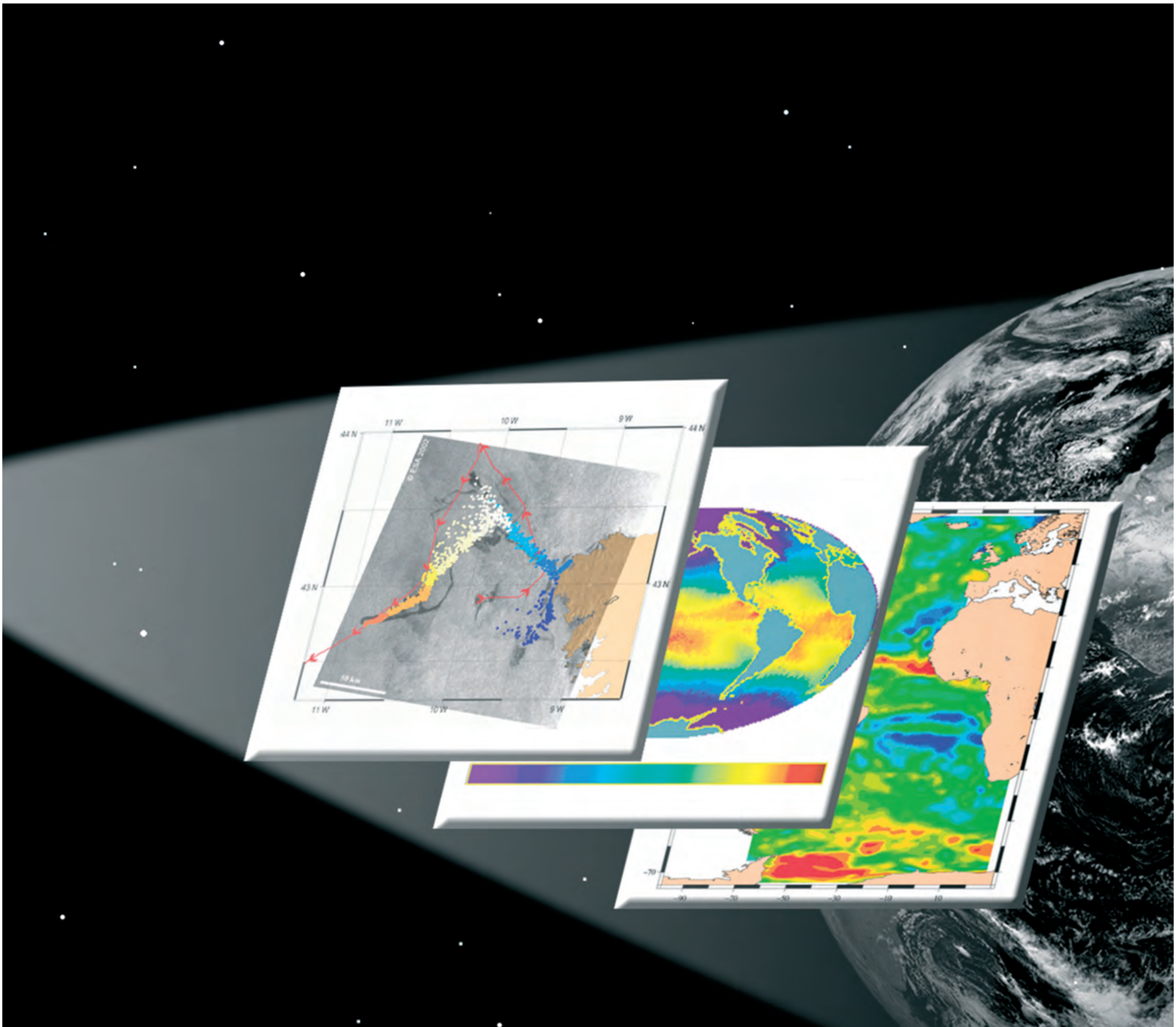

The Roadmap for a GMES Operational Oceanography Mission

Oceans cover approximately 70% of the Earth's surface and, with about 60% of the World's population living within 200 km of the coast, they have an untold impact on all of us. Not surprisingly, for people living close to the coast or those who depend on the ocean for their livelihood, regular forecasts of ocean conditions are just as important as traditional weather forecasts. Therefore, development of the infrastructure needed to support and sustain independent, European operational ocean forecasting, and the associated coastal and marine information services, are key priorities of the joint Global Monitoring for Environment and Security (GMES) initiative by the European Commission and ESA.

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Operational Oceanography

The development and maturation of operational weather forecasting during the last century has resulted in its ascendancy from broad public awareness to its common acceptance in everyday use. We can view 'operational oceanography' as the equivalent suite of forecasting and assessment capabilities for the state of the World's oceans. The development of these capabilities to a similar level of maturity and the same widespread use as meteorology is a major challenge for the 21st century. The near-term objective is to provide an integrated service to intermediate and end-users and decision makers in support of safe and efficient offshore activities, pollution monitoring, environmental management, security and sustainable use of marine resources. A routine integrated assessment of ocean state will also be extremely beneficial to weather forecasting, and ocean, ecosystem and climate research.

A Roadmap for GMES and the Sentinel-3 mission

