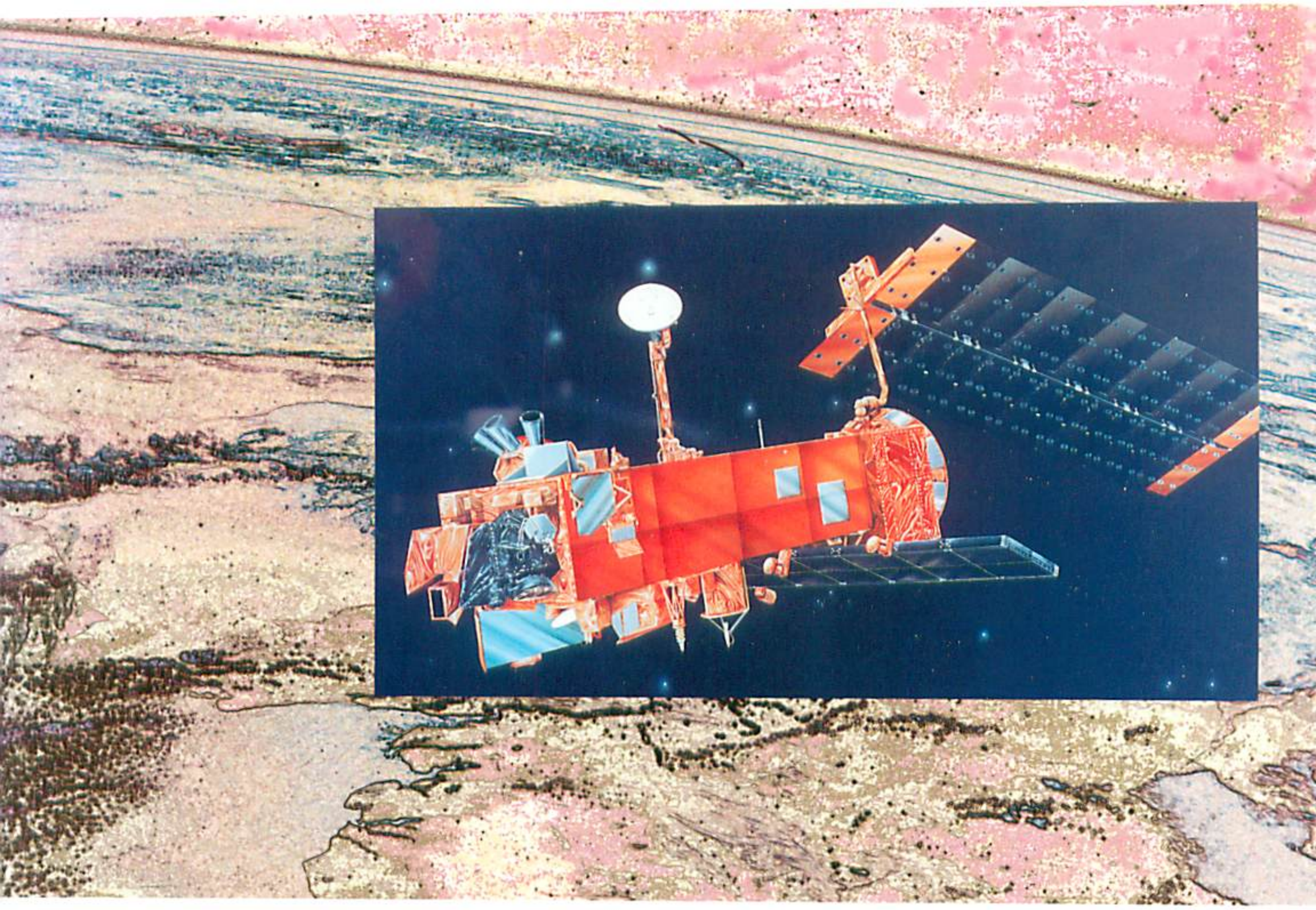
SP-1218
January 1998

Envisat Mission



Opportunities for Science and Applications

European Space Agency
Agence spatiale européenne

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Scientific Coordinator:	E. Attema, Earth Sciences Division, ESA
Technical Support:	M. Wooding, P. Fletcher, M. Stuttard, RSAC, U.K.
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Preface

Nearly every week public attention is drawn to events which concern the state of planet Earth, its climate and environment. Scientist and non-scientist alike are presented with intensive media coverage, bringing into open discussion topics such as ozone depletion, global warming and the need to take international action to reduce the impact of human activities. Events such as the 1997 Kyoto meeting of the UN Framework Convention on Climate Change and the impact of the El Niño phenomenon have further heightened the level of concern.

At a more local level, but perhaps also related to global climate change, natural disasters such as flooding, landslides and extreme weather conditions continue to feature in the headlines because of the threats to human life and sustainability.

Pressure is mounting to answer an increasing number of questions about the Earth's environment posed by the scientific community, government, industry and ordinary people in the street.

Europe has a impressive track record of contributing to environmental science and since the launch of METEOSAT-1 in 1977, has demonstrated its ability to design, build and operate Earth observation satellite systems to provide a new source of information from space. The ERS programme has built on this success, introducing new sensors and increasing the scope of available information.

The Envisat satellite is the latest and most capable so far. Funded through the European Space Agency, Envisat will provide information to virtually all research domains involved in the environment and global climate change. Whilst providing continuity with the ERS satellites and building on the capability of the radar and radiometer components of those systems, Envisat will provide information from new sensors supporting atmospheric chemistry and marine biology.

Envisat will encourage the routine use of its data by organisations which provide information for the benefit of the general public, such as environmental institutions, meteorological offices and the media. Whilst this remains as yet an immature market, it is critical to the funding of future missions. The flexibility offered by the Envisat payload provides an ideal training ground for assessing new technologies and for developing innovative processing techniques and new information services.

The success of the Envisat exploitation programme will rely on continuous interaction between the European Space Agency and the science and applications communities.

This document presents an overview of the opportunities for exploitation of Envisat data products and it is hoped that it will serve the purpose of encouraging scientists and application developers to plan for the use of Envisat data in their work. Publications will follow, presenting results from the mission as they become available.

Numerous contributions to this document are gratefully acknowledged, from experts external to ESA, from the Mission Management Office in ESA Headquarters, the Envisat System and Payload Division in ESTEC, the Earth Observation Projects and Engineering Division in ESRIN and the Earth Sciences Division in ESTEC.

Contents

Abbreviations

AATSR	Advanced Along Track Scanning Radiometer
ASAR	Advanced Synthetic Aperture Radar
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BMRC	Bureau of Meteorology Research Centre
CAP	Common Agriculture Policy
CCRS	Canada Center for Remote Sensing
CFCs	Chlorofluorocarbons
CLIVAR	Climate Variability and Predictability Study
CZCS	Coastal Zone Colour Scanner
DEM	Digital Elevation Model
DINSAR	Differential INterferometric SAR
DNMI	Det norske meteorologiske institutt
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
ECMWF	European Centre for Medium-Range Weather Forecasts
ERS	European Remote Sensing Satellite
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GCOS	Global Climate Observing System
GEWEX	Global Energy and Water Experiment
GFO	Geosat Follow-On
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring by Occultation of the Stars
GOOS	Global Ocean Observing System
GTOS	Global Terrestrial Observing System
HH	Horizontal transmit - Horizontal receive polarisation
HR	High resolution (MERIS)
HV	Horizontal transmit - Vertical receive polarisation
IGAC	International Global Atmosphere Chemistry
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme
IPCC	Intergovernmental Panel on Climate Change

IR	Infrared
JGOFS	Joint Global Ocean Flux Study
LST	Land Surface Temperature
LUCC	Land Use/Cover Change
MARS	Monitoring Agriculture with Remote Sensing
MERIS	Medium Resolution Imaging Spectrometer
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MODIS	Moderate-Resolution Imaging Spectrometer
MWR	Microwave Radiometer
NCEP	National Center for Environmental Prediction
NIR	Near Infrared
NOAA	National Oceanic and Atmospheric Administration
OCTS	Ocean Colour Temperature Scanner
PSC	Polar Stratospheric Clouds
RA-2	Radar Altimeter -2
RKA	Russian Space Agency
RR	Reduced resolution (MERIS)
SAGE-II	Stratospheric Aerosol and Gas Experiment -II
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter Ultraviolet
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SeaWiFS	Sea Wide Field Sensor
SLR	Satellite Laser Ranging
SST	Sea Surface Temperature
TOMS	Total Ozone Mapping Spectrometer
Topex/Poseidon	Topography Experiment for Ocean Circulation
UKMO	United Kingdom Meteorological Office
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
UV	Ultraviolet
VH	Vertical transmit - Horizontal receive polarisation
VIS	Visible
VV	Vertical transmit - vertical receive polarisation
WCRP	World Climate Research Programme
WOCE	World Ocean Circulation Model

1. The Envisat Mission

Envisat is an advanced Earth observing satellite designed to provide measurements of the atmosphere, ocean, land and ice over a five year period. As the successor to the highly successful ERS-1 and ERS-2 satellites it will provide direct continuity of measurement with most ERS instruments, thereby extending to more than 10 years the long term data sets critical for global environmental monitoring, and furthering many operational and commercial applications.

As a total package the capabilities of Envisat exceed those of any previous or planned Earth observation satellite. The payload includes three new atmospheric sounding instruments designed primarily for atmospheric chemistry, including measurement of ozone in the stratosphere. There is an advanced Synthetic Aperture Radar (SAR) which can collect high resolution images with a variable viewing geometry, together with new wide swath and selectable dual polarisation capabilities. A new imaging spectrometer is included for ocean colour and vegetation monitoring, and there are improved versions of the ERS radar altimeter, microwave radiometer and visible/near infra-red radiometers, together with a new very precise orbit measurement system.

1.1 Environmental Science

Over the last decade, large scale environmental change, and particularly the degree of human influence upon it, has become the subject of intense scientific investigation, public concern and inter-governmental action. The survival of mankind depends on learning to live in harmony with the environment. Man's activities are not only causing damage to the environment, but are also capable of influencing the system of the planet itself. It is important to understand the processes of change, where changes might be predicted and where appropriate, prevented, contained or reversed.

Priority issues in global environment research identified by the Inter-Governmental Panel on Climate Change (IPCC) are:

- sources, sinks and concentrations of greenhouse gases
- the Earth's radiation balance (and in particular the effect of clouds upon it)
- the effect of ocean circulation on the timing and pattern of climate change
- availability of land surface water for human development and within the hydrological cycle
- the proportion of global water locked up in polar ice sheets and the consequences for changing sea-level and climate
- ecosystem dynamics (e.g. desertification, biomass burning, habitats and bio-diversity, carbon cycling) as affected by, or affecting, climate change
- large-scale insertion of aerosols into the atmosphere (e.g. from volcanic eruption) and their short-term effects on climate.

Identifying global environmental changes and explaining their causes requires highly coordinated large scale research which views the Earth as a complete system (Figure 1.1). Information requirements are complex and several major international research and development programmes (IGBP, IHDP, UNEP, WCRP) are addressing them in specific projects (e.g. GEWEX, IGAC, LUCC, WOCE) and observing systems (e.g. GCOS, GOOS, GTOS). These programmes assist in the formulation and monitoring of international environmental agreements (such as the Montreal Protocol for worldwide reduction in the production of CFCs, or setting national targets for CO_2 emissions) which affect everyone on the planet. Research in many of these areas requires long term (10 years and more) data sets, which allow meaningful trends in geophysical parameters to be observed. Measurements must be synoptic, precise and consistent, both in space and time, in order to differentiate any long-term trends from more transient effects.

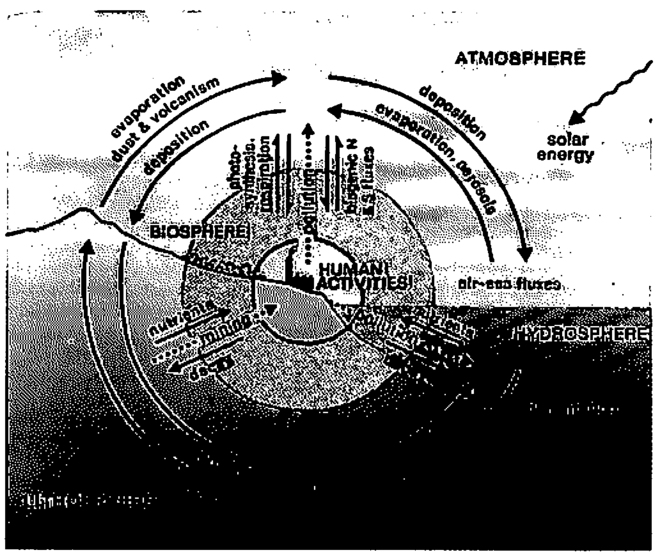


Figure 1.1 Earth system cycles

Earth observation plays a key role in many aspects of environmental science, and in many cases satellites are the only way to obtain suitable data for global environment monitoring. The ERS programme has demonstrated how satellites can provide a unique data source for synoptic measurements of the atmosphere, oceans, land and ice covering the whole Earth (ESA SP-1176/I, 1996). The main objective of Envisat is to improve the range and accuracy of such measurements.

For atmospheric science, instruments such as GOME on ERS-2 have demonstrated clearly the importance of satellite systems for global monitoring of ozone in the stratosphere (ESA SP-1212, 1997). Envisat will considerably extend the range of atmospheric constituents which can be measured and will provide much better height profiling. This information will be incorporated in models of the chemical, physical and dynamic processes in the atmosphere. It will also be used in driving models of surface processes which govern the fluxes of energy, momentum and chemical constituents between the biosphere and the atmosphere.

For large scale ocean studies the ERS satellites are making a major contribution, helping to solve the problem of insufficient data from *in situ* ship and buoy measurements. Envisat will ensure continuity for global measurements of ocean topography and circulation, wind and waves, and add new biophysical measurements. Data from different satellite instruments will be combined with *in situ* data and models, to give a better understanding of the ocean and its role in the climate system.

Remote sensing of vegetation status, land cover and soil moisture provides an important input for land process studies. There have been very significant developments in land applications of all-weather SAR imaging in both tropical and temperate regions during the ERS programme. Envisat will take this much further, using the variable viewing and selectable dual polarisation capabilities of the advanced SAR, together with the addition of simultaneous imaging spectrometer coverage. More detailed monitoring of land cover change is important to advance understanding of ecosystem interactions with the atmosphere in the context of global climate change.

The ability of microwave instruments to collect data in the polar regions, independent of weather or daylight, is especially important for polar studies. Envisat will provide further improvements in ERS measurements of ice sheet mass balance, sea ice extent and movement of glaciers and ice sheets.

Envisat has a unique combination of sensors which will improve the range and accuracy of scientific measurements of the atmosphere, oceans, land and ice, particularly for environmental monitoring on a global scale.

1.2 Supporting Human Activity

The need to make better use of resources is imperative for environmental as well as economic reasons. The information age is leading to the introduction of new management tools and procedures which require detailed, accurate and timely data to be provided on a regular basis. The growing demand for data, chiefly in the marine and renewable resources sectors, can best be met using satellite sensors. Stimulated by data available from the ERS satellites, important applications now include sea-ice and sea-state monitoring for ship routing and offshore operations, complementary use of radar and optical images for agricultural monitoring, radar altimetry for near-real time regional ocean circulation forecasting, tropical forest monitoring, oil slick detection for environmental monitoring or hydrocarbon exploration and flood mapping (ESA SP-1176/II).

Similarly, a range of monitoring requirements arises from the need for a better response to natural hazards or large scale industrial accidents. Major events such as fires, floods, oil spills, earthquakes and toxic algal blooms require the following:

- global coverage to predict and identify such events
- frequent re-visit capability over specific areas for detailed monitoring, in order to manage emergency response to catastrophes
- impact assessment and monitoring after an event (recovery of ecosystems, insurance loss adjustment).

Envisat will offer improved facilities for providing near real-time services to satisfy these requirements.

The frequency and coverage characteristics of several Envisat instruments improve discrimination of land and ocean surface conditions, and increase the possibility for providing invaluable information during major emergencies.

1.3 The Satellite System

Envisat will be launched from the Kourou Space Centre in French Guiana by an Ariane-5 launch vehicle. It has a payload mass of over 2000 kg, and includes the following 9 major instruments in its payload (Figure 1.2):

- ASAR - Advanced Synthetic Aperture Radar
- MERIS - Medium Resolution Imaging Spectrometer
- MIPAS - Michelson Interferometer for Passive Atmospheric Sounding
- GOMOS - Global Ozone Monitoring by Occultation of Stars
- SCIAMACHY - Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
- RA-2 - Radar Altimeter 2
- MWR - Microwave Radiometer
- AATSR - Advanced Along Track Scanning Radiometer
- DORIS - Doppler Orbitography and Radiopositioning Integrated by Satellite

In addition, the satellite platform is equipped with a Laser Retro Reflector (LRR) for tracking of the satellite by ground based laser stations. Envisat will be placed in a sun-synchronous polar orbit at an inclination of 98°, descending southward across the equator at 10 am local time. The selected orbit, which has a period of 100.59 minutes, provides a 35 day repeat cycle, as for the previous ERS missions, but also includes various subcycles. The 3 day subcycles provide a global sampling of the Earth, which, for the wide field instruments (i.e. MERIS, AATSR and ASAR), is well matched to the objective of data assimilation suitable for global meteorological or climate models. The 35 day cycle provides a good repeat grid for the altimeter and maximises potential global access for the ASAR in high resolution mode. For atmospheric chemistry,

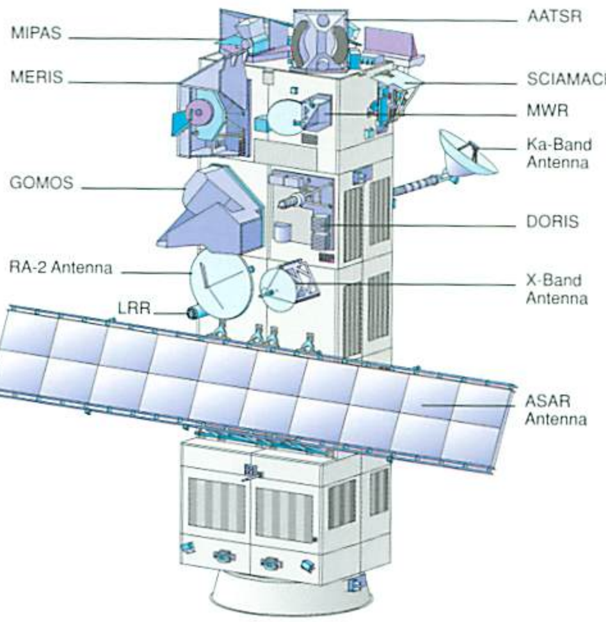


Figure 1.2 The Envisat scientific payload

thousands of atmospheric profiles will be collected each day.

The requirement for global data acquisition will be satisfied by the use of on-board data storage. Envisat has 3 tape recorders, each with a capacity in excess of 30 Gbit. For most instruments, complete orbits of data will be stored on-board for downloading to the main ESA ground stations. An additional solid state device will provide on-board storage of ASAR and MERIS HR data for later transmission to these same ground stations. Together with the Artemis data relay satellite, this will enable direct reception in Europe, of HR data from any point on the Earth's surface. Direct downloading to other ground stations will remain important for the provision of near real time services.

Envisat can acquire 22 GBytes of instrument data every orbit which could contribute to an archive of 1 PetaByte (10^{15}) of data accumulated over the nominal 5 year mission. This is equivalent in volume to 500 million scenes from the multi-spectral scanner on board Landsat-1, the first Earth resources satellite.

1.4 Instruments

ASAR (Advanced Synthetic Aperture Radar): is a C-band SAR which continues the all-weather microwave imaging capability of the ERS SARs. Figure 1.3 shows imaging configurations for the five different modes of operation. Image Mode provides up to 100 km swath coverage at 30 m resolution, similar to the ERS SARs, but the new beam steering capability enables acquisition to take place in any one of 7 different image swath positions (IS1 to IS7 with incidence angles 15° - 45°) spanning 500 km, in VV or HH polarisation. Alternating Polarisation Mode is similar, but will provide simultaneous dual-polarised images; either both VV & HH polarisation images, or one of two combinations of plane polarised and cross polarised images (VV&VH or HH & HV). Wide Swath Mode (150 m resolution) and Global Monitoring Mode (1000 m resolution) provide images covering a 400 km swath, in either HH or VV polarisation. Finally, in Wave Mode, imagettes of 5 km by (5 to 10 km) will be acquired, spaced 100 km along track and alternating between 2 of 7 across track positions, in either VV or HH polarisation. ASAR will be able to operate continuously in Global Monitoring Mode, or for up to 30 minutes per orbit in the higher resolution modes (n.b. ERS SAR operates for 12 minutes per orbit).

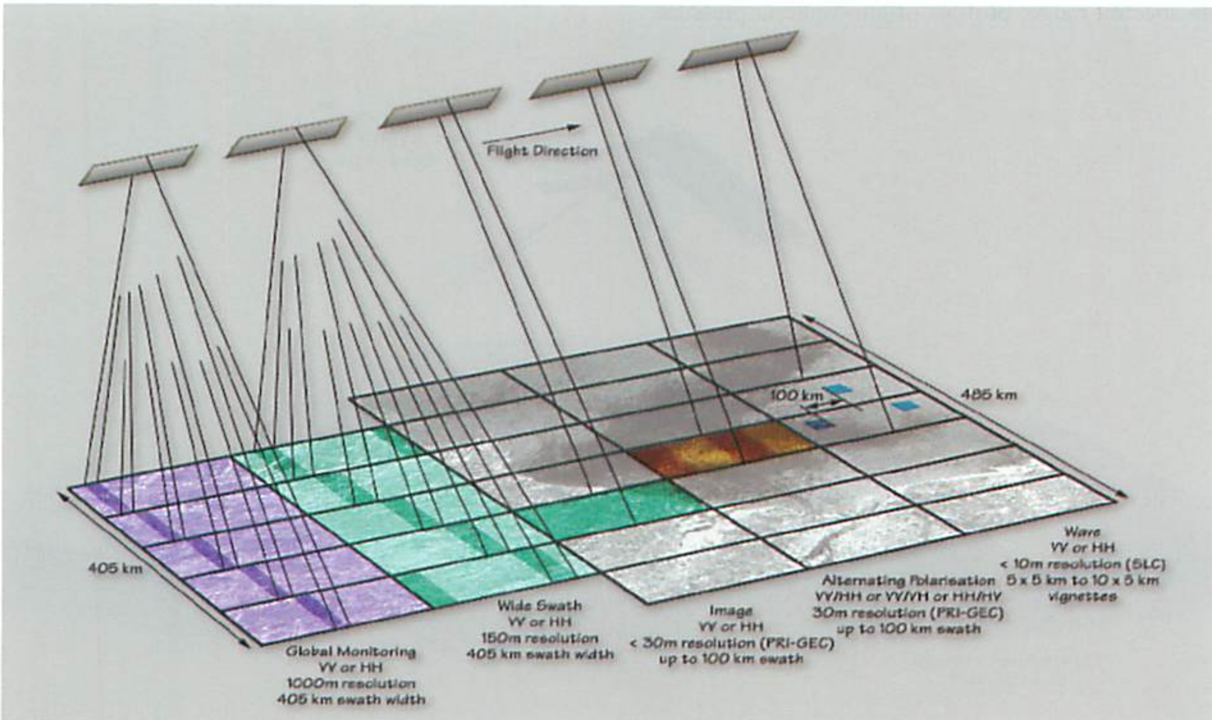


Figure 1.3 ASAR operating modes

MERIS (Medium Resolution Imaging Spectrometer): operates in the visible and near-infrared in 15 programmable narrow bands at a spatial resolution of either 300 m or 1200 m (Figure 1.4). With a swath width of 1150 km, MERIS is very well suited to global and regional monitoring on a 3-day repeat cycle, primarily of ocean colour, but also of cloud/water vapour, aerosol and vegetation conditions (Ref. ESA SP-1184, 1996). MERIS provides well calibrated top-of-atmosphere radiance measurements at high spectral resolution, plus a range of geophysical products.

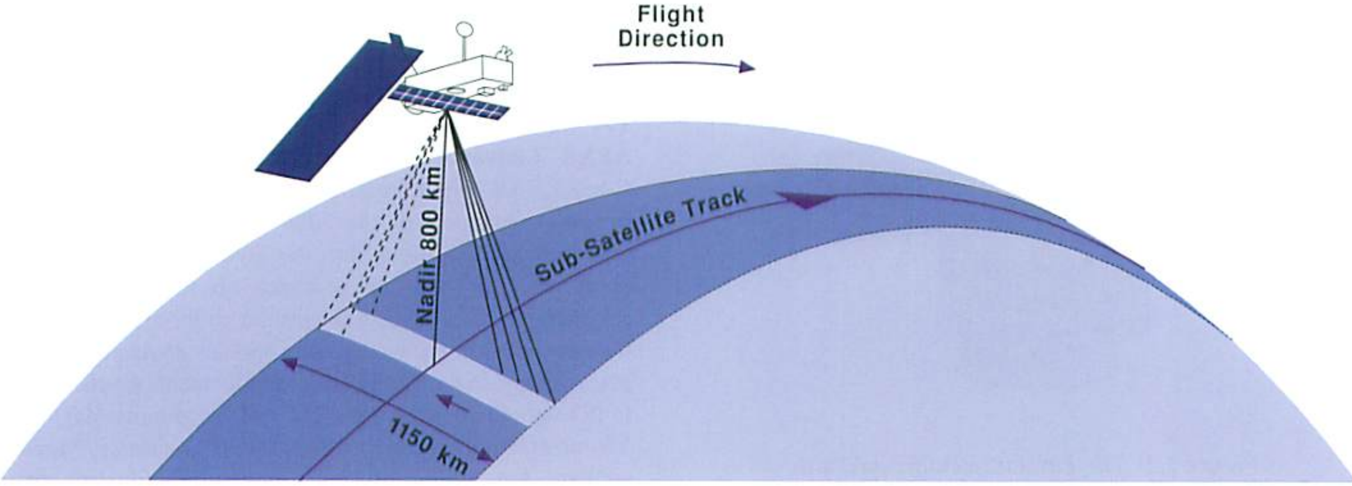


Figure 1.4 MERIS imaging configuration

MIPAS (Michelson Interferometer for Passive Atmospheric Sounding): is a Fourier transform spectrometer measuring emission spectra in the infrared region between 4.15 and 14.6 microns. It is a limb sounding instrument making a series of measurements at different tangential heights by performing elevation scan sequences through different sections of the atmosphere (Figure 1.5) with a vertical resolution of 3 km. An important aspect of MIPAS data collection is that it will provide global coverage for all seasons, independent of illumination conditions. With its high spectral resolution and wide spectral range, profiles of atmospheric pressure, temperature and volume mixing ratios (VMR) of many trace gas species are obtained. Simultaneous measurements are made across the whole of the middle infrared part of the spectrum. The azimuth scan geometry of MIPAS in the anti-flight direction has the principal objective of providing complete global coverage. In addition, MIPAS will also be capable of scanning perpendicularly to the flight track so that data can be acquired of volcano eruptions and trace gas concentrations above major air corridors and across the dawn/dusk boundary.

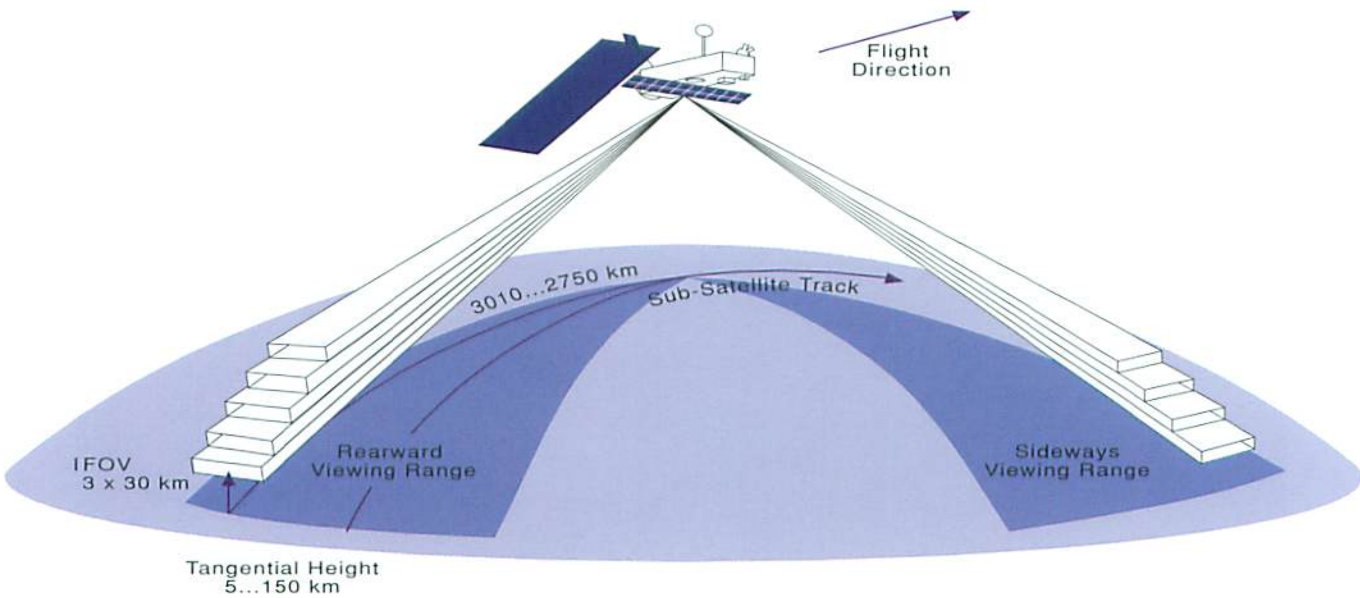


Figure 1.5 MIPAS limb sounding of the atmosphere

GOMOS (Global Ozone Monitoring by Occultation of Stars): is a UV-visible and near-infrared spectrometer which measures star light as seen through the atmosphere (Figure 1.6). GOMOS is a novel instrument measuring ozone and other trace gases in the altitude range between 20 km and 100 km, with a vertical resolution of 1.7 km. The occultation technique is very stable and inherently self-calibrating. This is due to the fact that the integrated quantity of trace gases along the line of sight is obtained from the ratio of two measurements taken by the same instrument within a short time interval. Therefore, even if the instrument characteristics change slowly over time, the ratios will still produce valid results. This long term reliability is highly relevant in the context of long term studies of ozone variability. Daytime occultations are planned in order to determine diurnal variations in the concentration of gas species, but the instrument performs best at night. The two high speed photometers are able to gather information on the scintillation of starlight and thereby provide information on the fine structure of the atmospheric vertical temperature profile and transport processes.

