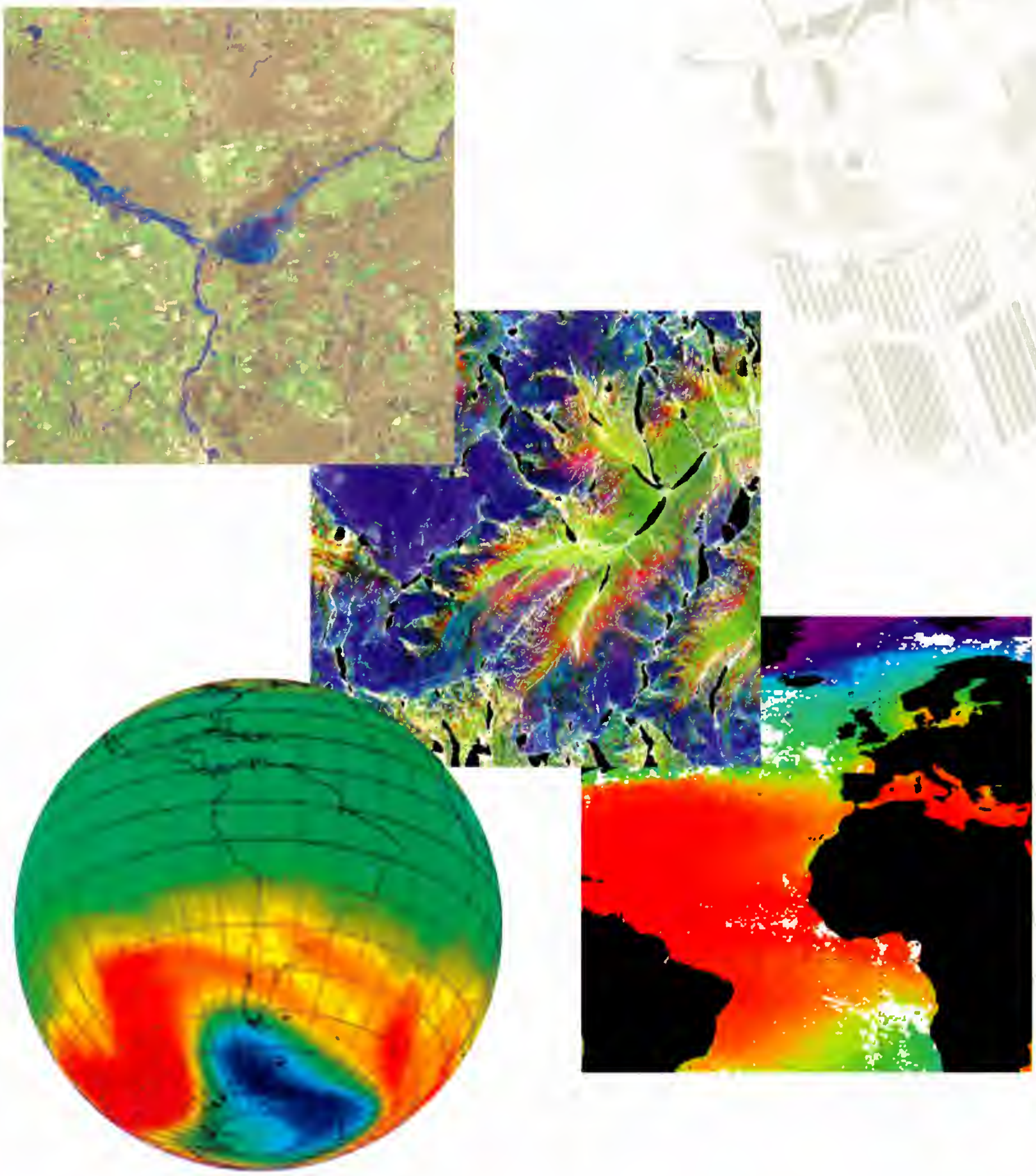
SP-1228

Further Achievements of the ERS Missions



European Space Agency
Agence spatiale européenne

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Further Achievements of the ERS Missions

European Space Agency
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Contents

Foreword

Since the launch of the first European Remote-sensing Satellite (ERS-1) on 17th July 1991, a consistently high quality data stream from its sensors has been delivered to the international science community and European and Canadian companies developing value-adding applications.

Data from both ERS-1 and ERS-2 (launched on 20th April 1995) are continuing to enable our scientists to improve their understanding across all the major Earth science disciplines: oceanography, polar science, coastal zones, glaciology, land studies and atmospheric processes. They have contributed to major research breakthroughs in climate change, tectonic evolution and ice dynamics. The ERS satellites have established Europe as a major data provider for international science programmes.

Furthermore, ERS data used with complementary geo-spatial data have stimulated European companies to initiate commercial applications, serving particularly the marine, agricultural and oil and gas industries in home markets and overseas. The same data are also helping to improve public services for the European citizen and for industry, notably in weather forecasting, sea ice navigation and more recently in helping to limit the consequences of natural and man-made disasters.

The diversity of the high quality data that has routinely been available is a tribute to the partnerships between scientists, industry and ESA that have contributed to high engineering standards in manufacturing and operating the satellites, in the distributed ground segment and evolution of individual data processing systems.

The original objectives established for ERS-1 by the ESA Member States were both scientific and economic. Reflecting this, ESA has published a series of documents entitled 'New Views of the Earth' that highlight how scientists and companies in Europe have taken advantage of ERS data. There are a surprising number of examples in which the data have been used in novel ways that were not originally foreseen. These achievements are due to the innovation of European scientists and engineers and to the support provided by ESA staff. They demonstrate how Europe is leading the world in satellite data interpretation and exploitation.

But time moves on. The political environment within Europe has changed and our space industry is responding to greater commercial pressures in the global marketplace. Consequently, 1998 is a milestone year when Europe is redefining its strategy for Earth observation. The ERS series has provided a strong foundation for Europe to continue to develop new Earth observing technologies. Envisat, for example, scheduled for launch in 2000, includes more advanced microwave sensors than flown on ERS and introduces new European multispectral capabilities. Envisat will continue to serve the scientific community primarily, with potential for spin-offs for the commercial sector. In co-operation with EUMETSAT, ESA is also contributing to the Metop series of operational weather satellites that will support public forecasting services and provide an essential European contribution to the worldwide meteorological observing system.

The concept of research and development and operational missions in parallel is a theme that is being reinforced through a proposed new European programme for Earth observation, **"The Living Planet"**. Earth Explorer missions will emphasise science needs and offer R&D opportunities for industry. Earth Watch missions will offer a stepping stone for industry to develop a commercial business for future Earth observation satellites, in which constellations of satellites provide a better market offering and in which industry increasingly shares the investment risk.

However the missions are defined, the emphasis for the future is on reducing the cost of supply and focusing the missions more tightly on specific science, policy or commercial market objectives which, with its ERS experience, Europe is now in a better position to judge.

Much needs to be accomplished to meet these objectives, at the political level, in taking industry-led initiatives and in pushing Earth observation derived information more into the mainstream of government, corporate and eventually consumer life. Today, ERS continues to provide us with the experience needed to take these steps effectively. This publication will show how experience in the use of these data is consolidating into key scientific advancements, support to European policy making and commercial returns for industry. The three key pillars of the future strategy for Earth observation.

Guy Duchossois

Head of EO Mission Management Office

Acronyms and Abbreviations

ACSYS	Arctic Climate SYstems Study
AETNA	Analysis of problem areas and Experimental Test of possible solutions arising from the Need to Acquire and process interferometric SAR data for geodynamic purposes on a large scale basis')
AMI	(ERS) Active Microwave Instrumentation
ASAR	(ENVISAT) Advanced SAR
ASCAT	Advanced SCATterometer
ASEAN	Association of South East Asian Nations
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced High Resolution Radiometer
CAMP	Central African Mosaic Project
CERSAT	Centre ERS d'Archivage et de Traitement
CFC	ChloroFluoroCarbons
CFRP	Carbon Fibre Reinforced Plastic
CLIVAR	Climate Variability & Predictability Research Study
CORE	
CRISP	Centre for Remote Imaging, Sensing and Processing
DEM	Digital Elevation Model
DESA	X-band antenna front-end demonstrator
DGi	(EU) Directorate General 'i'
DMSP	Defense Meteorological Satellite Program
DXF	Vector file format
ECMWF	European Centre for Medium Range Weather Forecasting
ECU	European Currency Unit
EO	Earth Observation
EUMETSAT	European Meteorological Satellite Organisation
GEWEX	Global Energy & Water Cycle Experiment
GIS	Geographical Information System
GOME	Global Ozone Monitoring Experiment
GPS	Global Positioning System
ICSU	International Council of Scientific Unions
IFREMER	Institut Français de Recherche pour l'Exploitation de la MER
IGBP	International Geosphere-Biosphere Programme
IGS	International GPS Geodynamic Service
InSAR	Interferometric SAR
IOC	Intergovernmental Oceanographic Commission
IRRI	International Rice Research Institute
IUCN	International Union for the Conservation of Nature
IWRB	International Waterfowl and Wetlands Research Bureau (now Wetlands International)
LBR	Low bit rate

MARS	Monitoring Agricultural statistics with Remote Sensing
MAST	MArine Science and Technology
Metop	Meteosat Operational Programme
MRD	Mekong River Delta
NOAA	(US) National Oceanic & Atmospheric Administration
NRL	(US) Naval Research Laboratory
PAF	Processing and Archive Facility
PI	Principal Investigator
PP	Pilot Project
PRI	PRecision Image (ERS SAR product)
RA	Radar Altimeter
RAM	Random access Memory
RAPIDS	Real-time Acquisition & Processing Integrated Data System
SAFE	Study of the Cost Benefits of a SAR Mission for Agriculture & Forestry in Europe
SAGA	South American Geodynamic Activities Project
SAR	Synthetic Aperture Radar
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CartograpHY
SDHS	SAR Data Handling System
SLC	Single Look Complex
SPARC	Stratospheric Processes and their Role in Climate
SPOT	Satellite Pour l'Observation de la Terre
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
TOGA	Tropical Ocean & Global Atmosphere project
TOMS	Total Ozone Mapping Spectrometer
TOPEX/POSEIDON	US/French joint project, consisting of the US satellite Topex (Topography experiment for ocean circulation) carrying a French altimeter (Poséidon)
TREES	Tropical Ecosystem & Environmental observation by Satellite
TSS	Tromsø Satellite Station
UNCED	United Nations Conference on Environment and Development
UNEP	United National Environment Programme
UV	Ultraviolet
WCRP	World Climate Research Programme
WEU	Western European Union
WEUSC	WEU Satellite Centre
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment

1. Introduction

1.1 Measuring Progress Through Success in Exploitation

Throughout seven years of operation of ERS-1 and ERS-2, ESA has monitored and published the achievements of the missions, compared with the original objectives. A series of three publications entitled ***'New Views of the Earth'*** has shown the extent to which these satellites have delivered scientific, application and engineering results that have more than surpassed the original objectives defined by ESA Member States. These documents provide an extensive overview of how the data are being used by the international science community and by European and Canadian companies building information service businesses based on remote sensing.

This publication shows how with time, the various uses of ERS data are developing and consolidating in key areas of science and economic exploitation. Themes are emerging in which the combination of ERS data, European skills and innovation lead the world.

As scientists become more familiar with ERS data and as longer time series become available, the data are assisting in major scientific breakthroughs in fields as diverse as tectonic evolution, prediction of El Niño events and tropical forestry. No longer are scientists just using the data to map key aspects of the Earth's atmosphere, ocean and ice surfaces. ERS is now contributing directly to improved understanding of Earth processes. It is consequently assisting in the development of more sophisticated models which satisfy public and political demands to predict the impacts of environmental change.

- The process of prediction in Earth sciences is complex. It depends on the use of consistent measurements of environmental variables at a range of spatial scales to initialise or validate the models that help our leading scientists to improve predictions. ERS data are increasingly used to support modelling work. The use of ERS data in this way is most advanced for the atmospheric sciences, although new techniques for assimilating observations into models of land and ocean processes are developing. This is driven by a strong trend towards integrated modelling of atmosphere, ocean and land processes.

- There is a wide range of examples in which commercial applications are delivering promising results for customers. The experience of value-adding companies in ESA Member States is giving them a competitive advantage in the global market. It is widely recognised that there is ultimately a limit to the commercial revenue that can be earned from a single, general purpose and scientifically oriented satellite like ERS. It physically cannot offer the data coverage or revisit frequency that all potential markets demand. Promising revenues are nevertheless being realised, particularly from oil and gas companies, agricultural and marine sectors. This is allowing European and Canadian companies to develop valuable experience for the creation of future, more commercially oriented missions.

- Many applications of ERS data that were experimental at the start of the mission have now matured into operational and in many cases commercial contributions to public services, including weather forecasting, environmental monitoring and ship routing.

1.2 The Role of ESA

ESA was responsible for procuring the ERS satellites and their ground segment, operating them and ensures, either directly or through contracts with industry, that the standard products are available and distributed. ESA has had a limited remit to undertake or contract applications development or exploitation activities. Despite these limitations, the Agency has made an important contribution to applications development through its Principal Investigator (PI) and Pilot Project (PP) activities. Using the Announcements of Opportunity mechanism, ESA select specific scientific investigations (PI) or more commercially oriented applications (PP) and supports these by providing free ERS data. The teams working on these projects seek funding for their work from other sources, typically national programmes within the ESA Member States. Table 1.1 summarises different aspects of ESA's role in applications development through the various stages from research to operations.

Exploiting the data within science programmes, public services and in commercial markets is beyond the direct control of ESA. This has largely been co-ordinated at national levels, within the individual programmes of the Member States, and more recently by initiatives in the European Commission and especially within its Joint Research Centre (ISPRA). For some national programmes, a special emphasis is placed on developing the capability to use ERS data. For others, the focus is more on developing services for specific markets. These are built up from many sources of Earth observation (EO) data, including ERS, as deemed appropriate by the EO supplier and the customer needs. Of course ESA has a direct influence on the success of these national activities, by virtue of the quality of the ERS data and user services that it provides. ESA keeps in touch with many scientific and commercial groups actively pursuing ERS data exploitation and stimulates discussion and cross fertilisation particularly through major international meetings. Some of the most important meetings and publications are summarised in Fig. 1.1.

1.3 The Original Vision for ERS

1998 is a defining year for EO in Europe, in which all the experience of ongoing ERS operations and preparations for Envisat launch are being harnessed into a new vision for the future. Strategic developments are being discussed within ESA and between ESA, the European Union and EUMETSAT. Most importantly industry and Earth scientists, whether working in space hardware, software, operations or applications of the data, are facing the

Requirements	Research & Technology Development	Demonstration	Pilot Project	Pre-operational	Operational
Funding of applications projects	PI - validation	PI: science applications PP: economic & policy issues	Selected applications - large scale environmental and baselining	Selected applications - large scale environmental and baselining	
Tools & technologies	Respond to technology & market needs	Technical support to EO service suppliers	User orientation	Cost reductions	
Data supply	Improved availability & quality	Availability of products & information	Flexibility	Affordability & availability	Guarantee of continuity & priority
Co-ordination	Generalisations	Within the EO community	Promote to new users	Forum for exchange of operational experiences	Qualifying future needs
Training	Documentation support	EO service suppliers	Support to user awareness	New techniques for cost reduction	
Data policy	Free data	Low price data	Market orientation & flexibility	Long term commitment	Operational priorities

Table 1.1: ESA high level roles during applications development

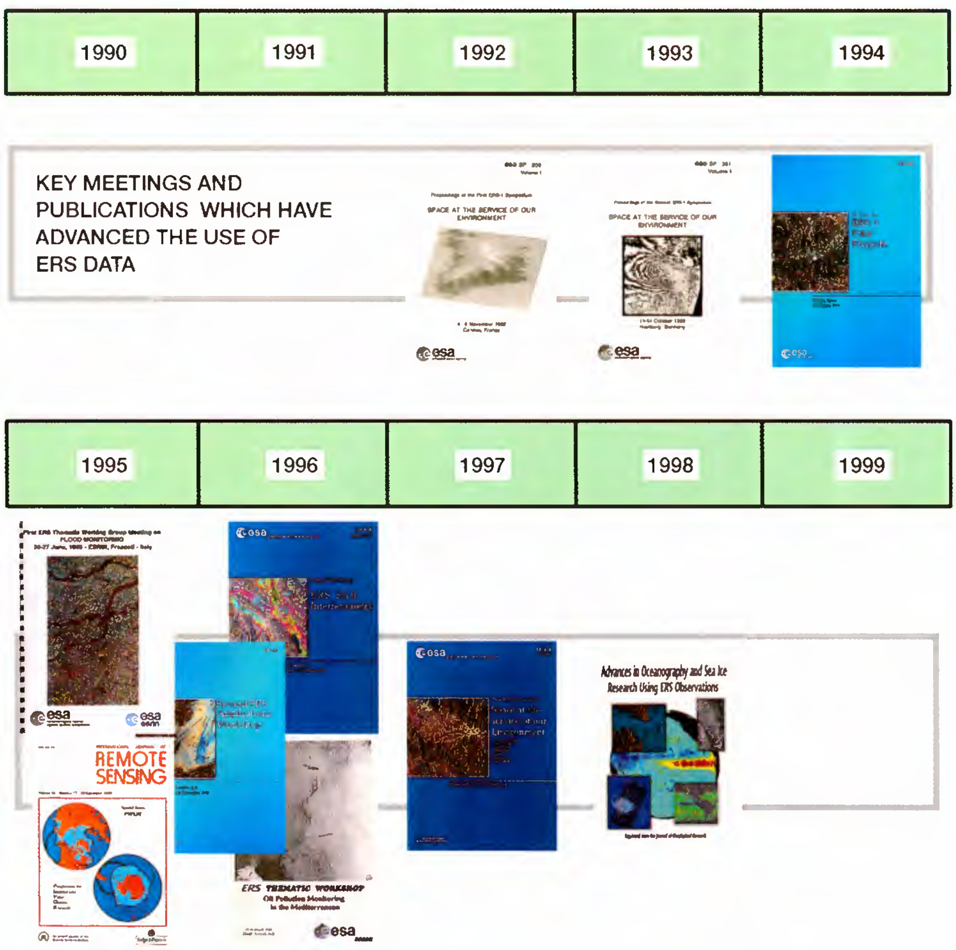


Fig. 1.1: Key meetings and publications in the development of ERS applications

Original vision for ERS-1: To increase our scientific understanding of coastal zones, global ocean processes and polar regions	
Specific objectives set in 1981 that have been met by the work of scientists in the international community	Applications developed beyond what was originally foreseen in 1981
Open oceans • global ocean circulation, its variability & associated transfers of energy • ocean/atmosphere interactions • ocean tides	• detecting and measuring the structure of atmospheric events, including tropical cyclones, monsoons, lee waves and boundary layer rolls • contributing to the generation of climatological databases
Regional seas • science studies and forecasting for Mediterranean, North Sea and other enclosed European seas • observing coastal processes and shallow water bathymetry	
Polar oceans • North Atlantic and Arctic ocean coupling • marine ice sheet instabilities, particularly W Antarctic Ice Sheet • variability in sea ice cover and its influence	
Land-ice • growth, decay and dynamics of ice sheets	• studying the structure of temperate glaciers
Land • explore the potential of radar data for land process studies and applications	• modelling crop growth, agricultural productivity, deforestation, hydrologic processes, geology and geomorphology
Solid Earth • measuring the shape of the Earth and associated gravitational features	• detecting the shape of the ocean bed under sea ice allowing a better understanding of tectonic history in polar regions • detecting surface movements associated with Earthquakes and volcanoes, triggered by the success in interferometry

Table 1.2: Summary of the original objectives for ERS and additional achievements

Table 1.2 (continued)

Original vision for ERS-1: To develop and promote economic and commercial applications	
Specific objectives set in 1981 that have been met by the work of scientists in the international community	Applications developed beyond what was originally foreseen in 1981
Forecasting weather, ocean and ice conditions for: • offshore operations • ship routing • fishing • navigation and other economic activities in ice-ice-infested waters	• bathymetric applications
Experimental applications, such as: • oil pollution monitoring • coastal management • land applications	**Many land applications have matured quicker than anticipated and have generated early commercial revenues:** • cartography • monitoring land cover change • monitoring water resources, hydrology and soil moisture • monitoring forestry change • geological mapping and mineral exploration • seasonal and perennial snow mapping • hazard management
Development aid, especially: • natural resource and environmental management • control of marine resources • offshore activities	

critical issue of whether there will be any further ESA missions after Envisat to complement the operational systems for which EUMETSAT are responsible.

In its original concept, ERS-1 was designed in part as an experimental system to demonstrate that the end-to-end system could achieve the specified performance. It was also conceived as a pre-operational system to contribute to key scientific investigations in global monitoring, emphasising ocean and ice disciplines, and as a 'market-opener' to prepare new users and European suppliers for subsequent satellite systems. It was designed around requirements, recalled in Table 1.2, that represented Europe's understanding in 1981 - more than ten years before the launch. Table 1.2 also identifies areas in which applications not originally envisaged have developed as a result of European innovation, growing confidence in handling the ERS data sets and specific targets of opportunity, like the Tandem operations.

1.4 Highlighting the Achievements of ERS

The major achievements of ERS have been recorded in three ESA publications.

SP-1176/I
Scientific Achievements
Published
April 1995

- Showed the broad range of Earth science research already benefiting from ERS-1 data within three and a half years of receiving the first data.

- By 1995, 275 research groups worldwide, involving at least 2,000 scientists, were using ERS-1 data directly and 64 discrete examples of this work were included.

- The examples reported in the 1995 edition already showed that uses of ERS data were not confined to mapping, but that they were also supporting the development of process understanding and modelling capabilities. Fig. 1.2 shows the broad range of real achievements that this document reported, across six major Earth science disciplines.

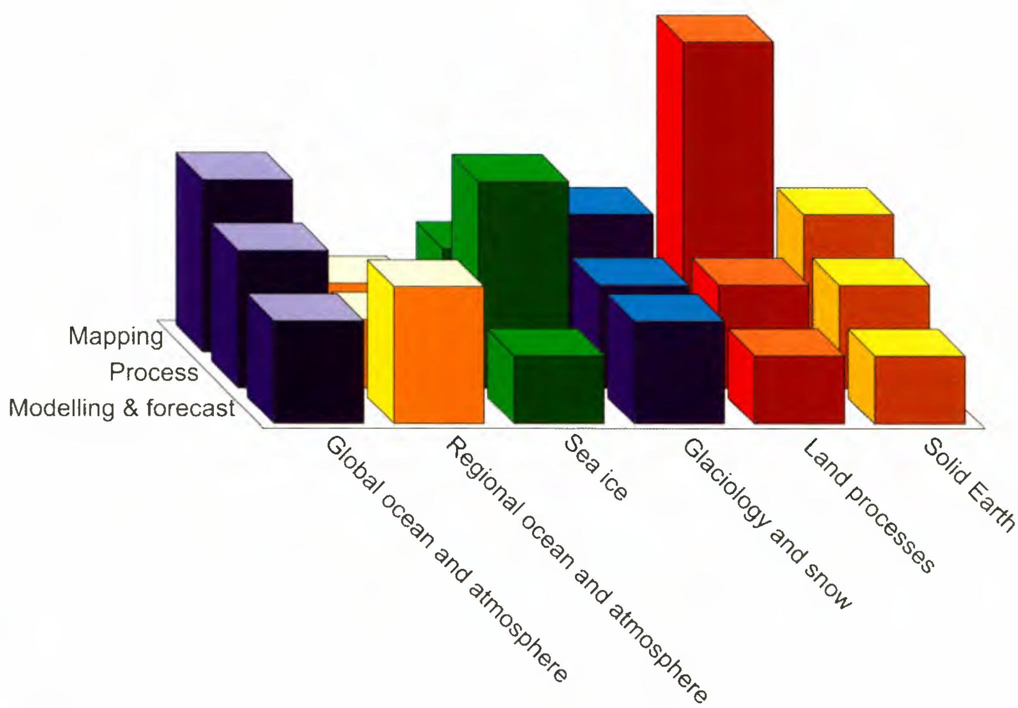


Fig. 1.2: Distribution of scientific achievement examples by discipline

SP-1176/II
Application Achievements
Published
February 1996

- Showed how ERS data are playing an increasing role in decisions at all levels from international government right out to offshore industries and individual farmers - decisions which affect all our lives through their environmental or economic impacts.

- Featured case studies of successful weather and sea-state forecasting and sea-state climatology services being offered by 14 public and private organisations within the ESA Member States. The services provide business critical information for assessing risks and planning marine operations (ship routing, fishing, offshore installations, ship detection and co-ordinating rescue services). These are the most advanced commercial services that have developed, based on the fast delivery products from ERS.

- Presented examples of how sea ice services were developing for the Baltic, the Barents Sea, the Greenland Northern Sea Route and the Great Lakes shipping areas. Coastguards and offshore operators in Europe, Canada and Alaska were major users.

- Showed how the ability to monitor land-cover change, crop development and forestry independently of weather conditions is offering one of the major potential economic returns from ERS-1, despite these being viewed originally as experimental applications.

- Included some examples of a wide range of examples in which ERS data are starting to be used to help mitigate the impacts of environmental hazards, particularly oil slicks at sea, river floods, subsidence and volcanic mudflows, and to identify potentially active tectonic faults.

- Showed how the all-weather capability, high geolocation accuracy and geological and elevational information content is opening up new commercial opportunities among exploration, civil engineering and construction companies, government agencies and telecommunications and environmental agencies. Digital maps of topography, bathymetry, land use, geology, gravity and off-shore basin screening from ERS data are providing a marked improvement in the accuracy of maps produced worldwide.

SP-1176/III Engineering Achievements ***Published December 1997***

- Showed how the advanced engineering on ERS made the scientific and application achievements possible.

- Illustrated how the high standards applied to construction and testing resulted in a system with very few failures and which has lasted more than twice as long as expected. The long lifetime of ERS-1 enabled the Tandem Mission, whose results are prominent in the examples in this document, and has continued to add value as the consistent data records from ERS grow even longer.

- Highlighted the importance of the characterisation, calibration and validation process which has been (and remains) a major component of the mission, ensuring maximum information retrieval from the data.

