Sentinel-1, the GMES Radar 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 preliminary technical concept for the system.

Index Terms— **SAR, C-Band, Satellite, Space-borne Radar**

I. Introduction

As part of the GMES space component, ESA is undertaking the development of a European Radar Observatory (Sentinel-1), an European polar orbiting satellite system for the continuation of SAR operational applications. Sentinel-1 is an imaging radar mission at C-band consisting of a constellation of two satellites aimed at providing continuity of all-weather day-and-night supply of imagery for user services. Special emphasis is placed on services identified in ESA's GMES service elements program and on projects funded by the European Union Framework Programmes. Three priorities (fast-track services) for the mission have been identified by user consultation working groups of the European Union: Marine Core Services, Land Monitoring and Emergency Services. These cover applications such as:

- Monitoring sea ice zones and the arctic environment
- Surveillance of marine environment
- Monitoring land surface motion risks
- Mapping of land surfaces: forest, water and soil, agriculture
- Mapping in support of humanitarian aid in crisis situations.

II. ESA's SAR Mission Heritage

A first glimpse of the potential of imaging radar from space was provided by the short-lived but ultimately successful Seasat mission launched in 1978 by the US. Subsequently the European Space Agency then initiated its own program to develop and launch advanced microwave radar instruments culminating with the launch of the European Remote Sensing Satellites ERS-1 (launched 17 July 1991) and ERS-2 (launched 20 April 2005). The ERS missions demonstrated for the first time not only the feasibility of developing reliable, stable and powerful radar imaging systems for space, but, the dependability and all-weather capability of the instruments also provided a foundation for the development and exploitation of radar images in a wide variety of applications. While the initial objectives for ERS-1 at launch were predominantly oceanographic, other applications were also considered during the initial phases of the mission preparation. Interestingly the ESA Remote Sensing Advisory Group in 1974, as an example, emphasized commercial applications such as agriculture, land use mapping, water resources, overseas aid and mapping of mineral resources when formulating their advice on the ERS mission objectives. As the ERS mission showed, the rigorous design of the SAR instruments - which emphasized instrument stability combined with accurate well-calibrated data products – has created new opportunities for scientific discovery, revolutionized many Earth science disciplines and laid the foundations for the development of commercial applications exploiting spaceborne SAR data. An example of note can be found in the field of SAR interferometry which was developed mainly on the basis of ERS SAR data and is now commonly used in Earth sciences and a number of commercial applications. In a further step, the potential of spaceborne radar with short time-intervals between successive acquisitions in applications was demonstrated in 1996 and 1997 during the ERS tandem mission, when ERS-1 and ERS-2 flew in a two satellite constellation with one day interval between acquisitions. A further important milestone came with the launch of the Advanced SAR (ASAR) onboard ENVISAT which was launched on 28 February 2002. This not only ensured the continuation of C-Band data for applications, but provided new enhanced capabilities such as wide swaths and dual polarization which have since rapidly been integrated into and exploited by many radar-based applications. The archive of radar data spanning from 1991 to the present has also proven highly valuable for science and applications providing consistent time-series of data over 16 years.

III. GMES User Requirements

Data products from the Agency's successful ERS-1, ERS-2 and Envisat missions form the basis for many of the pilot

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GMES services. Consequently Sentinel-1 data products need to maintain data quality levels of the Agency‘s previous SAR missions in terms of spatial resolution, sensitivity, accuracy, polarization and wavelength. Feedback from users following the consolidation phase of the GMES services indicate unambiguously that the crucial requirements for operational sustainable services are continuity of data supply, frequent revisit, geographical coverage and timeliness. Compared to the current satellites in orbit substantial improvements of data provision in terms of revisit frequency, coverage, timeliness and reliability of service would be required. As an example, services related to ocean and sea ice encompassing ship and oil spill detection, wind speed measurements and sea ice monitoring require frequent revisit (once per day, mostly at northern latitudes) and timeliness (near-real-time delivery of data within one hour of acquisition). Services related to land encompassing interferometry and land cover classification mostly require global coverage every two weeks at most and consistent data sets that are suitable for interferometry [1].

