optical thickness and water vapour content are derived from the images themselves.

The algorithm also generates an enhanced cloud mask and scene classification compared with the one generated through the Level-1c processing. Figure 9.1 provides an example of simulated Sentinel-2 data before and after atmospheric correction.

9. Sentinel-2 Applications and Products

Observations from the Sentinel-2 mission will be used by three GMES service elements, namely Geoland-2, Services and Applications for Emergency Response (SAFER) and GMES services for Management of Operations, Situation Awareness and Intelligence for regional Crises (G-MOSAIC). The mission has been designed to fulfil their user requirements for a number of operational applications summarised in this chapter. Figure 9.1 visualises a cloud correction process on simulated Sentinel-2 data.

9.1 Geoland-2

The pre-operational land service of GMES is currently provided through the EU FP7 project Geoland-2 (*www.gmes-geoland.info*). The Geoland-2 project aims to provide geoinformation data at regional, European and global scales, and covers a wide range of thematic domains organised into three core mapping services and seven core information services:

- The European Land Monitoring Service (Euroland) addresses the local (Urban Atlas) and continental components (high spatial resolution land-cover parameters and land-cover change) of the Land Monitoring Core Service (LMCS).
- The Biogeophysical Parameter (BioPar) service has established pre-operational infrastructures for providing an extensive range of parameters characterising Europe's vegetation, energy budget and water cycle.
- The Seasonal and Annual Change Monitoring (SATChMo) service aims to close the gap between low- and high-resolution global coverage by providing seasonal to annual Europe-wide coverage of physical properties describing biogeophysical information parameters such as land cover (LC) and land-cover change (LCC). Products will be delivered in the form of indicators, maps and statistics. SATChMo will deliver products less frequently but with more spatial detail than BioPar, and more frequently but with less spatial and thematic detail than Euroland.

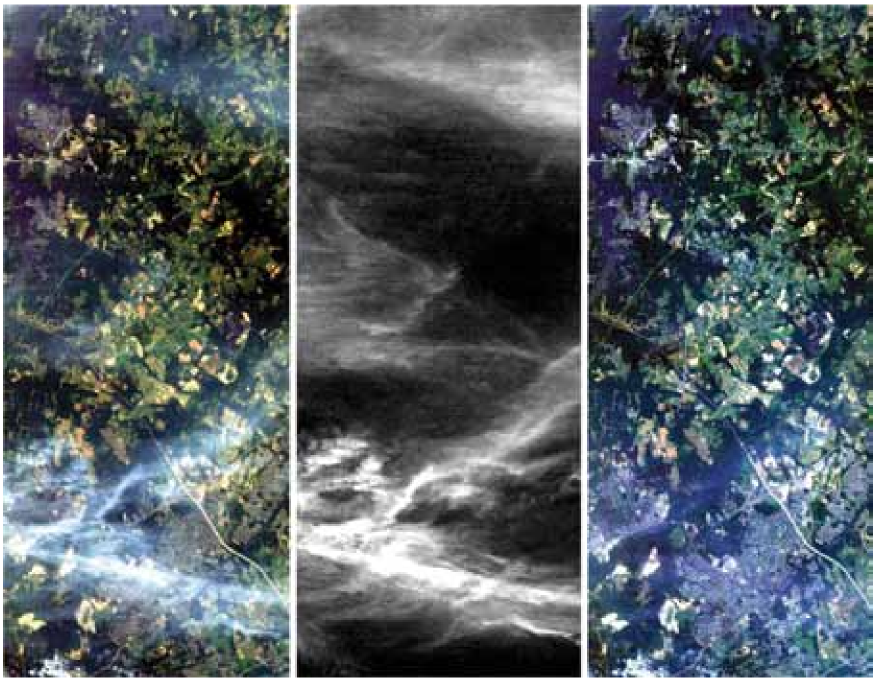


Figure 9.1. Simulated Sentinel-2 scene containing cirrus clouds. True colour coding: red/green/blue = bands 4/3/1 (665, 560 and 443 nm). *Left:* Original scene; *centre:* cirrus band (1.375 μm); *right:* after cirrus detection and atmospheric correction. (Data simulation, DLR Germany; Aviris data supply, NASA/JPL, USA)

