→ SENTINEL-1

ESA's Radar Observatory Mission for GMES Operational Services

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Foreword

Within the Global Monitoring for Environment and Security (GMES) Space Component programme, ESA undertook the development of a European Radar Observatory, Sentinel-1, a polar orbiting satellite system that will ensure the continuation and improvement of synthetic aperture radar (SAR) operational services and applications.

In addition to technological innovation, the improvement comprises the mitigation of by far the most important weaknesses of current experimental/pre-operational satellite services: the update rate of the information, the delays associated with data requests, observation planning and data dissemination to the end-user, and finally the data access restrictions.

With its open and free access to data, its data refresh rates in the order of days and its timeliness down to 10 minutes for special applications, it is anticipated that Sentinel-1 will maximise the use of data for the widest range of applications and for a fast-growing user community.

In view of the above there will be a demand for a comprehensive and concise description of the GMES Sentinel-1 mission that addresses many different aspects such as data products, data quality, observation scenarios, technology, reliability, manufacturer details and programmatic context. This report has therefore been written for a large audience with very different interests. As a consequence, not every single chapter may be equally attractive to all and it is recommended to look carefully at the guide to this document – in the introductory chapter – to find relevant information quickly.

Following the planned launch of Sentinel-1A in 2013, the contributors to this report are looking forward to sharing with the user community the above mentioned benefits and observing the Sentinel-1 mission come to fruition.

Contents

→ SENTINEL-1

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 operational monitoring information for environmental and security applications. ESA's role in GMES is to provide the definition and development of the dedicated space and ground segment system elements, and to manage access to the contributing national missions for GMES users.

To deal with user requirements for both high- and medium-resolution data, conventional synthetic aperture radar (SAR) system designs include different operational modes that either optimise the spatial resolution or extend the swath width. Taking account of data access through GMES to complementary national very-high-resolution SAR missions (e.g. TerraSAR-X by DLR/Astrium GmbH, and Cosmo-SkyMed by ASI), Sentinel-1 has been designed to address primarily medium- to high-resolution applications through a main mode of operation that features both a wide swath (250 km) and high geometric (5 × 20 m) and radiometric resolution, allowing imaging of global landmasses, coastal zones, sea ice, polar areas, and shipping routes at high resolution. This approach will ensure the reliability of service required by operational services and build up a consistent long-term data archive for applications based on long time series.

The GMES programme foresees a series of satellites, each with a lifetime of 7.25 years, over a 20-year period, starting with the launch of Sentinel-1A in 2013 and Sentinel-1B some 18 months later. During full operation, the two identical satellites will be maintained in the same orbit, phased 180° apart, providing a revisit time of six days at the equator.

This document aims to provide a comprehensive and concise description of the GMES Sentinel-1 mission.

Structure of this report

Chapter 2, 'GMES Programme Context', introduces the GMES programme, and in particular the GMES Space Component programme with the Sentinel missions.

Chapter 3, 'Sentinel-1 Mission and Ground Segment', gives an overview of the mission requirements, and the payload complement that has been identified in order to satisfy them. The chapter describes the GMES Sentinel Ground Segment, including the Flight Operations Segment (FOS) and Payload Data Ground Segment (PGDS) components.

Chapter 4, 'Sentinel-1 Satellite' describes the platform and payload that comprise the Sentinel-1 space segment, and the orbital characteristics.

Chapter 5, 'Sentinel-1 CSAR Instrument', describes the C-band Synthetic Aperture Radar instrument and the associated architecture.

Chapter 6, 'Sentinel-1 PDGS and CSAR Processor', describes the ground segment of the mission including the generation of CSAR data.

Chapter 7, 'Sentinel-1 Operation and Observation Capabilities', describes the way in which the mission will be operated, based on dual-polarisation systematic acquisitions in the main Interferometric imaging Mode and Wave Mode.

Chapter 8, 'Sentinel-1 User Products', describes the nature of the data products that will be delivered to users from the Sentinel-1 mission. An extended description is given in Appendix B.

Chapter 9, 'Calibration and Validation of Sentinel-1 Data Products', introduces the in-orbit commissioning phase calibration activities and the long-term validation plan.

Chapter 10, 'Sentinel-1 Product Performance', describes the expected theoretical performance of the CSAR products.

Chapter 11, ‘Campaigns’, gives an overview of the pre-launch, airborne and space-borne campaign activities.

Chapter 12, ‘Sentinel-1 and GMES Services’, introduces the GMES services that will use SAR data, including some anticipated data products that will be required by those services. Chapter 12 also describes the expected performance of a number of potential examples of Level-2 products derived from Sentinel-1.

Chapter 13, ‘Sentinel Data Policy’, summarises the principles of the data policy for the Sentinels.

Chapter 14, ‘Scientific Use of Sentinel-1 Data Products’, provides an overview of the role of the high-quality global observations of Sentinel-1 for the international Earth science and climate research communities.

Chapter 15 gives a summary and conclusions.

2. GMES Programme Context

The Global Monitoring for Environment and Security (GMES) programme is a European initiative to provide information services for environmental and security applications, based on data received from Earth observation (EO) satellites and ground-based networks.

Within the GMES programme, the GMES Space Component (GSC) is responsible for delivering EO data to the GMES Service Component, which in turn is responsible for providing value-added services to users.

While GMES overall is led by the European Union (EU), ESA is responsible for the coordination of the GSC. As part of this responsibility, ESA Member States have approved the GSC programme as an optional ESA programme, to which the EU also contributes financially. As such, ESA is responsible for developing a fully operational space-based capability to feed the GMES Service Component with satellite data (see Fig. 2.1). This capability will be achieved by facilitating access to data from GMES Contributing Missions as well as by developing new GMES dedicated EO missions, called the Sentinel missions. The satellite data will be stored in a long-term archive that will allow for repeated use of long time series.

The Sentinels have been designed to meet the requirements defined in the Mission Requirement Documents of the individual missions (ESA 2005, 2007a, 2007b, 2008), with a view to satisfy the evolving needs of the GMES user communities, notably those expressed in the Strategic Implementation Plans prepared by the EC GMES Core Services Implementation Groups in 2007 (ESA, 2007c,d,e), and in the GSC Programme Declaration approved by the participating ESA Member States.

2.1 Missions

The ESA Sentinels constitute the first series of operational satellites that will respond to the EO needs of the EU–ESA GMES initiative. The GSC relies strongly on complementary new developments by ESA in addition to existing and planned space assets of various national agencies. As part of the GSC, ESA is currently developing three Sentinel mission families, each of which is based

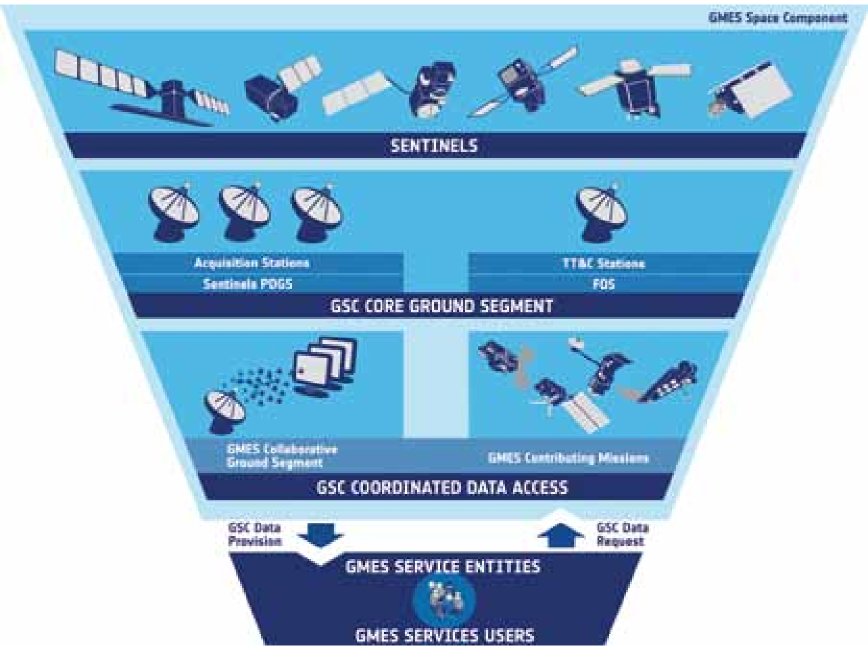


Figure 2.1. The GMES system.

on a constellation of two satellites in the same orbital plane. (In addition, two units of Sentinel-4 instruments to be carried on Meteosat Third Generation (MTG) meteorological satellites and a Sentinel-5 precursor mission have been adopted as part of the GSC programme.)

With this two-satellite configuration it will be possible to fulfil the revisit and coverage requirements, and to provide a robust and affordable operational service. The lifetime of the individual satellites is specified as seven years, while the consumables onboard each satellite will allow for mission extensions of up to 12 years. The life cycle of a satellite generation is planned to be of the order of 15–20 years. ESA is now elaborating a strategy for Sentinel procurement and replacement over this period.

The current phase of the GSC includes the following missions and satellites:

Sentinel-1 – SAR imaging for:

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

Sentinel-2 – Multispectral imaging for:

- land cover, land usage and land-use-change detection maps;
- geophysical variable maps (leaf chlorophyll content, leaf water content, leaf area index);
- risk mapping; and
- fast images for disaster relief efforts.

Sentinel-3 – Multispectral imaging, radiometry and altimetry for:

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

Sentinel-4 and Sentinel-5 – Multispectral imaging and profiling for:

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

2.2 GMES Space Component Ground Segment

The GSC Ground Segment is composed of three elements: 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 contributing mission data. The GSC Core Ground Segment consists of the Sentinels Core Ground Segment and the GMES Data Access Layer.

The Sentinels 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 Sentinels:
  – 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 GMES Sentinels and 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, with their own specific control functions, data reception, data processing, data dissemination and data archiving facilities, will deliver essential complementary data to ensure that a wide range of observational requirements is satisfied.

2.3 Terms and Conditions of Access to and Reuse of EO Data

The EC and ESA have agreed to ensure free and open access to all GMES Sentinel data. Conditions of access to and reuse of data from GMES Contributing Missions are determined by the respective mission owners; for more details see Chapter 13.

3. Sentinel-1 Mission and Ground Segment

3.1 Sentinel-1 Mission

Sentinel-1 is designed to work in a pre-programmed conflict-free operation mode, imaging global landmasses, coastal zones, sea-ice zones, polar areas and shipping routes at high resolution, and the world's oceans in so-called imagettes. The mission will ensure the reliability required by operational services and will create a consistent long-term data archive for applications based on long time series.

Sentinel-1's revisit frequency and coverage are dramatically better than those of the European Remote Sensing satellites (ERS-1 and 2) SAR, and the Envisat Advanced SAR (ASAR). The two-satellite constellation offers six-day exact repeat and conflict-free operations based on two main operational modes that will allow the exploitation of every single data take. Compared with its predecessors, the Sentinel-1 mission represents a significant increase in capability as expressed by the performance indicators developed in Section 7.2. In the framework of international interoperability agreements, the effective revisit and coverage performance may be further improved by access to the planned Canadian C-band SAR constellation.

The observation requirements for GMES services are defined in terms of data availability, coverage and revisit, timeliness and the characteristics of data products. The service requirements for C-band SAR observations were translated into 18 Sentinel-1 mission requirements, shown in Table 3.1, providing the basis for the mission design.

To deal with user requirements for both high- and medium-resolution data, conventional SAR system designs include different operational modes that either optimise the spatial resolution (at the expense of the swath, and hence the coverage) or the swath width (at the expense of the resolution). Taking account of data access through GMES to complementary national very high-resolution SAR missions (TerraSAR-X by DLR/Astrium GmbH, Cosmo-SkyMed by ASI), Sentinel-1 has been designed to address primarily medium- to high-resolution applications

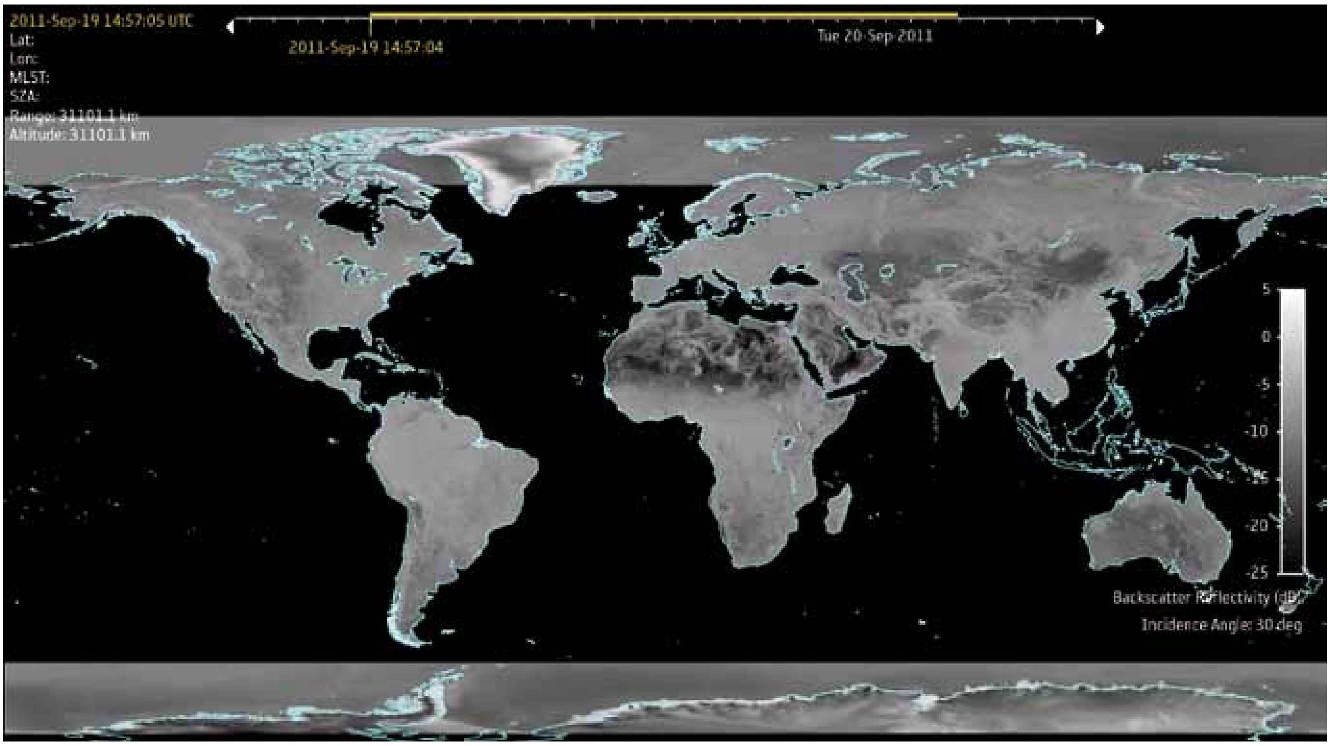


Figure 3.1. C-band reflectivity map measured by Envisat's Advanced SAR (ASAR).
(© ESA/Institute of Photogrammetry and Remote Sensing, TU Wien, Austria. Mosaic elaboration: Taitus Software. SaVoir swath acquisition planner © Taitus Software.)

Table 3.1. Sentinel-1 mission requirements

Data availability
1. In order to avoid gaps in service provision, Sentinel-1 operations shall start before the end of the operational lifetimes of ERS/Envisat and last for a period of at least 10 years.
2. Unless specified otherwise, performance shall satisfy ERS/Envisat requirements.
3. End-to-end product availability to the end user shall typically be better than 95%, based on a main mode of observation and on systematic operations with on-demand observations in exceptional cases.
4. Coverage, revisit and exact repeat observations necessitate the use of non-ESA satellites. Therefore similarity of data products and observation geometry is required as well as ground segment interoperability.
5. All products shall be processed to Level-0 and Level-1 and archived.
6. Data shall be delivered to users within the timeliness specification from the archive or in near real time.
Coverage and revisit
7. For interferometry, global exact repeat coverage shall be achieved bi-weekly (e.g. at intervals of up to 14 days).
8. Fast global access on demand shall be provided within the timeliness specification.
9. Daily full coverage shall be achieved north of +45°N and south of −45°S.
Timeliness
10. Near-realtime data shall be delivered to users within 3 h of observation.
11. User requests for archived data shall be completed typically within 24 h, and in no case more than 3 days after a user request has been issued.
12. Emergency operations shall be completed typically within 24 h, and in no case more than 48 h after a user request has been issued.
Characteristics of data products
13. The centre frequency shall be selected within 5250–5570 MHz (C-band).
14. The system shall be designed to support interferometry.
15. A 240 km swath width follows from revisit requirements for the main mode of observation.
16. A wave mode shall be provided with 20 × 20 km imagettes every 100 km along track.
17. The main mode of observation shall have both VV and VH polarisation.
18. Optional additional modes shall be provided, including a mode with both HH and HV polarisation.

through a main mode of operation that features both a wide swath (250 km) and high geometric (5 × 20 m) and radiometric resolution. Over sea-ice and polar zones or certain maritime areas, an extra wide swath mode may be used to satisfy the observation requirements of certain service providers (e.g. sea-ice monitoring agencies) in order to ensure in particular wider coverage and better revisit times by sacrificing geometric and radiometric resolution.

Figure 3.1 shows an example of a C-band reflectivity map of the land and sea-ice regions of Earth showing the average radar response normalised to 30° of incidence angle, based on measurements made by Envisat's Advanced SAR (ASAR).

As the operation follows a pre-programmed conflict-free scenario, there is no need to make data acquisition requests for these modes (see Chapter 7 for details). The imaging modes can be operated for a maximum of 25 min per orbit. For the remaining time, the instrument operates over the open ocean in the Wave mode, providing sample images of 20 × 20 km at 100 km along the orbit at a low data rate.

It is expected that Sentinel-1A will be launched in 2013 and Sentinel-1B in 2015.

3.2 Sentinel-1 Ground Segment

The GMES Sentinel-1 Ground Segment is in charge of the overall commanding and monitoring of Sentinel-1, as well as the acquisition, processing, archiving and dissemination of the observation data. The two primary components of the Ground Segment are the FOS and the PDGS.

The main responsibilities of the Flight Operations Segment encompass satellite monitoring and control, including execution of all platform activities and the commanding of the payload schedules. The principal components of the FOS are:

- The Ground Station and Communications Network, which performs telemetry, tracking and command (TT&C) operations within the S-band frequency. A single S-band ground station will be used throughout all mission phases, complemented by additional TT&C stations as launch and early operations (LEOP) and backup stations.
- The Flight Operations Control Centre (FOCC), which includes:
  - the Sentinel Mission Control System, which supports 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 Planning System (part of the Mission Control System), which supports command request handling, the planning and scheduling of satellite operations and the scheduling of payload operations as prepared by the PDGS Mission Planning System;
  - the specific Sentinel Satellite Simulators, which support procedure validation, operator training and the simulation campaign before each major phase of the mission;
  - the Sentinel Flight Dynamics System, which supports all activities related to attitude and orbit determination and prediction, the preparation of slew and orbit manoeuvres, satellite dynamics evaluation and navigation; and
  - the Sentinel Key Management Facilities, which support the management of the telecommand security function.
- A General Purpose Communication Network, which provides the services for exchanging data with any other external system during all mission phases.

The Sentinel Payload Data Ground Segment features:

- The Sentinel payload-specific Mission Planning System;
- X-band acquisition stations for the reception of realtime and recorded SAR, GPS and HKTM data;
- Sentinel-specific processing facilities, hosting the relevant Level-1 or Level-2 instrument processor components and precise orbit determination;
- Sentinel-specific calibration and monitoring facilities;
- data storage and long-term archiving systems; and
- support facilities providing monitoring, control and quality functions, and user and data distribution services.

Figure 3.2 provides a simplified top-level breakdown of the Sentinel-1 Ground Segment.

The FOS provides the capability to monitor and control the satellite and payloads during all mission phases. The FOS will be responsible for satellite commanding activities and the acquisition of S-band telemetry. It provides the functionality required for generation and uplink of routine platform and instrument command schedules, and the systematic archiving/analysis of the acquired housekeeping telemetry. The FOS also includes a Flight Dynamics System facility that allows orbit determination and prediction, and the generation of attitude and orbit control telecommands.

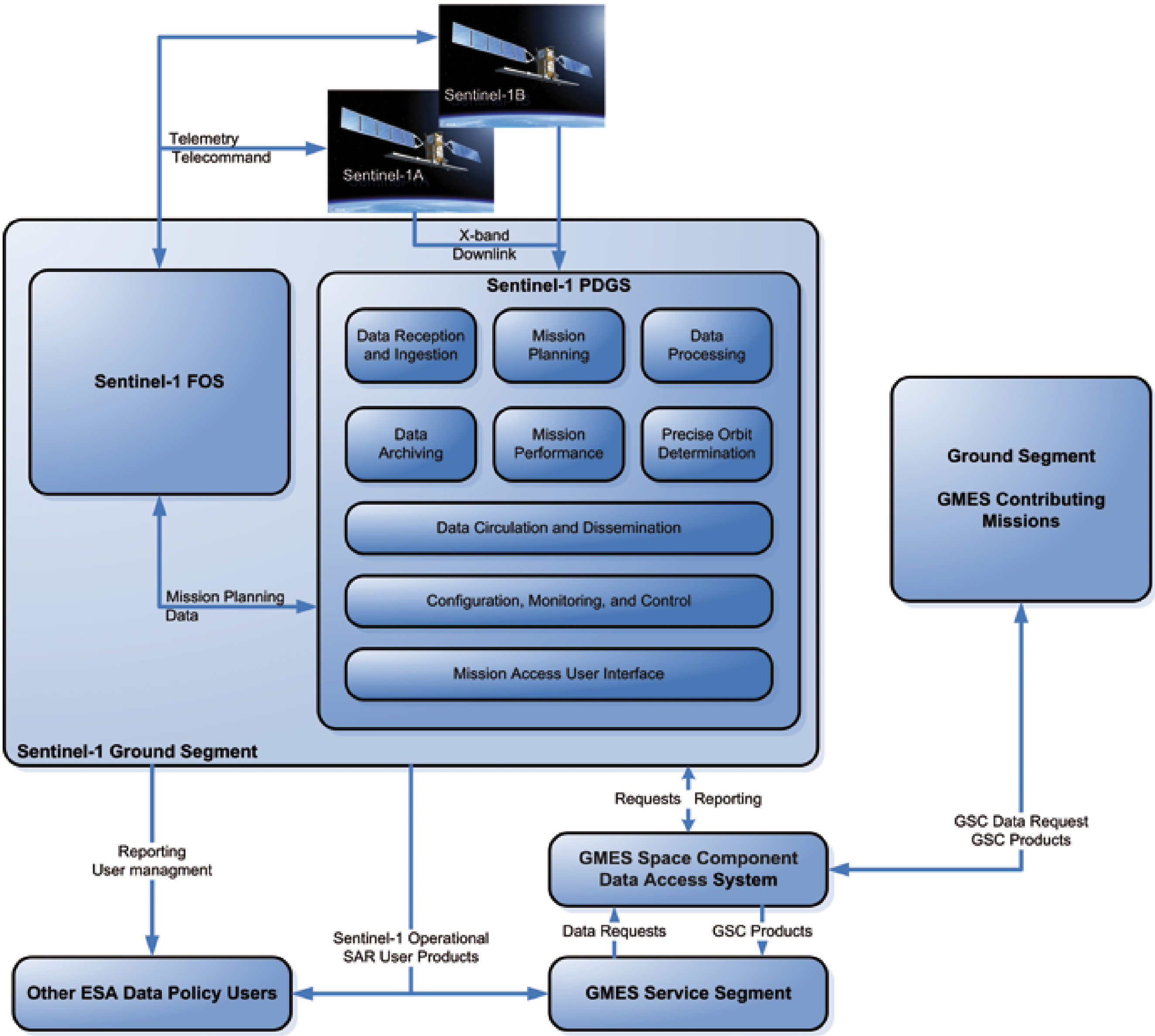


Figure 3.2. GMES Sentinel-1 Ground Segment.

Other FOS functions include scheduling of ground station visibility segments, providing access to archived HKTM to authorised external users, such as industrial expert groups. Besides performing these routine tasks, the Mission Control Team running the FOS will be responsible for monitoring the health of the satellites and implementing all necessary recovery actions in case of anomalies, and for verifying and uplinking onboard software patches.

The PDGS offers data access, production and preservation services to support the mission exploitation according to specifications and requirements previously introduced. In particular, the PDGS:

— offers flexibility and scalability to integrate complementary functions for evolving requirements (e.g. extension to downstream services) and scientific exploitation;
— allows the integration of facilities for additional product generation (e.g. global soil moisture estimates and land cover mapping) on the basis of potential future extended services; and

— offers Sentinel data access services as a comprehensive set of functions available to service providers to enable the utilisation of data for downstream operations.

It is emphasised that the principle of data access is to make everything available online with grouping/sorting functions aimed at grouping the data according to the downstream utilisation process and therefore maintaining control of and establishing priorities for the overall flows of data to users. In this respect, the PDGS data flows and access support:

— data storage administration across centres not only to ensure the preservation of data but also to optimise the overall retrieval performance for service projects;
— reductions in exploitation costs related to the distribution and replication of data within the overall GMES activities; and
— regional data access and exploitation (e.g. local station networks, user-hosted applications).