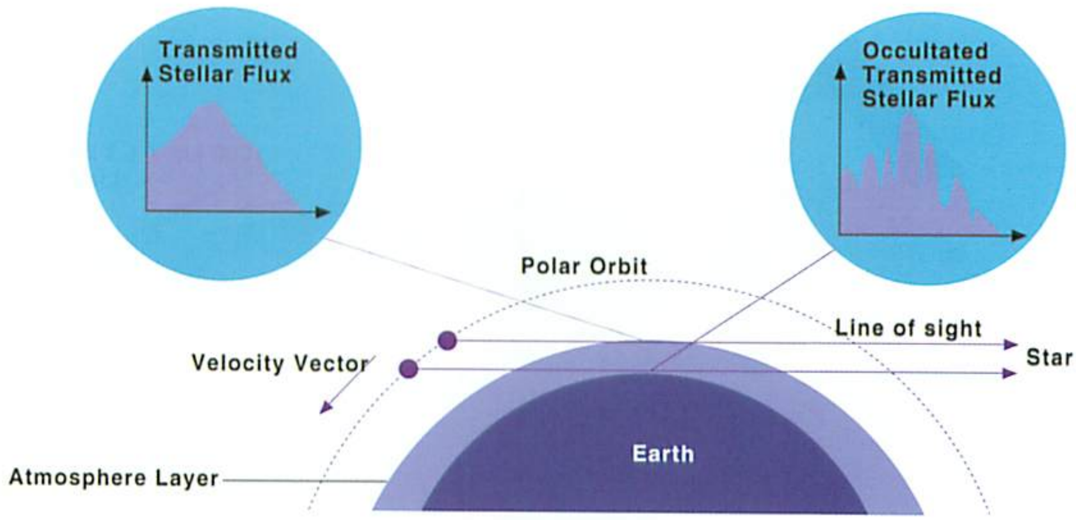


Figure 1.6 GOMOS stellar occultation

SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography): is an eight channel UV/visible, near to middle infrared, spectrometer which measures atmospheric trace gas and aerosol concentrations by observation of reflected and scattered sunlight (n.b. also by transmitted light when the sun or moon are viewed directly through the atmosphere). SCIAMACHY is essentially a more capable version of GOME. It views in either nadir or limb mode within a 1000 km swath providing total column measurements and atmospheric profiles up to 100 km, at 3 km vertical resolution (Figure 1.7). Global coverage will be completed every 3 days at the equator. Most measurements are achieved by alternating limb measurements with nadir measurements, providing the opportunity to observe the same volume of air under different viewing geometries within a short period of time. In limb mode, SCIAMACHY records atmospheric spectra corresponding to a part of the atmosphere about 3290 km ahead of the satellite. Soon after (i.e. within approximately 435 seconds) nadir measurements are made of the same part of the atmosphere. This data acquisition strategy enables both total column and profile measurements of trace gas species and aerosol contents to be obtained to a high degree of accuracy.

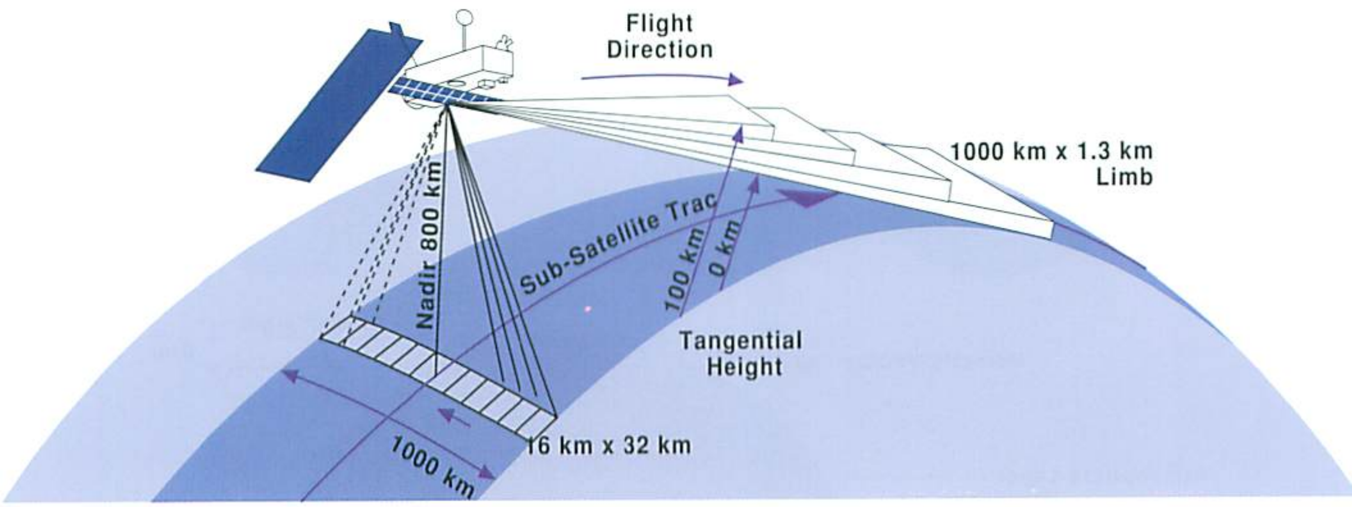


Figure 1.7 SCIAMACHY limb/nadir operating mode

RA-2 (Radar Altimeter): is an enhanced version of the ERS altimeter which measures the power level and return time of radar frequency echoes from the Earth's surface (Figure 1.8). RA-2 provides weekly global measurements of ocean surface topography (and hence circulation), wave height and wind speed. RA-2 will also provide improved mapping of ice-cap margins and sea-ice as well as land elevation and lake level. Enhancements to the ERS altimeters include the addition of an S-Band channel (to enable correction of errors introduced by ionospheric fluctuations) and a tracking system which automatically keeps the radar echoes within the sampling window for any surface, to overcome the problem of lost data at the important ice-cap/sea-ice boundary.

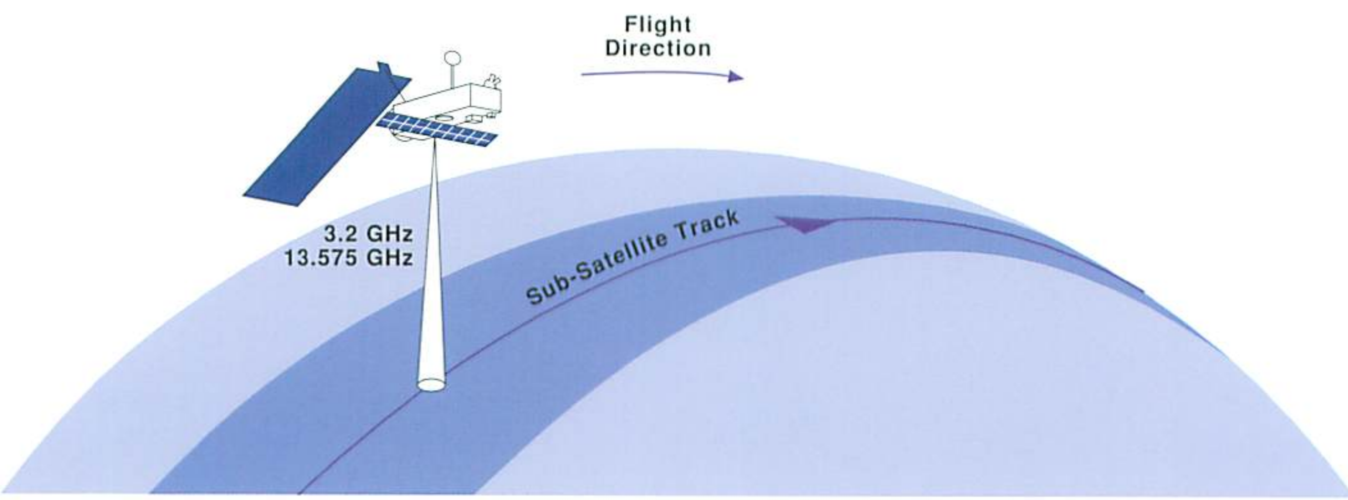


Figure 1.8 RA-2 operating configuration

MWR (Microwave Radiometer): is a K-band passive radiometer which measures the total atmospheric water vapour and cloud liquid water content within a cone having a 20 km diameter footprint (Figure 1.9). The main purpose of the MWR is to provide atmospheric correction for RA-2 timings. To achieve this the contribution of the Earth's surface is eliminated by taking differential measurements at two frequencies. The MWR can also be applied to low resolution measurements of surface emissivity and soil moisture, as well as supporting energy budget and ice characterisation research.

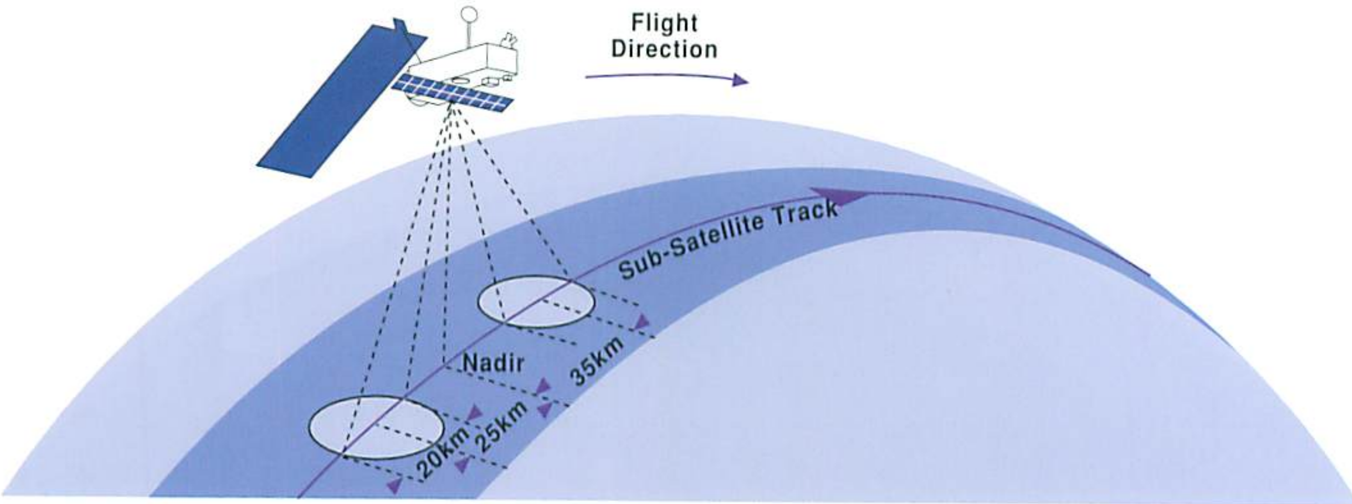


Figure 1.9 MWR operation

AATSR (Advanced Along-Track Scanning Radiometer): provides continuity with the ATSR instruments on ERS, ensuring the production of a near-continuous 10-year data set of sea surface temperature at an accuracy level of 0.3 K or better. AATSR will have the four well established mid/thermal infrared channels, together with three visible/NIR channels. The two-angle viewing method already established with ATSR will be used to achieve accurate atmospheric corrections (Figure 1.10). Spatial resolution is 1 km at nadir in a 500 km swath.

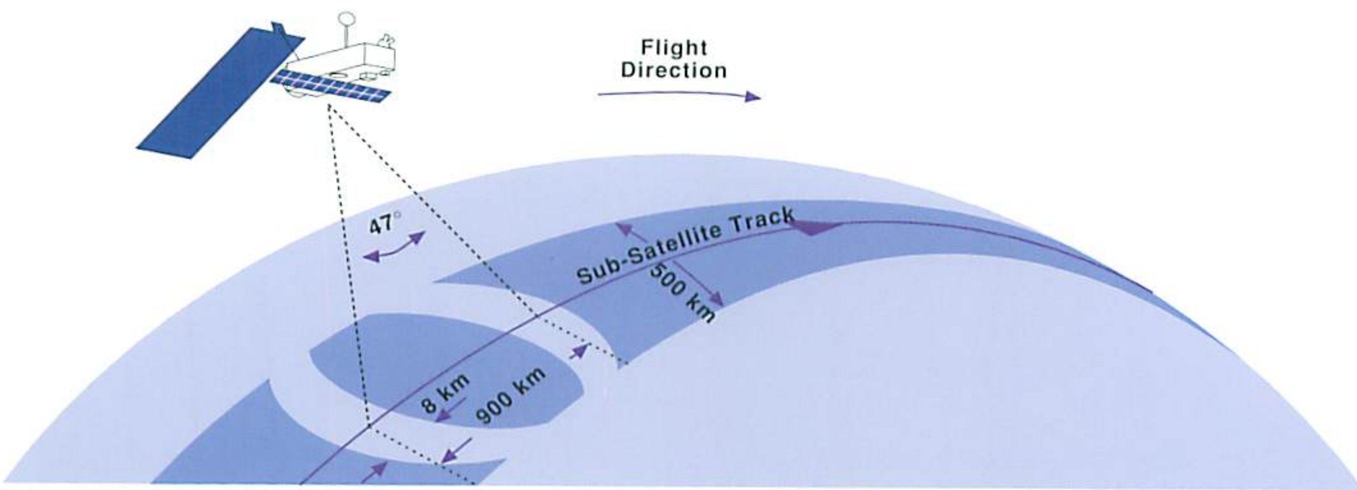


Figure 1.10 AATSR operating configuration

DORIS (Doppler Orbitography and Radio Positioning Integrated by Satellite): is an orbit determination system which allows the position of Envisat to be fixed to within 5 cm (Figure 1.11). On-board measurements are available in real-time to better than 25 m accuracy, but the very precise measurements are only possible after a time lag of 3 weeks. The precise orbit data are an essential input to most RA-2 applications and can also be used (with ground beacons) for monitoring ground movements (e.g. deformation of the Earth's crust). DORIS also enables the estimation of the total number of free electrons in the ionosphere.

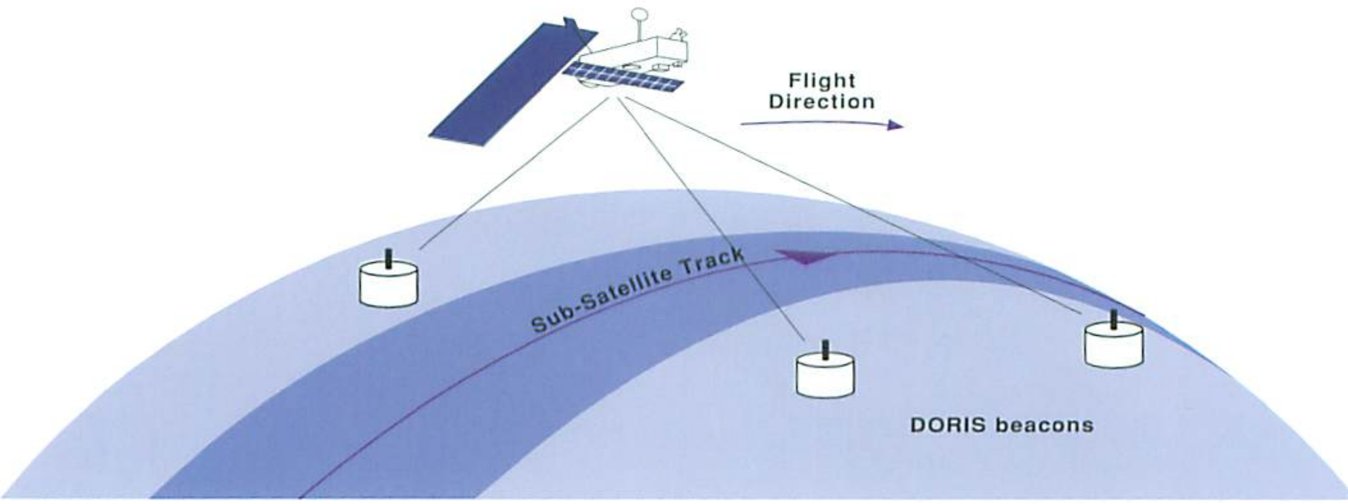


Figure 1.11 DORIS operating configuration

1.5 Instrument Synergies

Envisat carries a remarkably diverse range of instruments. Some have been designed to work closely together, thus for example, the RA-2 requires input from both the MWR and DORIS even for some of its basic geophysical products, whereas other Envisat instruments provide synergetic opportunities simply because several different types of observation are available for the same place and time. Table 1.1 shows the measurement capabilities of each of the instruments and the possibilities for combining instrument data within different applications.

There is clearly great scope for synergy and intercomparison of results with data from SCIAMACHY, GOMOS and MIPAS which are functionally quite different instruments, but measure similar atmospheric properties in partially overlapping profiles. Data from these instruments may also be integrated with surface measurements from MERIS and AATSR to examine atmosphere/biosphere interactions and improve atmospheric corrections.

	MWR	RA-2	ASAR	MERIS	AATSR	SCIAMACHY	MIPAS	GOMOS
ATMOSPHERE								
Temperature/Pressure				■		■	■	■
Trace Gases						■	■	■
Cloud Type/Height				■	■	■	■	
WaterVapour	■			■	■		■	■
Aerosols				■	■	■	■	■
Radiation Budget	■			■	■	░	░	░
Turbulence								■
OCEAN								
Marine Geoid		■						
Global Circulation		■			■			
Wave Characteristics		■	■					
Ocean Fronts			■	■	░			
Ocean Colour and Turbidity				■				
Sea Surface Temperature					■			
Coastal Dynamics			■	■				
Oil Slicks			■					
Ship Traffic			■					
LAND								
Global Vegetation Monitoring			■	■	■			
Surface Temperature	░				░			
Agriculture and Forestry			■	░	░			
Geology and Topography		░	■					
Hydrology Parameters	░	░	■	■	■			
Flooding			■					
Fire					■			
ICE								
Temperature					■			
Ice Sheet Dynamics	░	■	■	■				
Snow Cover			■	■	■			
Sea Ice Mapping	░	■	■	■				
Ship Routing			■					

■ Principal contribution

░ Secondary or experimental contribution

Table 1.1 Measurement capabilities of the Envisat instruments

Envisat will provide simultaneous measurements from AATSR/MERIS, and from MERIS/ASAR (Figure 1.12). The AATSR swath of 500 km around nadir falls within the MERIS swath of 1150 km. Whenever the ASAR is operating in daytime it will be possible to obtain simultaneous MERIS coverage, except at the highest incidence angles (i.e. not at IS6 or IS7, or for the far edge of the Wide Swath or Global Monitoring images). It will be possible to acquire a global coverage of simultaneous ASAR low resolution images and MERIS data approximately every 8 days.

Over the oceans these combinations of AATSR, MERIS, and ASAR, will provide a unique synergy for bio/geophysical characterisation. Simultaneous measurements of comparable spatial resolution at both microwave and optical wavelengths have not previously been available on a routine basis. These instruments permit small and large scale wave characteristics, ocean colour and temperature to be observed with frequent global coverage. It is therefore possible to study transient phenomena (ocean fronts, gyres, blooms, upwellings, surface films) and their dynamics in a way which was previously not readily possible. In addition, the combination of AATSR and RA-2 will provide coincident observations of ocean topography and sea surface temperature along the satellite track.

On land there is great potential to exploit synergies between ASAR low resolution products and MERIS data and also between MERIS and AATSR data. In addition, the combination of ASAR differential interferometry and RA-2 data will improve the potential for land surface height measurements.

The Envisat instruments will also complement instruments flying on other satellites at the same time. GOMOS, MIPAS and SCIAMACHY will complement SAGE II, TOMS and GOME. MERIS and AATSR complement SeaWiFS, MODIS and AVHRR. RA-2 complements Topex/Poseidon, JASON and the Geosat follow-on. Several of the instruments on these satellites will provide opportunities for improving the frequency of observations as well as for the inter-calibration and comparison of measurements derived from independent instruments. In addition some instruments will provide critical auxiliary data to assist in the retrieval of more accurate geophysical measurements.

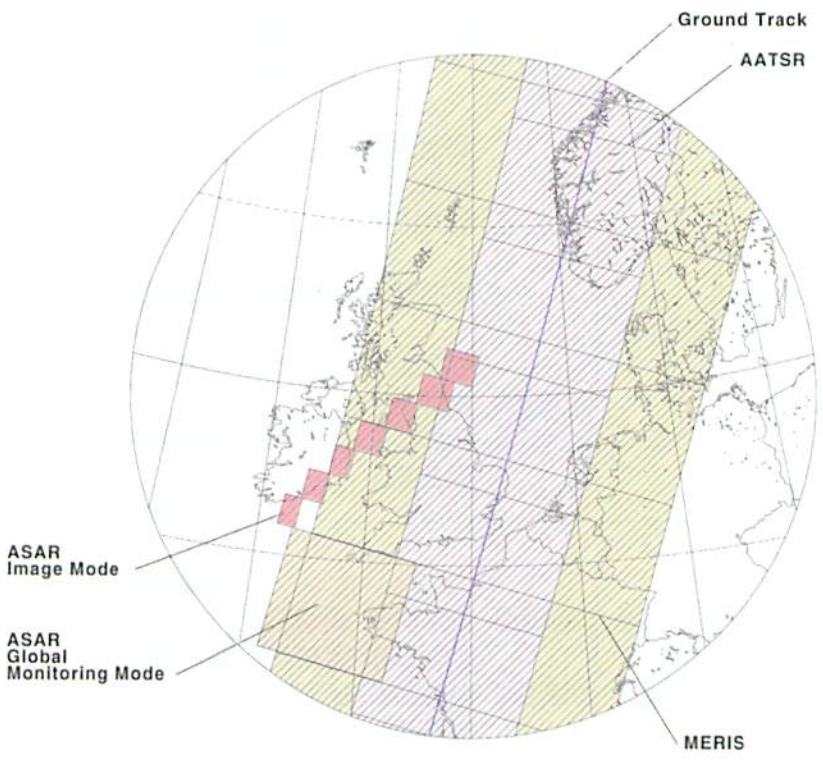


Figure 1.12 Comparisons of swath coverage for ASAR, MERIS, AATSR.

1.6 Retrieving Geophysical Parameters

Satellite sensors, such as those on Envisat, provide the only currently available means for making truly global and repetitive observations, but it must be emphasised that the only observations that can be made by these instruments are electromagnetic radiation measurements, precisely fixed in space and time. Quantitative and accurate models, preferably physically based, are essential to transform these radiation measurements into useful geophysical parameters such as the concentration of ozone, annual changes in water storage of an ice cap, extent of flooding, land surface deformation or net primary productivity of the ocean.

Figure 1.13 shows some of the major processes involved in algorithm development and testing, to transfer the measurements made into calibrated geophysical parameters. Good calibration of the instrument and the data coming from it, is needed to provide a satisfactory basis for establishing the stable retrieval of geophysical parameters. As part of the process of proving and refining an algorithm, the derived geophysical values need to be validated by comparison with in-situ measurements of these same parameters. Comparison of the results provides an accuracy or quality assessment, and feedback to the calibration for use in refining the models.

Much of the scientific work on the data sets generated by Envisat is concerned with applying, validating and improving such models. All Envisat instruments will provide well calibrated data and co-ordinated scientific activities will be organised to validate all Envisat geophysical products. Further exploitation of the geophysical products derived from Envisat involves setting up efficient information re-distribution channels which put the derived information to practical use with other environmental data for science and commercial applications.

Information on the algorithms used to produce ESA products is available on the Envisat Web site (http://envisat.estec.esa.nl/).

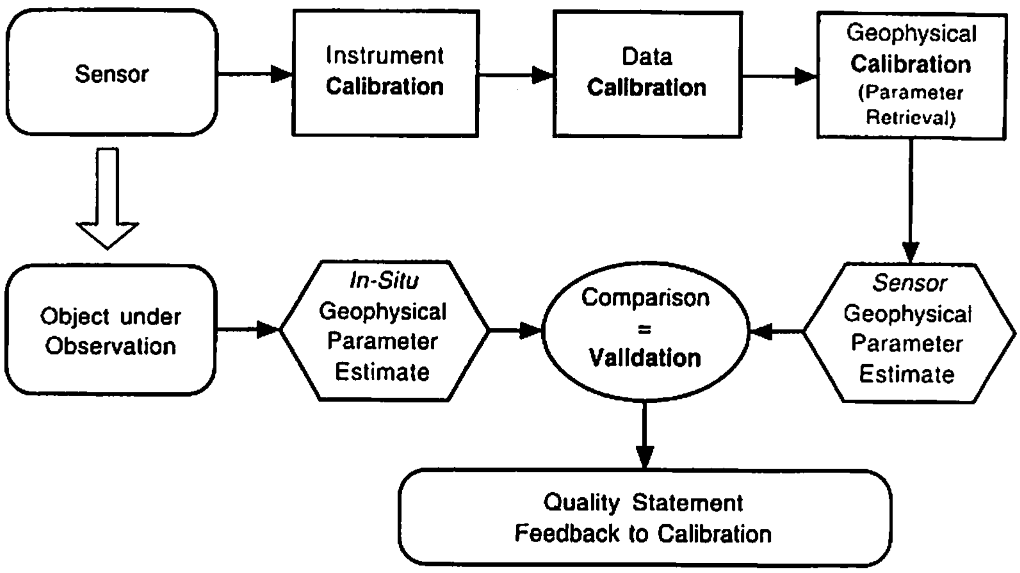


Figure 1.13 Processes involved in geophysical calibration and validation.

2. Atmosphere

Satellite remote sensing provides a unique way of monitoring the complex and dynamic processes that occur in the atmosphere. Since the future of the human race is critically dependent on the long term variability of the atmosphere, great efforts are being made to understand the many processes involved. In response to this, researchers develop models of the atmosphere as a mechanism whereby chemical reactions and physical changes in the atmosphere can be placed in context within the overall Earth system.

Such models require large amounts of data describing the spatial and temporal variability of the Earth's atmosphere at different locations and altitudes around the globe, taking account of diurnal, seasonal and longer term cycles. Sources, reservoirs and sinks of critical trace gases all need to be described. Satellite remote sensing provides a powerful set of techniques for acquiring these data to sustain models of the atmosphere, especially where information is required on a global scale and within a short time span.

2.1 Atmosphere Constituents

Many of the factors affecting the global environment are related to changes in the chemical composition of the atmosphere. The results of these changes include: the enhanced greenhouse effect, increase in the levels of ultraviolet-B radiation reaching the Earth's surface, acidification and reduced transparency. The atmosphere is very dynamic, both in terms of chemical composition and associated radiative properties and also in the way it transports materials around the globe, providing a link between land and ocean. The key role of the atmosphere in the maintenance of the Earth's environment emphasises the need to conduct research, to understand properly the processes involved and to monitor long term changes.

As a result of man's activities, which have become progressively more significant over the last century, large quantities of carbon, chlorine, nitrogen and sulphur compounds have been injected into the atmosphere and are disrupting the natural equilibrium which had become established. Whilst long term change has always been a feature of the atmosphere, it has become apparent that it is the increased rate of change, brought about by man's activities, which is having such a potentially detrimental effect on the Earth's system.

The reduction in stratospheric ozone concentrations over Europe since 1960 is the direct result of the use of ozone depleting chemicals such as refrigerants, industrial cleaners, foaming agents and those in fire extinguishers. Conversely, pollution at the Earth's surface has led to increased levels of tropospheric ozone, particularly over industrial areas, with consequent threats to human health. No other chemical in the troposphere has a concentration which is so close to being toxic.

The greenhouse effect, shown in Figure 2.1, concerns the warming of the troposphere by increasing concentrations of the so-called greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone and others). This warming occurs because the greenhouse gases are transparent to incoming solar radiation, but absorb infrared radiation from the Earth that would otherwise escape from the atmosphere into space. The greenhouse gases then re-radiate some of this heat back towards the surface of the Earth. The rise in carbon dioxide as a result of industrialisation, is primarily responsible for the enhanced greenhouse gas effect. Current carbon dioxide levels are more than double pre-industrial levels and are the focus of international efforts to reduce emissions and offset the consequences of changed climate patterns, sea level rise, effects on hydrology, threats to ecosystems and land degradation.

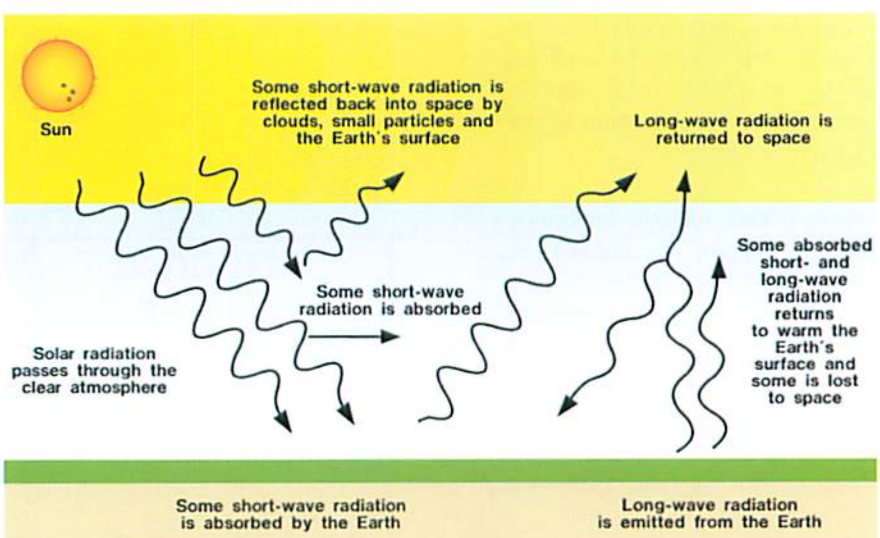


Figure 2.1 The greenhouse effect

Many studies of the effect of greenhouse gases on the climate have and are being carried out. An effective doubling of carbon dioxide concentrations is now predicted for 2030, which is expected to produce an estimated temperature rise of between 1.5° to 4.5°C, but with considerable variations in the rate of warming in different regions. The situation is highly complex due to mechanisms whereby, for example, an increase of sulphur dioxide in the atmosphere, through industrialisation, diminishes the greenhouse effect because of an increase in the atmosphere's reflectivity.

While predictions continue to be refined, the overall objective remains as that set out in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which calls for the stabilisation of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference with the climate system, and in a time frame that allows ecosystems to adapt naturally.

The amount of water vapour in the atmosphere is an important component of the Earth's climate system. It varies considerably in response to variations in temperature and relative humidity and acts as an energy carrier, redistributing energy around the planet. Water vapour has a large radiative effect and is the most important greenhouse gas. Water, in the form of clouds, liquid or ice, modifies the radiation reaching the surface and thereby strongly influences the surface energy flux. The role of clouds in the climate system is poorly understood and this undermines the overall validity of modelling and prediction activities. Research into the influence of water vapour and clouds is needed in order that anthropogenic effects can be isolated from long term natural climate variations.

The rising concentration of methane in the atmosphere since the beginning of the 19th Century is mainly due to changing agricultural practice, waste disposal, deforestation and mining. About 80% of the gas is produced by decomposition in rice paddies, swamps, the intestines of grazing animals and by tropical termites. The levels of methane have risen by 11% since 1978. The oxidation processes, which remove methane from the atmosphere, can be impaired by other emissions, principally those of man-made carbon monoxide, but also by natural hydrocarbons from plants. Up to 40% of the rise in methane concentration is ascribed to this reduction in the natural rate of its chemical decay.

Trace gases in the atmosphere also include ammonia, hydrogen sulphide and oxides of sulphur (emanating from volcanoes) which are washed out of the atmosphere by rain or snow. Anthropogenic emissions of sulphur, nitrogen oxides and ammonia from industry, transport and agriculture are also responsible for environmental degradation, as they return to the Earth's surface as "acid rain" (Figure 2.2) which disturbs the ecological balance of sensitive plant communities.

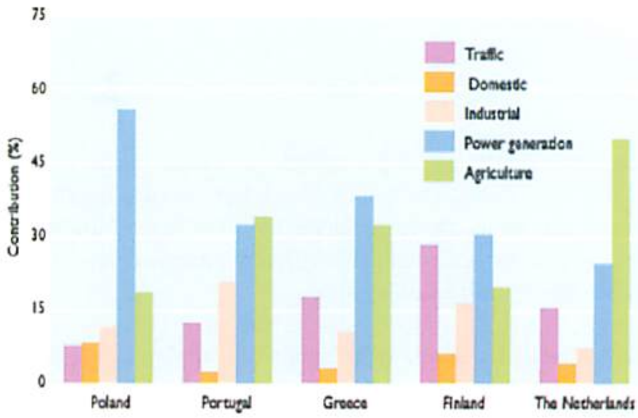


Figure 2.2 Relative comparison of source categories to potential acid deposition, 1990 (Acknowledgment: RIVM, The Netherlands)

Three instruments on Envisat (i.e. GOMOS, MIPAS and SCIAMACHY) are dedicated to providing information about the atmosphere, but others (i.e. MERIS, AATSR and MWR) also contribute. Figure 2.3 provides a comparison of these instruments in terms of the wavelengths at which they acquire data.

The interaction of individual gas species in the atmosphere with incoming solar (or stellar) radiation takes place at specific wavelengths within the electromagnetic spectrum. The fact that the shapes of these absorption features and the wavelength regions where they occur are different for each molecule, is the feature which is exploited in producing the required data. Figure 2.4 shows the absorption spectra for gases in the ultra-violet, visible and infra-red, as sensed by SCIAMACHY. The effectiveness of the instruments is strongly influenced by their spectral resolution and the strategies adopted to acquire data from the atmosphere; supported by a high emphasis on calibration.

