C-SAR Instrument Design for the Sentinel-1 Mission

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Abstract— The ESA Sentinels constitute the first series of operational satellites responding to the Earth Observation needs of the EU-ESA Global Monitoring for Environment and Security (GMES) programme. The GMES space component relies on existing and planned space assets as well as on new complementary developments by ESA. This paper describes the Sentinel-1 mission, an imaging synthetic aperture radar (SAR) satellite constellation at C-band. It provides an overview of the mission requirements, its applications and the technical concept for the system.

I. INTRODUCTION

‘Global Monitoring for Environment and Security (GMES)’ is a joint initiative of the European Commission (EC) and the European Space Agency (ESA), designed to support Europe’s goals regarding sustainable development and global governance of the environment by providing timely and quality data, information, services and knowledge.

In the frame of the GMES programme, ESA is undertaking the development of the European Radar Observatory Sentinel-1, a European polar orbiting multi-satellite system for the continuation of SAR operational applications. Sentinel-1 is an imaging radar mission in C-band, aimed at providing continuity of data for user services, in particular with respect to the ESA ERS and Envisat missions.

II. SENTINEL-1 MISSION

Sentinel-1 is designed to work in a pre-programmed conflict-free operation mode, imaging all global landmasses, coastal zones, shipping routes at high resolution and covering the global ocean with imagettes. This ensures a reliability of service required by operational services and a consistent long-term data archive built for applications based on long time series. Sentinel-1 revisit and coverage are dramatically improved with respect to the ERS-1/2 SAR and ENVISAT ASAR [1].

The two-satellite constellation offers six days exact repeat and the conflict-free operations based on two main operational modes allow exploiting every single data take. 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.

Observation requirements from GMES services are defined in terms of data availability, coverage & revisit, timeliness and characteristics of data products. The service requirements for C-band SAR observations were translated into 18 Sentinel-1 mission requirements shown in Table 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, hence the coverage) or the swath width (at the expense of the resolution).

<table>
<thead>
<tr>
<th>TABLE I. SENTINEL-1 MISSION REQUIREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data Availability</strong></td>
</tr>
<tr>
<td>1. In order to avoid service provision gaps Sentinel-1 operations shall start before the end of the operational lifetime of ERS/Envisat and last for a period of at least 10 years.</td>
</tr>
<tr>
<td>2. Unless specified otherwise performance shall satisfy ERS/Envisat requirements.</td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td>4. Coverage, revisit and exact repeat observation necessitate the use of non-ESA satellites. Therefore similarity of data products and observation geometry is required as well as ground segment interoperability.</td>
</tr>
<tr>
<td>5. All products shall be processed to Level-0 &amp; Level-1 and archived.</td>
</tr>
<tr>
<td>6. Data shall be delivered to the user within the timeliness specification from the archive or in near real time.</td>
</tr>
</tbody>
</table>

**Coverage and Revisit**

7. For interferometry global exact repeat coverage shall be achieved bi-weekly (e.g. with an interval of less or equal 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 deg. latitude north and south of - 45 deg.

**Timeliness**

10. Near real time data shall be delivered to users within 3 hours of observation.

11. User request for archived data shall be completed within typically 24 hours and in no case within more than 3 days after issuing of a user request.

12. Emergency operations shall be completed typically within 24 hours and in no case within more than 48 hours after issuing of a user request.

**Characteristics of Data Products**

13. The centre frequency shall be selected within 5250-5570MHz (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 x 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.

The remaining time the instrument operates over the open ocean in the Wave Mode providing sampled images of 20 x 20 km at 100 km along the orbit with low data rate. It is expected that Sentinel-1A be launched end 2012 and Sentinel-1B about 18 to 24 months later.

### III. 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 their observational data. The two primary components of the Ground Segment are the Flight Operation Segment (FOS) and the Payload Data Ground Segment (PDGS).