In order to satisfy the GMES service requirements, notably for land monitoring and emergency response services, data (including metadata) will be preserved in a long-term archive for repeated use of long time series. To ensure consistent data quality it is anticipated that periodic reprocessing will be required.

4. Sentinel-1 Satellites

The Sentinel-1 satellites are being built by an industrial consortium led by Thales Alenia Space (Italy) as the Prime Contractor, while Astrium (Germany) is responsible for the C-band Synthetic Aperture Radar (CSAR) payload, which incorporates the central radar electronics subsystem developed by Astrium UK.

The satellites are based on the Piattaforma Italiana Multi Applicativa (PRIMA) platform with a mission-specific payload module, in this case the CSAR instrument. The design of the satellites has benefited from the experience gained with the Canadian RadarSat-2 and the Italian Cosmo-SkyMed programmes for which PRIMA was also used.

The satellite designed for the Sentinel-1 mission is a 3-axis stabilised satellite, directly placed into circular polar Earth orbit by the launcher. The attitude is measured by Sun, star, gyro and magnetic field sensors, and a set of four reaction wheels and three torque rods are used for attitude control. Each satellite is equipped with two solar array wings capable of producing 5900 W (at end-of-life) to be stored in a modular battery. The platform provides highly accurate pointing knowledge (better than 0.004°) on each axis, high pointing accuracy (about 0.01° on each axis) and realtime position determination along the orbit. The orbit is accurately maintained by a dedicated propulsion system utilising hydrazine propellant and catalytic reaction thrusters.

An important feature of the satellite is the roll steering mode. This continuous roll manoeuvre around the orbit (similar to yaw steering in azimuth) compensates for the altitude variation. The roll steering rate is fixed at 1.6°/27 km altitude variation. The applied roll angle depends linearly on altitude and varies within the interval –0.8° (minimum sensor altitude) to +0.8° (maximum sensor altitude).

The satellite is designed to operate autonomously following nominal or single failure events without updating its mission commands for a period of up to 4 days. Retrieval and analysis of the satellite housekeeping telemetry is, however, scheduled to take place at least once per day. Satellite command and control and thermal control functions are implemented in the satellite Onboard Computer (OBC). An Atmel ERC-32 performs the core processing of the unit via patchable software. The computer also drives two redundant MIL-STD-1553B buses (one for the payload instrument, the other for the platform). The payload data handling is based on a 1.4 Tbit solid-state mass memory and the payload data downlink is performed by a dual-channel transmitter at a data rate of 260 Mbit/s per channel in the X-band with 8 PSK modulation and an isoflux antenna, compliant with the spectrum bandwidth allocated by the International Telecommunication Union (ITU).

Redundant S-band telemetry/telecommand (TM/TC) chains, compliant with ECSS/CCSDS communications standards, provide secure command and satellite telemetry links with the Ground Control Segment. Most satellite functions are redundant and can be reconfigured autonomously 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.

The total mass of the satellite at launch is around 2300 kg. The main characteristics of the Sentinel-1 satellites are shown in Table 4.1.

4.1 The Platform

The platform includes features for the management of the Attitude and Orbit Control Systems (AOCS), data handling and command and control functions

Table 4.1. Sentinel-1 satellite characteristics.

Lifetime	7 years (consumables for 12 years)
Orbit	Near-polar Sun-synchronous orbit at 693 km altitude; 12-day repeat cycle; 175 orbits per cycle
Mean local solar time	18:00 at ascending node
Orbital period	98.6 min
Maximum eclipse duration	19 min
Attitude stabilisation	3-axis stabilised
Attitude accuracy	0.01° (each axis)
Instrument	Right looking with respect to the flight direction
Steering	Zero Doppler yaw steering and roll steering (−0.8° to +0.8°)
Attitude profile	Geocentric and geodetic
Orbit knowledge	10 m (each axis, 3σ) using GPS
Operative autonomy	96 h
Launch mass	2300 kg (including 130 kg mono-propellant fuel)
Dimensions (stowed)	3900 × 2600 × 2500 mm
Solar array average power	5900 W (end-of-life)
Battery capacity	324 Ah
Satellite availability	0.998
S-band TT&C data rates	64 kbit/s telecommand; 128 kbit/s – 2 Mbit/s telemetry (programmable)
X-band downlink data rate	2 × 260 Mbit/s
Launcher	Soyuz from Kourou

of the satellite and all the necessary supporting functions. The main platform functions are:

- AOCS, including:
  - precise attitude measurements,
  - stable and precise 3-axis pointing,
  - precise orbit determination.
- Propulsion:
  - orbit injection,
  - orbit tube maintenance,
  - attitude control during ultimate safe mode,
  - end-of-life disposal.
- Satellite data handling, including:
  - telecommand reception, handling and distribution,
  - telemetry collection, packetisation and forwarding to the ground by TT&C communication equipment,
  - time and synchronisation signals management also in support of payloads.
- Satellite autonomy and failure detection identification and recovery:
  - payload and satellite status monitoring, management and recovery,
  - satellite Operations Planning support (mission timeline and sub-schedule).
- Power:
  - power generation and storage,
  - power conditioning, protection, distribution and switching,
  - pyrotechnic devices actuation.
- Thermal control:
  - temperature monitoring,
  - heat generation and removal.

- Structure:
  - primary structural support and interface on the launch vehicle,
  - appendage tie-down points and release mechanisms.
- Communication with the ground:
  - satellite telemetry transmission and telecommand reception via the S-band transponder,
  - X-band payload data handling for CSAR data, GPS raw data (or auxiliary data) and satellite and instrument telemetry data.

The general architecture of the platform is based on three main structure modules and functionally decoupled to allow the parallel modules integration and testing activities up to the satellite final integration. The modules are:

- the Service Module, which carries only platform units apart from the propulsion units; Fig. 4.1 shows the AOCS avionics test bench during on-ground measurements;
- the Propulsion Module, which carries all the propulsion items connected by propellant lines; and
- the Payload Module, which carries all the payload equipment and appendages.

Most of the Propulsion Module is enclosed within the Service Module, which is in turn integrated into the cone section interfacing the satellite to the launcher adaptor, while the Payload Module is mounted onto the Service Module allowing the allocation of payload units/appendages through four lateral panels and the upper platform.

The dedicated X-band payload data handling terminal (PDHT) comprises all functions necessary for the acquisition, storage and handling of data generated by different sources: CSAR data, GPS raw data (or auxiliary data) and satellite and instrument telemetry data. The PDHT has a data storage capacity of 1410 Gbit (end-of-life) and an effective downlink data rate of 260 Mbit/s each using two channels. In addition to data storage and handling functions, the PDHT will provide the capability for data formatting and data transmission to the ground stations.

The direct downlink transmission capability is available for all the acquisition modes of the CSAR in single or dual polarisation.

The PDHT includes the following subsystems: the Data Storage and Handling Assembly (DSHA), the Transmission Assembly (TXA) and the X-band Antenna Assembly (XBAA).

The onboard memory has been sized to 1410 Gbit. The memory segmentation in packet stores has been designed to enable the simultaneous storage of data from the two polarisation channels of the CSAR instrument and from the HKTM, and auxiliary data. Packet store sizes are not fixed but are dynamically selected and modified by way of access to a ‘pool of free memory segments’ that are allocated and used by any possible packet store whenever it needs to store data coming from the input channels. Thus no potential constraints at the operations level arise from having fixed packet store sizes, implying the need to re-allocate memory blocks by way of ground commanding.

The PDHT storage equipment is based on solid-state memory devices. The number of packet stores has been defined in order to allow prioritisation of the stored data during downlink activities, with at least four levels of priority, and the temporary storage of data to be transmitted in direct downlink.

The main tasks of the TXA are to:

- provide the necessary performance to meet the communication link requirements;
- provide full redundancy and cross-strapping for each function;
- receive discrete and serial telecommands to allow its configuration in flight and for on-ground testing;

Figure 4.1. Sentinel-1 AOCS avionics test bench. (courtesy TAS-I)

— provide discrete and serial telemetry to allow its control in flight and for on-ground testing; and
— interface the satellite power bus and generate the necessary power supply interfaces for TXA equipment.

The XBAA provides transmission to the ground of the X-band modulated signals received by the TXA. One of the main tasks of the XBAA is to limit the radiation of RF energy outside the nominal beam coverage, in order to avoid interference with the satellite environment, and especially with the CSAR antenna.

The PDHT is able to support the mission operations (data storage and data downlink) by performing:

— data acquisition from the CSAR potentially for the full extent of the orbit duration and on all orbits;
— a continuous dump equal to 20 min; and
— an overall dump duration of up to 30 min within any 100 min window.

5. Sentinel-1 CSAR Instrument

5.1 Operational Modes

The Sentinel-1 mission requirements indicate that one main operational imaging mode (Interferometric Wide-swath mode) in combination with the Wave mode satisfies most currently known service requirements, avoids conflicts and preserves revisit performance, provides robust and reliable service, simplifies mission planning, reduces operational costs and also satisfies future requests by building up a consistent long-term archive. However, mutually exclusive modes are provided in order to ensure continuity (with respect to ERS and Envisat) and to accommodate emerging user requirements. Two mutually exclusive dual-polarisation modes are provided for the imaging modes.

Based on the mission requirements, the following main operational measurement modes are implemented:

— Interferometric Wide-swath mode (IW),
— Wave mode (WV).

and for continuity reasons and emerging user requirements:

— Strip Map mode (SM),
— Extra Wide-swath mode (EW).

The SAR instrument measurement modes and their characteristics are summarised in Table 5.1.

Except for the Wave mode, which is a single-polarisation mode (selectable between HH and VV), the CSAR instrument supports operation in dual polarisation (selectable between HH+HV and VV+VH) implemented through one transmit chain (switchable to H or V) and two parallel receive chains for H and V polarisation. The specific needs of the four measurement modes with

Table 5.1. Main characteristics of the Sentinel-1 nominal measurement modes.

Parameter	Interferometric Wide-swath mode (IW)	Wave mode (WV)	Strip Map mode (SM)	Extra Wide-swath mode (EW)
Polarisation	Dual (HH+HV, VV+VH)	Single (HH, VV)	Dual (HH+HV, VV+VH)	Dual (HH+HV, VV+VH)
Access (incidence angles)	31° – 46°	23° + 37° (mid-incidence angle)	20° – 47°	20° – 47°
Azimuth resolution	20 m	5 m	5 m	40 m
Ground range resolution	5 m	5 m	5 m	20 m
Azimuth and range looks	Single	Single	Single	Single
Swath	250 km	Vignette 20 × 20 km	80 km	410 km
Maximum noise-equivalent sigma zero (NESZ)	−22 dB	−22 dB	−22 dB	−22 dB
Radiometric stability	0.5 dB (3σ)	0.5 dB (3σ)	0.5 dB (3σ)	0.5 dB (3σ)
Radiometric accuracy	1 dB (3σ)	1 dB (3σ)	1 dB (3σ)	1 dB (3σ)
Phase error	5°	5°	5°	5°

respect to antenna pointing require the implementation of an active phased array antenna.

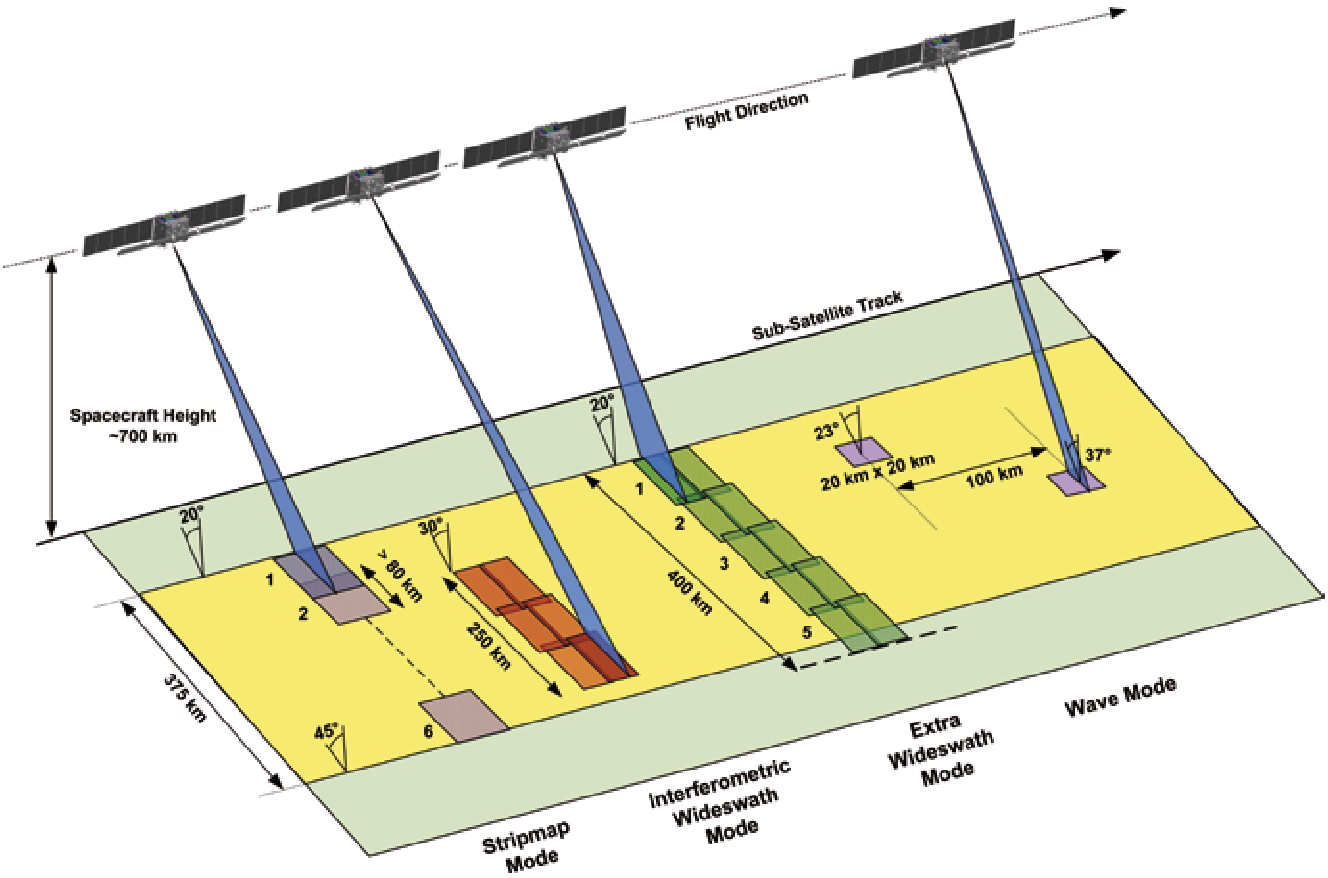
To meet the demanding image quality and swath width requirements, the IW mode is implemented as a ScanSAR mode with progressive azimuth scanning. This requires a fast antenna beam steering in elevation for ScanSAR operation, i.e. transmitting a burst of pulses towards a sub-swath. In addition, fast electronic azimuth scanning has to be performed per sub-swath using the Terrain Observation by Progressive Scans (TOPSAR) operation (De Zan et al., 2006) in order to harmonise the performance in the along-track direction and to reduce scalloping. Hence, the IW mode will allow the combination of a large swath width (250 km) with high geometric resolution (5×20 m on the ground). Interferometry is ensured through sufficient overlap of the Doppler spectrum (in the azimuth domain) and the wavenumber spectrum (in the elevation domain).

The Wave mode data product is composed of single strip map operations with an alternating elevation beam (between 23 and 37 mid-incidence angle) and a fixed on/off duty cycle, which results in the generation of vignettes 20×20 km in size in regular intervals of 100 km.

In Strip Map mode the instrument provides coverage with high geometric resolution (5×5 m) over a narrower swath width of 80 km. Six overlapping swathes cover the access range of almost 410 km. For each swath the antenna has to be configured to generate a beam with fixed azimuth and elevation pointing. Appropriate elevation beam forming has to be applied for range ambiguity suppression.

Finally, the Extra Wide-swath mode covers an ultra-wide-swath width of more than 400 km at medium resolution (20×40 m on the ground), which is achieved through the implementation of a ScanSAR mode with a fast beam

Figure 5.1. Sentinel-1 operational modes.



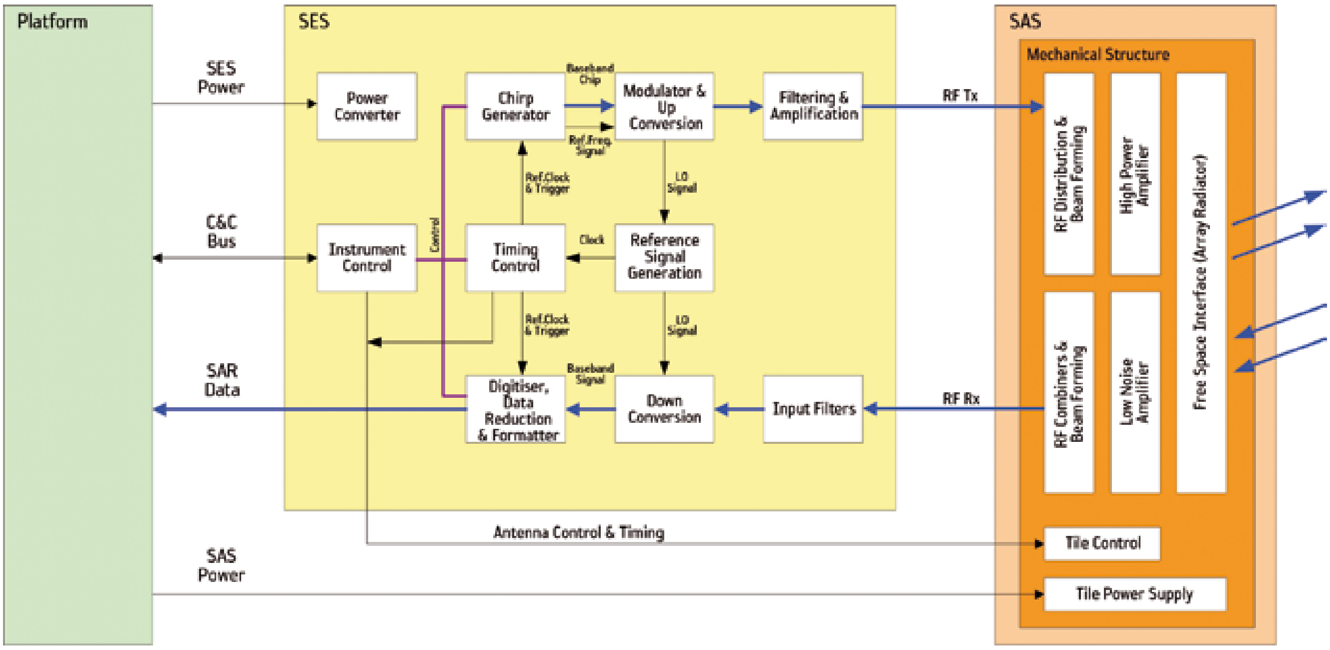


Figure 5.2. CSAR instrument functional block diagram.

scanning capability in elevation. As in the case of the IW mode, the EW mode is implemented with a progressive azimuth scanning (TOPSAR operation).

The four operational modes of Sentinel-1 are illustrated in Fig. 5.1.

5.2 Instrument Architecture and Functions

The CSAR instrument is a synthetic aperture radar operating in the C-band using horizontal and vertical polarisation for transmit and receive (see Fig. 5.2). It is composed of two major subsystems:

— the SAR Electronics Subsystem (SES) and
— the SAR Antenna Subsystem (SAS).

The radar signal is generated at base band by the chirp generator and up-converted to C-band within the SES. This signal is distributed to the high-power amplifiers inside the Electronic Front-End (EFE) transmit/receive modules via the beam-forming network of the SAS. Signal radiation and echo reception are realised with the same antenna using slotted waveguide radiators. In receive, the echo signal is amplified by the low-noise amplifiers inside the EFE transmit/receive modules and summed up using the same network as for transmit signal distribution. After filtering and down-conversion to base band inside the SES, the echo signal is digitised and formatted for recording.

Table 5.2 provides a brief overview of the instrument key parameters. The key design aspects of the CSAR payload can be summarised as follows:

— Active phased array antenna providing fast scanning in elevation (to cover the large range of incidence angles and to support ScanSAR operation) and in azimuth (to allow the use of TOPSAR techniques and to meet the image quality requirements).
— Dual-channel transmit and receive modules and H/V-polarised pairs of slotted waveguides (to meet the polarisation requirements; see Fig. 5.3).

Table 5.2. CSAR instrument key parameters.

Parameter	Value
Centre frequency	5.405 GHz
Bandwidth	0 ... 100 MHz (programmable)
Polarisation	Selectable between HH+HV and VV+VH
Antenna size	12.3 × 0.821 m
RF peak power (sum of all TRFM, at TRM o/p)	4368 W
Pulse width	5–100 μs (programmable)
Transmit duty cycle	
Max	12%
Strip map	8.5%
Interferometric Wide-swath	9%
Extra Wide-swath	5%
Wave	0.8%
Receiver noise figure at module input	3.2 dB
Pulse repetition frequency	1000–3000 Hz (programmable)
ADC sampling frequency	300 MHz (real sampling) (digital down-sampling after A/D conversion)
Sampling	10 bits
Data compression	Selectable according to FDBAQ
Instrument operation	Up to 25 min per orbit continuously in any of the imaging modes and for the rest of the orbit in Wave mode
Instrument mass	945 kg
DC power	3870 W (Interferometric Wide-swath mode, single or dual polarisation)

— Internal calibration scheme, where transmit signals are routed into the receiver to allow monitoring of amplitude/phase leading to high radiometric stability.
— Metallised carbon fibre reinforced plastic radiating waveguides to ensure good radiometric stability outside the internal calibration scheme.
— Digital chirp generator and selectable receive filter bandwidths to allow efficient use of onboard storage considering the ground range resolution dependence on incidence angle (see Fig. 5.4).
— Flexible dynamic block adaptive quantisation to allow the efficient use of onboard storage and to minimise downlink times with negligible impacts on image noise.

A rear view of the SAS tile, an elementary building block of the SAR Antenna subsystem, can be seen in Fig. 5.5.

The continuous roll manoeuvre around the orbit compensates for the altitude variation such that it allows usage of a minimal number of different pulse repetition frequencies (PRFs) and sample window lengths (SWLs) around the orbit. Only a single PRF and SWL are necessary per swath/sub-swath around orbit, with the exception of swath 5 of the Strip Map mode where two different PRFs have to be used. In addition, the update rate of the sampling window position around orbit is minimised (<1/2.5 min), leading to a significant simplification of instrument operations. Since the instrument can work with a single fixed beam for each swath/sub-swath over the complete orbit, the number of elevation beams is minimised.

The CSAR antenna comprises two wings that are stowed on the platform's lateral panels during launch, and are deployed once in orbit.