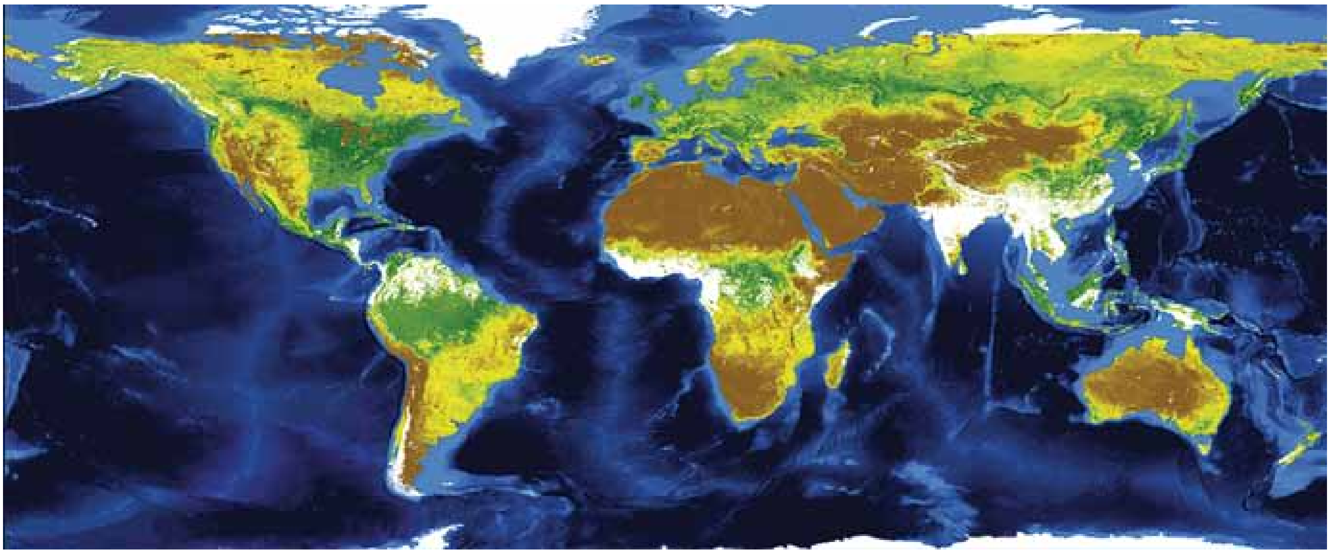


Figure 9.2. Leaf Area Index map derived from SPOT/Vegetation data for July 2002. (CNES France, Lacaze et al., 2010)

— The seven core information services are: spatial planning, agro-environmental monitoring, water monitoring, forest monitoring, land carbon, natural resource monitoring in Africa and global crop monitoring.

The first results from the Geoland2 BioPar core mapping service have been obtained using SPOT/Vegetation and Envisat/MERIS (Medium-Resolution Imaging Spectrometer) Full Resolution (FR) data (Lacaze et al., 2010). One prototype algorithm for Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) and Fraction of Vegetation Cover (fCover) data is based on observations from the Vegetation sensors that have been atmospherically corrected using the SMAC code (Baret et al., 2007). The resulting nadir view top-of-canopy reflectance data are used in a neural network to retrieve geophysical products. The neural network has been trained using data produced with the SAIL+PROSPECT radiative transfer models. This methodology is very similar to the Level-2 processing envisaged for Sentinel-2.

A full processing line for LAI products has been established at CNES within the framework of the Cyclopes project (FP7). Figure 9.2 shows a global map of LAI for July 2002, which was produced by CNES as part of a two-year global data set (Lacaze et al., 2010).

Infoterra France has developed a processing line to produce biophysical variables from MERIS FR data. Again, the core component of the algorithm is based on the SAIL+ PROSPECT model (Verhoef, 1984). The processing chain has been operated in offline mode and the existing MERIS FR (300 m spatial resolution) products now cover several European river basins (Rhine, Seine–Normandie, Guadalquivir, Adour–Garonne, Nemunas, Moselle–Sarre, Motala–Ström, Sventoji and Strymonas–Struma) for years of major interest to final users. As an example, Fig. 9.3 (from Lacaze et al., 2010) shows fAPAR over Europe as derived from MERIS FR data. The values vary from 0 (white) to 1 (red).

Sentinel-2 will make a significant contribution to land monitoring services by providing both land-cover/land-cover change maps and estimates of biogeophysical parameters based on frequent and systematic coverage.