Several major efforts have been initiated over the last five years to develop Europe's capacity in global operational oceanography. These efforts are now being integrated and pursued through the joint EC/ESA GMES initiative. Within the EC's Framework Programme, the Marine Environment and Security for the European Area (MERSEA) project is developing a European system for operational monitoring and forecasting of the ocean physics, biogeochemistry, and ecosystems, on both global and regional scales (www.mersea.eu.org). In parallel, the ESA GMES Services Element (GSE) is developing complementary 'downstream' marine and coastal environmental information services to end-users (www.esa.int/gmes). These EC and ESA initiatives will be coordinated with the implementation of the ocean-observing spaceborne component by the GMES Programme Office, to allow the development and deployment of the ocean component of GMES by 2015.

To develop a truly operational oceanography infrastructure that responds to the GMES requirements, a long-term commitment to ocean satellite-measurement systems must, however, be guaranteed. Without such global satellite measurements, these integrated systems will not be sufficiently supported by observations to provide routine, robust and reliable products. These thoughts are behind the development of the ESA GMES Sentinels, for which preparatory activities have now begun. These activities will pave the way for a decision on the full implementation of the GMES space component. The Roadmap described here targets the preliminary definition of the GMES ocean mission, Sentinel-3.

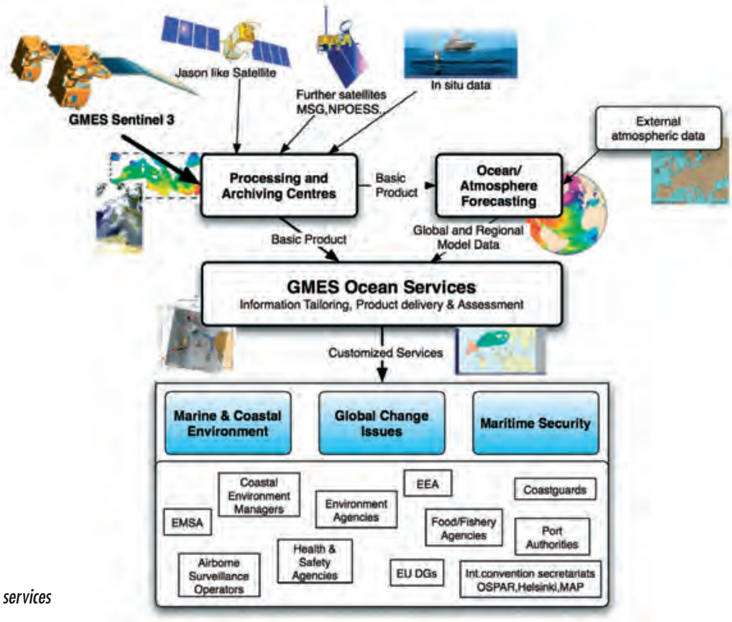
From February 2004 to March 2005, an ESA study titled 'Definition of Scenarios and Roadmap for Operational Oceanography' was carried out by a consortium led by CLS. The team consisted of eleven partners from six European countries: CLS, IFREMER, INGV, MERCATOR Ocean, NERSC, Satellite Observing Systems, Southampton Oceanography Centre, STARLAB, the UK Meteorological Office's National Centre for Ocean Forecasting, the University of Hamburg, and Alcatel Space. This article summarises the main results of this study, as essential background to the GMES Sentinel-3 preparatory study activities.