IV. Reliability of Service, a new Challenge

Operational requirements listed in the previous section present a new challenge to information provision by spaceborne radar. Unlike its more experimental predecessors ERS-1, ERS-2 and Envisat that supply data on a best effort basis, operational satellites like Sentinel-1 are required to satisfy user requirements and to supply information in a reliable fashion with the data provider accepting legal responsibility for the delivery of information. In this operational scenario failed acquisitions due to conflicting requests from users (requesting for instance different instrument modes at the same time and place) cannot be tolerated.

Sentinel-1 is designed to work largely in a pre-programmed conflict-free operation imaging all global landmasses, coastal zones, shipping routes in full resolution and covering the global ocean with imagettes. This way reliability of service consistent with the demand of operational services can be achieved 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 ERS-1/2 and ASAR. The two-satellite constellation offers six days exact repeat and the conflict-free operations based on a main operational mode allow exploiting every single data take. In the framework of international interoperability agreements the effective revisit and coverage performance could be further improved by access to the planned Canadian SAR Constellation.

To deal with user requirements for both high and medium resolution data traditional SAR system designs include different operational modes that either optimize the spatial resolution (at the expense of the swath, 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 medium resolution applications having a main mode of operation that features a wide swath (250 km) and a medium resolution (5 m x 20 m).

V. Sentinel-1 Data Products for Marine Core Services

SAR is the primary source of data for information on the ocean and the arctic environment. The all-weather day-and-night observation capability, problems of access to open ocean and the harsh arctic environments often makes radar the only reliable information source.

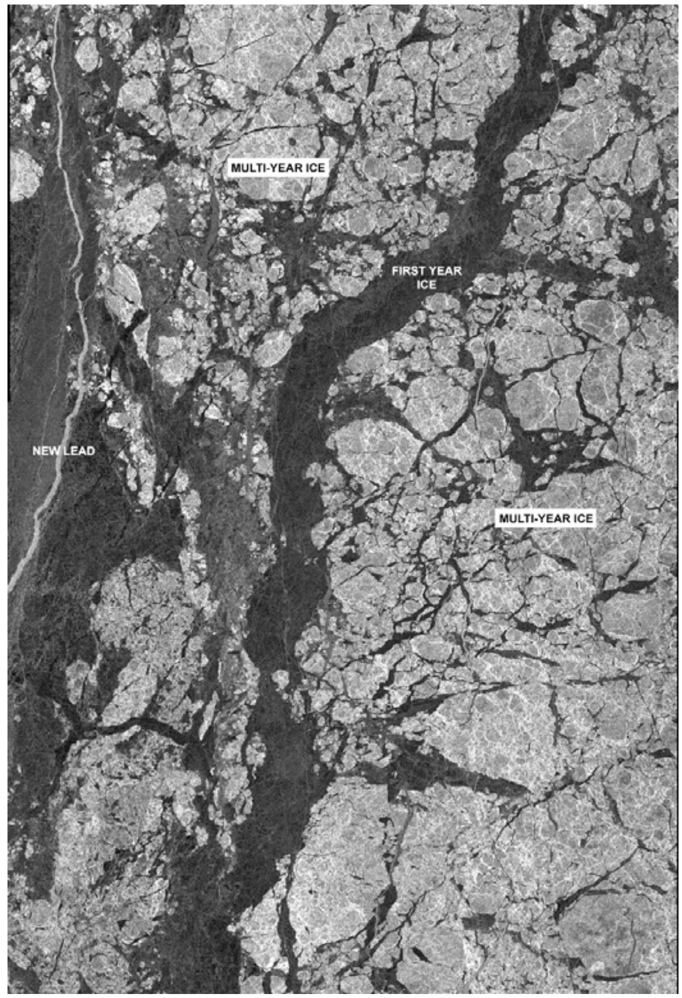

Figure 1 An ENVISAR ASAR image demonstrating the ability of SAR to clearly separate thinner, more navigable first year ice from the hazardous, stronger and much thicker multi-year ice. Courtesy of the Canadian Ice Service.