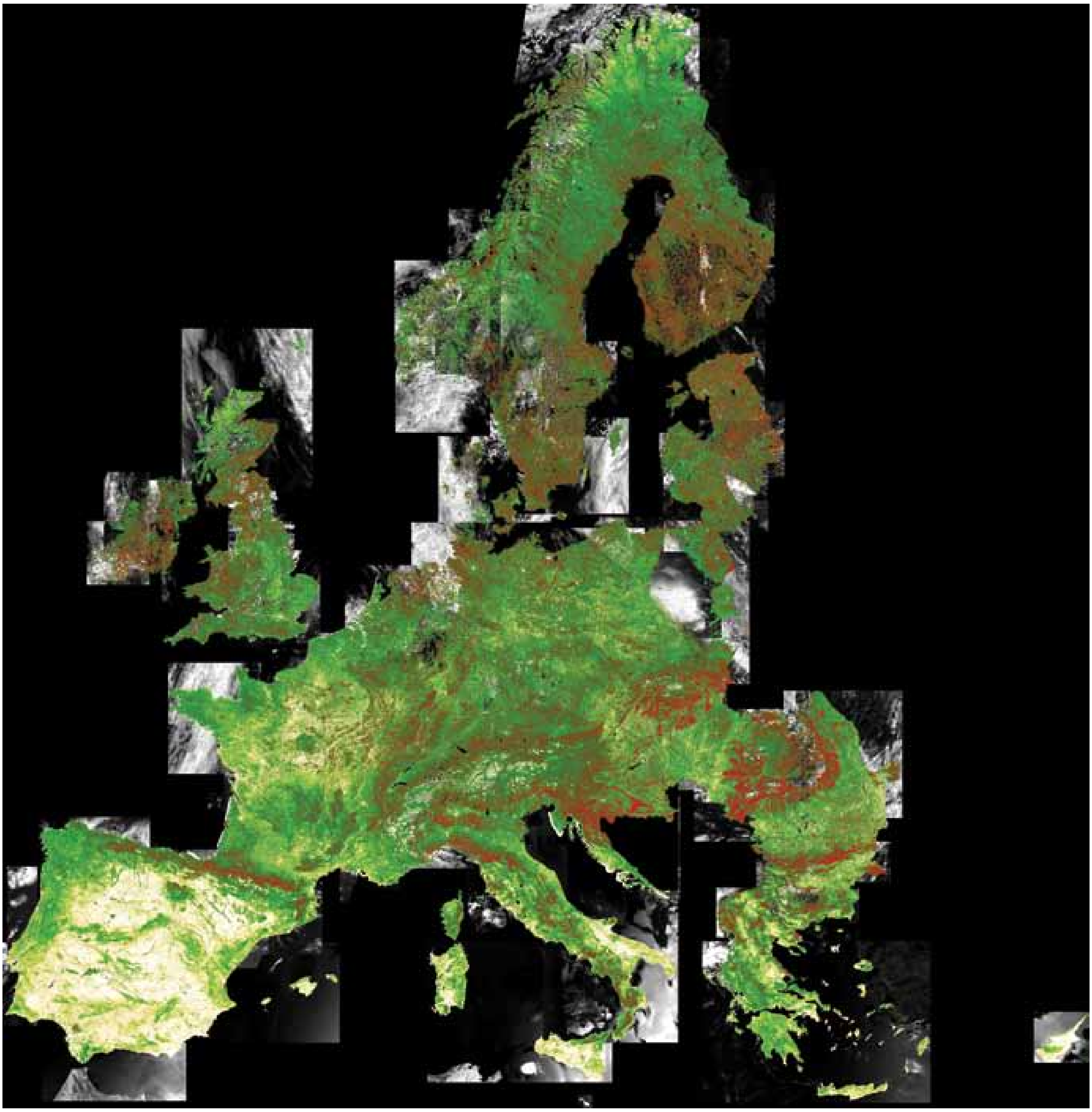


Figure 9.3. Map of Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), July 2011, as derived from MERIS FR data. The values vary from 0 (white) to 1 (red). (Astrium GmbH, Germany)

9.2 SAFER, RISK-EOS and Respond

The GMES SAFER project addresses potentially all types of disasters or crises: natural disasters (floods, fires, landslides, storms, earthquakes, etc.), technological accidents, humanitarian crises (for instance after a period of severe drought), and civil or military crises.

In recent years European institutions have funded numerous projects in the domain of emergency management, paving the way towards a pre-operational GMES service. These include projects such as RISK-EOS (*www.riskeos.com*) and Respond. Started in 2003, RISK-EOS aims to deliver operational geoinformation services to support the management of meteorological hazards such as floods, forest fires and, to a lesser extent, other natural hazards throughout all phases of disaster reduction, including prevention, early warning, crisis and post-crisis. The RISK-EOS services combine the use of satellite observation data (some provided in near-real time) with exogenous data and modelling techniques. The services are targeted to meet the needs of risk management agencies (for civil protection, firefighting and rescue services, land planning and risk prevention) at European, national and regional levels.

Another objective related to crisis management is to increase the efficiency and effectiveness of the European and international humanitarian community through the appropriate and reliable application of geographic information. The main target users of the GMES Services Element (GSE) project Respond are:

- the European Commission, in particular the European Community Humanitarian Office (ECHO), the DG for External Relations (RELEX) and the DG Environment Monitoring Information Centre (ENV/MIC);
- the United Nations, e.g. the UN Office for Coordination of Humanitarian Affairs (OCHA), the UN High Commissioner for Refugees (UNHCR), and the UN Department of Peacekeeping Operations (UNDPKO); and
- the International Committee of the Red Cross and other non-governmental organisations.