GMES Marine Services and Users

GMES marine services have been established that support, reinforce and improve European capacities linked to:

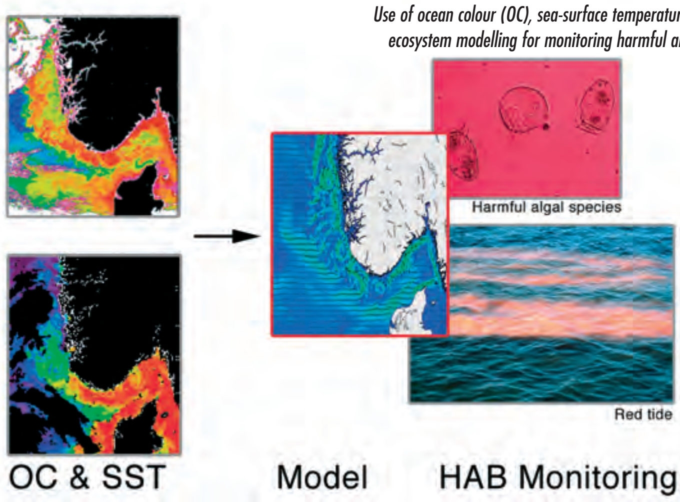
- Verification and enforcement of international treaties, and assessment of European policies.
- Sustainable exploitation and management of ocean resources (offshore oil-and-gas industry, fisheries, etc.).
- Improvement of safety and efficiency of maritime transport, shipping, and naval operations, as well as of national security and reduction of public-health risks.
- Anticipation and mitigation of the effects of environmental hazards and pollution crises (oil spills, harmful algal blooms, etc.).
- Advanced marine research for better understanding of the ocean ecosystems and their variability.
- Contribution to ocean climate variability studies.
- Contribution to seasonal climate prediction and its effects on coastal populations.
- Coastal management and planning services.

GMES marine services need to be able to rely on core services in global and regional operational oceanography with a mandate for remote sensing and in-situ data processing and distribution, modelling and data assimilation, and finally product distribution. These products will be exploited by end-user services tailored for specific applications and user communities (see figure). The core services that form the backbone of European operational oceanography will



GMES marine services

address the requirements from national and European policies, international conventions (e.g. OSPAR, HELCOM, UNCLOS), as well as European and international agencies (e.g. EEA, ICES, WCRP, UNFCC), for data, information products and indicators on the environment. Users will also include operational agencies responsible for marine meteorology, weather forecasting, maritime safety, and environmental monitoring. Companies from the private or public sectors providing ship-routing services, offshore operation support, environmental impact studies, coastal structure design or coastal management studies will also benefit from these core services. End-user services will successively build on these core services to address specific applications (e.g. for oil spills and illegal discharges, or harmful algae blooms) (see accompanying figures).