Table 2.1 provides a list of atmospheric constituents which can be measured by each of the instruments. A particular strength is the emphasis on providing measurements of atmospheric constituents according to altitude, which is more valuable for understanding the processes involved than total column measurements.

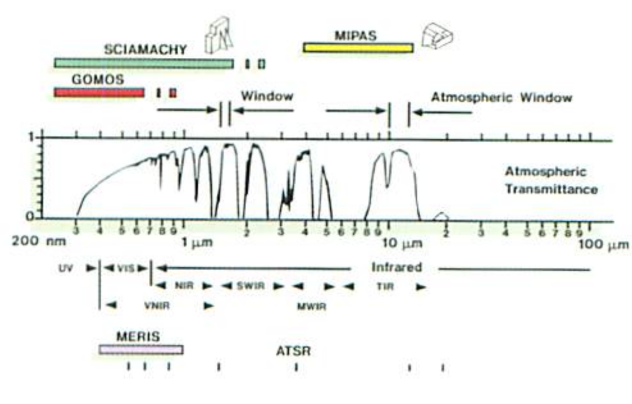


Fig. 2.3 Comparison of Envisat atmospheric sensors

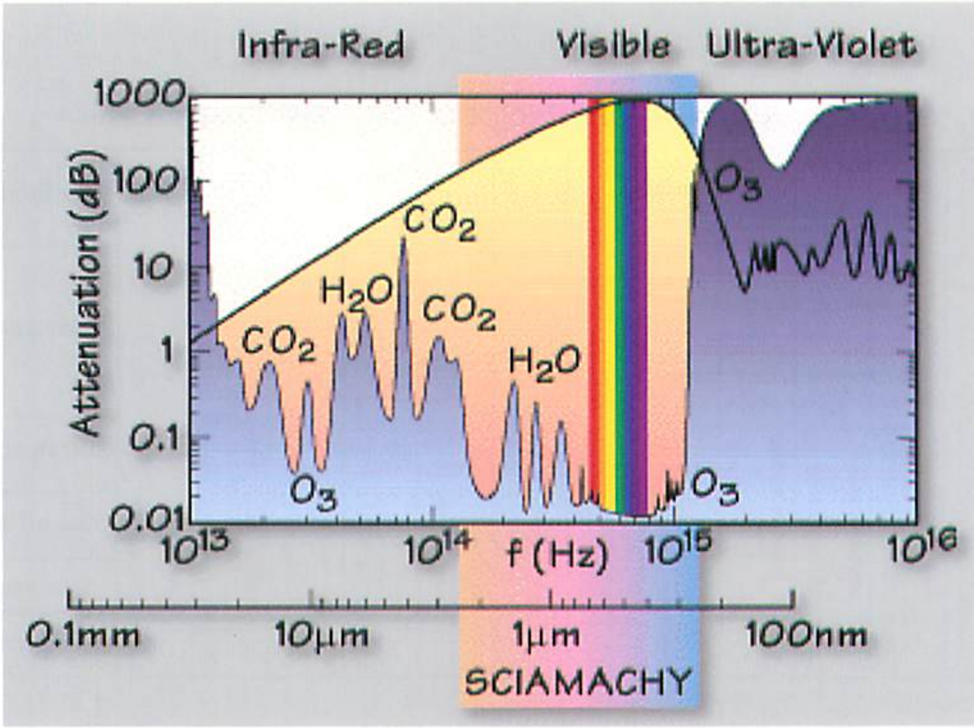


Figure 2.4 Absorption spectra for selected gas molecules and spectral region sensed by SCIAMACHY (Acknowledgment: IFE Bremen, Germany)

Sensor	Product Type
GOMOS	Vertical concentration profiles of O_3, NO_2, NO_3, O_2, H_2O, (OClO and BrO during ozone hole conditions), aerosol extinction coefficients, temperature, atmospheric turbulence, polar stratospheric clouds, (noctilucent clouds).
MIPAS	Vertical concentration profiles of around 20 relevant trace gases including primary species: O_3, H_2O, CH_4, N_2O and HNO_3, also temperature, distribution of aerosols, tropospheric cirrus and stratospheric ice clouds (including polar stratospheric clouds).
SCIAMACHY	Vertical concentration profiles of - in the troposphere: O_3, O_4, N_2O, NO_2, CO, CO_2, H_2O, CH_4, (HCHO, SO_2, in polluted conditions) in the stratosphere: O_3, O_2, O_4, NO, NO_2, CO, CO_2, H_2O, CH_4, volcanic eruption: SO_2 and Ozone hole conditions: OClO, ClO. Aerosol parameters, cloud measurements, pressure and temperature measurements.
MERIS	Aerosol optical thickness and type, cloud reflectance, cloud top height, water vapour column abundance.
AATSR	Cloud parameters: cloud type, water/ice discrimination and particle size distribution, aerosol distribution.
MWR	Water vapour and liquid water content of atmosphere.

Table 2.1 Atmosphere constituents measured by Envisat

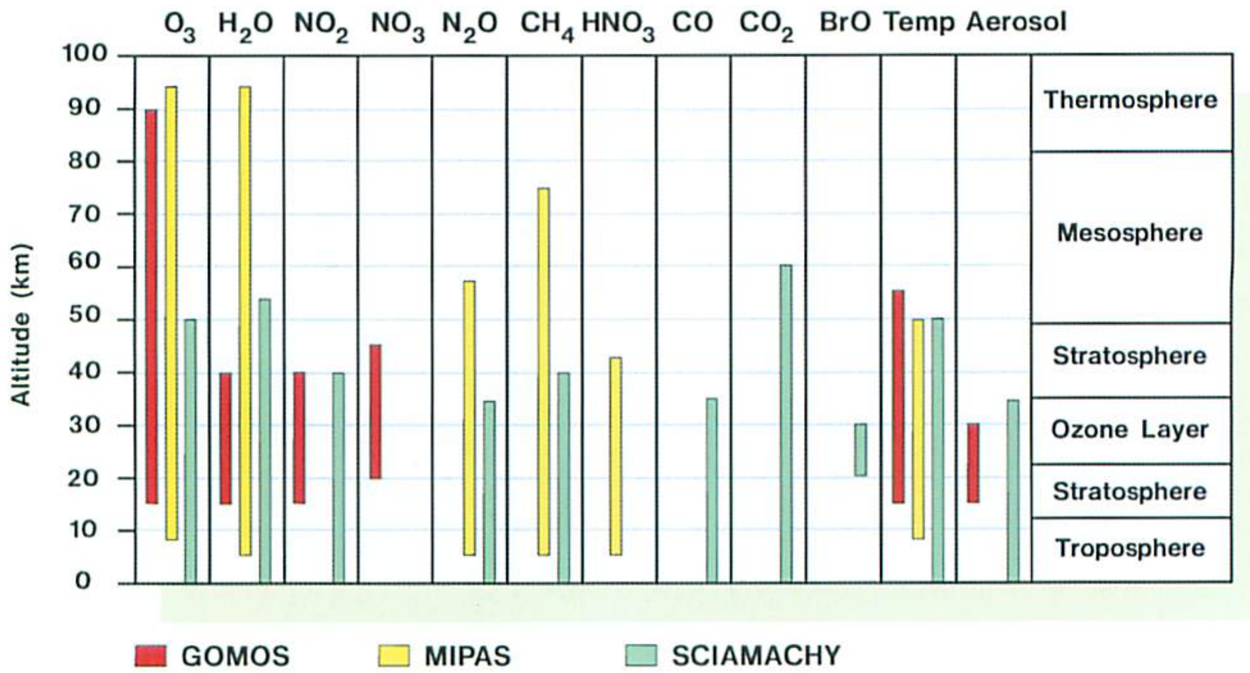


Figure 2.5: Altitudinal ranges over which atmospheric constituents will be measured by GOMOS, MIPAS and SCHIAMACHY (n.b. limited to main data products observable under nominal conditions)

Figure 2.5 shows the altitudinal ranges over which the different constituents will be measured by GOMOS, MIPAS and SCIAMACHY, and also illustrates the extent of the overlapping coverage. The presence of multiple atmospheric sensors on Envisat provides the opportunity for mutual geophysical validation activities and the generation of high quality and long term data sets which can be used with confidence for studying changes in the structure and composition of the Earth's climate.

The following sections discuss those areas of research into the atmosphere where Envisat is able to support particular scientific objectives.

2.2 Stratosphere

Whilst a large amount of research effort is focused on the issue of ozone depletion, it is not realistic to dissociate this from other chemical and physical processes in the stratosphere. The distribution and concentration of water vapour, for example, is directly related to ozone destruction. The reduction of the concentration in the ozone layer in the upper atmosphere, which protects living cells from ultraviolet-B radiation, has provided the clearest example of the impact of anthropogenic activity on the Earth's atmosphere. Prior to this, a state of natural equilibrium had been achieved within the biosphere. One of the results of this process was the production of a stratospheric ozone layer providing protection from the Sun's harmful ultraviolet radiation.

Large decreases in stratospheric ozone have been recorded over the Antarctic in successive years, with mounting evidence that these were due to human activity. More recently, significant reductions in ozone levels have been observed at mid and high latitudes in the Northern hemisphere. The link between stratospheric ozone depletion and the anthropogenic emission of certain trace chemicals into the atmosphere, in particular the chlorofluorocarbons, is now well established and has produced unprecedented political reaction. Following the implementation of the Montreal Protocol and subsequent amendments, the stratospheric loading of chemicals which lead to ozone depletion, principally those belonging to the chlorine and bromine families, is expected to decrease during the early years of the next century. The persistent nature of these precursor chemicals, coupled with inadequate knowledge of the processes involved, means, however, that the rate of ozone recovery is difficult to predict and model.

Models which simulate changes in atmospheric chemistry undergo an iterative development process, requiring the incorporation of the latest knowledge to improve their accuracy. To model ozone depletion properly, they need data describing the life history of all the constituents involved in the creation and destruction of ozone. The use of spaceborne instruments for measuring ozone is now well established and includes TOMS, SBUV, SAGE and latterly, GOME on ERS-2.

Figure 2.6 shows a global map from GOME and provides an indication of the type and quality of data which will be acquired from SCIAMACHY. GOME is a precursor to SCIAMACHY; observing the atmosphere in nadir sounding only and having four spectral channels, as opposed to the eight channels of SCIAMACHY (Figure 2.7). The complex scenario associated with ozone depletion necessitates the study of a wide range of stratospheric phenomena. Understanding the role of Polar Stratospheric Clouds (PSC), their relationship with water vapour content and the crucial role they play in the chemistry of chlorine, is just one such area.

In order to model the ozone destruction processes it is important to relate the measurements to altitude. Total column measurements have value with regard to the amount of harmful ultraviolet radiation reaching the ground surface. However, vertical profiles of ozone concentration are needed to derive information about the creative and destructive processes involved. The main atmospheric sensors on Envisat will routinely provide data on constituents, resolved by height with vertical resolutions between 1.7 km and 3 km.

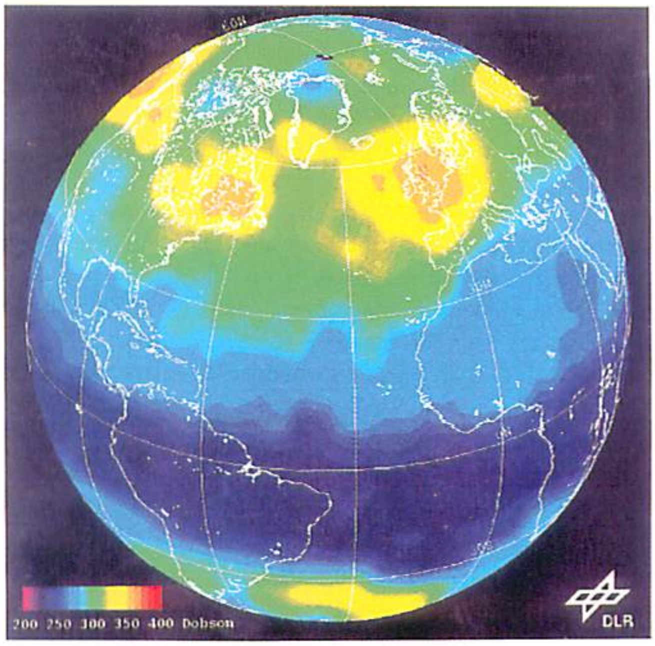


Figure 2.6 First operational GOME total column ozone map 5 - 7 July 1996.
(Acknowledgment: DLR, Oberpfaffenhofen, Germany)

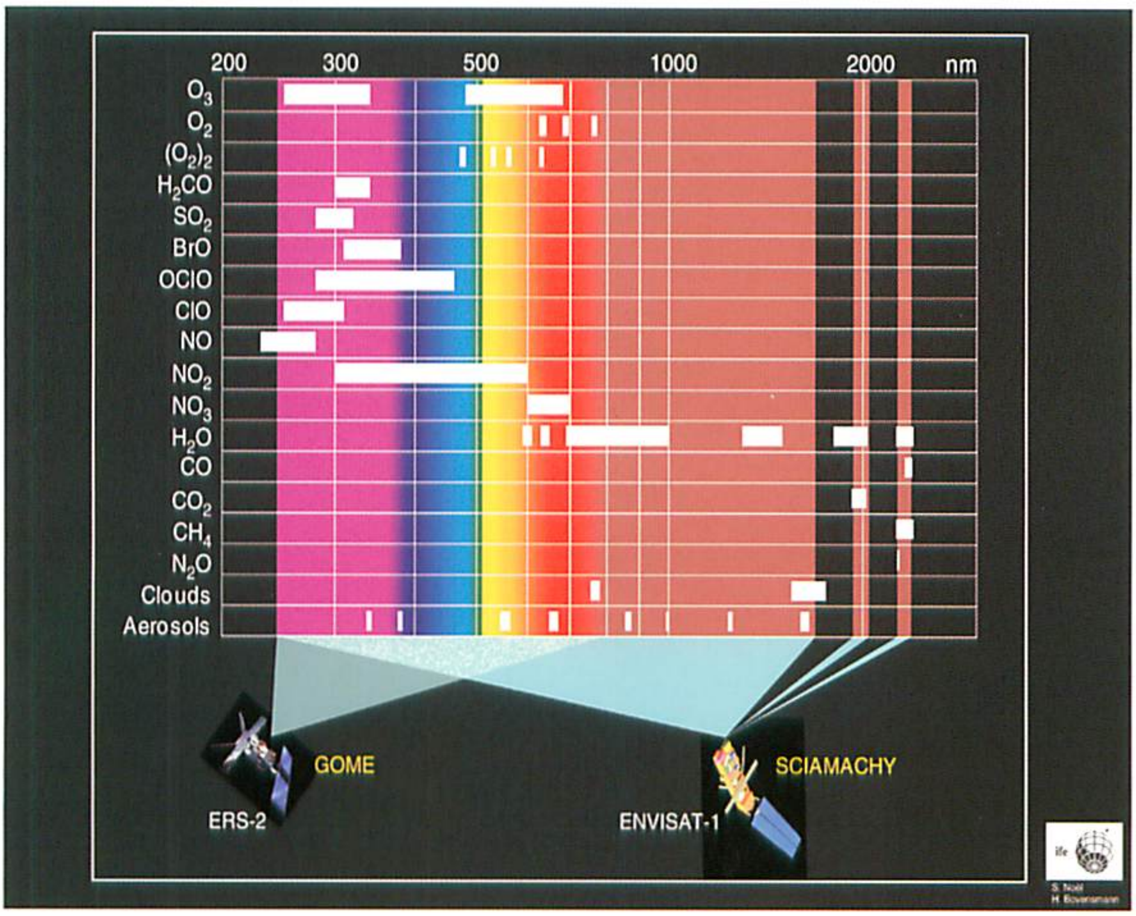


Figure 2.7 A comparison of the wavelength coverage of GOME and SCIAMACHY
(Acknowledgment: IFE, Bremen, Germany)

As shown in Figure 2.8, comparisons of GOME ozone concentration profiles with sonde measurements give excellent results. It is also clear that the limb sounders onboard Envisat will provide data in much better vertical resolution than GOME, which is limited to nadir viewing.

GOMOS, MIPAS and SCIAMACHY all produce data relevant to stratospheric chemistry, including the detection of those chemicals involved in ozone depletion and the presence of associated phenomena such as PSCs. Data describing the diurnal changes in trace gases will be obtained as a result of the complementarity between sensors as well the ability of MIPAS to routinely acquire data day and night. The precision with which ozone will be monitored will be sufficient to support studies which aim to identify the natural trends in ozone concentration and distribution.

Envisat will play an important role in the study of stratospheric chemistry, by routinely supplying relevant data throughout its lifetime, allowing the creation of data sets spanning several years.

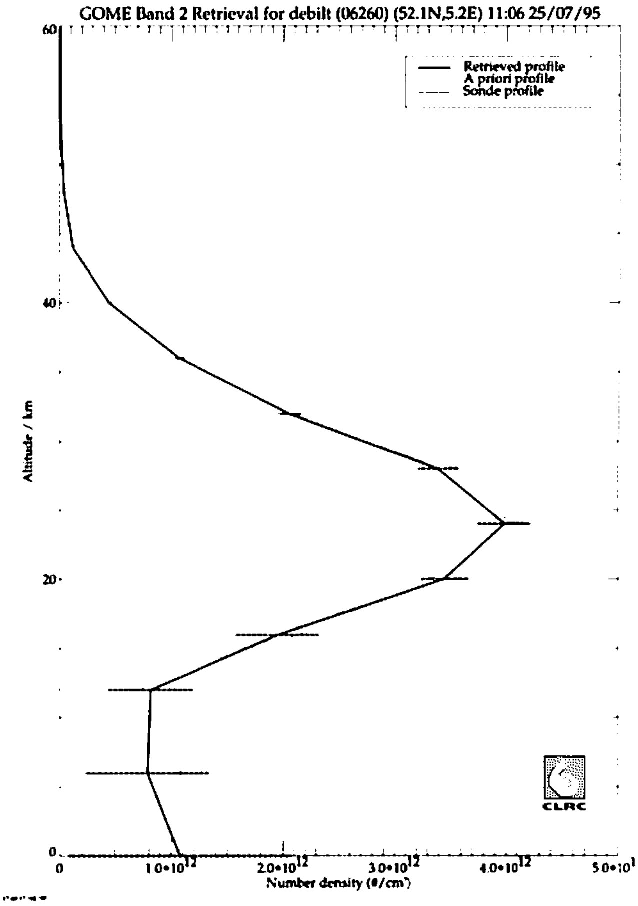
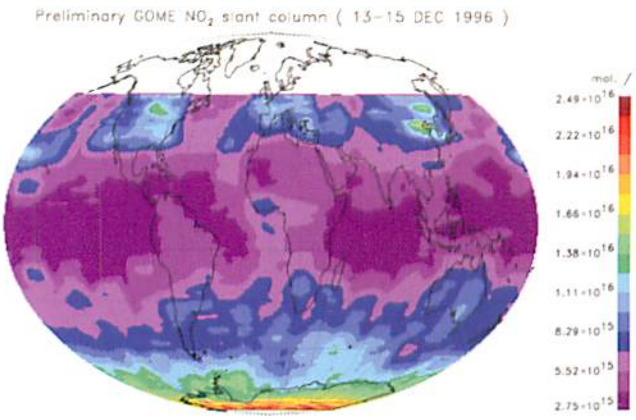


Figure 2.8 Retrieved GOME-1 profile (black) line from 25 July 1995 using channel 1 and channel 2 data from an overflight of De Bilt (NL), and corresponding sonde profile (red line). The a priori profile indicated (dotted line) is derived, as a first step, from the GOME measurements in channel 1 (from 265 to 307nm). The channel 2 measurements (in the Huggins bands) are then used to improve the retrieved profile below the ozone concentration peak.
(Acknowledgment: R. Siddans, Rutherford Appleton Laboratory, Didcot, UK)

2.3 Troposphere

Monitoring the troposphere provides further insights into the nature of human interaction with the atmosphere. Critical issues within the troposphere include the description of cloud types, temperature profiles, water vapour profiles, amounts of methane and other man-made pollutants released.

In the lower troposphere, increase in ozone is a major concern, brought about by increased levels of nitrogen oxides and hydrocarbons. Whilst mostly associated with industrial activities in the northern hemisphere, elevated tropospheric ozone levels also occur in the southern hemisphere as a consequence of biomass burning. Although it is clear that the levels of carbon and nitrogen in the atmosphere are increasing as a result of man's activities, more information is needed to help model the processes involved. Such information will provide support for a variety of studies including, for example, the effect of higher levels of carbon and nitrogen in the atmosphere on plant growth, due to increased atmospheric fertilisation. Figure 2.9 shows global NO_2 levels derived from GOME measurements.



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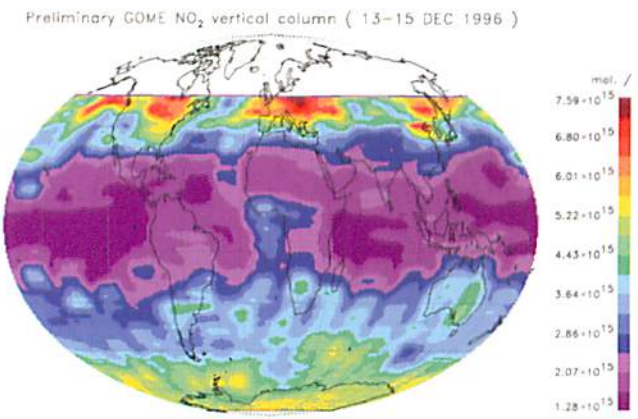

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Figure 2.9 NO_2 Levels Derived from GOME (Acknowledg^{mt}.: Ricarda Hoogen, IFE, Bremen, Germany)

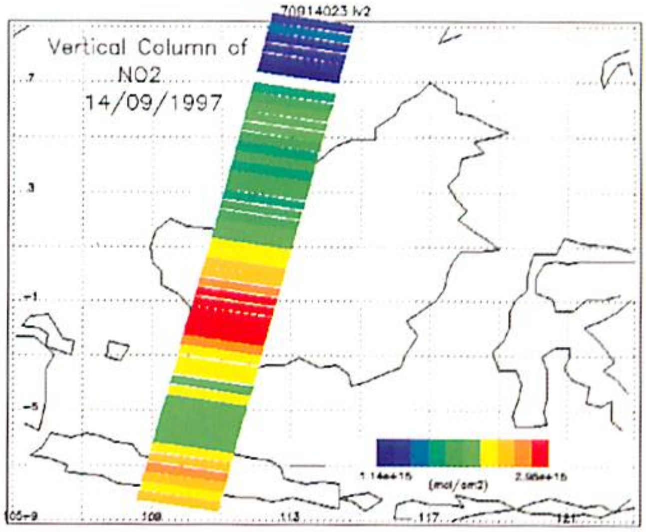


Figure 2.10 Total column NO_2 measured by GOME over Indonesia, showing high values over the forest fires in south west Kalimantan, 14 September 1997. (Acknowledgment: S. del Corso, ESRIN)

Figure 2.10 demonstrates the ability of GOME to identify anthropogenic pollutants at a regional scale, in this case caused by forest fires in Kalimantan.

Sensors onboard Envisat will provide information about clouds, temperature and pressure, in support of data produced by operational meteorological satellites. The provision of near real time data is especially relevant in this context. Data from Envisat sensors will contribute to medium term forecasts through the incorporation of these data into operational models.

The impact of air traffic on the atmosphere, and specifically the effect of NO exhaust emissions on the production of ozone in the upper troposphere, is a significant scientific issue which also receives both media and political interest. The distribution of NO in the upper troposphere depends on a number of sources: lightning, anthropogenic pollution, downward movement from the stratosphere and aircraft exhaust. Given that NO production by aircraft is concentrated along air traffic corridors, this may provide the opportunity to acquire more data about the associated chemical and dispersion processes.

MIPAS will provide data relevant to upper tropospheric chemistry and will support the analysis of NO emissions from aircraft exhaust in air corridors. SCIAMACHY is a particularly capable instrument for acquiring data from the lower part of the troposphere and has the potential to detect biomass burning, biogenic emissions, pollution incidents over populated regions, production of oxides of nitrogen by lightning, Arctic haze, forest fires, dust storms and industrial plumes. In nadir viewing, O_2, O_4, and CO_2 absorption will provide estimates of cloud top height.

2.4 Aerosols

There is evidence to suggest that in recent decades there have been long term changes in aerosol loading in the stratosphere. For example, amounts of sulphate aerosol in the stratosphere increased significantly in 1991 and 1992 as a result of the 1991 eruption of Mount Pinatubo. GOME data have been analysed to produce estimates of SO_2 loading of the atmosphere, for example from the eruption of the Nyamuragira volcano in Zaire (Figure 2.11). Whilst there is a good relationship between the degree of aerosol loading and volcanic events, an upward trend has been detected in background levels.

The impact of aerosols on the Earth's radiation budget (see below) is both direct, through scattering and absorption, and indirect, through the modification of cloud properties. In both cases, aerosols in the stratosphere seem to have a cooling effect with regard to the Earth's radiation budget. Sulphate aerosol loading in the mid-latitudes has also been correlated with ozone trends in mid-latitude and polar regions, through a modification of the concentration of gases involved in ozone depletion. However, the extent to which aerosols influence the Earth's climate has been difficult to assess since aerosols vary a great deal in terms of size, shape and chemical composition. Satellite borne sensors have the potential to improve knowledge of the origin, dynamics and fate of aerosols, through their ability to monitor the whole globe within very short data capture repeat cycles. Critical to the determination of aerosol types is the wavelength dependence of extinction coefficients in the visible and near infrared parts of the spectrum.

The use of spaceborne instruments to measure aerosols in the stratosphere is well established. The SAGE (Stratospheric Aerosol and Gas Experiment) series of instruments have demonstrated the concept and share features with the atmosphere sensors onboard Envisat; with GOMOS in particular. Several of the instruments onboard Envisat will be capable of making aerosol measurements with sufficient spectral coverage to determine size distribution and composition. GOMOS and MIPAS will make observations of the distribution and structure of the stratospheric aerosol layers. Moreover, the ability of MIPAS to acquire data perpendicularly to its flight direction, will strengthen its ability to record aerosol injections into the stratosphere from volcanic eruptions. SCIAMACHY will provide further information about aerosols through its ability to make polarisation measurements, and its large spectral coverage. MERIS has the capability to evaluate aerosol properties including aerosol path radiance, optical thickness and type. Data from ATSR-1 and -2 have been used to map stratospheric aerosol distribution and this capability will continue with AATSR.

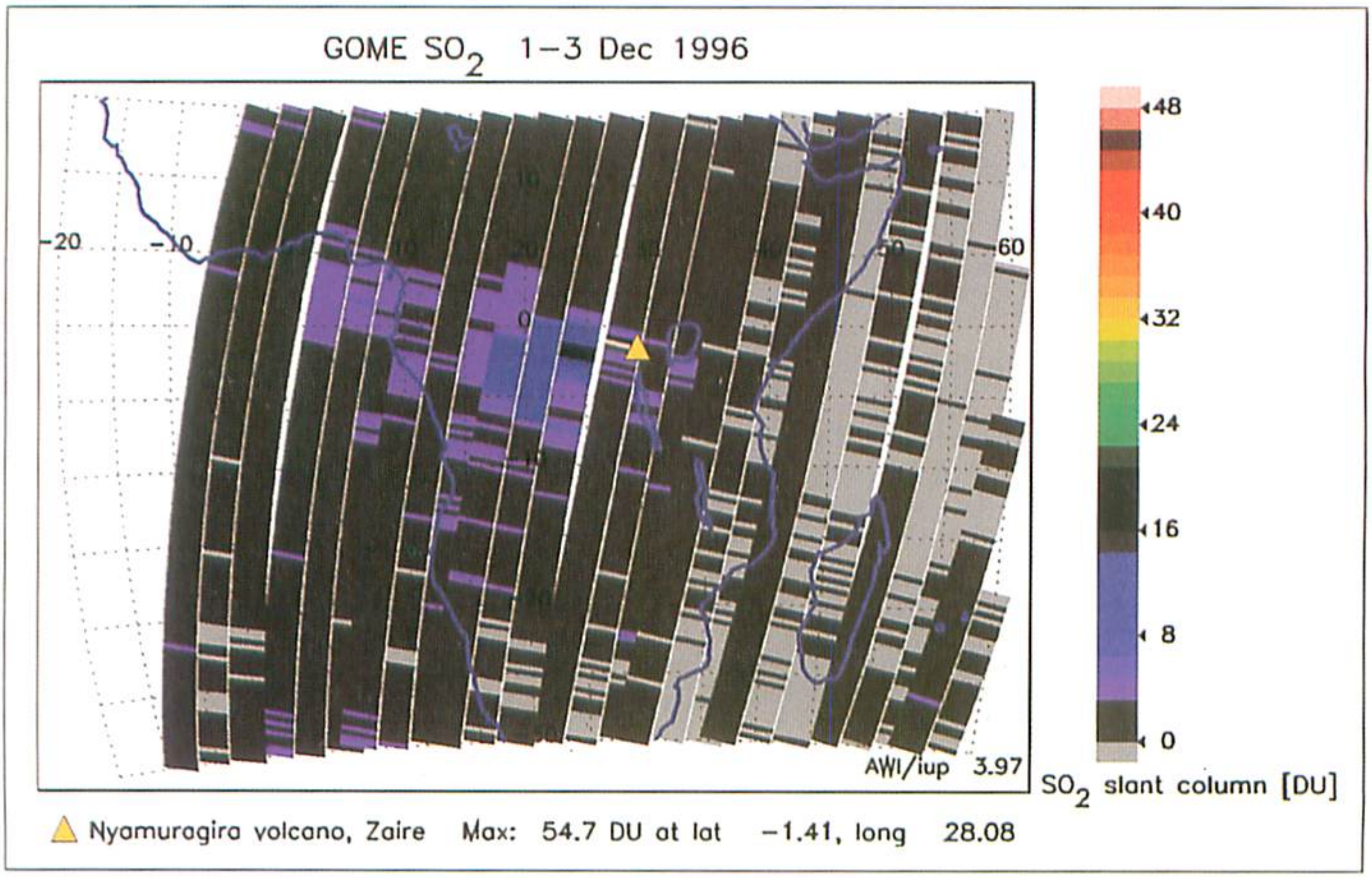


Figure 2.11 SO_2 retrievals from GOME data, Nyamuragira volcano, Zaire (Acknowledgment: IFE, Bremen, Germany).

2.5 Earth Radiation Budget

Processes in the atmosphere which alter the Earth's radiation budget need to be better understood. To achieve this it is necessary to monitor certain trace gases and other constituents such as aerosols, whose temporal changes affect the Earth's climate by modifying radiative transfer. Long term global measurements will improve current assessments of changes in the abundance of ClO_X, HO_X, and NO_X which are associated with decreases in stratospheric temperatures through their impact on radiative transfer in the atmosphere. Observations on the extent of radiative cooling of the atmosphere can be obtained from measurements of CO_2 and NO in the middle atmosphere.

Of particular interest, in the context of the "greenhouse effect", is the transportation of water vapour from the surface of the Earth into the free troposphere. Whilst climate models have suggested that this is a phenomenon associated with global warming, there is no firm evidence suggesting that the free troposphere is becoming more moist and therefore providing the positive feedback necessary to stimulate global warming to the levels being suggested. In terms of radiation budget, water vapour is the most important atmospheric gas in the context of cloud amount, precipitation and evaporation rates. Even small changes in global measurements of cloud albedo will have a significant effect on the Earth's radiation budget.

MERIS contributes to this work by providing information on cloud amount, cloud top height, cloud optical thickness, water vapour and cloud albedo, as well as the aerosol information discussed above. Cloud coverage and other parameters, including water/ice discrimination and particle size distribution, will also be available from the visible channels on AATSR. The MWR also produces total column measurements of water vapour and liquid water.