- Recorded the engineering achievements of the mission that have underpinned the success that the Member States have had in using the data. Without high standards of instrument performance, control and monitoring, the data could not be used with confidence for any application, be it in support of public policy, scientific discovery or commercial development.

1.5 Scope and Structure

Building on the heritage of these publications, this document has the following aims:

- to highlight some of the most significant science breakthroughs that have been made possible by ERS data since the earlier documents, particularly in the light of the success of the ERS Symposium in Florence in 1997;

- to emphasise the integration of science and application achievements according to the different emerging markets being stimulated - the partnership and transfer of experience between scientists and application companies is vital to future success;

- to present highlights from the special thematic workshops that have been held by ESRIN and which have drawn in new customers;

- to show how companies have made significant progress and achieved commercial growth based on the use of ERS data;

- to place the ERS mission in the context of the new ESA strategy for EO, highlighting the strong foundation which has been provided for the future;

- to link the ERS missions and the success of their instruments to the future ESA programmes and in particular to Envisat. The important contribution of the ERS mission towards the operational Metop mission to be provided by EUMETSAT, through items such as the ERS Wind Scatterometer is also described.

Accordingly, the structure of the document is as follows:

Section 2: The developing ERS mission: demonstrates how the mission for ERS-1 and 2 has evolved over time, and how ERS data have been used to meet new challenges. In particular, the contributions to international science programmes, government policy, operational use and industrial capability are highlighted.

Section 3: Case studies: are used to present the main body of achievements. Nineteen case studies are structured into the following groups:

- Contributions to international Earth science;

- Supporting government policy;

- Serving operational users and enhancing industrial capability;

- New and refined techniques to improve information content.

Section 4: Business development with ERS: summarises the areas in which ERS data are providing an important input to commercial ventures.

Section 5: The way forward: considers how the ERS programme provides the basis for the future ESA programme, 'The Living Planet'.

1.6 Acknowledgements

ESA gratefully acknowledges the support of all contributors to this document. Specific contributions and sources are acknowledged within each case study.

2. The Developing ERS Mission

The origins of the ERS programme lie in requirements framed in the early 1970s. Since then, these requirements have become more refined, but in outline have remained the same. What has changed to a greater extent is the context within which these needs have been expressed. Early in the mission definition during the 1970s, there was an emphasis on commercial exploitation. This gradually changed with the emergence of global climate and ocean monitoring programmes in the early 1980s, the time at which the mission configuration was finalised. More recently, the importance of global environmental monitoring has continued to be recognised. In parallel, the need to establish a commercial return on the data has reappeared, in line with current economic philosophy and the recognition that future missions will need to be more financially self supporting.

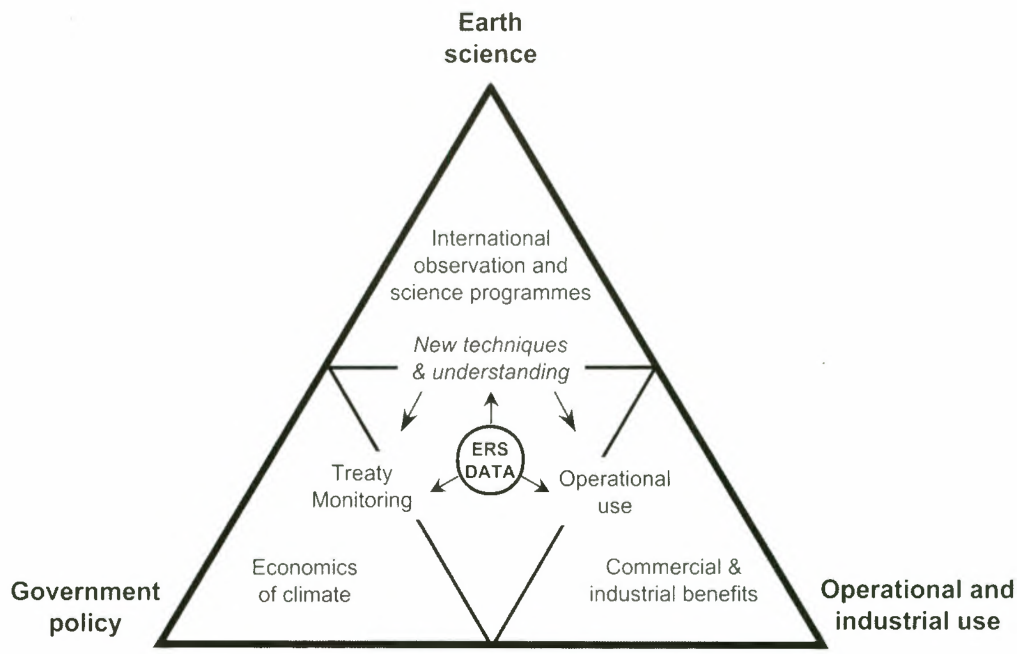
Since the launch of ERS-1 in 1991, the ERS missions have responded to the changing demands by continuing to provide a stream of very high quality data which satisfies most of the important requirements. In fact, the value of the data is increasing as a long term consistent record is established. There are three drivers for this increased value:

- most environmental monitoring tasks seek to identify subtle changes, so consistent data records over extended periods are fundamental;
- the initial approach to the study of process dynamics requires an empirical approach, for which extended data records are the foundation;
- most operational users are, quite reasonably, reluctant to rely on new data sources until their value has been established.

There are a number of important issues emerging in Europe as the basis for future development of EO in the Member States:

- the socio-economic importance of climatology and in particular the need for an independent view on the state of the global environment;
- the need to take scientific developments forward into commercially viable applications;
- selling European capabilities outside the European context;
- implementation of international science programmes and global observing systems.

Fig. 2.1: Major impacts of ERS



ERS is contributing to the realisation and future development of each of these issues as shown in Fig. 2.1. This chapter describes how.

2.1 ERS Contributing to International Earth Science

It is clear from the levels of international involvement in the ESA-organised ERS symposia alone that ERS data have been used worldwide. This has helped to place Europe and Canada in a prominent position within the international scientific community.

ESA SP-1176/I (Scientific Achievements of ERS-1) demonstrated the wide range of successful scientific applications of ERS data. Prominent among these are important contributions to international programmes of environmental observation and research.

Over the past three decades there has been a drive to integrate what were formerly regarded as separate systems. Models of the atmosphere and ocean are now coupled (see Case Study 1), land/coastal interactions are analysed (see Case Study 13) and land surface processes are increasingly handled within meteorological models (see Case Study 14).

Just as the science and modelling have become more integrated, the systems for observing and recording physical process behaviour have had to be coordinated, as have the efforts of individual scientists and research groups. This has led to the emergence of a number of international science programmes.

Satellite data are an important part of this research process. They offer global, repetitive data sets with consistent quality, addressing a large number of geophysical variables. In many cases, there is no alternative means of measurement. Data from the ERS satellites are an important part of the satellite contribution. Fig. 2.2 illustrates some of the important measurement

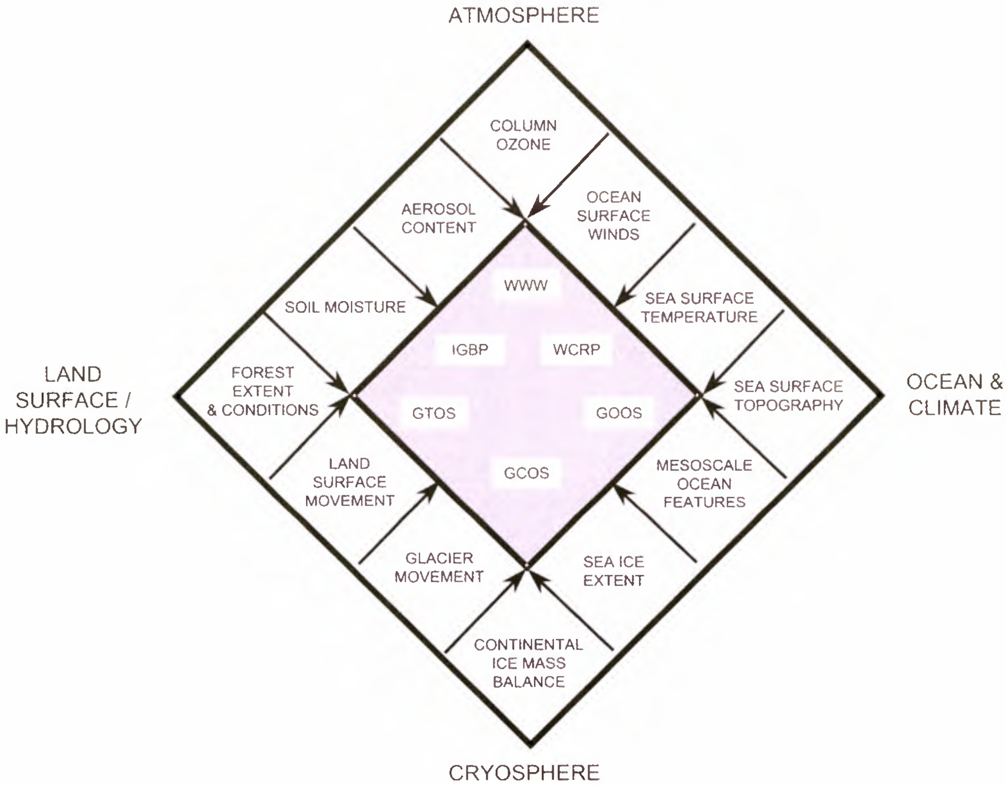


Fig. 2.2: Examples of the measurements which are used by international programmes and provided by ERS data

variables required by international programmes which are available from ERS data.

It should be noted that the programmes illustrated are only examples and many also have important subsidiary programmes. For example, the WCRP sponsored by the World Meteorological Organisation (WMO), Intergovernmental Oceanographic Commission (IOC) and International Council of Scientific Unions (ICSU) includes a number of activities to which ERS makes major contributions, as shown in Table 2.1.

The international programmes described above rely on observation and basic process research, but increasingly it is the modelling and data assimilation efforts which are crucial. This is partly because of the need to integrate science from different domains, but also to allow forecasts to be made for policy and decision making.

The most advanced system of modelling is that used for weather forecasting. ERS data are incorporated into the modelling process, along with measurements from other sources, using systems which take account of any specific biases and ensure that the data update the model variables without introducing instabilities. As progress with modelling continues, resolutions will increase, timesteps will reduce and, most importantly, integration will increase. All of these factors place growing demands on the data sources.

Fig. 2.3 illustrates some of the ways in which ERS data contribute to this modelling process.

WCRP Activity	Topics of research	ERS input examples
Global Energy and Water Cycle Experiment (GEWEX)	Studies of processes which determine the global hydrological cycle and energy budget	Regional scale soil moisture
Stratospheric Processes and their Role in Climate (SPARC)	Influence of the stratosphere on climate (such as ozone depletion)	Stratospheric ozone measurements
World Ocean Circulation Experiment (WOCE)	Studies of changes in the ocean circulation and heat storage resulting from atmospheric climate changes	Variations in sea surface topography with dense measurement network. High accuracy measurements of sea surface temperature
Tropical Ocean and Global Atmosphere (TOGA)	Observing and modelling the dynamics of the tropical ocean/ atmosphere system (1985 to 1994)	Highly accurate sea surface temperature measurements. Sea surface topography measurements
Climate Variability and Predictability Research Study CLIVAR)	Studies of climate variability on different timescales (seasons to decades)	Long term data series available from ERS-1 through ERS-2
Arctic Climate Systems Study (ACSYS)	Studies of the Arctic Ocean circulation, fresh water, sea ice and heat budget	Sea ice extent, age and dynamics monitored

Table 2.1: Importance of ERS measurements to WCRP activities

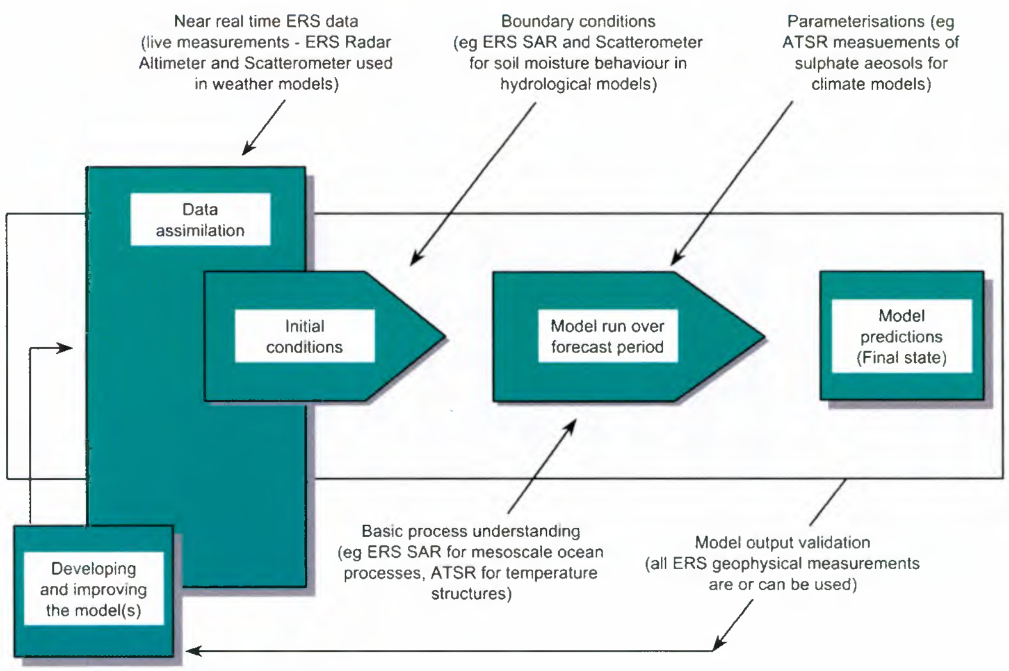


Fig. 2.3: ERS contributions to the modelling process

2.2 ERS Supporting Government Policy

The economic importance of climatology

The importance of the climate change issue is now universally recognised following the summit meetings at Rio in 1992 and Kyoto in 1997. What is increasingly recognised is the very large economic impact of the decisions made at these declarations in terms of:

- energy consumption and its effects on the market value of different energy sources;
- taxation and other instruments used to apply environmental policy;
- the effects of these policies in terms of peoples' lives - locating to reduce transport costs - effects on real estate values - effects on house building and thus on the rural landscape.

All of these changes, and many more, are based on our current understanding of the dynamics of the Earth climate and environmental system and how this may be affected by man-related factors such as carbon emissions. This understanding is known to be inadequate, leading to an unfortunate dilemma. Either take no action in the face of possible irreparable damage in the future, or be cautious and act to avoid the risk of damage. Neither of these actions is easy for any government, given the size and implications of the decisions. The best way forward is to ensure that our understanding of Earth system science is as comprehensive as possible. The first step towards this is to provide a sound baseline of measurements which are accurate, spatially consistent and maintain their accuracy over time.

An important aspect to emerge from the climate debate is the disagreement between different international groups on the status of the evidence on environmental change, how it should be interpreted and what the resultant actions should be. As a result of these differences, and taking due account of the scale of the implications, it has become increasingly evident that there is a need for Europe to be able to maintain an independent position. This position requires two key elements:

- an independent means of measuring and monitoring the key indicators of climate change at global and regional scales;
- world class scientific teams, capable of internationally credible scientific research which is policy-relevant.

It can be seen from earlier ESA publications (Section 1.4), and the case studies given below, that the ERS missions and their successors represent an important component of such an independent view. The data provided by the missions form a world class archive on which future European missions can build.

Monitoring international treaties

Environmental damage is an issue that crosses national boundaries. Consequently there are a large number of international treaties on the environment which complement national and regional legislation. These treaties have a number of common aspects:

- there is a considerable dependence on scientific understanding as the basis for the measures taken;
- methods of monitoring and implementation often vary from country to country;
- resources and capabilities for overall monitoring are often limited.

Taken together, these points imply that there is an important role for ERS data in defining future treaties and monitoring those which already exist. This is because ERS provides:

- insights into the processes which govern the state of the environment;
- consistent measurements of compliance for all parties to any agreement;
- global data which provide a cost effective complement to in-situ and other satellite data sources.

Table 2.2: Examples of international treaties which ERS is suited to monitoring

Treaty	Focus	Date
Habitats Directive (including Natura 2000)	EU	1992
Rio Declaration on Environment and Development	UNCED	1992
Agenda 21 (Rio de Janeiro)	UNCED	1992
Convention on Biological Diversity (Rio de Janeiro)	UNEP	1992
UN Framework Convention on Climate Change (Rio de Janeiro)	UN General Assembly	1992
Convention on the Protection and use of Transboundary Watercourses and International Lakes (Helsinki)	UN	1992
Convention on Environmental Impact Assessment in a Transboundary Context (Espoo, Finland)	UN	1991
Vienna Convention for Protection of the Ozone Layer including the Montreal Protocol on Substances that Deplete the Ozone Layer	UNEP	1987
EC Directive on Sewage Sludge Used in Agriculture	EU	1986
EC Directive on the Effects of Certain Projects on the Environment	EU	1985
Convention on the Conservation of European Wildlife and Natural Habitats (Bern)	Council of Europe	1979
Directive on the conservation of wild birds	EU	1979
Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention)		1972
Convention on Wetlands of International Importance (Ramsar)	IWRB/IUCN	1971
European Water Charter	Council of Europe	1968

Table 2.2 gives some examples of the treaties to which ERS data can contribute. In many cases, pilot projects and operational monitoring related to such treaties are already being conducted using ERS data. A particular example from Table 2.2 is the Ramsar convention on wetlands to which ERS data are contributing to provide a more comprehensive and consistent mechanism for wetland monitoring. It is important to remember that ERS data also play an important role in monitoring environmentally sensitive areas in response to national directives.

2.3 ERS Serving Operational Users and Enhancing Industrial Capability

It is well accepted that many applications of ERS are now operational, which means that they are routine rather than exceptional and are relied on by the users rather than seen as an optional extra. The ERS missions have been characterised by:

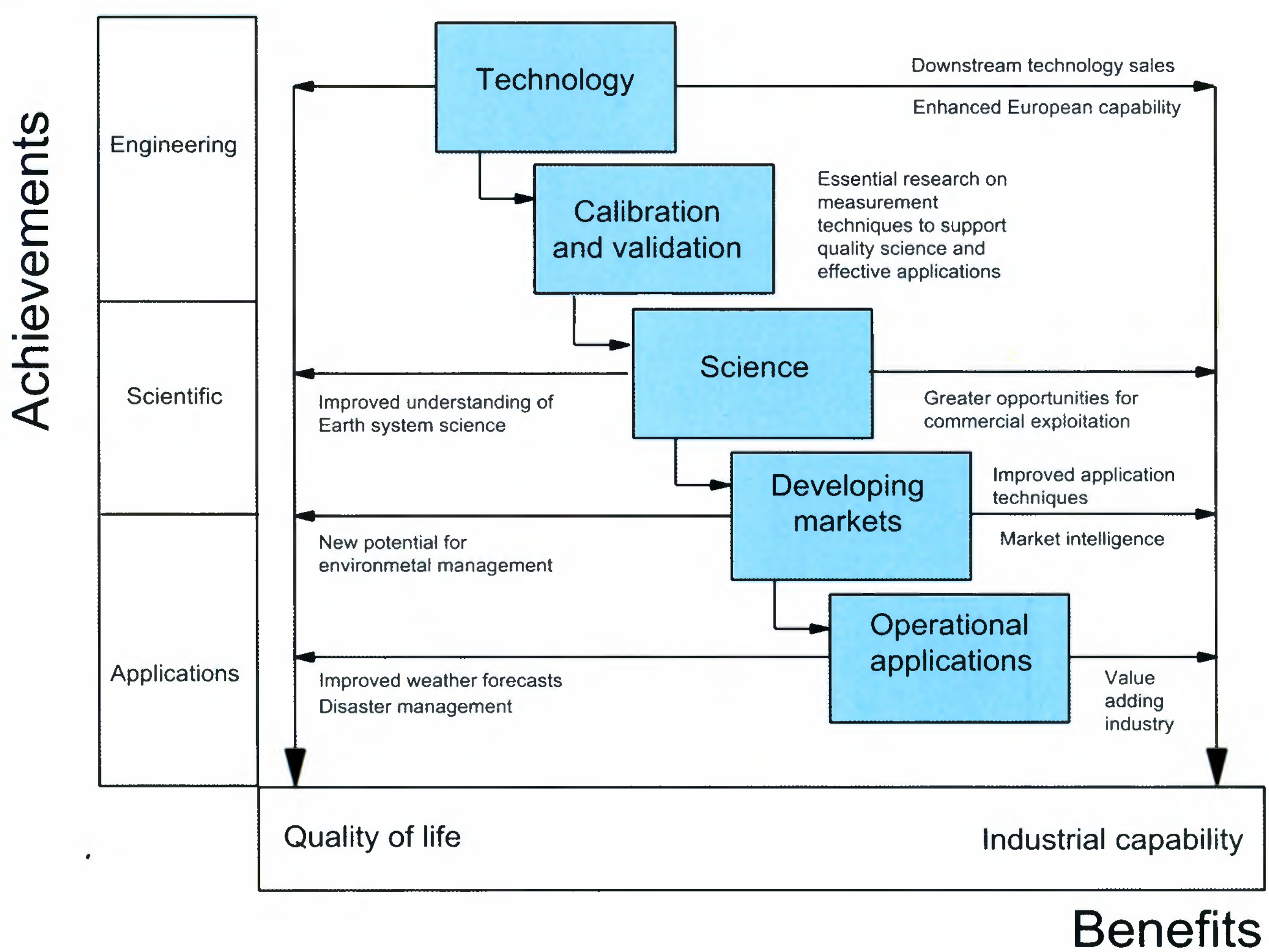
- high levels of system performance and reliability giving consistent long term data sets;
- ongoing calibration and validation campaigns, ensuring high quality accurate measurements;
- a large number of demonstrable successes in applying the data to real world problems;
- evidence that ERS data have contributed to commercial successes and the development of the European industrial capability.

An important finding for many applications is that the ERS data are not seen as a replacement for an existing data source, but as a completely new source which offers considerable advantages. Initially this requires new ways of working, which introduces a time lag between the use of the data and the realisation of benefits. For example, in hydrology, the measurements of soil moisture made by the ERS SAR offer new possibilities for spatially distributed models. These models, which have always been very difficult to initialise, can now move forward with greater confidence. This in turn will provide a much stronger capability to assess the possible effects of changes proposed within a river catchment.

The key stages in the success of ERS are described in Fig. 2.4, which shows how the 'operationalisation' of ERS has progressed since the early years of the mission. For example, the use of the Scatterometer has passed relatively quickly from the evaluation phase to fully operations status. This progression has led to the incorporation of a successor instrument the Advanced SCATterometer (ASCAT) on the operational meteorological satellite Metop. Developments in related fields such as GIS and data analysis are also enhancing the use of ERS data. To take the Scatterometer example again, the implementation of a 4-D variational analysis has allowed the ECMWF to use the Scatterometer data to better effect because it uses data at the time of observation rather than at the nearest synoptic interval.

The first two stages in Fig. 2.4 were described in more detail in the Engineering Achievements of ERS-1 (ESA SP-1176/III). These are the foundations of a successful mission, but it is important to recognise that this is a continuing process rather than a one off. In particular, work continues to refine our understanding of how the signals transmitted and/or received by the satellite sensors interact with the Earth's surface, thereby further improving the accuracy of the measurements. Similarly, improvements in orbit determination and modelling have allowed the accuracy of orbital position measurements to be refined, thus improving not only future measurements, but also the historical record.

Fig. 2.4: Stages in realising the benefit of ERS



Scientific achievements have continued to develop from those reported in SP-1176/I. These developments take a number of forms, including:

- new applications of the instrument data;
- greater spatial coverage and longer data records;
- improved data analysis techniques, leading to greater accuracy;
- observation of new phenomena;
- improved modelling.

This is evidenced by the growing participation in ESA ERS symposia (700 participants from 30 nations at Florence in 1997) as well as the increasing evidence of ERS results in mainstream scientific publications. A special edition of the Journal of Geophysical Research, published by the American Geophysical Union has also been dedicated to ERS data, entitled 'Advances in Oceanography and Sea Ice Research using ERS Observations.'

2.4 Summary of Benefits from the ERS Programme

Satellites are now a part of everyday life through applications of satellite communication and navigation. In these cases, the contribution of the satellites remains unseen, just as with earlier technologies of TV transmitter masts or navigation beacons. The same is true of the ERS satellites. While few have seen them and some may be unaware of their existence, their benefits are nevertheless enjoyed by the public at large. Furthermore, because of the long term view which underlies the mission philosophy, the value of the data from the mission will increase with time.

Benefits to the public from the ERS missions arise in a number of areas. Using the domains identified in the new ESA strategy for Earth observation, these are listed in Table 2.3.

Table 2.3: Summary of ERS benefits

Domain	ERS successes
Quality of life	• more informed and economically sound environmental decision making • enhanced hazard management through improved planning and post event analysis • improved weather and ocean forecasting • helping to build the knowledge base for a sustainable society
Scientific/technical capability	• a consistent long term data record for many key variables • measurements of key ocean, ice and land variables to support Earth system science • measurements of ozone and aerosols for atmospheric pollution studies • a consistent long term data record for climate research • increasing knowledge and fostering international cooperation among scientists. Europe is now a key partner in many investigations
Competitive industry	• developing industrial skills in a wide range of areas including radar technology, satellite construction and systems integration • improved export potential • dissemination of industrial skills within Europe • growth of a value-adding sector developing the applications of ERS data

3. Case Studies

This chapter contains 19 case studies highlighting scientific, policy and economic applications of ERS data that are emerging as key areas. They are divided into four categories as shown in Fig. 3.1, depending on whether they show how the data are contributing to Earth science, to the support of government policy (especially environmental policy), or to help operational users, or whether they show how new, improved techniques are increasing the information content and hence the support value of ERS data.

Chapter 1 emphasised that the previous series of three publications on the achievements of ERS-1 (Section 1.4) were quite comprehensive in their coverage of work. This document is more selective, using case studies to link together examples in a specific field. The criteria that have been applied to the case studies in Fig. 3.1 are that:

- new developments are evident in the work;
- a greater emphasis is placed on business development;
- the links to future programmes are emphasised.

A balance has been sought between work that is largely new, and work that represents a real development towards operational applications. This development process has continued since the early days of the missions.