Use of ocean colour (OC), sea-surface temperature (SST) and ecosystem modelling for monitoring harmful algae blooms

Operational Oceanography Requirements

The backbone of operational oceanography is formed by global/basin-scale/regional modelling and data assimilation systems that use remote sensing and in-situ measurements to provide a regular, robust, comprehensive description and forecast of the ocean state. A core objective for the Sentinel-3 mission is therefore to provide the space-based observations required by these 'integrated' systems.

The primary operational Earth Observation (EO) satellite observation requirements specified by the GMES MERSEA project, the ESA GSE studies, and the Global Ocean Data Assimilation Experiment (GODAE) are as follows:

- Global, near-real-time, high-accuracy and high-resolution observations of sea surface topography. The minimum requirement is at least two (preferably four) altimeter-bearing missions including one long-term and highly accurate mission for climate applications.
- Global, near-real-time, high-resolution sea-surface-temperature (SST) products as specified by the GODAE High Resolution SST Pilot Project (GHRSST PP). These products, based on the merging of satellite and in-situ data, are needed at time intervals of less than 24 hours and at a spatial resolution of better than 10 km for the global ocean, and better than 2 km for regional seas and coastal areas.
- While some R&D activities are still needed to develop the effective use of satellite ocean-colour (OC) data in ocean forecasting models, it is foreseen that by 2008 MERSEA operational models will routinely use ocean-colour data as an input to ecosystem models. Resolution requirements should be close to those specified for SST, though many near-shore coastal applications require spatial resolutions better than 1 km.
- Global sea-ice concentration and sea-ice drift (daily, with resolution better than 25 km) and possibly sea-ice-thickness fields.

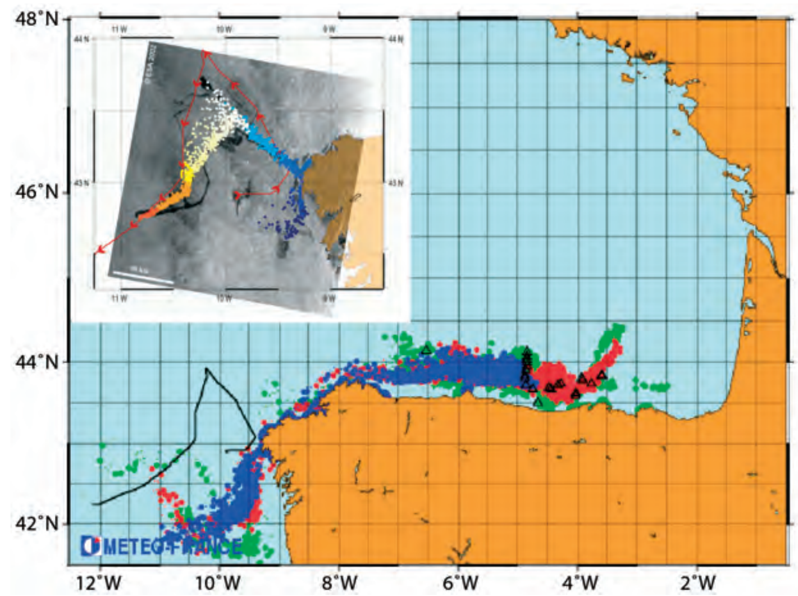
In addition to the above EO data requirements, meteorological forcing fields from Numerical Weather Prediction systems are required as inputs to the operational ocean models. These should be complemented by vector winds from at least two wide-swath wind scatterometers (including the Advanced Scatterometer on MetOp, planned for launch in 2006). Though ocean-surface salinity is also a very important parameter that should ultimately be monitored from space, the feasibility of salinity retrievals must first be demonstrated by ESA's SMOS and NASA's Aquarius missions.

Requirements for the Sentinel-3 Mission

As explained above, sea level, sea-surface temperature, sea ice, ocean colour and wind vectors are the key prognostic quantities in operational oceanography. The European contribution to ocean wind measurements is already addressed by the Advanced Scatterometer (ASCAT) instrument on the MetOp series of satellites. Existing and planned missions should additionally provide the required information on sea-ice edge, concentration and drift, but not the ice thickness. An ocean altimeter mission could, however, be adapted to address the sea-ice thickness requirement.