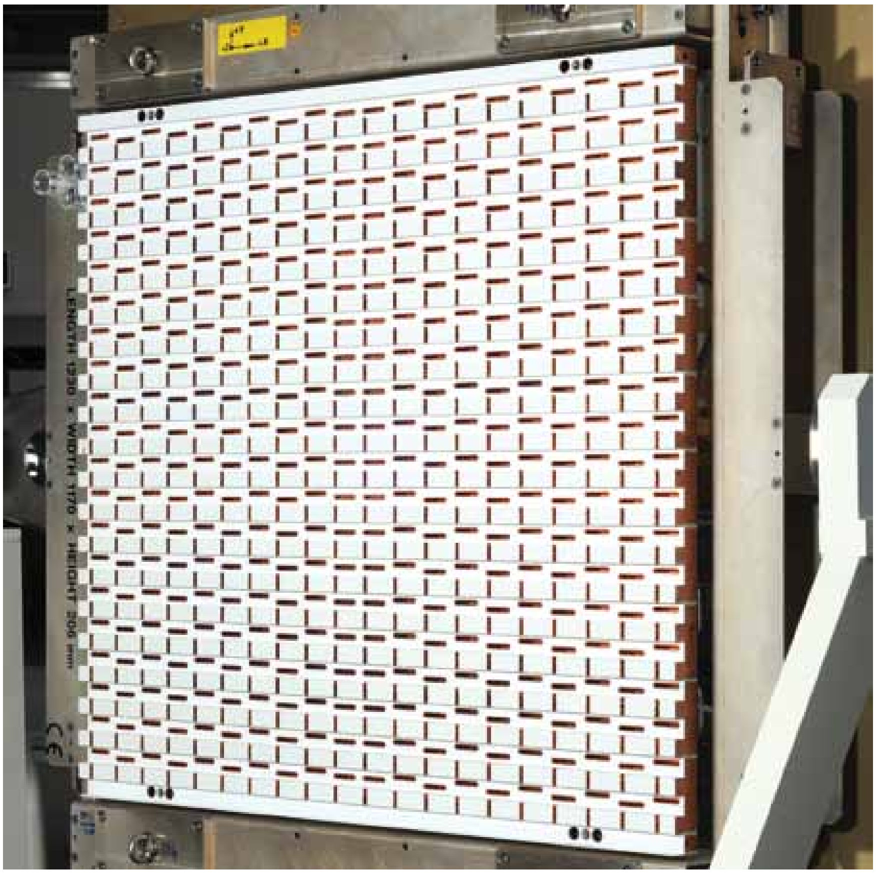


Figure 5.3. SAS tile, front view, with H/V-polarised pairs of slotted waveguides. (Astrium GmbH)

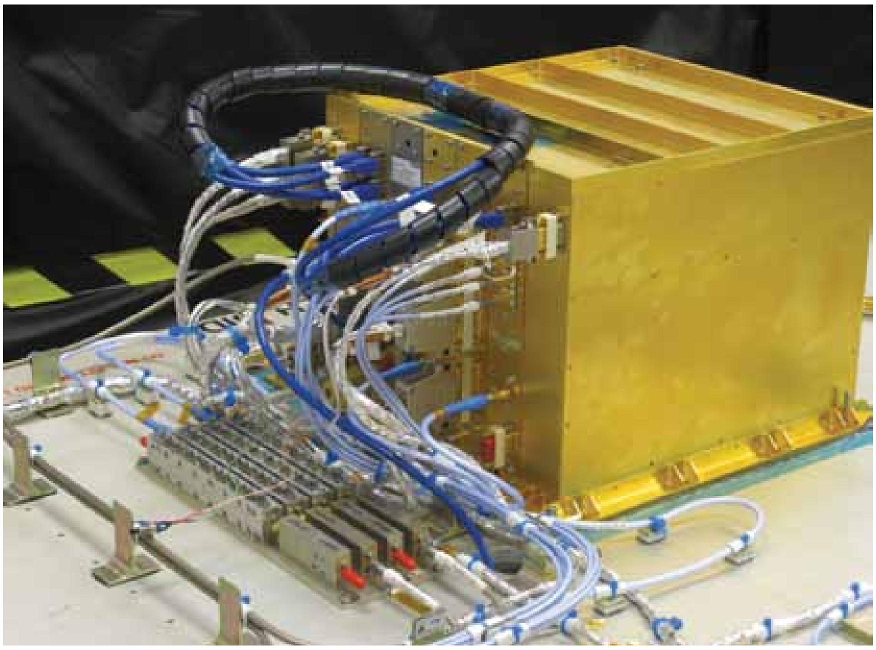


Figure 5.4. Integrated central electronics and filter equipment. (Astrium Ltd)

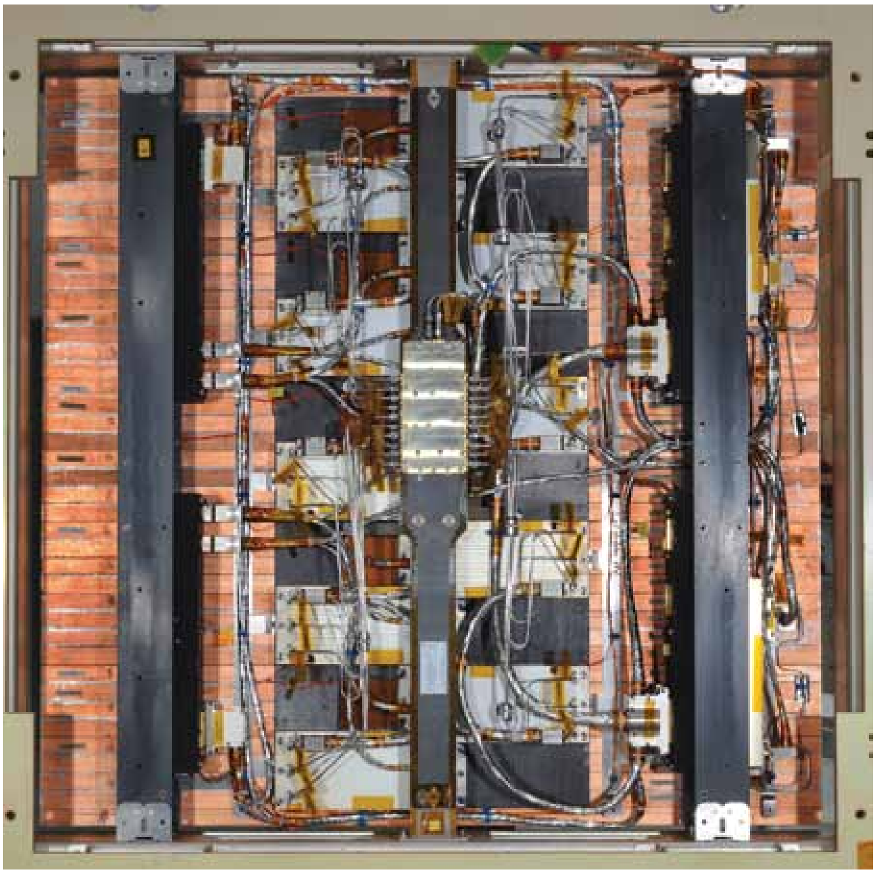


Figure 5.5. SAS tile, rear view. (Astrium GmbH)

6. Sentinel-1 PDGS and CSAR Processor

6.1 PDGS Functions

The Sentinel-1 PDGS will be in charge of the reception of CSAR instrument data, the systematic processing, archiving and dissemination of operational SAR data for the GMES services, and of various planning and monitoring tasks. In particular, data transmitted via the X-band will be down-converted, demodulated and transferred to the processing facilities for the systematic generation and archiving of Level-0 and Level-1/2 data products. Level-1/2 products will be made available to users in near real time (i.e. within 3 h after sensing) in the case of time-critical data and within 24 h after sensing for all acquired data.

The PDGS will be in charge of generating the planning of the CSAR instrument activities and X-band downlink operations, on the basis of a systematic predefined observation scenario. Planning information will be periodically (every day during working days) provided to the FOS for uplink to the satellite.

The PDGS will maintain the instrument parameter tables (radar database) under configuration control and will be responsible for issuing, whenever necessary, a new version with updated instrument parameters. The new instrument parameters will be provided to the FOS for uplink to the satellite.

Other PDGS functions include reprocessing of data products, routine screening of all generated data and monitoring of quality parameters, product calibration and data calibration and validation, instrument performance monitoring activities, the provision of user services and long-term archiving.

Within the Sentinel-1 PDGS the following main functions have been identified:

— *The Data Reception and Ingestion function* is in charge of receiving and decoding the Sentinel-1 CSAR data downlinked directly to the ground or via the European Data Relay System (EDRS) and generating the respective Level-0 products. This might be either realtime sensed data or CSAR data played back from the onboard PDHT. This function includes the demodulation of the downlinked data stream, the frame synchronisation and reconstruction of the CSAR data (Instrument Source Packets, ISPs) in a Computer-compatible Format (CCF) and the generation of Level-0 products.

— *The Processing function* applies all the necessary processing algorithms and formatting techniques to the payload Level-0 products/data to produce higher-level products. This function is able to produce the desired products systematically or on request. Depending on specific timeliness constraints, the processing function can be logically organised into near-realtime (NRT) or non-NRT processing. This function includes, wherever applicable, processing management as well reprocessing capabilities. It also includes the possibility to reassemble 'partial' Level-0 products (i.e. covering only part of an acquisition segment or part of a dual-polarisation acquisition segment) resulting from fragmented downlinks over different stations (or over the same station in different passes).

— *The Archiving function* provides a long-term archiving capability for Level-0 data (ensuring long-term Level-0 data preservation) and for a set of configurable systematic higher-level products. This covers configurable mid-term (months-years) storage capability for the products systematically generated to fulfil GMES service needs. This function includes all operations to be put in place to store these data and ensure their integrity according to the applicable requirements.

— *The Data Dissemination and Circulation function* is in charge of delivering GMES Sentinel-1 products to users, typically by electronic server access (e.g. online data provision) and of circulating within and among its physical

centre(s) and station(s) data generated and handled by the PDGS. Depending on specific timeliness constraints, the Dissemination function can be logically organised into NRT dissemination – allocated to the station(s) – or non-NRT dissemination, allocated to the assembly, processing and archiving centre(s).
- *The Mission Planning function* defines, and exchanges with the GMES Sentinel-1 FOS, the detailed payload sensing and downlink schedule. It also transfers to the FOS, for uplink to the satellite, the SAR instrument parameter table required to configure the instrument operations. The Mission Planning function is also in charge of transmitting the satellite contact schedules to the receiving ground stations.
- *The Mission Access User Interface function* includes several different capabilities for permitting and supporting the successful handling of submitted user queries, including user access management, responsible for managing all the information related to a user, and both documentation and help desk capabilities.
- *The Mission Performance function* performs mission performance assessment and data quality control activities, ensuring that data quality and instrument performance meet the expected requirements. It includes the necessary verification, calibration and validation activities.
- *The Monitoring and Control function* ensures that all available resources (i.e. hardware, software and the network) required to operate the PDGS according to its functional and performance requirements are operating nominally.

6.2 Sentinel-1 CSAR Instrument Processing Facility

The Sentinel-1 CSAR Instrument Processing Facility (IPF) can generate the following Level-1 (L1b) products from the four acquisition modes:

- Slant Range, Single-look Complex (SLC);
- Ground Range, Multi-look, Detected (GRD);
- Browse (BRW).

The products are further classified according to their resolution into:

- Full Resolution (FR) (SM mode);
- High Resolution (HR) (SM, IW and EW mode);
- Medium Resolution (MR) (SM, IW, EW and WV modes).

The IPF supports the processing of dual-polarisation data. The algorithms implemented in the Sentinel-1 IPF are as follows:

- pre-processing algorithms;
- Doppler centroid estimation algorithms;
- SLC processing algorithms;
- GRD processing algorithms.

The Sentinel-1 CSAR IPF will also be able to generate Level-2 ocean products, both from Wave mode data and from high-bit-rate mode data (SM, IW and EW modes). Level-2 ocean products include information on ocean swell spectra, ocean wind and currents (in the form of radial surface velocity). The exact content of the Level-2 ocean products may vary for different Sentinel-1 modes.

6.2.1 TOPSAR-Specific Processing

The Sentinel-1 IW and EW modes acquire wide-swath data (composed of three and five sub-swaths, respectively) using the TOPSAR imaging technique. This

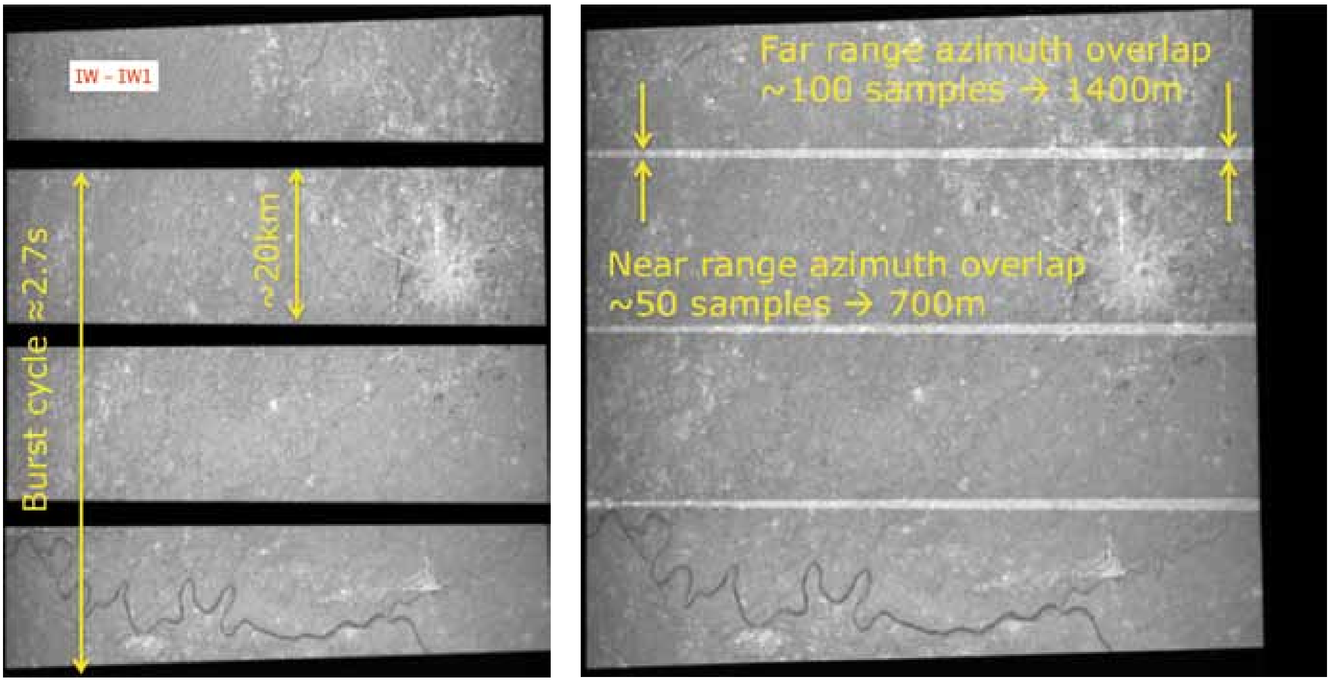


Figure 6.1. IW SLC de-burst azimuth overlap.

requires TOPSAR-specific algorithms to deal with the antenna steering rate and the DC rate due to the steering. The required azimuth pre- and post-processing of the data include de-ramping of the data prior to base-band DC estimation, azimuth ambiguity estimation and GRD azimuth processing.

The Sentinel-1 IW and EW SLC products contain one image per sub-swath and one per polarisation channel, for a total of three (single-polarisation) or six (dual-polarisation) images for IW data, and five (single-polarisation) or ten (dual-polarisation) images for EW data.

Each sub-swath image consists of a series of bursts, where each burst has been processed as a separate SLC image. The individually focused complex burst images are included, in azimuth-time order, into a single sub-swath image, with blackfill demarcation in between. Due to the one natural azimuth look inherent in the data, the imaged ground area of adjacent bursts will only marginally overlap in azimuth – just enough to provide contiguous coverage of the ground. The images for all bursts in all sub-swaths of an IW and EW SLC products are resampled to a common pixel spacing grid in range and azimuth (Fig. 6.1). Burst synchronisation is ensured for both IW and EW products. The processing is phase preserving.

6.2.2 Dual-Polarisation Processing

The steps required for the processing of dual-polarisation data are essentially the same as those required for single-polarisation data; generally, each polarisation is processed in the same manner. However, there are a few additional considerations when processing dual-polarisation data:

- A separate image is generated for each polarisation, and polarisation-specific correction and calibration factors will be applied during the processing of each polarisation (for example, calibration pulses, antenna patterns, etc.).
- The same estimated Doppler Centroid (DC) must be used for processing both polarisations, so that the two resulting images are accurately co-registered. Therefore the DC estimated from the co-polarisation channel will be used for DC estimation.

Table 6.1. Sentinel-1 examples of expected data volumes (GBytes).

			Dual polarisation	
			SLC	GRD HR
Segment length (min)	SM	2	36	3
		10	182	13
	IW	2	30	8
		10	150	39
Slice length (sec)	SM	25	8	1
	IW	25	6	2

6.2.3 The Slicing Concept

As a continuation of Envisat ASAR services, Sentinel-1 is required to give users systematic access to long product strips similar to the currently disseminated ASAR medium-resolution Wide-swath Mode or Image Mode (WSM or IMM) products. However, the product size for Level-1 imaging modes would be difficult for users to manage (see Table 6.1).

The Level-1 image mode products are therefore segmented into 'slices' of defined length along a track, optimised per mode and product type. The Level-1 slices cover a subset of the data take in the along-track direction, and the complete data take area in the across-track direction. These slices

— are referred to the start of each acquisition segment;
— are in the nominal product type projection (slant range for SLC, ground range for GRD);
— are stand-alone products and can be handled separately in terms of archiving and dissemination; and
— are seamlessly 'concatenable' into a continuous product or 'strip' covering up to the complete data take. Slice concatenation may be performed before or after dissemination by the PDGS.

7. Sentinel-1 Operation and Observation Capabilities

7.1 Mission Operation Concept

The Sentinel-1 mission is designed to provide ‘guaranteed data services’ for which liability can be accepted commensurate with the user needs following the GMES public institutional user model. This is common practice in the provision of meteorological data. Most acquisitions can be preplanned and the routine operations are normally not interrupted. Data access is mainly by subscription, supporting near-realtime generation. However, the system is designed to respond to emergency requests to support disaster management in crisis situations. All data are systematically processed and available within 24 h, and can be also retrieved offline from the archive.

7.2 ERS, Envisat and Sentinel-1 Performance Indicators

Radiometric resolution is a measure of the sensitivity of a sensor to differences in the intensity of the echo measured by the sensor. The finer the radiometric resolution of a sensor, the more sensitive it is in detecting small differences in echo intensity. Radar imagery suffers from intensity fluctuations due to speckle and thermal noise in the receiver. Therefore radiometric resolution is determined by the combination of the echo signal to noise ratio and the number of independent echo samples used for the formation of the pixel value in the final data product.

A number of factors have driven the instrument design in order to ensure that an adequate signal to noise ratio and a sufficient number of independent samples are available. One of the system parameters is the noise-equivalent sigma zero (NESZ), which relates to the final signal to noise ratio. Another system parameter is the single-look spatial resolution, which relates to the number of independent echo samples.

Another important design driver is the coverage of a SAR imaging mode. A performance indicator (PI) has been developed in order to be able to compare the different imaging modes of SAR systems. The PI is derived by dividing the swath width (in km) by the radiometric resolution of a 150×150 m product with a backscatter level of –20 dB. A large swath width in combination with a good radiometric resolution will yield a high value for the PI. The results for Sentinel-1 CSAR, Envisat ASAR and ERS are summarised in Table 7.1.

Table 7.1. Comparison of performance indicators for the Sentinel-1 C-band SAR, Envisat ASAR and ERS AMI.

Mission/mode	Azimuth resolution (m)	Ground range resolution (m)	No. of looks (N)	NESZ (dB)	Swath width (km)	Performance indicator	
						Absolute	Relative to ERS
Sentinel-1/ Interferometric Wide-swath	20	5	1	–22	250	2300	4.4
Sentinel-1/ Strip Map	5	5	1	–22	80	1472	2.8
Sentinel-1/ Extra Wide-swath	40	20	1	–22	400	1301	2.5
Envisat/ASAR wide swath	150	150	11.5	–23.5	400	937	1.8
Envisat/image	5	20	1	–22	80	736	1.4
ERS-2/image	5	20	1	–20	80	526	1.0

7.3 Satellite Operations Concept

The main characteristics of the Sentinel-1 mission that determine the Operations Concept can be summarised as:

— Each Sentinel-1 satellite has been designed such that its onboard resources allow the storage of the complete instrument schedule covering a maximum time interval of 4 days.
— In terms of onboard autonomy, the satellite can operate nominally for at least 96 h without any ground intervention.

The resulting routine Operations Concept is characterised by the following main features:

— With the exception of emergency response acquisitions the satellite will operate according to a preplanned schedule of commands (a predefined mission timeline similar for every cycle, with a few updates during the year to cope with seasonal variations e.g. for sea-ice and iceberg monitoring) uploaded from the ground.
— The ground operator will acquire housekeeping data via the TT&C ground station network. The downlinked housekeeping data from the platform and the payload will be processed to verify the health of the satellite.
— Realtime transmitted SAR data will be received by the X-band stations and via EDRS.
— The recorded SAR data will be downlinked every orbit using a network of X-band stations and via EDRS. The data dump will be managed via a predefined sequence of scheduled telecommands stored onboard.
— Updates to the mission timeline can be generated regularly to incorporate, for instance, changes to instrument settings as well as non-nominal specific requests for instrument sensing or data downloads.

7.4 Flight Operations Segment Concept

The FOS provides the capability to monitor and control the satellite during all mission phases. This includes facilities for the generation and uplink of the mission schedules, and for the systematic reception, processing, archiving and analysis of the acquired satellite housekeeping telemetry. Moreover, the FOS includes a Flight Dynamics System facility responsible for orbit determination and prediction, and for the generation of attitude and orbit control telecommands. Other FOS functions include the monitoring and control facilities for the TT&C ground station network.

The FOS provides satellite monitoring and control services to support the mission according to specifications and requirements previously introduced. More specifically, the FOS implementation shall:

— offer flexibility and scalability capabilities to integrate complementary functions for evolving requirements (e.g. extension to emergency services);
— offer efficient data exchange between the FOS and the PDGS;
— for each Sentinel mission, support the progressive buildup and operations management of the satellite constellation, in particular by providing orbit determination and maintenance services; and
— guarantee a high degree of reliability and availability in order to ensure the safety of the satellite under nominal and failure scenarios.

7.5 Sentinel-1 Observation Concept

The main drivers for the Sentinel-1 observation concept are, on the one hand, to provide a systematic coverage that fulfils the various large-scale observation requirements (including monitoring of sea-ice zones and the polar environment, maritime surveillance, monitoring of land surface motion, mapping of land surfaces, etc.), and, on the other, to ensure system responses to crises, disasters and emergencies, such as earthquakes, floods, volcanic activity and oil spills. The information needs are related to the delivery of reference maps, damage maps and inputs for forecasting models.

Medium- to high-resolution sensors, either optical or radar, are suitable for rapid damage assessment mapping. In almost all cases, a reference image is mandatory, or at least very useful, to detect changes, that is, potentially affected areas. Radar sensors can effectively map the extent of floods, especially if reference is made to archive image data. In cloud-covered regions and in bad weather radar is often the only available timely data source. Radar is very effective at detecting shipping and mapping the extent of oil spills. In summary, GMES emergency services require all-weather radar observations of emergency areas and a global reference image archive.

As a result of the above requirements, and taking into account the other Sentinel-1 mission requirements outlined in Section 3.1, a Sentinel-1 observation scenario has been developed based on systematic global coverage to secure the reference image archive and with sufficient resources to accommodate specific emergency acquisitions. The main outputs of the Sentinel-1 mission will be a dependable SAR image data flow and following a systematic, pre-programmed and conflict-free operational scenario with time-critical data dissemination in near-real time and all data available within 24 h.

Special efforts are being made to support rapid mapping for emergency response services. Global average response times are largely defined by the orbit configuration and swath width, and amounts in the worst case to about 5 days for a single satellite and 2.5 days for the two-satellite constellation. The actual performance will depend on the location of the satellite(s) with respect to the emergency site and on latitude, and is worst at the equator and best at high latitude.

In its main operational IW mode, operating up to 25 min per orbit, Sentinel-1 could potentially provide complete global coverage of all relevant land surfaces, sea ice, coastal zones and North Atlantic shipping routes once per 12 days for each of the two satellites. For high-priority areas in Europe, Canada and the North Atlantic coverage will be more frequent, ranging from 4 to 2 days per satellite, depending on latitude (see Fig. 7.1).

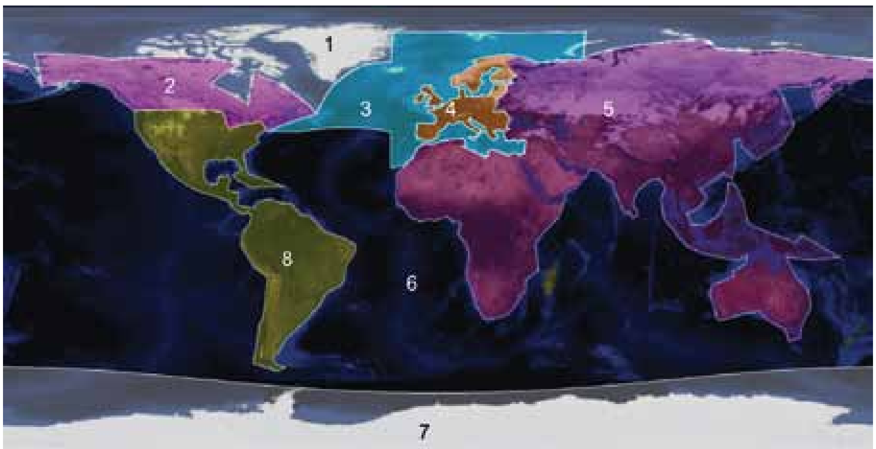


Figure 7.1. Areas of interest as defined for the Sentinel-1 observation concept.
1 – Arctic; 5 – Africa, Asia, Australia;
2 – Canada; 6 – Atlantic Ocean;
3 – European coastal waters and maritime transport zones; 7 – Antarctic; 4 – Europe;
8 – America (excluding Canada).

Over the open ocean, except the North Atlantic, data are normally collected in the WV mode operating all the time. This will provide images of 20 × 20 km separated by 100 km for use in data assimilation in global wave models.

In order to satisfy the service requirements for Sentinel-1 geographic coverage and temporal revisit, two satellites – Sentinel-1A and 1B – are required.

7.6 Mission Timelines

The continuous and systematic data acquisition and download required for the Sentinel-1 mission requires predefined mission timelines, i.e. sequences of SAR imaging that fulfil as many of the mission operational drivers and observation requirements of GMES services as possible, in line with system sizing and resource constraints.

Current mission scenarios used for system validation foresee the usage of the IW dual-polarisation mode to acquire data over landmasses, ice-covered areas and maritime transport zones, while ocean data are acquired in WV single-polarisation mode.

7.7 Systematic Acquisitions

This section presents the current system validation baseline scenario. Fig. 7.2 shows the coverage performance of this scenario for a single satellite. The map provides the number of acquisitions at each location in the region of interest within the orbit repeat cycle. Complete coverage is met, since all targets are acquired at least once within the orbit cycle. For some areas, in particular maritime transport zones and parts of Europe, this allows the revisit times to be greatly reduced. The average revisit time is 3.4 days on maritime transport zones and 6.7 days on Arctic and Antarctic areas.

