

→ NEW POSSIBILITIES FOR SCIENCE

ESA's operational Sentinel missions

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An exciting new period of integrated Earth observation science is set to begin, with the scientific exploitation of data from ESA's Earth Explorers and the upcoming Sentinel missions.

Since Earth observation from space first became possible some 40 years ago, it has been demonstrated as a key tool for the monitoring and studies of how our Earth system works. Now we have arrived at a point where operational

observations become a reality while new observation techniques continue to emerge. Such balance between innovation and continuity is one of the core aspects of the Earth Observation Programme.

The Sentinels are a set of five mission 'constellations' being implemented by ESA in cooperation with the European Union. Although primarily designed to provide routine observations for operational Global Monitoring for Environment and Security (GMES) Space Component

programme, the Sentinel missions will also support and stimulate innovative Earth system science.

Their ability to operate various sensors with global coverage and rapid revisit times, covering different spectral and spatial resolutions, makes Sentinel missions also highly useful in advancing our understanding of Earth system processes and interactions.

The continuity of data already widely used within the science communities, with a long-term operational commitment, is essential for the parametrisation of long-term forecasting. Furthermore, the high revisit time, well suited for capturing rapid changes, are strengthening model

Earth Explorers will be operating complementarily, offering a range of synergies starting from the provision of auxiliary information, to substantial inputs for addressing scientific challenges.

The timeliness calls for integrated data exploitation strategies that are very important for the development of a holistic Earth system model. Integrated data analysis will be further stimulated by ESA Announcements of Opportunity for dedicated theme-oriented exploitation, tailored to specific aspects of Earth system modelling and coordinated with international science communities.

Scientific use of the Sentinel data will in no way impact on or compromise the dedicated use of the data in support of GMES operational services. In practice, improved understanding of the data in pursuit of scientific questions, and the methods developed in addressing them, might in fact be of great benefit to the execution of existing operational services and the development of new ones. Hence, ESA will strive to ensure that data from the Sentinels are made available to the science community openly and freely.

The combined Sentinel and Earth Explorer missions programme is expected to reduce observation limitations and strengthen our ability to monitor the state and changes of our planet Earth. By filling in current gaps in our knowledge and improving our quantitative understanding, we will be able to develop more reliable model- and data-based assessments and predictions of the Earth system.

Relevance to Earth sciences

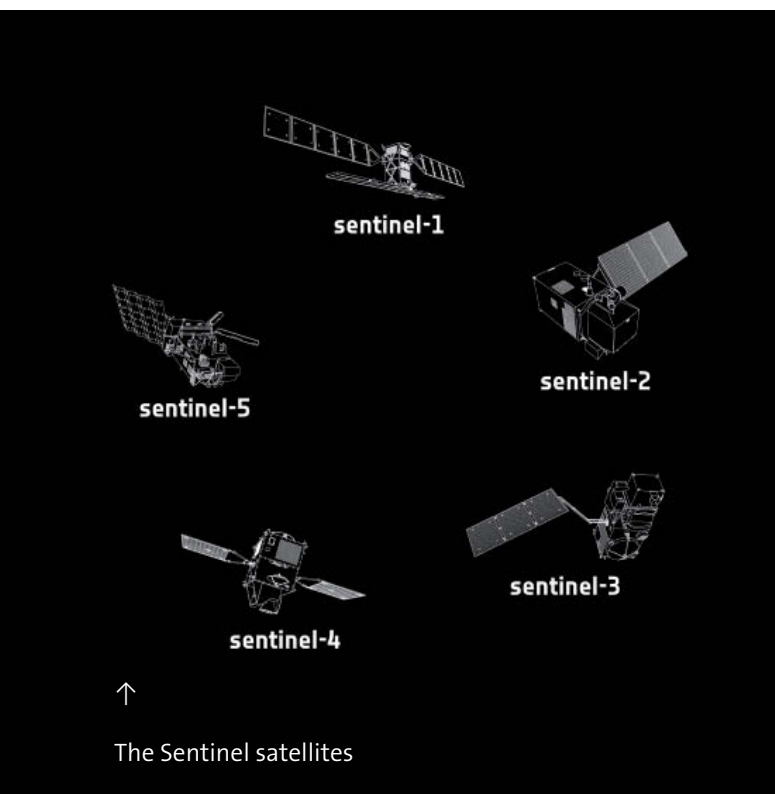
ESA's 'Living Planet' Programme - *The Changing Earth (SP-1304)* outlines the scientific challenges for Earth system sciences as defined by the European science community. Some of these challenges are addressed below with regard to the Sentinels and in conjunction with the Earth Explorer missions.