There is also a strong requirement for Synthetic Aperture Radar (SAR) data expressed by the marine user community, in connection for instance with oil-spill monitoring. The SAR marine requirements are addressed in principle by Sentinel-1, but will nonetheless benefit from forecast information provided by ocean models constrained by Sentinel-3 observation data. Other more critical marine services, such as oil-spill drift forecasting, would not be possible without Sentinel-3 data, since wind, wave and ocean current forecasts are required.

Existing EO data requirements for ocean surface-wave modelling and forecasting must also be addressed by the Sentinels. This calls for access to surface wind fields as well as satellite observations of sea state currently provided by altimeters (in the form



The Prestige accident in November 2002 demonstrated the importance of ocean model forecasts of large-scale currents, essential for accurate oil-spill spread prediction

of significant wave height) and SARs (as wave spectra). New concepts for effective global measurements of these parameters need to be developed, but in the meantime a combination of multiple altimeter and SAR-bearing EO satellite missions would provide a suitable alternative.

The main conclusion drawn from a detailed study of the requirements is thus that Sentinel-3 should be the first of an established series of operational, long-term ocean-monitoring satellites providing core measurements of ocean altimetry, sea-surface temperature and ocean colour. The Sentinel-3 measurement requirements summarised below have been distilled from the analysis of existing and planned missions (see tables).

Ocean/Ice Altimetry

The most urgent requirement is to fly a post-Envisat, radar-altimeter-bearing mission, while in the longer term a high-resolution altimeter measurement system should be in place for the operational GMES phase. It would also provide useful data both for operational ocean-wave forecasting and sea-ice-thickness monitoring.

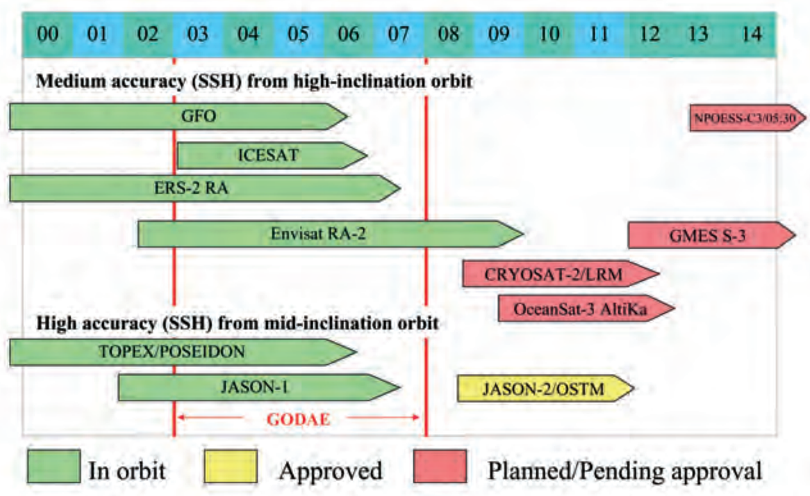
Altimetry provides the ocean topography in the form of precise sea-surface height measurements. Such data are required to adequately represent ocean eddies and associated currents (the 'ocean weather') in models. Most operational oceanography applications, such as marine security and pollution monitoring, require high-resolution surface-current data, which will not be adequately reproduced without a high-resolution altimeter system.

The altimeter system that is being proposed should complement the Jason series, which we assume will continue to provide precise long-term data. The European Commission's GAMBLE study (www.altimetrie.net) recommends a constellation of three optimised altimeter missions in addition to the Jason series.