The SAR schedule complies with the satellite operational duty cycle constraint of 25 min per orbit, where the orbit-by-orbit acquisitions duty cycle is always below the maximum limit. The constraint has to be satisfied over any 98 min (one orbit long) time window, independent of the window start time.

The system operations, driven by the timeline, allow the possibility to react successfully to non-systematic service requests in emergency circumstances, with a very limited probability of an overrun of the operational duty cycle of 25 min imaging per orbit.

The baseline scenario presented above is based on initial mission requirements established some time ago and is mainly used for system validation purposes. The standard observation plan for routine operations, which at the time of writing is in preparation, requires taking into account the evolution of the observation requirements of the GMES services currently being developed. For instance, more stringent requirements in terms of data timeliness for key monitoring services (e.g. oil spill monitoring) have been expressed and must be supported (see Chapter 10), and will impact the overall data acquisition strategy.

Fully in line with the concept developed so far, the objective for the Sentinel-1 mission exploitation phase is to implement a stable, predefined and conflict-free observation plan, with the aim of fulfilling, to the maximum feasible extent, the observation requirements of the various GMES services. This requires the need to find a priori solutions to potential conflicts among services. In addition to the WV mode operated over open oceans, the IW mode is planned to be the main mode of operation over land, while over oceans, seas and polar areas, the predefined modes will be either IW or EW, depending on the areas and the services to be supported (for details see Chapter 10).

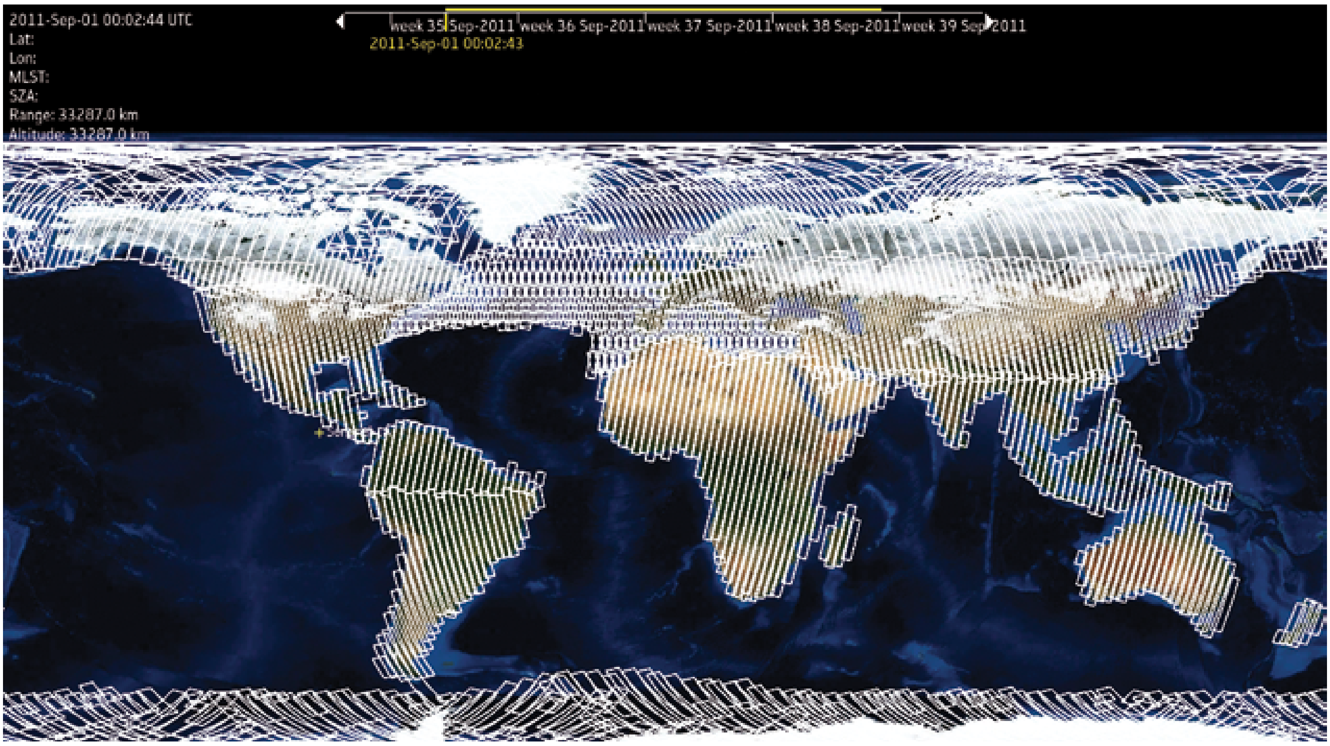


Figure 7.2. Sentinel-1A Interferometric Wide-swath mode coverage after 12 days. (© NASA (*visibleearth.nasa.gov*). Mosaic elaboration: Taitus software. SaVoir swath acquisition planner © Taitus Software.)

7.8 Emergency Acquisitions

An emergency order may be defined, from a system operations point of view, as any order for which the first SAR acquisition opportunity is not part of the nominal schedule. It should be noted that the nominal pre-programmed mission might best serve the majority of emergency response services, above all because of its fast response time and excellent data quality. However, the spatial resolution, swath width and incidence angle requirements may necessitate the use of the SM mode in lieu of the IW mode.

The baseline observation scenario refers to a fixed, predefined systematic SAR acquisition sequence designed to cope with predefined mission objectives. The possibility that the system can manage additional emergency acquisitions is part of the mission objectives, and needs to be reflected in the characteristics and performance of the mission timeline.

In contrast with other specifically designed Earth observation satellite systems, the Sentinel-1 mission is designed for systematic data collection, but also for fast and prompt reaction to emergency requests. However, an a priori reservation of capacity for unpredictable and infrequent emergency acquisitions would result in the under-exploitation of the available system.

When an emergency acquisition request is presented to the system, the first acquisition opportunity for that data take may or may not already be part of the nominal predefined mission timeline. In the first case, and provided that the default mode is satisfactory for support to the emergency acquisition (e.g. in particular in terms of spatial resolution, radiometric resolution and swath width), the nominal timeline (and its relevant data products) already fulfils the emergency needs. In the second case, the mission timeline needs to be modified to include the acquisition that will satisfy the request; this may mean that some scheduled acquisition may need to be replaced with the new one if the residual operational duty cycle is not long enough simply to add a conflict-free acquisition to the timeline.

7.9 Long-term Continuity of Observations

The capacity of the GSC is being built up progressively, starting with the launch of the A-units of Sentinels 1–3 in the 2013–14 timeframe, and augmented with the launch of the B-units in 2015–17.

The role of GMES Contributing Missions (GCMs) is essential, particularly in the time frame until all B-units are deployed. The GCMs are important in completing the observations provided by the Sentinels for GMES in time and space. As such, the GCMs and the Sentinels will provide the full observational capabilities that are necessary to sustain the GMES services.

It is expected that the long-term continuity of observations from the GSC beyond the period of the Sentinel A- and B-units will be necessary to sustain these services in the future.

8. Sentinel-1 User Products

Following the GSC data policy (see Chapter 13), access to Sentinel-1 data is based on systematic and free online data dissemination without the need for an ordering process except in cases where support is needed in emergency situations.

8.1 Information Products

The Sentinel-1 mission will be able to provide a variety of images and/or information products to users. The Sentinel-1 Core PDGS will generate some of these products operationally, the Sentinel-1 Core PDGS or the Sentinel-1 Collaborative PDGS may support some of them, and the GMES Core and Downstream services are expected to generate the final information products (e.g. ice charts, forest maps and ground-surface deformation maps). The Sentinel-1 products operationally generated by the Core PDGS and available to users include SAR 'raw' Level-0 data and 'SAR processed' Level-1/2 data.

Level-1 data fall into two main categories: complex imagery (Single-look Complex, SLC) for interferometric applications that require both image amplitude and phase information and Ground Range Detected (GRD) georeferenced imagery for applications for which only image intensity information suffices. For the SLC and GRD categories, image stacks (time series of repeat coverage) can be provided. As a baseline, Sentinel-1 provides Level-2 ocean products (wind, waves and currents).

The Sentinel-1 user products generated by the Core PDGS are summarised in Table 8.1. The table also introduces the concept of products generated by the Collaborative PDGS, with some examples of candidate collaborative products.

The Sentinel-1 user products generated by the Core PDGS are described in detail in Appendix B.

8.2 Processing Concepts and Timeliness

The processing concept for the Sentinel-1 Core PDGS User products is summarised in Table 8.2. All Sentinel-1 SAR data acquired are systematically processed to create predefined product types and are available within a defined timeliness. These systematically generated products can be classified as follows:

— *Global products* will be systematically generated for all acquired data. They include Level-0, detected Level-1 and Level-2 ocean products. These products are made available within 3 h after observation over NRT areas defined in the High-Level Operations Plan (HLOP), and in any case within 24 h after observation. These products are made available online, accessible with a subscription and archived for long-term access.

— *Regional products* will be systematically generated for a subset of the total acquired data, over well-defined regions/areas defined in the HLOP. These products are made available within 3 h after observation over specific NRT areas in line with the HLOP, and in any case within 24 h after observation. Regional products include Level-1 SLC products. These products are made available online, accessible with a subscription, and are archived for long-term access like the global products

— *Local products*. For critical GMES services, notably maritime surveillance, that require fast delivery, Level-0 products will be made available within 10 min after observation over local areas defined in the HLOP. This timeliness is foreseen for data acquired over European waters and is only possible when Sentinel-1 is inside the coverage zone of one of the core ground stations. Local products are systematically generated, made available online, accessible with a subscription, and are archived for long-term access in the same way as global products.

Table 8.1. Sentinel-1 user products from core and collaborative PDGS.

	Core PDGS (committed quality and timeliness)	Collaborative PDGS (non-exhaustive list)
L0	SAR L0	See Table 8.2
L1	SAR L1 SAR L1 GRD	See Table 8.2 SAR L1 orthorectified
L2 and higher	SAR L2 OCN (wind, wave, and currents) PS Cal products* Sigma-nought mosaic*	Soil moisture Swell propagation
* Products generated by the Core PDGS for calibration purposes only.		

Table 8.2. Sentinel-1 user products – processing concepts and timeliness.

Processing concept	Product type	Timeliness (availability after sensing)	Comments
Systematic global	SAR L0 SAR L1 GRD	<3 h	For regions/areas as defined in the HLOP
		<24 h	All acquired data
	SAR L2 OCN	<3 h	For WV mode data acquired over oceans and IW/EW mode data over areas as defined in the HLOP
Systematic regional	SAR L1 SLC	<3 h	Data available within 3 h after sensing from the Core PDGS for regions/areas as defined in the HLOP Faster availability of sensing relies on Collaborative PDGS
		<24 h	Data available within 24 h after sensing from the Core PDGS for regions/areas as defined in the HLOP
Systematic local	SAR L0	<10 min	Only for data acquired over oceans in direct downlink over Sentinel-1 core ground stations For areas outside the visibility of Sentinel-1 core ground stations, availability of sensing data within 10 min relies on Collaborative PDGS elements, notably third-party local ground stations

All systematically generated products (as shown in Table 8.2) are archived and available for download from archive within 24 h from observation. Products different from those available in the archive over a given area can be generated from the archived Level-0 data.

The generation of new products on request, different from those systematically generated, is supported but restricted to a limited number of authorised users (currently restricted to GMES emergency and security services).

9. Calibration and Validation of Sentinel-1 Products

The synthetic aperture radar measures a series of radar echoes that are processed within the PDGS to generate SAR data products. The main contents of these data products are the normalised radar cross-section and the phase of the individual pixels. Both quantities have to be provided with specified stability and accuracy. This is ensured through Calibration and Validation (Cal/Val) tasks executed throughout the mission.

The SAR images are generated on basis of individual radar echoes that will contain instrument noise. Transmit power, receiver gain and to a lesser extent antenna gain are subject to variations in time due mainly to temperature changes but also due to ageing or other effects. One main task of internal calibration is to provide corrections for changes in the transmit power and the electronics gain. The antenna model nominally covers the antenna gain and it is a task of internal calibration to ensure the validity of the antenna model.

Internal calibration also covers the signal phase. The overall phase of the echo signal depends on two major elements, the measurement geometry and the instrument internal phase stability. As the hardware can not generally provide the required phase stability, it is a task of the internal calibration scheme to cover the internal phase variations by adequate measurements. All internal calibration measurements, either for gain or for phase, are used within the ground processing to correct the data products in order to achieve the required stability.

The main task of external calibration is to derive the calibration constant by measurements of targets with exactly known backscatter coefficients. This is necessary as it will not generally be possible to know all parameters with sufficient accuracy prior to the inflight measurements.

9.1 The Logic of Calibration and Validation Activities

The logic of calibration and validation activities derives directly from the product definition, as illustrated in Fig. 9.1.

The key outputs of the Cal/Val activities are

- deriving and maintaining the system calibration parameters;
- quality assessments of Level-1, Level-2, and Level-3 products in the form of reports, diagrams, statistics, etc.; and
- feedback into the Sentinel-1 Space and/or Ground Segments by tuning the instrument, the Level-1 or the Level-2 and Level-3 processors, e.g. through calibration parameter updates.

For the sake of simplicity, Fig. 9.1 includes, under 'instrument update', operations as different as adjusting the onboard hardware or modifying the onboard software configuration. Similarly, processor tuning may be limited to setting values of static auxiliary data, or may require algorithm changes. The above logic will be implemented throughout the Sentinel-1 mission to cope with the degradation of instrument performance due to ageing, and to improve the quality of the products.

9.2 Sequencing of Activities

The generic sequencing logic shown below is intended to ensure the maximum efficiency of the Cal/Val activities. The principle is to build calibration and validation stepwise, with each step based on a stable foundation, in order to obtain:

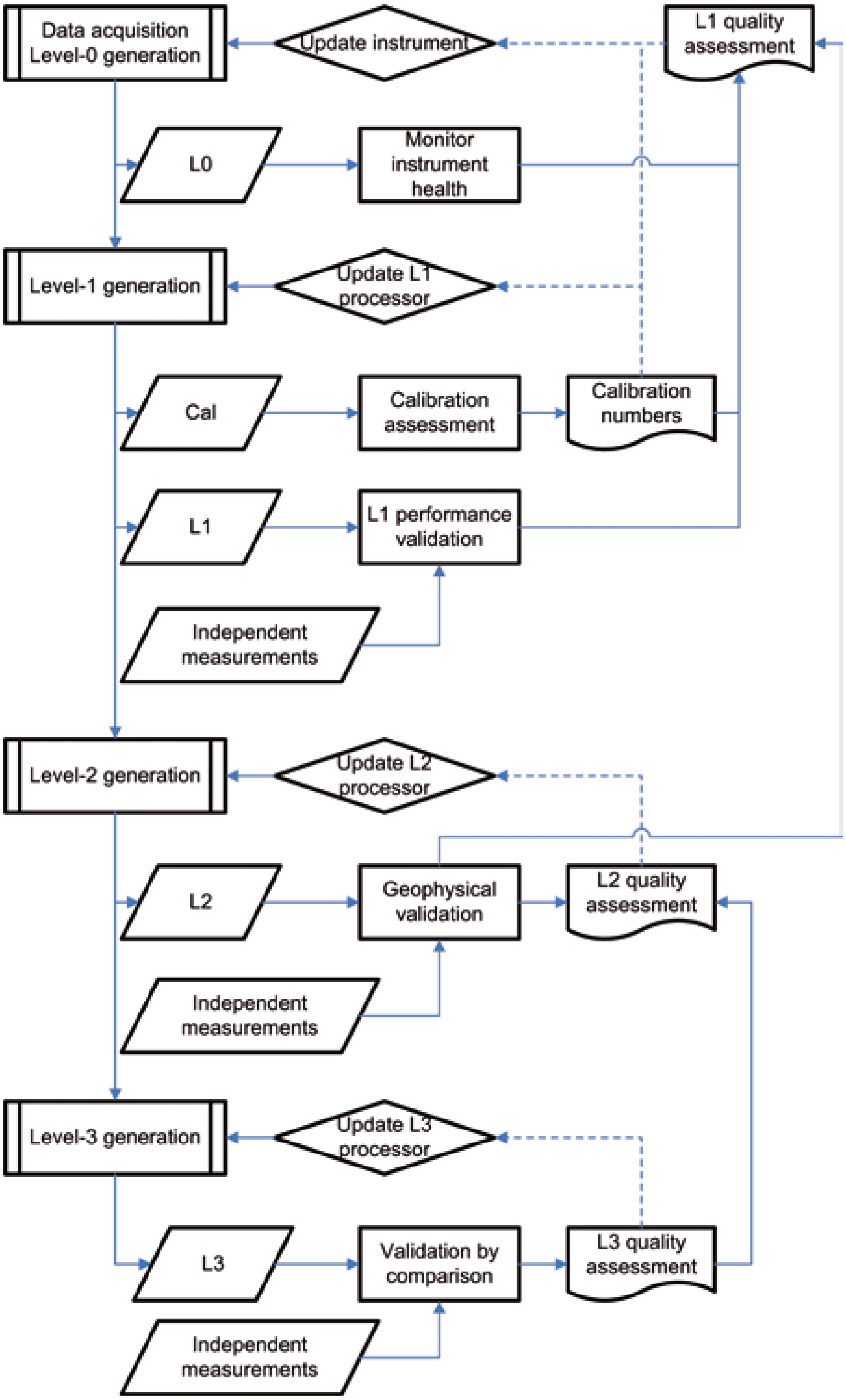


Figure 9.1. The logic of calibration and validation activities.
Boxes – Cal/Val activities;
double-edged boxes – product processing;
parallelogram – data;
rhombus – decision to update processing parameters;
dashed lines – feedback into product processing.
Note: 'Calibration products' designates outputs of the Level-1 processing that pertain to calibration and are not part of the Level-1b product. 'Independent comparable measurements' for Level-1 validation may be derived from geophysical measurements, or from the Level-2 validation.

— a stable instrument before starting Level-1 Cal/Val; any instrument configuration change is likely to have an impact on calibration, so that any work done before a configuration change would largely be lost;
— stable Level-1 processing before starting Level-2 tuning and validation; and
— stable Level-2 processing before starting Level-3 tuning and validation.

This leads to the sequencing of activities shown in Fig. 9.2. Boxes with a clear background pertain to the commissioning phase of the mission; boxes with a grey background represent activities pursued afterwards and throughout the mission.

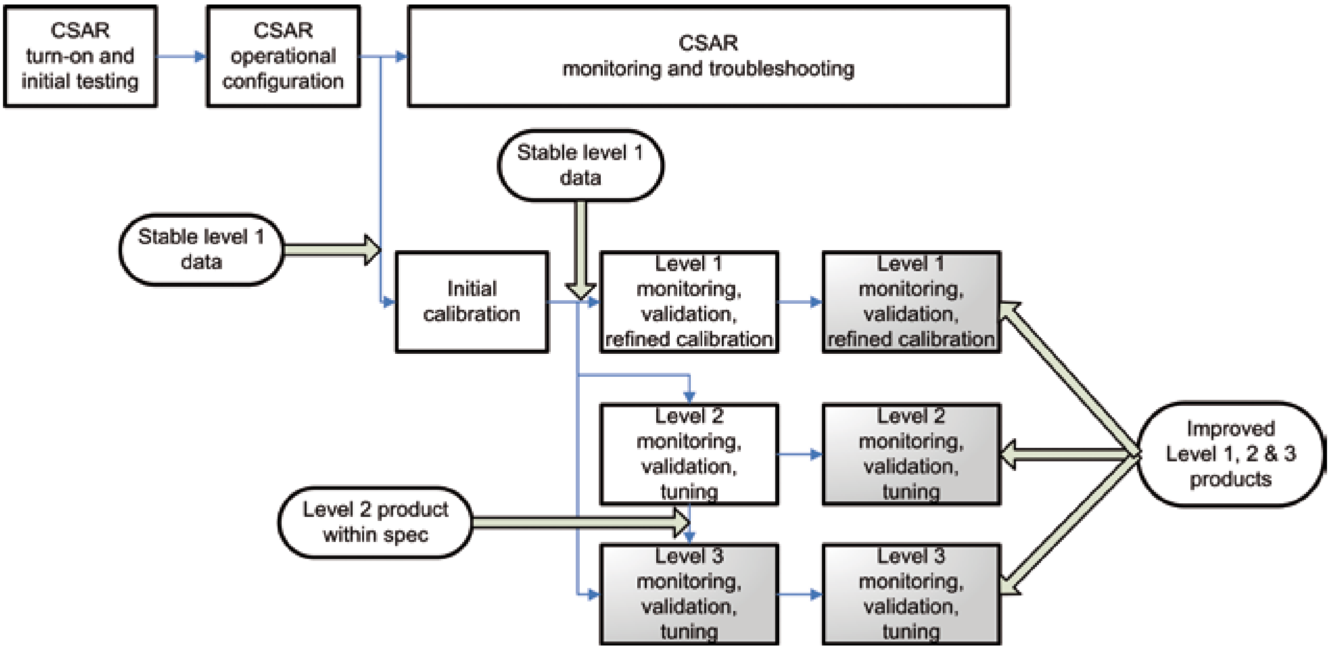


Figure 9.2. Sequencing of calibration and validation activities.

For the sake of simplicity, Fig. 9.2 does not show the same level of detail of Cal/Val activities as Fig. 9.1. Rather, a process such as 'Level-2 monitoring, validation, tuning' encompasses geophysical validation by comparison with independent data, quality assessment, and feedback into the Level-2 processing chain.

9.3 Calibration Activities

The internal calibration is based on calibration signals that are routed as closely as possible along the nominal signal path. These calibration signals experience the same gain and phase variations as the nominal measurement signals. Evaluation of the calibration signals within the ground processing allows the identification of gain and phase changes and corrections to the acquired images accordingly. The internal calibration scheme also has to include measurements of the instrument noise floor in the absence of echoes. Such measurements are to be performed as part of each data take.

The internal calibration scheme covers a dedicated calibration mode, also called the RF characterisation mode, which has the task of verifying inflight the correct function and the characteristics of the individual transmit–receive Modules (TRMs).

Not all elements of the signal path are included in the internal calibration measurements. This is the case for the radiators, for instance. Other parts of the signal path are covered only by calibration signals but not by the nominal measurement signals such as the dedicated calibration paths and the calibration coupler within the TRMs. All these path elements are characterised on the ground versus temperature, or need to be inherently stable so as not to affect the calibration process.

The antenna patterns need to be generated on the ground by the processor using the antenna model with the required quality. This implies that the actual amplitudes and phases of the individual radiators are within given limits. In the general case this is achieved by an onboard compensation of phase and amplitude variations versus temperature. This onboard compensation is based on characterisation data of the TRMs and on related temperature readings. In

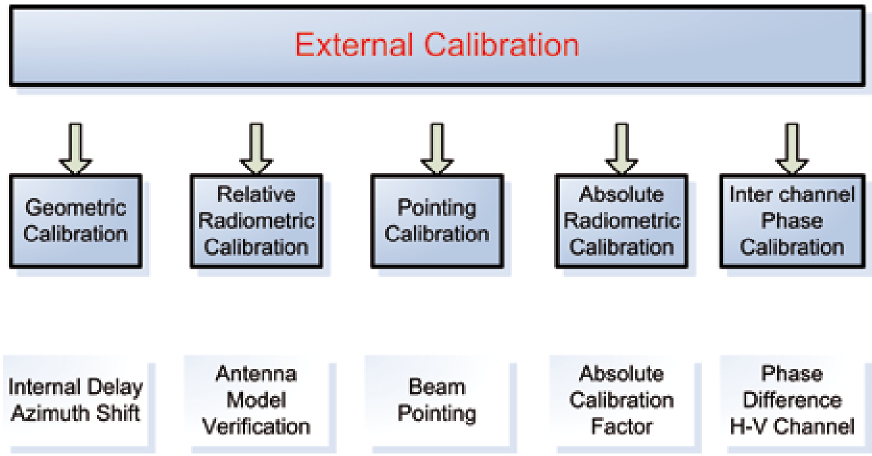


Figure 9.3. Objectives of external calibration.

the same way as for the TRMs at the front-end, temperature compensation is also performed for the tile amplifiers. Further characterisation measurements are related to the embedded sub-array patterns, which are main inputs to the antenna model.

Characterisation measurements are obtained on the ground at various integration levels and will in many cases be covered by measurements at lower integration levels. This is especially the case for the amplitude and phase behaviour of the TRMs versus temperature. Other such elements include the signal path outside the internal calibration loop (like the radiators) and path elements dedicated to the calibration path (like calibration couplers, etc.).

The external calibration is performed using point targets like the Sentinel-1 transponders and by measurements over a rainforest that represents a homogeneous isotropic extended target. Radiometric calibration is achieved by comparing the measured signal power over these targets with their precisely known radar cross-sections. Prerequisites for radiometric calibration are geometric calibration and pointing calibration. Azimuth pointing can be estimated with high accuracy on the basis of the Doppler Centroid. Estimation of this Doppler Centroid across the swath also allows the derivation of the normal pointing. Elevation pointing is estimated either with dedicated notch beams or from measurements with nominal beams over the rainforest (see Fig. 9.3).

The inter-channel phase accuracy is calibrated using the Sentinel-1 transponders that return the signal with H and V polarisation components, and which by this allow a direct phase comparison between H and V channels. The antenna model that is to be derived on the ground describes the antenna patterns with high accuracy. This antenna model is verified for a limited set of elevation beams via measurements over a homogeneous target, which means over rainforest. The azimuth beams will be measured using the receiver function of the Sentinel-1 transponder.

