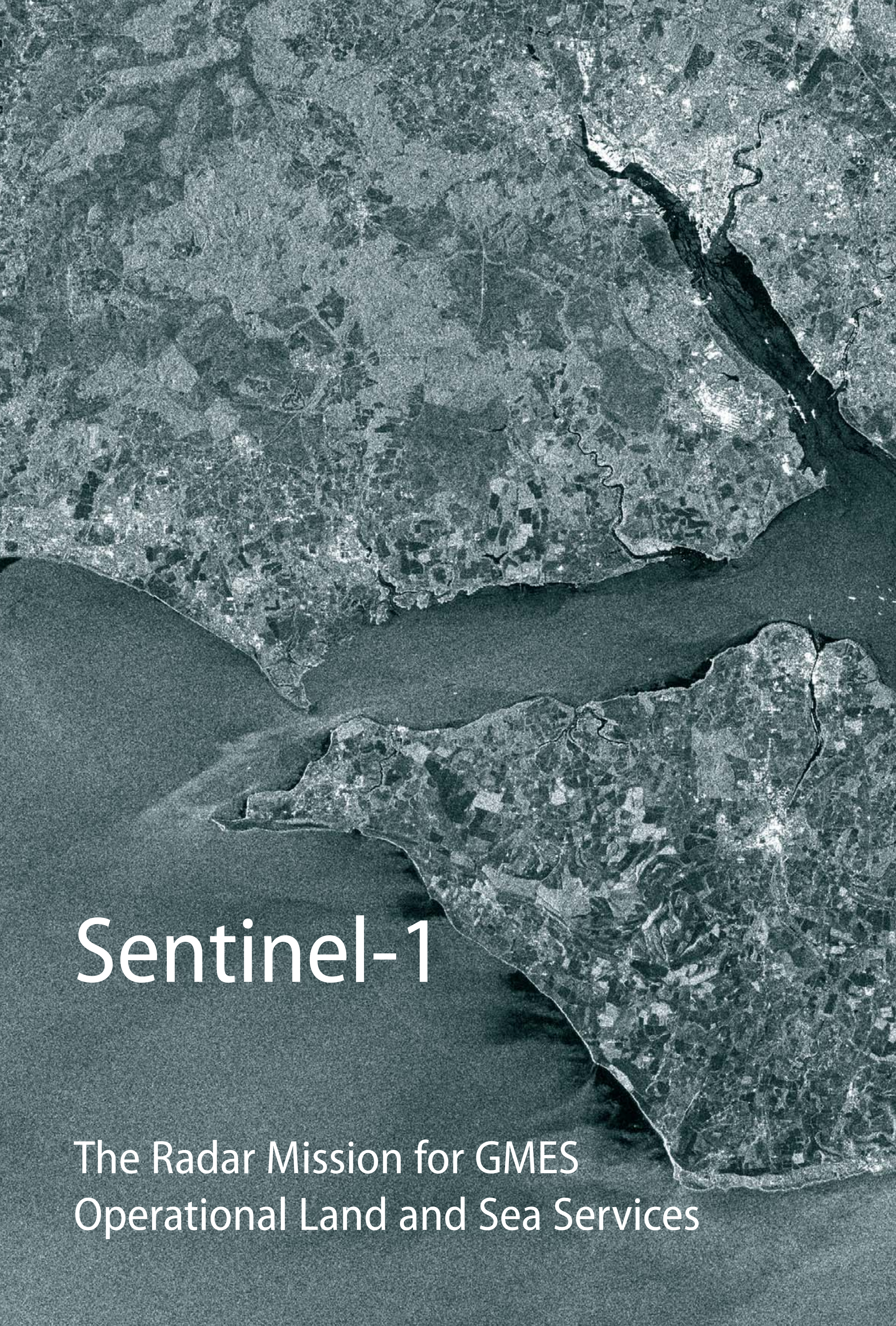

Sentinel-1

The Radar Mission for GMES Operational Land and Sea Services

Envisat radar image of the Solent between the Isle of Wight and Portsmouth, UK. Resolution is 30 m. At the time, in June 2005, Britain's navy was gathering for a fleet review

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The ESA Sentinels will be the first series of operational satellites to meet the Earth observation needs of the European Union-ESA Global Monitoring for Environment and Security (GMES) programme. Existing and planned space assets will be complemented by new developments from ESA. The first is Sentinel-1, a pair of synthetic aperture radar (SAR) imaging satellites.

Introduction

ESA is developing the Sentinel-1 European Radar Observatory, a polar-orbiting satellite for operational SAR applications. The constellation of two C-band radar satellites will provide continuous all-weather day/night imagery for user services, especially those identified in ESA's GMES service elements programme and on projects funded by the European Union (EU) Framework Programmes. Three priorities ('fast-track services') have been identified by EU user working groups: marine core services; land monitoring; and emergency services. These include:

– monitoring sea-ice zones and the Arctic;

– surveillance of the marine environment;
– monitoring land movements;
– mapping land surfaces: forest, water and soil, agriculture;
– mapping for humanitarian aid in crisis situations.