Respond will provide information for preparedness (pro-active) and for relief activities (reactive), and will support both slow and fast onset crises (e.g. famine – slow, and earthquake – fast). Geographic information has proven useful to organisations working in this arena for a large variety of purposes, from ensuring the rapid deployment of relief services following a disaster, to the planning of reconstruction and development activities for long-term recovery.

Sentinel-2 will make a significant contribution to disaster management services by providing recent synoptic views of an area affected by a disaster before it occurred and updated synoptic views to support disaster relief activities.

9.3 G-MOSAIC

The pre-operational security service of GMES is currently provided through the FP7 project G-MOSAIC (GMES Services for Management of Operations, Situation Awareness and Intelligence for Regional Crises; *www.gmes-gmosaic.eu*) and the FP6 project LIMES (Land and Sea Integrated Monitoring for European Security; *www.fp6-limes.eu*). These two projects, which combine Earth observation with communication and positioning technologies, address the following services:

- maritime surveillance (e.g. sea border surveillance within and outside Europe, illegal immigration and trafficking surveillance, sea lane safety/ piracy/ sensitive cargoes);
- infrastructure surveillance (e.g. land border surveillance, critical infrastructure); and
- support to peacekeeping, intelligence and early warning, and crisis management operations.

Before G-MOSAIC and LIMES, European institutions funded several projects dealing with different aspects of security, such as the Global Monitoring for Food Security project (GMFS; *www.gmfs.info*). GMFS services are tailored to meet the information requirements of specific core users and currently include two applications: continental-scale continuous monitoring of the status of vegetation in Africa by analysing long-term Earth observation time series data (usually on a 10-day basis); national monitoring, supplying detailed information on major food crops, such as planting dates and the extent of cultivation. These products are delivered once or twice per growing season.

Another important aspect of the service is in-situ data collection, including field data used for validation purposes and as inputs for agro-meteorological modelling. With its frequent and systematic coverage, Sentinel-2 will make a significant contribution to food security services.

9.4 Sentinel-2 Data Contributions

For the applications outlined above, a number of data sets will be produced on an operational basis either by ESA or the service elements. The baseline for the geophysical parameters is the bottom-of-atmosphere reflectance Level-2a product, corrected for atmospheric, adjacency and slope effects. Potential Level-2b products include generic maps of land cover, fraction of absorbed photosynthetically active radiation, leaf area index, fraction of vegetation cover, leaf chlorophyll content and leaf water content.

Additional Level-2b products that may be considered include maps of the fraction of non-photosynthetically active vegetation, surface albedo, burn scars, fuel load, structural fire risk indices, crown density, forest age, flood monitoring data, land-cover change detection and snow cover maps.

10. Sentinel-2 Calibration and Validation

The Sentinel-2 Calibration and Validation (Cal/Val) phase corresponds to the process of updating and validating onboard and on-ground configuration parameters and algorithms to ensure that the data product quality requirements are met. To meet the baseline product quality requirements, a well-defined Cal/Val plan will be systematically applied.

Cal/Val activities will be carried out in coordination and cooperation with other CEOS partners and, in line with the quality assurance guidelines endorsed by CEOS, the Quality Assurance Framework for Earth Observation (QA4EO). Further information about CEOS and QA4EO can be found at *www.ceos.org* and *http://qa4eo.org*, respectively.

10.1 Radiometric Calibration

This section outlines the operations applicable to the radiometric Cal/Val.

First, dark-signal assessment will be performed using images acquired over oceans at night. This will allow determination of the radiometric calibration parameters for removing the offset due to dark current. This operation will be automatic and data-driven based on the reception of the dark-signal calibration data that will be commanded every two weeks during the operational phase. Such acquisitions will be optimised so as to cover areas without luminescent plankton (such as the South Pacific CEOS test site) and to avoid full Moon conditions.

Second, detector relative sensitivities will be determined through the following operations:

- Onboard Sun-diffuser images acquired by the instrument will be used to determine the radiometric equalisation parameters for inter-pixel calibration (onboard and on the ground). This operation will be data-driven on reception of absolute calibration data with the Calibration and Shutter Mechanism (CSM) in the Sun-diffuser position that will be commanded every four weeks (Fig. 10.1).
- Images acquired over ground uniform areas (e.g. Greenland, Dome-C in Antarctica). In principle, this calibration operation will be triggered only during Phase-E1 (commissioning phase) for onboard diffuser validation, and on a contingency basis during Phase-E2 (operational phase). It will not be automated, but will be carried out when required by an expert Cal/Val team after appropriate commanding of specific image acquisitions in nominal mode.