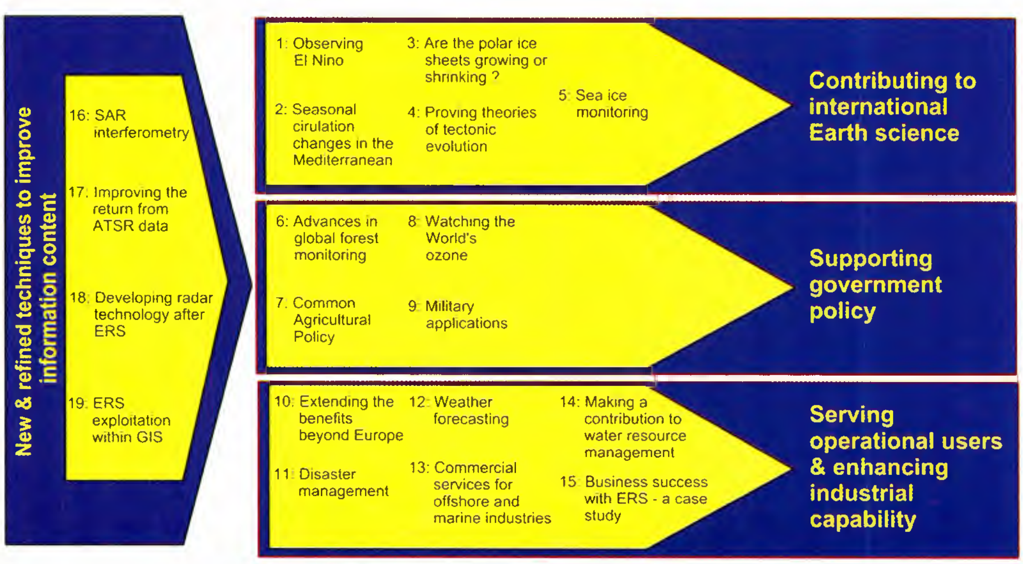


Fig. 3.1: Guide to case studies

Case Study 1: Observing El Niño

Category:	Contributing to international Earth Science
Description:	Radar Altimeter and ATSR data from ERS-1/2 help scientists to monitor the progress of an El Niño and to understand its impacts on regional weather conditions
Acknowledgements:	Austin Woods, European Centre for Medium range Weather Forecasting (ECMWF), UK Remko Scharroo, Technical University of Delft, The Netherlands GeoForschungsZentrum Potsdam (GFZ), Germany

Climate variations are normally measured in terms of decades or longer periods, but shorter term variations are also important. If the short term variations follow a pattern, this can be measured and understood, allowing the effects of the phenomena to be predicted with improved confidence. By understanding El Niño, the ability to forecast weather for a whole season is much improved.

The El Niño event

The El Niño is perhaps the most famous short term climate event. Its effects are linked to climate anomalies worldwide, including summer droughts in northern Australia, south-east Africa, north east Brazil and parts of Asia and central America, with devastating impacts on agriculture, growing seasons and thus world commodity supplies. The El Niño is also linked with wetter and milder winters in the northern hemisphere, often resulting in an increased incidence of serious flooding events. All of these changes have serious economic implications.

Normally, in the western tropical Pacific, the sea surface temperature is consistently high (about 29°C), the atmospheric pressure at sea level is low and as a result the precipitation is heavy. In the Eastern Pacific the water is normally cooler (between 21° and 26°C), the sea level pressure is higher and precipitation is low. The difference in sea surface temperature between these zones along the Equator is associated with westerly winds.

During an El Niño event, the warm pool in the western tropical Pacific spreads eastwards. At the same time, the regions of low sea level pressure and heavy rainfall move east, making the eastern and central Pacific become warm and rainy and leaving the western Pacific cooler and drier. This sequence is observed by the ERS Radar Altimeters as shown in Fig. 3.2. These instruments measure the sea surface topography, which is influenced by the variations in sea level pressure and temperature which accompany the El Niño. Fig. 3.2 shows how the sea surface topography during the El Niño varies from the conditions which would normally be expected.

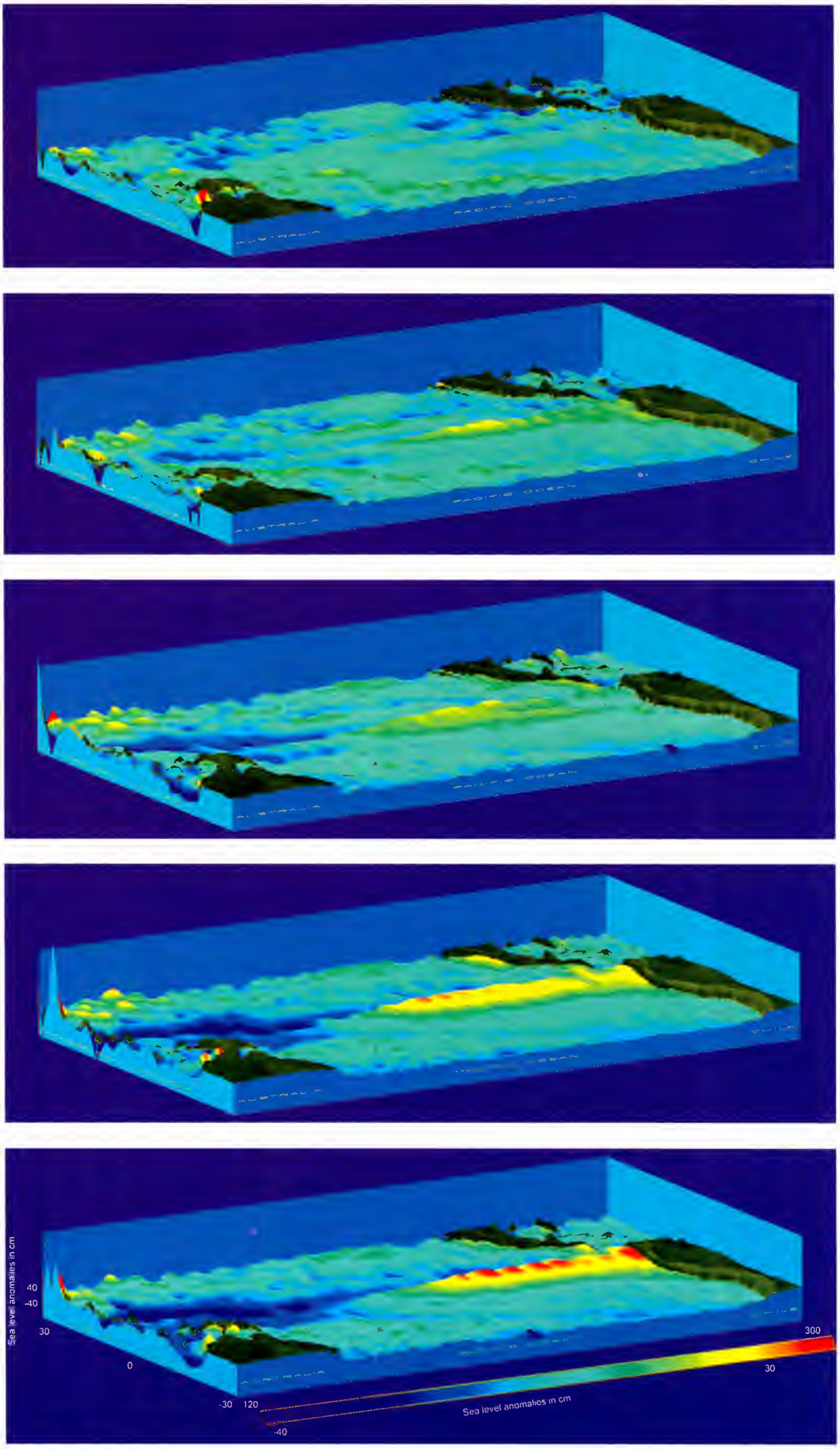


Fig. 3.2: Sequence of sea level anomalies (in cm) measured by the ERS radar altimeters from April 1996 (pre El Niño) to February 1998 (in the last stages of the El Niño) (ESA)

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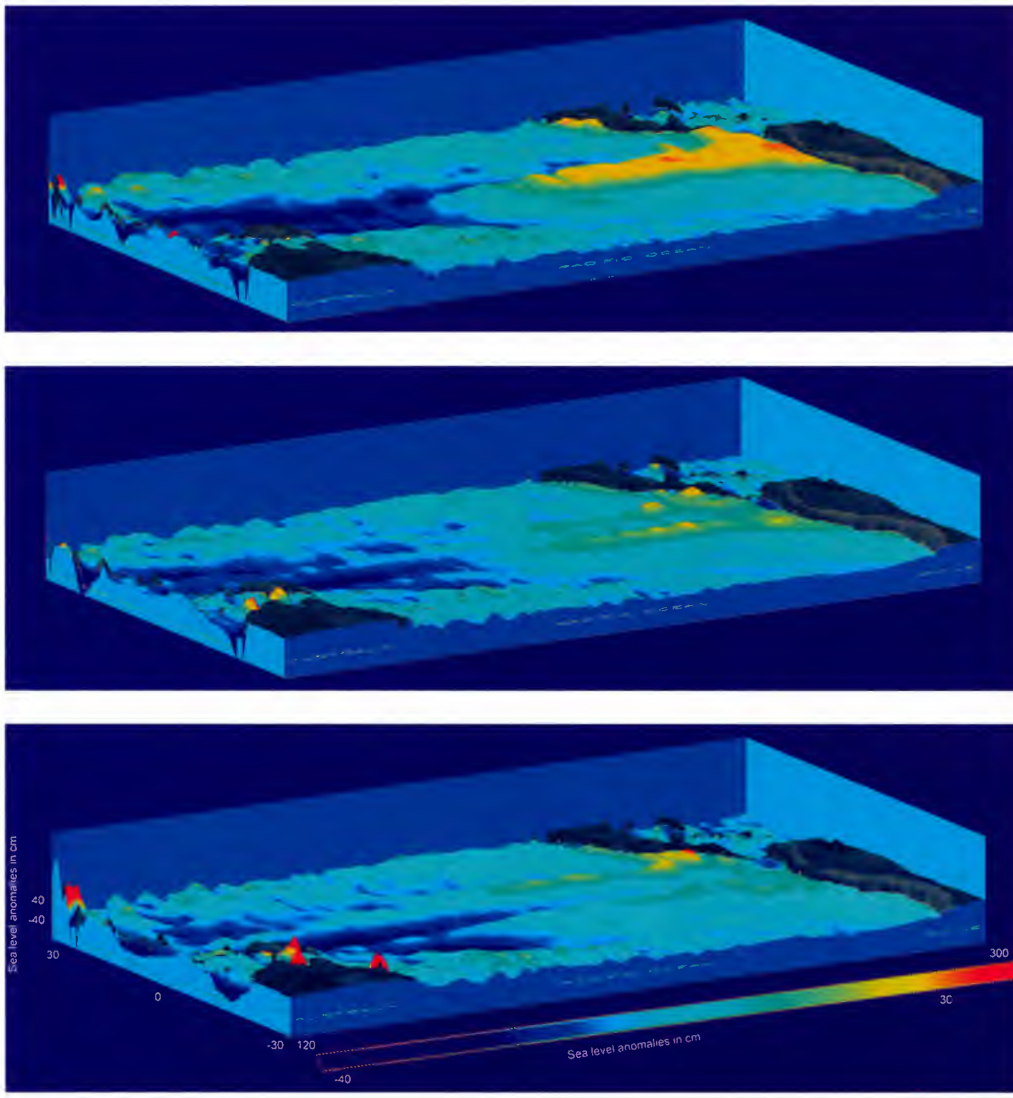
Fig 3.2 (continued)



As well as measuring the sea surface topography, ERS satellites also measure the sea surface temperature with the ATSR instrument. Fig. 3.3 shows the sequence of sea surface temperature change in the Pacific from June to September 1997 in terms of variations from normal conditions. The development of the tongue of warm water along the Equator can be seen in this sequence, particularly between the June and July images.

ERS provides a third source of complementary observations of the El Niño by making near surface wind measurements with the Wind Scatterometer.

Coupling ERS data with other satellite measurements and dedicated in-situ observations provided by large international programmes - and using these to drive numerical ocean models - has led to a better understanding of the dominant processes involved. This is how more reliable predictions of this climate event are achieved.

Recent work by ESA and university groups including TU-Delft has improved the known orbital accuracy of the ERS satellites from about 15 cm to as little as 3 cm, enabling new ocean features to be identified. These include the oceanographic equivalent of Rossby waves, which although they have a

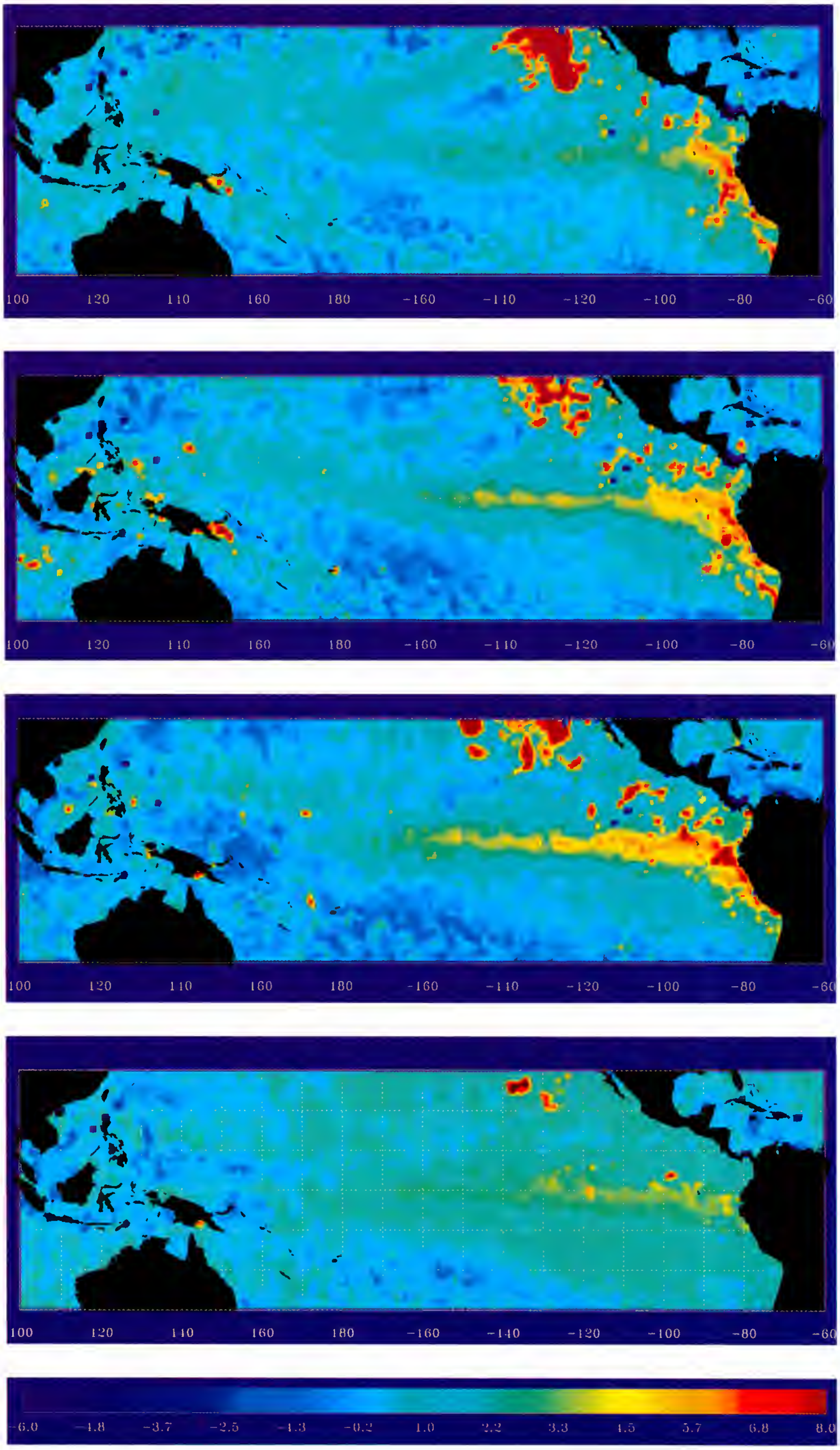


Fig. 3.3: Sequence of temperature changes in the Pacific, based on ERS ATSR measurements from June to September 1997 (ESA)

horizontal extent of over 500 km have a vertical signature of only 3 to 10 cm, making them particularly difficult to observe. Hitherto, these would have been lost in the measurement noise. This example of the continuous fine tuning of the engineering has increased the effectiveness of ERS data, particularly in monitoring phenomena such as El Niño. This continues to improve the science return from the mission.

As well as improving accuracy, ERS data on the El Niño are available shortly after observation, which allows the forecasts to be kept up to date. Fig. 3.4 shows an example of a weekly sequence of observations produced by the GeoForschungsZentrum Potsdam (GFZ) for a period of six weeks. This sequence shows a period during the retreat of El Niño. The El Niño index described in Fig. 3.4 illustrates the progress of the recent El Niño over the

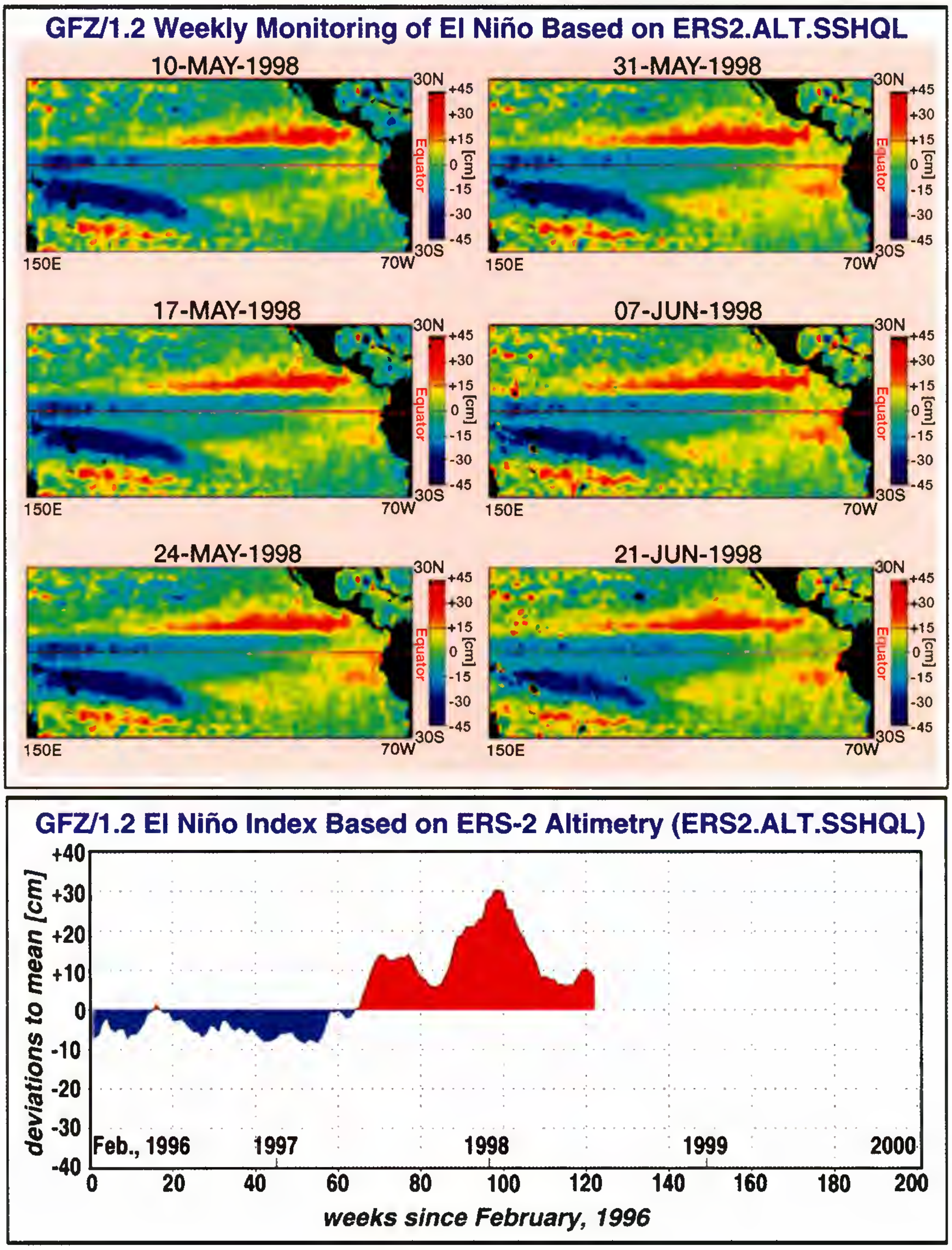


Fig. 3.4: Weekly sequence showing the retreat of the El Niño, based on ERS Radar Altimeter data GeoForschungsZentrum Potsdam (GFZ), Germany

whole of its lifetime. The index is based on deviations to a yearly sea surface mean for 1996 calculated for a region cut from the El Niño area in the Pacific Ocean (longitude between 268° and 272°; latitude between 10°S and 10°N). The small area is averaged to give the index which is then plotted with respect to time.

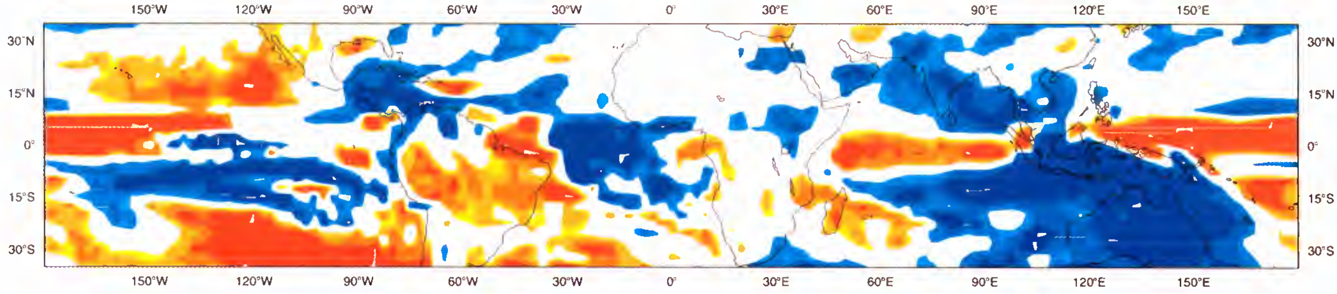
Seasonal forecasting

When making longer term weather forecasts, it is important to understand structural variations in the climate system, such as the El Niño, on a variety of timescales. Such forecasts need to take account of variables which have a longer term 'memory' and which may therefore influence the weather conditions beyond the period of the current weather system. Variables of this type include surface boundary conditions such as, ocean conditions, soil moisture and levels of snow cover. The best way to take account of these is to model them rather than treat them purely as boundary conditions. This allows the effects of feedbacks to be handled dynamically. It is notable that ERS data provide information on the variability of all three of the above variables, on a variety of scales. This allows effective parameterisation of the variables to be devised for modelling purposes.

A good recent example of integrated modelling for longer term weather forecasting is the seasonal forecasting programme operated since mid-1995 at the European Centre for Medium range Weather Forecasting (ECMWF). Through the use of coupled models of the atmosphere and ocean, this programme has taken advantage of both advanced buoy observations and satellite data, to provide effective predictions of temperature and rainfall up to six months ahead. Some of the most important measurements from satellites are, sea surface temperatures, surface winds and sea level anomalies. All of these are provided effectively by ERS instruments. Recent studies have further emphasised the sensitivity of these techniques to very small variations in sea surface temperature, reinforcing the need for ERS ATSR sea surface temperature data, which is calibrated to very high levels of accuracy and has been validated in a number of campaigns.

Fig. 3.5 shows an example of the predictions produced by the ECMWF system. This gives the probability of a given variable (precipitation in this case) being greater than the climate median. If the probability distribution for the coming season were identical to the long term climate pattern, the probability would be exactly 50%, and no signal would be present. In cases in which the probability is that there will be much more precipitation than normal climate statistics would suggest it is shown in dark blue, if the probability is for much less precipitation, it is shown in dark red. Lighter colours indicate intermediate conditions.

Fig. 3.5: Forecast of tropical rainfall 3 months ahead, from the ECMWF Seasonal Forecast System (ECMWF)



Summary

ERS data provide measurements which allow major components of the climate system, such as the El Niño to be better understood.
This, together with its contribution to the climate record, provides for better weather forecasting and climate prediction with the economic benefits these bring.

Case Study 2: Seasonal Circulation Changes in the Mediterranean

Category: Contributing to international Earth Science

Description: The ERS radar altimeters, when combined with data from the TOPEX/POSEIDON altimetry mission allow, scientists to monitor the surface topography of the Mediterranean. This in turn enables seasonal variations of the ocean circulation pattern to be better understood

Acknowledgements: P-Y LeTroan, CLS, Toulouse, France.

Methodology and approach

The circulation pattern of the Mediterranean has important implications for many applications, ranging from pollution dispersion to regional weather forecasting. The basic pattern of circulation is known, but the seasonal variations are less well understood. In this case study, the CLS Space Oceanography Division used ERS Radar Altimeters in combination with complementary data from the TOPEX/POSEIDON mission to provide the resolution necessary for monitoring these seasonal variations, as part of their EU MAST-III project.

Initially, the concept of using the combined ERS and TOPEX/POSEIDON data set was evaluated using a newly developed space-time objective analysis designed to take account of residual long wavelength errors. Sea level maps comparing specific observations to a four-year mean were calculated from TOPEX/POSEIDON alone, ERS-1/2 alone and the two sources combined. Fig. 3.6 shows the differences between the map from TOPEX/POSEIDON alone and the map produced using both sources.