The FOS main responsibility encompasses the spacecraft monitoring and control, including execution of all platform activities and the commanding of the payload schedules. The principal FOS components are:

- The Ground Station and Communications Network performing telemetry, telecommand and tracking 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 backup stations).
- The Flight Operations Control Centre (FOCC), including:
  - The Sentinels Mission Control System, supporting 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 Sentinels Mission Planning System (part of the Mission Control System), supporting command request handling and the planning and scheduling of spacecraft operations and the scheduling of payload operations as prepared by the PDGS Mission Planning System;
  - The specific Sentinels Spacecraft Simulators, supporting procedure validation, operator training and the simulation campaign before each major phase of the missions;
  - The Sentinels Flight Dynamics System, supporting all activities related to attitude and orbit determination and prediction, preparation of slew and orbit manoeuvres, spacecraft dynamics evaluation and navigation.
- A General Purpose Communication Network, providing the services for exchanging data with any other external system during all mission phases.

The FOS provides the capability to monitor and control the spacecraft and payload during all mission phases. The FOS will be responsible for spacecraft commanding activities and acquisition of S-band telemetry. It provides the functionality required for generation and uplink of the routine platform and instrument command schedules, and the systematic

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**Figure 1.** C-band reflectivity map measured by ASAR onboard Envisat

As the operation follows a pre-programmed conflict-free scenario there is no need to make data acquisition requests for this mode. This Interferometric Wide-swath (IW) Mode operates for a maximum of 25 minutes per orbit.
archiving/analysis of the acquired housekeeping telemetry. Moreover, the FOS includes a Flight Dynamics System facility allowing orbit determination and prediction, and generation of attitude and orbit control telecommands. Other FOS functions include scheduling of ground station visibility segments, access to archived HKTM to authorized external users e.g. industrial expert groups. Besides performing these routine tasks, the Mission Control Team running the FOS will be responsible for monitoring the satellite’s health status and implementing all necessary recovery actions in case of anomalies, and verification and uplink of on-board software patches.

The Sentinels PDGS features:

- The Sentinels payload specific Mission Planning System;
- The X-band acquisition stations for the reception of real-time and recorded SAR, GPS, and HKTM data;
- The Sentinels specific Processing Facilities, hosting the relevant Level-1-2 instrument processor components and Precise Orbit Determination;
- The Sentinels specific Calibration and Monitoring Facilities;
- The Data Storage and Long-Term Archiving Systems;
- Supporting facilities providing monitoring, control and quality functions, and Users and Data distribution services.

The PDGS is offering 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 capabilities to integrate complementary functions for evolving requirements (e.g. extension to downstream services) and scientific exploitation;
- allows the integration of facilities for additional products generation (e.g. global soil moisture estimation and land cover mapping) on the basis of potential future extended services;
- offers Sentinels data access services as a comprehensive set of functions available to service providers to enable the utilisation of data for downstream operations.

It is underlined that an obvious paradigm for data access is to make available everything online with grouping/sorting functions aimed at grouping the data according to the downstream utilisation process and therefore maintaining control and establishing priorities on the overall data flows to users. In this respect, PDGS data flows and access supports:

- data storage administration across centres to not only ensure preservation but to optimise overall retrieval performance for service projects
- reduction of exploitation costs related to data circulation and replication within the overall GMES activities
- regional data access and exploitation (e.g. local stations network, user hosted application)

In order to satisfy the GMES service requirements, notably for Land Monitoring Services and Emergency Response Services, data (including meta-data) shall be preserved in a long-term archive for repeated use of long time series. To ensure consistent data quality periodic re-processing may be required.

IV. SENTINEL-1 SATELLITE

Sentinel-1 is an imaging Synthetic Aperture Radar mission at C-band. The design of its system has been driven by the need for continuity of ERS/Envisat class data provision with improved revisit, coverage, timeliness and reliability of service. Its main technical characteristics are listed below. Sentinel-1 is being realized by an industrial consortium lead by Thales Alenia Space Italy as Prime Contractor, with Astrium Germany being responsible for the C-SAR payload, incorporating the central radar electronics sub-system developed by Astrium UK.

A. Spacecraft

The spacecraft designed for the Sentinel-1 mission is a 3-axis stabilized satellite, directly placed into the Earth orbit by the launcher. It is characterized by sun, star, gyro and magnetic field sensors, and a set of 4 reaction wheels, dedicated to orbit control and to attitude control and 3 torque rods as actuators, to provide steering capabilities on each axis. The S/C is equipped with 2 solar array wings capable of producing 4800 W (at End of Life) to be stored in a modular battery.