2.6 Dynamics and Stratospheric/Tropospheric Exchange

The distribution of the various trace gases, the thermal structure and the circulation in the atmosphere evolve as a result of complex interactions between radiative, chemical and dynamic processes. Insights into the dynamic nature of the atmosphere can be deduced from measurements of temperature and trace constituent species such as H_2O, CH_4, N_2O and O_3 in the lower stratosphere. Understanding the processes controlling the exchange of gases between the troposphere and stratosphere demands reliable information on variations in the concentration and distribution of long lived species. Specifically, measurements of the concentrations of a number of trace gases, whose mixing ratios change significantly near the tropopause, provide the means of studying processes which are at present poorly understood. In this context ozone is a particularly useful tracer for measurements of exchange between the stratosphere and troposphere.

MIPAS and SCIAMACHY will provide complementary information on the indicator trace gases at (or near) the tropopause. These will be the best data routinely available from satellites for this area of research.

3. Oceans

The ocean exerts a major influence on the Earth's meteorology and climate through its interaction with the atmosphere. Understanding the transfer of moisture and energy between ocean and atmosphere is therefore a scientific priority. Better observations are needed, to improve the accuracy of forecasts for weather, marine conditions and climatic change.

Earth observation satellites have revolutionised the study of the ocean. They now provide detailed repetitive measurements over remote areas of the world, where previously there were only a limited number of (isolated) observations from ships and buoys. Microwave instruments, including SARs and radar altimeters, have a remarkable sensitivity to the roughness and height of the ocean surface, enabling the detection of ocean currents, fronts and internal waves, oil slicks and ships, as well as accurate measurement of sea level changes, wave height and wind speed. Optical instruments provide measurements of ocean colour and temperature, which are important indicators of phytoplankton, yellow substance (Gelbstoff) and suspended sediments.

Envisat, by including advanced SAR, radar altimeter, ocean colour and ocean temperature instruments together on the same platform, offers particularly exciting opportunities for synergetic measurements over the oceans. It will provide an improvement in measurement capability compared with ERS, together with possibilities for many new geophysical measurements. The simultaneous combination of MERIS ocean colour measurements with both AATSR sea surface temperature, and ASAR sea surface roughness is particularly exciting.

3.1 Ocean Topography and Circulation

Our knowledge of the ocean's central role in modifying climate, through its large heat capacity and transport mechanisms and the complexity of its interactions with the atmosphere and cryosphere, is insufficient for the accurate prediction of climate change (as a result of fluctuations in natural or anthropogenic forcings). For example, it is known that at least half of the excess energy input (i.e. the incoming solar radiation minus the infrared radiation to space) in tropical areas is carried towards the poles by the oceans, the other half being transported by the atmosphere. Quantitative estimates are coarse however and predictions of how such fluxes would be modified by 'enhanced greenhouse forcings' are even coarser. The World Climate Research Programme (WCRP) includes very large oceanographic research programmes, such as WOCE and CLIVAR, focusing on this issue.

These programmes rely heavily on the availability of satellite altimetry data such as provided by the Geosat, Topex/Poseidon and ERS-1/2 missions. For example, Figure 3.1 shows data from ERS-1. Several satellites, operating in unison, allow the very precise, regular and quasi-global measurement of dynamic sea surface heights.

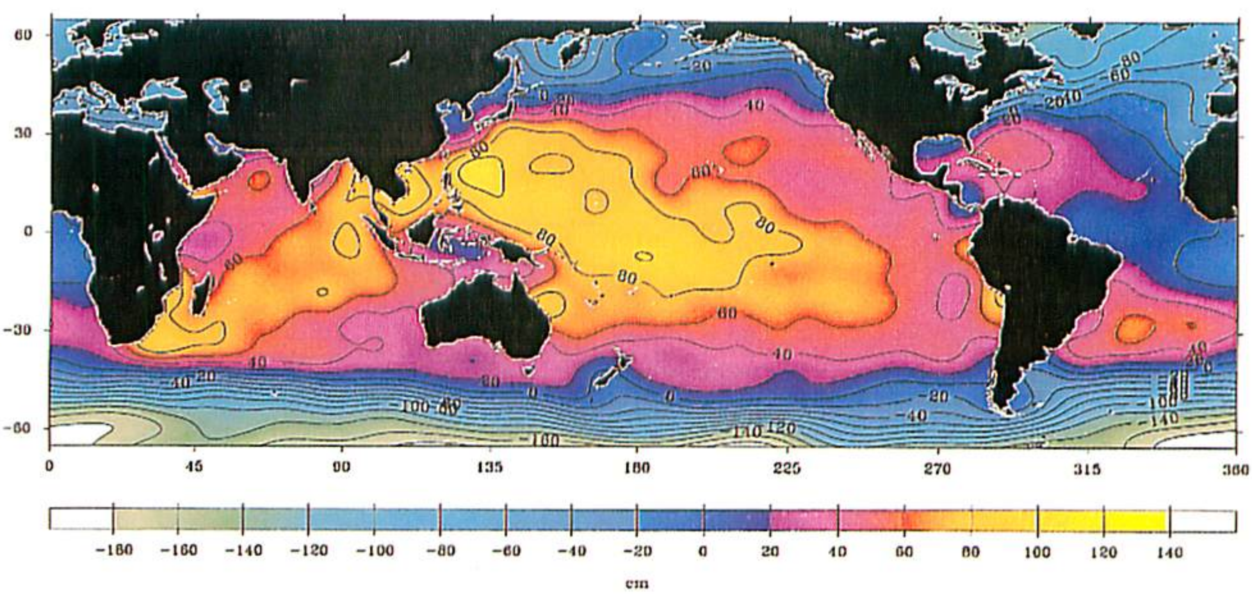


Figure 3.1 Global Ocean Topography: averaged topographic map as observed by the ERS-1 radar altimeter during a 35-day repeat orbit phase (Acknowledgment: B.Tapley, C.Shum, University of Texas at Austin, USA)

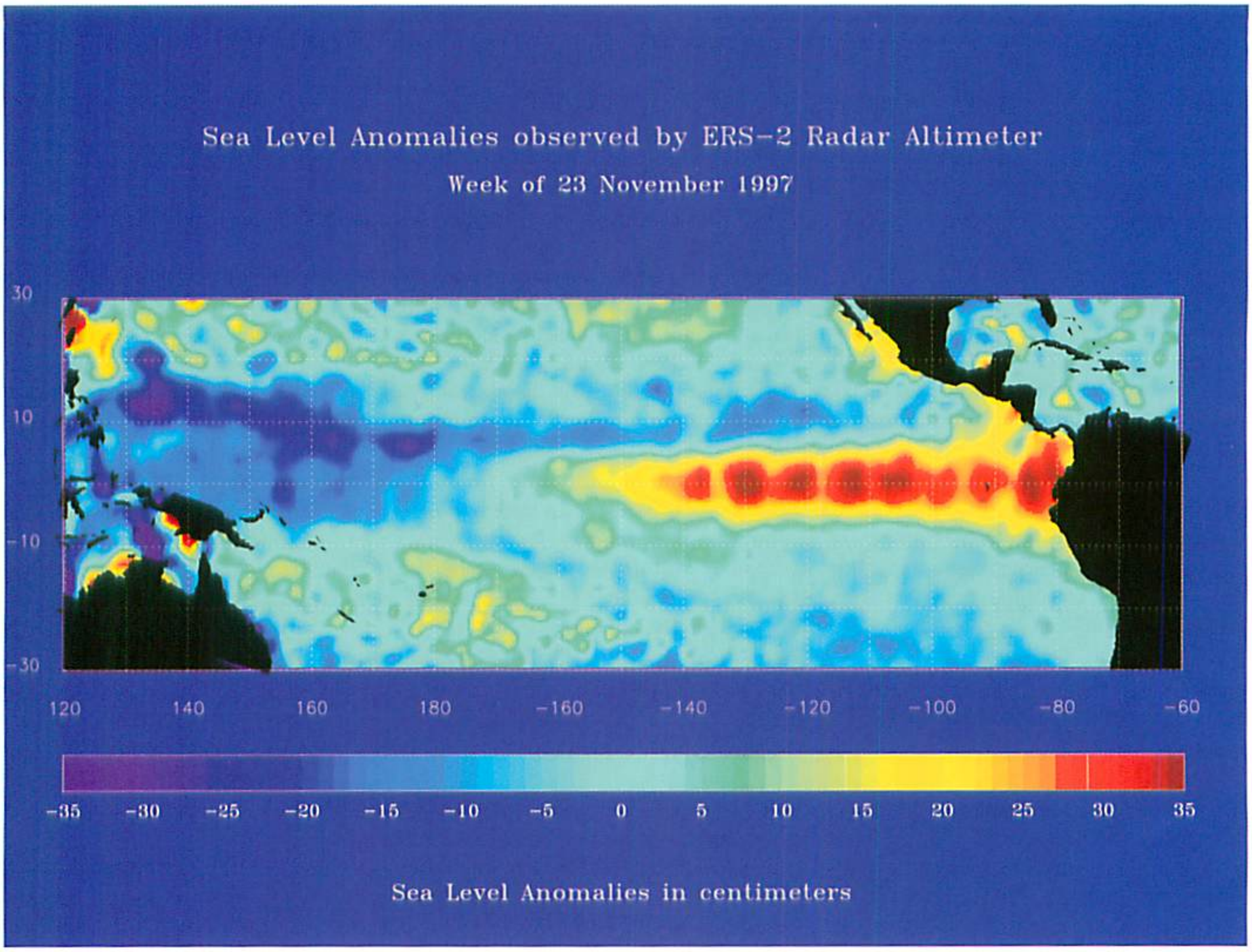


Figure 3.2 Change in ocean topography observed by the ERS-2 radar altimeter during the strong El-Niño event in 1997 (Acknowledgment: R.Scharro, Delft University of Technology and K.Cardon and J.Beneviste, ESRIN)

As most changes in ocean surface currents which have timescales of a few days or longer result in geostrophic balance, gradients of the sea surface 'dynamic topography', (i.e. the sea level above the geoid) as derived from radar altimetry can be employed almost directly as proxy surface current information. Unlike *in situ* measurements, altimeter measurements are global, synoptic and can be repeated for many years, and they are related to ocean processes and currents within the whole water column. They can also be assimilated directly into ocean and climate numerical models. During the last decade, the technique of radar altimetry has become fully developed, enabling routine, very precise, quasi-global measurements of sea level to be obtained. Analysis of almost 4 years of Topex/Poseidon and ERS altimetric data has provided observations of the ocean dynamic topography at an absolute accuracy of 3-4 cm [Le Traon, Mitchum].

One important practical application concerns the study of the El Niño Southern Oscillation phenomenon in the Pacific Ocean. Figure 3.2 shows an excellent example of how centimetric sea-level anomalies observed by the ERS-2 Radar Altimeter have detected an El Niño event. Normally the effect of the easterly trade winds is to produce a higher sea level on the western side of the Pacific, with an associated strong upwelling of nutrient-rich cold waters on the eastern side. However, during an El Niño event, the trade winds weaken, there is an eastwards flow of warm surface waters, a rise in sea level by up to 30 cm on the eastern side and an interruption in the upwelling of nutrient-rich waters. Fish die or migrate to higher latitudes and rainfall patterns change dramatically, causing heavy rain and floods on the west coast of South America and drought in Australia and S.E. Asia.

As far as data assimilation is concerned, model error statistics are essential in order to perform reliable predictions. In order to estimate these, models must be run for long periods (i.e. 10 years or more) and with a continuous data flow. It is therefore essential that continuity of the high-precision altimeter systems is ensured.

It is not possible to optimise the sampling of any single satellite mission to observe all oceanic processes and regions. The sampling problem must be thought of in terms of complementarity. The overlapping of ERS-1/2 on a 35-day orbit, and the 10-day orbit of Topex/Poseidon in 1993 and from 1995, provides such an example: the mesoscale features and high latitude areas are adequately observed by the former, but the latter provides better coverage of the fast-varying tropics, large-scale disturbances and western boundary currents. The coverage provided by the ERS RA and the Envisat RA-2 altimeters

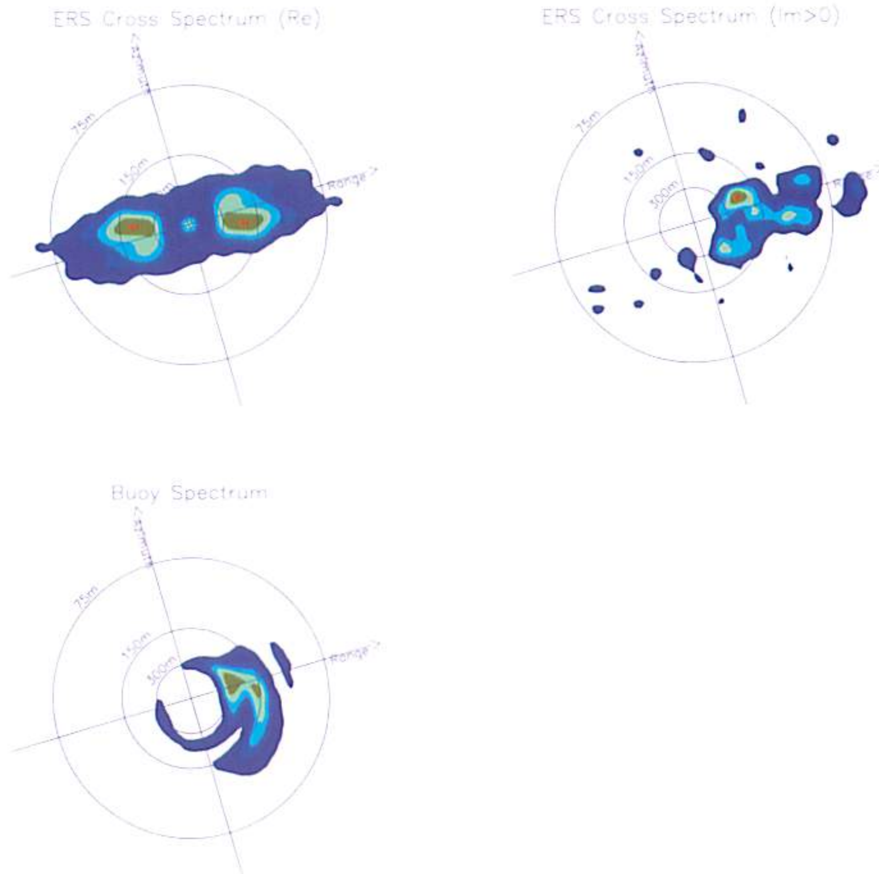


Figure 3.3 SAR ocean image cross spectra (real and imaginary part) processed from ERS-1 data using the Envisat ASAR Wave Mode Inter-Look Cross Spectra algorithm. The corresponding directional buoy spectrum is also shown (Acknowledgment: NORUT IT, Norway)

will continue to be vital for the study of mid-latitude mesoscale eddies and the impacts of high-latitude ocean and ice on seasonal and inter-annual climate predictability.

The RA-2 instrument offers improved measurement accuracy in comparison with the ERS RA, particularly with the improved tracker and through the use of DORIS data for more precise orbit determination. The second frequency channel at 3.2 GHz will enable height measurement corrections of the ionospheric effects on the signal. The near real-time products will include both this ionospheric correction and the tropospheric path correction using measurements from the MWR. Measurement accuracy after all geophysical corrections will be better than 3 cm in ocean mode.

3.2 Winds and Waves

Major features of the interaction between the ocean and the atmosphere are the creation of waves and ocean currents by surface winds. Wind and wave data are needed for climatological research, as inputs to meteorological models and for sea state forecasting in support of marine operations.

Envisat has two instruments, ASAR and RA-2, which will provide observations of surface waves and winds over the ocean. The ASAR Wave Mode will collect imagettes of minimum size 5 km x 5 km, similar to the ERS AMI Wave Mode, spaced 100 km along-track in either HH or VV polarisation. The position of the imagette across track can be selected to be either constant or alternating between two across-track positions over the full swath width.

ERS Wave Mode products are based on image spectra (frequency and direction) estimated from SAR intensity imagettes using standard Fourier transform techniques. These products are therefore symmetric, with a 180° propagation direction ambiguity. Techniques have been developed involving the use of wave model predictions to solve the ambiguity problem, though this can be subject to error when opposite or near opposite wave components exist.

For ASAR, this problem will be solved by using a new wave product preserving the phase and a new algorithm called "inter-look cross spectral processing", whereby information on the wave propagation direction is computed from pairs of single-look images separated in time by typically a fraction of the dominant wave period. Figure 3.3 shows a simulated ASAR Wave Mode Spectrum, with the top left plot being the cross spectrum real part (symmetric and equivalent to an ERS product), and the top right plot the new imaginary part (asymmetric giving wave propagation direction). In this example, the output from the new algorithm is seen to correspond with the wave direction provided by buoy measurements, as shown in the lower plot.

Recently, investigations have shown that it is possible to derive wind speed estimates from SAR, in particular when wind directional patterns such as wind streaks are visible in the images (Figure 3.4). The ASAR Global Monitoring Mode is of interest in this respect because of the large area coverage and the frequent revisit.

The RA-2 will provide a measure of the significant wave height through the distortion of the mean shape of the return pulse and an estimate of the wind speed based on its intensity. The earlier return from the wave crests and the retarded return from the wave troughs leads to a broadening of the return pulse which can be directly related to the significant wave height. In order to determine the mean pulse shape, several hundred pulses need to be averaged, giving one wave height measurement about every 7 km along the satellite track.

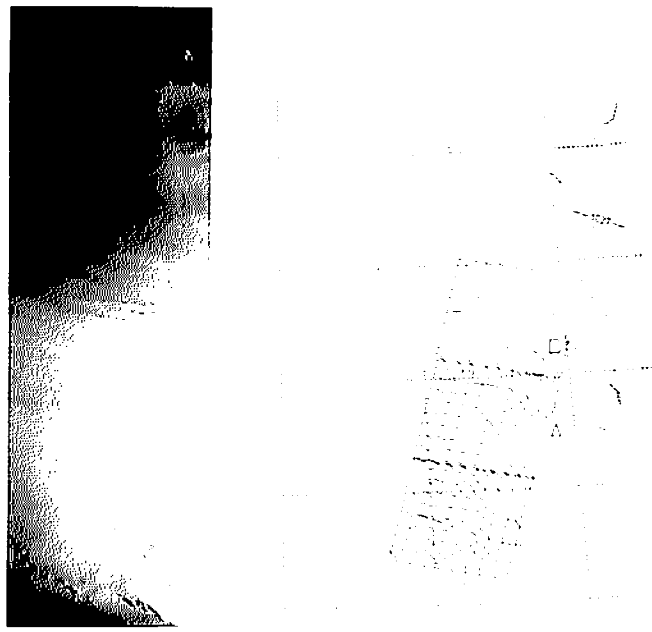


Figure 3.4 Wind field derived from ERS-2 SAR images, 17 September 1995. Weather model data and in situ observations used for validation. (Acknowledgment: Korsbakken et al. 1997)

The wealth of wave height data available from the ERS RA has had a large influence on wave modelling, and has also stimulated the development of wave height assimilation techniques. One of the principal motivations for developing the third generation wave model (WAM) was to provide a state-of-the art model for the assimilation of global data from satellites for improved wind and wave field analysis and forecasting. Presently, the WAM model is in use at a number of meteorological centres (NCEP, Washington; FNMOC, Monterey; BMRC, Melbourne; ECMWF, Reading; DNMI, Oslo) and altimeter wave height data are assimilated at UKMO, Bracknell and at ECMWF, Reading. Figure 3.5 provides an example of the ability of altimeters to measure ocean wave height for the study of wave climate on a global scale.

By doubling the pulse power, the quality of the ERS-2 altimeter wave height measurements was improved compared to those from ERS-1. The RA-2 on Envisat is expected to give further improvements so that even more accurate determination of the echo waveform will be possible. RA-2 processing will take into account deviations from Gaussian statistics of the ocean surface. This is important for 'young' wind seas, and therefore more accurate determinations of wave height are expected.

Altimeter wind speeds are used in the wave data assimilation scheme at UKMO; while at ECMWF altimeter wind speed data are used for monitoring the quality of the analysed surface wind speed.

Radar altimeter wind and wave data are also potentially useful for monitoring changes in the wind and wave climatology. In particular, the wave height field depends in a sensitive manner on the forcing wind field, and changes in the wave climate are therefore an indicator of changes in the atmospheric climate.

The data produced by Topex/Poseidon, GFO, JASON, ERS-1/2 and Envisat will provide valuable contributions to the monitoring of these wave climate changes. However, it is of considerable importance to ensure a continuous and uniform data set. Apart from cross calibration between successive satellites, during their period of overlap, this can be achieved either by using buoy observations as a go-between, or else by comparison with long term running wave model products.

Sea state forecasting for ship routing has been an important commercial application of ERS data, and this will continue, using data from the RA-2 and ASAR.

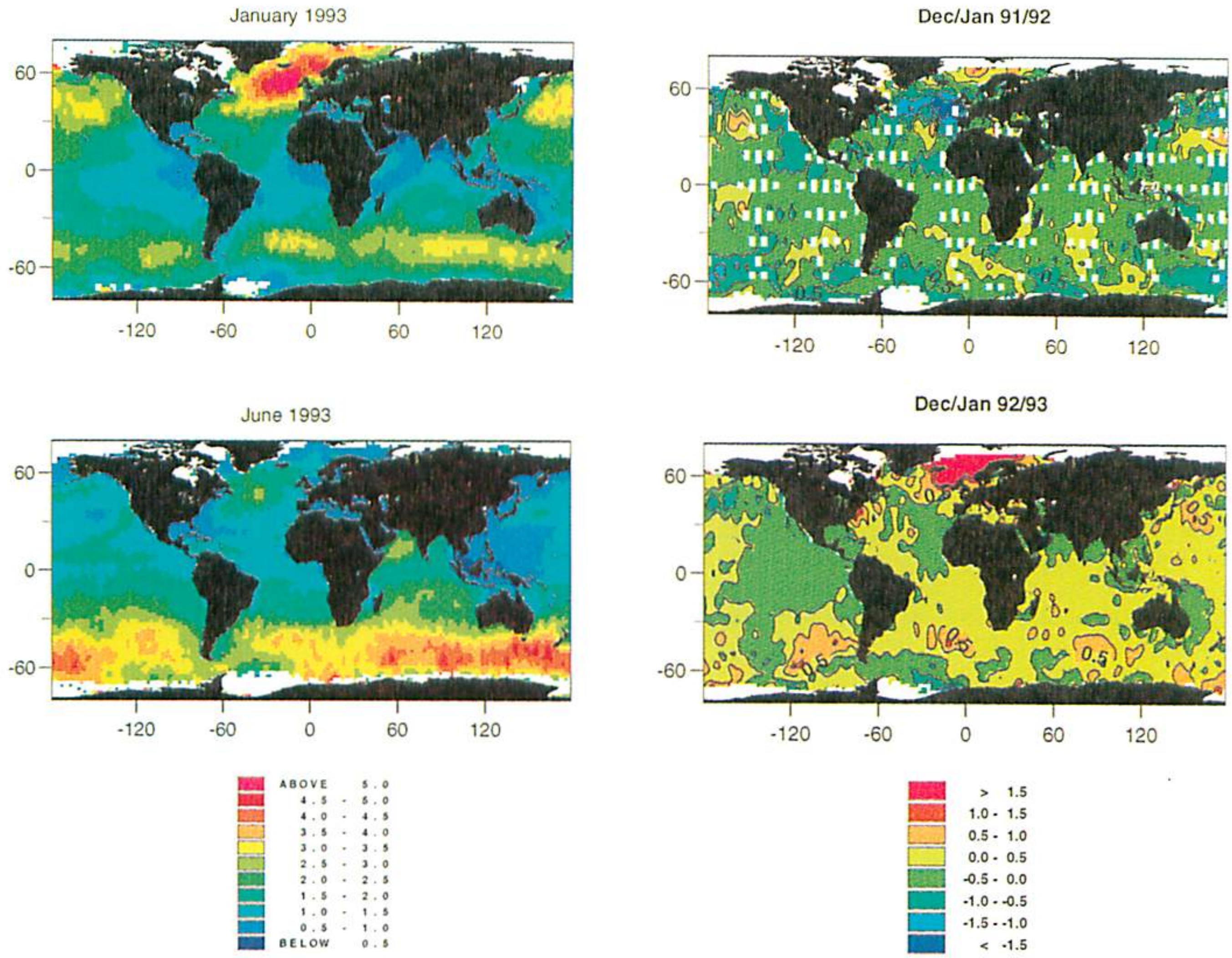


Figure 3.5 Measurement of global ocean wave height using the ERS Radar Altimeter.

a) Seasonal variations in wave height between January and June 1993. The high values shown in the North Atlantic at the start of the year are seen in the Southern Ocean in the middle of the year.

b) The difference in wave climate is shown for two years referenced against an average wave climate retrieved from Geosat data for 1987-88. In 1991-92, for example the lower than average values in the North Atlantic were replaced by higher than average values during the following year.

(Acknowledgment: D.Cotton, James Rennell Centre for Ocean Circulation, Southampton, UK)

3.3 Ocean Fronts and Internal Waves

Regional features in the oceans are of interest for two reasons. Firstly, they are critical components of the climate response of the ocean. Secondly, in many coastal areas and regional seas there are economic pressures which require more detailed investigations of specific phenomena.

Mesoscale dynamical features such as eddies and fronts (at length scales of the order of 50 to 200 km) driven by transient, dynamic instabilities or related to seabed topography, can influence larger-scale transport processes. Eddies develop and influence the horizontal dispersion of chemicals such as nitrates which are essential for biological activity. Understanding the mechanisms by which such features operate and influence large-scale processes is the key to their successful parameterisation in climate models.

Surface slicks evident in SAR images can serve as tracers for delineating surface flow patterns associated with eddies (Figure 3.6). Such slicks may be naturally occurring phenomena associated with algae, or result from chemical pollution such as oil spillage.

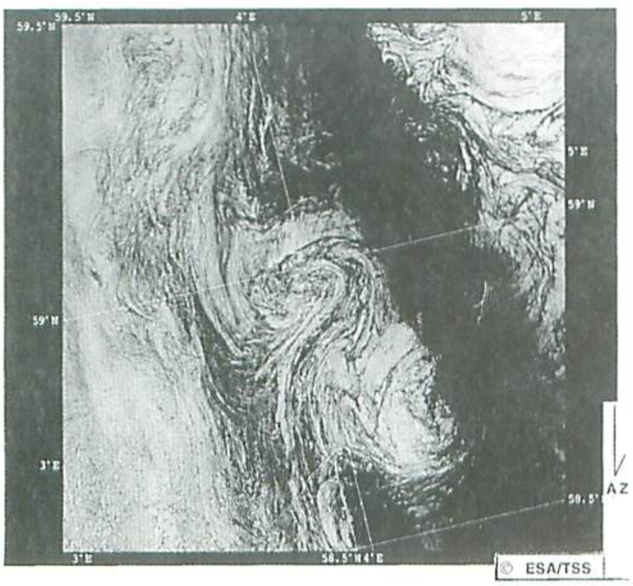


Figure 3.6 ERS-1 SAR image obtained off the west coast of Norway on 6 May 1993 showing a 20 to 30 km diameter cyclonic eddy feature. The spiralling lines are assumed to be the result of a natural surface film at sufficient concentration to dampen out the Bragg waves (Acknowledgment: J.Johannessen et al., 1996).

The combination of SAR and radiometer measurements can be useful for mesoscale ocean circulation studies. Figure 3.7 shows ERS SAR and AVHRR sea surface temperature images acquired on 3 October 1992 off the west coast of Norway. In the AVHRR IR image the surface temperature decreases from nearly 14°C (white) in the coastal water to 12°C (purple) in the Atlantic water offshore. The pattern of the sea surface temperature field (with the curvilinear temperature fronts) represents meso-scale variability of 10 to 50 km, characteristic of the unstable Norwegian Coastal Current (Johannessen et al., 1996). The ERS image, acquired 7 hours later, contains frontal features at a scale, configuration and orientation that are in good agreement with those seen in the IR image. The SAR image shows both bright and dark radar modulations of various widths across the boundaries. It clearly verifies that the SAR can image current boundaries, including meanders.

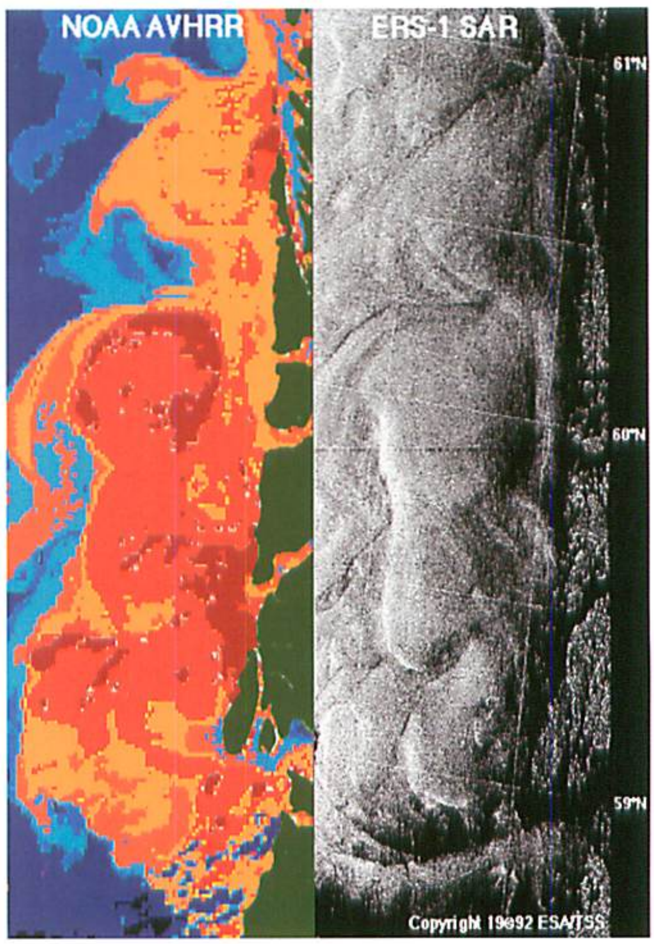


Figure 3.7 Comparison of a 1 km resolution AVHRR image (left) acquired at 1420 hours on 3 October 1992 (white is 14°C and purple is 12°C; land is masked in green and clouds in black) and a 100 m resolution ERS-1 SAR image (right) acquired at 2135 hours on 3 October 1992. Both images cover the same 100 km x 300 km region off the west coast of Norway between 59° and 62°N (Acknowledgment: J.Johannessen et al., 1996).