9.3.1 Internal Calibration

The pulse-coded calibration (PCC) technique for internal calibration uses a unique pulse code on a signal such that it can be identified and measured when embedded in other signals. This allows the amplitude and phase of individual signal paths to be measured while operating the complete antenna. The PCC technique is implemented by sending a series of coherent calibration pulses in parallel through the desired signal paths. The individual successive signals are multiplied by factors of '+1' or '–1'. Factor '–1' is implemented by adding a phase shift of 180°, while factor '+1' means no additional phase. Each path is identified by a unique sequence.

The PCC technique can be applied if:

- the receiver detects the signals coherently;
- the whole sequence is executed in a sufficiently short time such that the parameters to be measured are stationary; and
- the system is linear with respect to the individual signals.

The PCC technique can measure the signal paths via individual TRMs or via groups of TRMs (either TX or RX paths, either polarisation).

The average properties of rows or columns of TRMs can be measured by a short PCC sequence. The length of a PCC sequence is always a power of two. There are 20 rows of waveguides and therefore the PCC sequence has a minimum of 32 pulses. Although the 14 columns (this means the 14 tiles) could be measured by a PCC sequence of 16 pulses, it is assumed that a sequence length of 32 pulses is also used. All 20 rows are operated together, which means the antenna is in a full operational state. The overall signal from all rows is received, digitised and packed into calibration packets. These packets are evaluated (on the ground) to evaluate the properties of the individual rows. The approach for measuring the average azimuth excitation coefficients is similar to the elevation pattern with just using columns of TRMs instead of rows.

The PCC-32 measurements described above need on the order of 129 pulses. Additional warm-up pulses maybe also needed. Such a large number of calibration pulses represents a significant interruption in image generation when operated within the image acquisition of the Strip Map mode. For intermediate calibration pulses in Strip Map mode, and also for calibration pulses related to each sub-swath measurement in the ScanSAR modes, a shorter sequence is needed. The shortest possible PCC sequence is based on two measurements. This procedure introduces PCC inherent error contributions, however. These latter errors are to be expected, although they are significantly smaller than those due to leakage signals.

9.3.2 RF Characterisation Mode

The RF characterisation mode is not related to the imaging data takes. It will be operated at least once per day outside the periods with imaging mode, which basically means it is interleaved in the long durations of the wave mode. Operating it two or more times at different temperatures during the cool-down phases between the high dissipating imaging modes can provide in-orbit characterisation versus temperature where necessary.

The RF characterisation mode performs measurements with internal signals and is designed to achieve a number of goals. The calibration mode will:

- cover all those measurements that are needed in orbit but which are not required for each individual data take;
- provide data sets to assess the instrument health and performance as far as possible;
- verify the correct function of the individual TRMs, both within the front-end and the tile amplifiers; and
- verify the excitation coefficients for the TX and RX patterns to ensure the validity of the antenna model.

This mode is based on the same measurement types as the internal calibration. The mode has to address the individual TRMs while operating the full antenna in representative thermal conditions and with the nominal power consumption. This can be achieved using the PCC technique. As a standalone mode, it is not forced to use the signal parameters of a dedicated imaging mode, but instead an optimised set of parameters can be used. The calibration mode is to be operated for both TX polarisations. The receiver will measure both polarisations in any case.

9.3.3 External Calibration

The time frame for performing all calibration activities is defined by the three-month commissioning phase of Sentinel-1. Considering a repeat cycle of 12 days, a three-month commissioning phase results in 7.5 repeat cycles. About half of the first cycle is dedicated to checking out the complete Sentinel-1 system, including space and ground segments, as well as one cycle for product release at the end of the commissioning of Sentinel-1, so six repeat cycles remain for performing all calibration campaigns. The minimum number of measurements being performed, and consequently of passes required, is driven by the radiometric accuracy budget and the strategy to execute the radiometric calibration on selected beams. Due to the tight schedule the co- and cross-polar receiving channels will be measured simultaneously. Test sites within the crossover areas of ascending and descending swaths at mid-latitude have been selected for logistical reasons.

The following external calibration scenario is a first assessment to demonstrate the capability to perform the different calibration procedures within the commissioning phase.

Radiometric calibration

Due to the high demand on the radiometric accuracy of 1 dB (3σ) in all four operational modes, it is recommended to measure at least one beam of each mode against the Sentinel-1 transponders deployed at different locations. Each selected beam will be measured during two passes (ascending and descending). Furthermore, two receive polarisation combinations per operation mode are to be measured simultaneously.

By measuring Sentinel-1 against the three transponders for selected beams, the radiometric calibration can be performed within a limited number of repeat cycles. The absolute calibration factor of all other beams is then derived by applying the antenna model.

Antenna model verification

The verification of the antenna model is performed for selected beams, at least one with low, one with mid- and one with high incidence angle, all with the same polarisation condition. In addition, some of the beams are selected for measuring the second polarisation condition.

Assuming acquisitions for each of the selected beams and using the receiver mode of the transponders, and by using acquisitions over the rainforest, the antenna model verification can be performed within a few cycles.

Geometric calibration

In addition to the antenna model verification geometric calibration is performed. For this purpose the acquired scenes are measured simultaneously against point targets deployed and precisely surveyed.

Antenna pointing determination

The determination of the antenna pointing by the receiver mode of the transponders is performed using notch patterns in azimuth with different incidence angles (near, mid- and far). Using three transponders with a receiver function within one cycle (two passes) sufficient measurements can be acquired to derive the required accuracy.

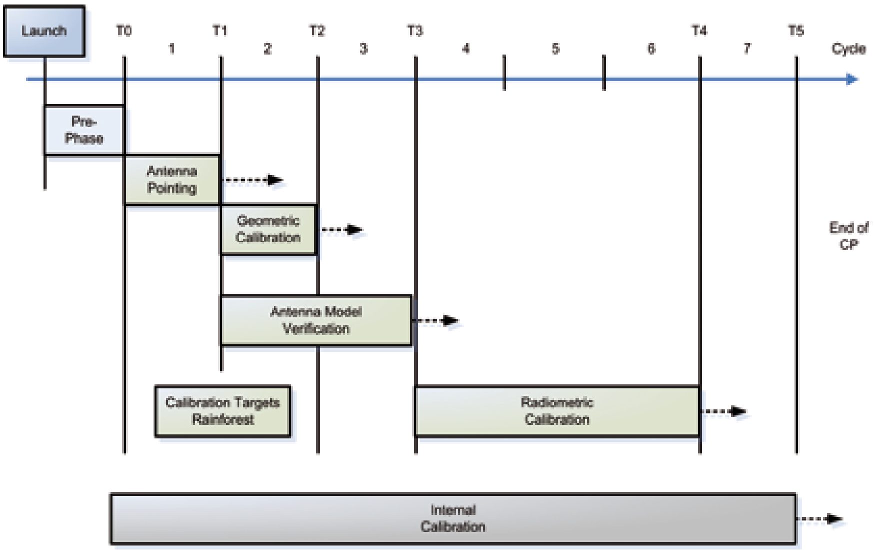


Figure 9.4. Schedule of the in-orbit calibration plan versus repeat cycles of 12 days.

9.4 In-orbit Calibration Plan during the Commissioning Phase

The schedule depicted in Fig. 9.4 provides an overview of the sequence of all procedures required to calibrate the Sentinel-1 CSAR instrument. The different calibration processes are subdivided into acquisitions across deployed calibration targets and across the rainforest. The dashed arrow at the end of each calibration 'box' in Fig. 9.4 indicates that the proper measurements performed by dedicated calibration campaigns are finished but the reception and the evaluation of all measured data takes need additional time. Based on the experiences of campaigns already performed, at least one additional cycle should be considered for this purpose.

Starting with the launch of Sentinel-1, the following milestones have to be achieved before the different calibration campaigns for Sentinel-1 can start:

— LEOP (platform and instrument functional checkout);
— Ground Segment checkout (planning, commanding, data reception and provision);
— attitude and orbit verification and provision of orbit/attitude data;
— data take and complete processor chain functional checkout;
— instrument verification/characterisation; and
— check of the calibration facility.

After a successful completion of this phase, there are six milestones for calibrating Sentinel-1:

— T0: start of antenna pointing determination campaigns;
— T1: start of geometric calibration as well as antenna model verification campaigns and end of antenna pointing determination campaigns;
— T2: end of geometric calibration campaigns;
— T3: end of antenna model verification campaigns and start of radiometric calibration campaigns;
— T4: end of radiometric calibration campaigns; and
— T5: end of commissioning phase.

Finally, in order to ensure the stability of the instrument and to compensate for drift effects, the internal calibration facility and corresponding procedures are operated in parallel during the lifetime of the instrument.

9.5 Validation Activities

9.5.1 Level-1 Product Validation

The Level-1 product validation is based on the Level-1 product generated by the Sentinel-1 processor and calibrated using the means explained in the previous sections, and focuses on the Level-1 parameters introduced in Table 5.1. Some performance parameters have been defined based on point target measurements and external calibration targets will be used in their validation. The other performance parameters have been defined based on measured backscatter from distributed targets, and would ideally be validated using natural targets with accurately known backscatter.

As suitable natural targets are not available, distributed target validation has to be done in two stages. First, the absolute validation has to be done by analysis based on point target measurements at a limited number of points across the radar antenna diagram. Second, the relative validation across the antenna diagram has to be done based on distributed target measurements. Fortunately, suitable natural targets exist (such as rainforest, sea ice and the oceans) for which the relative backscatter properties (in terms of σ_0 measurements) have been well established after years of experience with C-band SAR using the ERS Active Microwave Instrument (AMI) and Envisat ASAR.

It is noted that the validation of Level-1 performance implicitly carries out a validation of the instrument calibration. For that reason, the resulting Level-1 validation quality statement should feed back to the instrument calibration, and as a consequence might eventually require a recalibration of the instrument at any point during the mission lifetime.

Because of the annual cyclical variations in the backscatter properties of these natural targets, it may not be possible to complete the validation of Level-1 by this means during commissioning. This activity will continue during the operational phase.

The instrument linearity for the range of backscatter values in the Level-1 product will also need to be validated. Finally, a very important product validation to be carried out at Level-1 involves quantitative and qualitative assessments of the effectiveness of the product quality flags.

9.5.2 Level-2 Geophysical Validation

The geophysical validation of the Sentinel-1 Level-2 products consists of comparing retrieved Level-2 products using a geophysical model function from Sentinel-1 measurements with independent 'equivalent' measurements. This allows assessments of the information content and the quality of the Sentinel-1 Level-2 products.

The required Sentinel-1 inflight radiometric performance has been established to allow the achievement of certain Level-1 and Level-2 product quality standards. The validation exercise is intended to identify an appropriate reference data set and to assess whether the objectives in terms of geophysical quality have been met. This should be done during commissioning and carried out during the mission lifetime as a routine monitoring activity.

It is noted that Level-2 validation carries out implicitly a validation of the instrument calibration. For that reason, the resulting Level-2 validation quality statement should feed back to the instrument calibration and, as a consequence, might eventually require a recalibration of the instrument at any point during the mission lifetime.

As for Level-1, a validation of the quality control mechanisms and resulting flags needs to be carried out.

9.5.3 Level-3 Validation

For the validation of the Sentinel-1 Level-3 products a similar strategy to that described for Level-2 products will be followed.

As for Level-1 and Level-2, a validation of the quality control mechanisms and resulting flags needs to be carried out.

10. Sentinel-1 and Applications

10.1 GMES Services

The European Commission has identified six GMES service themes for which it will support the provision of operational services based on Earth observation (EO) data: Emergency Response, Marine Monitoring, Land Monitoring, Atmospheric Monitoring, Security, and Climate.

Pre-operational services in five of these themes are currently being developed in projects funded by the EC's 7th Framework Programme (FP7). These services are based partly on projects funded as part of the EC's 6th Framework Programme and by ESA in the GMES Service Element (GSE) of the Earth Watch programme. The Consolidated GSE projects, by theme, are: Risk–EOS, Respond and TerraFirma in the Emergency Response and Risk theme; PolarView and MarCoast in the Marine Monitoring theme; GSE Land, GMES Forest Monitoring and Global Monitoring for Food Security (GMFS) in the Land Monitoring theme; PROMOTE in the Atmospheric Monitoring theme; and MARISS in the Security theme. At the time of writing, the FP7 projects are:

- SAFER: GMES Emergency Response Services;
- MyOcean: GMES Marine Monitoring Services;
- Geoland2: GMES Land Monitoring Services;
- MACC: GMES Atmospheric Monitoring Services;
- G-MOSAIC: GMES Security Services.

Taken all together, the FP7 and parts of the GSE projects, plus existing European and national level service development efforts, are progressively converging towards the future operational GMES service framework.

It is expected that a GMES downstream sector will develop as value-adding firms build upon the EC-financed GMES services in order to provide targeted and customised information products to meet niche customer needs. The downstream sector of GMES is expected eventually to be sustained through funding from its users. However, FP7 funds are being used to launch some downstream services and ESA is providing additional funding to guide several GSE services not taken onboard the FP7 projects to the point of sustainability,

The following sections provide a brief, non-exhaustive overview of selected service applications that could be served by the Sentinel-1 mission, for illustrative purposes. In each case, the most appropriate Sentinel-1 observations (SAR mode, polarisation, timeliness) to support these applications are briefly described.

10.2 Emergency Response Applications

The Sentinel-1 mission will provide critical EO data for several applications related to emergency response, including:

- crisis mapping and risk assessments related to floodplain inundation; and
- precise terrain deformation mapping for geohazard risk assessments.

10.2.1 Crisis Mapping and Risk Assessment related to Floodplain Inundation

Crisis mapping and risk assessment services related to floodplain hazards are vital components of emergency response activities within Europe and beyond, since flooding represents over 75% of natural disasters that occur worldwide.

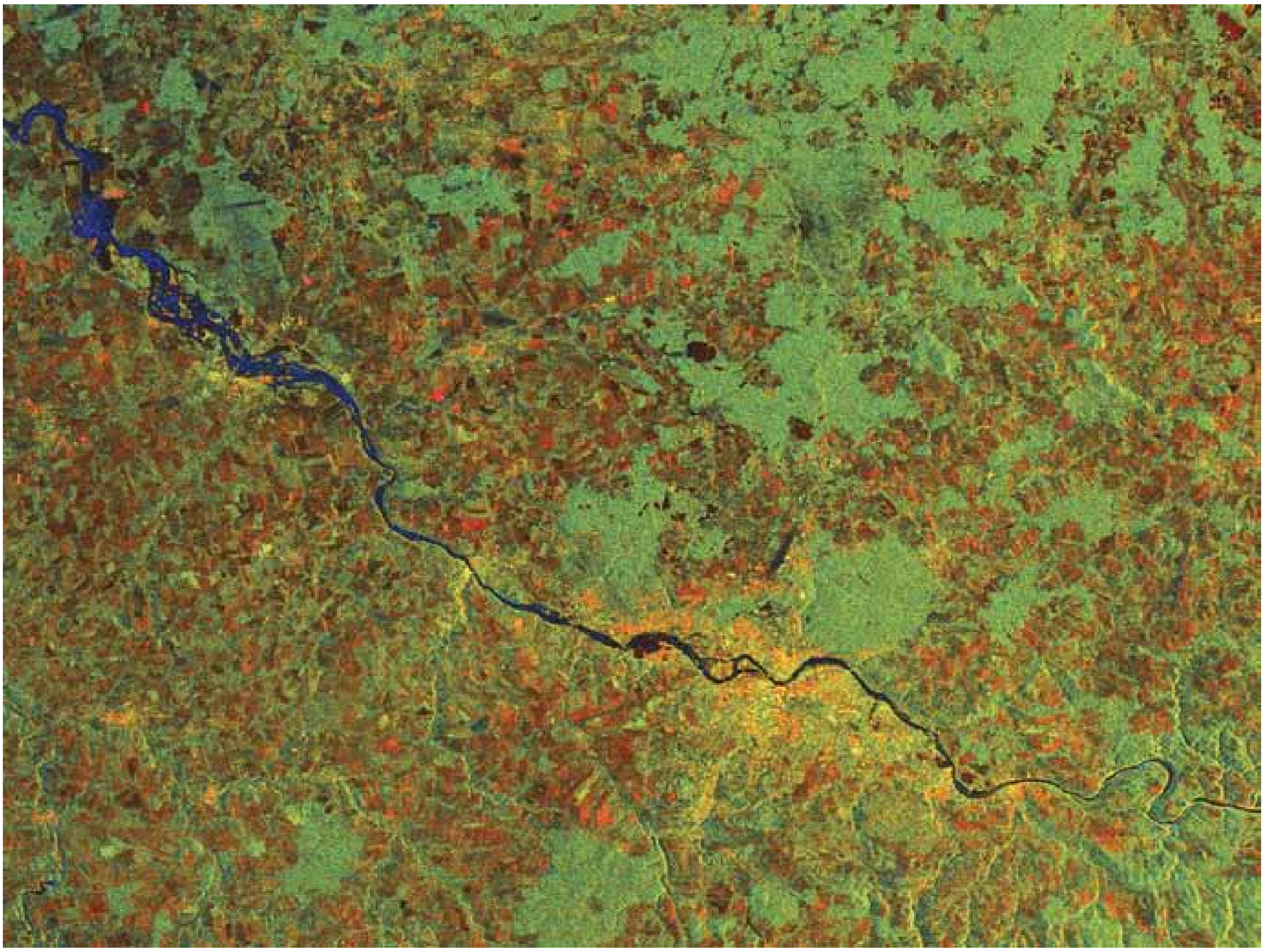


Figure 10.1. ASAR image, acquired in August 2002, showing the extent of flooding of the River Elbe, near Dresden, Germany. Alternating polarisations (HH, HV, diff. HH–HV).

The flood crisis mapping service is 'on demand' and is intended to provide flood extent information on a reference image or cartographic map within 24 h of a user request, and as a monitoring service on a daily basis during the crisis time window. Among other uses, these maps can be used to orient emergency response teams on the ground by highlighting potential access routes or areas at risk.

The floodplain risk assessment service relies on maps of historical flood events (e.g. maximum extent, duration and frequency) in order to feed models that estimate risk. The outputs of such modelling exercises can then be used in decision support systems that look at the environmental or economic costs associated with different planning or flood early warning options.

The EO data required include both optical and radar data, but preference is given to all-weather radar data due to the high probability of cloud cover. The contribution of Sentinel-1 data products to this application arises from the sensitivity of the backscatter signal to open water. Through radar intensity imagery, in the absence of wind, the specular reflection of C-band signals over open water means that the signal is significantly lower than average. Typically, change detection techniques are then applied to detect backscattering variations and to identify water bodies not present in historical reference data (Fig. 10.1).

Concerning the plain flood crisis mapping service, Sentinel-1 products using the Interferometric Wide-swath and Strip Map modes have adequate specifications to support the production of flood maps in emergency scenarios.

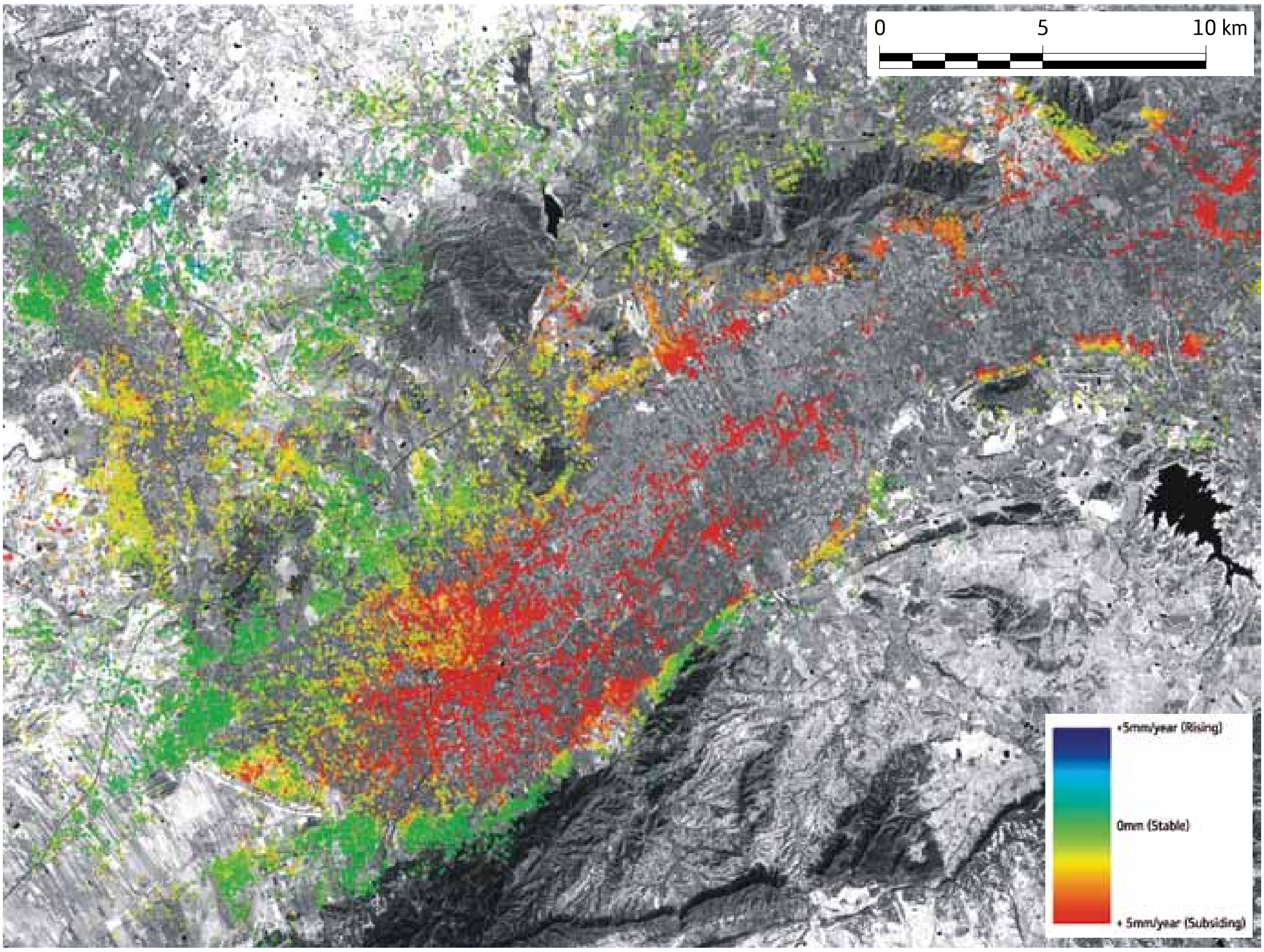


Figure 10.2. Terrain deformation map of Murcia, Spain, processed by Altamira Information for stage 2 of the TerraFirma project.

In the case of European alluvial plains, the Sentinel-1 IW mode is useful for systematic observations of affected areas during major flood events. In addition, Sentinel-1 SM acquisitions (to be used in exceptional cases only) are useful for emergency response services in urban or peri-urban areas. The products should be available in near real time from sensing.

Concerning the floodplain risk assessment service, the Sentinel-1 IW mode, with systematic acquisitions over Europe, should satisfy user requirements. In the case of European alluvial plains, the Sentinel-1 IW mode is useful for systematic observations of flood-prone areas in different seasons in order to generate historical hazard mapping to support risk estimation. Free and easy access to Sentinel-1 data will mean that the services will be affordable and as they could be used for all major river basins of Europe, the demand will increase. The volume of services could therefore increase significantly to cover Europe, with high potential to extend to the rest of the world.

10.2.2 Precise Terrain Deformation Mapping for Geohazard Risk Assessment

Terrain deformation maps are important tools that can be used to support geohazard risk assessment and mitigation, and are used by many geoscience centres (e.g. national geological surveys), disaster management and civil protection agencies, and coastal and transport authorities, as well as the civil engineering specialists who support them. Such maps are relevant in such domains as hydrogeological risks (e.g. subsidence and landslides), flood defence in coastal and lowland areas (e.g. dyke monitoring systems), and tectonics (e.g. seismic risk assessments).

Precise displacement measurements can be used to map ground stability and identify and characterise motion patterns. Particularly relevant to geohazard risk assessment is the long-term data continuity offered by space-borne SARs. More than 15 years of archived data are available for historical hazard mapping, and the guaranteed continuity of observations make terrain deformation mapping a unique technique.

The contribution of Sentinel-1 data products to various applications is based on the ability of the phase of the coherent radar signal to relate to the position and displacement of point targets. Using the Persistent Scatterer Interferometric (PSInSAR) technique, large volumes of radar data can be processed to determine populations of points (PSI points) with accurate geometric information, including velocity. This technique has been validated and allows for measuring ground deformations of a few millimetres per year, as illustrated in Fig. 10.2. This method is particularly robust with respect to artefacts introduced by the atmosphere, which typically alter the radar signal when conventional interferometry is used.

Sentinel-1 interferometric products (from IW mode) will provide high-resolution data with high spatial coverage (250 km) and high temporal sampling (12 days), helping to ensure a high density of persistent scatterers to provide (line of sight) velocity measurements. The combined use of ascending and descending acquisitions can provide improved motion measurements in 3D.