The first satellite is expected to be launched in 2011 aboard a Soyuz from Kourou.

ESA's SAR Heritage

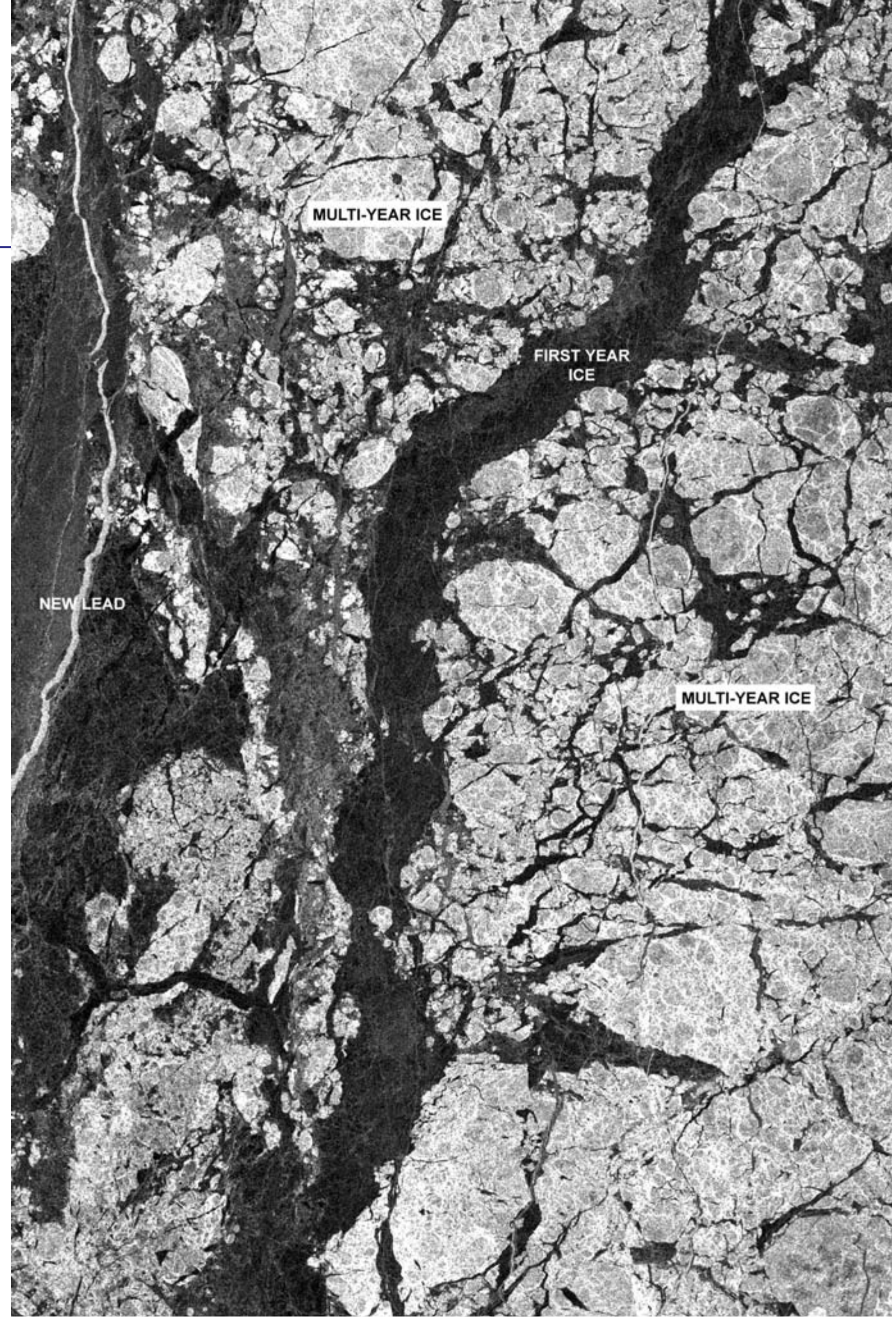
A first glimpse of the potential of imaging radar from space was provided by the short-lived but successful US Seasat satellite in 1978. ESA's own programme to develop advanced microwave radar instruments culminated with the launches of ERS-1 (17 July 1991) and ERS-2 (20 April 1995). Remarkably, ERS-2 is still operating.