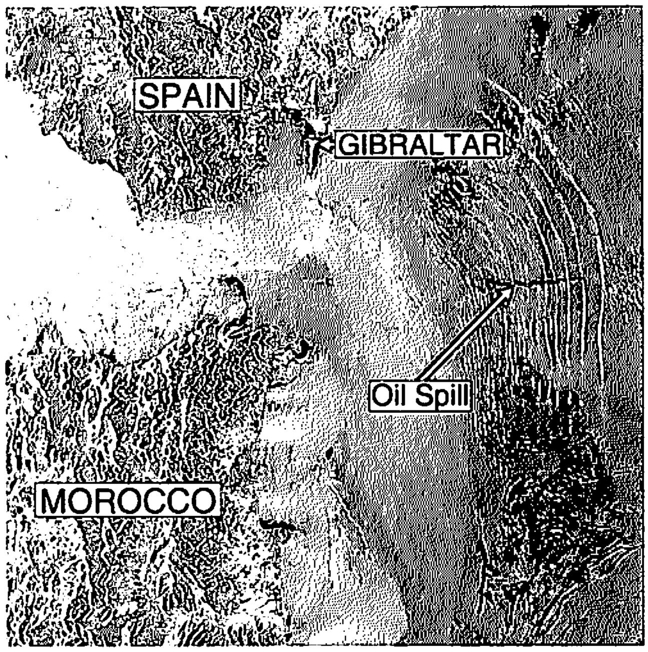


Figure 3.8 An ERS-1 image showing surface roughness patterns associated with an internal wave packet propagating eastwards in the Strait of Gibraltar (Acknowledgment: W.Alpers, C.Bruening, University of Hamburg, Germany)

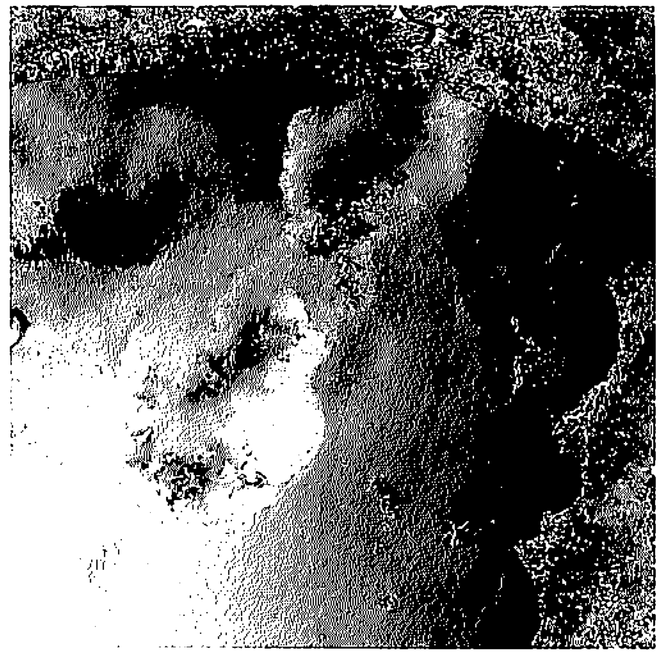


Figure 3.9 ERS-1 SAR image of the Gulf of Thailand showing footprints of thunderstorm clouds (Acknowledgment: Lichtenegger, 1996)

Internal waves are undulations in the interface between layers of water of different density. They are caused by mechanisms such as the flow of water over sills in the Strait of Gibraltar, or tidal currents meeting coastal shelves. Their significance relates to the fact that internal waves can break at the ocean margin. This is an important cause of vertical mixing in the ocean and thus contributes to global water circulation. Observations of the spatial structure and propagation characteristics of internal waves is only possible by using SAR, as it is able to detect the surface roughness signature created by internal waves (Figure 3.8).

3.4 Atmospheric Effects on the Sea Surface

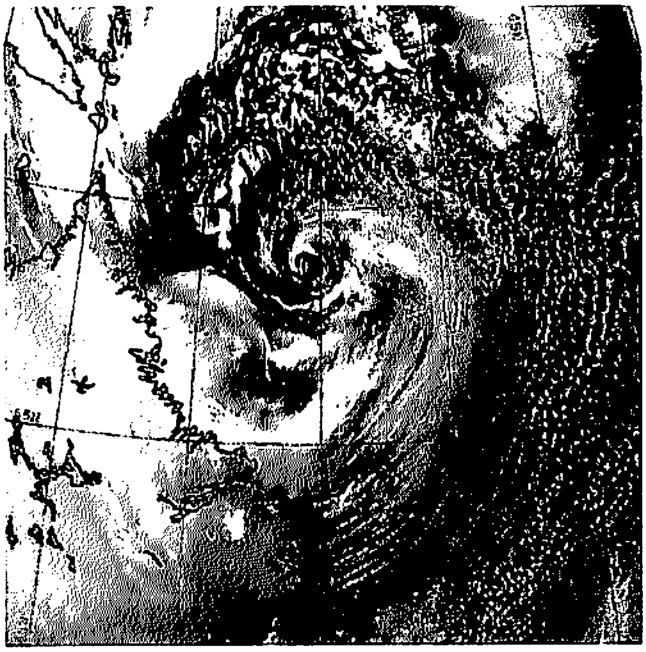
The local variability of sea surface winds can produce distinctive patterns in sea surface roughness patterns which are more readily revealed by SARs such as the ASAR than by optical instruments. ASAR will provide similar images to the ERS-1/2 SAR. The type of atmospheric features seen on images include:

- Tropical cyclones and monsoons
- Storm structures
- Katabatic winds and convective cells
- Atmospheric gravity waves
- Atmospheric boundary layer rolls

Figure 3.9 shows an example from the Gulf of Thailand in which the footprints of thunderstorm clouds are clearly seen (Lichtenegger, 1996). SAR is highly sensitive to changes in surface roughness of the sea caused by the wind (both wind strength and direction). Higher intensity brightnesses are seen where wind downdrafts impact on the sea surface. Zones of sudden change of wind speed and direction, so-called 'wind fronts' outline the presence of single thundercloud cells in the image. By analysing these wind fronts one can identify up to six cloud cells in this particular example.

There are limitations, of course, in the use of SAR for analysing weather phenomena. Such phenomena are only present under certain atmospheric/oceanic conditions, but when identified they allow detailed studies of the atmospheric boundary layer process to be carried out. This is not possible using in-situ measurements, because of lack of sufficient coverage.

This being said, the low resolution modes of ASAR, combined with simultaneous optical data acquisition by MERIS, will offer some important improvements in coverage in comparison with that offered by the ERS satellites. Figure 3.10 provides an illustration of the type of simultaneous SAR and optical large area data acquisition which will be possible. In this example a low pressure system is seen on both a wide swath radar image and a NOAA AVHRR image acquired within 30 minutes of each other. On the SAR image one sees the differences in sea surface roughness associated with the depression, while on the AHVRR image the same feature is depicted through cloud patterns. The scales and projections of the two images differ.



a

b

Figure 3.10 Low pressure system in the north Atlantic on (a) NOAA AVHRR and (b) wide swath SAR images, acquired on March 30, 1997. Area shown is 500 km x 700 km (Acknowledgment: Radarsat Data Copyright Canadian Space Agency/Agence spatiale canadienne 1996. Imagery enhanced and interpreted by CCRS).

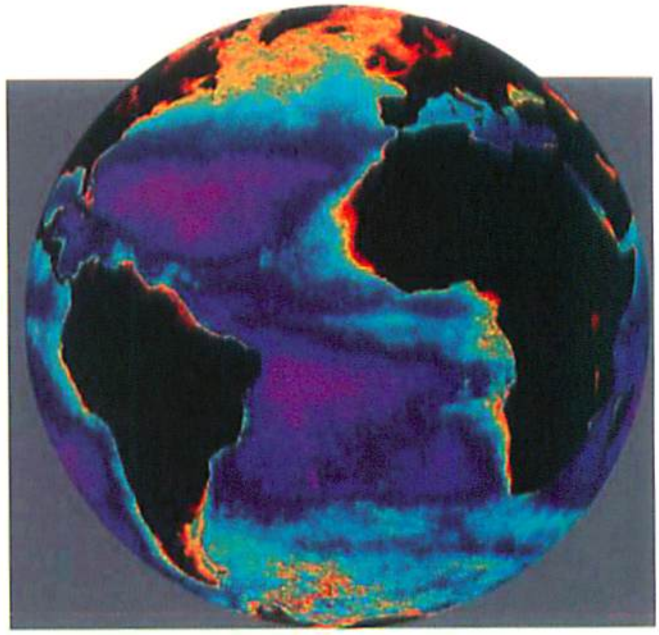
3.5 Ocean Bio-Physical Properties

Open Ocean

There remain major uncertainties about the amount of carbon stored in the ocean and the biosphere, and about the fluxes between these reservoirs and the atmosphere. In particular there is an important need for better information on the spatial distribution of biological activity in the upper ocean and its temporal variability, especially in the case of oceanic phytoplankton biomass, which has an important role in fixing CO_2 through photosynthesis. In the upper layers of the open ocean, chlorophyll concentration is the most convenient index for phytoplankton abundance and this can be measured using the visible part of the spectrum.

"The remote measurement which has caused the greatest interest within the JGOFS (Joint Global Ocean Flux Study) is the estimation of basin and global-scale variability in the concentration of chlorophyll in the upper ocean. The images of the global distribution of these pigments, derived from data taken by the coastal zone scanner (CZCS) on board the United States' Nimbus-7 spacecraft, have revolutionised the way biological oceanographers view the oceans. For the first time, the blooming of the ocean basins in spring has been observed, as has the extent of the enriched areas associated with the coastal ocean." (International Geosphere-Biosphere Programme (IGBP) *A study of Global Change*, Report No. 12, 1990).

Although CZCS, launched in 1978, was intended as a one year proof of concept mission, the sensor continued to transmit data over selected oceanic test sites until early 1986. Figure 3.11 shows examples of CZCS chlorophyll maps of the Earth and the Mediterranean Sea.



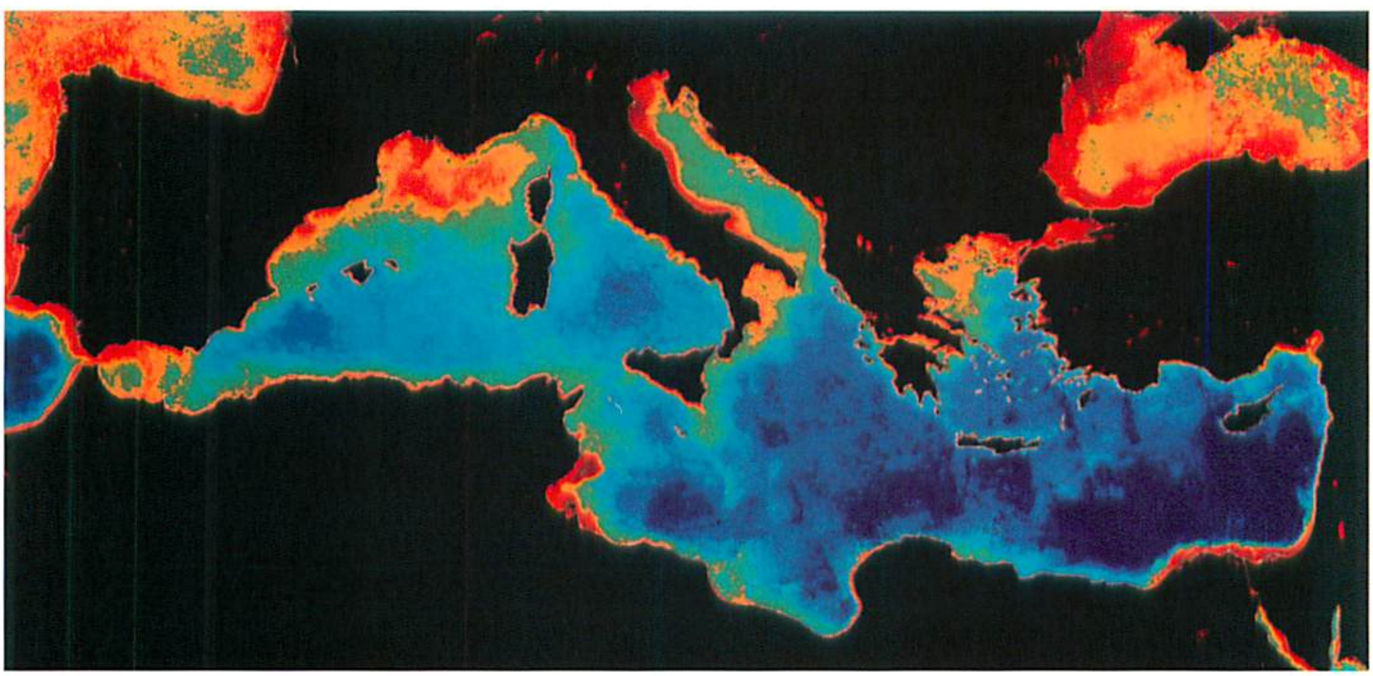


Figure 3.11 CZCS Chlorophyll Maps of the World and the Mediterranean produced by the ESA/JRC Ocean Project.

Remotely sensed information about global ocean colour is now again available, firstly from the OCTS instrument on the Japanese ADEOS mission, from the NASA SeaWifs satellite launched in August 1997 (Figure 3.12) and from the MOS instrument on IRS-3. MERIS will provide data continuity with improved spectral and spatial performance. This results from the use of several near infrared channels to perform atmospheric corrections and several narrow visible channels to compute radiance values.

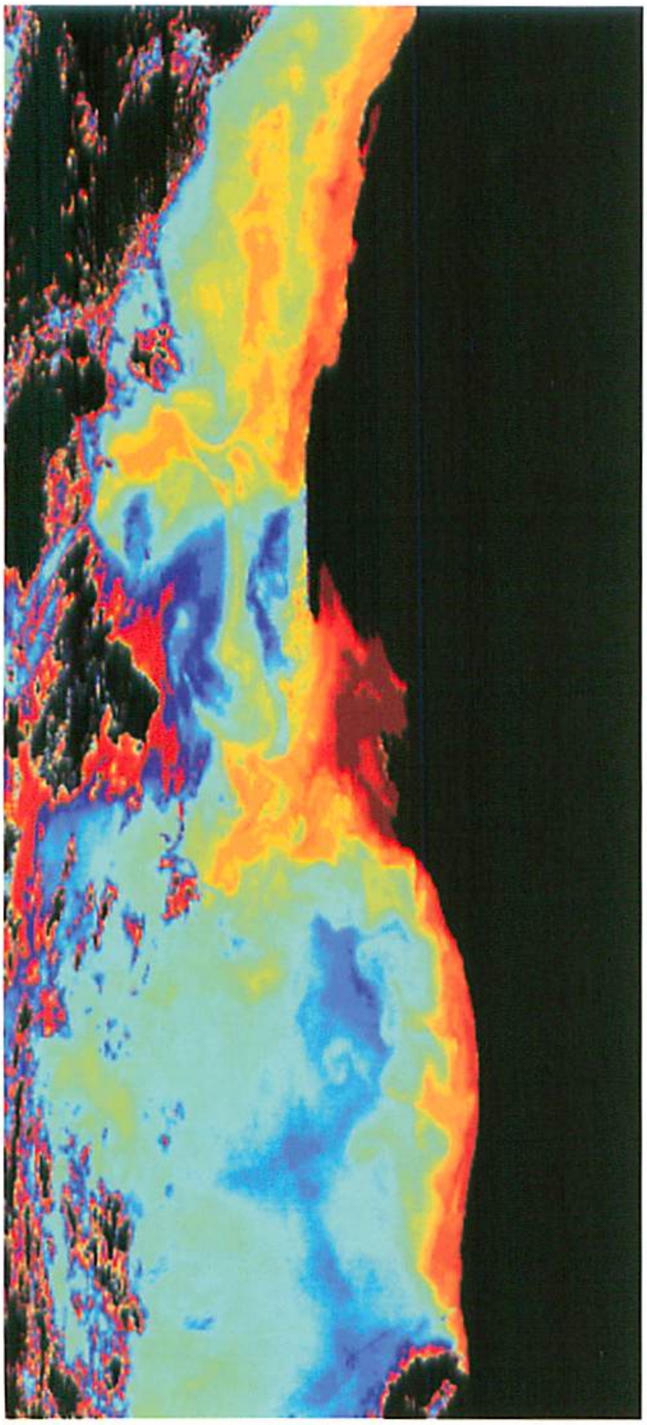


Figure 3.12 SeaWiFs Level 2C Chlorophyll product located south of the Canary Islands off the west coast of Africa (processed by the ESA SeaSHARK system developed by VEGA, UK).
(Acknowledgment: J-M Melinotte, ESRIN)

Phytoplankton abundance varies from less than 0.03 mg m^{-3} in oligotrophic waters (i.e. waters poor in nutrients and therefore in phytoplankton), up to about 30 mg m^{-3} in eutrophic waters (i.e. in nutrient rich waters, supporting high biomass). Ocean colour responds in a nonlinear way to these large changes in chlorophyll content. It is conveniently depicted by the ratio of blue to green radiation backscattered by the ocean, with the ratio which is most sensitive based on wavelengths of 445 and 565 nm. It varies within a range of 1 to 20 for the types of pigments considered, and decreases, almost linearly, with the logarithm of the concentration (Figure 3.13).

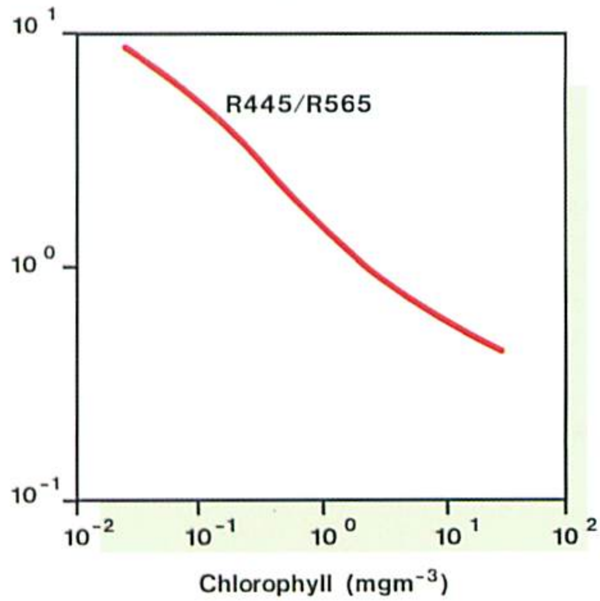


Figure 3.13 Ratio of ocean reflectances at the wavelengths 445 and 565 nm as a function of the chlorophyll concentration for oceanic case 1 waters.

The design of MERIS is driven by the radiometric, spectral and spatial requirements of ocean colour observations, with the aim of identifying 30 classes of pigment concentration over the naturally occurring range. However, since the radiances recorded at the satellite within the visible part of the spectrum are dominated by the atmospheric signal associated with Rayleigh and aerosol scattering and the contribution of the water-leaving radiance to the signal amounts to a few percent in most cases, the sensitivity is essentially determined by the aerosol load. The atmospheric correction is based on the data from several infrared channels, and an extrapolation of this estimate towards the shorter wavelengths. This extrapolated atmospheric contribution is then subtracted from the total signal recorded by the sensor, to obtain the water signal.

MERIS will provide global coverage every three days. Over the oceans it will be operated in a Reduced Resolution (RR) mode, acquiring data at 1200 m resolution at the sub-satellite point, with a swath of about 1150 km. If higher spatial resolution is required a 300 m Full Resolution (FR) mode is available, which is aimed primarily at coastal water and land studies.

No.	Band centre (nm)	Bandwidth (nm)	Application
1	412.5	10	Yellow substance and turbidity
2	442.5	10	Chlorophyll absorption maximum
3	490	10	Chlorophyll and other pigments
4	510	10	Turbidity, suspended sediment and red tides
5	560	10	Chlorophyll, suspended sediment
6	620	10	Suspended sediment
7	665	10	Chlorophyll absorption
8	681.25	7.5	Chlorophyll fluorescence, red edge
9	705	10	Aerosol, red edge transition
10	753.75	7.5	Oxygen absorption reference band, vegetation
11	760	2.5	O_2 absorption R-branch
12	775	15	Aerosol, vegetation
13	865	20	Aerosol
14	890	10	Water vapour, vegetation
15	900	10	Water vapour

Table 3.1 Nominal MERIS Spectral Bands

MERIS is a flexible programmable imaging spectrometer with the capability to observe the Earth over the entire spectral range from 390 to 1040 nm, at a resolution of 2.5 nm. The 15 band configuration with which MERIS will be flown will be finalised during the course of the algorithm development phase though this configuration may be modified further during the commissioning phase. Table 3.1 shows the current nominal set of spectral bands, together with the width of each spectral band, and its main application.

Coastal Waters

The coastal regions are the most populated areas in the world and coastal waters are highly affected by human activities. These marine ecosystems are subject to bio-geochemical forcing, due to the influx into the coastal seas of pollutants from rivers and the atmosphere, which inhibit or stimulate marine productivity. In addition, large amounts of agricultural and industrial pollutants and sewage are discharged into these waters.

Continuous long term observations of coastal waters, which cover more than three million square kilometres, is most important for climate impact studies and for environmental monitoring. Remote sensing measurements from satellite are the only available means for providing us with a synoptic view of such large areas of water.

The major water constituents, which determine the marine and estuarine ecology and the bio-geochemical budget and whose concentration and distribution can be determined by optical remote sensing, are suspended matter, phytoplankton and Gelbstoff.

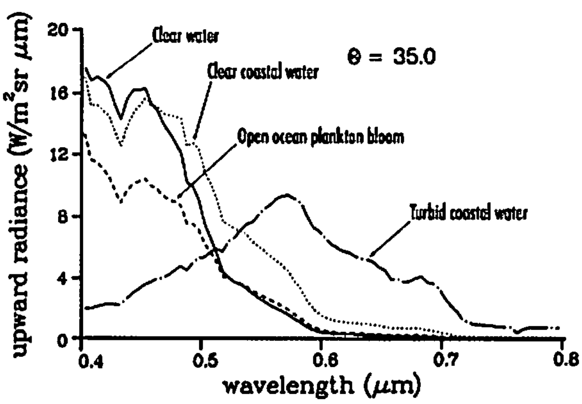


Figure 3.14 Simulated multispectral radiances for a spectral resolution of 5 nm just above the water surface.

Suspended matter is defined as a combination of:

- inorganic particles and detritus, present due to re-sedimentation and advection processes
- atmospheric inputs
- dead material of plankton

Gelbstoff consists of various polymerised dissolved organic molecules which are formed by the degradation products of organisms. These originate in brackish and underground water as well as in extraordinary plankton blooms. All these constituents have different optical properties, but there are similarities in their spectral scattering and absorption coefficients.

The upward radiance at any visible wavelength is composed of contributions from all these substances. Figure 3.14 shows simulated multispectral radiances for different ocean waters. Suspended matter usually enhances the upward radiances through reflection within the visible spectrum, while Gelbstoff reduces these radiances mainly in the blue.

To convert from the optical properties of the water constituents, used in the radiative transfer model, to pigment or suspended matter concentration units, robust algorithms have been developed with global applicability. The accuracy of derived oceanic properties depends strongly on the precision of the atmospheric correction procedure.

The development of inverse modelling techniques for the interpretation of MERIS measurements is an ongoing process. For monitoring coastal regions world wide, precise multispectral radiances, with contemporary optical and concentration measurements of the water constituents, are needed. As well as the chlorophyll concentration and several atmospheric parameters, planned geophysical products include total suspended matter and yellow substance concentration.

3.6 Ocean Surface Temperature

Sea surface temperature (SST) is a sensitive indicator of global climate change. This is due to the thermal inertia of the oceans, which has the effect of damping out short term variations in the climate. In order to capitalise on the oceans as an indicator of climate change it is necessary to acquire global measurements of SST to a high level of accuracy and compile these over a long period of time, e.g.. a minimum of 10 years. The ATSR series of instruments which have flown on ERS-1, ERS-2 and now on Envisat as AATSR, provide both the necessary accuracy, within 0.3 K, and the long term data continuity (Figures 3.15 & 3.16).

The contribution of AATSR data has to be seen in the context of the collection of SST measurements which have been compiled over the past 150 years using a variety of measurement techniques. AATSR data provide the opportunity to validate existing models using an unbiased external source and thereby increase the confidence which can be placed in long term assessments of climate change.

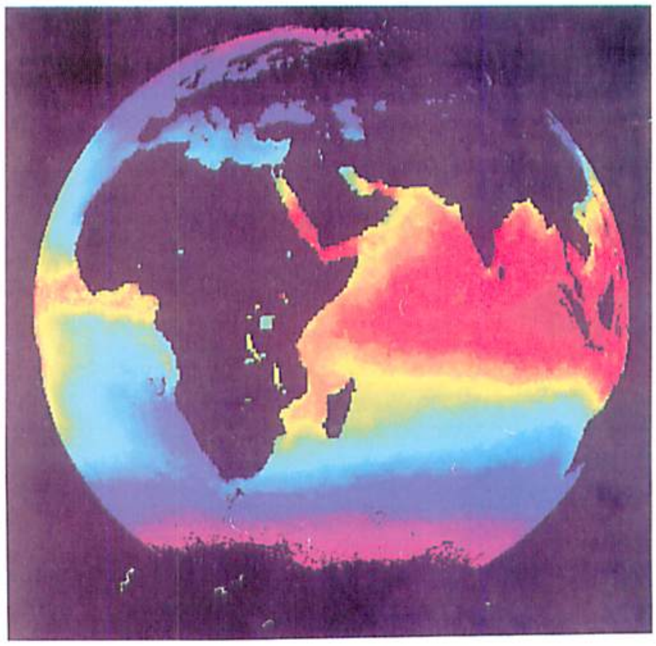


Figure 3.15 Image Global ATSR data averaged for one year (Acknowledgment: Rutherford Appleton Laboratory, Didcot, UK).

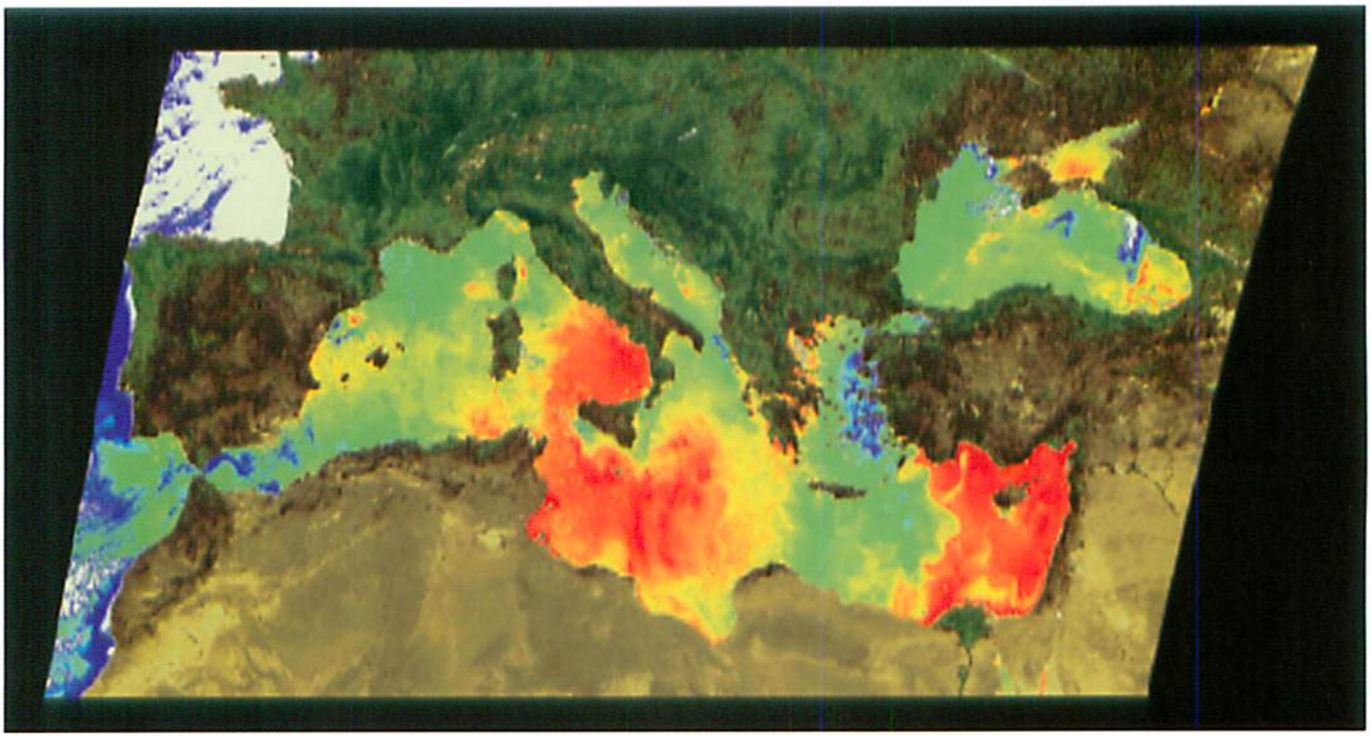


Figure 3.16 Daytime SST of the Mediterranean Sea for August 1997 from ATSR data. (Acknowledgment: J-M Rosaz, ESRIN)

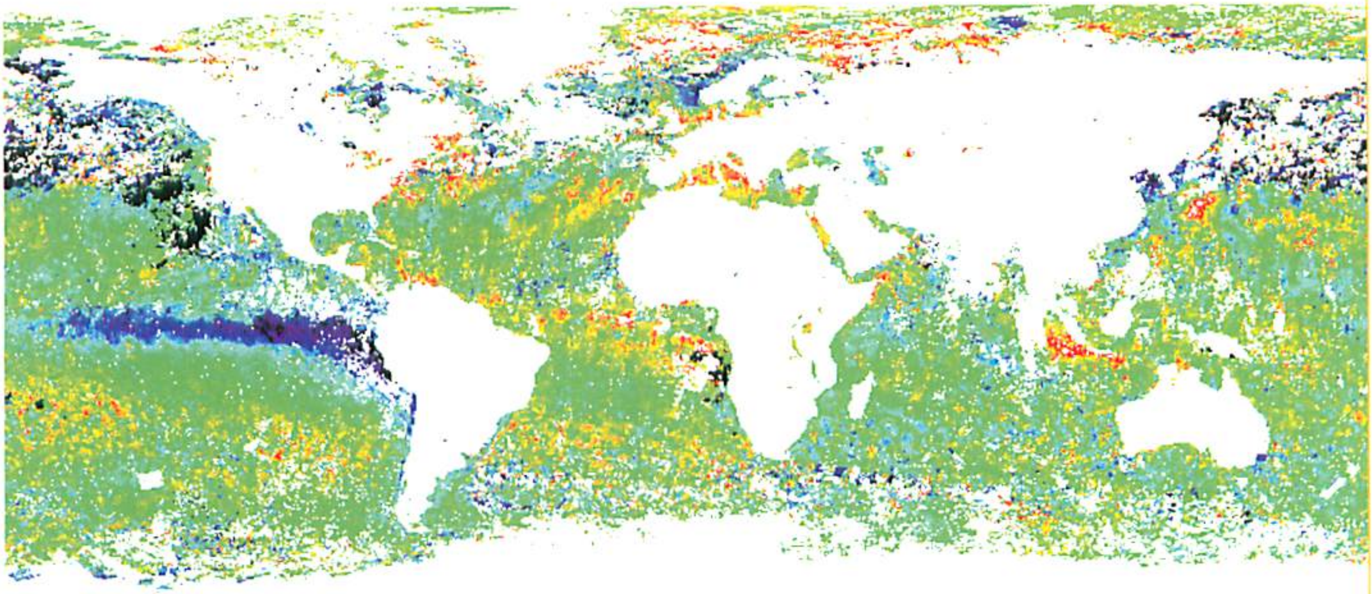


Figure 3.17 Global SST differences between July 1995 and July 1997, showing temperature increase of 3° - 6°C in the eastern Pacific (in blue) (Acknowledgment: P. Goryl, ESRIN)

Interactions between the atmosphere and the circulation of currents around the globe involve the transfer of vast amounts of energy which can only be effectively monitored by remote sensing from space. AATSR will continue to increase knowledge of the processes reflecting the way in which the oceans, as reservoirs of heat, dominate the weather systems which are critical to life on the planet. A good example is the El Niño anomaly in the tropical east Pacific, where a change in atmospheric circulation is reflected in the pattern of SST distribution in this area (Figure 3.17). In addition to changes in the local and global climate, there are more specific impacts of El Niño, for example, the way the economic life style of populations in adjacent countries is affected through the wholesale displacement of fishing grounds. The accuracy of AATSR data makes it a unique source of information for this type of research.

Sea surface temperature information helps resolve many phenomena associated with the ocean circulation, such as mesoscale eddies, meanders, coastal currents and up-welling.

AATSR data are applicable to research into fishing as a global source of nutrition for an ever expanding human population. The propensity of fish to be found at fronts between warm water and cold upwelling water containing food sources, demonstrates the value of SST measurements derived from AATSR. Moreover, the analysis of SST trends can be of assistance in deriving information on the migration of marine species. Pre-operational fishery support systems have been developed, for example ESA SeaSHARK for processing SeaWiFS and AVHRR data.

3.7 Coastal Bathymetry and Sediment Movements

Knowing the shape of the sea floor is vital for shipping, fisheries and off-shore activities. It is also needed for the calibration and validation of morphodynamic models which are being developed to forecast changes in sea-bed topography linked with sediment transport, river deposition and coastal erosion. Traditional bathymetric surveys conducted by ship are time consuming and expensive. Assessments have shown that the efficiency of bathymetric surveys can be improved by combining traditional measurements and models with SAR data. SAR images of the water surface can be used to estimate the shape of the sea bed in shallow waters, typically less than 30 m deep. Interactions between tidal flows and the sea floor cause modulations in the surface current velocity. These modulations lead to local variations in the spectrum of short gravity waves at the ocean surface or the surface roughness, which show up as intensity variations in SAR images.