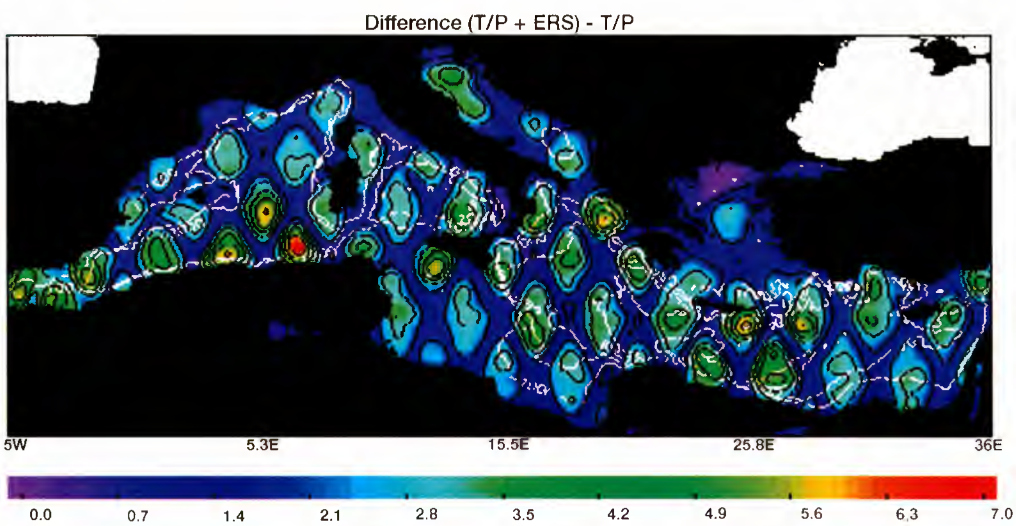


Fig. 3.6: Root mean square difference between TOPEX/POSEIDON only and TOPEX/POSEIDON and ERS-1/2 combined maps over the period October 1992 - December 1993 and April 1995 - September 1997. Units are from 0 to 7 cm (CLS)

It can be seen that in the areas between TOPEX/POSEIDON tracks, the differences can be as large as the signal itself (Fig. 3.7) emphasising the need for the additional data from ERS.

The reason that these two sources work so well together is that they have complementary sampling patterns and track densities. Merging data from these sources is therefore valuable for monitoring mesoscale signals in the Mediterranean, particularly when used with the new analysis approach. This methodology was shown to provide a much better mapping of sea level variations and ocean circulation in the Mediterranean sea.

Seasonal and interannual variations of the circulation
Fig. 3.8 represents the seasonal variations in sea level anomaly observed by the combination of TOPEX/POSEIDON and ERS-1 in autumn and winter of 1993, both averaged over a three-month period.

This figure and examples for other 3-month periods show the main characteristics of the Mediterranean circulation (Alboran gyres; Algerian eddies; Ionian, Ierepetra, Mersa-Matruh and Shikmona gyres, etc.) and the seasonal variations in these features (strengthening of cyclonic circulation in winter, strengthening of anticyclonic Alboran and Ierepetra gyres in summer and autumn). TOPEX/POSEIDON and ERS-1/2 together reveal some of the particularly strong signals very well, in particular the Alboran gyres east of Gibraltar and the Ierepetra gyre south-east of Crete. The strong seasonal signal from the Ierepetra gyre is probably linked to direct forcing by strong Etesian winds, which interact with the Cretan topography.

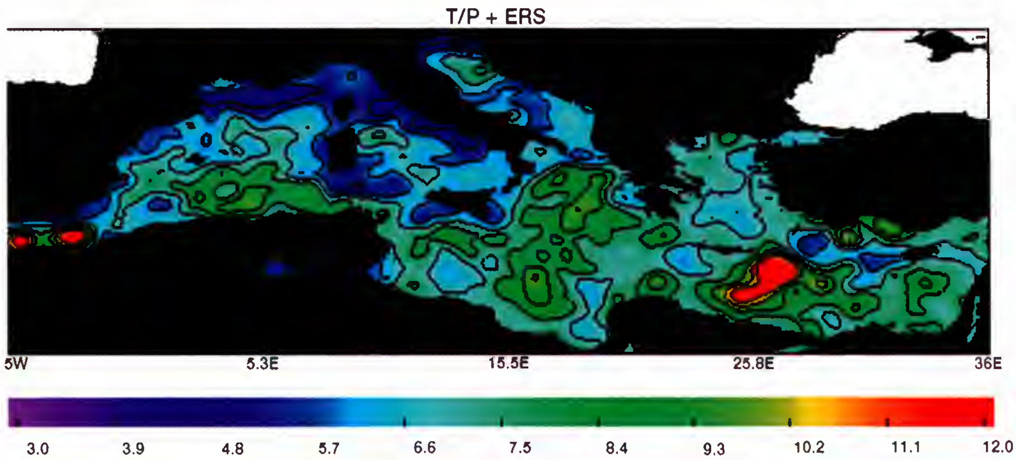


Fig. 3.7 : RMS of sea level variability from T/P and ERS-1/2 combined maps over the period October 1992 - December 1993 and April 1995 - September 1997.
Units are from 3 to 12 cm (CLS)

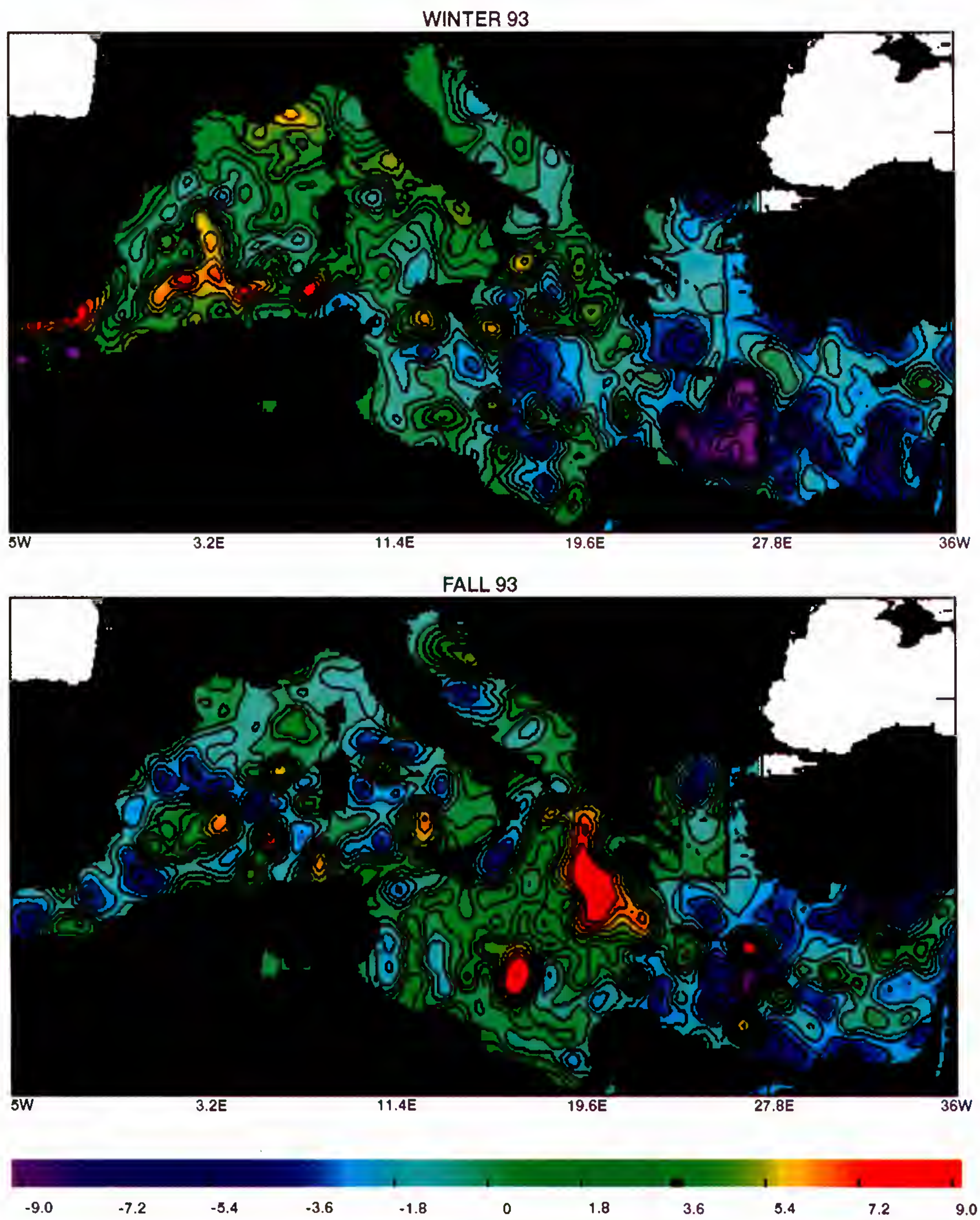
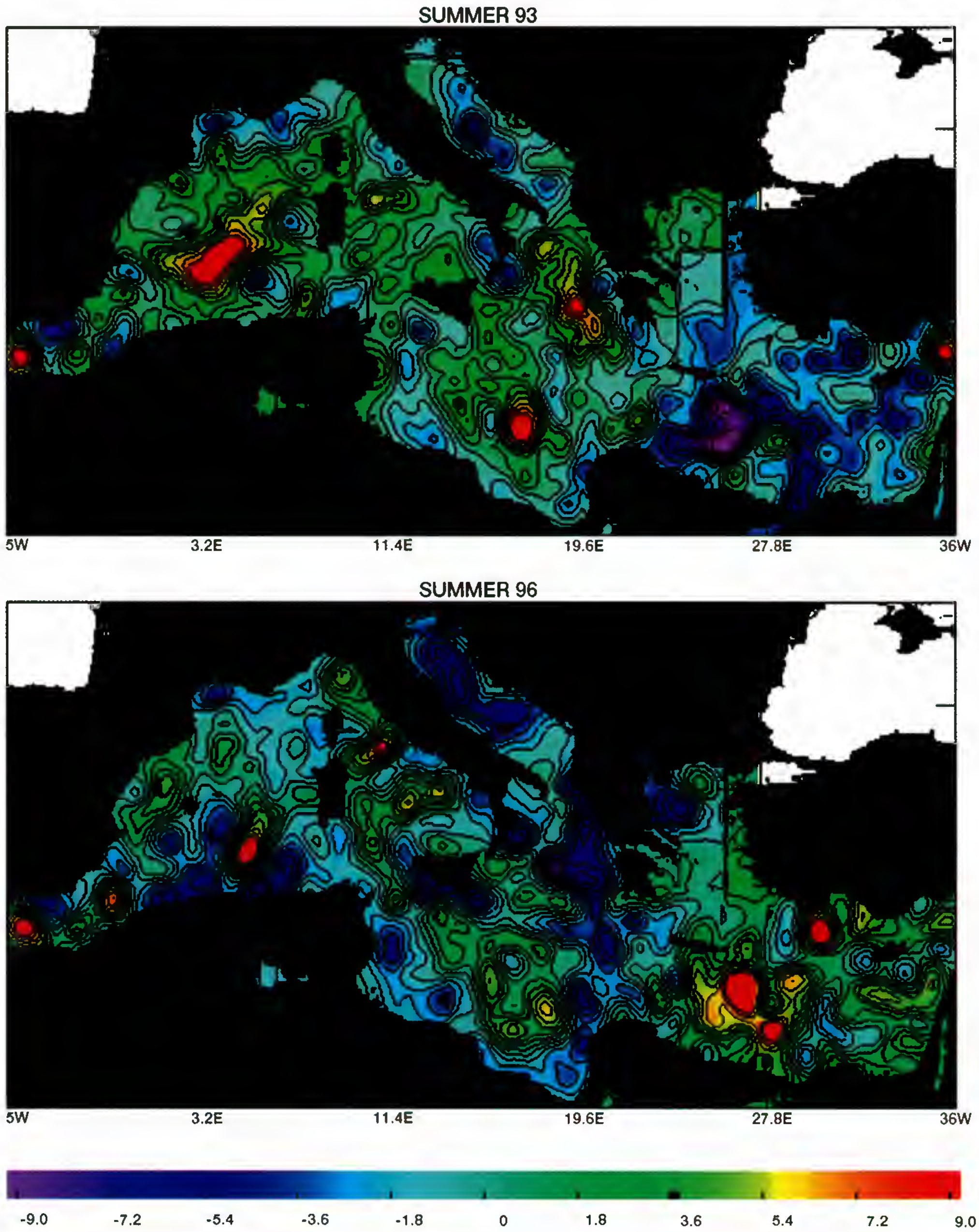


Fig. 3.8: Sea level anomaly (relative to a 4-year mean) observed by the combination of Topex/Poseidon and ERS-1 in Winter 1993 and Autumn 1993. The map is an average over a three-month period. The scale is from -9 cm (blue) to +9 cm (red) and contour interval is 1 cm (CLS)

Fig. 3.9 : Sea level anomaly (relative to a 4-year mean) observed by the combination of Topex/Poseidon and ERS-1/2 in Summer 1993 and Summer 1996. The map is an average over a three-month period. The scale is from -9 cm (Blue) To +9 cm (Red) and the contour interval is 1 cm (CLS).



There is also a large interannual variability, particularly in the Levantine basin. This is exemplified in Fig. 3.9 which shows the combination of TOPEX/POSEIDON and ERS-1/2 data in Summer 1993 and Summer 1996.

The interannual variability in the Levantine basin is thought to be related to a change in the Etesian winds and the switching from a state with a well developed Ierepetra gyre to a state with a large anticyclonic system in the central Levantine basin (with the development of the Mersa-Matruh and Shikmona anticyclonic gyres).

These results agree well with what is known about individual elements of the circulation in the Mediterranean. In addition, they provide for the first time an overall view of the seasonal and interannual variations. The successful combined use of altimetry data from two missions with complementary sampling regimes emphasises the need to maintain this capability in the future.

Summary
Data from the ERS Radar Altimeters and the TOPEX/POSEIDON mission combine well to help our understanding of mesoscale phenomena and circulation in the Mediterranean. This results from the fact that although the coverage densities and repeat frequencies are different, they are strongly complementary. This dual capability needs to be maintained beyond the Envisat era, to ensure that consistent long term records are available to support these important studies.

Case Study 3: Are Polar Ice Sheets Growing or Shrinking?

Category:	Contributing to international Earth Science
Description:	The ERS Radar Altimeters and SARs are monitoring the patterns of change in polar ice sheets and helping us to understand the driving processes
Acknowledgements:	MSSL, UK Michael Anzenhofer, German Remote Sensing Data Centre (DFD), Germany Søren Madsen, Technical University of Denmark

The processes controlling change in the polar ice sheets are important elements of the global climate system. They are also very sensitive indicators of change within this system. ERS data are being used to determine the balance between growth and decay in the polar ice sheets on two scales. Firstly, by developing topographic maps of the ice sheets and then re-creating them at a later date, it is possible to assess whether ice is accumulating or melting at the continental scale. Secondly, by monitoring the behaviour of major system components such as large glacier systems, it is possible to understand the processes which drive the continental changes.

At present, it is not clear whether the balance between the accumulation and loss of ice from the Antarctic ice sheet is positive or negative. The annual height change is constrained by known physical processes to a maximum of about 5 cm. The rate of mass loss or gain of the ice sheet may therefore be determined if the average height of the ice sheet can be repetitively determined with this accuracy. Such an accurate topographic map of the ice sheet surfaces is very difficult to obtain from in-situ sources. Even where maps have been created from in-situ sources, they are rarely accurate and are difficult to update consistently. The Radar Altimeters on the ERS-1 and ERS-2 satellites make the measurement to the required accuracy, provided careful processing is applied.

The ERS satellites completely survey the height of the Antarctic ice sheet to as far south as 2° every 35 days. Accordingly, an accurate map of the height of the ice sheet can be made approximately once per month. Maps of changes in height can then be produced by simply differencing two of these height maps. When several maps of the ice sheet height change have been produced, the average change in height for the whole of the ice sheet can be calculated.

Over 20 million height estimates from the ERS-1 Radar Altimeters have been used to generate a 10 km digital elevation model of the ice sheet which is accurate to better than 1 m for slopes less than 0.5°, as shown in Fig. 3.10. Recent developments have refined the technique using high resolution airborne laser altimetry surveys, continued pulse analysis and improved understanding of the effects of surface roughness.

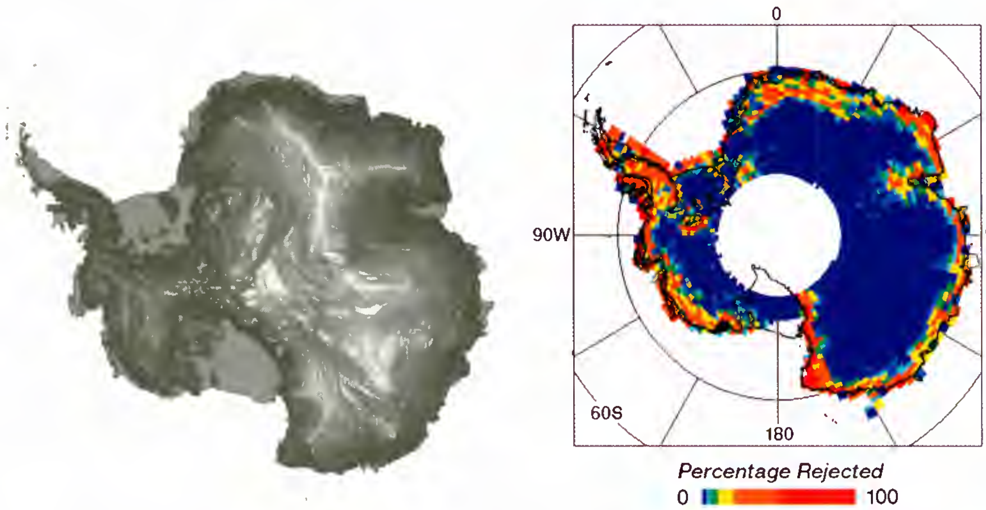


Fig. 3.10: A shaded relief map of the Antarctic ice sheet derived from ERS-1 Radar Altimeter data and map showing where the slope assumptions are valid (MSSL)

Data now being processed will permit changes to be determined over a five-year interval, the minimum period over which significant changes can be identified. It is expected within the next few years to settle the question of whether the Antarctic Ice Sheet is growing or shrinking. The results of the research over the earlier years of the ERS programme are given in Figs. 3.11 and 3.12.

To illustrate the global application of altimetric ice elevation measurements, Fig. 3.13 shows an elevation map of the Greenland ice sheet, the other major land based ice sheet. The elevations, averaged to 3 minutes of arc, are also shown for the surrounding ocean areas. A total of 6.7 million ERS Radar Altimeter measurements were used to create this map, all of them taken in the winter of 1994/95.

To interpret large scale changes in the ice sheets, it is important to understand the mesoscale processes which determine the extent and distribution of this change. In a study recently published in the Journal 'Nature', it has been

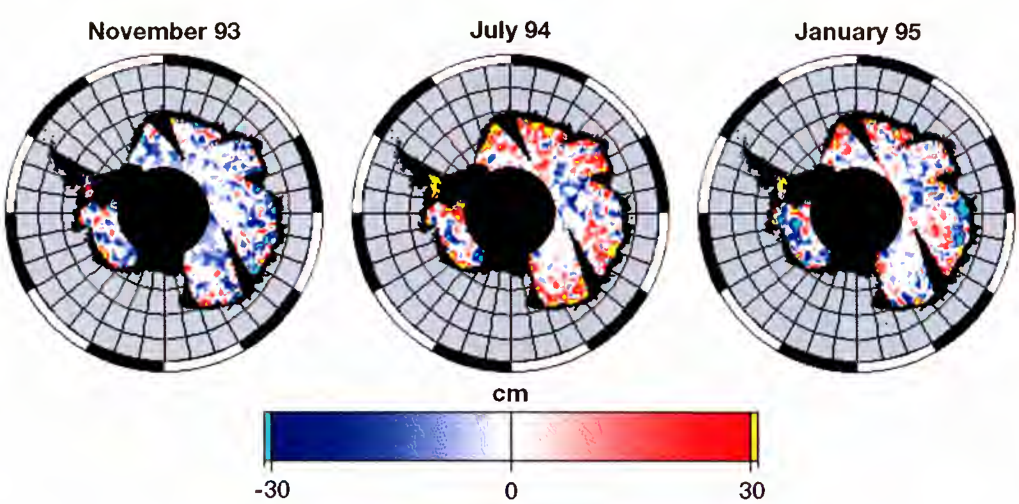


Fig. 3.11: Changes in Antarctic elevation relative to a July 1993 baseline (MSSL)

Fig. 3.12: Average changes in the elevation of the Antarctic ice sheet (MSSL)

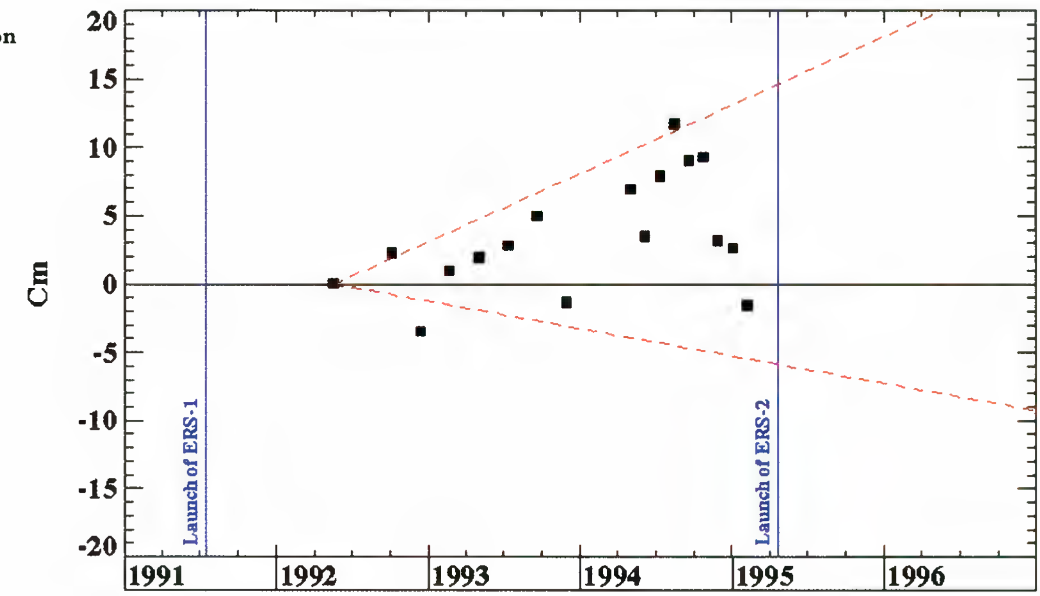
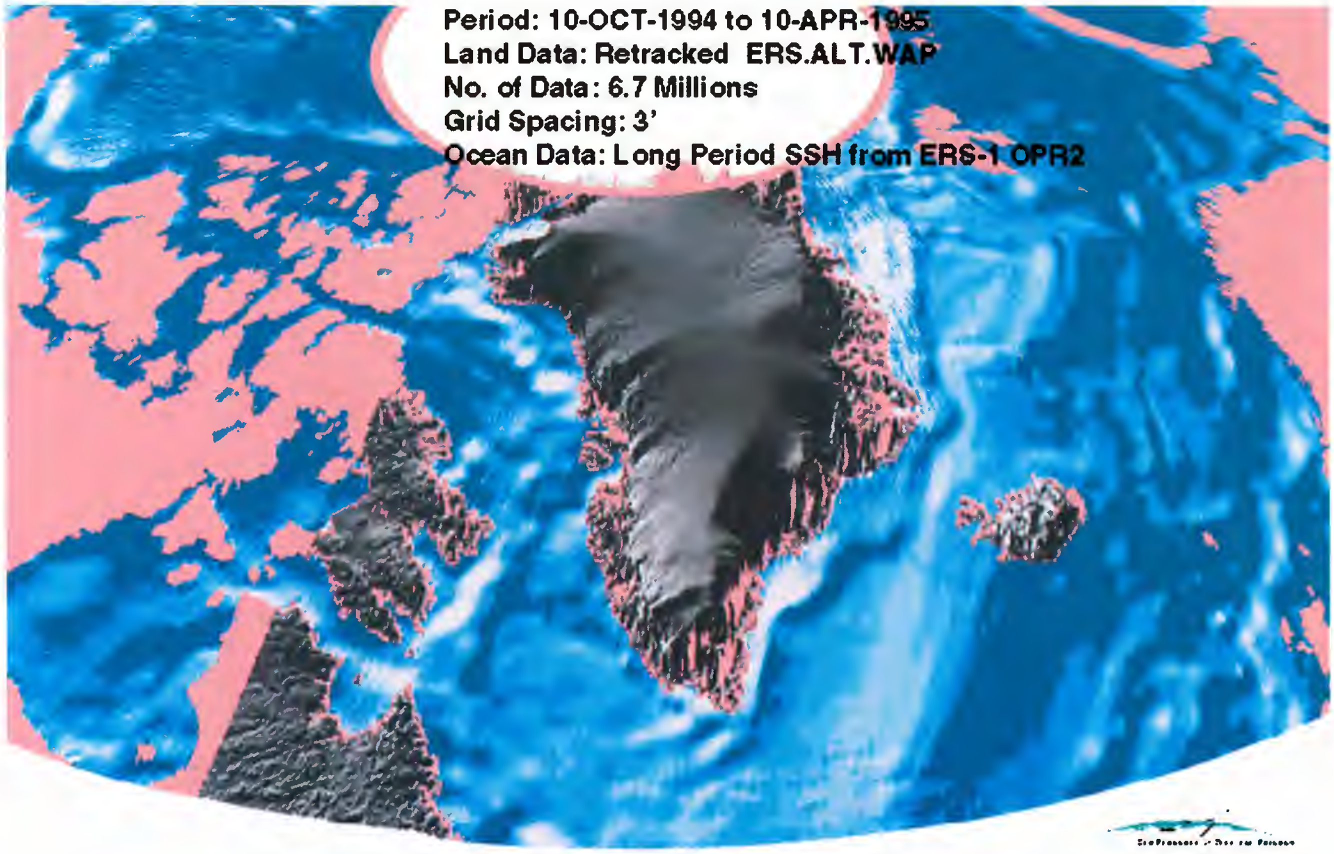


Fig. 3.13: Greenland & Arctic ice shown as shaded relief. (GeoForschungsZentrum Potsdam (GFZ), Germany)



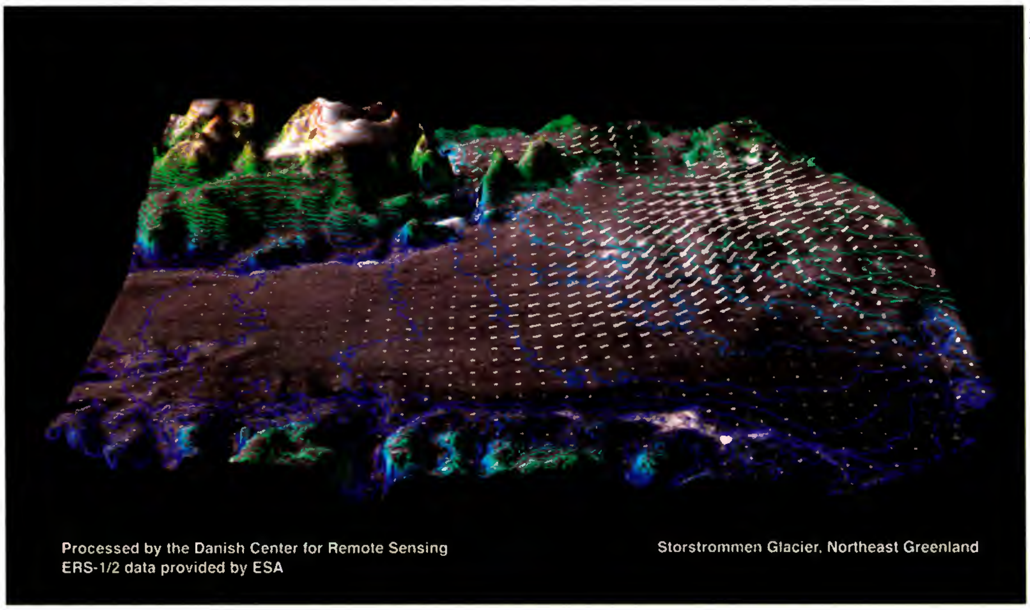


Fig. 3.14: Perspective view of the flow field on the Storstrømmen Glacier, northeast Greenland (Technical University of Denmark)

shown how, by using SAR interferometry with data from the ERS Tandem Mission, it is possible to estimate full three dimensional flow patterns for glaciers, including outlet glaciers where the flow direction is not already known. It is the availability of interferometric pairs for both ascending and descending passes that makes the full determination of three dimensional velocities possible. Two interferograms were used for each satellite track to calculate topography and displacement, overcoming the need for an independent digital elevation model.