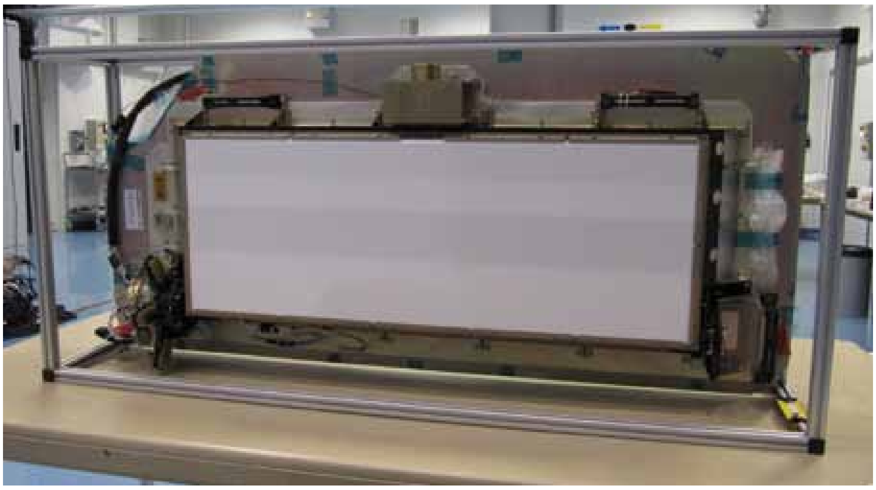


Figure 10.1. MSI Calibration and Shutter Mechanism showing the Sun calibration diffuser. (Sener, Spain and CSL, Belgium)

Third, the absolute radiometric calibration parameters will be determined through the following operations:

- Calibration using onboard Sun-diffuser images will be data-driven on reception of absolute calibration data that will be performed every four weeks reusing the predefined planning outlined for the detector relative sensitivities determination.
- Various Cal/Val based on image acquisitions over specific areas such as snow-covered sites (e.g. Dome-C in Antarctica), instrumented Cal/Val sites from the CEOS network (e.g. Tuz Gölü in Turkey or La Crau in France), and desert sites (e.g. the Libyan desert) for cross-calibration with other sensors and for monitoring temporal stability.
- Inter-band calibration through the processing of Sun-glint measurements. During operations, this will only be done to consolidate and monitor the calibration performed during the commissioning phase.
- Refocusing of the instrument by varying the M3 mirror temperature. During commissioning or operations, this calibration will be performed only in case of contingency.

10.2 Geometric Calibration

During operations, geometric calibration will mainly involve updating the Global Reference Images (GRIs) used to meet multitemporal registration requirements. Calibration will be complemented with a set of activities that will be triggered in case of contingency, and a validation plan to check that user requirements are being met. Contingency geometric calibration will include corrections:

- between reference frames (steered/camera), to be performed during operations only in case of contingency; and
- between detector reference frames, to be done only during the commissioning phase and only in case of contingency during operations.

The validation of the geometric performance will be performed during commissioning and subsequently on a yearly basis, and will include:

- geolocation accuracy assessment using reference sites with geometric patterns and for which geometry is mastered;
- multitemporal registration assessment using image correlation techniques; and
- multispectral registration assessment using correlations between images of different bands.

10.3 Atmospheric Corrections

For atmospheric correction and cloud screening algorithms, the calibration of the algorithms and the validation of the obtained products (bottom-of-atmosphere reflectance, aerosol optical thickness and water vapour content) will be performed using a series of test sites that are representative of main surface–atmosphere types.

For a quantitative validation, these sites will include the Landnet sites – the set of Land Equipped Sites (LES) endorsed by CEOS as standard reference sites for the calibration of space-based optical imaging sensors. In addition, ad hoc validation campaigns involving airborne, balloon and ground measurements will be organised.

Further information about the test sites mentioned above, and the CEOS Cal/Val activities, can be found at *http://calvalportal.ceos.org*.

11. Sentinel-2 Pre-flight Campaigns

One of the most important aspects of developing an Earth observation mission is to ensure that the eventual data meet the exacting requirements of various users. Considerable efforts are therefore put into pre-flight campaigns to evaluate the future performance of a mission. In order to meet this objective, airborne and ground measurements have to be acquired so that the final data products can be simulated and evaluated.

In order to support of the development of Sentinel-2 mission, in 2007 ESA organised the CEFLES2 campaign, which involved CarboEurope, the Fluorescence Explorer (FLEX) and Sentinel-2. The CEFLES2 campaign allowed participants from France, Germany, Italy, the Netherlands and Spain to exploit the synergies between the large collections of airborne and ground measurements performed in coordination with the CarboEurope Regional Experiment Strategy (CERES).