The bus provides highly accurate pointing knowledge (better than 0.004°) on each axis, high pointing accuracy (about 0.01° on each axis), and real time orbit determination together with a dedicated propulsion system for precise orbit control.

Computer, avionics and the satellite communication backbone is based on the MIL-1553 command bus with the ERC32-SC processor providing high performance computing and processing capabilities on-board.

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

B. Payload

The payload is composed of a CSAR instrument operating in C-band supporting 4 main modes, Strip Map, Interferometric Wide swath, Extended Wide-swath and Wave mode, and a dedicated X-band Payload Data Handling Terminal (PDHT), both having their dedicated antennas, located on the bus lateral panels. The CSAR antenna has to be deployed once in orbit.

The PDHT comprises all functions necessary for the acquisition, storage and handling of data generated by different sources:

- CSAR data
In addition to data storage and handling functions the PDHT will provide data formatting and transmissions capability of the data to the ground stations. Direct downlink transmission capability is available for all the acquisition modes of the CSAR in single or dual polarisation. The PDHT is build up from the following subsystems: Data Storage and Handling Assembly (DSHA), Transmission Assembly (TXA) and X-band antenna (XBAA).

The on-board memory has been sized to 1410 Gbit. The memory segmentation in Packet Stores has been designed to enable simultaneous storage of data from the two polarisation channels of the CSAR instrument and from HK TM, 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” which are allocated and used by any possible packet store whenever it needs to store data coming from input channels. This way no potential constraints at 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 prioritising of the stored data during downlink activities with at least 4 levels of priority, and temporarily storing data to be transmitted in direct downlink.

The X-Band Antenna Assembly provides transmission to ground of the X-Band modulated signals received by the TXA. One of the main tasks of the XBAA is that of limiting the radiation of RF energy outside the nominal beam coverage, to avoid interference with the spacecraft environment and especially with the CSAR antenna. The PDHT is able to support the mission operations (data storage and data downlink) by performing:

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

C. Data Delivery

Due to consistent and conflict-free mission operations Sentinel-1 provides a high level of service reliability with near-real time delivery of data within one hour after reception by the ground station and with data delivery from archive within 24 hours.

D. Launch Date

It is expected that Sentinel-1A be launched in 2012 and about 18 months later Sentinel-1B.

E. Mission Operations

Once in orbit Sentinel-1 will be operated from two centres on the ground, the Agency’s facilities in Darmstadt, Germany for commanding the satellite and ensuring its proper functioning along the orbit.

The mission exploitation will be managed at the Agency’s facilities in Frascati, Italy, including the planning of the acquisitions by the SAR instrument according to the mission requirements, the processing of the acquired data and the provision of the resulting products to the users.

<table>
<thead>
<tr>
<th>TABLE II. SENTINEL-1 SPACECRAFT CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
</tr>
<tr>
<td>Orbit</td>
</tr>
<tr>
<td>Mean Local Solar Time</td>
</tr>
<tr>
<td>Orbital Period</td>
</tr>
<tr>
<td>Max Eclipse Duration</td>
</tr>
<tr>
<td>Attitude Stabilisation</td>
</tr>
<tr>
<td>Attitude Accuracy</td>
</tr>
<tr>
<td>Nominal flight attitude</td>
</tr>
<tr>
<td>Attitude Profile</td>
</tr>
<tr>
<td>Orbit Knowledge</td>
</tr>
<tr>
<td>Operative Autonomy</td>
</tr>
<tr>
<td>Launch Mass</td>
</tr>
<tr>
<td>Dimensions (stowed)</td>
</tr>
<tr>
<td>Solar Array Average Power</td>
</tr>
<tr>
<td>Battery Capacity</td>
</tr>
<tr>
<td>Spacecraft Availability</td>
</tr>
<tr>
<td>Science Data Storage Capacity</td>
</tr>
<tr>
<td>S-Band TT&amp;C Data Rates</td>
</tr>
<tr>
<td>X-Band Science TM Data Rate</td>
</tr>
<tr>
<td>Launcher</td>
</tr>
</tbody>
</table>