10.3 Marine Monitoring Applications

The Sentinel-1 mission will provide critical EO data for three applications related to marine monitoring:

— oil spill detection and polluter identification;
— sea-ice and iceberg monitoring;
— wind and wave information.

10.3.1 Oil Spill Detection and Polluter Identification

In order to strengthen operational responses to accidental and deliberate oil discharges from ships, the European Maritime Safety Agency (EMSA) has developed the CleanSeaNet service for all coastal EU Member States, Iceland and Norway. CleanSeaNet offers a near-realtime service that is integrated into national and regional response chains in order to assist coastal states locate and identify polluters in their areas of jurisdiction.

Illegal discharges of oil are distinctly visible in SAR imagery as characteristic dark features, as illustrated in Fig. 10.3. Trained operators analyse SAR images and are able to identify features of interest whose characteristics indicate with a high probability that a feature is an oil slick. In addition, possible sources of such oil (e.g. shipping vessels) are identified within the imagery. This information is correlated with cooperative vessel identification data (e.g. Automatic Identification System (AIS) or Long-Range Identification and Tracking (LRIT) information) for vessels in the area of the detected slick to support the identification of possible polluters. All information is provided to national authorities via EMSA sufficiently rapidly (within 10 min) after the satellite overpass so that airborne surveillance platforms can be cued to verify the presence or absence of the oil slick and obtain additional surveillance data.

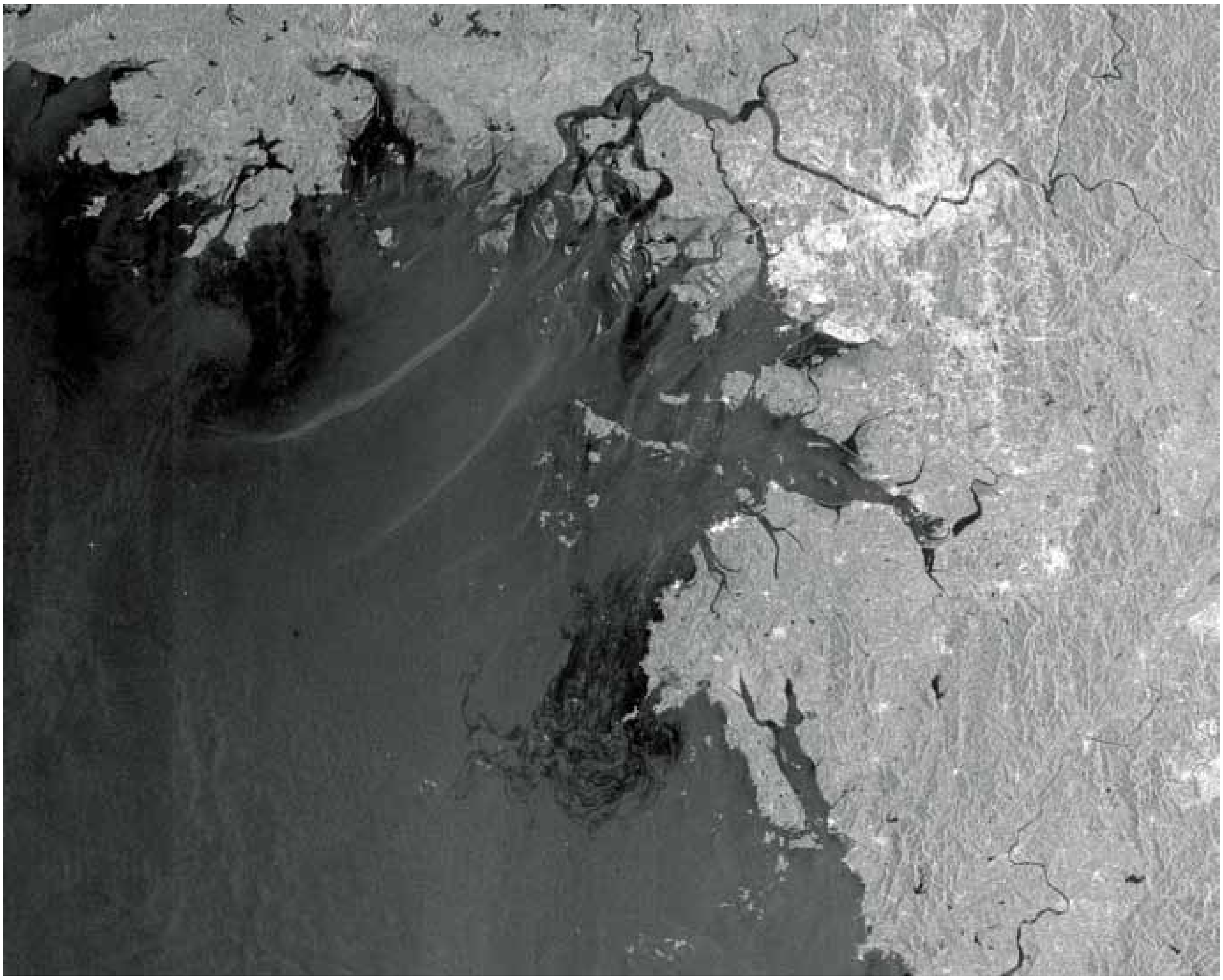


Figure 10.3. Crude oil from the wreck of the 146 000 tonne tanker, *Hebei Spirit*, off the coast of South Korea. More than 10 000 tonnes of oil from the tanker is reported to have leaked into the sea since it collided with another vessel on Friday 7 December 2007. The image was acquired on 11 December 2007 at 01:40 UTC by Envisat ASAR, while operating in its wide-swath mode covering an area approximately 400 × 400 km.

It is expected that the demand for such data will grow significantly because of the more frequent and timely imaging of EU waters than currently available and of the geographic expansion of the services to other areas.

10.3.2 Sea-ice and Iceberg Monitoring

Interest in sea ice and icebergs covers a number of issues, including the safety of shipping and offshore operations, climate monitoring and polar species habitat monitoring. In order to address these and other issues, the information on sea ice needs to include variables such as ice concentration, extent, type, thickness and drift velocity. The information on icebergs should include location, size and drift.

Two of the main services within sea-ice monitoring applications are sea-ice charting and ice-drift monitoring.

Sea-ice charting services are provided by national ice centres in Europe and Canada. For ice charting services the EO data requirement is for near-real time (<1 h) wide-swath C-band SAR (~100 m resolution) observations. The ice centres need to maximise the area covered in each EO acquisition, in combination with high radiometric resolution, requiring Sentinel-1 EW dual-polarisation products (e.g. HH + HV) that will allow better ice discrimination than is possible with Envisat single-polarisation data.

The requirements of ice-drift monitoring services are similar to those of ice charting services, although in most cases the use of a single polarisation (e.g. HH) may cover their needs.

The International Ice Patrol (IIP) provides operational monitoring of icebergs under the International Convention for the Safety of Life at Sea (SOLAS) near the Grand Banks off the coast of Newfoundland to promote safe navigation of the Northwest Atlantic Ocean where the risk of iceberg collision is high. The IIP has gradually increased its use of EO data over the last 5 years, and the Sentinel-1 IW mode data could assist the IPP achieve its objective of replacing aircraft surveillance with satellite observations. The IW mode should allow better iceberg detection due to the higher resolution compared to the EW mode and the use of dual-polarisation products will allow better iceberg (and ship) detection than from Envisat single or alternating polarisation data. For the IIP, the key areas for iceberg monitoring are localised and limited in extent.

10.3.3 Wind and Wave Information

Sea state and wind information are the two most important parameters for maritime safety and rescue operations. Offshore industry and marine engineering operations, shipping, coastguards, and pollution tracking and cleanup operations all require information on sea state and winds. In Europe, the primary sources of wind and wave forecast products are the Numerical Weather Prediction (NWP) models and wave models developed and operated by integrated weather centres at European (e.g. the European Centre for Medium-range Weather Forecasting, ECMWF) and national levels.

Following the necessary verification and validation, satellite data are gradually being assimilated by NWP model systems giving appropriate weights to satellite and other data inputs in an optimal manner. In this way, the best possible forecast is provided taking proper account of the data input quality in terms of uncertainty, representativeness as well as spatial and temporal sampling. Wave forecasting models have some limitations in their ability to handle accurately the movement of longer-wavelength swells generated by storm systems. Wavenumber spectra for the longer wavelengths are routinely retrieved from SAR wave mode products and are used to correct the longer-wavelength components in the wave models in order to improve the overall forecast accuracy. For NWP-based wind forecasts, in areas such as coastal regions, the spatial resolution of the basin- or global-scale forecasting models is not adequate and higher-resolution wind fields are required (e.g. for the management of wind farms). In such cases, wind information can be extracted directly from the SAR imagery based on standard algorithms that relate small-scale ocean surface roughness to the wind speed at a height of 10 m.

Sentinel-1 data will also be used for internal wave detection and monitoring, for instance, for offshore oil and gas production activities.

While SAR global ocean coverage at high resolution is currently relatively poor, Sentinel-1 data will significantly improve coverage and capability, providing a continuity of Envisat wave spectra, significant wave height, ocean currents and wind speed data (see Fig. 10.4). This information will be derived from the Wave mode, which will be systematically operated over open oceans when the other modes are not in operation, but also from the other modes planned to be used over oceans and seas (IW and EW).

10.4 Land Monitoring Applications

Two applications related to land monitoring for which the Sentinel-1 mission will provide critical EO data are:

— land use mapping for forestry and agriculture; and
— monitoring of snow, river and lake ice.

10.4.1 Land-Use Mapping for Forestry and Agriculture

Maps of land use and changes in land use underpin most activities related to studying and monitoring the environment. When considering land areas covered by forest, such mapping activities enable states to meet the reporting requirements specified in international agreements such as the Kyoto Protocol, and allow for credible measurement, reporting and verification of activities under the Reducing Emissions from Deforestation and Forest Degradation (REDD) programme. Such maps are also used to support forest management in Europe, and the monitoring of illegal timber harvesting worldwide.

The production of agricultural maps enables provision of independent and objective estimates of the extent of cultivation in a given country or growing season, which can be used to support efforts to ensure food security in vulnerable areas, especially in Africa. In the case of rice cultivation, for example, the sensitivity of the C-band backscatter to the crop and to the water in paddy fields, in combination with the all-weather capacity of SARs, mean that it is possible to provide very accurate monitoring services.

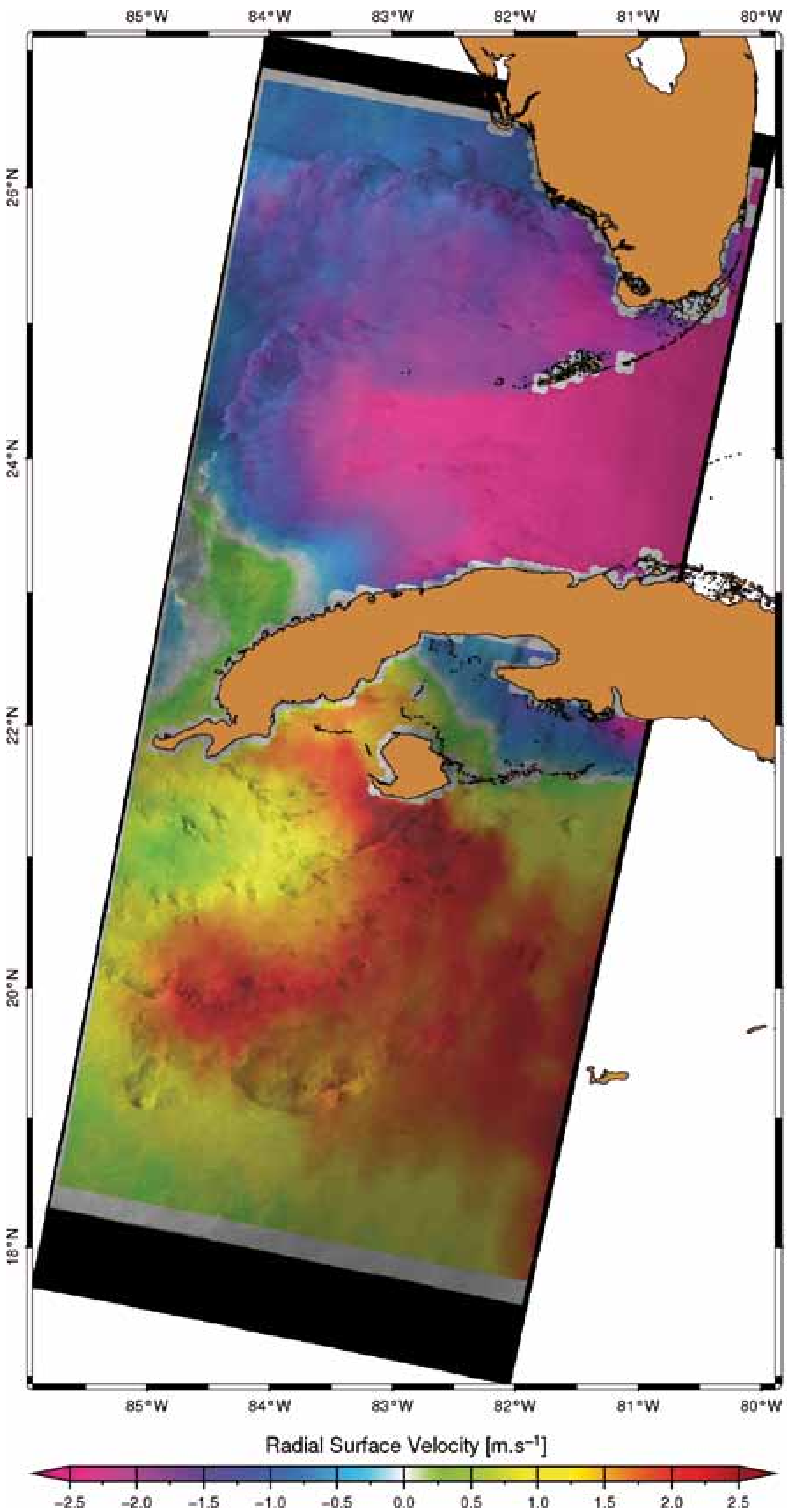
In the Sentinel age, the primary source of high-resolution land-use mapping will be Sentinel-2 data, but for areas subject to frequent cloud cover, especially in the higher latitudes and the tropics, synergy with Sentinel-1 is a possible remedy. The Interferometric Wide-swath mode (250 km swath) is particularly suitable for covering large areas regularly with a good geometric resolution (typically 20 m, with 5 ENL). The systematic use of dual polarisation, if feasible within the overall mission data acquisition constraints, will add value to the information provided by the relevant services. The use of the interferometric coherence is expected to improve mapping performance markedly compared with the use of the backscattered intensity alone.

10.4.2 Monitoring Snow, River and Lake Ice

Melting snow, and river and lake ice, or conversely, ice formation, can have significant implications for a wide range of activities, including flood forecasting and warning, and hydroelectric power production, as well as freshwater fish ecology. Furthermore, monitoring the timing of freeze-up and break-up of lake ice can be used to track the impacts of climate change on the affected populations in high-latitude regions.

The typical EO data requirement is for near-real time (or within 1 day after sensing) wide-swath C-band SAR observations. The IW mode is particularly well adapted, preferably acquired in dual polarisation, in particular for improving the accuracy of river ice classes, better snowline discrimination, etc.

Figure 10.4. Map of the radial component of sea-surface velocity over Cuba, produced in near-real time from Envisat's ASAR data, acquired at 15:29:38 (UTC) on 9 September 2008. (Courtesy of BOOST Technologies)



10.5 Security Applications

The GMES Security services are at an early stage of definition. However, one application related to security for which the Sentinel-1 mission will provide critical EO data is maritime surveillance. There are two elements of maritime surveillance of European waters that support and enhance awareness of the situation for security or critical infrastructure, law enforcement, traffic safety, fisheries control, and environmental protection.

The first element is the detection and tracking of vessels not transmitting Vessel Monitoring System (VMS) messages such as AIS or LRIT signals. For such vessels, it is necessary to investigate if they are engaged in illegal activity.

The second element is the monitoring and control of all vessels in defined areas of interest. These areas, typically 100 × 100 nautical miles but sometimes larger, as in the case of the Gulf of Aden, could be third-party territorial waters or international waters transited by traffickers or where monitoring is required for fisheries protection.

Shipping vessels provide strong reflections of the radar signal due to the scattering by the different structures on the ship. This results in characteristic bright features in the SAR imagery. Non-metallic and smaller vessels may also be visible but with a lower level of brightness. For vessels travelling sufficiently rapidly, wakes are also detectable in SAR imagery as characteristic V-shapes. Automatic detection software can rapidly scan SAR imagery and identify possible vessel targets based on the high backscattering intensity. Such analyses can provide information such as the location of a vessel, estimates of its size, heading and, if wake features are also visible, also its speed. For higher-resolution imagery or for larger vessels, key properties of the vessel structure can be identified allowing an initial classification of the vessel (e.g. container ship, oil tanker, ferry/cruise ship, etc.). This information is automatically correlated with available cooperative identification data (e.g. AIS, LRIT, VMS). Such correlations can indicate vessels that are not transmitting appropriate information or verify the information transmitted.

As in the case of activities related to oil spill monitoring, EO data should be made available as soon as possible in near-real time (i.e. the first images processed within few minutes of satellite overpass, in particular for areas on the edge of coverage by coastal systems), so that national services can cue conventional surveillance platforms or optimise their patrols. In the majority of cases, for medium to large vessels, the use of IW mode would guarantee the required geometric and radiometric resolution, and ensure a relatively wide coverage with an acceptable revisit frequency. Higher geometric resolution (from one to a few metres) is required for small targets and wake detection, but usually for smaller areas of interest; in these cases, therefore, the provision of relevant EO data by very high-resolution space-borne SAR systems should be ensured.

The use of the dual polarisation improves the ship detection performance. Similar to the case of oil spill monitoring services, the demand is estimated to grow significantly assuming higher sampling of EU waters as well as some geographic expansion of the service to other areas.

Figure 10.5 shows internal waves in the Strait of Gibraltar between Spain (top) and Morocco. From space, internal waves can be detected very efficiently using SAR instruments that are sensitive to changes in the small-scale surface roughness on the ocean surface. Internal waves in this image show up as a semicircular rippled pattern east of the strait in the Mediterranean. Additional sets of internal waves generated in the Atlantic are visible as dark lines on the western side of the strait. The image was created by combining three Envisat SAR acquisitions (on 12 August 2010, 1 October 2009 and 27 August 2009) over the same area.

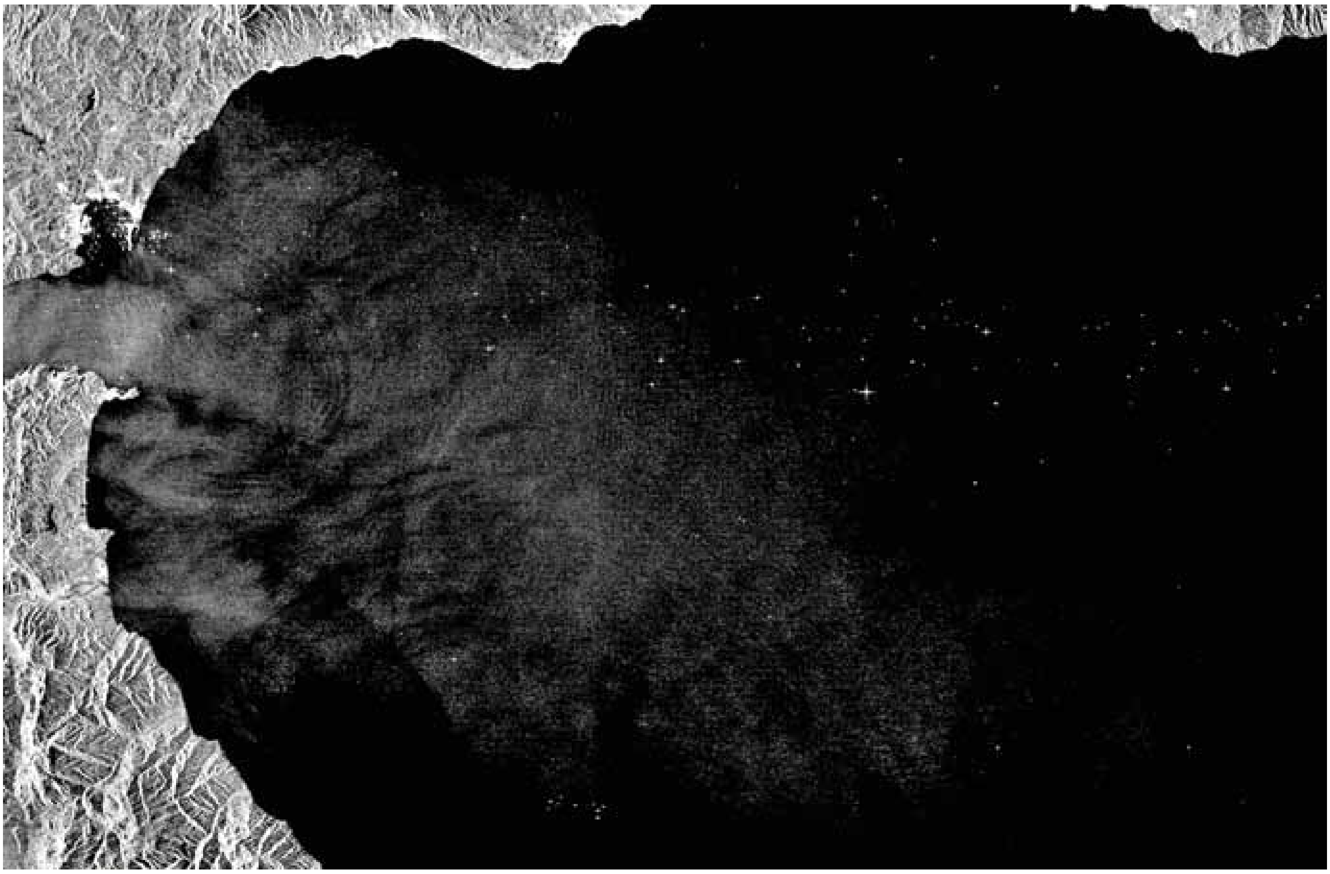


Figure 10.5. Example of a ship detection image to be expected from Sentinel-1.

10.6 Links to Projects

Emergency response applications

www.emergencyresponse.eu
www.terrafirma.eu.com
www.riskeos.com
www.respond-int.org/respondlive

Marine monitoring applications

www.myocean.eu.org
cleanseanet.emsa.europa.eu
www.polarview.org

Land monitoring applications

www.gmes-forest.info
www.gmfs.info
www.gmes-geoland.info
www.land.eu

Security applications

www.gmes-gmosaic.eu

11. Campaigns

In order to verify and then demonstrate the capabilities of the Sentinel-1 mission to meet both current and future user requirements, considerable effort has been put into pre-launch airborne and space-borne campaign activities supporting Sentinel-1.

A first large-scale airborne campaign organised by ESA was the IceSAR 2007 campaign that took place in Svalbard, Norway, and included participants from Canada, Germany and Norway. This multi-aircraft campaign was instrumental in collecting reference airborne SAR data over the different sea-ice regimes present near the archipelago, together with optical imagery and in-situ measurements to aid image interpretation. The collected image data were then used to carefully verify the suitability and demonstrate the performance of Sentinel-1 dual-polarisation imagery for sea-ice mapping applications, one of the key areas of application supported by the mission.

Using these data, the participating institutions and scientists were able to study and confirm that the technical choices made in the implementation of the mission, such as the dual-polarisation instrument modes and resolution, were highly suitable for operational sea-ice mapping. The IceSAR campaign also provided the first opportunity to simulate Sentinel-1 imagery directly from airborne data and to disseminate simulated image examples to the user community.

A second large-scale space-borne campaign, AgriSAR 2009, was started in 2009 to support the user community in preparing and developing methods to use future Sentinel-1 data in land cover and agricultural mapping applications. A particular feature of this campaign was that, for the first time, it involved the collection of a dense temporal series of images throughout the growing season at three sites with different agro-climatological conditions: Indian Head in Saskatchewan, Canada, Flevoland in the Netherlands, and Barrax near Albacete in Spain.

In total, 193 fully polarimetric Radarsat images were acquired throughout the growing season, which were processed and distributed for analysis to more than 25 participating institutions in Europe and North America. Among the various results of the campaign has been the demonstration of the capabilities of Sentinel-1 for crop status monitoring, i.e. the ability to follow and map the stages of crop growth over time. This process requires the continuous, weather-independent and pre-programmed acquisitions that only the Sentinel-1 mission will provide. Another breakthrough achieved by AgriSAR 2009 was the testing and benchmarking of multi-temporal filtering pre-processing steps, which have resulted in dramatic improvements in the quality of the SAR imagery by reducing the 'speckle' noise characteristic of radar images.

Overall, the above campaigns have greatly contributed to the Sentinel-1 mission through the simulation of Sentinel-1 products in terms of repeat observations, resolution and polarisation. They have also helped future users of the SAR data stream to visualise the types of data the mission will provide, and to prepare their applications to best make use of this new and valuable data source.

12. Sentinel-1 Product and Application Performance

Data products from Sentinel-1 consist of imagery representing radar echoes from the Earth surface. Basic calibrated data are provided in the form of both complex (in-phase and quadrature components) and intensity images, which are referred to as Level-1. Level-1 performance is defined by the parameter values listed in Table 5.1.