This is illustrated in the figure above showing SAR imagery in support of navigation in the Arctic. Typical specific information products for the ice and snow services include monitoring glaciers and snow, icebergs, sea ice (floe edge) and the near shore ice complex.

For the determination of the direction, wavelength and (extreme) heights of waves at the surface of the open ocean SAR imagettes are being used in near real time in conjunction with global ocean wave models. The extensive wave mode archive built up by the ERS and Envisat background mission is a critical resource for the analysis of regional wave climate and of extreme wave events.

SAR is also the primary source of information for oil spill information services (such as surveillance, drift forecasting and decision support) and for ship detection services required for fisheries and security.

VI. Sentinel-1 Data Products for Land Monitoring Services

SAR data is not always the primary source for basic land cover classification (forest, agricultural crops, urban areas, etc.) if multi-channel optical imagery with high spatial resolution is available. However, SAR is commonly used as a complementary or alternative data source under adverse atmospheric conditions (e.g. cloud cover).

The contribution made by SAR to basic land cover classification has been greatly enhanced by the dual polarization mode introduced by ENVISAT ASAR. The dual polarization mode has become a favorite product for land classification as illustrated by the ASAR image of the Elbe river flooding below. For this reason Sentinel-1 has been designed to fully exploit the capabilities of dual polarization. A dramatic improvement is to be expected from the more frequent revisit of the same area by Sentinel-1 compared to its predecessors. This feature facilitates the use of time series observation with close to daily sampling. Combined with its interferometric capability Sentinel-1 will offer routinely products that have only been available from the ERS-1/ERS-2 tandem mission on an experimental basis. During the tandem mission data pairs were collected on successive days.

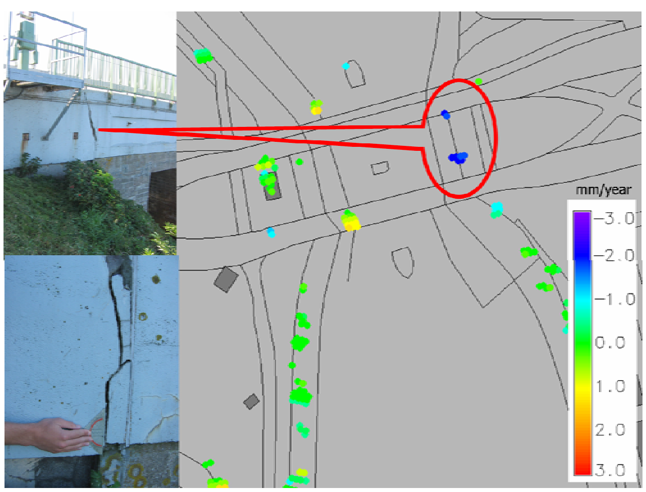

Figure 2 Detection of structural damage from space by interferometric radar. The green spots show little movement, while the damage is highlighted in blue.

Classification of land cover is not the only important application of SAR to land monitoring. As interferometric radar can detect surface movements with an accuracy of a few millimeters per year this technique has been established to monitor the effects of land slides, earthquakes and of man-made activities such as building construction, tunnel construction (subways), water extraction, extraction of natural gas and mining. Figure 2 gives an example of this technique: constructional damage detection of a lock.

VII. Sentinel-1 Data Products for Emergency Services

Its all-weather day-and-night observation capability makes spaceborne radar the ideal workhorse for information provision prior, during and after emergency situations provided fast access to satellites and their data products.

For this type of application the Sentinel-1 constellation (Sentinel-1a and -1b) provide during routine operations a global revisit of three days on the equator improving with latitude as shown in Figure 3 without using the optional emergency procedure to further accelerate access.