3.8 Oil Slicks

Oil pollution of the ocean is of major international concern because it can have a devastating effect on fragile marine and coastal habitats. Monitoring illegal discharges and the early detection of events leading to accidental damage is an important component in ensuring compliance with marine protection legislation and the general protection of coastal environments. By contrast, natural oil seepages on the sea surface are of special interest to oil exploration companies.

The use of radar for detecting oil slicks is well established, with airborne surveillance radar having been used since the late 70's by many countries with jurisdiction over large maritime areas. In comparison with the aircraft operations, satellite SAR offers considerable extension in coverage and cost advantages. The use of ERS SAR for oil slick detection is now an important operational application.

Radar backscatter from the sea surface is related to the roughness of the sea surface. The presence of spilled oil causes a dampening of the short gravity waves, resulting in a detectable signature in ERS SAR images. However, the sensitivity of these waves to the prevailing wind influences the detection capability. Wind speeds lower than about 2-3 m/s fail to produce sufficient surface roughness in the surrounding sea to contrast with the oil, while high winds will result in increased backscatter from the spill area, reducing its contrast with the surrounding sea. Furthermore, at high wind speeds (typically above 15 m/s) the oil is washed down by the waves and the spill can disappear below the surface. Evidence also suggests that the wind-speed range, in which reliable detection is possible varies depending on the SAR parameters, as well as on the type of oil and the age of the spill.

A large study of oil pollution in the Mediterranean Sea using ERS data (Pavlakis et al. 1996) demonstrates the value of spaceborne SAR for monitoring and policing marine pollution. Figure 3.18 shows the shapes of some of the detected spills, while Figure 3.19 is a map of the 190 SAR scenes analysed and the location of the detected spills. The shapes of many of the detected spills are indicative of leakages or bilge-water discharges; none of the spills detected on ERS images corresponds to a reported ship incident.

Figure 3.18 Typical shapes of detected spills on the corresponding ERS-1 SAR orbits and frames
(Acknowledgment: Pavlakis et al. 1996).

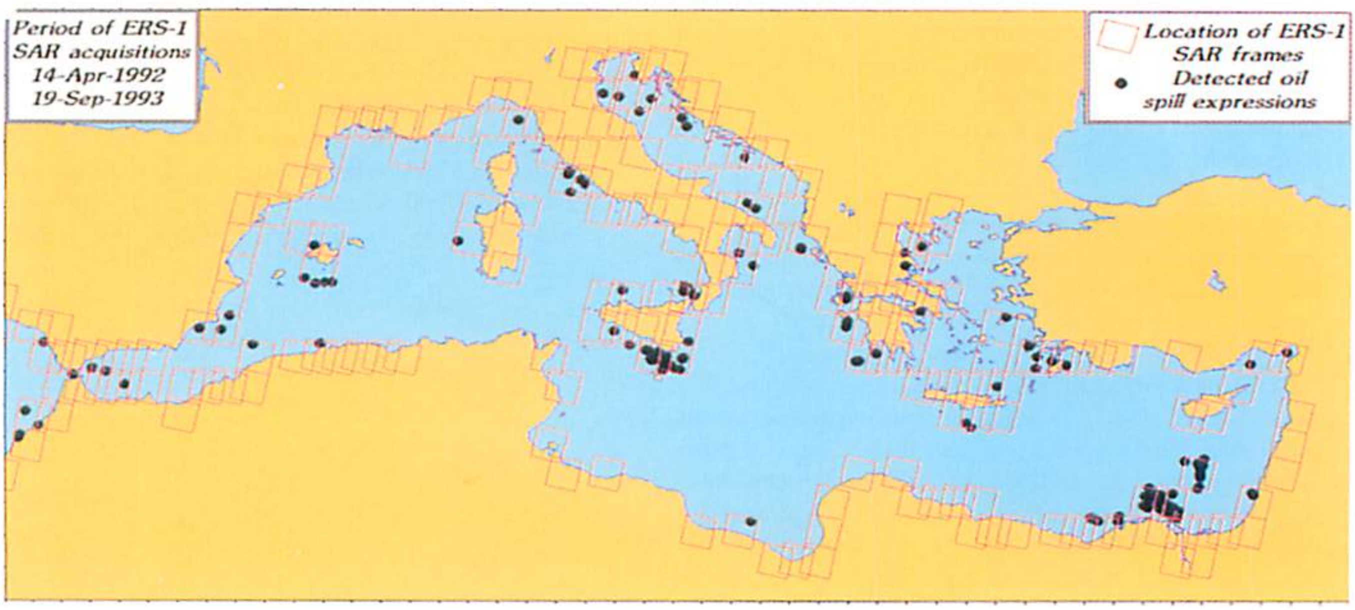


Figure 3.19 Frames of the interpreted ERS-1 SAR images and the detected spills (Acknowledgment: Pavlakis et al., 1996)

ASAR will have a much improved capability for oil slick monitoring, because of its higher sensitivity in the far range. Wide Swath Mode is of particular interest, because of its potential for more frequent large area coverage than Image Mode. It has been difficult to justify the development of operational surveillance systems based on the 35 day repeat cycle of ERS. The 3 day repeat possible using the Wide Swath Mode is much more appropriate. Some of the operational systems currently used for ERS data employ techniques to reduce the spatial resolution from 25 m to around 100 m, so the 150 m resolution in Wide Swath Mode is expected to be appropriate for this application. The optimum polarisation will be VV, because there is less contrast between slicks and the ocean with HH polarisation.

3.9 Ship Traffic

The ERS programme has demonstrated the potential of SAR data for ship detection and prototype systems have been developed, not just to identify ships automatically, but also to distinguish between different types of vessel and to determine the speed and direction of motion. However, ship detection with ERS data was limited because of the low incidence angles.

ASAR will have improved capability because of the higher incidence angles and dual polarisation. As illustrated in Figure 3.20, ERS roll-tilt mode images, obtained at high incidence angles are better for the detection of large ships and fishing vessels. Outer ASAR standard beams, therefore, will be best for ship detection, although this is countered somewhat by the fact that imaged swaths become narrower at higher incidence angles. Also, cross polarised images in the Alternating Polarisation Mode should further improve detection capability at steeper incidence angles.

Figure 3.20 ERS roll-tilt image (i.e. incidence angle range 33° to 37°) showing ships in the North Sea close to Rotterdam harbour. This image, produced by the ASAR generic processor, shows the expected ASAR performance at higher incidence angles. (Acknowledgment: P. Lim, P. Meisl, MDA)

4. Land

The Earth's land surface is a critical component of the Earth system as it carries over 99% of the biosphere. It is the location of most human activity and it is therefore on land that human impacts on the Earth are most visible. Within the biosphere, vegetation is critical as it supports the bulk of human and animal life and largely controls the exchanges of water and carbon between the land and the atmosphere.

Observations of the land surface by Envisat will allow the characterisation and measurement of vegetation parameters, surface water and soil moisture, surface temperature, elevation and topography. Global scale measurements (1 km resolution) will provide critical data sets for improved climate models, in particular estimates of albedo, vegetation productivity and land surface fluxes.

Envisat also provides managers of local natural resources with a capability to monitor their land with detailed (selective) observations on a monthly basis. In particular, ASAR provides 30 m spatial resolution multi-look images for monitoring economically important land units, such as agricultural fields and forest compartments. Natural resources can also be monitored at global and regional scales every few days using the low resolution imaging of MERIS, AATSR and the ASAR Global Mode.

The relatively high frequency of global coverage provided by Envisat is also of great value for hazard monitoring, in which locally infrequent events such as earthquakes, volcanic eruptions, floods and fires, require intensive observation over short periods. The beam steering mode of ASAR (in conjunction with its independence from cloud and illumination conditions) will also permit (at least) 3-day repeat observation of certain localised events at high spatial resolution. Whilst locally rare, certain natural hazards are frequent events on a global scale, thus they can have substantial effects on climate, especially large vegetation fires and volcanic dust clouds. Hazard monitoring is therefore an important component of the Envisat mission.

4.1 Global Land Cover

A major scientific uncertainty in global change research is the cycling of carbon in the Earth system. It is well known that CO_2 contributes to the greenhouse effect and that over the last few centuries increased human activity, especially the burning of fossil fuels and deforestation, have resulted in an increase in the release of CO_2 into the upper atmosphere. Much of the estimated anthropogenic CO_2 emission cannot currently be accounted for, indeed there is an order of magnitude uncertainty in the global carbon budget.

Critical to this carbon accounting activity is global vegetation monitoring. Figure 4.1 shows a global land cover product, and Figure 4.2 a forest map of S.E Asia, both derived from 1 km AVHRR data. The narrow bands of MERIS will make it possible to derive more accurate global maps and more effective vegetation indices than have previously been available. From physically based vegetation indices it is then possible to retrieve key variables in modelling plant productivity (and thus carbon sequestration), surface-atmosphere gas exchanges and energy transfers at the land surface.

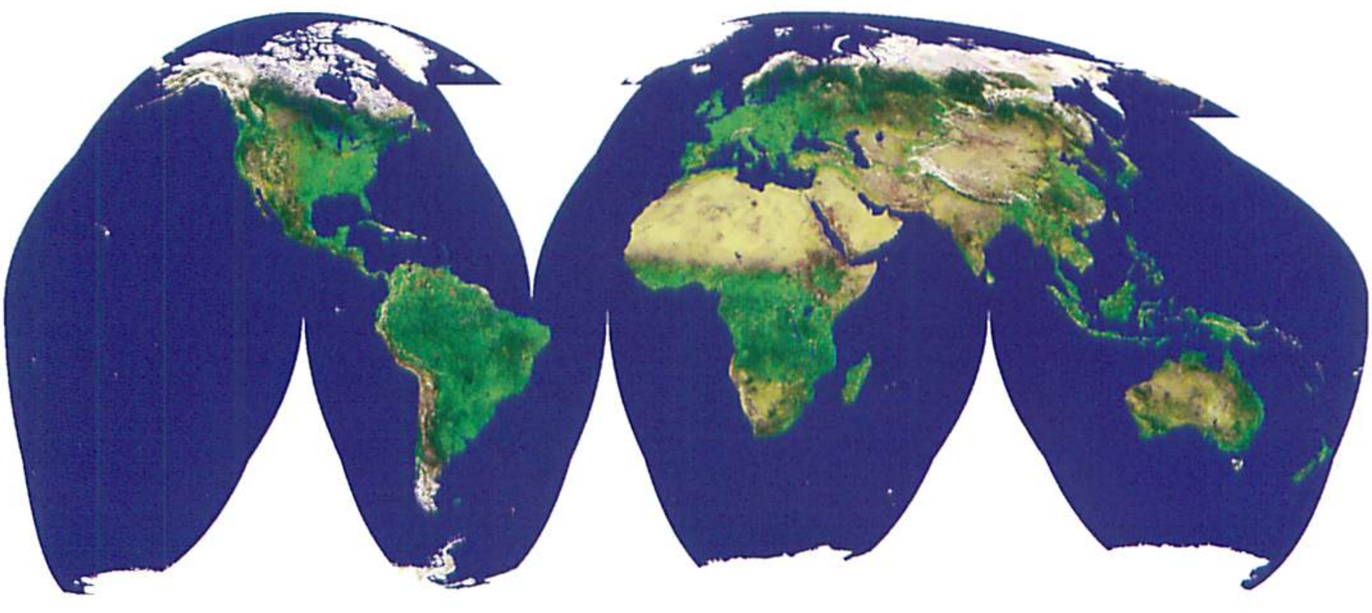


Figure 4.1 Global land cover map (Acknowledgment: IGBP Global Landcover Project)

Figure 4.2 Forest map of South-east Asia (Acknowledgment: JRC/ESA TREES Project.

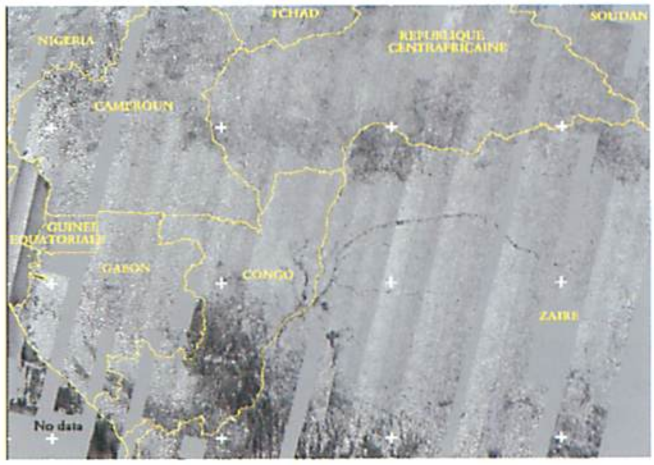


Figure 4.3 ERS-1 SAR mosaic of Central Africa (Acknowledgment: JRC/ESA TREES Project).

For practical reasons (e.g. obtaining sufficient cloud free coverage on a seasonal basis), global vegetation monitoring is based on low resolution (1 km) data. However, vegetation products (such as land cover, leaf-area index and biomass) at this resolution cannot be validated directly and this is usually done by scaling up data collected at higher resolution on a sample site basis. The availability of contemporary data sets at resolutions of 1000 m from AATSR, 300 m from MERIS and 30 m from ASAR, is thus of key importance in producing and validating global vegetation products.

ASAR data and products developed from the Global Monitoring and Wide Swath Modes will be of particular interest for obtaining large area coverage and in improving temporal coverage in cloudy areas. Figure 4.3 shows an ERS SAR mosaic of central Africa, which will be produced from only 4 or 5 Wide Swath scenes at 150 m resolution. Currently there are few robust techniques available to determine vegetation parameters from ASAR, particularly at regional or global scales. One of the main issues here concerns the changes in incidence angle across the 405 km swath, and whether or not this will have a serious impact on the utility of the data.

The potential value of Global Monitoring Mode is indicated by previous work carried out over land, using the ERS Wind Scatterometer at 50 km spatial resolution. Figure 4.4 shows how the ERS Wind Scatterometer has been used to monitor seasonal variations in vegetation over the African continent.

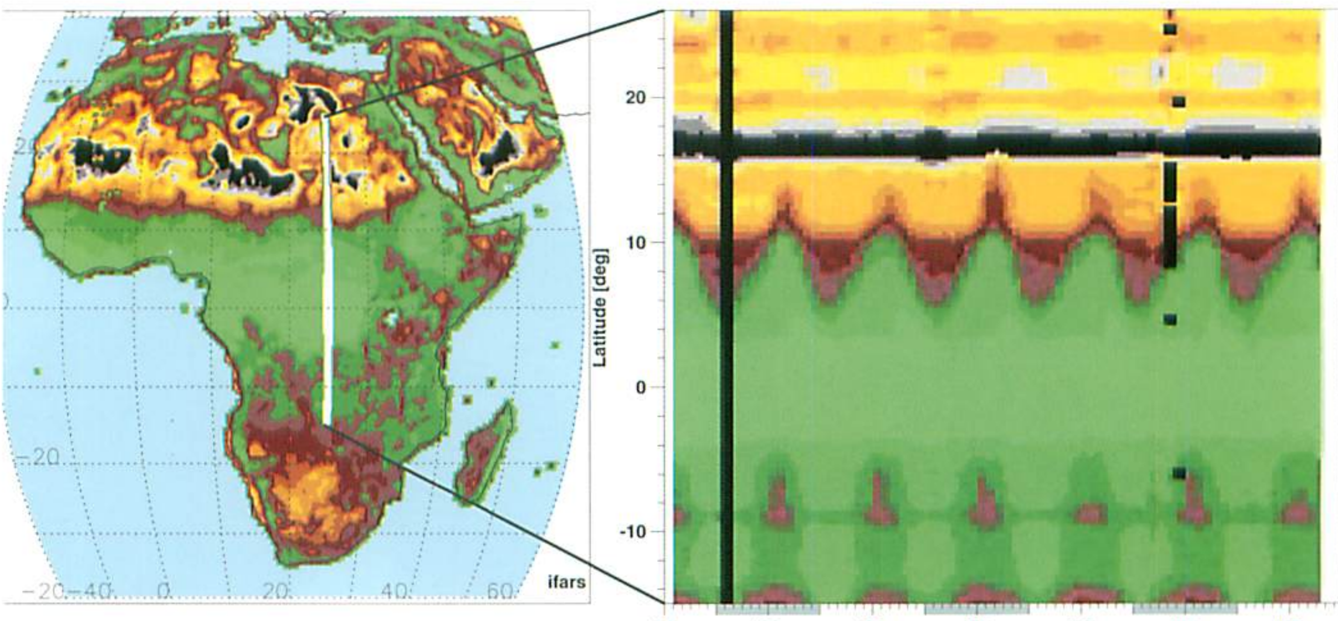


Figure 4.4 ERS-1 scatterometer map of Africa and a Hovmoeller diagram for a slice through Africa from 35° N to 35°S at the longitude of 20°E. Monthly averages are plotted for 1991 to 1997 (Acknowledgment: V.Wismann and K. Boehnke, IFARS, Germany, 1997).

Besides the scatterometer image, the so-called Hovmoeller diagram shows a slice through Africa from 35°N to 35°S extending longitudinally from 20° to 26°E. Monthly averages of the radar intensity are plotted for 1991 to 1997. The predominant signal in the Hovmoeller diagram is the annual variation in radar backscatter in the savanna regions north and south of the rain forest and it can be seen how the seasonal backscatter patterns are repeated every year. The much better resolution of the ASAR Global Monitoring Mode will provide a significantly better capability for such continental or regional scale measurements.

4.2 Local Land Cover

For local land-cover mapping, ASAR high resolution products will continue the role already established for ERS SAR in complementing conventional optical images from other satellites, particularly under poor solar illumination conditions or in cloudy areas.

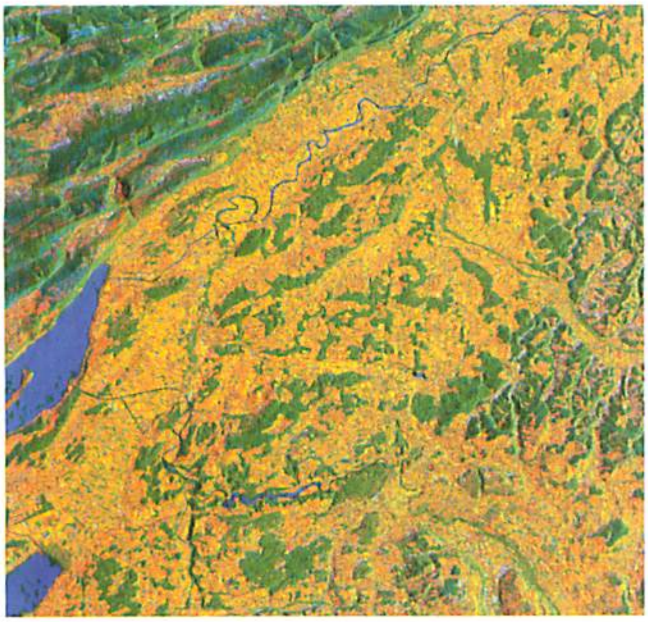
The new features of ASAR include image acquisitions at multiple incidence angles and with dual polarisation, which will open up new possibilities in land-cover classification from SAR.

Figure 4.5 provides an illustration of the use of multiple incidence angles to improve land cover discrimination for an area (18 x 17 km) near Oxford, UK. In this case 3 Radarsat images, taken within a period of 10 days have been combined (Blue - 23° - 23 March 97, Green - 37° - 13 March 97, Red - 43° 3 March 97). Most of the coloured areas on the image, indicative of backscatter differences related to incidence angle, are bare soil fields, while grassland, woodland and urban areas tend to have grey tones, showing a similar backscatter at the different incidence angles. In the northern half of the area, which has clay soils, practically all bare soil fields have a blue colour indicating higher backscatter at the lowest incidence angle, as one would expect. In the southern half of the area which has chalk soils, some of the bare soil fields also have blue colours, but some of the fields coloured red are also bare soil fields and this seems somewhat of an anomaly. Possible explanations are that these fields have marked differences in soil roughness, or possibly that cultivation changes took place during the period over which the 3 images have been acquired.

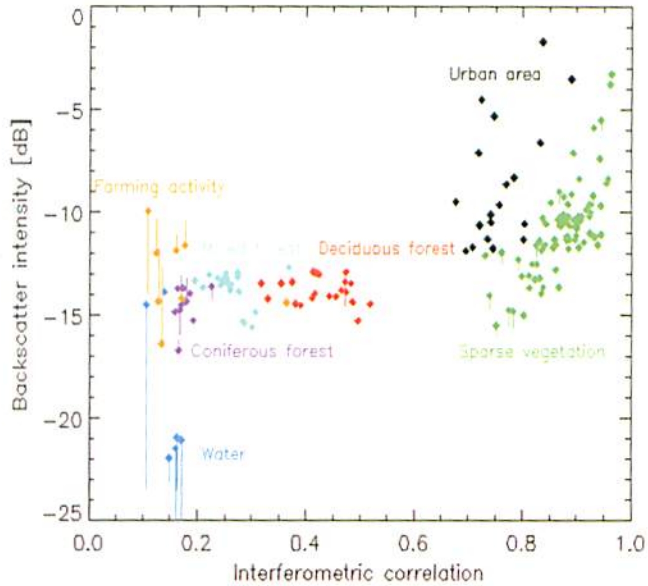
Figure 4.5 Multi-incidence angle composite for Thames, UK, produced from 3 Radarsat images (Blue: 23° 23 March 97, Green: 37° 13 March 97, Red: 43° 3 March 97) (Acknowledgment: Remote Sensing Applications Consultants, Alton, UK & Radarsat Data Copyright Canadian Space Agency/Agence spatiale canadienne 1997).

There will be further developments in the use of interferometric coherence for land cover classification, which was established within the ERS programme (ESA SP-406, 1996), although the availability of only 35 day repeat data will be a limitation. Figure 4.6 shows some results obtained by the interferometric analysis of ERS data acquired 3 days apart in November 1991. Figure 4.6a shows a colour composite comprising a red channel which is proportional to the coherence, a green channel which is a mean intensity image, and a blue channel which is the intensity difference between the 2 images.

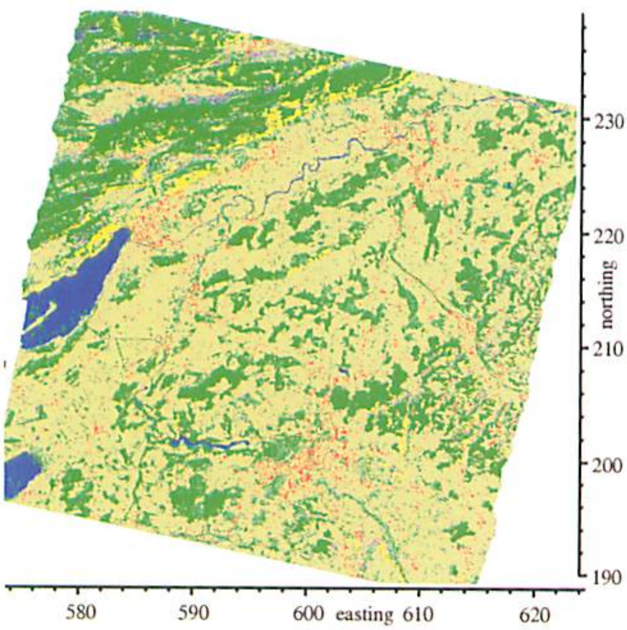
In Figure 4.6b the plot of backscatter intensity against interferometric coherence illustrates clearly the discriminatory value of coherence, with agricultural and forested land having very low coherence in comparison with urban areas, and some separability between deciduous and coniferous forest. The land use map in Figure 4.6c shows land classes such as lakes, urban, forest and agriculture, identified with 90% overall classification accuracy. The classification was obtained by combining the mean intensity, the intensity differences and the coherence image (Wegmueller et al, 1995).



a. RGB interferometric image



b. plot of backscatter intensity against interferometric coherence



c. land cover classification

Figure 4.6 Interferometric analysis of ERS-1 data acquired on 24 and 27 November 1991 over the Bern test site (U. Wegmueller et al 1995)

4.3 Soil and Land Surface Properties

Information on the state of soil and land surface is critical for many purposes: global climate modelling, monitoring ecosystem dynamics, hydrological forecasting, water resources management, agriculture and forestry. Important instruments for measuring land surface properties at a global or regional level are the ASAR (in Wide Swath and Global Monitoring Modes), MERIS, AATSR and MWR.

Hydrology

Hydrology in particular will benefit from Envisat, as detailed spatial and temporal information on a wide range of land surface parameters is required in order to run physically based models and management scenarios. Major variables which can be derived from Envisat observations include land surface temperature, vegetation state, soil moisture, surface roughness and terrain. Much hydrological modelling is based on gridded data at around 1 km. Because of its narrower bands and improved radiometry, MERIS may be better suited for providing vegetation parameters for hydrology than other instruments such as AVHRR. Some hydrological applications require information on snow cover distribution and snow-water equivalent (see Section 5.4). Research is required on how to derive these variables from ASAR data at high incidence angles, particularly in mountainous terrain.

Land Surface Temperature.

Physical relationships link the land surface temperature (LST) to the evapotranspiration of vegetation canopies. Earth observation provides a unique source for global LST measurement.

It is expected that AATSR will make a significant contribution to the measurement of LST to the required accuracy of, typically, 1 K. The AATSR LST algorithm will rely only on nadir AATSR split window radiances. Further research is required before the forward view AATSR data can be reliably incorporated into the algorithm.

Soil Moisture and Roughness

Previous research has demonstrated the relationship between soil moisture and SAR backscatter across a range of soil conditions (Le Toan et al, 1993). The use of multi-polarised and multi-incidence angle data available from ASAR should increase the accuracy of soil moisture retrievals at high resolution by reducing the effect of surface roughness and vegetation. There is however a constraint that the multi-angle images must be acquired within a short time period.

For regional/global soil moisture monitoring, the much improved revisit capability of the ASAR Wide Swath and Global Monitoring Modes (in comparison with what is possible with ERS in a standard 35 day orbit) is of particular interest. Figure 4.7 shows simulated Image, Wide Swath and Global Monitoring Mode images for an area of 20 x 17 km near Oxford, UK. This illustrates how land cover discrimination becomes progressively more difficult with decreasing resolution. Although the field pattern disappears from the Global Monitoring Mode image it is still possible to identify land cover units which might provide the basis for monitoring soil moisture changes (Zmuda et. al. 1997).

Lake Levels

Closed lakes provide a potential indicator of regional climate change. The enhancements in range gating provided with RA-2 will allow more effective monitoring of lake levels around the world, because this will eliminate the 'loss of lock' over small lakes which was experienced with the simpler ERS Altimeters.

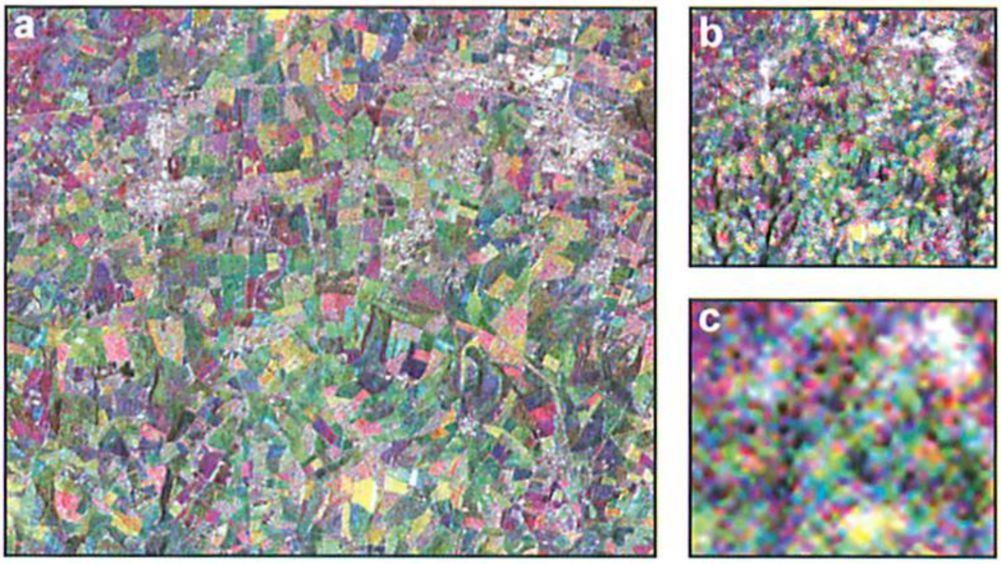


Figure 4.7 Simulated multi-temporal ASAR images:
a. Image Mode, b. Wide Swath Mode, c. Global Monitoring Mode
(Acknowledgment: Remote Sensing Applications Consultants, Alton, UK).

4.4 Agriculture

The control of subsidies at the field level using satellite remote sensing has become an operational activity in Europe. Inventory and estimation of agricultural yields at a national and international level has had a poorer take-up, but is becoming more operational, particularly in developing countries. ASAR provides important data for this, with supporting products also coming from MERIS and AATSR.

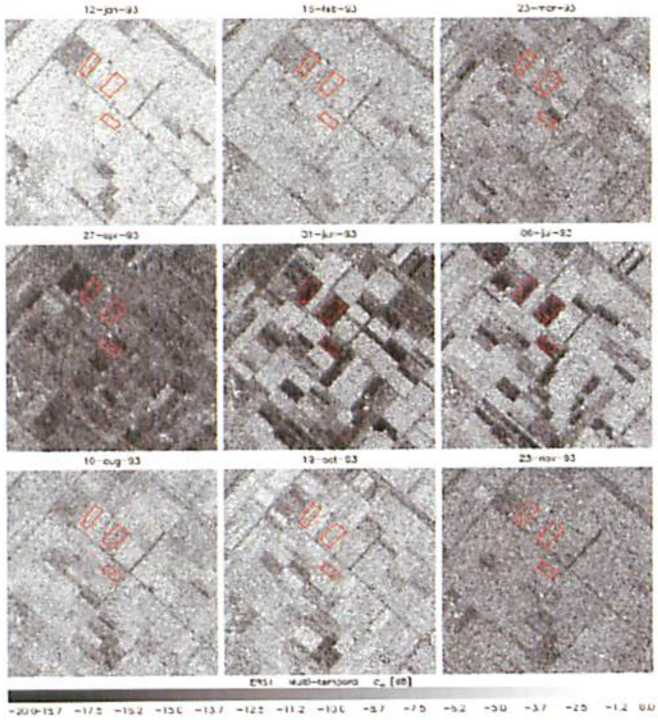
The ERS programme has demonstrated the ability of satellite radars, independently of weather conditions, to identify crops and monitor seasonal land cover changes. Multi-temporal techniques are used, which involve the collection and analysis of SAR data on a series of different dates over the period of interest.

Figure 4.8 shows a sequence of 9 ERS SAR images (each 3.75 km x 3.75 km) taken over the crop growing season (January to November 1993) in Flevoland, The Netherlands, and the corresponding backscatter temporal profiles for the three winter wheat fields highlighted. Research carried out with ERS data has shown that many crop types have distinctive temporal profiles which can be used successfully for crop classification purposes. ERS data are now being used operationally within major European programmes concerned with agricultural statistics (MARS STAT) and the control of agricultural subsidies (MARS CAP). Within MARS STAT the use of ERS data has improved the estimation of crop area early in the crop growing season. ERS data are used as a substitute for optical data in the MARS CAP control activity when cloudy conditions are encountered at key times during the crop growing season.