F. Ground Segment

Following mission requirements mission exploitation plans need to facilitate systematic acquisition, reception, processing, archiving and provision of large amounts of data to the users. The SAR instrument will be operated - to the maximum extent
possible - in a pre-programmed conflict-free sensing mode. Payload data handling will be driven by the data as received from the spacecraft by a large system able to handle data flows from the satellite exceeding 1 Terabyte per day and to provide large data volumes within one hour after reception on the ground. The operations concept allows the satellite to operate autonomously and in a cost-effective manner with a mission plan on-board covering a period of 4 days, thus allowing automated operations over weekends. At the same time it is possible to insert individual emergency requests up to three hours prior to the nominally planned update of the mission plan to the satellite. This allows considerably shortening the response time of Sentinel-1 compared to its predecessors.

V. C-SAR INSTRUMENT DESIGN

A. Introduction

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 robustness and reliability of service, simplifies mission planning, decreases operational costs and satisfies also tomorrow’s requests by building up a consistent long-term archive. However mutually exclusive modes are provided for continuity reasons (with respect to ERS and Envisat) and for accommodation of 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)

Except for the Wave Mode, which is a single polarization per vignette mode (HH or VV), the SAR instrument has to support operation in dual polarisation (HH-HV, VV-VH), which requires the implementation of one transmit chain (switchable to H or V) and two parallel receive chains for H and V polarisation. The specific needs of the four different measurement modes with respect to antenna agility require the implementation of an active phased array antenna.

In Stripmap mode the instrument has to provide an uninterrupted coverage with a high geometric resolution (5 m x 5 m) at a medium swath width of 80 km. Six overlapping swathes cover the required access range of 375 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.

To meet the ambitious image requirements, the Interferometric Wide-swath mode has to be 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 (TOPS operation [2]) in order to average the performance in along track direction (reduction of scalloping). Hence, the Interferometric Wide-swath mode will allow combining a large swath width (250 km) with a moderate geometric resolution (5 m x 20 m). Interferometry has to be ensured by sufficient overlap of the Doppler spectrum (in the azimuth domain) and the wave number spectrum (in the elevation domain).

Extra Wide-swath mode and Wave mode complement the SAR data products. In Extra Wide-swath mode a huge swath width of 400 km has to be covered with low resolution (20 m x 40 m), which can be met by the implementation of a ScanSAR mode with a fast beam scanning capability in elevation. As the Interferometric Wide-swath mode also the Extra Wide-swath mode is implemented with a progressive azimuth scanning (TOPS operation).

Finally, the Wave mode data product is composed of single stripmap operations with an alternating elevation beam (between 23 and 36.5 mid incidence angle) and a fixed on/off duty cycle, which results in the generation of vignettes of 20 km x 20 km size in regular intervals of 100 km.

B. Instrument Architecture and Functionality

The radar signal is generated at baseband by the chirp generator and up-converted to C-band within the SAR electronics. This signal is distributed to the High Power Amplifiers inside the Transmit/Receive Modules via the beam forming network of the SAR antenna. Signal radiation and echo reception is realized 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 baseband inside the SES, the echo signal is digitised and formatted for recording. Table III provides a brief overview on the instrument key parameters.

The key design aspects of the C-SAR Payload can be summarized as follows:

- Active phased array antenna providing fast scanning in elevation (to cover the large range of incidence angle and to support ScanSAR operation) and in azimuth (to allow use of TOPS technique to meet the required image performance)
- Dual channel Transmit & Receive Modules and H/V-polarised pairs of slotted waveguides (to meet the polarisation requirements)
- Internal Calibration scheme, where transmit signals are routed into the receiver to allow monitoring of amplitude/phase to facilitate high radiometric stability
- Metallised Carbon Fibre Reinforced Plastic radiating waveguides to ensure good radiometric stability even though these elements are not covered by the internal calibration scheme
• Digital Chirp Generator and selectable receive filter bandwidths to allow efficient use of on board storage considering the ground range resolution dependence on incidence angle