ERS demonstrated for the first time the feasibility of flying reliable, stable and powerful radar imaging systems in space. The dependability and all-weather capability of the instruments also provided a foundation for developing and exploiting radar images for a wide variety of applications. While the initial objectives for ERS-1 at launch were predominantly oceanographic, other applications were considered during the project's preparation. The ESA Remote Sensing Advisory Group in 1974, for example, emphasised commercial applications such as agriculture, land-use mapping, water resources, overseas aid and mapping of mineral resources in its advice on ERS objectives.

The rigorous design of the ERS SAR hardware – emphasising instrument stability in combination with accurate and well-calibrated data products – created new opportunities for scientific discovery, revolutionised many Earth science disciplines and laid the foundations for commercial applications.

For example, 'SAR interferometry', which can track land shifts of only a few millimetres, was developed mainly using ERS data and is now commonly used in Earth sciences and commercial applications. The potential of space radars viewing the same scene only a short time apart was demonstrated in 1995 and 1996 during the ERS 'tandem mission', when the orbits of ERS-1 and ERS-2 were carefully matched but with a 1-day gap.

An important milestone was the launch of the Advanced SAR (ASAR) on Envisat on 28 February 2002. This ensured the continuation of C-band data and added enhanced capabilities such as wide swaths and dual polarisation, features that have since rapidly been integrated into and exploited by many applications. The archive of radar data since 1991 is extremely valuable for science and applications, providing a consistent set of data spanning 16 years.

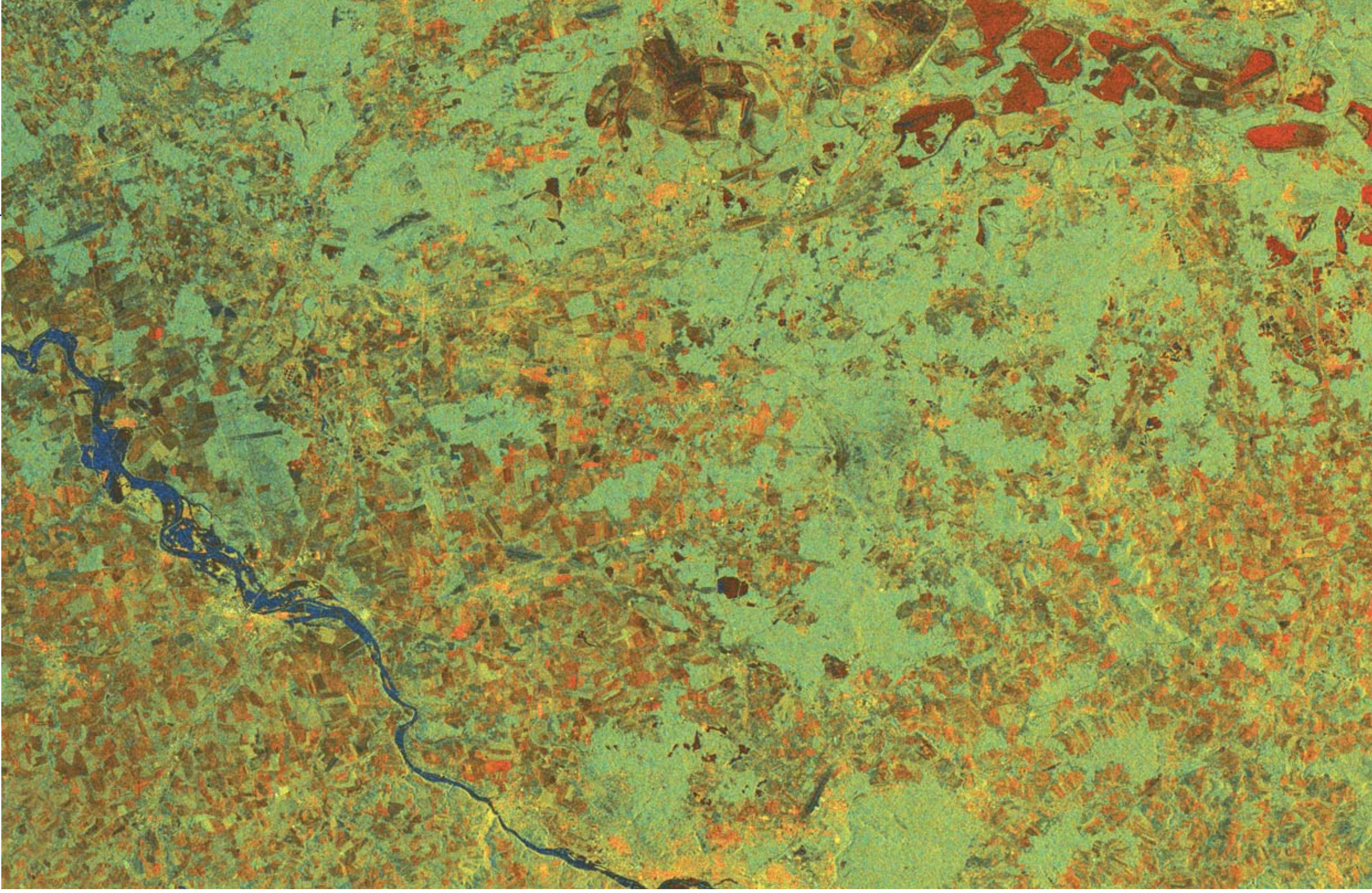


An Envisat ASAR image in the Arctic's Beaufort Sea, demonstrating the ability of SAR to distinguish clearly between the thinner, more navigable first-year ice and the hazardous, much thicker multi-year ice. (Canadian Ice Service)