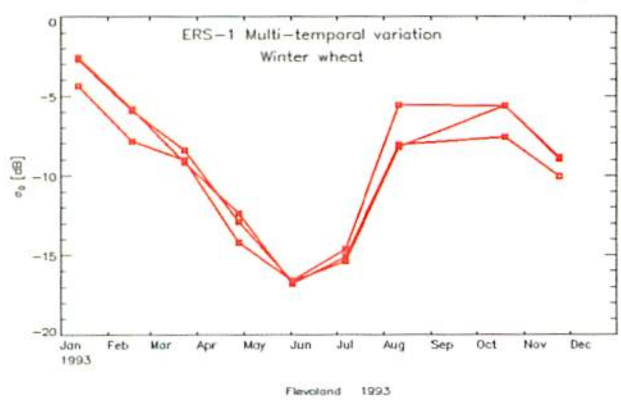
The use of ERS data for rice mapping in south-east Asia is becoming a commercially important area of application. Rice fields have a distinctive appearance on multi-temporal SAR images, based on the fact that fields have a very low backscatter when flooded, and then increase significantly during the reproductive and ripening phases (Figure 4.9). High mapping accuracies have been achieved using ERS data, which should be improved further using Envisat dual polarisation data.

For development of agricultural applications there is an established requirement for multi-temporal data for the identification of major crop and cover types and from which backscatter models of crop type, area, height and condition can be developed. ASAR Image Mode offers data continuity with the ERS SAR for these applications, enhanced by the availability of variable incidence angles (giving possibilities for increasing temporal coverage) and dual polarisation.

Improvements in the accuracy of crop identification, in the number of crops which can be identified and in assessing crop condition will increase the size of the market for which such products are of interest. However, this is dependent on more research to assess the use of different polarisation combinations for a range of crops and for key periods during the growing season. The use of different ASAR incidence angles will improve the selective observation of vegetation (high incidence angles) or underlying soil characteristics (low incidence angles).



a Time Series



b Temporal Backscatter Profiles

Figure 4.8 Time series of ERS-1 images covering (a) the crop growing season, and (b) temporal backscatter profiles for the 3 winter wheat fields highlighted, Flevoland, The Netherlands (Acknowledgment: M.Borgeaud, ESTEC)

Figure 4.10 is a simulated alternating polarisation image (HH/VV) produced using ERS and Radarsat images taken one day apart, for an area (20 x 17 km) in Oxfordshire, UK. In this example a large number of agricultural fields are seen to have a blue colour which is indicative of a high backscatter in HH polarisation in comparison with VV. Since these are all cereal fields, this provides a good indication of the value of alternating polarisation images for improving crop classification. Over the remainder of the image, urban areas, woodland and grassland all have grey tones indicative of no significant differences in HH and VV backscatter.

Mapping the area of crops, for the policing of subsidies and crop area inventories, is expected to continue as a primary application to be supported by Envisat. However, yield estimation techniques will also be improved through the availability of Envisat data. Regional yield estimation has been previously accomplished by exploiting the temporal curve of vegetation response obtained from satellite borne instruments such as AVHRR which have low spatial resolution but frequent revisit capability. This information is compared with previous years and combined with meteorological data and crop growth modelling to predict year-on-year yield variations.

MERIS will greatly improve the quality of the spectral information compared to AVHRR, as its spectral bands are narrower and less sensitive to atmospheric effects. MERIS calibration and atmospheric correction is also more accurate than AVHRR, and the spatial resolution is improved whilst still providing regional revisit every 3 days. Although the VIS/NIR bands on AATSR are broad, the superior atmospheric correction capability and multi-angle view will assist in improving estimates of bi-directional reflectance distribution functions for crop growth modelling. ASAR could also contribute to improved crop yield estimates and the identification of stress and disease in crops, particularly in very cloudy areas, but considerable research still needs to be undertaken to prove the potential of ASAR data in these areas.

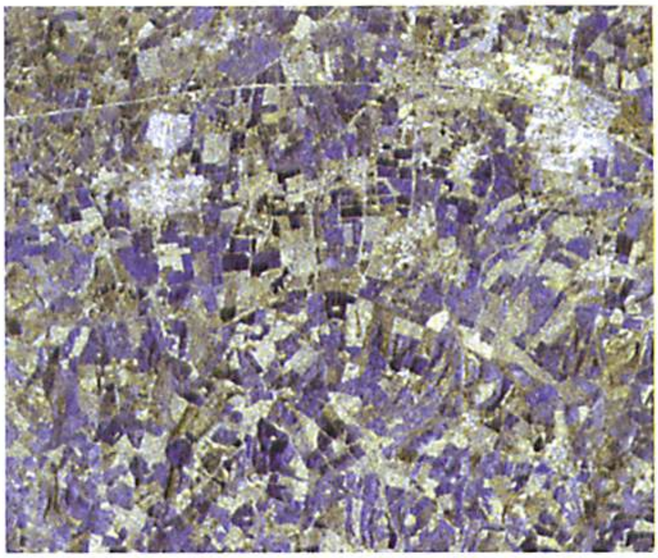


Figure 4.10 Simulated Alternating Polarisation image of an area in Oxfordshire, UK, based on the combination of ERS-2 and Radarsat images taken 1 day apart (Acknowledgment: Remote Sensing Applications Consultants, Alton, UK & Radarsat Data Copyright Canadian Space Agency/Agence spatiale canadienne 1997).

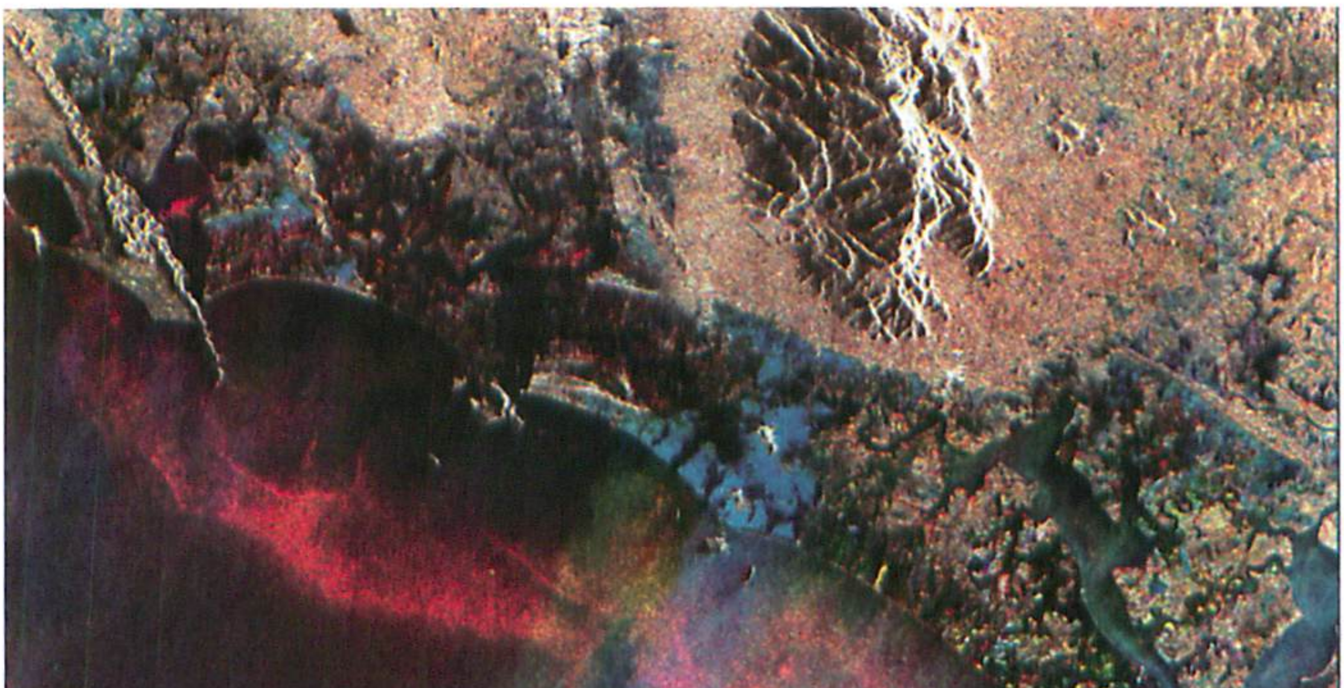


Figure 4.9 Mapping rice in Chantaburi, eastern Thailand. This composite image has been derived from 3 ERS SAR images acquired during 1993 (18 September, 23 October and 27 November). The rice growing area, shown in light blue, can be identified because, unlike the surrounding land, the backscatter from rice increases as the crop matures. (Acknowledgment: R. Schumann, ESA/AIT, Bangkok, Thailand)

4.5 Forestry

Forestry information is important as an aid to formulating land use, forest and environment policy, for long-term regional, national and local planning, and for the assessment and monitoring of natural resources, ecosystems and the environment. The qualitative information requirements include vegetation and forest type, species composition, vigour and health, as well as site conditions. The quantitative requirements include area, volume, age and density of forest stands as well as growth forecasts for sustained production. For large parts of the world, and specifically in developing countries, forest maps and statistics are outdated, unreliable or sometimes completely lacking. For regional inventories, available national maps and statistics are difficult to compare.

Global and regional forest inventory for change detection, particularly of tropical forests is an important aspect of global vegetation mapping to which ASAR, AATSR and MERIS will provide improved capabilities. Figure 4.11 illustrates the usefulness of ATSR for mapping tropical deforestation. ATSR data are being used in the JRC/ESA TREES project, to update the tropical forest map.

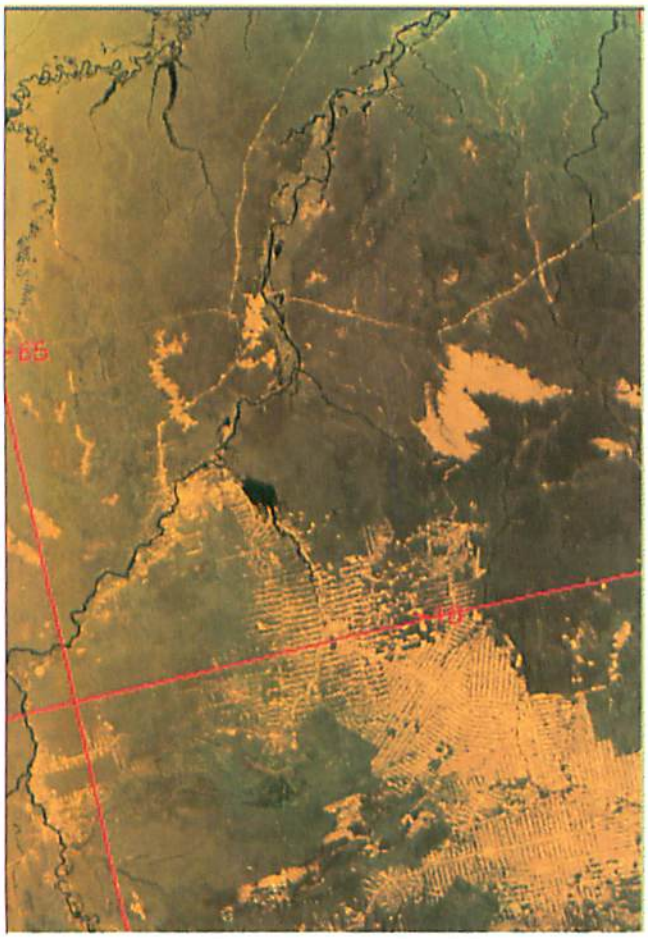


Figure 4.11 Deforestation in Rondonia, Brazil, as seen by ATSR.
(Acknowledgment: A. Bongiorno, ESRIN)

Many important forests occur in tropical areas, where there is cloud cover for much of the year, or at high latitudes, where there are long periods of darkness during the winter months. In both areas SAR is one of the few sources of satellite data available.

For local forest applications therefore, the primary Envisat products will be ASAR high resolution images. The use of low incidence angles enhances the sensitivity to biomass, whereas the use of high incidence angles improves the discrimination of forest types through interaction with forest structure. Initially there was only limited success using ERS SAR data, but the use of interferometric coherence images has now been shown to produce much better forest classification results (see Section 4.2, Figure 4.6), and the availability of multi-polarised and variable incidence angle data from ASAR should further improve the potential accuracy. Research topics include the classification of forest types, identification of burned forest, assessment of forest stress and monitoring logging concessions.

Figure 4.12 provides an excellent example of how vegetation mapping can be enhanced by using high incidence angle data. This pair of Radarsat images show discrimination of forest clearcuts in Whitecourt, Alberta, an active logging area in the foothills of the Rocky Mountains.

On the first image, acquired at an incidence angle of 20° - 27° there is poor contrast between the clearcuts and the forest. However, on the second image, which was acquired at a greater incidence angle (45° - 49°), the dark tones of the clearcut areas contrast strongly with the brighter returns from the surrounding forest.

For many vegetation applications, the use of different polarisations, in particular cross polarisation, using ASAR will improve the discrimination between vegetation (volume scattering) and soil (surface scattering). In the case of forestry, the use of cross polarisation will improve the forest/non forest discrimination and the retrieval of low biomass values (forest regeneration, regrowth, plantation).

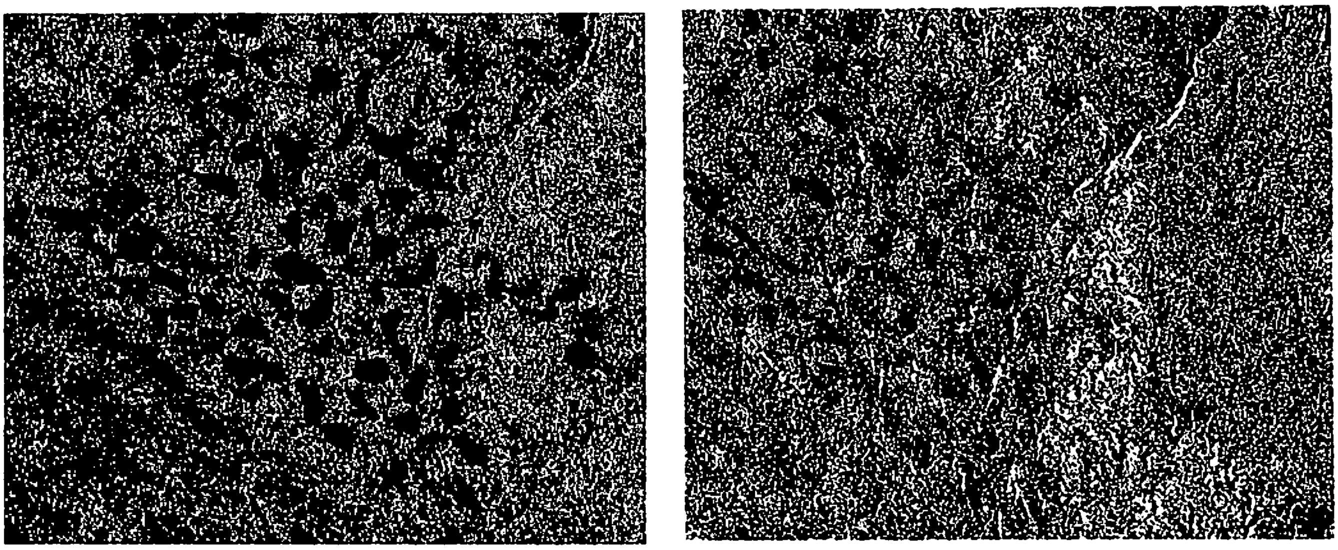


Figure 4.12 Radarsat images acquired at different incidence angles: a. 20° - 27°, b 45 °- 49°
(Acknowledgment: L.Gray, CCRS & Radarsat Data Copyright Canadian Space Agency/Agence spatiale canadienne 1997).

4.6 Geology and Topography

Envisat will have a range of capabilities for determining land surface elevation (ASAR and RA-2) as well as changes in elevation over time. Already the ERS Tandem Mission has achieved global SAR coverage with a one day repeat, which is well suited to the generation of Digital Elevation Models (DEM). RA-2 will provide a capability for making accurate land surface elevation measurements, but at a coarse scale bearing in mind the large footprint. Data on elevation and elevation change support a wide range of pure and applied science topics in geology and geomorphology.

Differential Interferometry

In the 35 day repeat orbit scenario, the wide swath capabilities of ASAR, combined with the predictable high reliability and repeatability of the orbits, will allow the retrieval of extremely useful data for differential interferometry (DINSAR). As with ERS, several conditions have to be satisfied in order to image the terrain with differential interferometry:

- surface conditions should be stable, such that more than 30-40% of the strong scatterers remain unchanged in two images acquired 35 days apart
- terrain motion should be slow so that few aliasing effects appear: this requirement reduces the possibilities of measuring terrain motions faster than say 1 cm/day
- to avoid aliasing, the horizontal variation in the velocity of the scatterers should be small
- finally, the motion variations along azimuth and range should be fast enough to be distinguishable from atmospheric effects.

ASAR will be able to measure very small terrain displacements e.g. due to co-seismic motions and slow Earth motions like bradi-seismic motion, subsidence and volcanic upswelling. It may also be possible to study oscillatory effects such as Earth tides and the loading of sea tides on the continental shelf. Landslides too can be studied and monitored.

Low Resolution Interferometry

There are interesting possibilities for using ASAR Wide Swath (or Global Monitoring Mode) data in conjunction with high resolution Image Mode data. A full resolution image with exactly the same incidence angle is needed. Reduced revisit times can be achieved if an archive of Wide Swath Mode reference images is available and a full resolution image is collected with matching incidence angle. By implication, the reference images are at least 35 days old. This makes low resolution differential interferometry suitable only for stable terrains; but for these situations there will then be the advantage of very high revisit frequencies.

A lower resolution implies that fewer looks are available, and the quality of the fringes will be proportionally lower. As an example, Figure 4.13 shows fringes of Vesuvius taken after 35 days and two simulations of the same image for Wide Swath Mode and Global Monitoring Mode.

Another important benefit of ASAR will be the availability of different viewing angles and in particular higher incidence angles, that enhance the interferometric visibility of steeper slopes, which are otherwise in radar layover shadow with the 23° incidence angle of ERS-1/2.

The availability of the Alternating Polarisation Mode will make it is possible to produce coherence images and interferograms using different polarisations.

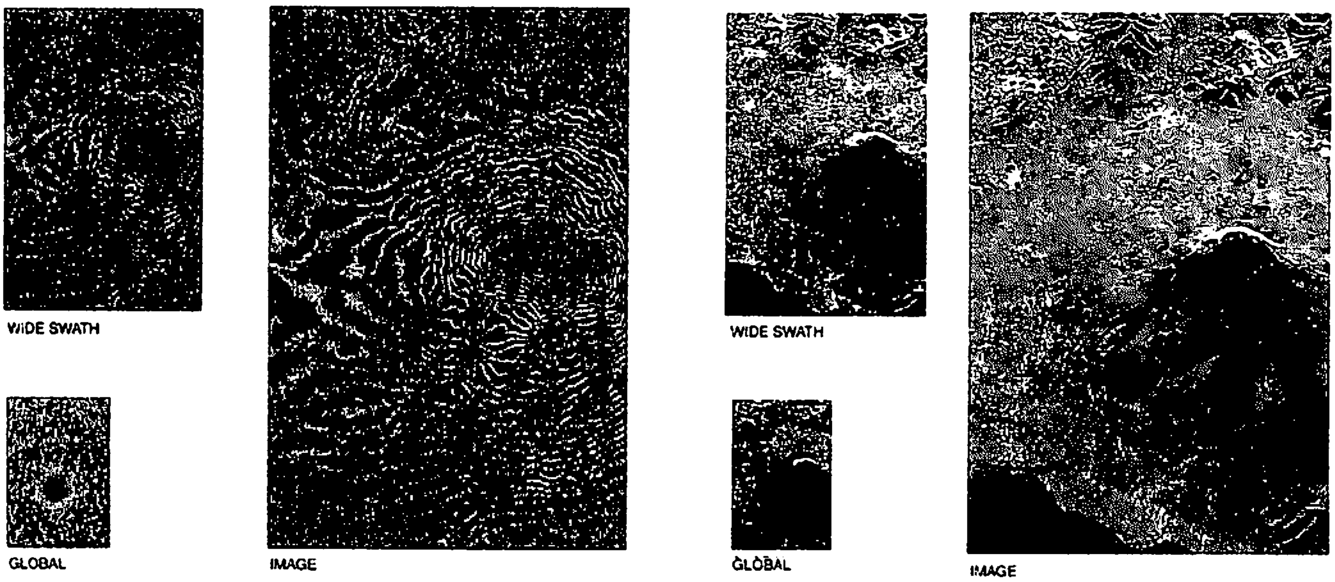


Figure 4.13 ERS Image and Interferogram for Vesuvius, together with simulations for Wide Swath Mode and Global Monitoring Mode (Acknowledgment: F. Rocca, University of Milan, Italy).

Geological mapping

Geological mapping with SAR data has become well established and a number of organisations offer a commercial service to the oil and gas industry for mapping structures, but the effect of radar layover in hilly terrain prevents widespread use of the data. ASAR Image Mode with high incidence angles is therefore of particular interest as it can be used to reduce terrain distortion. Alternating Polarisation Mode may also be of value for texture analysis in arid areas. The synoptic view provided by Wide Swath Mode is of interest for looking at regional and continental geological structures.

Tectonics

The capability of ASAR for monitoring large scale tectonic motions of continental plate boundaries in unvegetated terrain could lead to new and important results. A very interesting problem to study could be the prediction of topographic changes resulting from tectonic motion.

Earthquakes

SAR can provide high resolution maps of co-seismic deformation generated by an earthquake (Figure 4.14). Geodetic networks undersample the deformation field and in any case, very frequent measurements are needed when strain accumulation is suspected. Satellite observations can help in the creation of a global data set to study the statistics of Earth motion in connection with seismic phenomena. This could help in the prediction of the locations of future earthquakes. The temporal coverage needed is in the order of a day, and the cooperation of several wide swath satellites like ASAR and Radarsat could allow just that.

Volcanism

In addition to their important atmospheric consequences (see Section 2.4), volcanic eruptions are a serious local hazard which requires prediction. Vulcanologists will be able to use AATSR to assist ground observations and temperature measurements of volcanoes and large lava flows.

The ability to remotely sense volcano deformations would be an enormous benefit to volcano studies; SAR interferometry holds tremendous potential, but possible artefacts due to atmospheric effects have to be identified and, if possible, corrected. Volcanoes with vegetation cover cannot usually be studied using DINSAR due to loss of coherence. ASAR, in its global coverage and wide swath modes, will frequently be able to revisit volcano locations around the globe so that, if the technical problems can be overcome, a suitable data base could be available to monitor possible surface dilations on a daily basis, as an alarm for volcanic activity.

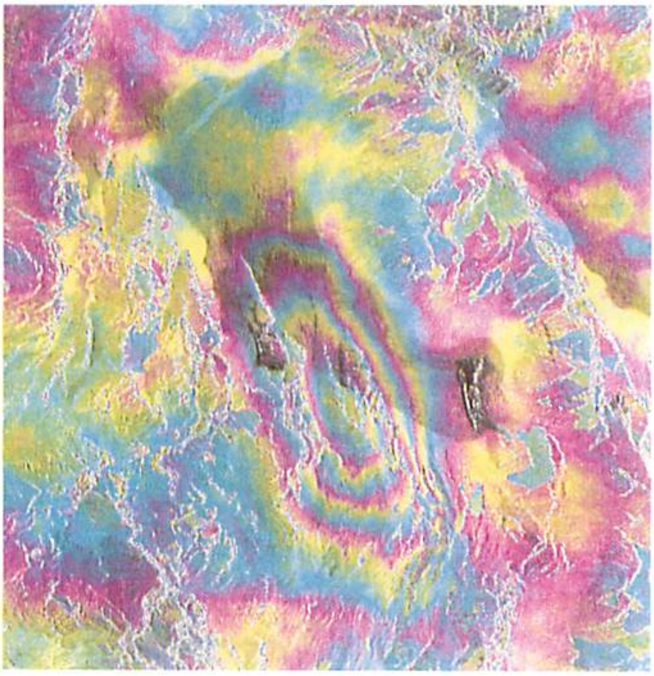


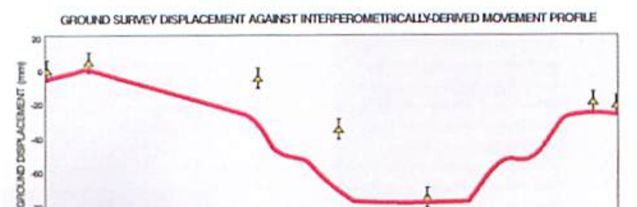
Figure 4.14 Interferogram derived from three ERS-1 images showing the results of an earthquake in Eureka Valley, California in May 1993. The interferogram clearly depicts elongated, concentric ring-shaped fringes resulting from the subsidence of the fault block overlying the inclined fault. The maximum displacement measured is 10-20 cm (Acknowledgment: G. Peltzer, JPL, Pasadena, USA)

Subsidence, Heave and Mass Movement

Extensive studies on subsidence have been carried out and interesting results found that could lead to the systematic use of DINSAR for monitoring ground subsidence (Figure 4.15). The long term availability of ASAR and its multiplicity of off-nadir observation angles will allow better identification of artefacts due to systematic atmospheric effects.

The change in elevation of man-made structures in permafrost can also be monitored, in a unique way, using DINSAR. The control of vast and remote areas where the damage due to human intervention could be difficult to control is yet another possibility offered by ASAR.

a. An interferogram covering an urban area 12 km x 16 km in size, made with ERS images taken 2 years 4 months apart



b. Graph comparing the interferometric results with GPS measurements made on the ground.

Figure 4.15 Urban Ground Subsidence (Acknowledgment: Nigel Press Associates for image processing and WS Atkins for ground validation).

4.7 Flooding

It is possible to map flooded areas using SAR, which is especially useful considering that flooding is often associated with poor weather conditions, when clear images from optical sensors are usually not available. The ERS SAR has demonstrated its value for flood monitoring on a pilot basis (see Figure 4.16). However, accurate mapping is not always possible operationally, particularly if the water surface is rough.

For floodplain mapping and emergency management a resolution of at least 30 m is required and an acquisition period better than three days is needed for use in activities such as emergency response and repair of flood defences. The main problem has been lack of operationally useful data on these short time frames, but the beam steering capability of ASAR will allow frequent revisits. In addition the high incidence angles and HH polarisation capabilities of ASAR will give better mapping than the low incidence and VV polarisation of the ERS SAR.

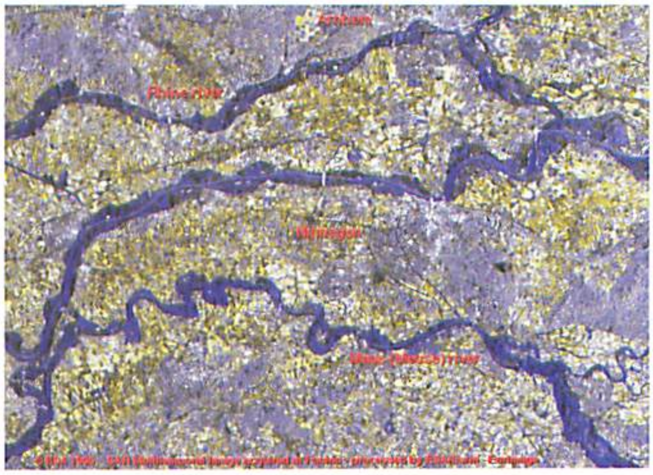


Figure 4.16. Combined ERS SAR and Landsat Image showing flooding in the southern Netherlands during January 1995. The flooding along the Lower Rhine, the Waal and Maas, is derived from the analysis of multitemporal ERS SAR imagery with additional information provided by the Landsat data (Acknowledgment: C. Pohl, Y.Wang, B.N. Koopmans, ITC, Enschede, The Netherlands)

4.8 Fires

Large vegetation fires are a major source of atmospheric pollutants and fire is a key indicator of anthropogenic activity and biomass destruction. In some ecosystems and economies, fire is a normal and locally beneficial phenomenon whereas in others it is a major hazard which needs monitoring. A number of environmental research programmes have an interest in fire monitoring at a global level (notably the IGAC core project of the IGBP) in order to monitor destruction of vegetation and assist with flux calculations of carbon and other elements which are sequestered in vegetation and released upon combustion.

The ATSR-2 instrument on ERS-2 has already demonstrated a capability for monitoring fires. ATSR-2 has a 3.7 μm channel which corresponds to the peak radiative emission of fires. Figure 4.17 is an ATSR-2 image showing fires in Kalimantan, Indonesia, on 15 September 1997. The maps shown in Figure 4.18 have been derived from a time series of images taken over a three month period, during which the fires caused the well publicised severe smoke and haze problems across the region.

AATSR will provide continuity, and contribute with other sensors, such as MODIS and AVHRR, to improve the frequency of global fire monitoring.

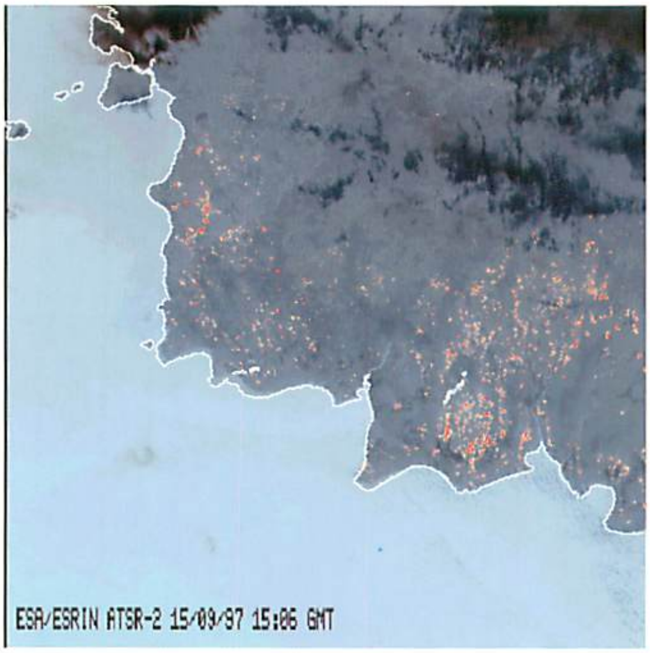


Figure 4.17 Fires in south west Kalimantan detected at night using ATSR-2 channel 3.7 μm, 15 September 1997. (Acknowledgment: A. Bongiorno et al, ESRIN)

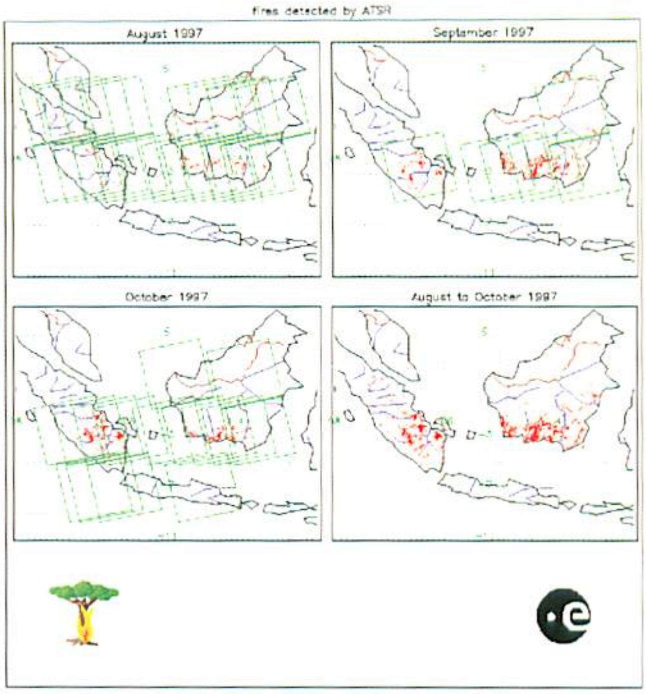


Figure 4.18 ATSR-2 mapping of fires in Kalimantan and Sumatra, August to October 1997. (Acknowledgment: E. Antikidis and O. Arino, ESRIN)

5. Cryosphere

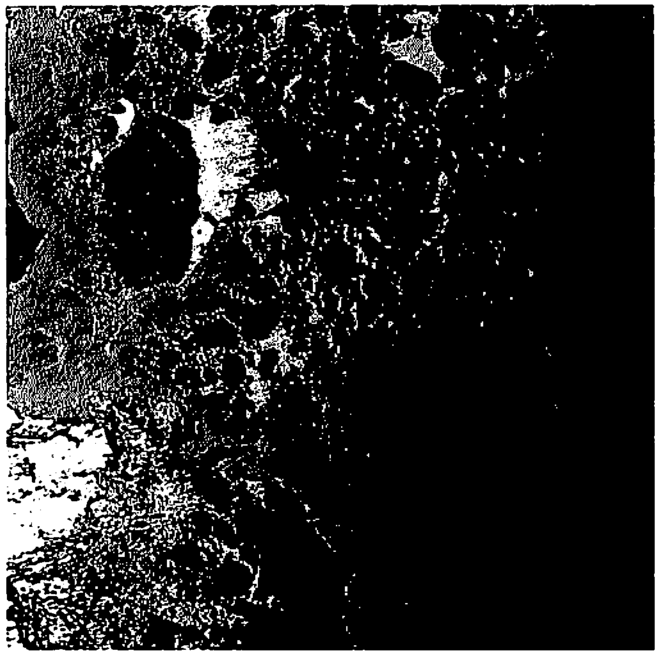
The hostility, remoteness, winter darkness, rough weather conditions and frequent cloud cover of the high latitude ice covered regions, make the use of earth observation data well suited for monitoring ice cover. The ERS satellites have already proved the all weather capability of SAR and radar altimetry for collecting data at high latitudes and have, for example, produced the first reliable high resolution coverage of sea ice regions.