Sea-Surface Temperature and Ocean Colour

Analysis of planned missions shows that the basic operational oceanography requirements should be fulfilled from 2011 onwards with the VIIRS optical and CMIS microwave sensors that will fly on all NPOESS satellites. Europe has, however, developed a strong heritage and leadership in the highest-precision measurement of climate-quality SST with the ERS and Envisat ATSR and A/ATSR sensors. These sensors have so far been the 'gold standard' for high-quality ocean-surface-temperature measurements, and a successor would provide an extremely important complement to the planned NPOESS and MetOp missions. Similar logic holds for precise/high-resolution ocean-colour monitoring applications using Envisat data,

Existing Approved and Planned Ocean Altimetry Missions*



*Whereas three altimeters (including one high inclination and one lower inclination) are required for effective operational oceanography, the number of altimeter missions falls below three from 2007 onwards. Unless the Envisat RA-2 and Jason Instruments remain operable, there may potentially be a gap in altimetric measurements until the launch of Jason-2 (expected in late 2008). The only planned altimeter mission in the post-2011 timeframe is the NPOESS C3 altimeter.

whereby the MERIS instrument channels provide specific benefits for GMES marine and coastal services. The important synergies between SST and ocean-colour measurements also make a strong case for a combined SST/OC sensor capability on the same platform.

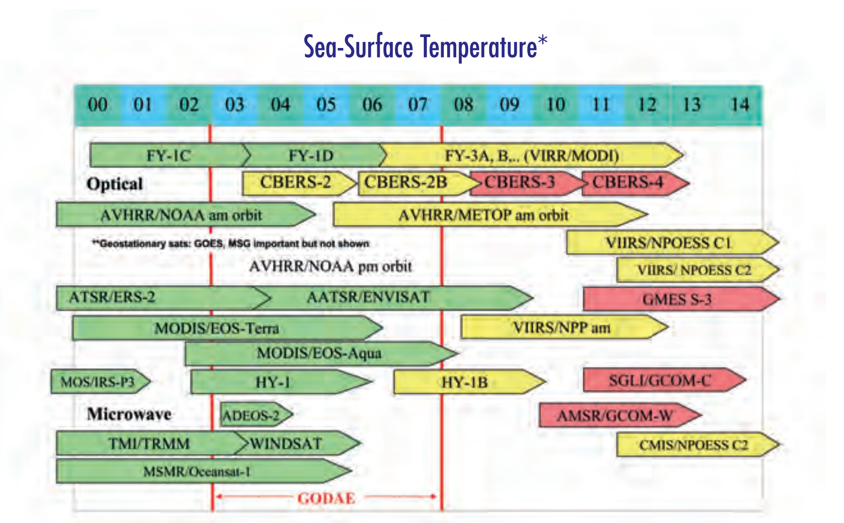
The Sentinel-3 Concept

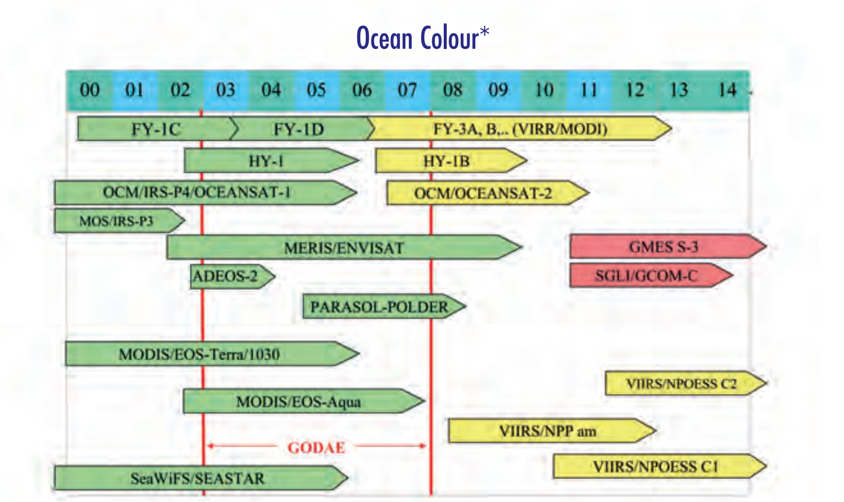
Two concepts have been analysed as part of the Sentinel-3 Roadmap exercise:
– Concept 1: Altimetry/SST/Ocean Colour on single platform in a polar orbit.
– Concept 2: Altimetry and SST/Ocean Colour on two independent polar orbiting platforms.