What GMES Users Want

Data products from ESA's successful ERS-1, ERS-2 and Envisat missions form the basis for many of the pilot GMES services. Sentinel-1 must maintain these quality levels in terms of spatial resolution, sensitivity, accuracy, polarisation and wavelength. Feedback from users indicate unambiguously that the crucial requirements for operational sustainable services are continuity of data, frequent revisits, 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 are required. As an example, services encompassing ship and oil-spill detection, wind speed measurements



The flooded Elbe River in Germany, demonstrating the value of 'dual-polarisation' radar coverage for land-cover classification. Envisat transmits and detects radar waves polarised in the horizontal and vertical directions, yielding more extensive information than could a single polarisation on the ground surface reflecting them. Sentinel-1 will exploit this feature

and sea-ice monitoring require daily revisits (mostly at northern latitudes) and delivery of data within an hour of acquisition. In contrast, land services involving interferometry and cover classification require global coverage every 2 weeks at most and consistent datasets.

Service Reliability: A New Challenge

The operational requirements present a new challenge for spaceborne radar. Unlike its ERS and Envisat experimental predecessors, which supply data to users on a best-effort basis, operational satellites like Sentinel-1 must satisfy user requirements and supply information in a reliable fashion. The data provider accepts legal responsibility for delivering the information. Acquisition failures owing to conflicting requests from users (such as requesting different instrument modes at the same time and place) cannot be tolerated.

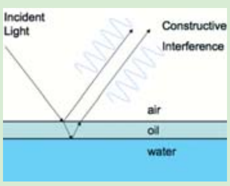
Sentinel-1 will work largely in a programmed conflict-free manner imaging all landmasses, coastal zones and shipping routes globally, and covering the oceans with imagettes. This way, the reliability demanded by operational services is achieved and a consistent long-term data archive is built for applications based on long time-series.

Sentinel-1 revisit frequency and coverage are dramatically improved with respect to ERS and Envisat. The orbits of the two-satellite constellation repeat every 6 days, and conflict-free operations allow every single data-take to be exploited. The effective revisit and coverage performance could be further improved by access to Canada's planned SAR constellation.

User needs at both high and medium

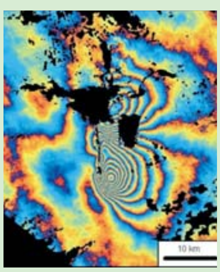
Radar Interferometry: How it Works

If light travels paths of different lengths, the observed brightness is either increased or reduced depending on the wavelength (colour) and the path length difference. This 'constructive' and 'destructive' interference shows up nicely as beautiful rainbow-like patterns when sunlight reflects off a thin film of oil (far right).

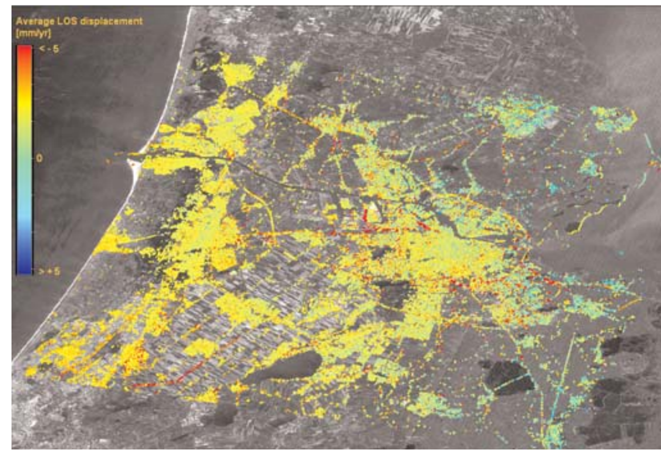


Radar waves can be made to behave in the same way when they are bounced off the Earth. If the satellite comes back another time in exactly the same orbit and the surface has not moved, adding the two measurements gives a brighter image because of constructive interference. However, if parts of the surface have shifted between observations, the destructive interference could dim areas of the combined images.

So combining two radar images from before and after an earthquake, for example, generates rainbow-like patterns from which surface movement can be determined to within typically 1 mm/year.