Atmosphere

The atmosphere is a central component in the Earth system and acts as a natural transport system for energy, water, nutrients and pollutants. It exchanges momentum, heat, water, carbon and all trace gases and aerosols between the oceans and land surfaces. Atmospheric circulation is driven by these interactions, as well as sea-surface temperature, soil moisture and surface albedo.

Since water vapour is the most abundant greenhouse gas, accounting for one to two thirds of the 'greenhouse effect', scientists are looking for a better understanding of the coupled processes of clouds, aerosols and atmospheric chemistry, including the global water cycle.

Clouds and their radiative feedback processes also require wind, temperature and humidity profile observations. Aerosols produce a direct radiative forcing by their scattering and absorption of solar radiation, and an indirect forcing by changing the radiative properties of clouds. A quantitative understanding of the various sources of aerosols, their



The Sentinel satellites

validations and their subsequent improvements. Long-term climate forecasting will certainly benefit from this development.

In addition, the Sentinels offer an increased spectral coverage which supports data harmonisation, a prerequisite in establishing a fundamental climate data record, and additional science products with many potential applications, fostering knowledge transfer into the GMES service domain.

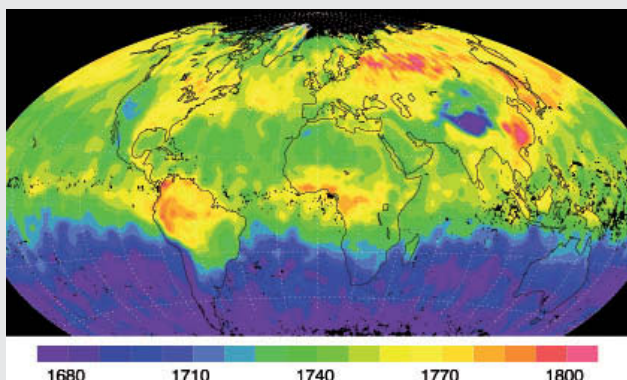
A key part in the exploitation of the Sentinels will be 'data synergy'. Such synergistic exploitation of data coming from the different Sentinel systems will increase the potential for the development of new tools and advanced products, leading to new capabilities for scientific exploitation. Another asset of the Sentinels is the timeliness of their data. All of the missions will be operational simultaneously from the middle of 2015 onwards. It is expected that most



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Scientists are looking for a better understanding of clouds, their chemistry and radiative properties

chemical composition and their sources and sinks is needed. This focuses on the role of aerosol particles and microphysical cloud processes, convection and the properties of cirrus clouds and how they link atmospheric composition and climate change. New aspects in this area are the roles of reactive carbon species of natural origin and the coupling of the nitrogen and carbon cycles.

It is now well established that the chemical composition of the atmosphere is changing as a result of human activities. These changes have a direct impact on the environment, on climate, and on air quality and health on global and regional scales. These effects need to be better understood and it is becoming very urgent to have access to reliable, global, vertically resolved observations with high horizontal



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Global atmospheric methane averaged distribution (column averaged dry air mole fractions in parts per billion) obtained from ESA's Envisat between 2003 and 2005 (ESA/University of Bremen)

resolution of both atmospheric gas phase species and particles, due to an accelerating global population growth, massive urbanisation, and increased transportation and further industrialisation in developing countries.

In addition, the complementary Earth Explorer ADM-Aeolus mission will provide wind profiles to improve our understanding of atmospheric dynamics, the global atmospheric transport and the cycling of energy, water,

aerosols and chemicals. EarthCARE will provide vertical profiles of natural and anthropogenic aerosols, vertical distribution of atmospheric liquid water and ice and better knowledge of the interactions between cloud, radiation and aerosol processes.