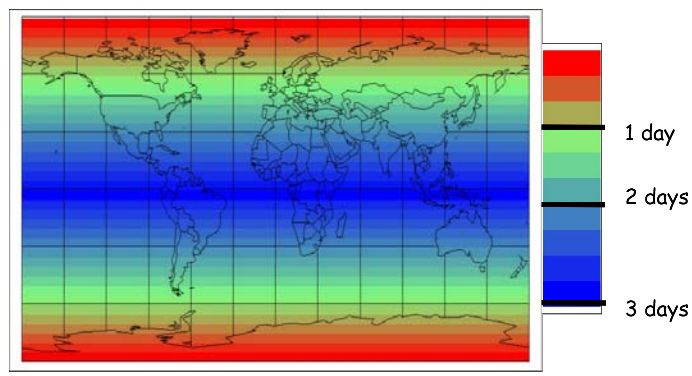

Figure 3 Average revisit time for the Sentinel-1 constellation across the world: 2 satellites in a 12 day repeat orbit with 250 km swath width.

In the framework of an international agreement with other satellite operators a daily access (or better) will be a realistic assumption. This excellent revisit performance is feasible due to a modest spatial resolution of 5 to 20 meters. In order to observe finer detail regional coverage by satellites with higher spatial resolution (radar and/or optical) will be required.

Sentinel-1 will be contributing a multi-temporal global interferometric image archive to support mapping the situation prior to an event and to form interferometric pairs to map the effect of earthquakes.

Even with the current very much restricted coverage C-band SAR products have become an established source of information in emergency situations such as flooding and oil spills.

VIII. Sentinel-1 System

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.

Spacecraft

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. The industrial set-up will be finalized during the initial phase of the program. The spacecraft is based on the PRIMA (Piattaforma Italiana Multi Applicativa) bus, with a mission specific payload module as per the PRIMA concept. Experience gained from the RadarSat-2 and from the Cosmo-Skymed programs, in which PRIMA also was selected as the spacecraft baseline, is a benefit for the Sentinel-1 implementation. The Sentinel-1 main characteristics are shown in Table 1.

Lifetime	7 years (consumables for 12 years)
Orbit	Near-Polar Sun-Synchronous @ 693km; 12-day repeat cycle; 175 orbits per cycle
Mean Local Solar Time	18:00 at Ascending Node
Orbital Period	98.6 minutes
Max Eclipse Duration	19 minutes
Attitude Stabilisation	3 axis stabilised
Attitude Accuracy	0.01 deg (each axis)
Nominal flight Attitude	Right Looking
Attitude Profile	Geo-centric and Geodetic
Orbit Knowledge	10 m (each axis, 3 sigma) using GPS
Operative Autonomy	96 hrs
Launch Mass	2300 kg (incl. 130 kg monopropellant fuel)
Dimensions (stowed)	3900 x 2600 x 2500 mm^3
Solar Array Average Power	4800 W (End-of-Life)
Battery Capacity	>300 Ah
Spacecraft Availability	0.998
Science Data Storage Capacity	900 Gigabits (End-of-Life)
S-Band TT&C Data Rates	4 kbps TC; 16/128/512 kbps TM (programmable)
X-Band Science TM Data Rate	600 Mbps
Launcher	Soyuz from Kourou (baseline), Zenith II (backup)

Table 1 Sentinel-1 Spacecraft Characteristics

Instrument

The Sentinel-1 satellite carries a Synthetic Aperture Radar (SAR) instrument. The SAR design capitalises on Envisat ASAR technologies and consists of an electronically steered array antenna. Figure 4 shows the antenna in deployed configuration.

Operational Modes

Sentinel-1 has four nominal operational modes designed for inter-operability with other systems.