The technique has been applied to glaciers in the North of Greenland, where GPS measurements of glacier movements have been made which allow validation of the measurements. To quote from the Nature article, 'radar measurements such as these (ERS SAR data), made regularly and at high spatial density have the potential to enhance our understanding of glacier dynamics and ice sheet flow, as well as improve the accuracy of glacier mass balance estimates.'

Fig. 3.14 shows a perspective view of the flow field with white arrows indicating the glacial flow direction. The diagram shows evidence of slowing of flows towards the end of the glacier (to the left of the figure). This is the expected condition, given that the glacier has recently surged. With further refinements to the technique, it is expected that accuracies of 1 to 2 m per year could be achieved.

Fig. 3.15 shows the area covered by ascending and descending passes in which the analysis was conducted. The tie points (on bedrock) used to calibrate heights and velocities are marked with crosses. Fig. 3.16 shows the full 3-D velocity vectors established using the technique.

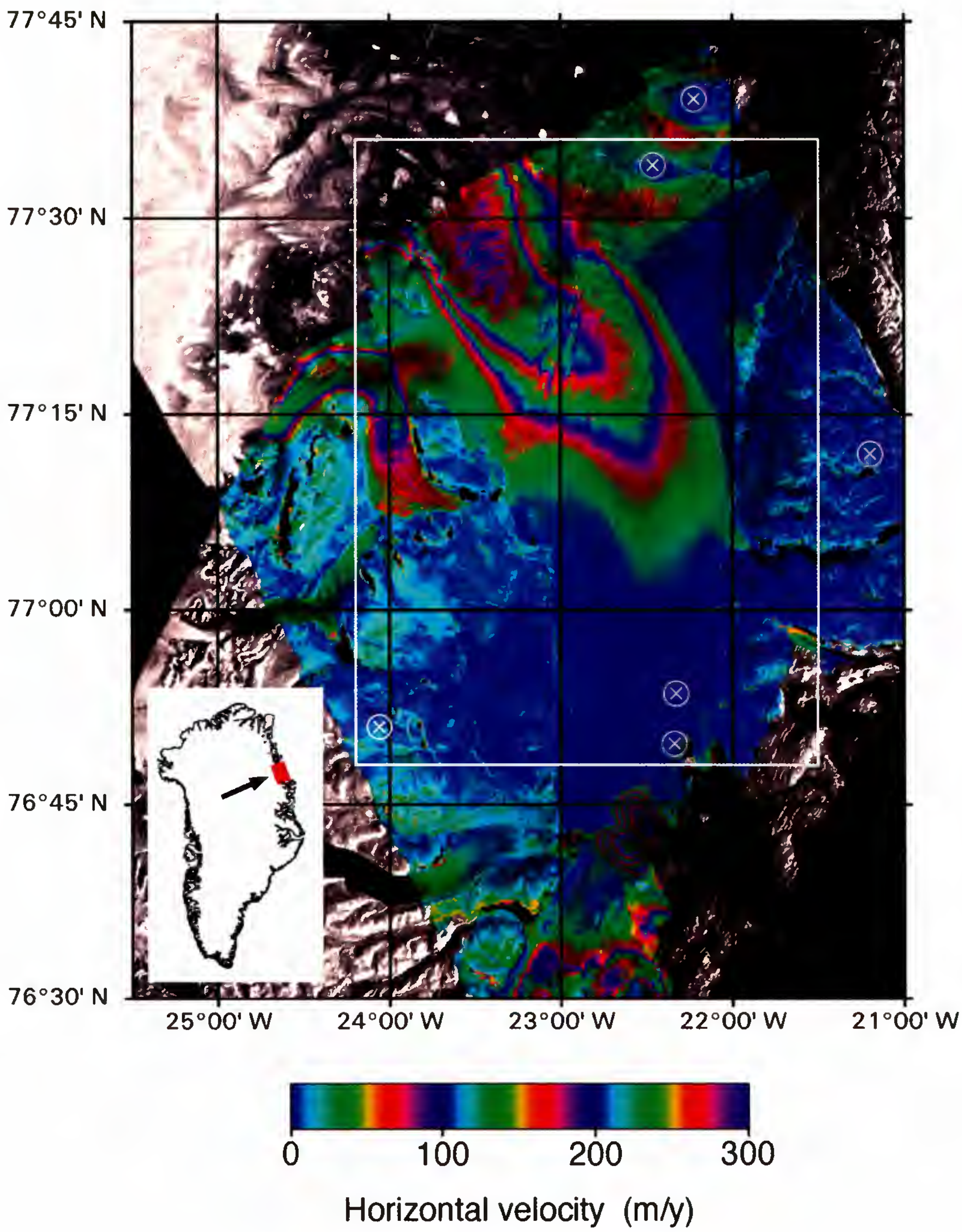


Fig. 3.15: Annual horizontal displacement in aregion around the Storstrømmen Glacier, northeast Greenland (the coloured area is that covered by both ascending and descending tracks) (Technical University of Denmark)

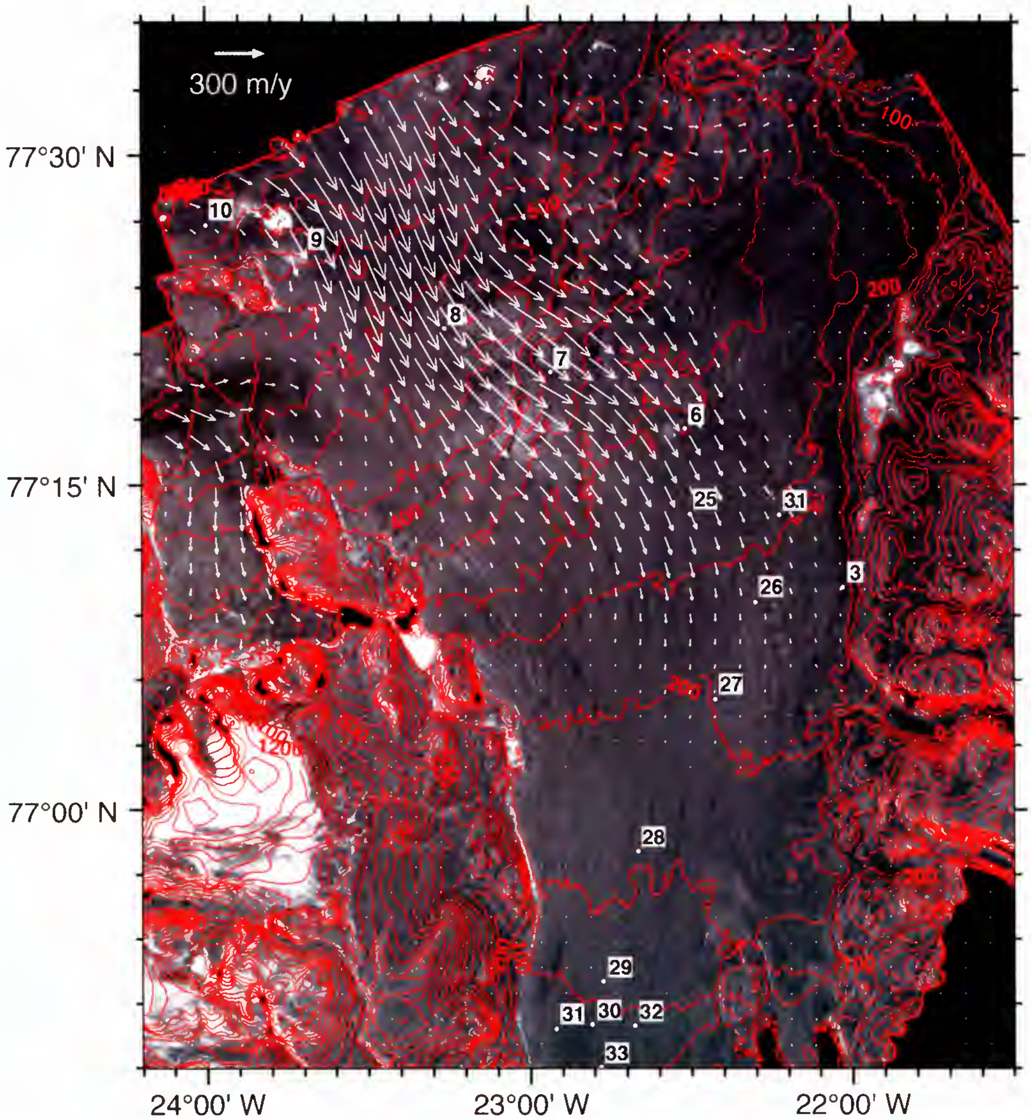


Fig. 3.16: Elevations and flow vectors derived from ERS SAR data. White dots show the numbered locations of stakesused to provide in-situ validation (Technical University of Denmark).

Summary

By measuring the large scale changes in the elevation of the polar ice sheets using the ERS Radar Altimeters, methods for measuring the overall ice mass balance are being developed. Measuring glacier flow characteristics with ERS SAR interferometry helps us to understand the reasons for the observed changes.

Case Study 4: Proving Theories of Tectonic Evolution

Category:	Contributing to international Earth Science
Description:	ERS Radar Altimeter data have been processed to provide a unique gravity map of the sea bed off Antarctica, including areas covered by sea ice. These maps allow theories on the tectonic history of the area to be confirmed, to the benefit of both science and mineral exploration. More conventional use of ERS data for mapping the structure of the ocean floor has also gained international acceptance.
Acknowledgements:	Seymour Laxon, University College, London, UK Dave McAdoo, NOAA, Washington T.J. Majumdar, Indian Space Applications Centre

Mapping the structures of the ocean floor is difficult, particularly in polar regions where sea ice regularly covers the ocean surface and the climate makes operations difficult for survey ships. Despite these difficulties, such mapping is needed, both from the scientific perspective of tectonic evolution and also for mineral exploration companies as the search for non renewable resources reaches into more remote areas.

The Radar Altimeters on the ERS satellites offer the potential for tectonic mapping of the polar ocean basins because, unlike other altimetry missions, the ERS orbit allows observations right up to 82° latitude. This potential can only be realised because of work at UCL (UK) and NOAA (USA) which allows the sea surface topography to be determined when the sea surface is covered with sea ice. Variations in the sea surface topography can then be related to the shape of the sea bed. Initially, this work was applied to the Arctic Ocean when a previously undetected spreading ridge was discovered in the ocean basin north of Canada. This was presented in the Scientific Achievements of ERS-1 (SP-1176/I). Since then, the technique has been validated, developed and applied to areas off the coast of Antarctica where the signal is weaker, placing greater demands on the technique.

To validate the method, a comparison was made between ERS-1 marine gravity measurements and those obtained from an aircraft survey carried out by the US Naval Research Laboratory (Fig. 3.17). Agreement between the longer wavelength components is extremely close. At shorter wavelengths the ERS-1 gravity measurements exhibit oscillations which are likely to be caused by height errors left by retracking over sea ice.

In this new application of the technique, a gravity map of the sea floor adjacent to Antarctica has been developed and is shown in Fig. 3.18. This provides observations which allow theories on the tectonic history of the area to be verified. These theories surround the earliest stages in the break-up of the supercontinent Gondwanaland some 100 million years ago. Ten years ago, workers in the US attempting to fit the jigsaw of current continents back

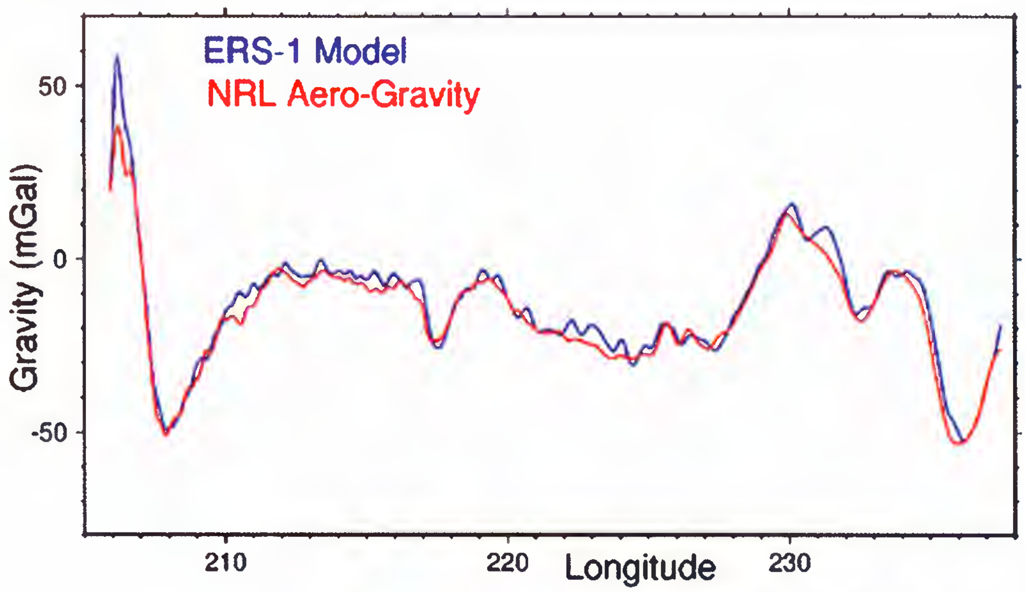


Fig. 3.17. Comparison of ERS-1 and NRL airborne gravity measurements over a trackline in the Canada Basin. The inset image shows the locations of the track (airborne data are courtesy of Skip Kovacs and Jon Brozena, Naval Research Lab., Washington).

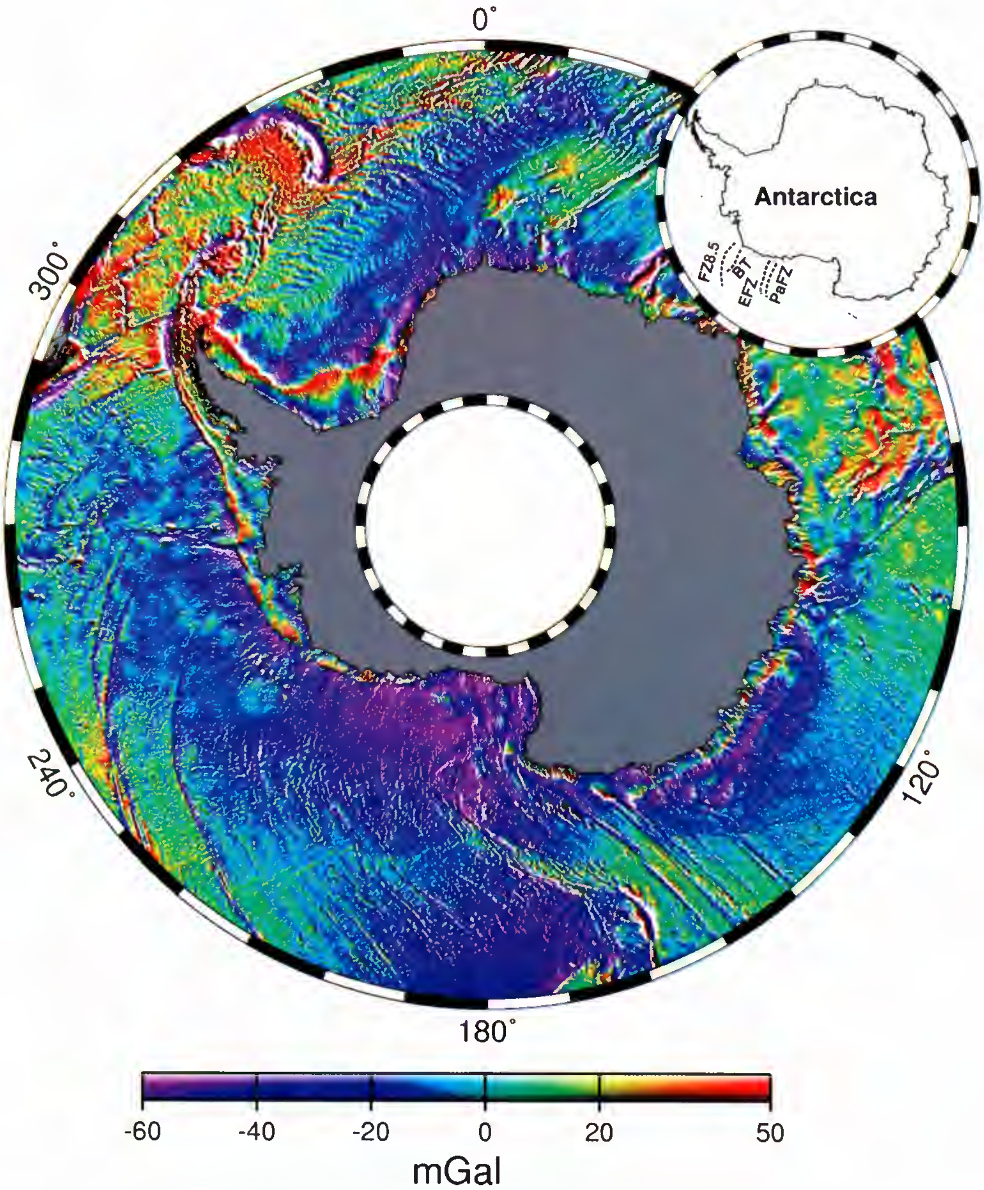


Fig. 3.18: Gravity map of the area around Antarctica (UCL/NOAA)

together discovered a mismatch in the area where the Campbell Plateau, on which New Zealand is now located, broke away from Antarctica. To explain this mismatch they proposed that a previously unknown tectonic plate, the 'Bellingshausen plate', must have existed at the time of the break-up and that it has since fused with the current Antarctic plate. However a lack of data concerning the structure of the seafloor in the region has meant that this theory has remained unproved since it was first proposed.

By mapping the fracture zones adjacent to Antarctica it has been possible to trace the paths taken by Antarctica and the Campbell Plateau during the earliest stages. A divergence of the fracture zones close to the continent provides the first firm proof for the existence of the Bellingshausen plate. This result has a major impact on our understanding of the break-up of Gondwanaland and the tectonic evolution of Antarctica. The new results are of great interest to geologists and to those interested in the tectonic evolution of our polar regions. Higher resolution versions of the Arctic Ocean gravity field have also attracted considerable interest from oil exploration companies for whom the data provide a valuable overview of regions and allows the identification of target areas for more detailed surface survey.

ERS data have thus provided the first view of some of the most poorly mapped areas of the ocean floor. The results have solved two major remaining problems in the Earth's tectonic history, namely the origin of the Canada Basin and the existence of the Bellingshausen plate. Efforts are now concentrated on better understanding the nature of the height signal obtained over sea ice in terms of instrument response to the return echoes. Data from ERS-2 are being used to reduce the remaining noise in height retrievals, allowing further refinements. The contribution of ERS data to this investigation is to allow gravity fields to be determined in inhospitable areas where conventional surveys are very difficult. The measurement of gravity fields through sea ice is a particularly novel development.

In parallel with these developments, ERS Radar Altimeter data are increasingly used for oil exploration in open oceans, even where conventional surveys exist or are planned. For example, recent work by the Indian Space Application Centre, using ERS-1 data, found the 'altimeter data to be useful as a time and cost effective reconnaissance tool for mapping the megastructures in the offshore region of India.' (T.J. Majumdar et al International Journal of Remote Sensing, July 1998). Fig. 3.19 shows the level of agreement between the ERS-1 Radar Altimeter data and the ship measurements made as part of this study.

Summary
The original implementation of this technique using the ERS Radar Altimeter to determine the gravity of the Arctic basin through sea ice was responsible for the discovery of an extinct spreading ridge. New applications of the technique to Antarctica required considerable refinement of the method, but it has provided invaluable information for mineral exploration companies operating in the area, as well as contributing to studies of tectonic evolution.

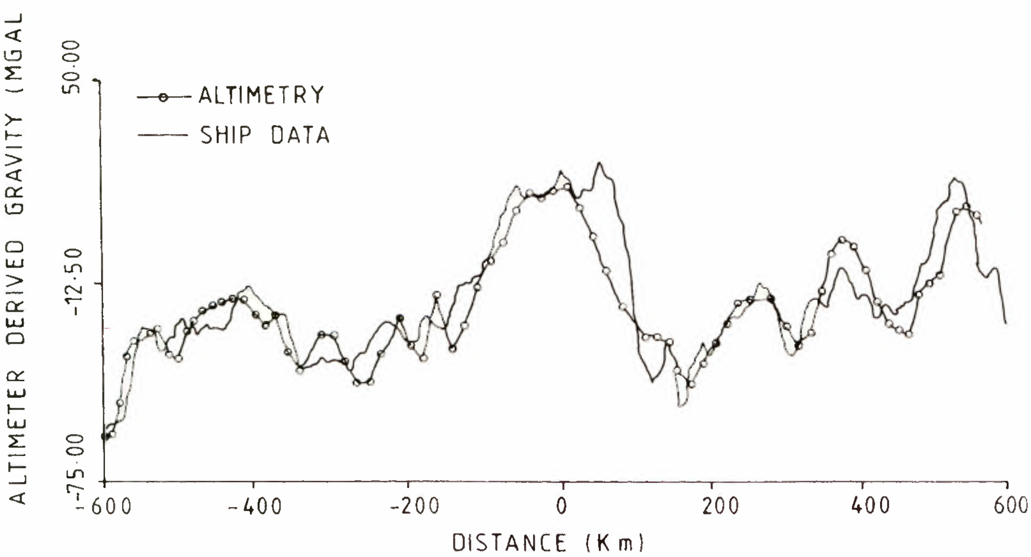


Fig. 3.19: Shipborne vs altimeter-derived gravity across a 90°E ridge (Indian Space Applications Centre/International Journal of Remote Sensing)

Case Study 5: Sea Ice Monitoring

Category: Contributing to international Earth Science

Description: Two aspects of sea ice monitoring are discussed. The ERS Radar Altimeters allow a detailed picture of the sea ice edge to be built up over a period of 35 days. An overall picture of sea ice cover can be provided more quickly using the ERS Scatterometers, which also allow details of the spatial distribution of different aged ice to be extracted

Acknowledgements: GeoForschungsZentrum Potsdam (GFZ), Germany
Francis Gohin, IFREMER, France

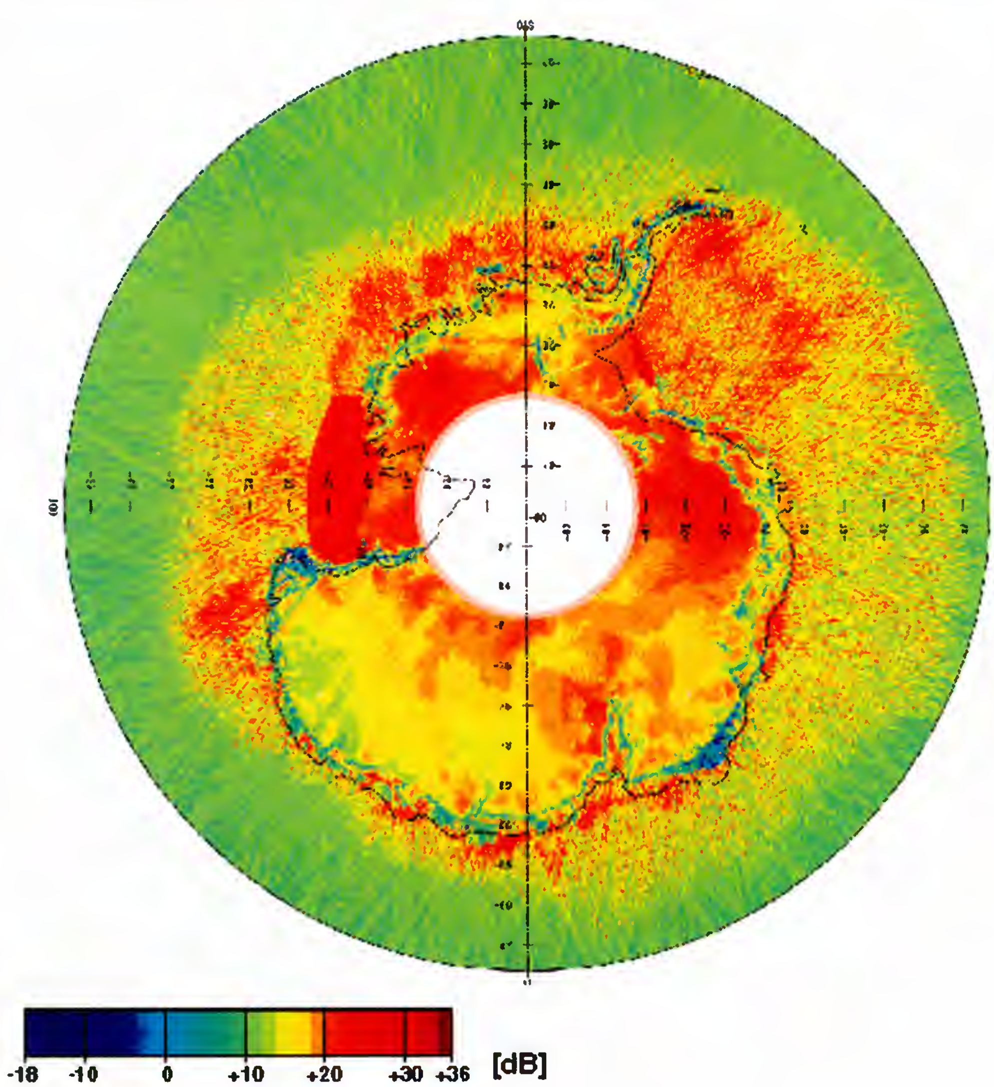


Fig. 3.20: Overview of Antarctic sea ice from the ERS Radar Altimeter: (GeoForschungsZentrum Potsdam (GFZ), Germany)

All of the instruments on the ERS satellite are capable of monitoring sea ice cover. The SAR and ATSR provide detailed coverage of small areas. The Radar Altimeter provides good resolution in the line of its ground track, and builds up a detailed continental scale picture over a period of time. Fig. 3.20 shows a picture of the Antarctic sea-ice acquired from the ERS Radar Altimeter in the period from 10th October 1994 to 12th April 1995. This is based on the backscatter coefficient from the ERS-1 waveform product, in which the fine ripples indicate sea ice and the smooth values indicate the Antarctic polar ice cap.