Sentinel-4 and -5, and the Sentinel-5 precursor mission, will be dedicated to atmospheric chemistry observations, air quality assessment and climate research issues. Products will support the science issues related to the atmospheric transport system and any alterations in it caused by climate change, such as the long-range transport of long-life compounds and aerosols, their impact on air quality and possible trends in oxidising capacity. Sentinel-3 Ocean and Land Colour Instrument (OLCI) data will also be instrumental in improving atmospheric products, including estimates of aerosols, water vapour and cloud properties.

Ocean

The oceans and their interactions with the atmosphere and land play a major part in driving the global climate through the large amount of heat and mass transported by ocean currents, the evaporative fluxes and momentum exchange. More than 70% of Earth's surface is covered by oceans, which absorb more than half of Earth's total absorbed solar radiation. Moreover, about 40% of the anthropogenic carbon dioxide emission is absorbed in marine biological processes.

Complex ocean–atmosphere interaction and feedback mechanisms occur across a wide range of temporal and

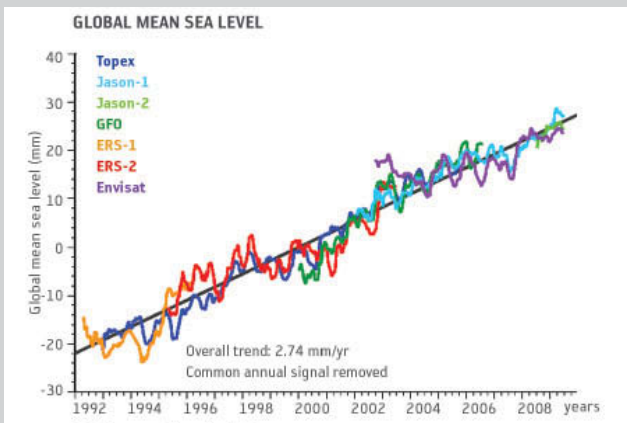


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More than 70% of Earth's surface is covered by oceans

spatial scales, including momentum exchange, radiative and turbulent heat fluxes and freshwater fluxes through evaporation, precipitation, sea-ice growth and melt, ablating ice sheets and mountain glaciers and river discharges. Added to this are exchange processes with the land biosphere as well as oceanic biogeochemical processes invoked by shortwave absorption and scattering, the biological CO₂ pump and the exchange of gases, aerosols, dust and other natural or man-made chemicals.

A broad spectrum of phenomena, such as global warming and sea-level rise, decline in fish stocks, seasonal oxygen depletion, acidification, episodic harmful algal blooms and loss of biodiversity, are all now showing troubling trends in their magnitude and frequency in open oceans as well as in many coastal areas. In the context of climate change the challenges of seasonal-to-decadal-to-centennial prediction are further aggravated by the existence of several unresolved key scientific problems, such as the coupling between wind-driven gyres and the thermohaline circulation, the convective overturning and the connection between tropical and extra-tropical disturbances at seasonal to decadal timescales.

In addition to securing provision of data to reduce knowledge gaps and meet the complicated challenges as

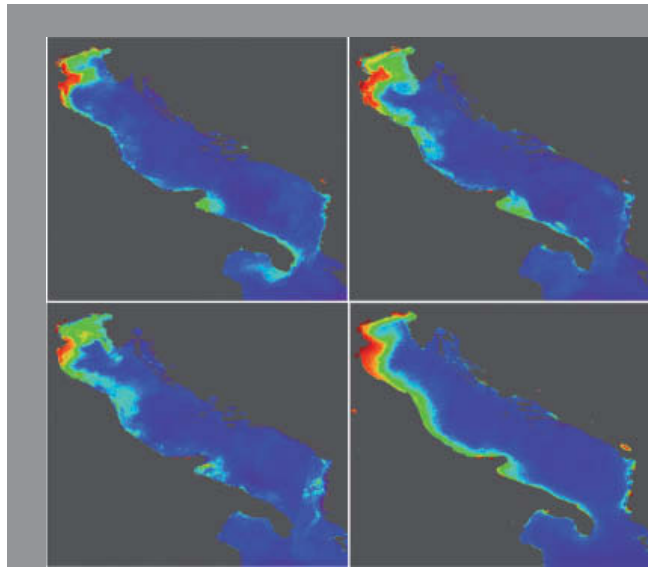


↑ Global sea-level rise derived from radar altimeters carried on various satellite missions. The overall trend shows an increase of 2.89 mm over the period 1992–2008 (R. Scharroo/Altimetrics LCC)