- Strip map Mode with 80 km swath and 5x5 metre spatial resolution
- Interferometric Wide Swath Mode with 250 km swath, 5x20 metre spatial resolution and burst synchronisation for interferometry using the TOPS mode [2] to minimise scalloping.
- Extra-wide Swath Mode with 400 km swath and 25x100 metre spatial resolution (3-Looks)
- Wave Mode with low data rate and 5x20 metre spatial resolution. Sampled images of 20x20 km at 100 km along the orbit.

Figure 4 Sentinel-1 Satellite Concept

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.

Polarisation

Sentinel-1 has selectable single polarisation (VV or HH) for the Wave Mode and selectable dual polarisation (VV+VH or HH+HV) for all other modes.

Data Quality

The sensitivity of Sentinel-1 expressed by the noise-equivalent sigma naught is specified to be −22 dB or better. The radiometric accuracy of its data products is within a statistical error (3-sigma value) of 1.0 dB. For distributed targets the ambiguity ratio is specified to be −22 dB or better.

Radiometric Resolution

For the end-user of SAR imagery the radiometric resolution is a critical parameter as it defines the typical image noise in radar images caused by thermal noise and speckle. Image noise defines how well different surfaces (e.g. ice types, agricultural crops, soil moisture levels) can be classified. To illustrate the improvement to be expected from Sentinel-1 compared to existing systems in orbit Figure 5 shows the radiometric resolution of a 500 x 500 metre image pixel for the ASAR wide swath mode, the Sentinel-1 extra-wide swath mode and the Sentinel-1 interferometric wide swath mode. In its extra-wide swath Sentinel-1 offers 30% performance improvement with respect to Envisat while the interferometric wide swath of Sentinel-1 offers a further improvement by a factor of three.

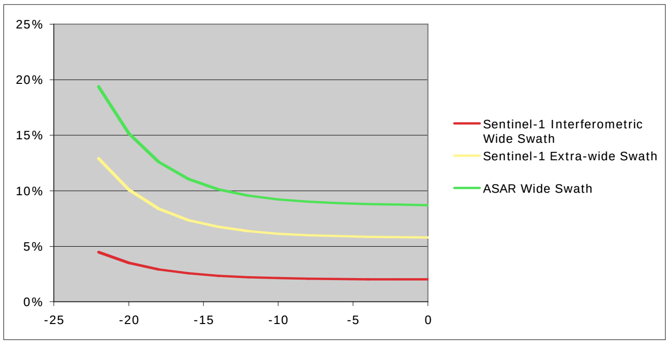

Figure 5 Radiometric Resolution of Radar Images: percentage image fluctuation in radar imagery as a function of radar backscattering coefficient for a pixel size of 500 x 500 metres.

Launch Date

It is expected that Sentinel-1 be launched in 2011.

Ground Segment and 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

The ground segment design and operations concept however allow for operations to be handed over – partially or fully - to other operating entities in the future. Compared to previous missions the Sentinel-1 satellite operations and its mission exploitation present new challenges; the spacecraft needs to operate within a tight orbital tube of only 100 meters and needs to comply with GMES security requirements for command and control of the spacecraft. Its operations will be largely automated for nominal operations but emergency requests in support of disaster management applications have to be accommodated on short notice. 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. An extensive ground segment is required with several ground stations receiving instrument data from the satellite at a rate of 600Mbit/sec, with cumulative processing capacities above 500 GHz, with archiving requirements exceeding 10000 Terabytes, and with a data dissemination exceeding current systems by one order of magnitude. In order to fully satisfy the GMES service requirements the Sentinel-1 ground segment is required to facilitate coordinated mission planning and data exchange with other GMES contributing missions. The ground segment needs to guarantee a Quality of Service to the user in line with the operational nature of GMES, ensuring that the data products are accurate, complete and provided on time.

IX. 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. In addition to responding directly to current needs of the GMES program, the design of the Sentinel-1 satellite mission with its focus on stability, reliability, global coverage, consistent operations and quick data delivery is expected to enable the development of new applications and meet the evolving needs of GMES, for instance in the area of climate change and associated monitoring needs.

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