This type of overview is important for climatological research. The Scatterometer, intended for sea surface wind measurement, has also been applied to measure sea-ice extent and provides a complementary set of measurements. The advantage of the Scatterometer is its ability to provide a snapshot of the ice cover rather than a collage acquired over an extended period. The ERS Scatterometer is also known to be highly sensitive to the ice surface topography, with variations in the incidence angles (fore/mid/aft) being used to detect the age of the ice. It is this feature, together with high levels of time stability, that make the ERS Scatterometer particularly well suited to this type of research.

In the microwave frequencies, sea-ice areas appear as isotropic surfaces. Four different backscatter curves, expressed in dB as a measure of the return signal, as a function of the incidence angle, can be related to the composition of the observed surface, i.e. the age of the ice (Fig. 3.21).

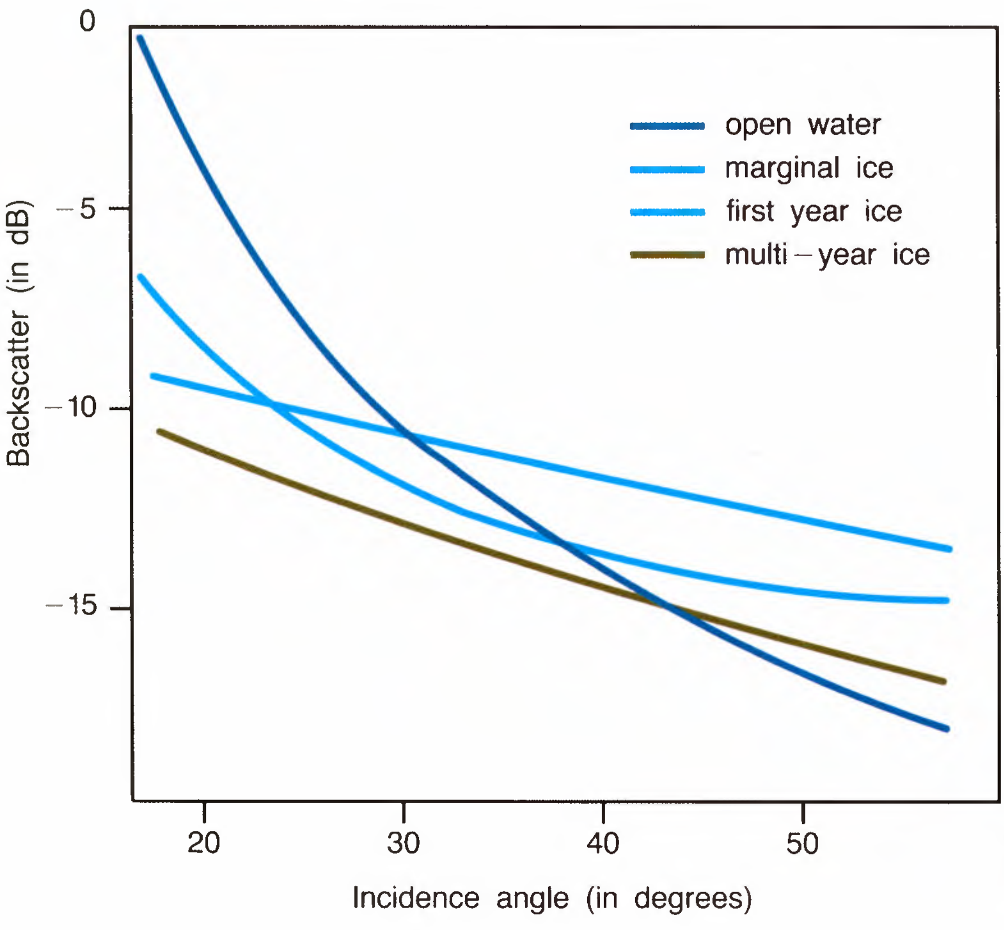


Fig. 3.21: Relationships between incidence angle and backscatter for different surfaces (IFREMER)

Several features are apparent:

- in open water, the curve shows a strong decrease with the incidence angle;

- the compact first-year ice shows relatively low backscatter coefficients. The backscatter coefficient decreases linearly with increasing incidence angle;

- the multi-year ice, that has survived the melt period, is broken and less saline. High backscatter coefficients are attained on this type of ice;

- the marginal ice, covering huge surfaces on the southern oceans, has a very distinct backscatter curve.

As a result, marginal ice can be distinguished from open water and from the surrounding first-year ice. Between 20° and 30°, the backscatter coefficients vary strongly as a function of the incidence angle while, at 50° the derivative of the curve is lower and high values of the backscatter coefficients are observed.

These relationships allow the surface to be classified according to the type of sea ice present. Weekly images of key parameters of the backscatter curves have been generated at CERSAT since August 1991 and will continue to be generated until the end of the ERS mission. Two of these parameters characterise effectively the state of the polar ocean surface. The derivative of the backscatter as a function of the incidence angle, chosen at the steep angle of 28°, is an efficient parameter for discriminating ice and water. The highest values of this parameter are obtained for open water while marginal ice zones, in which the water concentration is significant, are coloured in yellow-orange on the polar grids (Figs. 3.22 and 3.23). Polynyas (regions more or less free of ice) show signatures similar to the marginal ice zone and the formation of the Weddell Sea polynya (at about 5°E, 65°S) within the body of the ice pack can be seen in Fig. 3.22. In contrast to new ice, the lowest values of the derivatives indicate concentrated and broken ice, very often multi-year or fast-ice drifting away from the coast.

The backscatter coefficient at a, large, incidence angle of 50° shows strong sensitivity to the ice surface topography and to the ice/water transitions. Marginal ice and multi-year ice are characterised by the highest values. The Weddell sea polynya area can be considered as marginal ice zone and is clearly distinguished from the consolidated first-year ice in Fig. 3.23 (as the darker spot at 65°S in the upper part of the figure).

The size of the polynya and its central position within the pack have considerable implications for the exchanges between the ocean and atmosphere and on deep water renewal. On one hand the thermal contrast between water at -1.5°C and much colder air favours the venting of large heat fluxes into the atmosphere. On the other hand, the cold surface water sinks and enhances the convection as the warm water rises. Open ocean polynyas like the Weddell Sea polynya and coastal polynyas contribute to the formation of the Antarctic bottom water which then moves well beyond the Equator.

The mechanisms leading to the formation of open sea polynyas are not yet clearly explained but they are studied as major oceanographic events which influence the general circulation of the world ocean and ultimately the world climate. Thanks to spaceborne sensors such as ERS, working in active and passive microwave modes, observations of these highly variable phenomena are now carried on routinely.

Summary
The sea ice zone surrounding the Antarctic is an important area from the point of view of climate change. The ERS Radar Altimeters provide a detailed assessment of the coverage. The ERS Scatterometer allows the extent of the sea ice zone to be determined in a short period of time (giving a 'snapshot') but also allows the sea ice to be classified according to its age.

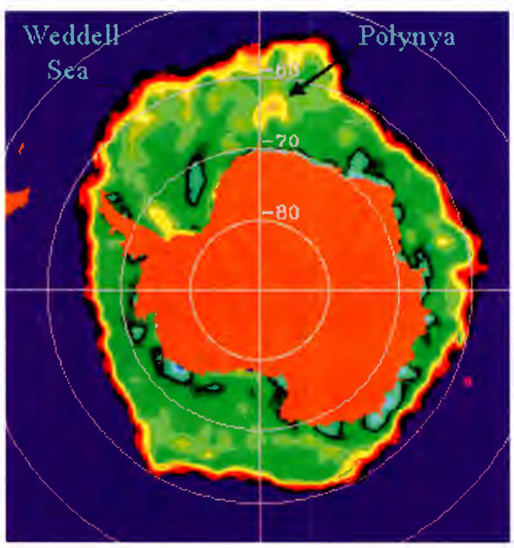


Fig. 3.22: Southern ocean grids from 15th to 21st August 1994 (IFREMER)

Scale:
- derivative from 0 to 0.5 dB/degree

Low **High**

Scale:
- backscattering from -23.3 dB to -6.7 dB

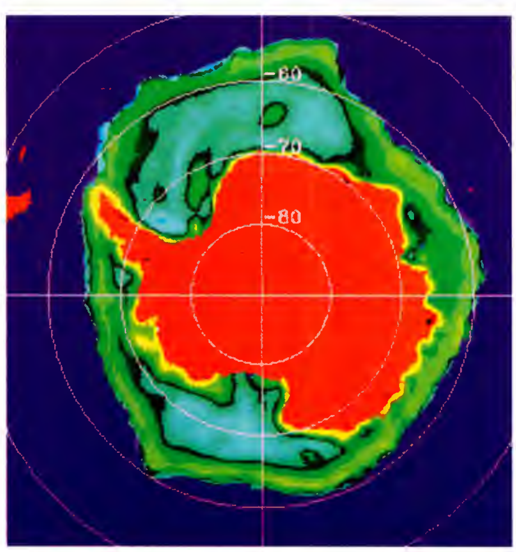


Fig. 3.23: Antarctic ice of different ages (IFREMER)

Case Study 6: Advances in Global Forest Monitoring

Category:	Contributing to international Earth science
Description:	Large scale changes in tropical forests are an important aspect of environmental concern. Documenting change is difficult because of the scale of the problem and limited access. Remote sensing has considerable potential, but the use of optical instruments has been limited by continuous cloud cover. ERS SAR data are not affected by this, and can therefore provide an effective solution to the monitoring problem.
Acknowledgements:	TREES project, JRC, Ispra, Italy Urs Wegmueller, Gamma RS, Germany Florian Siegert, Zoologisches Institut der LMU, München, Germany

Monitoring the World's forests is an important task. It is necessary to ensure preservation of biodiversity, prevent soil degradation and in the long term to uphold the economic interests of the areas supporting these forests.

Effective forest monitoring requires that a number of indicator variables are measured. These include:

- forest characteristics and health;
- location and extent of forest clearing;
- burning patterns;
- settlement patterns;
- land use/cultivation, both shifting and permanent.

Obtaining an overview of these variables is difficult for the following reasons:

- field surveys provide good detail, but cannot cover the area required, either physically or economically;
- the use of aerial surveys provides better coverage, but the remote locations and large areas that need to be covered make this a very expensive approach, especially when regular updates are needed;
- satellites carrying optical sensors provide limited coverage of many areas because in many important forest areas, there is almost continuous cloud cover.

The microwave instruments on the ERS satellites can monitor forest cover effectively without being affected by weather or illumination conditions. The examples given in this case study show some of the techniques being developed to enhance the use of ERS data for forestry monitoring, and the resulting applications.

The advances in interferometry techniques and the availability of data from the Tandem Mission have combined to enhance the ERS contribution as follows:

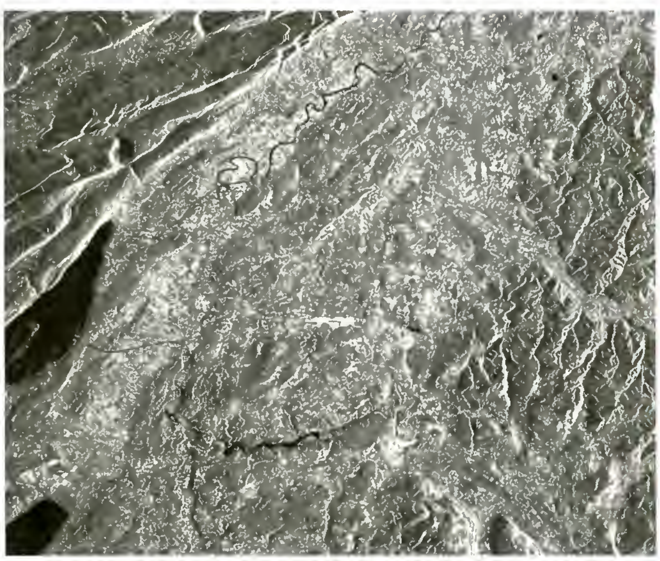
- forest classification and inventory is improved using coherence imagery;
- the ability of the SAR to detect the levels of water available in the canopy has been developed to allow the vitality of forests to be monitored.

The use of interferometric coherence to assist with visual forestry classification has been demonstrated on test sites in Switzerland. Fig. 3.24 shows two images of the same area. The first is a standard complex image while the second is a composite of three images derived from two original ERS SAR images taken three days apart. The composite image is presented as follows:

- Red channel: proportional to the coherence between the two images;
- Green channel: the mean of the amplitudes from the two images;
- Blue channel: the amplitude difference between the two images.

The improved visual classification of the surface that is clear from Fig. 3.24, has been verified against field observations.

ERS-1 SLC scene over Bern Switzerland



RGB composite over Bern Switzerland

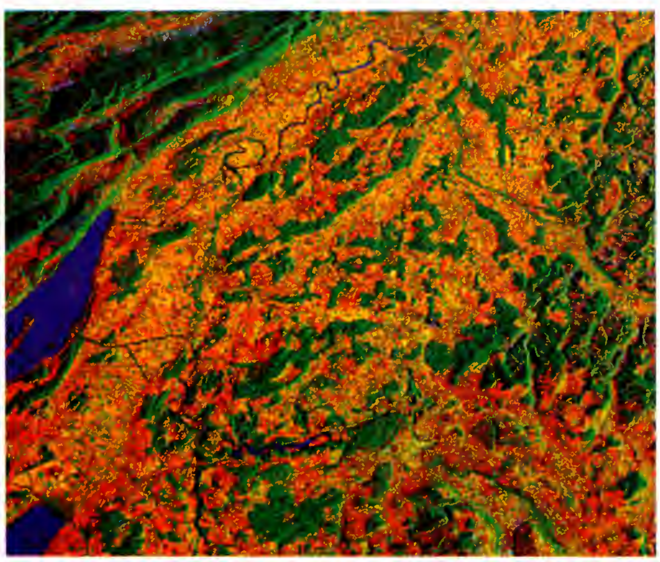


Fig. 3.24: Comparison of a standard (SLC) SAR scene with a composite of coherence, amplitude and amplitude difference (Gamma RS)

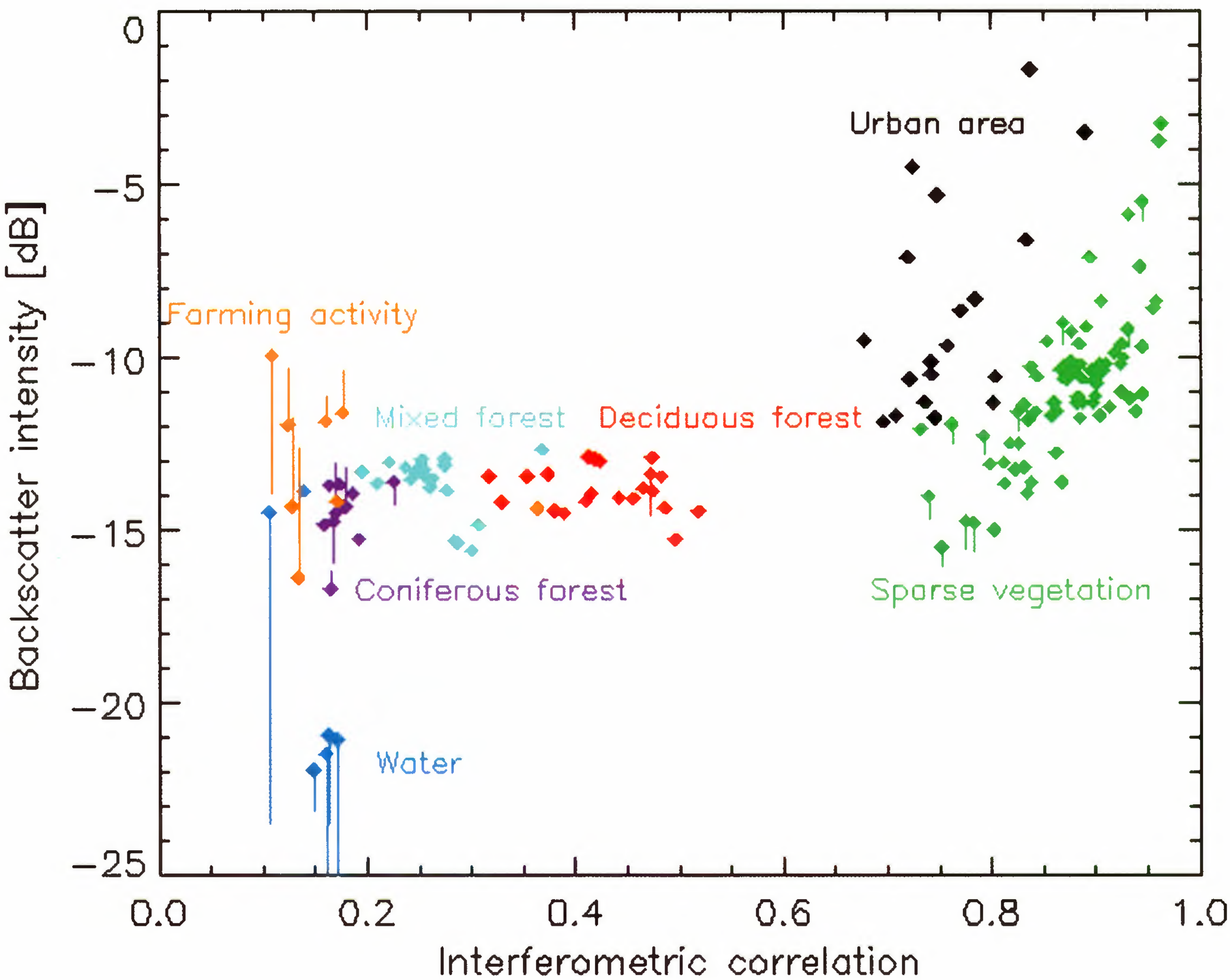


Fig. 3.25: Variation of backscattering coefficient as a function of the interferometric coherence for different types of land surface (Gamma RS)

Fig. 3.25 is a plot of the normalised backscatter intensity against the interferometric coherence. This shows that when backscatter images are insufficient to determine forest type, the addition of coherence information can allow this distinction to be made.

In the last two decades, fire has become one of the greatest threats to tropical rainforests, especially in Indonesia. The process of selective logging produces millions of tons of dead biomass, which serves as fuel for fires. Furthermore, fire is used for large-scale land clearing, e.g. for pulp wood plantations.

As a result of the severe drought caused by the 1997/98 El Niño event, fires spread without control over large areas of Indonesian rainforest and bush land. Thick haze covered large areas for months. Due to its cloud and haze penetration capability, the ERS-2 SAR sensor complements existing fire monitoring systems based on NOAA AVHRR hot spot data, providing much higher spatial resolution. A clear change in radar backscatter and/or image texture on fire affected vegetation has been verified using ground truth data (Fig. 3.26A and B and Fig. 3.27A and B).

Two methods were employed for the detection of burned areas. With band ratioing, an RGB composite image was created (Fig. 3.26C) in which areas with no change appear in dark green, while changed areas appear in red, blue or

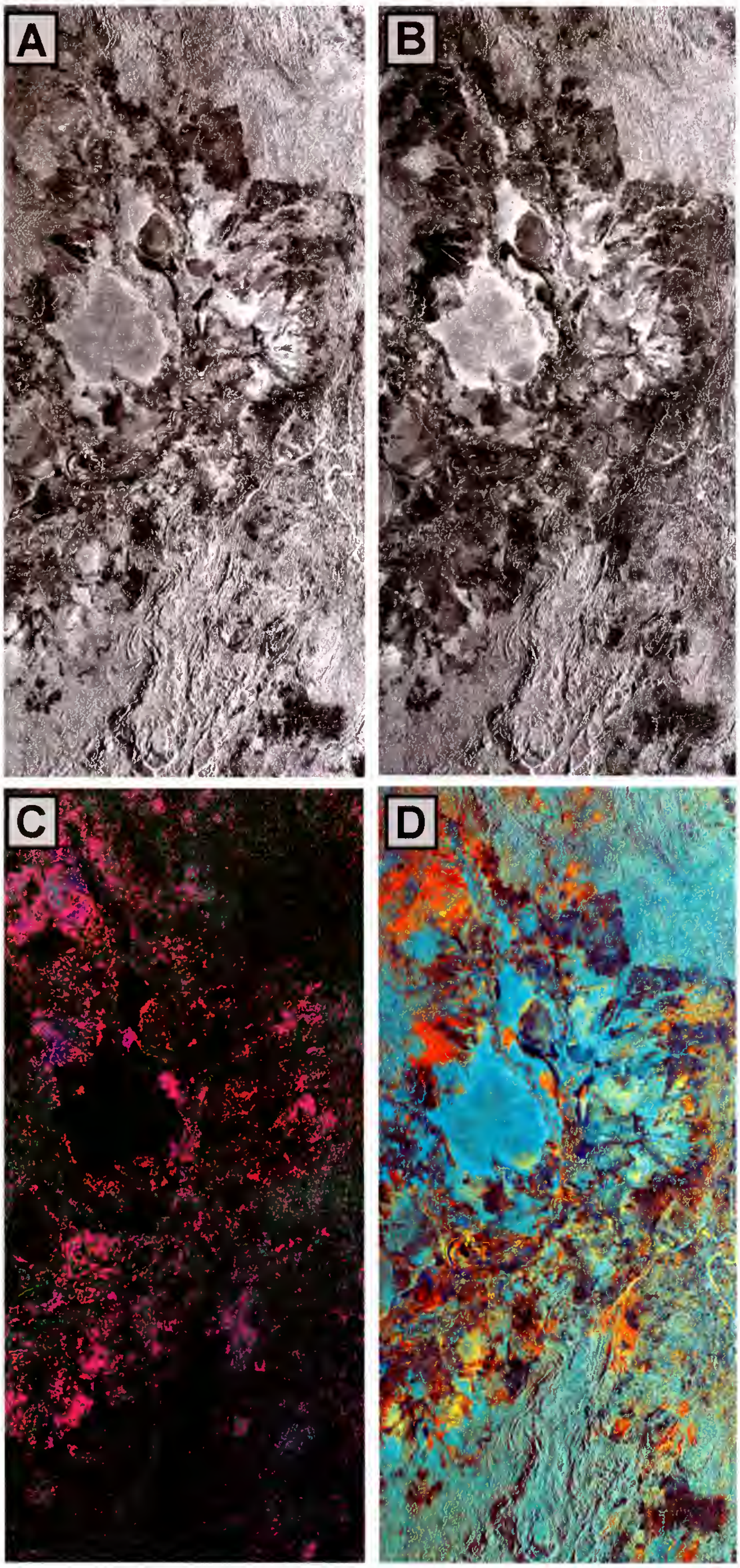


Fig. 3.26. Comparison of composite ERS images produced using the band ratio and principal components analysis. A) ERS-2 image mosaic acquired in February 1998 and B) acquired in March 1998; C) band ratio image RGB composite; D) principal components image RGB composite. Areas of no or little change appear in shades of blue-green, burnt areas appear in different shades of orange depending on the severity of damage. (University of München)

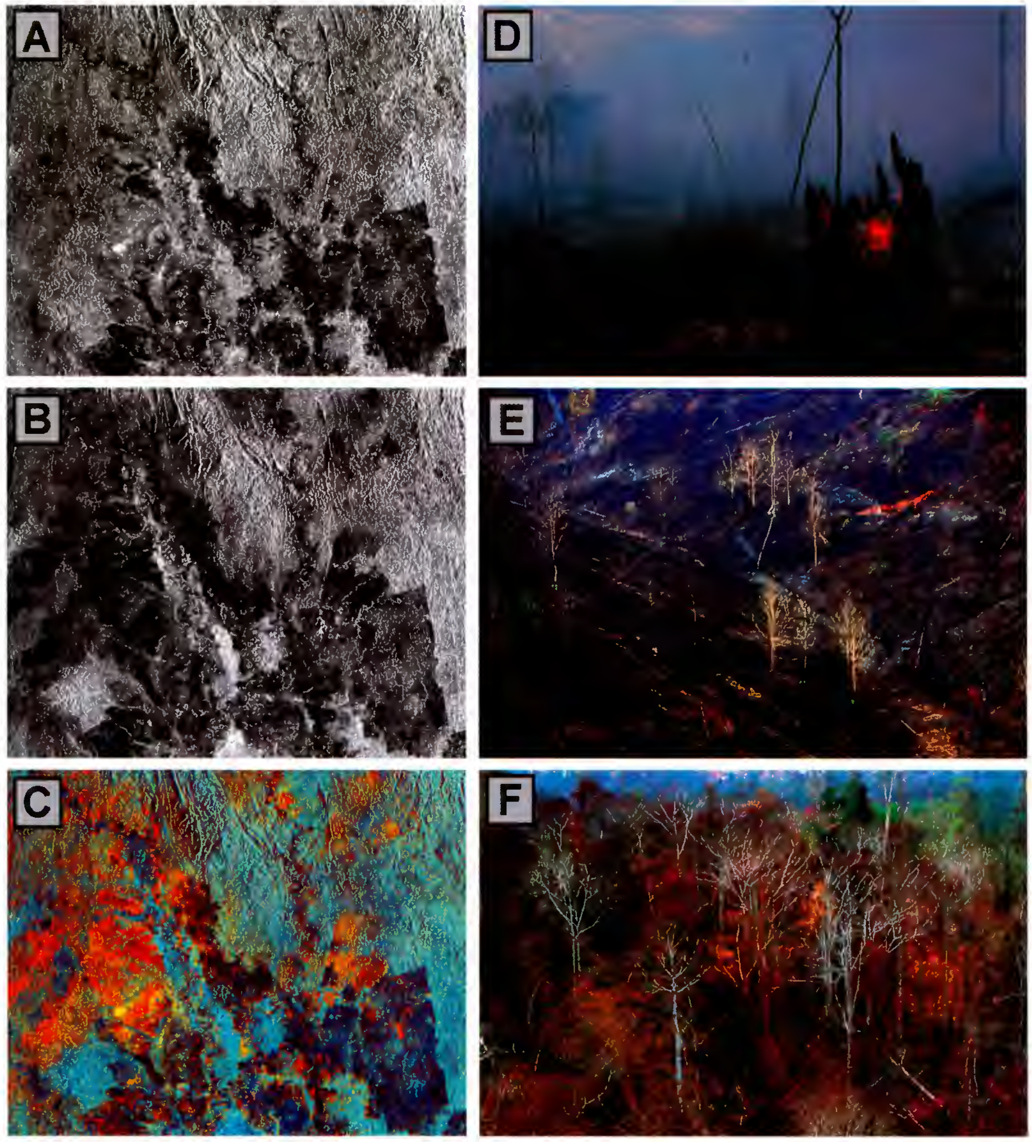


Fig. 3.27: Fire in a pulp wood plantation:
A) ERS-2 image subset acquired in February and
B) in March,
C) principal component image composite.
D) severely damaged selectively logged forest after the fire.
E) burnt pulp wood plantation.
F) selectively logged forest affected by ground fire (University of München)

magenta depending on the nature of the change. Using Principal Components Analysis, the second component was combined with two ERS SAR images giving RGB colour-composite images for February and March (Fig. 3.26D and Fig. 3.27C). In these images, burnt areas are visible in orange tones of different intensity while unburned vegetation appears in blue-green.