mentioned above, the Sentinels-1, -2 and -3 will moreover support a range of Earth observation capabilities that are needed to develop and implement knowledge-based operational marine information and prediction systems for delivery of Marine Core (e.g. MyOcean) and Downstream Services. In so doing, the missions ensure data continuity with ERS and Envisat sensors with increased radiometric, spectral and temporal resolution.

The Sentinel-3 ocean colour sensor will allow estimation of marine productivity, the detection and monitoring of algal blooms and estimation of the eutrophication state of

the ocean through monitoring of water constituents like chlorophyll, yellow substances and sediments. Sentinel-3's thermal sensor will monitor sea-surface temperature and its variability connected with both global climate change and mesoscale frontal dynamics and upwelling zones. Near-surface wind and wave information will be obtained from Sentinel-1 C-band synthetic aperture radar (SAR) and Sentinel-3 SAR radar altimeter (SRAL) data. The SRAL will moreover allow the highly needed monitoring of the mean sea-level change. Monitoring and studies of surface current, upper-ocean mesoscale dynamics and air–sea interaction will also be carried out using Sentinel-1 and -3 (SRAL).



↑ Adriatic Sea chlorophyll concentrations (µg/l), top left: 1–10 July 2009 mean, top right: 11–20 July 2009 mean, bottom left: 21–31 July 2009 mean, and bottom right: June 2006 – August 2008 mean percentile 90 (ESA/MERIS and NASA/MODIS, Planetek and ACRI/MarCoast)

The synergistic use of Sentinel missions will furthermore support investigation of sea-level change, physical and biochemical air–sea interaction processes, internal waves, mesoscale processes and wave–current interaction. Sentinel-2 data, in combination with Sentinel-3 data, may also provide useful information in the study of coastal areas, with potential applications in monitoring coral reefs and their bleaching caused by warming oceans.

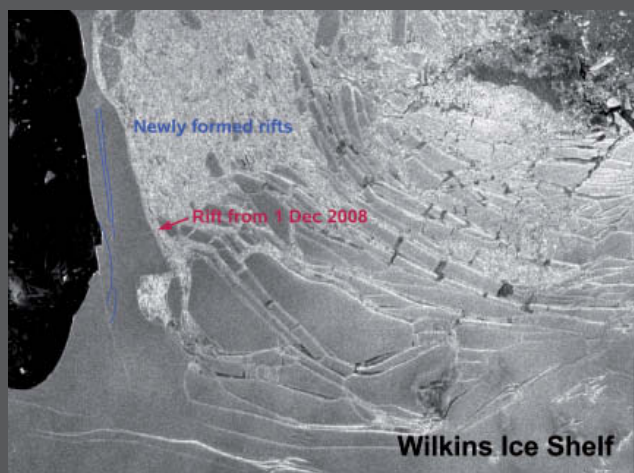
Important complementary contributions to many of these challenges are expected from the Earth Explorers, notably SMOS and the Gravity field and steady-state Ocean Circulation Explorer (GOCE). These missions will observe the sea-surface salinity and the marine geoid, which will provide new and highly valuable data for advancing the exploration of ocean circulation and quantifying its transport of mass and heat, as well as large-scale patterns of evaporation and sea-level change.

Cryosphere

The cryosphere refers to regions of Earth's surface where water is frozen, including sea ice, lake and river ice, snow, glaciers, ice caps and ice sheets, and frozen ground (including permafrost). This plays an integral part in all other Earth system components because of the high shortwave reflectivity of snow and ice, and because of all the freshwater locked up as ice (almost 80% of the freshwater on Earth). It has a strong influence on the surface energy and moisture fluxes, precipitation, hydrology, sea-level rise and atmospheric and ocean circulation. (Note that the freshwater provided by the melting of glaciers and land ice sheets is responsible for an increase in sea levels of 18 cm during the last century.)