The main CEFLES2 campaign site is located within the CERES experimental area in Gascony, southwest France, with additional airborne acquisitions taken over Madrid, Spain, and the Mediterranean coast. The first set of measurements was acquired between April and June 2007 and a second set in September 2007, so that different stages of crop growth were represented. The aim was to obtain reference datasets (including simulated Sentinel-2 imagery; see Fig. 11.1) to address the specific needs of the development activities for Sentinel-2.

The objective of the CEFLES2 campaign was to collect high-quality, coordinated airborne optical and in-situ measurements. Hundreds of kilometres of airborne imagery over many types of landscape have been acquired, along with a complete set of ground measurements taken by a consortium of European laboratories. This campaign generated a unique dataset that has contributed to the consolidation of the Sentinel-2 mission specifications (e.g. for the determination of the optimum compression ratios per spectral band) and to the definition of Level-1 and Level-2 processing algorithms.

Figure 11.1. *Left:* Natural colour 'quick-look' image of one of the CEFLES2 test areas in France, taken from an INTA CASA 212-200 aircraft with Airborne Hyperspectral Scanner (AHS) and SIM.GA HYPER imaging sensors. Some of the ground-measured fields are outlined in red. (Instituto Nacional de Técnica Aerospacial, INTA, Spain)
Right: Taking ground reflectance measurements over a bare field during the CEFLES2 campaign. (Forschungszentrum Jülich, Germany)

12. Conclusions

Sentinel-2 has been designed to support GMES land, emergency and security applications, namely Geoland2, SAFER and G-MOSAIC. The Sentinel-2 wide-swath high-resolution MultiSpectral Instrument system will ensure the continuity of the SPOT and Landsat series of multispectral observations. With improved revisit times, area of coverage, spectral bands, swath width, radiometric and geometric image quality, Sentinel-2 will make a significant contribution to the fulfilment of GMES needs in terms of the delivery of information products for operational land and emergency services.

The five-day revisit time achieved with two satellites in orbit and an instrument swath width of 290 km will make it possible to monitor rapid changes in the environment, in particular vegetation cover, and provide access to areas with high cloud coverage that are currently not well covered by high-resolution multispectral missions. The MSI's 13 spectral bands will provide valuable information that will be used to improve the accuracy of land-cover maps and to retrieve geophysical parameters, in particular for vegetation, thanks to the red-edge bands. Ambitious targets have been set for radiometric and geometric performance, and test results from the MSI EM programme confirm the good quality of the instrument.

Following the MSI and satellite system Critical Design Reviews conducted in autumn 2010, the two models of the MSI and satellite platform are currently being manufactured, integrated and tested. The first engineering and flight equipment already delivered are being integrated and tested, including engineering models of the Video and Compression Unit, front-end electronics, the Onboard Computer and GPS receiver and flight models of the mirrors, the SiC telescope baseplate, the detectors and the propulsion subsystem.

The first satellite, Sentinel-2A, is expected to be launched in late 2013, and Sentinel-2B about 18 months later.

→ APPENDICES

Appendix A: Members of the Sentinel-2 Industrial Consortium

Satellites Platform procurement and AIT, mass memory, Coarse Earth and Sun Sensors, propulsion	Prime Contractor: Astrium GmbH (Germany)
MultiSpectral Instrument Inertial Measurement Unit, beam splitter and VNIR detectors	Astrium SAS (France) with the support of ISAE (France) and e2v Technologies (UK) for the VNIR detectors
Platform structure, thermal hardware and harness	Casa Espacio (Spain)
Power conditioning and distribution unit, instrument front-end electronics	CRISA (Spain)
Mission analysis	GMV (Spain)
GPS receiver	RUAG (Austria)
Onboard Computer, S-band and GPS antennas	RUAG (Sweden)
Solar Array Drive Mechanism	RUAG (Switzerland)
Remote interface unit	Patria (Finland)
X-band subsystem, S-band transponder	Thales (Spain)
X-band antenna	Thales (Italy)
Reaction wheels	Bradford Engineering (Netherlands)
Star sensors, Video and Compression Unit, optical filters	Jena-Optronik (Germany) with the support of Optics Balzers Jena (Germany) and Materion/Barr (USA) for optical filters
Magnetometers and magnetorquers	ZARM (Germany)
Miniature Inertial Measurement Unit	Honeywell (USA)
Batteries	ABSL (UK)
Software support	Critical Software (Portugal)
Independent software verification and validation	Rovsing (Denmark)
Mechanical Ground Support Equipment (MGSE) for the instrument primary and secondary structure and the satellites	APCO (Switzerland), with the support of Iberespacio (Spain) and Xperion (Germany)
Electrical Ground Support Equipment (EGSE)	SSBV (Netherlands), Siemens (Austria), Clemessy (Italy)
MGSE	Sermati (Canada)
Silicon carbide telescope and mirrors	Boostec (France)
Mirror polishing	AMSO (Belgium)
Calibration and shutter mechanism	Sener (Spain)
SWIR detectors	Sofradir (France)
Telescope metallic hardware	Admatis (Hungary)
Instrument harness	Latelec (France)
Ground prototype processor	ACS (Italy)
Data decompression software	Magellium (France)
Satellite environmental test facilities at ESTEC	ETS (Germany, France)