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



Monitoring long-term surface vertical movements by interferometric SAR near Amsterdam, The Netherlands, 1993–2000. Red indicates sinking faster than 5 mm per year (Courtesy Terrafirma Project)

Revisiting a scene only a day later allows interferometry to distinguish between water bodies, forest, urban areas and agriculture. In this single ERS-1/ERS-2 image pair over The Netherlands, colours are assigned so that generally trees appear green, water appears blue and agricultural fields appear orange

resolution have meant so far that SAR systems include different operational modes that either optimise the spatial resolution (at the expense of the swath width, hence the coverage) or the swath width (at the expense of the resolution). GMES will provide access to very high-resolution SAR national missions (Germany's TerraSAR-X and Italy's Cosmo-SkyMed), so Sentinel-1 is designed to address medium-resolution applications with its main mode: a wide swath (250 km) and medium resolution (5 x 20 m).

Products for Marine Core Services

SAR is the primary source of data for information on the oceans and the Arctic environment. The problems of access to the open oceans and the harsh Arctic often make radar, with its ability for observations in all weather and day or night, the only reliable information source. Typical products for the ice and snow services include monitoring glaciers and snow, icebergs, sea ice (floe edge) and the near-shore ice complex.

For determining the direction, wavelength and (extreme) heights of waves on the open oceans, SAR imagettes are being used in near-realtime in conjunction with global ocean wave models. The extensive wave mode archive built up by ERS and Envisat is a critical resource for analysing regional wave climate and extreme wave events.

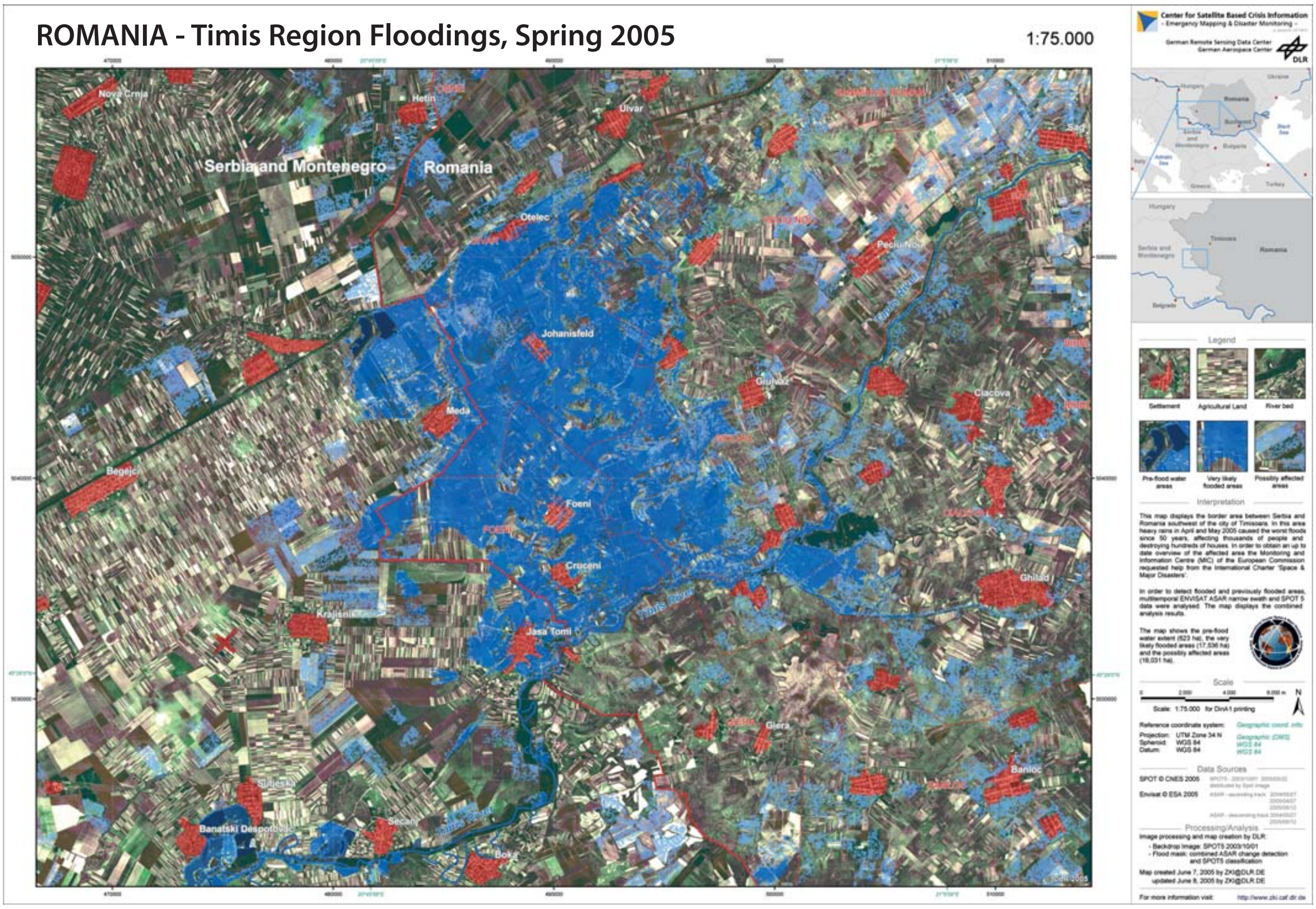
SAR is also the primary source of information on oil spills, such as surveillance and drift forecasting, and on ship detection for fisheries and security.