While co-located SST, ocean-colour and altimetry observations show scientific potential in the context, for example, of ocean-atmosphere exchanges and coupling between physical and biochemical components of the upper ocean, there are currently no specific GMES requirements for flying an altimeter and an SST/OC payload on the same platform. Concept 2 would allow optimisation of the orbit choices (e.g. repeat/non-repeat orbit, altitude, minimisation of Sun-glint effects, etc.) and to have different observing schedules for the altimeter and the SST/OC missions.

Altimetry

A high-inclination altimetry mission is recommended to cover high-latitude regions. The orbit could be Sun-synchronous, preferably using the same repeat track as Envisat. The main requirement for high-resolution ocean altimetry would be to fly three altimeters in addition to the Jason series, either directly as a constellation or built up progressively with a launch every 2 to 3 years. The preferred option would be to phase the orbit of each satellite to improve the sampling interval as much as possible. Swath altimetry is an attractive means for improving the spatial/temporal coverage, but a demonstration of the concept prior to entering operational status is required. In the longer run, use of Global Navigation Satellite System (GNSS) reflected signals should also be considered to supplement conventional radar-altimetry data.





* Overall outlook appears to ensure good available of SST and OC observations from space, but the European contribution to OC monitoring is very limited and calls for readjustment. The main issue for SST is to continue to provide high-quality products for climate applications.

Sea-Surface Temperature/Ocean Colour

The primary requirement is to retrieve SST with AATSR instrument-type accuracy. In this case, an along-track view (bi-angular observation) is mandatory to compensate for atmospheric-dust and aerosol-induced errors. Ideally, the system should thus provide high-quality SST measurements over a wide swath, as well as a dual view over a narrower swath as a 'gold standard' for all other SST measurements. The objective of the ocean-colour instrument is to monitor the global open ocean, whilst also supporting several important applications in coastal areas. This will require a selection of wavelengths similar to MERIS. A revisit time of 1 day at European latitudes should be a goal for the SST/OC mission and this requires large swath widths (>2000 km). Orbit time and/or phasing should be optimised versus NPOESS and MetOp.

Time schedule

The timetable for Concept 1 could be to fly the first mission as early as possible (2010/2011) and to ensure continuity of the data streams currently provided by Envisat. One should allow some overlap between the missions for a precise inter-calibration of the different sensors. The schedule for Concept 2 might be slightly different. One should first start as early as possible (2009) with the first altimeter component (post-Envisat 'gap filler') and then fly new altimeter missions every two years or so in order to have at least two simultaneous missions by 2011 (assuming a lifetime of 4/5 years). The SST/OC component could follow the same schedule as for Concept 1.

Sentinel-3 Mission Characteristics

Altimeter payload

The altimetry payload must include an altimeter, a radiometer for atmospheric-moisture correction, a precise navigation receiver for orbit determination, and a laser retro-reflector for absolute calibration of the orbit. Nadir altimeters are proposed as the baseline for the ocean mission and the following possibilities have been identified:

- Poseidon-3 recurrent altimeter: this dual-frequency (Ku+C bands) altimeter is the main instrument on the Jason-2 mission.
- SAR Radar Altimeter (SRAL): this is a dual-band (C+Ku) altimeter operating in conventional radar-altimeter mode as on Poseidon-3, and in SAR mode over sea ice and coastal regions. As a secondary objective, the SRAL will provide sea ice-thickness measurements of the same quality as the SIRAL payload on CryoSat.
- Alti-Ka: this instrument includes a single-frequency Ka-band (35 GHz) altimeter and a dual-frequency radiometer. Due to its compactness, it is particularly well-suited for implementa tion on a micro satellite. The first implementation of Alti Ka should be on the Indian OceanSat-3 mission in the framework of a CNES/ISRO partnership.