These methods allow the detection of burnt scars at a high spatial resolution because there is a significant reduction in the backscatter signal after burning, no matter what kind of vegetation was affected. Prevailing vegetation types in the project area are selectively logged forest, plantations, shrubs and grassland.

With the use of NOAA data, GPS and geo-referenced ERS-2 images, it was possible to verify specific signature changes caused by fire. The decrease in backscatter is correlated to a decrease in volume scattering and subsequently, an increased proportion of backscatter from dry soil. Three categories of burning can be identified in processed ERS images - complete burning of the vegetation, severe damage and a thinned out canopy as shown in Fig. 3.27D to F.

Multitemporal ERS-2 SAR images complement existing NOAA fire monitoring systems in three important ways:

- during active burning fire scars can be located with high levels of accuracy. In conjunction with daily NOAA hot spots, the spreading of the fires can be analysed spatially. This is important to identify the starting point of fires and the responsible parties and also to plan immediate action to prevent the spreading of the fires;

- different intensities of damage can be identified, thus improving estimates of economic and ecological impacts;

- "fuel" remaining after burning can be estimated, providing valuable information for the prevention of future fires in the same area. Furthermore, digitally enhanced ERS-2 images allow basic vegetation and land use mapping, in general. In conjunction with the exact location and extent of burnt scars this would provide important data on CO_2 emission and global warming.

Monitoring change in tropical forests on global and regional scales is a formidable challenge, but vital for ecological, environmental and economic reasons. The size and inaccessibility of the areas concerned are the main problems and make remote sensing the only practical way to obtain the overview required. As a result, the 'TREES' project (TRopical Ecosystem and Environmental observation by Satellites) was established by the JRC and ESA and produced the first global reference map of the world's tropical forests, using satellite images acquired between 1992 and 1994. The map allows tropical forest dynamics to be studied and provides the starting point for a worldwide tropical forest inventory. The main satellite data used for this analysis are from the NOAA AVHRR instruments and from ERS SAR. ERS SAR data are particularly valuable for tropical forests because continuous cloud cover is common.

The TREES project shows that using high resolution ERS SAR images in combination with the baseline maps is an extremely efficient approach to detect changes in tropical forest cover. Part of the TREES project (known as the Central Africa Mosaic Project - CAMP) has concentrated on producing a mosaic of ERS SAR images for central Africa.

The CAMP mosaic contains 477 scenes acquired during the period from July 15th to August 28th, 1994. It covers more than 3,000,000 km^2, including the whole tropical rain forest domain of Central Africa and the northern and southern transition zones. Countries covered include Cameroon, Nigeria, Gabon, Guinea Bissau, Central African Republic, Congo Brazzaville, Zaire, Rwanda and Burundi. Apart from Gabon and the eastern part of Zaire, the terrain has little relief and is little dissected. The mosaic database contains 62 GByte of high resolution ERS SAR data (12.5 m pixel spacing) and 1 GByte of low resolution ERS SAR data (100 m pixel spacing). All frames were acquired by a mobile receiving station installed at Libreville (Gabon), and processed by the German PAF.

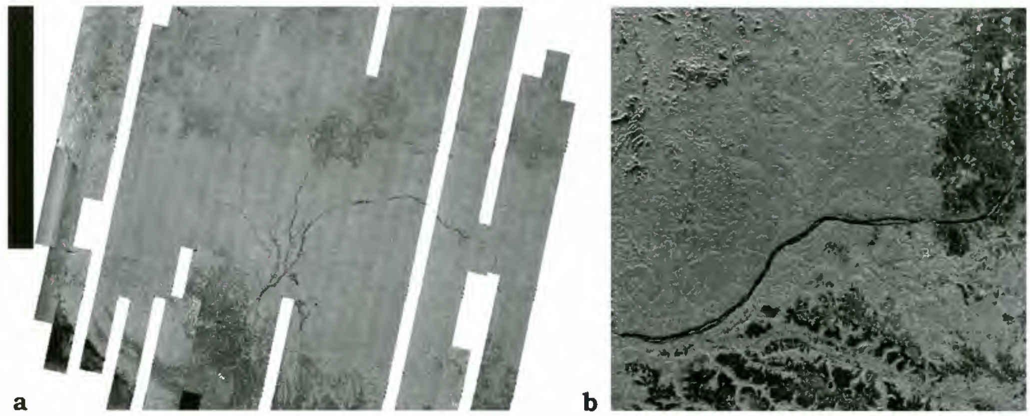


Figure 3-28: a) an overview of the CAMP Central Africa mosaic of ERS SAR images, b) an extract from the CAMP mosaic at 100 m pixel size (TREES project)

Fig. 3.28 shows the CAMP mosaic at two different levels. Fig. 3.28a is an overall view of the mosaic, while Fig. 3.28b is an extract showing the boundary between a mix of evergreen/semi-deciduous mesophyllous forest formations and the mixed savannah formations in the southern part of the Congo Basin. At this latitude, the timing of this acquisition (July and August) corresponds to the dry season when the contrast between the evergreen cover and the more deciduous (trees) or senescent (grass) cover is clearly detected.

The information contained in the CAMP data set has proved very valuable for the study of the forest cover of Africa. A number of specific features have been identified which form the basis for long term monitoring. For example:

- the distinction between the rainforest domain and the savannah in both the northern and in the southern parts of the Congo Basin is clearly evident in the radar signal;
- forest openings are visible when occupied by savannah;
- large areas of secondary forest regrowth can be identified along roads and old settlement areas;
- landscapes of shifting cultivation can be identified.

Since completion of these mosaics, work has continued, to develop and refine the classifications and to ensure that the different resolutions of data sources are used effectively. The end result will be an effective system for monitoring large scale tropical ecosystems on regional and global scales. The important contribution from the ERS radar to this continuing process is clearly defined and is increasingly seen as operational.

Summary
ERS data make an important contribution to monitoring tropical forests by providing effective discrimination between areas of different forest cover without being affected by cloud cover and haze. This in turn means that the effects of changing management can be monitored reliably. Various methods, including use of interferometry, are also available for monitoring the taiga. The SAR has also been shown to be very effective in analysing the effects of change, such as those resulting from forest fires.

Case Study 7: The Common Agricultural Policy

Category:	Supporting Government Policy
Description:	The ERS SAR has supported a number of commercial successes for European companies in monitoring agriculture. This case study presents two aspects of this - firstly the improvements in basic science necessary to ensure that the results are effective and secondly an example of how ERS SAR is improving estimates early in the season, even before crops have emerged from the ground.
Acknowledgements:	R. Cordey, Marconi Research Centre, UK A. Sowter, NRSC, UK

The use of ERS SAR has become an integral part of the monitoring programmes for the EU Common Agricultural Policy. There are two types of information required to do this effectively:

- areas being used to grow relevant crop types;
- early season yield estimates.

By monitoring the types of crops farmers are growing and estimating yields it is possible to combat fraud and target subsidies more effectively. The information is needed at very specific times within the crop growth cycle. This limits the use of optical satellite measurements because periods of cloud cover often prevent imaging at the required times. Although in the early stages, the use of SAR was seen as the 'reserve' data source, more recent work has shown that it has a classification capability at least the equal of optical sources, with the added benefit of being available when imaging is required.

Two elements of agricultural applications are presented in this case study. The first shows how on-going research on the use of SAR for agricultural monitoring is increasingly using theoretical methods to explain the variability observed and providing greater confidence in the results. The second element illustrates the effective use of ERS SAR to provide early season estimates for crop areas.

Research to improve interpretation
The Marconi Research Centre (MRC) has undertaken a research project with the following aims:

- to develop understanding of how changing crop structures affect radar backscatter;

- to optimise requirements for temporal and spatial sampling and thus improve the cost-effectiveness of using ERS SAR for agricultural monitoring;

- to suggest strategies for using future Envisat SAR data for agriculture and to support the design of future advanced radars.

The project involved the following elements:

- Experiments: a programme of detailed crop measurements during spring and summer 1997 timed to coincide with radar imaging by ERS-2;

- Theory: use of advanced computer models to understand better the link between the radar images and the crops and soils;

- Demonstration: rapid data ingestion and processing of radar crop images;

- Implications: provide guidance on strategies for exploiting or applying Envisat data and advice on design choices for future satellites.

Fig. 3.29 shows the Great Driffield test site in the UK used for the project. This image is a radiometrically and geometrically-corrected composite of three ERS-2 images over the site. The allocation of image dates to colours is:

- Red: 17th March 1997

- Green: 26th May 1997

- Blue: 30th June 1997

It shows the relative changes in backscatter in the early part of the growing season and illustrates the complexity associated with interpreting the image

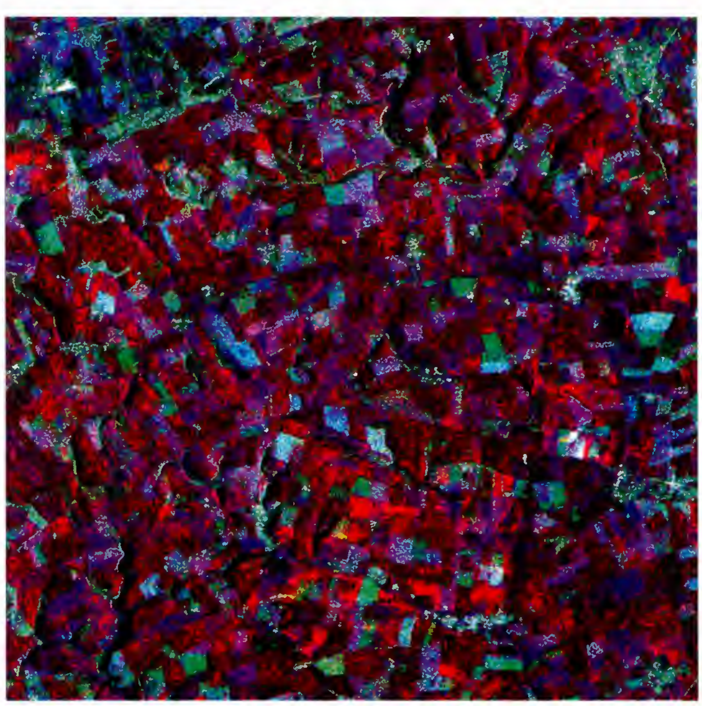


Fig. 3.29: The agricultural area (the Great Driffield test site) used as part of the MRC project (Processed by NRSC)

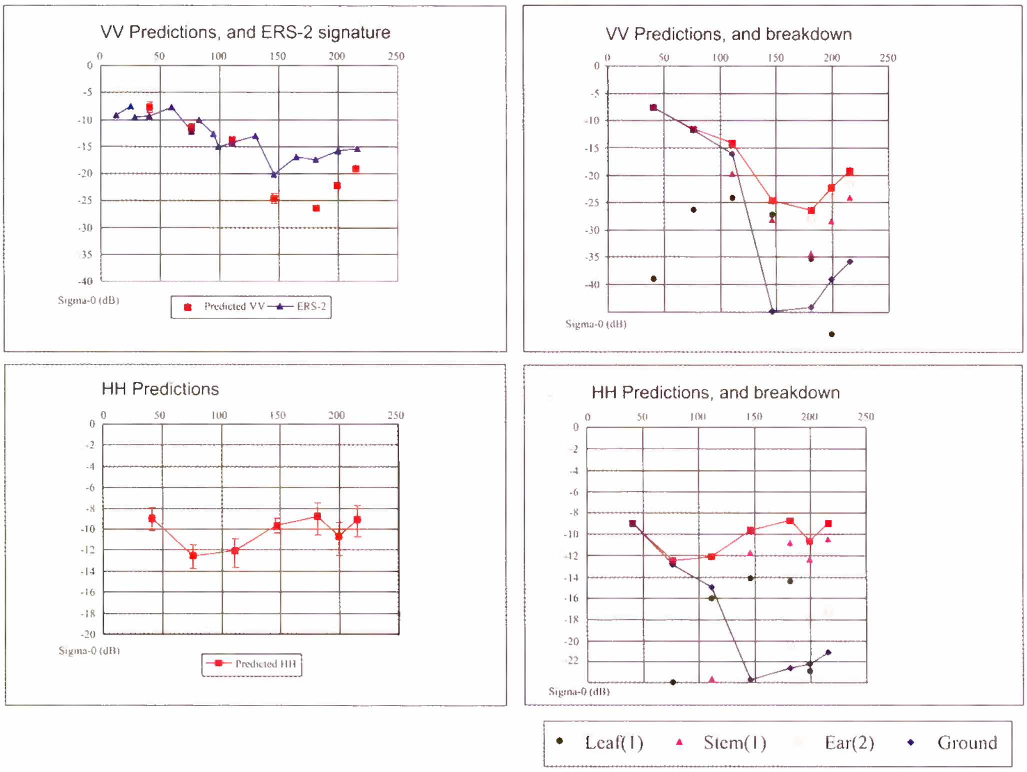


Fig. 3.30: Backscatter modelling results based on in-situ data compared with ERS-2 SAR measurements taken at the same time (MRC)

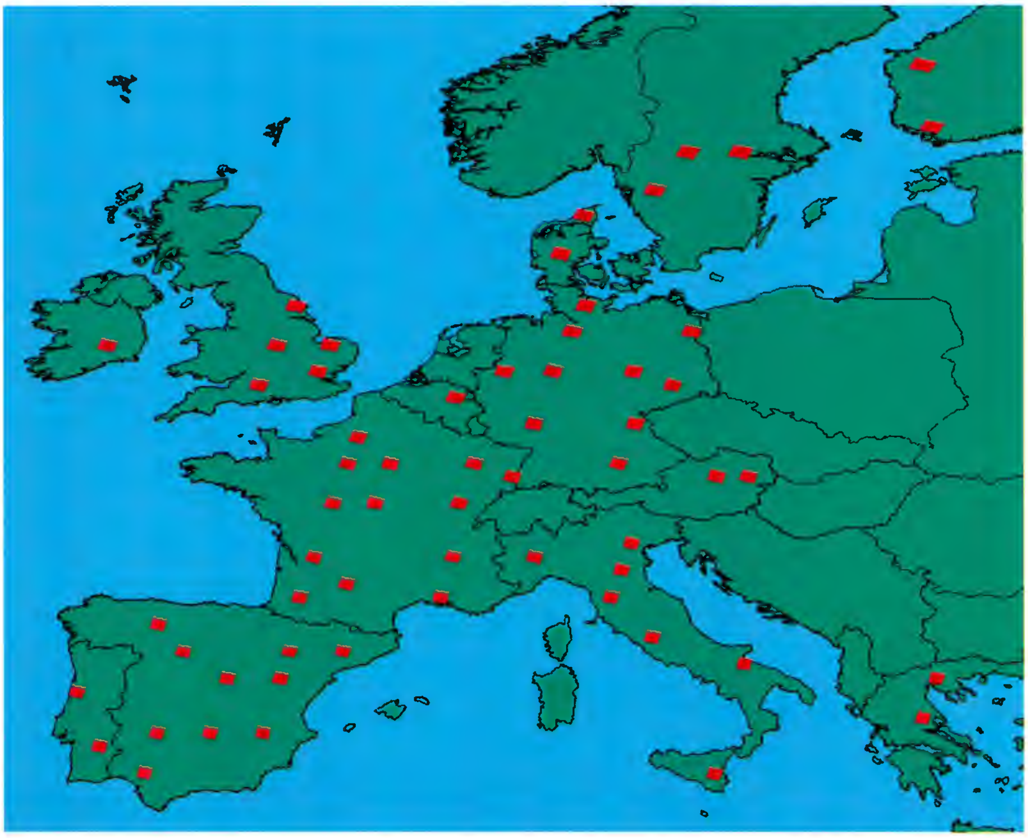
for a variety of crop types, all of which having different backscatter profiles. This highlights the need to break the response down into the different crop components (i.e. leaf, stem, ear and ground), which is achieved by the modelling approach used in this MRC project.

Fig. 3.30 shows the results of theoretical scattering modelling based on in-situ measurements made simultaneously with ERS-2 imaging. In the case of vertically polarised C-band (i.e. VV), it is possible to compare the results directly with the ERS-2 observations. The scattering model also allows predictions for other channels for which Envisat will have a capability, such as C-band horizontally polarised (transmit and receive) and horizontal transmit/vertical receive.

The comparison of the VV polarisation data with the observed ERS-2 signatures shows some discrepancies late in the season. These are thought to be due firstly to the presence of moisture from rain and secondly, overestimation of attenuation of the C-band VV signal by ears on the crop. The graphs on the right side of Fig. 3.30 help to explain the relative contributions to the backscatter from the different crop elements. By analysing the signal in this way, it is possible to improve the level of interpretation of ERS SAR imagery.

Research and development projects such as this one are used to provide improvements to the techniques eventually to be applied by commercial companies and also to ensure that the requirements and sensor characteristics for future missions are effectively specified.

Fig. 3.31: Location of the 60 MARS Activity B sites (NRSC)



Early season estimation

In 1997, a project was started on the use of active microwave satellite remote sensing for rapid area estimation of agricultural crops during winter and spring. The work was carried out by NRSC, SYNOPTICS and SOTEMA on behalf of the European Commission's Directorate General VI for Agriculture. In addition to using the crop structure as a means of identification, this illustrates how changing tillage patterns in the early season can be identified and used to produce early estimates of crop areas.

The objectives of the work were twofold:

- to determine agricultural crop area estimates at the end of the field preparation period of winter crops and of spring crops;
- to analyse and define the requirements for an operational SAR monitoring activity in the framework of the Monitoring Agriculture by Remote Sensing (MARS) Project for the provision of crop area estimates at two key dates, mid-January and mid-May.

The first objective was based entirely on the analysis of ERS SAR imagery of the 60 current MARS Activity B sites throughout Europe, acquired during the Winter 1996 - Spring 1997 season and shown in Fig. 3.31. Five images per site were used to complete the tasks.

ERS SAR is favoured because of constraints on alternative data sources which may limit the accuracy of the bulletins issued by MARS Activity B and prevent them being available on time. Particular benefits of SAR include:

- independence of cloud and sun angle, which is a particular benefit during the early season. This ensures that there are sufficient data to allow a statistically rigorous estimation;

- the ability to provide estimates of crop area before the crops have emerged, which is not possible with alternative satellite sources.

SAR imagery can be used to distinguish between different bare fields by detecting differences in surface structure and moisture content. Accurate backscattering models have been developed to support the classification of bare fields in this way. The classified bare fields can be linked to crop types because, under modern agricultural practices, land preparation is crop specific. Before crops are planted, planting areas can be recognised from the type of tillage activities underway. Timing of land preparation is also influenced by local meteorological conditions and other factors which need to be taken into account using knowledge-based interpretation schemes.

The value of the SAR data is not limited to the early season capability. As the research example showed, by developing a sound understanding of the backscattered signal, accurate crop identification with SAR can also be achieved later in the season, helping to confirm the earlier estimates.

The study confirmed without reservation the operational use of ERS SAR for agricultural monitoring. Within the project, comparisons with the current MARS Activity B methodology have also shown that SAR can be adopted by existing methodologies and integrated into a multi-sensor scheme to satisfy early and growing season requirements in one single implementation.

The project also demonstrated that the processing and interpretation of SAR data can be undertaken by a geographically distributed set of partners, using local ground knowledge at their own premises to increase both insight and accuracy. This solution is also made possible by the use of modern communications capabilities. It is also important to note that non SAR specialists were able to conduct the image interpretation, which is a clear demonstration of the operational, low-cost capability that SAR can now offer.

The cost of the whole SAR project was about one third of the cost of the current MARS Activity B project. For the early season work described here, problems with SAR information content are minimal, SAR data are demonstrably cheaper and they are more reliable, making them attractive for operational use. Therefore, a synergistic use of SAR with optical data, based on a SAR driven approach, has greater economic and reliability impact than the current optical-only solution.

The capability of SAR data is now reaching a level of validated maturity that means it must be taken seriously as a provider of agricultural information. This project has demonstrated conclusively that this is the case.

Summary
The use of ERS SAR in agricultural monitoring work has progressed significantly in recent years, and the instrument has made a substantial contribution to monitoring the Common Agricultural Policy. Independence from poor weather conditions is a vital asset because of the narrow time window within which information is often required. A particular development has been the use of the SAR early in the season to provide an accurate assessment of the season's cropping patterns by measuring the tillage patterns which are highly crop specific.

Case Study 8: Watching the World's Ozone

Category:	Supporting government policy
Description:	The GOME instrument on ERS-2 provides a capability for monitoring global ozone patterns regularly. In addition to total column measurements, methods for extracting vertical distributions are also being developed. The instrument has performed effectively, builds on existing records and has both direct and indirect successors which will establish a long term record of this important atmospheric constituent
Acknowledgements:	M Weber et al., IUP, University of Bremen, Germany R van der A, KNMI, The Netherlands P Peeters et al, Belgian Institute for Space Aeronomy

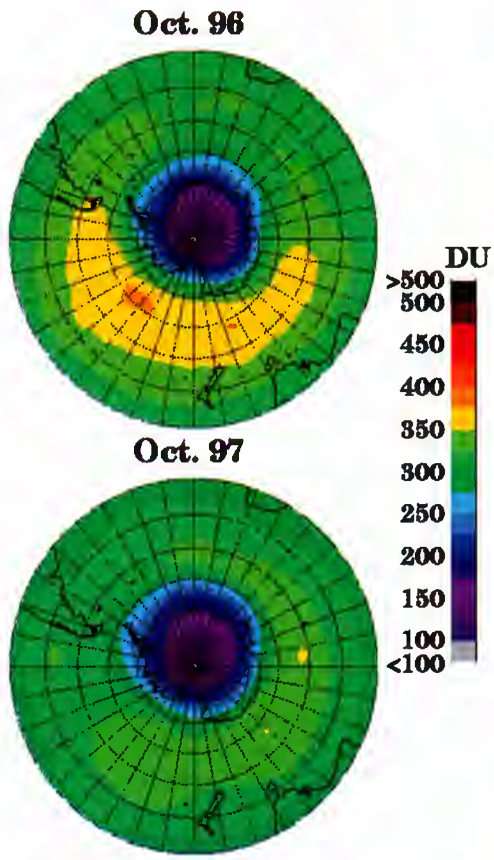
The GOME (Global Ozone Monitoring Experiment) instrument on ERS-2 is the first of a new generation of instruments designed to measure atmospheric composition. The top priority for GOME is to measure the 'total column' ozone. This allows maps of global ozone to be produced. It has now been established through comparison with ground based measurements that GOME measurements agree, to within two to four percent, with the ground measurements at northern and middle latitudes.

One of the high profile activities associated with GOME is the assessment of the status of the 'ozone hole'. The Montreal Protocol, which aims to reduce and eventually ban the use of CFC, halons and other ozone depleting substances, has considerable environmental and economic implications. As a result, it is vital to be able to monitor the effectiveness with which the end goal of the Protocol, namely a return to pre-1970s ozone levels, is being achieved. The value of the output from GOME in this regard can be seen clearly from Fig. 3.32 in which the status of the Antarctic ozone hole is shown for 1996 and 1997. The ozone amounts are expressed in Dobson Units, the standard measure of ozone amount. The area of the ozone hole is considered to be that area where the ozone levels fall below 220 Dobson Units.

It is interesting to note that ozone holes are not confined to polar regions. Fig. 3.33 shows an example of a 'mini ozone hole' over northern Europe in early 1996.