Scientists need to better understand cryosphere–climate coupling and their mutual feedback through the freshwater cycle and the surface energy balance. This is not only including changes imposed by global warming on ice sheets, the ablating of glaciers, oceanic thermodynamics, rivers, lakes and ice, but also the freeze–thaw conditions in permafrost soils. Current trends show that our models by far underestimate these effects. Space observations can contribute to advancing our knowledge of state, changes and mutual feedback of the cryosphere by regular monitoring of the physical properties of snow and ice surfaces including their roughness, emissivity, dielectric characteristics, surface reflectance and temperature.

Sea-ice monitoring is not only a well-established remote sensing application for assessing ship navigation in ice-infested waters, but also as a climate change indicator. In addition to its impact on the albedo, the salinity and thus the density of the upper–ocean is strongly influenced by



Envisat's Advanced Synthetic Aperture Radar captured the early stage of the disruption of the ice bridge that connects the Wilkins Ice Shelf to Charcot and Latady Islands in Antarctica in April 2009. The new rifts that developed along the length axis of the ice bridge are visible (ESA/A. Humbert/Munster University)



Almost 80% of the freshwater on Earth is locked up as ice

growth of sea ice. Reduction in sea ice growth will thus affect local salinity and convective processes, water mass properties and ocean circulation.

Current observations of sea ice show a considerable seasonal, regional and interannual variability in both hemispheres, with larger amplitudes in the Arctic. The Sentinel-1 and -3 missions will ensure data continuity for monitoring changes of the cryosphere, including its surface roughness and elevation, temperature and albedo. In addition, the interferometric capability of Sentinel-1 is suitable for monitoring polar glacier outlets and ice streams by determining velocities which in turn can be converted into mass flux data.

Adding to this, the Earth Explorer CryoSat will provide new and precise quantitative estimates of the thinning and thickening of polar land and marine ice. The improved spatial resolution of its two-antenna radar altimeter, coupled with its interferometric cross-track capability, will also allow repeat observations of the steeper ice-sheet margins and smaller ice caps. These highly needed observations can also be complemented with the SMOS brightness temperature observations as well as the GOCE gravity and geoid data.

Solid Earth

The 'solid Earth' processes are those affecting the surface and interior of the planet. Tectonic processes driven by mantle convection and associated deformation at the surface, leading to earthquakes and volcanic activity, are affecting daily life for millions of people. The global distribution of gravity is indicative of such processes in the interior, a driver for ocean currents, and sensitive to mass redistribution, for example, due to melting land ice. Anomalies in the magnetic field tell us more about Earth's geological history and mass motion in its fluid core.

Earthquakes, tsunamis and volcanic eruptions in some of the most densely populated areas on Earth continue to take their toll, so there is an urgent need to better understand such processes. Whereas seismic stations are able to pinpoint locations and focal mechanisms, it is poorly understood how strain accumulation over many decades is

eventually relieved, and how earthquakes interact in fault systems. Direct observation of the surface deformation related to strain accumulation is essential, and is needed over vast areas of the world. The scale of such (interseismic) deformations is in the range of ‘millistrain’, or deformation of millimetres per horizontal kilometre per year.

Sentinel-1, with its multi-pass polarimetric interferometric observation capability and rapid revisit time, will strongly benefit solid Earth science. Radar interferometry provides accurate measurements of ground deformation, with millimetre precision. Maps of ground deformation can be produced over regions spanning hundreds of kilometres, with a horizontal resolution of a few tens of metres, to assess seismic hazards by monitoring the rate of strain accumulated within that region. Radar interferometry is also used to monitor the activity of volcanoes and subsidence caused by the extraction of ground water.

Earth’s gravity field varies due to uneven mass distribution and the dynamics of the surface and Earth’s interior. These include high mountains, deep ocean trenches, ground water reservoirs, oil, gas and mineral deposits, tidal effects, sea-level rise, Earth’s rotation, volcanic eruptions and changes in topography. A precise knowledge of the ‘geoid’ – a virtual surface with an equal gravitational potential – is needed for many applications, such as levelling and construction, and for understanding ocean currents and monitoring sea-level dynamics.