SRAL is a mature concept supported by the strong heritage from Poseidon-3 and the CryoSat SIRAL instrument, and would provide the required ocean and sea-ice thickness measurements, as well as inland-waters and coastal measurements. It is therefore favoured as the baseline for the first Sentinel-3 mission.

A recurrent radiometer derived from the Envisat MWR is considered the baseline solution for the microwave radiometer.

SST/OC payload

A first optical payload trade-off exercise has highlighted a preference for two separate instruments, one optimised for SST and the other for ocean colour.

The SST requirement for a dual-view and large-swath (1800 km) instrument calls for very specific scanning assemblies. The in-beam dual scanner, with a dual-mirror arrangement using a single scanner, continuously rotating at a moderate and constant speed, is preferred for its simplicity and reliability. The main drawback is the need to duplicate the calibration sources, but this solution should provide the required radiometric accuracy, thanks to the excellent calibration blackbodies available.

For the ocean-colour instrument, two possible solutions have been identified:

- Push-broom instruments based on MERIS cameras or using a new spectro imaging camera with larger field-of view than MERIS, providing a 1100 km swath.
- A high-performance scanner allowing large swath (1800 km) and along-track dynamic tilting to avoid Sun-glint problems; a high-transmittance spectro-meter is used for superior spectral and radiometric performances.

The latter solution is the preferred baseline for the ocean-colour instrument as it provides a larger swath to meet the coverage requirements.

Satellite

In the Concept 1 scenario, the altimetry, ocean-colour and sea-surface-temperature missions are accommodated on a single platform, compatible with a 1 tonne-class launch vehicle such as Rockot. A local observation time of 12:00 hrs would be preferable for the ocean-colour mission in order to avoid morning haze, while an early afternoon orbit should be avoided for good SST retrieval. Optimisation of the local time with regard to the NPOESS local time will probably lead to the selection a local time of around 11:00 hrs. The satellite's overall mass is 942 kg and the maximum power budget is 1100 W, which can be satisfied by a 9.6 m^2 solar array. The data volume budget is compatible with state-of-the-art telemetry and mass memory hardware without any need for compression.

Concept 2 foresees dedicated spacecraft for the altimetry and SST/OC missions, with the development of a common platform probably the most cost-effective option. The accommodation of large-swath (1800 km) instruments forms the baseline for both concepts.

Owing to the compactness of the French Alti-Ka altimeter, an alternative for the altimetry mission's implementation would be to use micro-satellites and multiple launches. This solution is particularly well suited to ocean mesoscale requirements, and would offer flexibility in the maintenance of an altimeter constellation.

Conclusions and Recommendations

The GMES Sentinel-3 mission will provide the core observations required for the operational global and regional ocean monitoring and forecasting systems that Europe is setting up. Given the expected gaps in altimetry and precise SST and ocean-colour measurements in the post-Envisat timeframe (2009-2011), a decision on its implementation is urgently needed and any delay poses a major risk for the future of operational oceanography and GMES in Europe.

A long spacecraft lifetime (~10 years) should be targeted to reduce the number of satellites needed for the overall duration of the mission. This is helped by the fact that the solutions identified for the altimeter, ocean-colour and SST instruments use mature technologies and concepts with a low development risk and high reliability.

The final choice between the two candidate mission concepts will depend on many criteria, including refined requirements, operational needs, reliability, lifetime, development risk and schedule, and overall life-cycle costs. Taking cost alone as the overriding criterion, Concept 1 would be the preferred solution, but Concept 2 would allow the long-term requirements for high-resolution altimetry to be addressed more effectively.