Level-2 data products include information extracted from the Level-1 imagery in the form of estimated values of geophysical variables. This type of Level-2 product requires a retrieval algorithm, so the Level-2 performance therefore depends on both the Sentinel-1 system performance and the retrieval algorithm. In the following sections the links between the instrument specifications presented in Table 5.1 and Level-1 and Level-2 image quality are briefly discussed.

12.1 System noise

The Sentinel-1 specification of –22 dB for noise-equivalent sigma zero (NESZ) encompasses all sources of system noise including thermal noise and quantisation noise sources. The impact of system noise on Level-1 quality will depend on the actual signal strength of the backscatter, and will generally broaden the distributions of amplitude and phase, reducing the accuracy of the Level-2 product.

Phase noise affects interferometric performance and in particular the error budget associated with subsidence monitoring using permanent scatterers.

12.2 Radiometric Accuracy and Stability

Radiometric accuracy and stability are specified for Sentinel-1 for all measurement modes to be within 1 dB (3σ) and 0.5 dB (3σ), respectively. The 3σ specification is based on the confidence intervals of a Gaussian (normal) distribution and refers to the probability of the instrument exceeding the specified interval.

The accuracy and stability numbers refer to measurement uncertainty of the radar backscattering coefficient using the image intensity excluding the effect of speckle and noise. These effects are defined by the radiometric resolution that is only implicitly part of the system specification and can be derived from the NESZ and the spatial resolution.

12.3 Radiometric Resolution

Radiometric resolution refers to the measurement uncertainty of the radar backscattering coefficient using the image intensity arising from speckle and noise for an otherwise perfect system. Radiometric resolution is expressed as the standard deviation of the measurement uncertainty normalised with respect to the mean. For an imaging system with noise bias subtraction, equation (1) gives the expression for radiometric resolution or accuracy. The expression applies if the noise bias is derived from a relatively large number of system noise estimates.

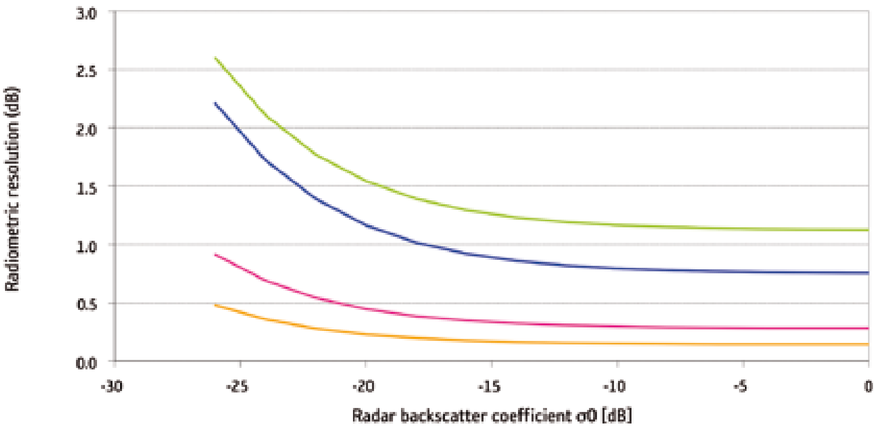


Figure 12.1. Radiometric resolution (in dB) as a function of the radar backscatter coefficient of a 150 × 150 m spatial resolution product.

IW mode 20*5, 1 look 250 km;
Strip Map mode 5*5, 1 look 80 km;
EW mode 40*20, 1 look 400 km;
ASAR Wide swath, 11.5 looks, 400 km.

$$\frac{\sigma_{st}}{I_o} = \frac{1 + \frac{1}{SNR}}{\sqrt{L}} \tag{1}$$

where

σ_{st} is the standard deviation of the image intensity in linear power;
I_0 is the mean image intensity in linear power;
SNR is the signal-to-noise ratio; and
L is the effective number of looks and is equal to (mean intensity)^2/variance.

The radiometric resolution has been calculated using equation (1) for a radar backscatter coefficient σ_0 varying from –26 dB m^2 m^{-2} up to 0 dB m^2 m^{-2} for the different imaging modes of Sentinel-1 with a NESZ of –22 dB. The results for a 150 × 150 m spatial resolution product are shown in Fig. 12.1. For comparison, the radiometric resolution of the Envisat ASAR Wide Swath is also given. It is clear that the IW mode of Sentinel-1 combines coverage with a high radiometric resolution capability.

12.4 Phase Errors

Phase errors are specified for the Sentinel-1 imaging modes to be within 5°. This number refers to the measurement uncertainty of the complex radar backscattering signal excluding the effects of speckle, noise, orbit errors and atmospheric effects. Some of these effects are defined separately and are therefore implicitly part of the system specification.

In an otherwise perfect linear system, phase errors associated with thermal noise could be related to the signal-to-noise ratio. Representing a linear process such as additive noise by a multiplicative effect such as a phase shift is questionable, but for relatively strong point scatterers and bright pixels with sufficient SNR the following relation can be used:

$$\Phi_N = \sqrt{<\varphi^2>} = \sqrt{\frac{N/2}{S}} = \frac{1}{\sqrt{2SNR}} \tag{2}$$

where Φ_N is the standard deviation of the phase error and SNR >> 1. This relation is illustrated in Fig. 12.2.

It is noted that the above relationship also applies in the case of permanent scatterer phase noise arising from background clutter. In this case the power N would represent the sum of noise power and clutter echo power.

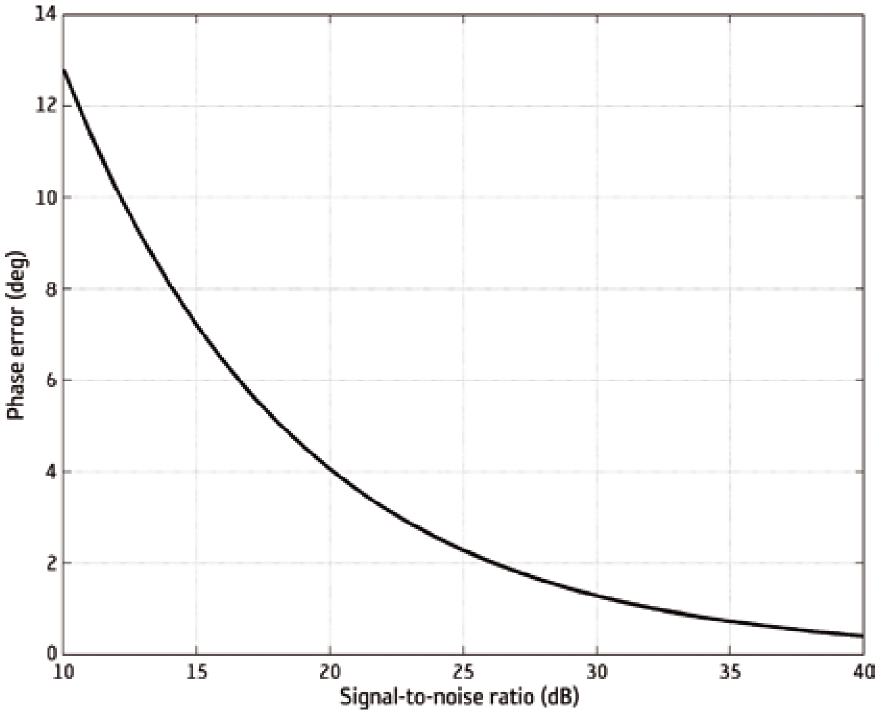


Figure 12.2. Phase error as a function of signal-to-noise ratio.

12.5 System Errors related to Level-2 Retrieval Performance

Retrieval algorithms such as those used for estimating soil moisture and wind speed rely on the absolute level of the received radar signal, while those used for land cover classification are generally based on simple generic algorithms:

- application of a threshold to a single intensity channel;
- maximum likelihood as a discriminator between two surfaces; and
- estimation of the ratio between two intensity channels (prior to comparison with a threshold).

For a number of algorithms currently in use and expected to be used for Sentinel-1 Level-2 product generation, the performances related to the measurement uncertainties of the Level-1 products have been studied.

12.5.1 Sentinel-1 Subsidence Monitoring Performance

Repeat observation and interferometric processing of the phase information of the radar echo facilitate observation of minute movements of Earth's surface from space with millimetre accuracy. This technique has found many applications, such as the observation of volcanoes, earthquakes, stability of buildings, surface expression of subsurface processes and glacier movements. The subsidence rate error budget can be calculated by inserting the total phase noise coming from the individual terms in the model derived by Davidson et al. (2009).

The calculated subsidence rate (mm yr^{-1}), taking into account the system geometry, parameters and performance of Sentinel-1, as well as other items affecting the estimate, e.g. temporal changes, atmospheric disturbances, orbital tubes, satellite attitude and assuming linear motion, and the standard deviation of the overall phase noise for Sentinel-1. The resulting subsidence rate error is on the order of 1.3 mm yr^{-1} (see Fig. 12.3).

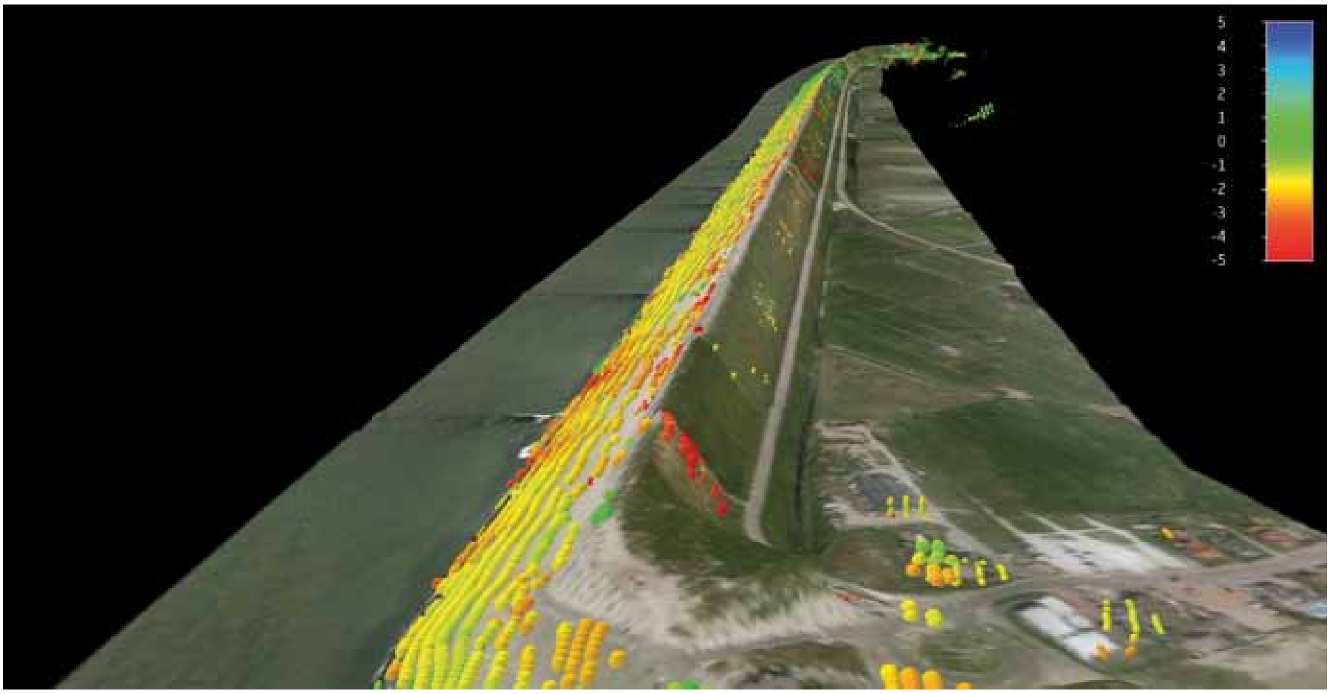


Figure 12.3. Subsidence monitoring of a dyke in the Netherlands. The coloured dots show the measured amount of subsidence (in mm yr^{-1}) as indicated by the colour bar on the right. (Hansje Brinker bv)

12.5.2 Sentinel-1 Sea-ice Classification Accuracy

Among potential users of Sentinel-1 SAR image products are operational services that provide information on ice conditions (extent, density, thickness, deformation) to ships and marine platforms in ice-covered ocean regions. Sea-ice mapping includes the visual or automatic separation of different types and structures of ice. Dierking (2010) has shown that the radar intensity contrast between different ice types depends on the ice regime and on environmental conditions. Table 12.1 presents a list of mean intensity contrasts between dominant ice classes for three different ice regimes in the region of Svalbard. The notation 'dominant ice class' indicates that an operator who analyses an SAR image can clearly recognise the respective ice type or feature and distinguish it from other classes. The data are valid for an incidence angle range of 30° to 45°. They are based on the simulations of images with the characteristics of the Sentinel-1 IW mode, using a pixel size of 20 × 20 m, which implies approximately four looks.

At like-polarisation, the classification accuracy using an image with number of looks = 4 (20 × 20 m) is moderate for the Storfjord and the Barents Sea ice regimes. With pixels of double size and a corresponding increase in the number of looks, the accuracy improves to values >80%. The use of even larger pixel sizes, however, will have a considerable impact on the ability to perceive narrow deformation structures such as ice ridges and brash ice between ice floes because of the related reduction in spatial resolution. It has to be taken into account that the effective radar intensity contrast of a structure relative to the adjacent ice is decreased if the structure does not fill the entire area of a given pixel. For the Fram Strait ice regime, the classification accuracy is already ≥90% for 20 × 20 m pixels.

At cross-polarisation, the intensity contrast between the dominant ice classes is low, with the exception of the deformed ice in the Fram Strait ice regime. Hence, the classification accuracy for an automated separation of ice types is not sufficient. Only if the neighbouring pixels are averaged such that the number of looks is increased to values close to L = 100, would the accuracy

Table 12.1 Intensity contrast (IC) between major ice classes in Sentinel-1 IW images and classification accuracy (A, in parentheses).

Location	Pairs of dominant ice classes	IC (dB) and A (%) for classes 1 and 2, VV-polarisation	IC (dB) and A %) for classes 1 and 2, HH-polarisation	IC (dB) and A (%) wfor classes 1 and 2, cross-polarisation
Storfjord	1: young level ice 2: broken + brash ice	1.46 (62.9)	1.67 (64.7)	1.02 (59.1)
	1: new ice 2: young level ice	3.58 (78.9)	7.93 (96.0)	0.21 (51.9)
Barents Sea	1: young/first-year level ice 2: brash + rubble ice	2.96 (74.7)	3.26 (76.8)	1.16 (60.3)
	1: new ice 2: young/first-year level ice	2.92 (74.4)	2.40 (70.5)	0.02 (50.2)
Fram Strait	1: first-year level ice 2: ridges + brash ice	7.28 (94.7)	6.42 (92.3)	11.47 (99.3)
	1: new + young ice 2: first-year level ice	5.62 (89.5)	6.37 (92.2)	0.57 (55.1)

be >80%. But in this case, the theoretical gain may be outweighed by the loss of spatial resolution as explained above.

Increasing the coverage by using the EW mode would reduce the classification accuracy to unacceptably low levels due to the decrease in radiometric resolution of the EW mode compared with the IW mode.

12.5.3 Sentinel-1 Snow-Cover Monitoring Performance

C-band SAR can be applied for mapping the extent of snow area (melting snow only). The requirements in terms of spatial resolution and repeat observations of the Snow-covered Area (SCA) product are specified in the IGOS Cryosphere Theme Report.

The requirements in Table 12.2 indicate that spatial resolution of the SCA product is not a primary issue with Sentinel-1, allowing for considerable multi-looking. The temporal requirement of 1 day is challenging. This number refers to the hydrometeorology of lowlands, where snow cover may be quite volatile. Obviously, the contemporaneous operation of two Sentinel-1 satellites will enable operational products with a temporal resolution of less than 5 days. For practical applications, the integration of SCA products in hydro-meteorological models means that it is possible to bridge gaps in the temporal sequence.

It should be pointed out that C-band SAR is not able to supply the full SCA product, because it is not sensitive to dry snow. But there are various possibilities to infer the extent of dry snow from other sources, as briefly addressed below. For hydrological applications, the timely and accurate observation of melting snow areas that is possible by means of Sentinel-1, is very important.

For the spatial resolution of the snow product the target requirement of 5% measurement accuracy from IGOS for 100 × 100 m products is assumed (a 10% figure is assumed for the threshold requirement). Only the speckle-related

Level	Measurement accuracy	Spatial resolution	Temporal resolution	Driver
Threshold	10%	0.5 km	1 day*	Hydromet
Target	5%	0.1 km	12 h*	

* Temporal requirements are relaxed for climate research (5–7 days) and for the hydrology of mountain areas (3–5 days).

Table 12.2. Requirements for Snow-Covered Area (SCA) products.

Table 12.3. Specifications for SCA products derived from Sentinel-1 IW mode data.

Mode	IW
Pixel size of SCA product	100 × 100 m
Azimuth looks	5
Range looks	20
Total number of looks for SCA products	100

uncertainty for the classification of wet snow is taken into account. The IW mode of Sentinel-1 has been used as the baseline for the SCA retrieval. The number of looks for the required size of the SCA product is 100, as specified in Table 12.3.

The probability of error in the discrimination of two classes is 5% for a 2 dB difference between the classes using the Sentinel-1 IW mode. Using the average of several images for the reference and by reducing the spatial resolution of the product the error can be reduced.

12.5.4 Sentinel-1 Rice Field Mapping Performance

Rice is a vital food crop. In many countries, it forms the basis of the economy and is the staple food of many people. To control and maintain a close balance between rice production and food needs, an effective rice-monitoring programme is required at regional, national and international scales.

For rice field mapping, C-band SAR intensity data are particularly well suited to rice monitoring, because of the all-weather capability of the SAR systems to acquire data over rice-growing regions that are frequently covered by cloud, and the remarkable increase in backscatter intensity throughout the growth cycle as the rice plants grow above the water surface and interact with the incident radar signal.

Quantitative performance requirements in terms of the threshold or target accuracies required by individual applications are generally not available.

The traditional method of rice cultivation involves flooding the fields while, or just after, planting out the young seedlings. From a previous assessment of the use of Envisat ASAR data for rice mapping in China, it has been shown that for Sentinel-1 the temporal behaviour of co-polar signals can be used as a classifier over areas where rice paddies are flooded.

Based on the use of Sentinel-1 for rice crop mapping the following conclusions can be drawn:

— The NESZ has a limited impact on the quality of the segmented maps based on the multi-temporal co-polar images. This was to be expected as the σ_0 values for these natural surfaces are relatively high, at least for co-polar images. A sensitivity analysis has shown that there is not much gain in performance when the NESZ is lowered below –22 dB.
— The increased number of acquisitions by Sentinel-1 during the growing season enables proper sampling throughout the growth cycle and limits the impact of geophysical noise (such as by identifying a date with no wind when the water surface is very smooth). With one Sentinel-1 acquisition every six days, it is expected that the performance of the multi-temporal algorithm will be dramatically improved compared with that obtained with ASAR. In addition, in regions where multiple agricultural practices are common (e.g. different sowing dates throughout the region), a higher temporal sampling will be very beneficial.

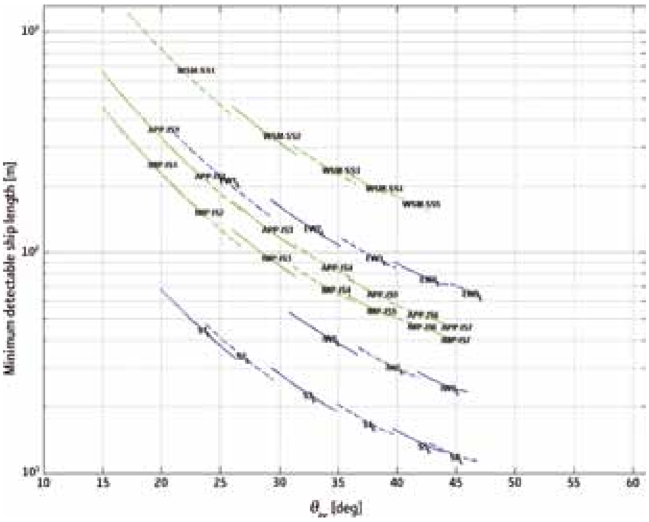


Figure 12.4. Minimum detectable ship length for Sentinel-1 HH (blue) and Envisat ASAR HH (green).
HH, U = 12 m s^{-1}, φ = 0°; ν = 4; PFA = 2.5e–009; PD = 0.9; margin = 3 dB.

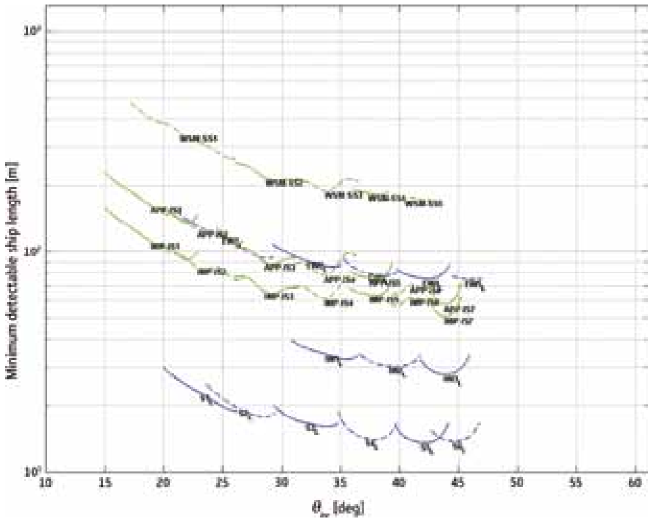


Figure 12.5. Minimum detectable ship length for Sentinel-1 HV (blue) and Envisat ASAR HV (green).
HV, U = 12 m s^{-1}, φ = 0°; ν = 4; PFA = 2.5e–009; PD = 0.9; margin = 3 dB.

The better range resolution of Sentinel-1 will allow for more efficient spatial multi-looking, which is important for this application when used in regions with very small paddy fields.

12.5.5 Sentinel-1 Ship Detection Performance

The minimum ship lengths that can be detected by Sentinel-1 are shown in Figs. 12.4 and 12.5 (the fixed parameters used in each case are shown in the captions). The plots use the actual ground range resolution and NESZ specific to each position in the swath. The plots are colour coded by sensor and include Sentinel-1 (blue), and Envisat ASAR (green). For each sensor, the beams are plotted alternately with solid and dashed lines, and the beam mode labels are placed at the centre of each swath (some of the plots are quite busy). The curves for the HH case tend to be smooth and co-linear due to the clutter-limited imaging. The curves for the HV case follow the shape of the noise floor due to the noise-limited imaging.

From Figs. 12.4 and 12.5, it can be noted:

- The minimum detectable ship length for the groups of single-beam modes decreases with increasing incidence angle, which illustrates the importance of the incidence angle in reducing the background ocean clutter level.
- The minimum detectable ship length decreases for modes with increasing (i.e. smaller) resolution.
- For co-polarisation, the ship radar cross section (RCS) is larger, but the clutter level is higher, especially for smaller incidence angles. For the co-polarisation case, the clutter level is generally limited.
- For cross-polarisation the ship RCS is smaller, but the clutter is below the noise floor; the cross-polarisation case is noise-limited. There are significant benefits to using cross-polarisation, especially for acquisitions at smaller incidence angles. Furthermore, cross-polarisation provides more uniform ship detection performance across the image swath since the noise floor is somewhat independent of incidence angle.

Considering Sentinel-1, using EW mode for its broader swath incurs the penalty that its resolution is coarser than IW mode.

12.6 Sentinel-1 Level-2 Product Performance Summary

The expected performance of Sentinel-1 Level-2 products is summarised in Tables 12.4, 12.5 and 12.6 for a given spatial resolution adapted to a product type. Note that the results given here are based on ideal retrieval cases, with no other errors than those related to the Sentinel-1 performance. The retrieval algorithm is assumed to be error-free.

Table 12.4. Sentinel-1 Strip Map mode Level-2 product performance.

Level-2 product	Resolution	Performance	Units
Subsidence rate	10 × 10 m	1.3	Rate uncertainty (mm yr^{-1})
Land cover (2 dB contrast)	30 × 30 m	90.0%	% correct classification
Forest/non-forest classification	30 × 30 m 100 × 100 m	98.3% 100 %	% correct classification
Soil moisture	100 × 100 m	3.2 (3σ)	Moisture content uncertainty (vol%)
Flood mapping	30 × 30 m	93.0%	% correct classification
Snow-cover classification (3 dB contrast)	30 × 30 m	80.0%	% correct classification
Ship detection HH–HV polarisation	5 × 5 m	12–23 (90%) (swath dependent)	Minimum ship length (m) (probability of detection)
Sea surface wind speed	100 × 100 m	1.3 (3σ)	Speed uncertainty (m s^{-1})
Sea surface currents	5 Hz	30	Speed uncertainty (cm s^{-1})

Table 12.5. Sentinel-1 Interferometric Wide-swath mode Level-2 product performance.