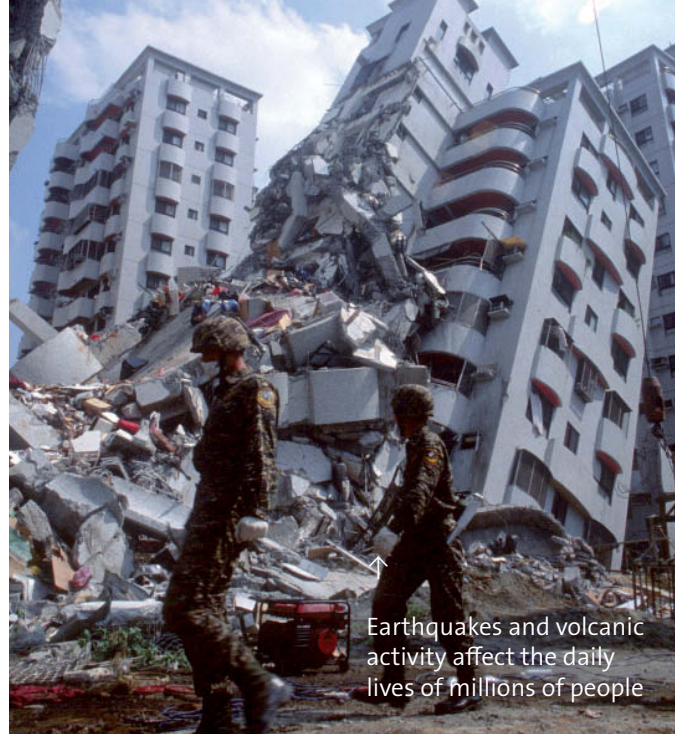
The Earth Explorer GOCE is currently measuring such density variations in Earth’s interior. Hereby, it is effectively monitoring processes occurring in the lithosphere and upper mantle, down to a depth of 200 km. These, together with seismic data, allow a better understanding of the processes that lead to earthquakes and volcanic eruptions.

Our planet’s magnetic field, which is to a large part generated by a ‘dynamo’ effect in Earth’s fluid outer core, plays an important role in shielding us from hard cosmic rays, which was essential for the development of life. The field and its temporal change provide insight into Earth’s interior processes.

The Earth Explorer Swarm mission will provide the best-ever survey of the geomagnetic field and its time-variability aspects, allowing the decoupling of the spatial and temporal variations of the geomagnetic field. The geomagnetic field models resulting from Swarm will further our understanding of underlying processes and will have practical applications in many areas, such as space weather and radiation hazards.

Land surface

Land surface processes are currently the least represented in operational numerical weather predictions and Earth system models. This is because the modelling of the different processes of land surfaces is very difficult owing to the heterogeneity and the diversity of spatial and temporal scales involved in matter and energy exchanges.



Earthquakes and volcanic activity affect the daily lives of millions of people

Processes within soil and vegetation control the fluxes of energy, water and carbon (and greenhouse gases such as methane) to and from the atmosphere. The changes in land-use and land-cover due to human exploitation of natural resources, or those induced by natural disasters (fires, erosion, floods), introduce effects that also need to be considered when monitoring land surface processes.

There are limited Earth observation capabilities to observe variables directly related to organic soil processes, such as decomposition and the related carbon dioxide (CO₂) release. However, indirect observation is possible via the coupling of different processes through modelling. The freeze–thaw conditions of permafrost soils in northern latitudes are of particular interest because the process of their large storage of CO₂ and methane being released on thawing can be indirectly observed through the monitoring of surface temperature and soil moisture conditions. The Earth Explorer Soil Moisture and Ocean Salinity (SMOS) mission will provide global soil moisture observations of relevance for such assessment.