Products for Land Monitoring Services

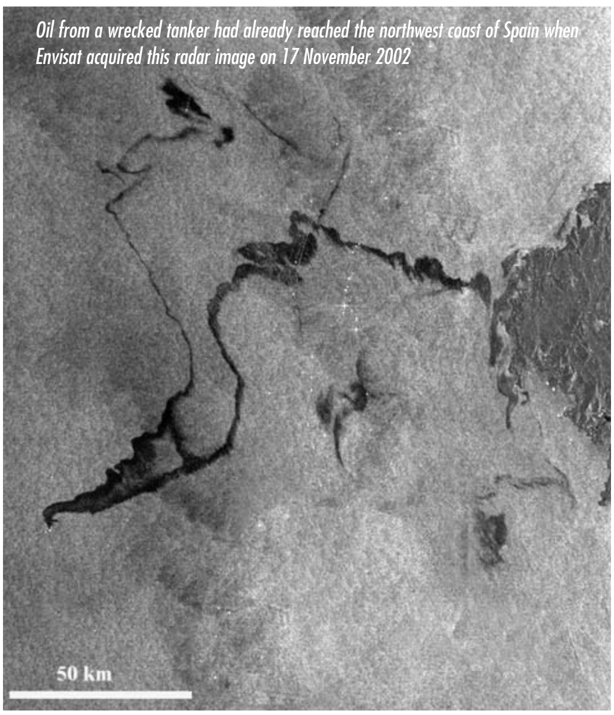
SAR data are not always the primary source for basic land-cover classification (forest, agricultural crops, urban areas, etc.) if multi-channel optical imagery with high spatial resolution is available. However, SAR is commonly used as a complementary or alternative data source under adverse atmospheric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

The contribution made by SAR to basic land-cover classification was greatly increased by the 'dual polarisation' mode introduced by Envisat's ASAR. Because the reflective properties of a surface depend on the polarisation of the incoming signal, the use of more than one type of polarisation provides valuable extra information. This has become a favourite for land classification. For this reason, Sentinel-1 is designed to exploit the full capabilities offerred by dual polarisation.

A dramatic improvement is expected from the more frequent revisits to the same area by Sentinel-1. This feature enhances time-series by adding close to daily sampling. Combined with its interferometric capability, Sentinel-1 will routinely offer products that were only available experimentally from the



Map of the flooding in the Timis region of Romania in May 2005, based on Envisat ASAR Narrow Swath and SPOT-5 data. (Image processing and map creation by DLR; SPOT © CNES 2005, distributed by Spot Image ENVISAT ASAR © ESA 2005)



Oil from a wrecked tanker had already reached the northwest coast of Spain when Envisat acquired this radar image on 17 November 2002

ERS-1/2 tandem mission. During the ERS tandem phase, data pairs were collected on successive days.