• Flexible Dynamic Block Adaptive Quantisation to allow efficient use of on-board storage and minimise downlink times with negligible impact on image noise

A three dimensional view of the SAS Tile, which is the elementary building block of the SAR Antenna Subsystem, is given in Fig. 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Frequency</td>
<td>5.405 GHz</td>
</tr>
<tr>
<td>Instrument Mass</td>
<td>945 kg</td>
</tr>
<tr>
<td>DC-Power Consumption</td>
<td>4075 Watt (Interferometric Wideswath Mode, two polarisations)</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0 … 100 MHz (programmable)</td>
</tr>
<tr>
<td>Polarisation</td>
<td>HH-HV, VV-VH</td>
</tr>
<tr>
<td>Antenna Size</td>
<td>12.3 m x 0.821 m</td>
</tr>
<tr>
<td>RF Peak Power (sum of all TRM, at TRM o/p)</td>
<td>4368 W</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>5-100 us (programmable)</td>
</tr>
<tr>
<td>Transmit Duty cycle</td>
<td></td>
</tr>
<tr>
<td>Stripmap</td>
<td>8.5 %</td>
</tr>
<tr>
<td>Interferometric Wideswath</td>
<td>9 %</td>
</tr>
<tr>
<td>Extra Wide swath</td>
<td>5 %</td>
</tr>
<tr>
<td>Wave</td>
<td>0.8%</td>
</tr>
<tr>
<td>Receiver Noise Figure at Module input</td>
<td>3 dB</td>
</tr>
<tr>
<td>Pulse Repetition Frequency</td>
<td>1000- 3000 Hz (programmable)</td>
</tr>
<tr>
<td>ADC Sampling Frequency</td>
<td>260 MHz (real sampling) (Digital down-sampling after A/D conversion)</td>
</tr>
<tr>
<td>Sampling</td>
<td>10 bits</td>
</tr>
<tr>
<td>Data Compression</td>
<td>Selectable according to FDBAQ</td>
</tr>
</tbody>
</table>

Important to mention is also the roll steering mode of the spacecraft. This continuous roll manoeuvre around orbit (similar to yaw steering in azimuth) compensates for the altitude variation such that it allows usage of a minimal number of different pulse repetition frequency’s (PRFs) and sample window lengths (SWLs) round the orbit. So, only one single PRF and SWL are necessary per swath/sub-swath around orbit, with the single exception of Stripmap swath 5 where two different PRFs and SWLs have to be used. In addition, the update rate of the sampling window position around orbit is minimised (< 1/2.5 min), which simplifies instrument operations significantly. Since the instrument can work with a single fixed beam for each swath/sub-swath over the complete orbit, also the number of elevation beams is minimised. The roll steering rate has been fixed to 1.6 deg/ 27 Km altitude variation. The roll applied to the sensor attitude depends linearly on altitude and varies within the interval -0.8 deg (minimum sensor altitude) to 0.8 deg (maximum sensor altitude).

Figure 2. THREE-DIMENSIONAL VIEW OF THE SAS TILE LAYOUT

VI. CONCLUSIONS

The Sentinel-1 synthetic aperture radar (SAR) constellation represents a completely new approach to SAR mission design by ESA in direct response to the operational needs for SAR data expressed under the EU-ESA Global Monitoring for Environment and Security (GMES) programme. The mission ensures continuity of C-Band SAR data to applications and builds on ESA’s heritage and experience with the ERS and ENVISAT SAR instruments, notably in maintaining key instrument characteristics such as stability and accurate well-calibrated data products. At the same time a number of mission design parameters have been vastly improved to meet major user requirements collected and analysed through EU Fast Track and ESA GSE activities, especially in areas such as reliability, revisit time, geographical coverage and rapid data dissemination. As a result, the Sentinel-1 constellation is expected to provide near daily coverage over Europe and Canada, global coverage all independent of weather with delivery of radar data within 1 hour of acquisition – all vast improvements with respect to the existing SAR systems.

REFERENCES


TABLE III. INSTRUMENT KEY PARAMETERS