Particular attention is being devoted to the dynamics of ecosystems because of their important role in the carbon and water cycles. The terrestrial ecosystem uptake of carbon amounts to about 120 gigatonnes (Gt) per year through photosynthesis, which is much larger than the annual fossil fuel emission estimated at 6–7 Gt. Thus, small changes in this balance are likely to have a major impact on the variations of atmospheric CO₂ concentration. To simplify representation of flora in these processes, ecology modellers introduced the concept of Plant Functional Types (PFT) based on plant traits, describing the functioning of the plants under certain environmental conditions. Modellers working at the regional and global scale prefer to use coarse PFT classifications based on a small number of plant traits (life form, phenology and photosynthetic pathway), while experimental scientists focus on a larger range of plant traits, and nowadays even prefer avoiding discrete plant type classifications. In either case, the global time series to be provided by Sentinels offer a range of tools for assessing and

quantifying plant traits and provide essential inputs to these modelling communities.

Data from Sentinel-1, -2 and -3, including the polarimetric interferometric capability of Sentinel-1, are well suited for the parametrisation of land surface processes, providing improvements over the above mentioned biogeophysical products taking advantage of the increased temporal and spectral resolutions and including their synergistic use. These data products will undoubtedly support the development of a range of new applications and the large and consistent time series are of very high scientific value.

Specifically designed for land applications, Sentinel-2 with its five-day geometric revisit time at the equator (based on two satellites operating simultaneously) will allow global and systematic acquisitions with high spatial resolution

and with a high revisit time tailored towards the needs of land monitoring. Current optical observations have been limited by revisit time, the lack of proper cloud screening and atmospheric corrections, but the dedicated wavebands available on Sentinel-2, which allow the needed corrections, represent an important step towards a proper exploitation. These will guarantee consistent time series, showing actual variability in land surface conditions without the artefacts introduced by atmospheric variability.

Contrary to previous missions, the optical instruments of the Sentinels are designed to allow for systematic atmospheric corrections and precise cloud screening, providing reliable multitemporal data series and making possible higher-level applications. Expected operational products (such as land cover maps, Leaf Area Index or Fractional Vegetation Cover) will be enhanced with new scientific applications through

→ Increased capabilities

The five Sentinel missions, their ground segments and contributing missions are the space component of the EU's GMES initiative. Their designs are driven by the needs of GMES services for the continuity of data from current operational Earth observation missions, such as ERS-2, Envisat, Jason-2, SPOT-HRV and SPOT Vegetation. To provide robust datasets, revisit and coverage requirements were also taken into account. This led to the series of Sentinels with an operational commitment up to 2025. In addition to continuity of data, the Sentinels offer increased observation capabilities.

Sentinel-1
(SAR) has one main operational mode (>250 km interferometric wide swath mode) that satisfies most service requirements identified under GMES core and downstream services. The operation of this mode simplifies mission planning, optimises revisit

SAR is capable of observing in the strip map mode (>80 km), wave mode (20 km), or extra wide swath mode (>400 km) to accommodate future user requirements or ERS/Envisat continuity requests. All Sentinel-1 modes offer dual polarisation and single-look spatial resolution ranging from 5 m (strip-map) to 40 m (extra wide swath).

Sentinel-2
Besides data continuity of 'SPOT-HRV'-type observations in the visible and near-infrared spectral range, the Sentinel-2 Multispectral Imager instrument offers 13 spectral bands in the visible, near-infrared and shortwave infrared regions, with resolutions of 10–20 m, including dedicated bands for atmospheric corrections and cloud screening with a resolution of 60 m. Narrow spectral bands positioned along the vegetation 'red-edge' allow improved quantitative estimates of

key biochemical parameters that will provide potential new applications and enhanced capabilities for scientific exploitation. The increased swath width of about 290 km



Sentinel-1

times for priority services and decreases operational costs. Apart from the main operational mode, the



Sentinel-2

together with the global revisit time of five days is very advantageous for assessing rapid changes such as vegetation characteristics during growing seasons and improved change detection techniques.

Sentinel-3

In comparison to Envisat's Medium Resolution Imaging Spectrometer (MERIS), Sentinel-3's Ocean and Land Colour Instrument (OLCI) offers a sunglint-free design, a slightly larger swath, six additional spectral bands in the visible and near-infrared and an improved global

increased spatial resolution in the visible bands (500 m instead of 1 km) and additional spectral coverage (nine bands instead of seven) to support atmospheric correction.