Appendix B: Associated Industrial Partners

Launch service providers	Eurockot (Germany, nominally for Sentinel-2A) and Arianespace (France, nominally for Sentinel-2B)
Optical Communication Payload (in-kind contribution of DLR to the Sentinel-2 programme)	Tesat GmbH (Germany), with significant contributions from RUAG (Switzerland)

Appendix C: The Sentinel-2 system

Mission objectives

European wide-swath high-resolution twin satellites super-spectral imaging mission designed for data continuity and enhancement of Landsat and SPOT-type missions, for GMES operational land and security services. Applications include:

- Land cover, usage and change detection maps
- Geophysical variable maps (leaf chlorophyll content, leaf water content, leaf area index, etc.)
- Risk mapping
- Fast images for disaster relief

Mission profile

- Launch: 2013, Launcher: Vega or Rockot
- Lifetime: 7.25 years (consumables 12 years)
- Sun-synchronous orbit at 786 km mean altitude
- Mean Local Time at Descending Node: 10:30
- Global revisit time: 5 days with two satellites flying concurrently (2–3 days in extended mode)
- Twin satellites in the same orbit, 180° apart
- Land coverage: –56° to + 83° latitude
- Maximum imaging time per orbit: 40 min
- Nominal nadir pointing, extended viewing capabilities
- Geolocation: 20 m (2σ) without ground control points
- Calibration: radiometric calibration onboard
- Security: TC authentication
- Operational configuration comprises two satellites

Satellite platform

- 3-axis stabilised Earth pointing
- Startracker, inertial measurement unit and 2-band GPS receiver for precise attitude and positioning knowledge
- Rate measurement unit, Coarse Earth/Sun Sensors, magnetometer and magnetic torquers, thrusters, wheels
- Propellant: 117 kg hydrazine (N2H4)
- Onboard position knowledge: <20 m (3σ)
- Onboard attitude knowledge: <10 µrad (2σ)
- Launch mass: 1200 kg
- Satellite dimensions (stowed): 3.4 × 1.8 × 2.35 m
- Electrical power: solar array: 7.2 m^2, 1700 W (EOL), GaAs triple junction cells, battery capacity: 87 Ah (EOL)
- Satellite power consumption: 1.4 kW (nominal mode)
- Payload data storage capacity: 2 Gbits (EOL) TM/TC storage capacity; 2.4 Tbit (EOL) mission data storage capacity
- Communication links:
  - X-band science data: effective 520 Mbit/s (8 PSK);
  - Optical Communication Payload for mission data retrieval through the EDRS;
  - S-band TT&C: 64 kbit/s (Split Phase Level/Phase Modulation, SPL/PM) up; 128 kbit/s (SPL/PM) / 2048 kbit/s (Offset Quadrature Phase Shift Keying, OQPSK) down
- Thermal control: passive with Deep Space Radiator; thermistor-controlled heater circuits.
- Reliability: 0.7
- Availability: 97%

Satellite Payload

- Image principle: filter based push-broom imager
- Telescope design: three-mirror anastigmatic telescope with SiC mirrors and structure, and dichroic beam splitter to separate VNIR and SWIR spectral channels
- Focal plane arrays: Si CMOS VNIR detectors, HgCdTe SWIR detectors, passively cooled (190K)
- Electronics: front end, video and compression electronics, including state-of-the-art wavelet-based data compression.
- Combination of onboard absolute calibration with a solar diffuser covering the full field of view, dark calibration over ocean at night, and vicarious calibration over ground targets
- 13 spectral bands: 443–2190 nm (including three bands for atmospheric corrections)
- Spectral resolution: 15–180 nm
- Spatial resolution: 10 m, 20 m and 60 m
- Swath: 290 km
- Radiometric resolution/accuracy: 12 bit/<5%