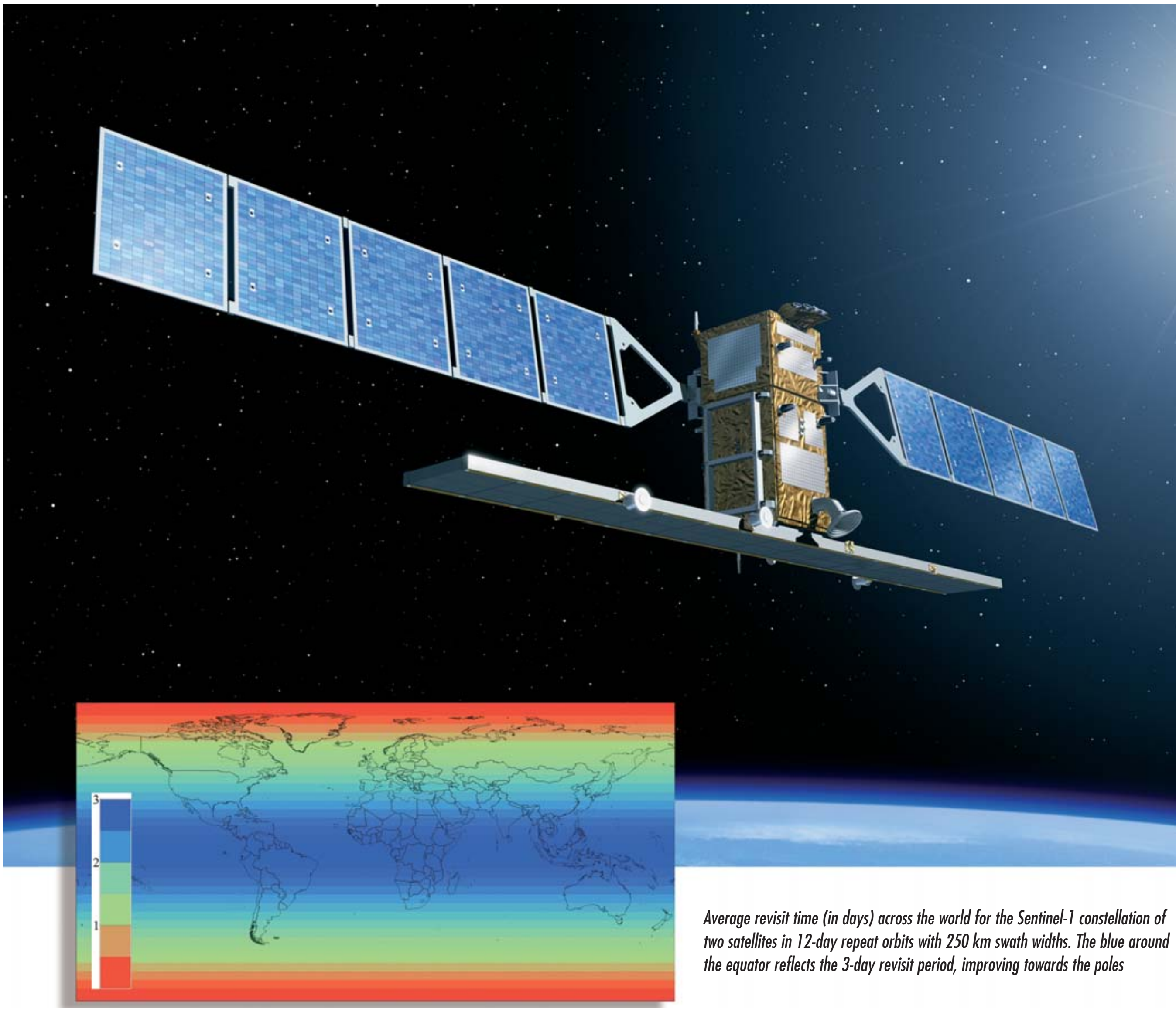
Classifying land cover is not the only important application of SAR to land monitoring. Since interferometric radar can detect surface movements to within a few millimetres per year, it is now an established technique to monitor the effects of landslides, earthquakes and man-made activities such as building construction, tunnelling, water or natural gas extraction, and mining.

Products for Emergency Services

Its all-weather day/night capability makes space-borne radar the ideal workhorse for providing information before, during and after emergencies. Sentinel-1's two-satellite constellation will routinely revisit all sites within 3 days at the equator and improving with latitude. In addition, an optional emergency procedure could accelerate access.

Agreements with other satellite operators will make daily access or even better a realistic assumption. This excellent revisit performance is feasible even while maintaining a spatial resolution of 5 x 20 m. In order to observe finer detail, regional coverage by satellites with higher spatial resolution (radar and/or optical) will be required.

Sentinel-1 will build a multi-temporal global interferometric image archive that can be called on in emergency situations.



Average revisit time (in days) across the world for the Sentinel-1 constellation of two satellites in 12-day repeat orbits with 250 km swath widths. The blue around the equator reflects the 3-day revisit period, improving towards the poles

For example, interferometric pairs will map the effects of earthquakes.

Even with the highly restricted coverage of today, C-band SAR is an established source of information in emergencies such as flooding and oil spills.

The Sentinel-1 System

The Sentinel-1 satellites are being built by an industrial consortium headed by Thales Alenia Space Italy as Prime Contractor, with Astrium Germany responsible for the 'C-SAR' payload, incorporating the central radar electronics subsystem developed by Astrium UK. The industrial set-up will be finalised during the project's initial phase. The satellite is based on the PRIMA (Piattaforma Italiana Multi Applicativa) bus, with a mission-specific payload module. Experience gained from Canada's Radarsat-2 and Italy's Cosmo-SkyMed projects, which also use PRIMA, will benefit Sentinel-1.

The design is driven by the payload requirements, with particular implications for data transmission and orbit control. The SAR data volume needs relatively large onboard storage capacity, and a downlink rate about six times that of Envisat. The X-band subsystem design has not yet been selected, requiring further analysis. Likewise, the Sentinel-1 requirements for operational interferometry place stringent requirements on attitude accuracy, attitude and orbit knowledge, and data-take timing accuracy.