5.1 Sea Ice

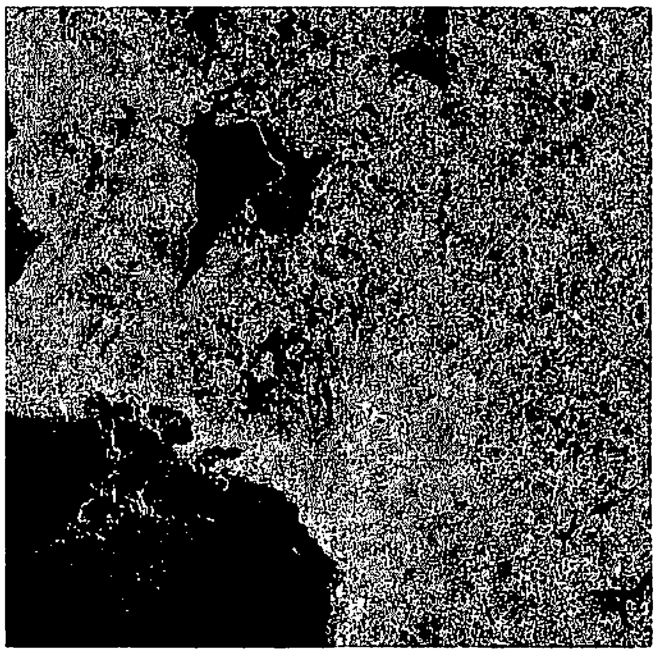
The long term monitoring of sea ice extent and thickness in Arctic and Antartic regions, provides a sensitive indicator of climate change. In addition, the seasonal and annual sea ice changes influence the Earth's albedo and fresh water cycle in the shorter term. It is necessary to monitor sea ice at a global level for climate change studies and also, more locally, to advance understanding of the processes involved. Information about sea ice is also required to satisfy operational needs for navigation, offshore operations and weather forecasting.

The Envisat sensors will ensure the continuity of data supply following on from those onboard ERS, with the exception of the scatterometer derived sea ice field. ERS has shown how SAR images can distinguish different ice types and map leads, polynyas, shear zones, landfast ice, drifting ice and the location of the ice edge. ASAR provides certain advanced capabilities which enhance its performance for sea ice monitoring. The lower resolution modes will open up new possibilities for applications requiring large area coverage and more frequent revisits. The sea-ice edge is also better determined using higher incidence angle data which are available from the ASAR. Wide Swath Mode and Global Monitoring Mode, will both provide near daily revisit capability of wide swaths (400 km) of sea ice in polar regions.

Research effort will be necessary to determine the optimum choice of polarisation for specific elements of sea ice monitoring. At present it is believed that cross polarisations (i.e. HV or VH) will be particularly useful for mapping ice topography (ridging and rafted ice) and that this mode is also likely to give improved ice type discrimination. As shown by Figure 5.1, comparisons between ERS (VV polarisation) and Radarsat (HH polarisation) have already demonstrated the different information content of the two channels which will be acquired simultaneously with ASAR.



a. ERS-2 (VV polarisation)



b. Radarsat (HH polarisation)

Figure 5.1 Almost simultaneous ERS and Radarsat images covering 80 km x 80 km in the Baltic Sea. The ERS image was acquired from a descending orbit and the Radarsat image from an ascending orbit, both on 19 Sept. 1996. (Acknowledgment: J.Askne and A. Li, Chalmers Univ. of Technology. Gothenburg, Sweden. Radarsat data copyright Canadian Space Agency/Agence spatiale canadienne, 1996)

Individual ice floes and specific features can be recognised through analysis of consecutive SAR images. Advanced image processing and interpolation techniques can retrieve the motions of sea ice between the pairs of images (Figure 5.2). This type of information will, together with meteorological data, provide the locations where leads may be expected to open or dense ice pack develop. Several countries are using microwave Earth observation data in operational ice monitoring services. Operational demonstrations of the use of ERS and Radarsat data have been implemented for many ice covered regions.

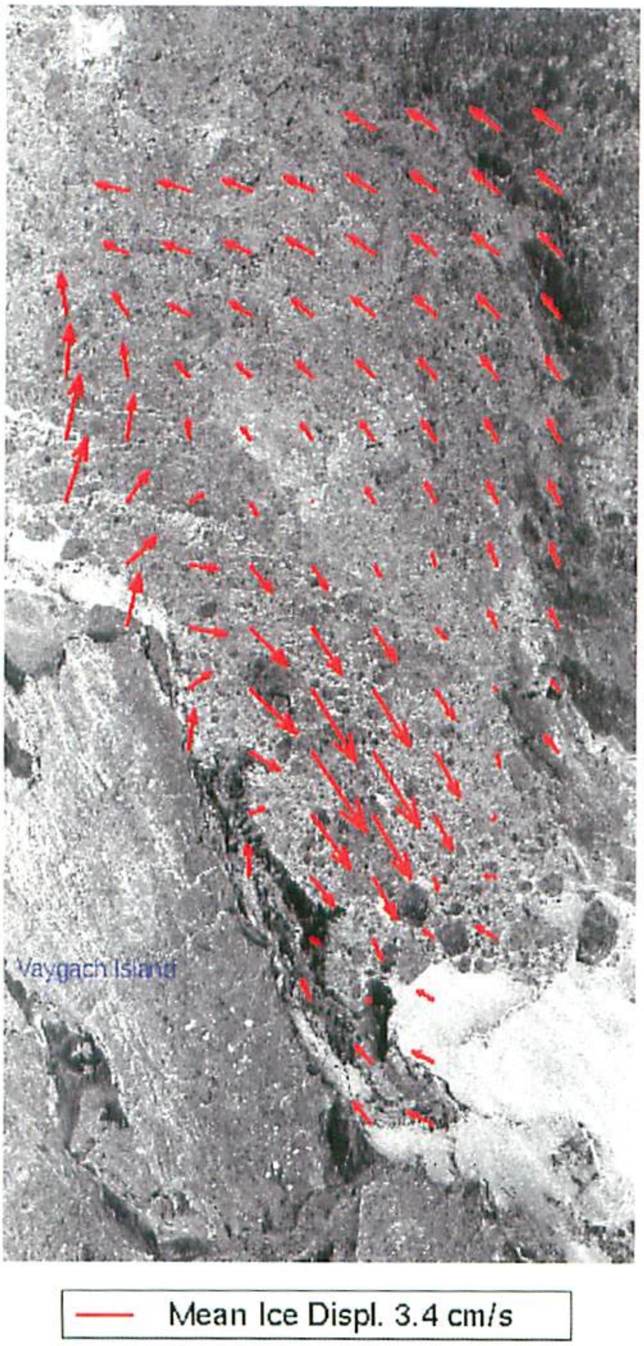


Figure 5.2 Ice kinematics in the Kara Sea from two consecutive ERS-1 SAR images taken with three days interval during the 3-day repeat cycle in 1994. The image shows the velocity field of the ice, which is dominated by inflow through the Kara Gate and along the coast of Vaigach Island. (Acknowledgment: NERSC, Bergen, Norway).

The use of SAR images from satellites is playing an increasingly important role in operational sea ice monitoring. In 1995 the ICEWATCH project - the first joint project within Earth observation between the Russian Space Agency (RKA) and ESA - was initiated. The overall objective of the project is to implement satellite monitoring by combined use of ERS SAR, RKA Okean SLR and other remote sensing data, to support sea ice navigation in the Northern Sea Route, offshore industry and environmental studies (Figure 5.3). The project also includes a plan for a SAR receiving station in Siberia. The rationale for the project was practical as well as scientific.

- Ships traversing the Northern Sea Route along the Siberian coast need good knowledge of ice conditions on a daily basis, as well as long term, for safe and efficient navigation.
- Oil exploration and production facilities in areas such as the Eastern Barents and the Kara Sea areas will require both reliable and timely monitoring and forecasts of sea ice behaviour.
- Fishing vessels need daily updating of accurate ice maps in order to operate in ice edge regions throughout the year.
- Monitoring of Arctic sea conditions is essential to provide an early indicator of global climate change, which is predicted to become most severe in polar regions.

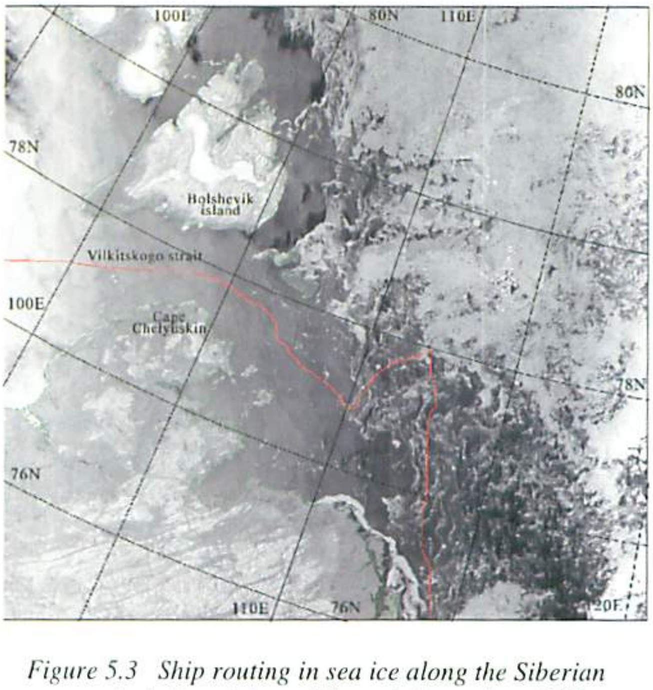


Figure 5.3 Ship routing in sea ice along the Siberian coast, including ship track in red, September 1997. (Acknowledgment: NERSC, Bergen, Norway. Radarsat data, Copyright Canadian Space Agency/Agence spatiale canadienne 1997).

Experience in operational applications leads to the conclusion that the Wide Swath Mode, with 150 m resolution, will be the main tool for operational surveillance and ship routing purposes. Through expert knowledge and by the use of dedicated software, sea ice information can be interpreted from the SAR images. The current limitations of single frequency and single polarisation operation imply that only one channel of information is available for interpretation of the SAR images. For the tactical navigation of icebreakers, information down to the level of individual ice floes is needed for both rough and smooth ice conditions.

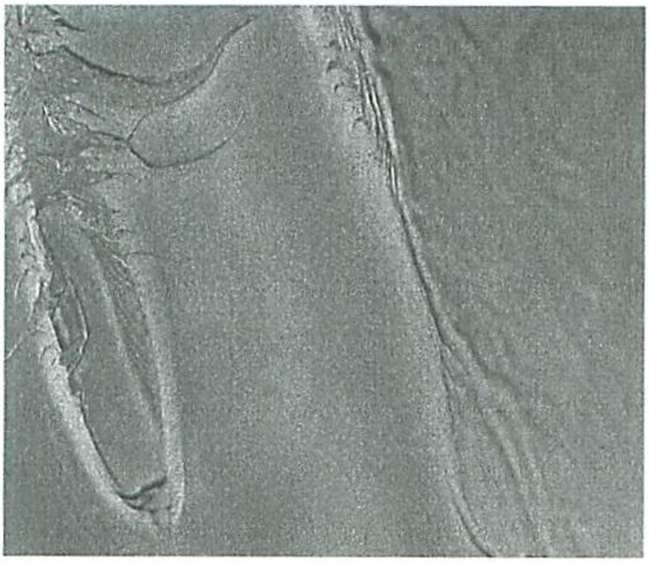
Figure 5.4, a simulation using ERS browse data, shows that the ice-edge location will probably be identifiable at 1 km resolution. It is also expected that there will be sufficient detail in the imagery to recognise areas of different ice pack concentration and, through the analysis of multi-temporal imagery, to identify large scale movement. The Global Monitoring Mode also has the advantage of being in continuous operation, thereby supporting global climate modelling through the generation of regularly updated maps of sea ice cover.

The dual frequency Radar Altimeter (RA-2) not only provides data continuity with the ERS Radar Altimeters, in terms of measuring ice sheet elevation and extent, but also has new capabilities which make possible the more precise geographical determination of sea ice margins. This is achieved principally through autonomous selection by the instrument of the tracking window. When the radar echo is about to move out of the tracking window, due to a change in land surface elevation, the window is broadened to re-capture it. This enables the uninterrupted collection of data over the boundaries between different surfaces.

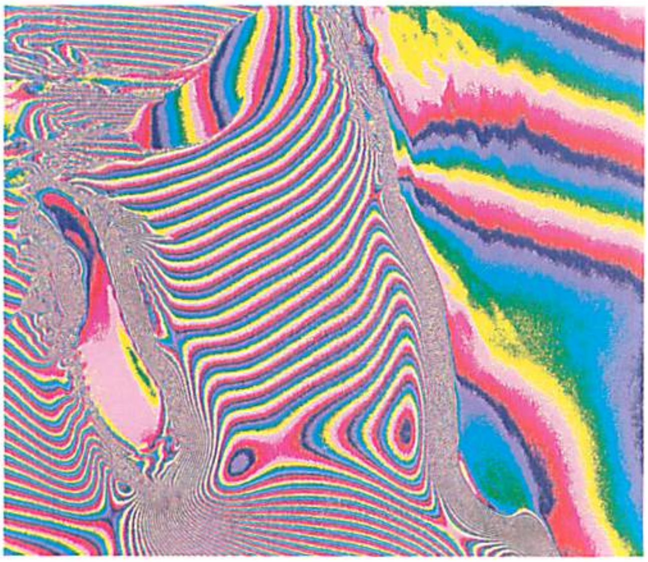
Figure 5.4 ASAR Global Monitoring Mode simulation, using ERS browse image mosaic, of Svalbard (Norway). The ice-edge location is indicated by the white line. The area north of Spitsbergen (top left on the image) shows an ice-edge which is easy to distinguish from the open water, while in the area north of Nordaustlandet (top right on the image) it is possible to see two ice-edges. This is due to the ice movement within the 10 days separating the various ERS acquisitions used for the mosaic. (Acknowledgment: S. Dokken, H. Laur, ESRIN)

5.2 Polar Ice Sheet Dynamics and Mass Balance

Change in the global sea level is related to climate change and global warming. The contribution of polar ice sheets to changes in sea level continues to be an area for research, elements of which are focusing on time series measurements of changes to floating and grounded ice in Antarctica and Greenland. Models have been constructed which relate the state of the polar ice sheets to climatic parameters. These attempt to determine how future climate change will cause the polar ice sheets to grow or shrink, and include allowances for the feedback from the changing ice sheets in terms of their influence on the atmosphere and ocean.



a.



b.

Figure 5.5 SAR interferometry used to detect ice motion in the area around Hemmen Ice Rise on the Filchner Ronne Ice Shelf. a. ERS-1 SAR image showing the Ice Rise to the left and Berkner Island on the right. b. interferogram with the fringes generated by dynamic effects: the rise and fall of the ocean tide and seaward of the ice movement (towards the top of the image).
(Acknowledgment: P.Hartl, H.Thiel, X Wu, University of Stuttgart, Germany; J.Sievers, Institut für Angewandte Geodäsie, Frankfurt, Germany; C.Doake, British Antarctic Survey, UK).

Models are also used to predict changes in sea level, salinity and global circulation as a result of ice sheet change. Ice sheets that are grounded below sea level are particularly sensitive to changes in mass balance. Retreat of floating ice shelves in front of the grounded ice may accelerate the mass transport across the grounding line and thus initiate a disintegration process. In order to improve the level of knowledge it is necessary to collect long term data sets describing ice sheet elevation, ice sheet dynamics, change of mass flux across the grounding line and surface properties (snow cover, ablation, melt line and ice free areas).

Within the ERS programme, multi-temporal sequences of SAR images and radar interferometric techniques have provided a completely new dimension for studies of ice dynamics, enabling flow velocity fields to be derived. For example, Figure 5.5 shows SAR interferometry results monitoring ice sheet motion in Antarctica. The mapping of ice motion by comparing images one year apart can also provide useful information on ice boundary zones.

The new acquisition modes of ASAR, especially Alternating Polarisation Mode, will provide more information relating to surface characteristics and the structure of the snow pack as it varies across the ice sheet. AATSR will be able to provide accurate temperature measurements of the surface of ice sheets which provide further insights into local climatology and an indicator of long term global climate change.

The ERS RA had a special mode for mapping ice sheet topography and investigating volume changes. For example, Figure 5.6 is an RA topographic map of Greenland. On Envisat, RA-2 will have improved performance due to the window tracking algorithm, and changes in the onboard processing which makes the instrument tolerant to changes in surface topography.

5.3 Temperate Glaciers

Temperate glaciers and small ice sheets are also sensitive indicators of climate change, more particularly in a regional context. Most of the world's glaciers are in retreat and have been for the past century or so. Glacial melt water is an important component of the hydrological cycle in the mountainous areas where glaciers are to be found. In order to understand the relationship between climate change and glacial advance and retreat it is necessary to model the mass balance and dynamics of glaciers and their departure from equilibrium, according to the various inputs driving the change, including snow accumulation and ablation.

Figure 5.6 Topographic Map of the Greenland Ice Sheet Produced from ERS-1 Radar Altimeter Data (Acknowledgment: J. Bamber, Mullard Space Science Laboratory, University College London, UK)

ERS SAR data have already provided significant information on the changes which take place as snow compacts and changes to ice, within an annual cycle. By analysing successive years of data it is possible to infer climate change by monitoring critical boundaries between ice and melting snow at the end of the summer melt season. Similarly, by mapping the frontal extent of glaciers on a regular basis, made feasible by using spaceborne radar sensors, long term and increasingly valuable data sets can be compiled, which represent trends in global climate change.

SAR interferometry has been used to monitor the changes which take place in a glacier and the relative velocities of the components involved. Figure 5.7 provides an excellent example of how mapping surface topography can provide information on glacial processes. In this case, the effects of sub-glacial volcanic activity could be quantified in terms of the volume of melt water.

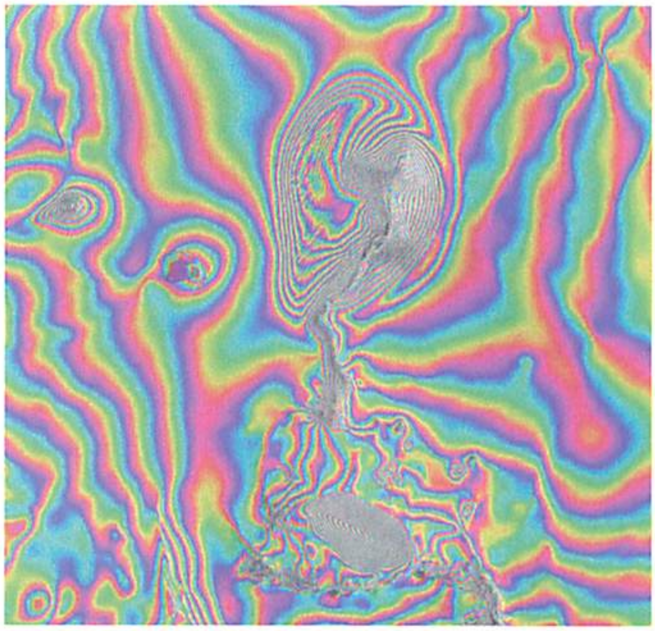
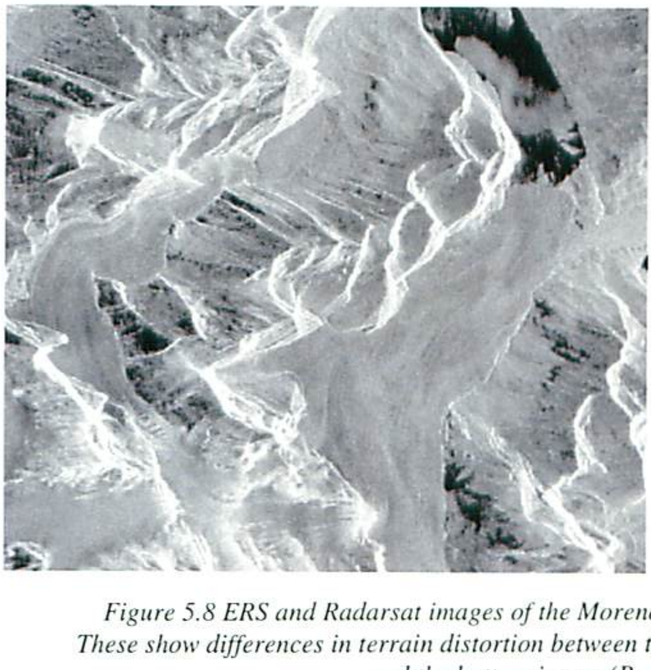


Figure 5.7 Interferogram from ERS Tandem data, of part of the Vatnajokull Glacier, Iceland, May 1997. This shows glacial topography, including a major depression (400 - 600 m deep) in the upper central part of the image, caused by sub-glacial volcanic eruption (Acknowledgment: H.Rott, Institut für Meteorologie und Geophysik, Innsbruck, Austria).

It is often difficult to use SAR images in glaciated mountainous areas because of severe terrain distortions. Figure 5.8 shows how the degree of terrain distortion relates to incidence angle, with distortion being much less at higher incidence angles. The higher incidence angles available from ASAR will provide imagery more suited to monitoring glaciers in deeply dissected terrain. The new capability for supplying dual polarisation images will provide more accurate information on the conversion process undergone by snow during the year.



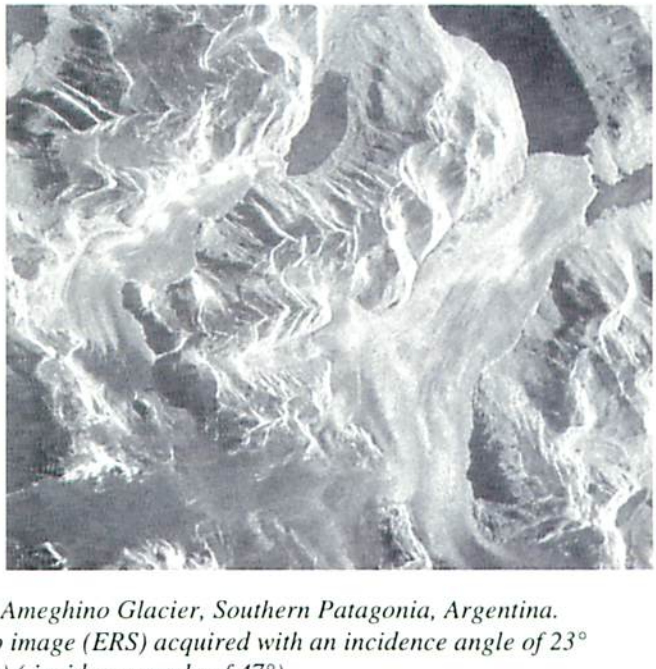


Figure 5.8 ERS and Radarsat images of the Moreno and Ameghino Glacier, Southern Patagonia, Argentina. These show differences in terrain distortion between the top image (ERS) acquired with an incidence angle of 23° and the bottom image (Radarsat) (incidence angle of 47°). (Acknowledgment: H.Rott, Institut für Meteorologie und Geophysik,Innsbruck, Austria).

5.4 Snow Cover

Earth observation techniques have been applied to the monitoring of seasonal snow cover. The acquisition of images on a regular basis provides information on the local climate, as snow is quick to react to changes in air temperature. Snow cover increases the surface reflectivity and therefore alters the Earth radiative balance. This has the effect of cooling the atmosphere and potentially increasing the amount of snow cover. Such a positive feedback mechanism has the effect of distorting trends in climate change and needs to be incorporated within the appropriate models.

The accumulation of snow and its subsequent melting is also significant in a socio-economic context in relation to water resource management and hydro-electric power generation. ERS-1 SAR data have allowed the detection of melting snow within an operational procedure to estimate melt water run-off. Multitemporal analysis of SAR data is able to discriminate between dry snow and melting snow.

ASAR provides data continuity and again the alternating polarisation mode is able to provide more information about the state of snow cover. High resolution data are required because of the need to correct for the mountainous terrain often associated with snow fields. High incidence angle data from ASAR will also increase the amount of information from imagery of mountainous areas (Figure 5.9). The Global Monitoring Mode is of special interest for monitoring the area extent of snow and the temporal dynamics during the melt period. Data for this application are needed on a weekly basis.

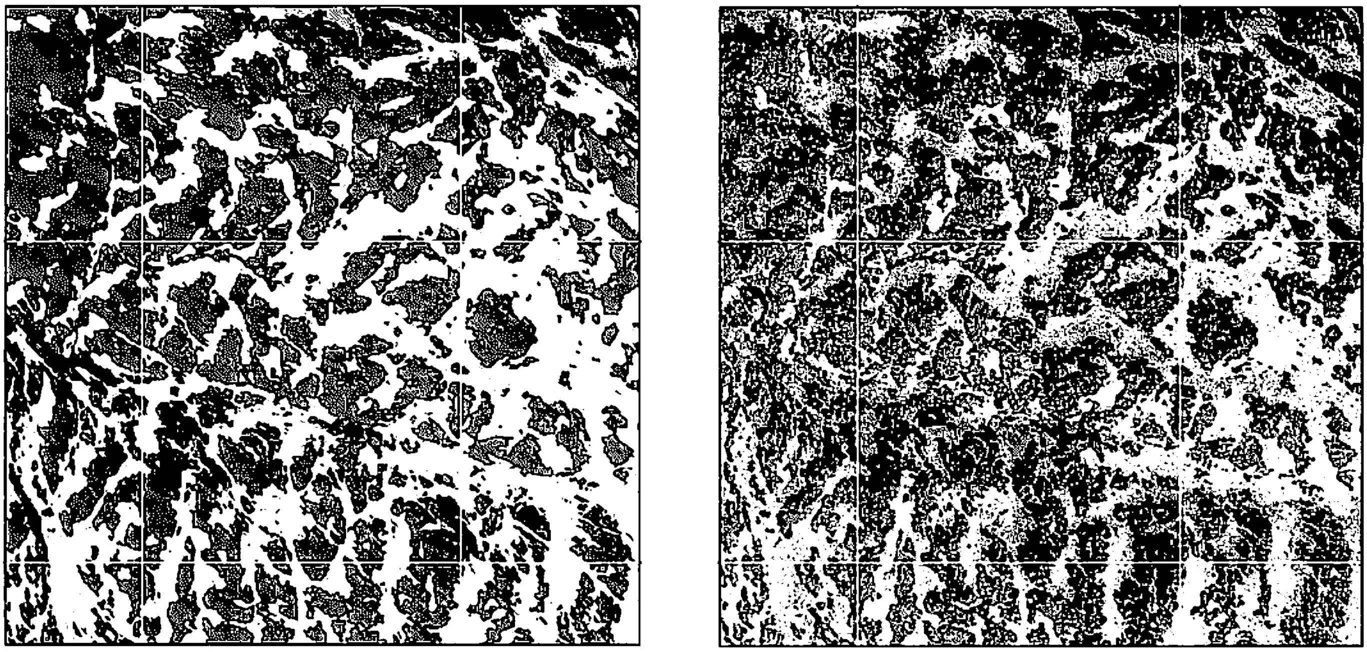


Figure 5.9 Comparison of airborne optical (left) and SAR (right) images for snow mapping over the Okstindan area, Norway. The C-band VV SAR image was acquired with high incidence angles around 45°, and is reproduced here as a negative image, with areas of low backscatter appearing white (snow). The gridlines are spaced by 1 km. (Acknowledgment: T.Guneriussen and H.Johnsen, NORUT IT, Bergen, Norway1996).

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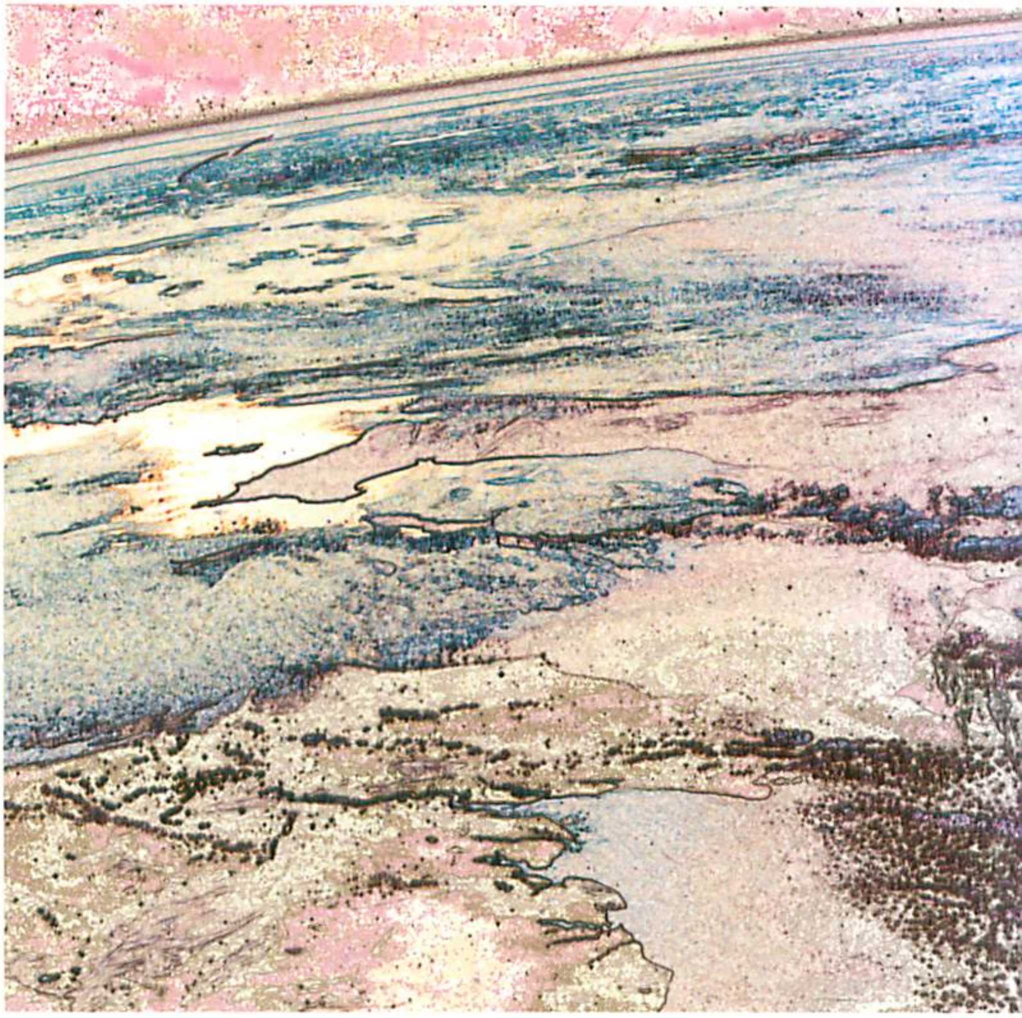

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c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
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