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Acronyms and Abbreviations

ADM-Aeolus	Atmospheric Dynamics Mission (Earth Explorer)
Ah	ampere-hours
AHS	Airborne Hyperspectral Scanner
AIT	Assembly, Integration and Test
AOCS	Attitude and Orbit Control System
ATCOR	Atmospheric/Topographic Correction for Satellite Imagery
BioPar	Biogeophysical Parameter (Geoland-2)
BOA	Bottom of Atmosphere
Cal/Val	Calibration and Validation
CEOS	Committee on Earth Observation Satellites
CERES	CarboEurope Regional Experiment Strategy
CESS	Coarse Earth and Sun Sensors
CMOS	Complementary metal oxide semiconductor
CNES	Centre National d'Etudes Spatiales
CRFP	Carbon-fibre Reinforced Polymer
CSL	Centre Spatial de Liège, Belgium
CSM	Calibration and Shutter Mechanism
CSW	Central Software
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft und Raumfart
EC	European Commission/European Community
ECHO	European Community Humanitarian Office
ECSS/CCSDS	European Cooperation for Space Standardization/Consultative Committee for Space Data Systems
EDRS	European Data Relay System
EFM	Electrical Functional model
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
EMC	Electromagnetic Compatibility
ENV/MIC	Directorate-General for Environment, Monitoring and Information Centre (EC)
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESOC	European Space Operations Centre
ESRIN	European Space Research Institute
ESTEC	European Space Research and Technology Centre
ETC	ESTEC Test Centre
ETM	Enhanced Thematic Mapper
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
Euroland	European Land Monitoring Service (Geoland-2)
fAPAR	Fraction of Absorbed Photosynthetically Active Radiation (FP7)
fCover	Fraction of Vegetation Cover (FP7)
FDS	Flight Dynamic System
FLEX	Fluorescence Explorer (CEFLES2)
FOCC	Flight Operations Control Centre
FOS	Flight Operations Segment
FP	Framework Programme (EC)
FPA	Focal Plane Assembly
FR	Full resolution
GCP	Ground control point
GEO	Geostationary Orbit
GLAS	Geoscience Laser Altimeter System
GMES	Global Monitoring for Environment and Security
GMFS	Global Monitoring for Food Security
G-MOSAIC	GMES Services for Management of Operations, Situation Awareness and Intelligence for Regional Crises
GNSS	Global Navigation Satellite System
GPP	Ground Prototype Processor
GPS	Global Positioning System
GRI	Global Reference Image
GSC	GMES Space Component
HKTM	Housekeeping telemetry
HRV	High-resolution visible
IMU	Inertial Measurement Unit
INTA	Instituto Nacional de Técnica Aerospacial (Spain)
ITU	International Telecommunication Union
LAI	Leaf area index
LC	Land cover
LCC	Land-cover change
LDCM	Landsat Data Continuity Mission
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LES	Land Equipped Site
LIMES	Land and Sea Integrated Monitoring for European Security (FP6)
LMCS	Land Monitoring Core Service (Euroland, Geoland-2)
LTDN	Local time for the Descending Node
LUT	Look-up table
Mbit/s	Megabit per second
MCS	Mission Control System
MCT	Mercury–cadmium–telluride
MERIS	Medium-Resolution Imaging Spectrometer (Envisat)
MetOp	Meteorological Operational satellite programme
MGSE	Mechanical Ground Support Equipment
MIL-bus	Data bus fulfilling the military standard 1553 (US Department of Defense)
MIMU	Miniature Inertial Measurement Unit
MSI	MultiSpectral Instrument
MSS	MultiSpectral Scanner
MTF	Modulation Transfer Function

NASA/JPL	National Aeronautics and Space Administration/Jet Propulsion Laboratory (USA)
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration (USA)
NRT	Near Real Time
NUC	Non-Uniformity Coefficient
OBC	Onboard Computer
OCHA	Office for the Coordination of Humanitarian Affairs (UN)
OLI	Operational Land Imager
OQPSK	Offset Quadrature Phase Shift Keying
OST	Operations System Test
PDGS	Payload Data Ground Segment
PFM	Protoflight Model
PM	Phase Modulation
PSK	Phase-shift keying
QA4EO	Quality Assurance Framework for Earth Observation
RBV	Return Beam Vidicon (camera)
RELEX	Directorate-General for External Relations (EC)
RT	Real Time
SADM	Solar Array Drive Mechanism
SAFER	Services and Applications for Emergency Response (FP7)
SAIL	Scattering by Arbitrary Inclined Leaves model
SATChMo	Seasonal and Annual Change Monitoring (Geoland-2)
SiC	Silicon carbide
SNR	Signal-to-noise ratio
SPL	Split Phase Level
SPOT	Satellite pour l’Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSD	Smoothing by spectral dispersion
STB	Software test bench
SVT	System validation test
SWIR	Short-Wave Infrared
TDI	Time Delay Integration
TIRS	Thermal Infrared Sensor
TM/TC	Telemetry/telecommand
TMA	Three-Mirror Anastigmatic
TOA	Top of atmosphere
TT&C	Telemetry, tracking and command
UNDPKO	United Nations Department of Peacekeeping Operations
UNHCR	United Nations High Commissioner for Refugees
USGS	United States Geological Survey
VCU	Video and Compression Unit
VNIR	Visible and near-infrared

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