Operational modes

Sentinel-1 has four standard operational modes, designed for interoperability with other systems:

- Strip Map Mode, 80 km swath and 5 x 5 m spatial resolution;
- Interferometric Wide Swath Mode, 250 km swath, 5 x 20 m spatial resolution and burst synchronisation for interferometry;

Sentinel-1 Satellite Characteristics

Lifetime: 7 years (consumables 12 years)
Launcher: Soyuz from Kourou (baseline), Zenith-2 (backup)
Orbit: near-polar Sun-synchronous 693 km; 12-day repeat cycle; 175 revs per cycle
Mean Local Solar Time: 18:00 at ascending node
Orbital period: 98.6 minutes
Attitude stabilisation: 3-axis
Attitude accuracy: 0.01 deg (each axis)
Orbit knowledge: 10 m (each axis, 3-sigma) using GPS
Operating autonomy: 96 hours
Launch mass: 2300 kg (including 130 kg monopropellant fuel)
Size (stowed): 3900 x 2600 x 2500 mm
Solar array average power: 4800 W (end-of-life); battery capacity: >300 Ah
Spacecraft availability: 0.998
Science data storage capacity: 900 Gb (end-of-life)
S-band TT&C data rates: 4 kbit/s telecommand; 16/128/512 kbit/s telemetry (programmable)
X-band science data rate: 600 Mbit/s

– Extra-wide Swath Mode, 400 km swath and 25 x 100 m spatial resolution (3-looks);
– Wave Mode, low data rate and 5 x 20 m spatial resolution. Sampled images of 20 x 20 km at 100 km intervals along the orbit.

Data delivery

With its continuous and conflict-free operations, Sentinel-1 will provide a high level of service reliability with near-realtime delivery of data within an 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.

Radiometric resolution

For the end-user of SAR imagery, the radiometric resolution is a critical parameter becasue it defines the typical image noise in radar images caused by thermal noise and speckle. Image noise defines how well different surfaces, such as ice types, agricultural crops and soil moisture levels, can be classified. With its extra-wide swath, Sentinel-1 offers 30% improvement with respect to Envisat, while the interferometric wide swath offers a further improvement by a factor of three.

Ground segment and operations

Once in orbit, Sentinel-1 will be operated from two centres. ESA's facilities in Darmstadt, Germany will command the satellite, while mission exploitation will be from Frascati, Italy, including the planning of the SAR acquisitions, the processing of the acquired data and the provision of the resulting products to the users. However, the ground segment design and operations concept allow operations to be handed over – partially or fully – to other operating entities in the future.

The satellite operations and mission exploitation present new challenges: the spacecraft needs to work within a tight orbital tube only 100 m in diameter, and must comply with GMES security requirements for command and control. Its operations will be largely automated during normal operations but emergency requests have to be accommodated at short notice.

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 in conflict-free sensing modes as much as possible. The ground system must be able to handle data flows from the satellite exceeding 1 Terabyte (10^{12} bytes) per day and to provide large data volumes within an hour of reception on the ground.

The operations concept allows the satellite to operate autonomously and cost-effectively with a 4-day mission plan stored onboard, thus allowing automated operations over weekends. At the same time, it is possible to insert individual emergency requests up to 3 hours before the planned update of the mission plan to the satellite. This allows considerable shortening of the response time of Sentinel-1 compared to its predecessors.

An extensive ground segment is required, with several ground stations receiving instrument data at 600 Mbit/s, with cumulative processing capacities above 500 GHz, archiving requirements exceeding 10 Pentabytes (10^{15} bytes), and with data dissemination exceeding current systems by an order of magnitude.

In order to fully satisfy the GMES service requirements, the ground segment must include coordinated mission planning and data exchange with other missions contributing to GMES. It 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.

Conclusions

The Sentinel-1 constellation is 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 GMES programme. The mission ensures continuity of C-band SAR data and builds on ESA's heritage and experience with the ERS and Envisat instruments, notably maintaining key characteristics such as stability and accurate well-calibrated data products. At the same time, mission parameters have been vastly improved to meet major user requirements collected and analysed through EU Fast Track and ESA GMES Service Element activities, especially in areas such as reliability, revisit time, geographical coverage and rapid data dissemination. As a result, the Sentinel-1 pair is expected to provide near-daily coverage over Europe and Canada, independent of weather with delivery of radar data within an hour of acquisition – vast improvements over the existing SAR systems.

In addition to responding directly to the current needs of GMES, the design of the Sentinel-1 mission is expected to enable the development of new applications and meet the evolving needs of GMES, such as in the area of climate change and associated monitoring.