The Sentinel-3 SAR radar altimeter (SRAL) offers dual-band acquisition, Ku-band for height determination and C-band for ionospheric correction. In comparison to Envisat's radar altimeter, SRAL features along-track SAR operation tailored to advance the discrimination of ocean and sea ice and the transitions from land to sea in coastal or inland water areas. SRAL will measure the topography over all types of surfaces such as sea, coastal areas, sea ice, ice sheets, ice margins and in-land waters with higher coverage and increased accuracy.

Sentinel-4/5 and Sentinel 5 precursor

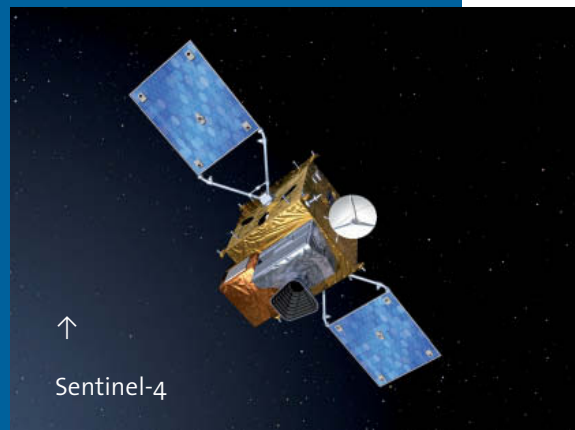
The Sentinel-4/5 and Sentinel-5 precursor missions will be devoted to atmospheric composition monitoring for the GMES Atmosphere Service. There will be two families of atmospheric chemistry monitoring missions, one in geostationary orbit (Sentinel-4) and one in low Earth orbit (Sentinel-5 precursor, Sentinel-5). The Sentinel-4 mission will consist of an Ultraviolet-Visible-Near-Infrared (UV-VIS-NIR) spectrometer accommodated on Meteosat Third Generation

Sounder (MTG-S) platforms. In addition, TIR sounder data on the same platform, and a cloud imager on the MTG-Imager platform will be exploited by the services. The low Earth orbit Sentinel-5 mission will consist of an UV-VIS-NIR and Shortwave Infrared spectrometer on post-EPS which will also house a TIR sounder and imager. The Sentinel-5 precursor mission will bridge the data gap from the end of the Envisat mission to the launch of Sentinel-5. It will provide data continuity and support the transition into an



revisit time of one day instead of four. The additional spectral bands are tailored towards optimised land and ocean products including those needed for atmospheric correction.

Unlike Envisat's Advanced Along-Track Scanning Radiometer (AATSR) and MERIS, Sentinel-3's Sea and Land Surface Temperature instrument has a total overlap with the OLCI instrument, offering a major advantage for many applications. Compared to AATSR, it has an



operational scheme. The UV-VIS-NIR instrument will be provided as a national contribution from the Netherlands, which will be complemented by a Shortwave Infrared module.

synergy among the different Sentinels. The Earth Explorer SMOS mission will provide new insight of the large-scale soil moisture conditions and their influence and interaction with the biosphere.

Access to Sentinel data

Access to Sentinel data is governed by the Sentinel data policy, which is formulated within the framework of a wider GMES data and information access policy. Principles of such a Sentinel data policy have been defined by ESA and the EC and were recently approved by ESA Member States in September 2009. EC approval is part of a co-decision process involving the European Parliament and EU Council and is expected to occur in the course of 2010. These Sentinel data policy principles stipulate free and open access to Sentinel data to the largest possible user community. Only technical

constraints, such as processing/access limitations, or security constraints are today considered to eventually limit such free and open access. Prioritisation among different user communities will be governed through a high-level operations plan. Users will be required to accept specific Terms and Conditions for Sentinel data access through a web-based acknowledgement process.

The Sentinel data policy, which will result from the current Sentinel data policy principles, aims at providing such free and open access also to the scientific community, recognising the community's catalytic impact in improving operational GMES services apart from the expected significant advancement of our Earth's scientific understanding through this vast data source.