Level-2 product	Resolution	Performance	Units
Subsidence rate	5 × 20 m	1.3	Rate uncertainty (mm yr^{-1})
Land cover (2 dB contrast)	30 × 30 m	90.0%	% correct classification
Forest non-forest classification	30 × 30 m 100 × 100 m	74.3% 100 %	% correct classification
Soil moisture	100 × 100 m	3.9 (3σ)	Moisture content uncertainty (vol%)
Flood mapping	30 × 30 m	79.4%	% correct classification
Snow-cover classification (3 dB contrast)	30 × 30 m	75.0 %	% correct classification
Ship detection HH–HV polarisation	5 × 20 m	25–34 (90%) (swath dependent)	Minimum ship length (m) (probability of detection)
Sea surface wind speed	100 × 100 m	2.4 (3σ)	Speed uncertainty (m s^{-1})
Sea surface currents	5 Hz	30	Speed uncertainty (cm s^{-1})

Table 12.6. Sentinel-1 Wave mode Level-2 product performance.

Level-2 product	Resolution	Performance	Units
Significant wave height	20 × 20 km	0.3	Height uncertainty (m)
Dominant wavelength	20 × 20 km	40	Wavelength uncertainty (m)
Dominant direction of propagation	20 × 20 km	12	Direction uncertainty (°)

13. Sentinel Data Policy

An open and free Sentinel data policy has been approved by ESA Member States, endorsed by the European Commission, and finally approved by the EU Parliament and EU Council.

The principles of the Sentinel Data Policy are as follows:

— anyone can access acquired Sentinel data; in particular, no distinction is made between public, commercial and scientific uses, or between European or non-European users;
— licenses for the use of Sentinel data are available free of charge;
— Sentinel data will be made available to users via ‘generic’ online access, free of charge, subject to a user registration process and the acceptance of generic terms and conditions;
— additional access modes and the delivery of additional products will be tailored to specific user needs, and thus will be subject to tailored conditions; and
— in the event that security restrictions apply, affecting the availability or timeliness of Sentinel data, specific operational procedures will be activated.

It is expected that this open and free access to the data (for any purpose, within or outside Europe), will maximise the beneficial use of data for the widest range of applications. It will strengthen EO markets in Europe, in particular the downstream sector, with a view to promoting growth and job creation.

This data policy is in line with the principles of the Infrastructure for Spatial Information in the European Community (INSPIRE), the Global Earth Observation System of Systems (GEOSS), etc.

14. Scientific Use of Sentinel-1 Data Products

The Sentinel missions, although primarily designed to provide routine observations for the operational GMES services, will also be supporting and stimulating innovative Earth system science.

The long-term operation of various sensors with global coverage and high revisit times, covering different spectral and spatial resolutions, will lead to advances in the understanding of Earth system processes and interactions. The continuity of Earth observation data that are already widely used within the scientific communities, with a long-term operational commitment, is essential for the parameterisation of long-trend forecasting. Furthermore, the high temporal frequencies are well suited for capturing rapid changes, and for supporting the validation of forecasting models and their subsequent improvement. Long-term climate forecasting will certainly benefit from this development. In addition, the Sentinels offer an increased spectral coverage that supports data harmonisation, which is a prerequisite for establishing an undisputed climate data record, and additional science products with many potential applications, thus fostering knowledge transfer to the GMES service domain.

'Data synergy' will play a key part in the exploitation of the Sentinels. The synergistic use of data is recognised as a convenient way of extracting the maximum potential from the combined time series, but in practice the synergy among the different types of data will require new developments for extracting consistent information from all Sentinels combining different data sets from radar, optical imagers, spectrometers and profilers with different spatial, temporal and spectral sampling characteristics. Such synergistic exploitation of data coming from the different Sentinel systems will increase the potential for the development of new tools and advanced products, leading to new capabilities for scientific exploitation. Synergistic processing is further supported by the timeliness of the Sentinel and Earth Explorer data. The first Sentinel missions (Sentinel-1/-2/-3 A-units) will be operational from 2013 onwards, although they will require two units flying in parallel in order to have an operational system in place. The B-units will be ready for launch approximately 18 months after the A-units. It is expected that the operation of most Earth Explorers will be complementary, offering a variety of synergies ranging from the provision of auxiliary information, to making substantial contributions to efforts to address scientific challenges.

The need for timeliness calls for integrated data exploitation strategies that are very important for the development of a holistic Earth system model. The combined Sentinel and Earth Explorer missions programme is expected to reduce observation limitations and strengthen our ability to monitor the state and changes of planet Earth. By filling in the gaps in our knowledge and improving our quantitative understanding, we will be able to develop more reliable model- and data-based assessments and predictions of the Earth system.

Integrated data analysis will be further stimulated by ESA's support of dedicated themes, tailored to specific aspects of Earth system modelling and coordinated with the international research community. That community will undoubtedly continue to play an indispensable role in the implementation of the Group of Earth Observation's (GEO) GEOSS, including its evolution and sustainability.

The Earth observation system necessary to meet the operational global monitoring requirements of end-user organisations (environment and security) has resulted in the Sentinel mission design, data product specifications, data access mechanisms, and the 'free and open' Sentinel data policy. The scientific use of the Sentinel data will in no way impact on or compromise the dedicated use of the data in support of GMES services. In practice, improved understanding of the data obtained in pursuit of scientific questions, and the methods developed to address them, may in fact be of great benefit to the execution of existing services and the development of new ones. ESA will therefore strive to ensure that data from the Sentinels are made available to the science community.

15. Summary and Conclusions

In the frame of the Global Monitoring for Environment and Security (GMES) Space Component programme, ESA is undertaking the development of a European Radar Observatory (Sentinel-1), a polar orbiting satellite system that will ensure the continuation and improvement of SAR (synthetic aperture radar) operational services and applications addressing primarily medium- to high-resolution applications through a main mode of operation that features both a wide swath (250 km) and high geometric (5×20 m) and radiometric resolution, allowing imaging of global landmasses, coastal zones, sea ice, polar areas, and shipping routes at high resolution.

Sentinel-1 is designed to respond to emergency requests to support disaster management in crisis situations but otherwise works in a pre-programmed, conflict-free operation mode that will ensure the reliability required by operational services and will create a consistent long-term data archive for applications based on long time series.

The Sentinel-1 satellites are being built by an industrial consortium led by Thales Alenia Space (Italy) as the Prime Contractor, while Astrium (Germany) is responsible for the C-band Synthetic Aperture Radar (CSAR) payload, which incorporates the central radar electronics subsystem developed by Astrium UK.

The Sentinel-1 ground segment will monitor and control the satellite during all mission phases. It has facilities for the generation and uplink of the mission schedules, and for the systematic reception, processing, archiving and analysis of the acquired satellite housekeeping telemetry.

It also will be in charge of reception of SAR instrument data, systematic processing, archiving and dissemination of operational SAR data for the GMES services, and of various planning and monitoring tasks.

Sentinel-1 is expected to become one of the main data sources for the six GMES service themes identified by the European Commission for which it will support the provision of operational services based on Earth observation data: Emergency Response, Marine Monitoring, Land Monitoring, Atmospheric Monitoring, Security, and Climate.

An open and free Sentinel data policy has been approved by ESA Member States, endorsed by the European Commission, and approved by the EU Parliament and EU Council. It is expected that this open and free access to the data (for any purpose, within or outside Europe), will maximise the beneficial use of data for the widest range of applications. It will strengthen EO markets in Europe, in particular the downstream sector, with a view to promoting growth and job creation.

The Sentinel missions, although primarily designed to provide routine observations for the operational GMES services, will also support and stimulate innovative Earth system science.

→ APPENDICES

Appendix A: Members of the Sentinel-1A and -1B Industrial Consortium

Prime contractor	**TAS-I (Italy)**
System activities	
Orbit analysis	GMV (Spain)
Mission & operation scenario analysis	OHB (France)
End-to-end SAR system calibration	DLR (Germany)
Basic products	MDA (Canada)
Raw data simulation/processor prototype	Aresys (Italy)
Satellite	
TRM, HPA/DRV/LNA chip	UMS (France)
SAS TRM core chips	OMMIC (France)
Avionics & subsystems	
SMU	TAS-I (Italy) RUAG (Sweden)
SMSW	SSI (Italy)
GPS	RUAG (Austria) RUAG (Sweden)
FSS	Jena-Optronik (Germany)
CRGS	Honeywell (USA)
STT	Galileo Av. (Italy)
MGM	Lusospace (Portugal)
MGT	Iai Tamam (Israel)
RW	Rockwell C (Germany)
GYRO	Astrium SAS (France)
Independent SW verification & validation	
ISVV	DNV (Norway) SCV (Portugal)
Electronic Power S/S	
PCDU	TAS-Etca (Belgium)
CAPS	Galileo Av. (Italy)
BTA	ABSL (UK)
SAW	Dutch Space (Netherlands) Astrium (Germany)
SRM	Kongsberg (Norway)
Structure and thermal control	
STR	RUAG (Switzerland) Apco (Switzerland)
TCS	ECE (Spain) RUAG (Austria)
TT&C	
SBT	TAS-E (Spain)
SBA	RUAG (Sweden)
Propulsion	
PVF	Astrium (Germany)
LT	Rafael (Israel)
RCT	Rafael (Israel)

PDHT	
DSHA	TAS-I (Italy) Scysis (UK)
TXA	TAS-E (Spain) TAS-F (France) TAS-Etca (Belgium)
XBAA	TAS-I (Italy)
Satellite harness	
DC & Pyro Harness	Latelec (France)
RF Harness	Rymsa (Spain)
1553 B Harness	Axon (Germany)
PDHT EGSE	Siemens A (Austria) Space Eng (Italy) SSBV (Netherlands)
S/C EGSE	
PWR SCOE	Rovsing (Denmark)
TT&C SCOE	Siemens (Austria) SSBV (Netherlands)
DC LAS	Clemessy (Switzerland)
TM/TC FE	SSBV (Netherlands)
S/C MGSE	Apco (Switzerland)
Propulsion GSE	TAS-I (Italy)
S-band Suitcase	SSBV (Netherlands)
SAR Instrument	Astrium (Germany)
SAR performance analyses	Astrium (Germany)
APDN, EPDN, RFHN	DA-Design (Finland)
TPSU	Galileo Av. (Italy)
TCU	RUAG (Sweden)
DCU	TAS-E (Spain)
Thermal H/W	RUAG A (Austria)
APF & ASS	RUAG (Switzerland)
Tile antenna non-RF harness	Altran (Germany)
DEM	Sener (Spain)
SAS SCOE, power SCOE	Clemessy (Switzerland)
DCU SCOE	Clemessy (Switzerland)
Containers, handling & integration, MGSE, test adapter & depl. test device	Apco (Switzerland)
Test Facilities	IABG (Germany)
HRM	Astrium (Germany)
SAR Electronics Subsystem (SES)	Astrium Ltd (UK)
TXM	RUAG (Sweden)
TGU	DA-Design (Finland)
SES MGSE	EPS (UK)
SES Harness	Kayser-Threde (Germany)
SES ICM	Syderal (Switzerland)
SES MDFE	DA-Design (Finland)
SES DC DC	Blu Electronics (Italy)
SES EGSE	Siemens (Austria)
Echo simulator	SEA (UK)
EGSE software	Terma (Denmark)
Test equipment	SSBV (Netherlands)

Appendix B: Sentinel-1 Product Descriptions

To satisfy the different user requirements, the Sentinel-1 mission will be able to provide a variety of image and/or information products.

The Sentinel-1 Payload Data Ground Segment shall be able to generate and make available to users different types of Sentinel-1 products based on:

- requirements given in the Sentinel-1 Mission Requirements Document (MRD);
- current data requirements from GMES core services;
- new data requirements from GMES downstream services;
- requirements from currently supported ESA users, including meteorological offices and the scientific community;
- the expected data requirements from EU agencies and national requests; and
- the projection of these requirements for the GSC operations phase from 2013/2014 onwards.

The complete portfolio of Sentinel-1 products shall respond to the different sources of requirements mentioned above and also ensure their compatibility with existing Envisat ASAR or ERS SAR products to provide long-term continuity.

The Sentinel-1 Core PDGS will generate some of these products operationally, while the Core or the Collaborative PDGS may support some of them and the GMES Core and downstream services are expected to generate the final information products (e.g. ice charts, forest maps and ground surface deformation maps).

This section focuses on the operational products generated by the Sentinel-1 Core PDGS and made available to Sentinel-1 users. These products are based on validated processing algorithms. They are generated by the Sentinel-1 Core PDGS with committed timeliness, reliability and certified quality.

In addition to the SAR Operational User products, the Core PDGS will support the generation of SAR Hosted User products. These products are based on the capability of the Sentinel-1 PDGS to offer a hosted processing service. The aim is to bring user processing or post-processing steps closer to the data source (i.e. the PDGS) in order to reduce the end-to-end timeliness or the overall data volume to be disseminated. The generation of these products can be supported by the Sentinel-1 PDGS infrastructure, according to algorithms and processor functions implemented by Sentinel-1 users. In these cases, ESA has not defined the processing algorithm and final product quality.

Section B.1 describes the Sentinel-1 operational user products and Section B.2 introduces the hosted user products.

B.1 Sentinel-1 Operational Products

Sentinel-1 operational SAR user products generated by the Core PDGS provide continuity with existing Envisat ASAR products or with other current or planned Sentinel-1 group missions, which include Level-0, Level-1 and Level-2 products.

B.1.1 SAR Level-0 Products

Level-0 products contain the compressed, unprocessed instrument source packets, with additional annotations and auxiliary information to support the processing.

Level-0 products are stored for long-term data preservation and can be used to generate any type of product from the archive during the mission lifetime and for 25 years after the end of the space segment operations.

SAR Level-0 products contain the downlinked sequence of SAR instrument source packets for a data take, including noise, internal calibration and echo source packets.

Only SAR Level-0 products for SAR SM, IW and EW modes are made available to Sentinel-1 users.

B.1.2 SAR Level-1 Products

The following types of operational Level-1 products can be generated and disseminated by the Sentinel-1 PDGS:

- Slant-Range Single-Look Complex (SLC) products provide focused data in slant-range geometry, single-look, containing phase and amplitude information. Sentinel-1 SLC products provide continuity with ERS SAR, Envisat ASAR and other Sentinel-1 group mission SLC products.
- Ground Range Detected (GRD) georeferenced products. Focused data are projected to ground range, detected (phase information is lost) and multi-looked with different numbers of looks and resolutions. A square pixel size is adopted according to the selected resolution. Data are projected to ground range using an Earth ellipsoid model and a digital elevation model (DEM), maintaining the original satellite path direction and including complete georeferenced information.

The following characteristics are applicable to Sentinel-1 Level-1 products:

- All the information needed to convert digital pixel values to backscattering is included in the product and is applicable as a simple operation (no technical documentation will be required to perform the conversion). A calibration matrix will be annotated as part of the product, which allows the simple conversion of image intensity values into sigma or gamma nought values.
- Spatial and radiometric resolution values are defined for standard Sentinel-1 GRD products.

For standard Sentinel-1 GRD products, three levels of resolution are defined: full resolution (FR), high resolution (HR) and medium resolution (MR). For the same resolution class, pixel spacing values are common (whenever feasible) for different acquisition modes. Table B.1 summarises the characteristics at mid-range and mid-orbit height, for the defined standard Sentinel-1 ground range products. Note that small resolution variations from sub-swath to sub-swath for the SM mode are not shown in the table.

Table B.1. Sentinel-1 ground range detected product characteristics: resolution, pixel spacing and equivalent number of looks (ENL).

<table>
<tr><th rowspan="2"></th><th colspan="3">FR (full resolution)</th><th colspan="3">HR (high resolution)</th><th colspan="3">MR (medium resolution)</th></tr>
<tr><th>Resolution (m)</th><th>Pixel (m)</th><th>ENL</th><th>Resolution (m)</th><th>Pixel (m)</th><th>ENL</th><th>Resolution (m)</th><th>Pixel (m)</th><th>ENL</th></tr>
<tr><td>SM</td><td>9</td><td>4</td><td>4</td><td rowspan="2">23</td><td rowspan="2">10</td><td>34</td><td rowspan="3">90</td><td rowspan="3">40</td><td>>400</td></tr>
<tr><td>IW</td><td rowspan="2" colspan="3">–</td><td>5</td><td>100</td></tr>
<tr><td>EW</td><td>50</td><td>25</td><td>3</td><td>12</td></tr>
</table>

B.1.3 SAR Level-2 Products

Sentinel-1 Level-2 products are defined for marine applications as the continuation of existing operational Envisat ASAR products, considering the expected evolution of existing demonstration products.

Ocean wind fields, swell wave spectra and surface current information as derived from SAR data, are provided as part of a combined Level-2 Ocean product to take maximum benefit of the cross-relations between these parameters.

The swell wave spectra information corresponds to two-dimensional ocean surface wave spectra estimated from a complex SAR image (Level-1 SLC product) by inversion of the corresponding image cross-spectra. The cross-spectra are computed by performing multi-looking in azimuth followed by co- and cross-spectra estimation among the detected individual look images.

The provided ocean wind field information represents gridded estimates of the surface wind speed and direction at a height of 10 m above the ocean surface.

The ocean surface currents information is derived from the Doppler anomaly, and relies on very accurate local estimates of the Doppler centroid frequency from the acquired data as well as very accurate estimates of the geometric Doppler centroid frequency.

B.1.4 Sentinel-1 SAR Operational User Product Format

The format of the Sentinel-1 Operational products will comply with the ESA Standard Archive Format for Europe (SAFE), an XML-based format.

The format for Sentinel-1 mission operational products will apply to all processing levels (L0, L1 and L2) and will contain the complete set of parameters and annotations required for the calibration, analysis, quality assessment and post-processing of the products.

A generic Sentinel-1 operational product will be provided as a directory folder containing a collection of data sets, with three possible categories of data set:

— Measurement data sets containing instrument data (L0) or images/binary information derived from instrument data (L1 and L2). Measurement data sets will be provided in GeoTIFF or JPEG 2000 format for Level-1 products and NetCDF format for Level-2 products.
— Annotated data sets containing data describing the properties and characteristics of the measurement data or how they were generated. Annotated data sets will be provided in XML format. Sentinel-1 annotations will be based on Envisat ASAR heritage, augmented to include the specialisation required to fully support Sentinel-1 characteristics, and enhanced by the experience gained from other SAR missions.
— Representation data sets containing information about the format or syntax of the measurement and annotated data sets and can be used to validate and exploit these data. Representation data sets will be provided in XML format (i.e. XSD files).

B.2 Sentinel-1 Hosted User Products

Information products from Sentinel-1 mission data will be generated by the GMES services, based on operational products distributed by the Sentinel-1 PDGS. However, to cope with the large data volume or stringent timeliness requirements, it is envisaged to support part of this processing or the complete end-to-end processing until the final information product either within or in direct interface with the Sentinel-1 Core PDGS.

Table B.2. Summary of Sentinel-1 operational products available to users (part of ESA Core PDGS operations).

Product type	SM	IW	EW	WV
SAR L-0, compressed ISP data stream	×	×	×	–
SAR L-1 SLC slant-range single look complex	×	×	×	×
SAR L-1 GRD georeferenced	×	×	×	×
GRD-FR	×	–	–	–
GRD-HR	×	×	×	–
GRD-MR	×	×	×	×
L-2 Ocean (wind, waves, currents)	×	×	×	×

The hosted processing capability is also intended to respond to evolving product requirements, particularly for Level-2/3 products. The hosted product processor is defined, or even implemented by the recipient operational service.

Sentinel-1 hosted user products are not part of the initial Sentinel-1 product portfolio, but the Sentinel-1 PDGS design and operations concept will be able to support their integration and automated and regular product generation.

A non-exhaustive list of potential candidates of hosted products includes:

— Ground Range Detected geocoded products (GEC);
— Ground Range Detected orthorectified products (GTC);
— low-resolution land-motion products;
— multi-temporal product stacking across modes or beams or tracks;
— soil moisture products;
— land-use products;
— ice type charts;
— ship detection; and
— pollution maps.

Figure B.1 features an Envisat radar image of the Netherlands, with the capital Amsterdam visible in white on the south bank of the waterway (the North Sea Canal), which extends across the centre of the image. The port of Rotterdam and the province of Zeeland are visible at the bottom left of the image. The country's second largest city, Rotterdam, extends inland from the port at the estuary of the Rhine.

This image is a multi-temporal composite, made up of three ASAR separate images acquired on different dates, with different colours assigned to each acquisition. In this composite, blue, green and red represent the images acquired on 12 March 2008, 30 July 2008 and 28 November 2007, respectively.

Figure B.1. Envisat radar image of the Netherlands.

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Acronyms and Abbreviations

ADC	Analogue-Digital Convertor
AIS	Automatic Identification System
AOCS	Attitude and Orbit Control Systems
AMI	Active Microwave Instrument (ERS)
ASAR	Advanced Synthetic Aperture Radar
BRW	Browse
Cal/Val	Calibration and Validation
CCF	Computer-compatible Format
Cosmo-SkyMed	COnstellation of small Satellites for Mediterranean basin Observation
CSAR	C-band Synthetic Aperture Radar
DEM	Digital Elevation Model
DC	Doppler Centroid
DC	direct current
DG	Directorate-General (European Commission)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DSHA	Data Storage and Handling Assembly
EC	European Commission
ECMWF	European Centre for Medium-range Weather Forecasting
EDRS	European Data Relay Satellite
EFE	Electronic Front-End
EMSA	European Maritime Safety Agency
ENL	Equivalent number of looks
Envisat	Environmental Satellite
EO	Earth observation
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
EU	European Union
EW	Extra Wide-swath mode
FDBAQ	Flexible Dynamic Block Adaptive Quantisation
FE	Front-end
FOCC	Flight Operations Control Centre
FOS	Flight Operations Segment
FP7	7th Framework Programme (EC)
FR	Full Resolution
GCM	GMES Contributing Mission
GEC	Geocoded Ellipsoid Corrected image product
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GMFS	Global Monitoring for Food Security
GMES	Global Monitoring for Environment and Security
G-MOSAIC	GMES services for Management of Operations, Situation Awareness and Intelligence for regional Crises (FP7)
GPS	Global Positioning System
GRD	Ground Range Detected
GSC	GMES Space Component
GSE	GMES Service Element
GTC	Geocoded Terrain Corrected (image product)
HBR	High Bit Rate
HH	Horizontal transmit, Horizontal receive polarisation
HKTM	Housekeeping Telemetry
HLOP	High-Level Operations Plan
HR	High Resolution
HV	Horizontal transmit, Vertical receive polarisation
IGOS	Integrated Global Observing Strategy
IMM	Image-Mode Medium resolution
INSPIRE	Infrastructure for Spatial Information in the European Community
IPF	Instrument Processing Facility
ISP	Instrument Source Packet
ITU	International Telecommunication Union
IW	Interferometric Wide-swath Mode
LEOP	Launch and Early Operations
LRIT	Long-Range Identification and Tracking
MACC	Services and applications for emergency response (FP7)
MARISS	European Maritime Security Services
MR	Medium Resolution
MRD	Mission Requirements Document
MTG	Meteosat Third Generation
NESZ	Noise-Equivalent Sigma Zero
netCDF	network Common Data Form
NGO	Non-Governmental organisation
NRT	Near-Realtime
NWP	Numerical Weather Prediction
OBC	Onboard Computer
OCN	Ocean
PCC	Pulse-Coded calibration
PDGS	Payload Data Ground Segment
PD	Probability of Detection
PDHT	Payload Data Handling Terminal
PFA	Probability of False Alarm
PI	Performance Indicator
PRF	Pulse Repetition Frequency
PRIMA	Piattaforma Italiana Multi Applicativa
RCS	Radar Cross Section
REDD	Reducing Emissions from Deforestation and Forest Degradation
RF	Radio Frequency
RX	Receive
SAFE	Standard Archive Format for Europe
SAFER	Services and Applications for Emergency Response (FP7)
SAR	Synthetic Aperture Radar
SAS	SAR Antenna Subsystem
SaVoir	Swath Acquisition Viewer
SCA	Snow Cover Algorithm / Snow-covered Area
ScanSAR	Scanning Synthetic Aperture Radar

SCOE	Special Check-Out Equipment
SES	SAR Electronics Subsystem
SLC	Single-Look Complex
SM	Strip Map Mode
SNR	Signal-to-Noise Ratio
SOLAS	International convention for the Safety Of Life At Sea
SWL	Sample Window Length
TAS	Thales Alenia Space
TM/TC	Telemetry/Telecommand
TOPSAR	Terrain Observation by Progressive Scans
TRM	Transmit–Receive Module
TSAG	The SAR Advisory Group
TT&C	Telemetry, Tracking and Command
TX	Transmit
TXA	Transmission Assembly
VH	Vertical transmit, Horizontal receive polarisation
VMS	Vessel Monitoring System
VV	Vertical transmit, Vertical receive polarisation
WSM	Wide-Swath Mode
WV	Wave mode
XBAA	X-band Antenna Assembly

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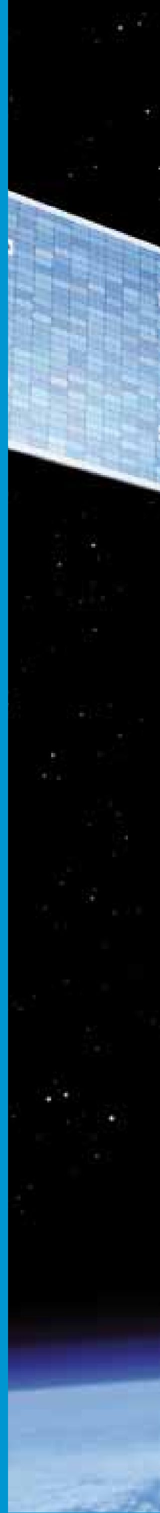

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