GOME continues the monitoring of ozone distribution started by the Total Ozone Mapping Spectrometer (TOMS) instrument flown on Nimbus-7 during the 1980s. By putting these instruments on a common footing, a longer data record has been achieved, enhancing the value of both datasets to climatologists. The value of this common footing is clear from Fig. 3.34 which shows how the Arctic ozone conditions have changed between 1980/82 and 1996/97.

Fig. 3.32 (left): Monthly means of total column ozone in the southern hemisphere, as measured by GOME in October 1996 & October 1997 (University of Bremen)



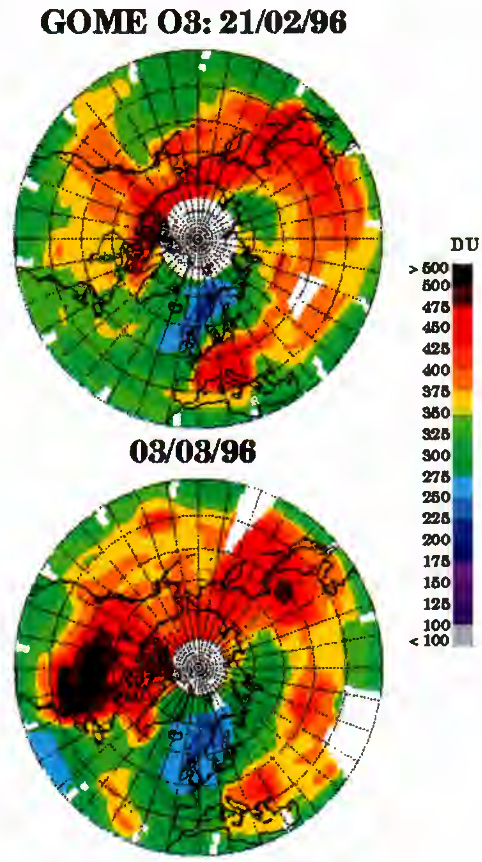


Fig. 3.33 (right): GOME observations of 'mini hole' events above northern and central Europe on 21st February and 3rd March 1996 (University of Bremen)

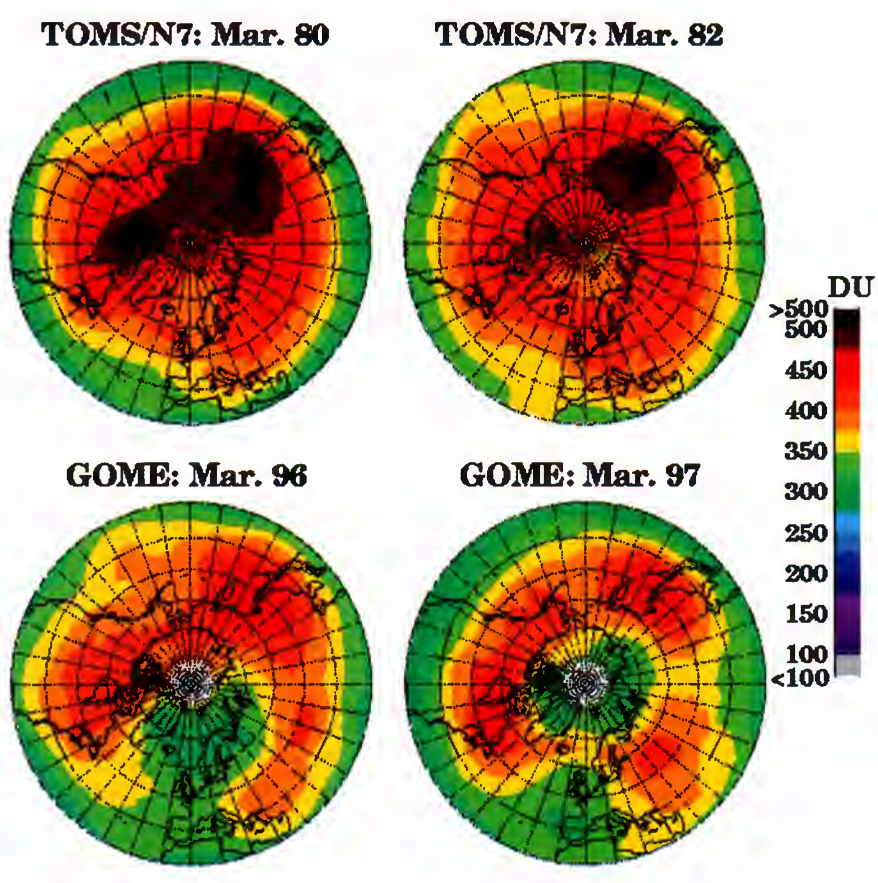


Fig. 3.34: March total column ozone (monthly means) observed in 1980 and 1982 by TOMS on NIMBUS-7 (top) and in 1996 and 1997 by GOME on ERS-2 (bottom) show the decline in polar total column ozone in spring (University of Bremen)

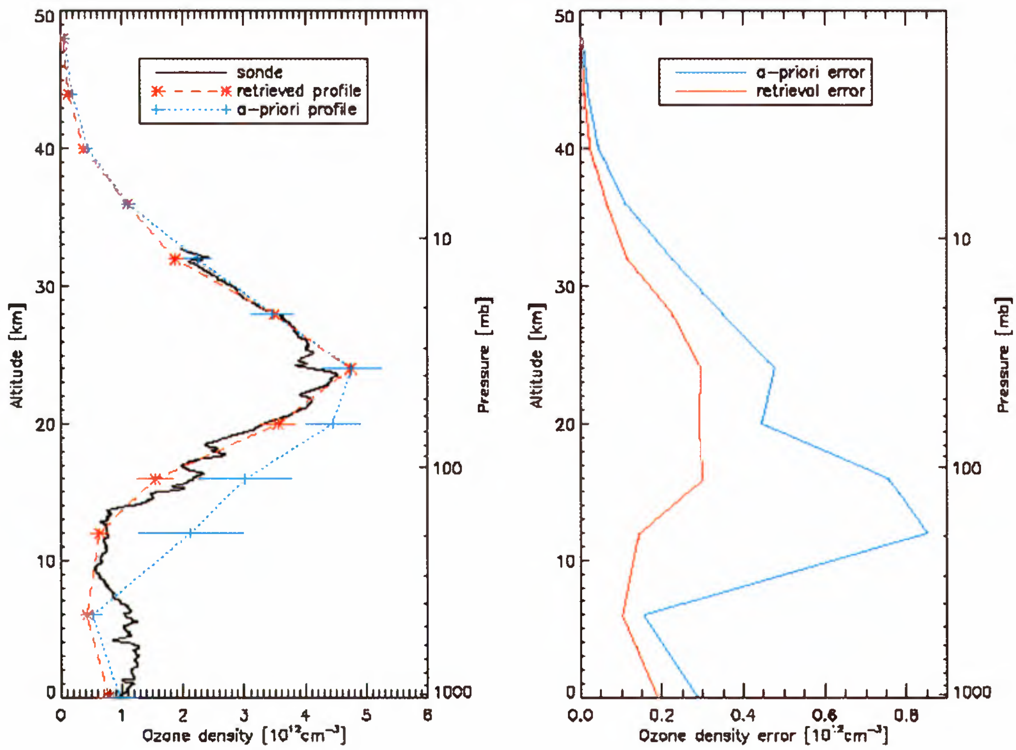


Fig. 3.35: Comparison of ERS GOME retrieved ozone profile with weather balloon ozone data over De Bilt, Netherlands (KNMI)

Although total column data are the priority for GOME, there has also been considerable scientific interest in other information which can be derived from its data. Examples include the height resolved ozone information from the instrument covering both the stratosphere and the troposphere, together with retrievals of trace gas contents such as sulphur dioxide, bromine monoxide and chlorine dioxide.

Taking the example of height resolved data, a priori profiles from climatology and expected radiances from a forward model have been used to optimise ozone density retrievals from GOME. Figure 3.35 shows the results of this approach. On the left, the GOME ozone density profile retrieved in this way is compared to a climate based a priori profile (in blue) and in situ measurements made by a weather balloon (in black). The GOME profile is clearly much closer to the in situ measurements. The right hand part of Figure 3.35 plots the ozone density errors from the GOME retrievals and the a priori sources as they vary with height. This highlights the fact that improvements due to GOME are particularly significant in the tropopause zone (about 8 to 20 km from the surface). Thus by using ERS GOME data with suitable models, very accurate, globally available measurements can be obtained.

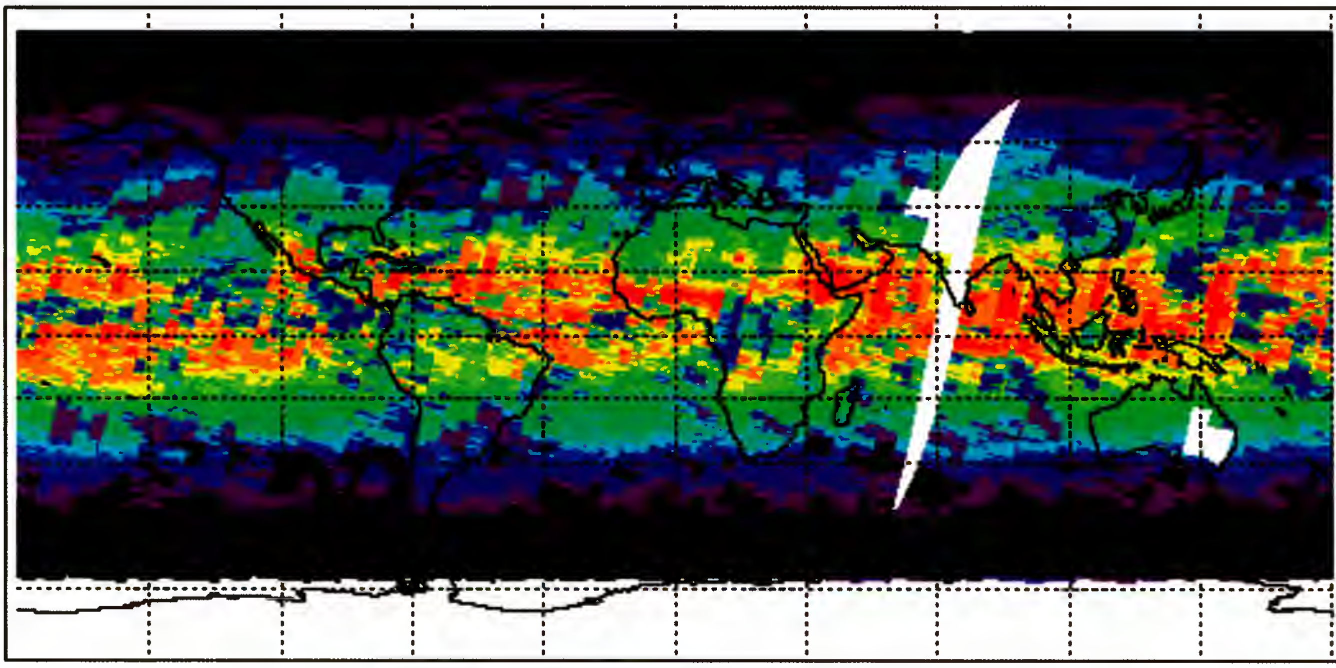


Fig. 3.36: Global distribution of UV doses as measured by GOME (Belgian Institute for Space Aeronomy)

Finally, one of the main reasons for concern over depleted ozone levels is that excessive UV radiation produces harmful effects. To date, most of the UV measurements made have been ground based. By measuring the radiation backscattered from the atmosphere and from the ground, GOME can provide global assessments of the UV levels likely to be encountered in different locations throughout the World. An example is shown in Fig. 3.36.

Summary
The issue of the 'ozone hole' has remained in the public eye for an extended period. This has paralleled the issue of increased risk to public health from exposure to UV radiation. The GOME instrument on ERS-2 complements inadequate ground measurements of UV and thus helps to ensure that the threat is effectively countered. In the longer term, the understanding of global ozone helps policy makers to know whether measures such as the Montreal Protocol are effective.

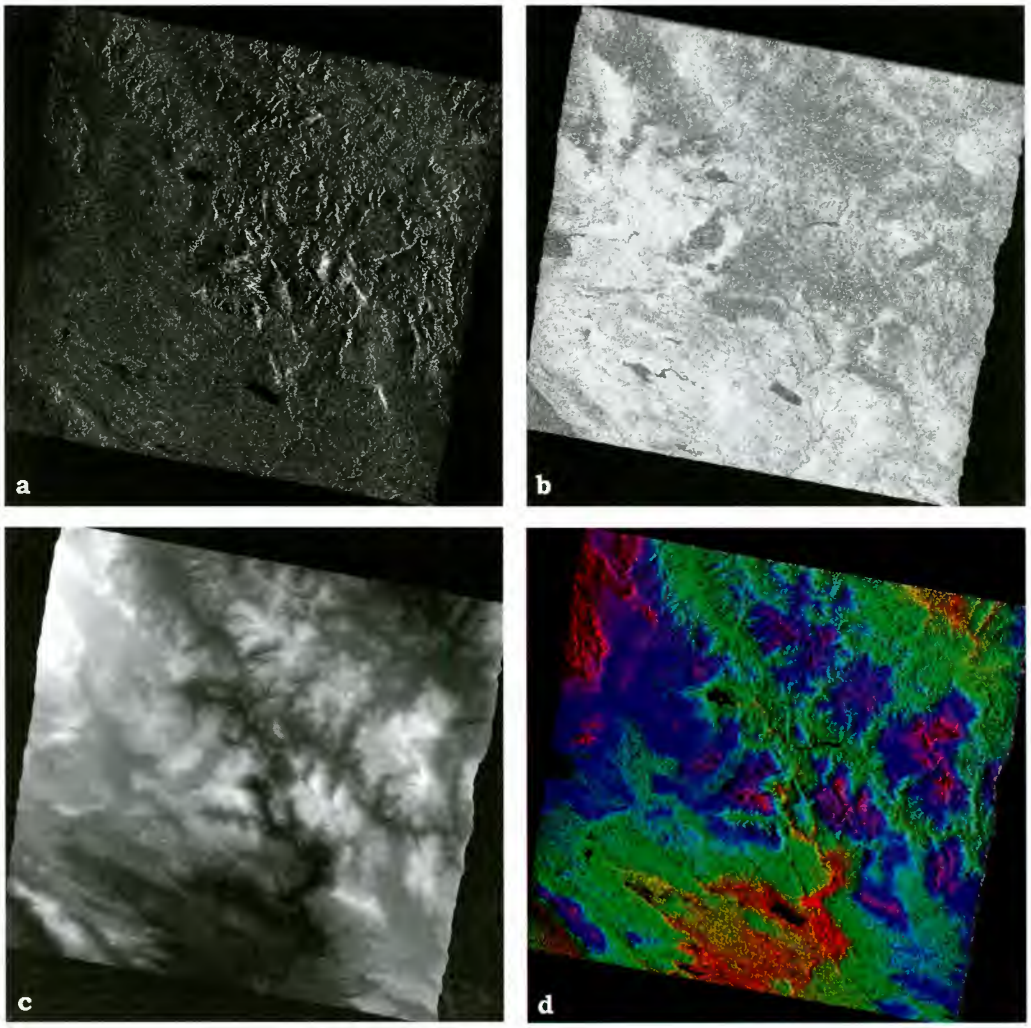
Case Study 9: Surveillance Applications

Category:	Serving operational users and enhancing industrial capability
Description:	The Satellite Centre of the Western European Union has used ERS data to support its work in surveillance and humanitarian missions. Innovative applications include the use of ERS data to provide three dimensional fly throughs which are useful for military operations planning
Acknowledgements:	C. Pohl and J.L. Valer, Western European Union Satellite Centre, Spain

Tools for ERS-1/2 SAR data exploitation
The Western European Union (WEU) is an international organisation promoting European intergovernmental co-operation in the field of security. Space-based observation provides repeated, unrestricted access to every corner of the globe, in full compliance with international law, and this new capability provides early warning of crises before action has to be taken to deal with them. On this basis the WEU established a Satellite Centre which operationally exploits imagery derived from Earth observation satellites for security and defence purposes. Its missions include the following:

- General security surveillance:
- General security surveillance of areas of interest for WEU on the basis of a mandate of the Council defining the conditions of the surveillance mission;
- Support for treaty verification;
- Support for arms control and proliferation control.
- Support for Petersberg missions:
- Humanitarian and rescue missions;
- Peacekeeping missions;
- Tasks of combat forces in crisis management including peacemaking.
- Surveillance in more specific spheres:
- Maritime surveillance;
- Environmental monitoring.

Fig. 3.37: Geocoded ERS-1 SAR output of SHDS (a) intensity image; (b) coherence map; (c) DEM; (d) fused product using a, b & c (C Pohl and J Valero, WEU Satellite Centre)



Within its Technical Development Programme the WEUSC provides advanced tools to support the image analysis which is the core operational task of the Centre. Some of those tools are contained in the SAR Data Handling System (SDHS).

The SDHS is an end-to-end SAR data handling system with an emphasis on interferometric processing, which is being developed for the WEU Satellite Centre by DLR, IRECE-CNR, INDRA and ONERA. The main features of the SDHS, the operational utility of its products and its handling of ERS SAR data are illustrated below with examples from the area of Mostar in Bosnia. All data products have been built using the SDHS and input data from the ERS Tandem Mission. Several input data sets have been used to achieve 3-D terrain modelling over a 100 × 100 km area around Mostar.

The current SDHS takes raw ERS data as input and generates output products such as images, digital elevation models and coherence maps (Fig. 3.37). A colour-coded combination of these information products is shown Fig. 3.38.

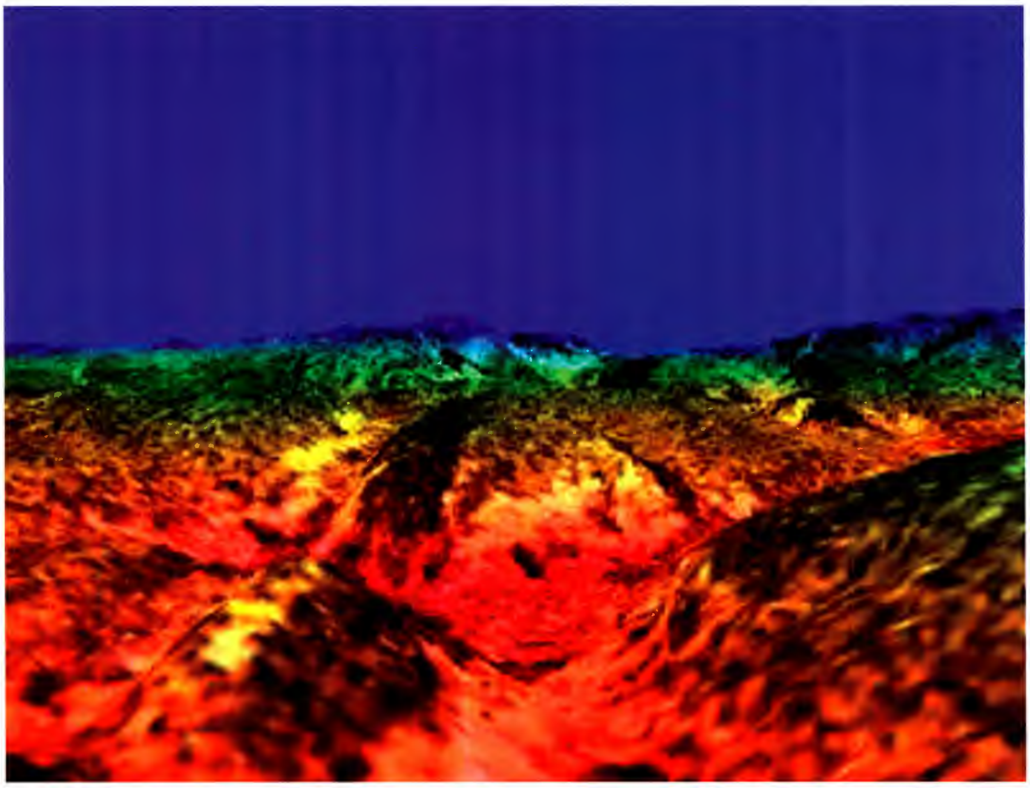


Fig. 3.38: 3-D perspective view of Mostar created by fusing ERS SAR products from the SDHS (C Pohl and J Valero, WEU Satellite Centre)

The main components of the SDHS are:

- SAR Processing and co-registration;
- interferogram generation;
- phase unwrapping;
- phase to height conversion;
- geocoding.

The example in Fig. 3.38 was used to produce multi-media fly-throughs of the area around Mostar which were presented for use by the WEU and its member countries.

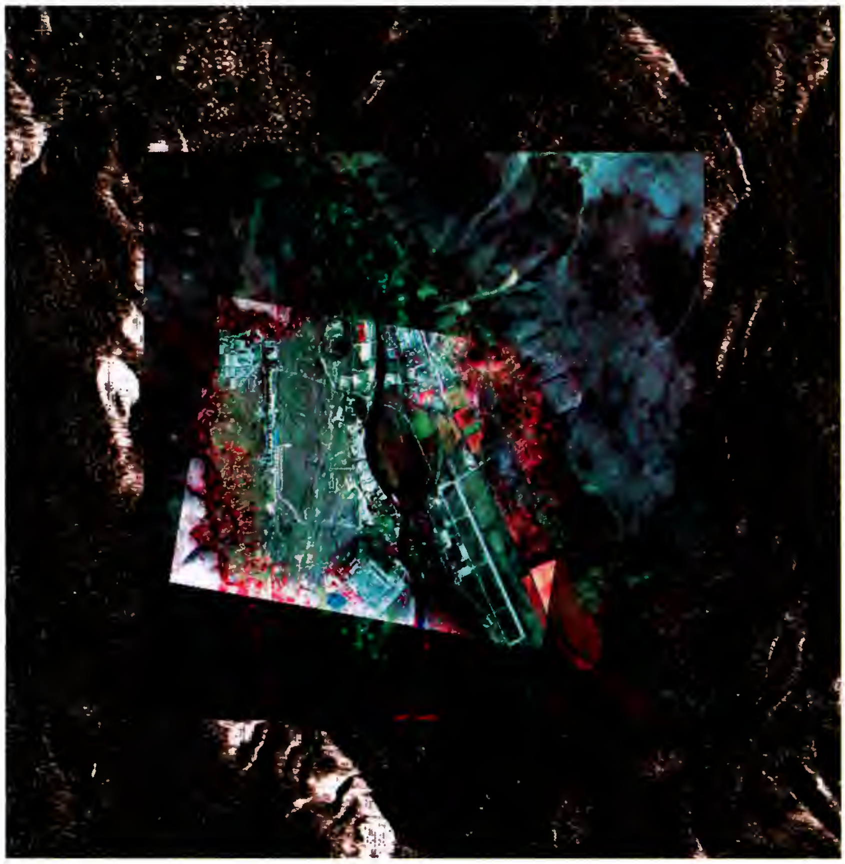


Fig. 3.39: Fused image of ERS-1 SAR, SPOT XS and Russian image (C Pohl and J Valero, WEU Satellite Centre)

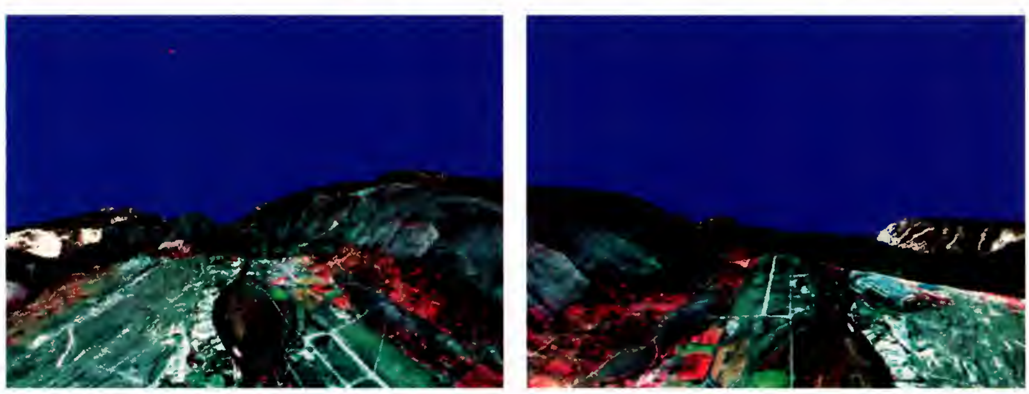


Fig. 3.40: 3-D visualisations of fused image using DEM from ERS Tandem Mission (C Pohl and J Valero, WEU Satellite Centre)

The benefits of multisensor products

Fusion of remote sensing imagery is used to exploit the complementarity of visible and infrared data with SAR data. In their daily work the Image Analysts of the WEU Satellite Centre combine images from a variety of sensors. Using the data fusion approach, the Image Analysts benefit from the contribution of the disparate data sets which help to improve interpretation capability, reliability of results and quality of the output.

The example displayed in Fig. 3.39 shows a successful integration of various types of image with their specific characteristics. First, the ERS-1 SAR image provides a large coverage of the area of Mostar. In addition it contributes texture and a quasi 3-D effect. The SPOT XS scene contributes multispectral information to the final product. Last but not least the high resolution of the Russian image provides spatial detail at the centre of the image.

A further step in data fusion and presentation is the use of a digital elevation model derived from ERS SAR data acquired during the Tandem Mission. Using SAR interferometry, ERS data can be used to derive digital elevation models suitable to produce perspective viewing and 3-D-fly-throughs as shown in Fig. 3.40. Both products are extremely useful in the interpretation process because of the real-world impression a 3-D environment provides. Furthermore those products are advantageous in the problem solving concerning certain types of tasks, for the interpretation itself and for the representation of results to non-expert end-users.

The example forms part of the data set presented to the WEU and its member states in the form of a multi-media fly-through, using the explanations from the Image Analysts in parallel to the video sequence.

Summary
The role of the military in Europe has changed dramatically in the past ten years, with a much greater emphasis now on peacekeeping activities and out of area operations. The theatre of operations is also much less predictable. These changes increase the need for timely spatial information, a need which ERS has helped to provide at national level and through international groups such as the WEU. The WEU satellite centre has made effective use of ERS data and is investing in technology to develop its ability to use SAR data to even greater levels of sophistication.

Case Study 10: Extending the Benefits Beyond Europe

Category:	Serving operational users and enhancing industrial capability
Description:	It was intended that the ERS programme should support non-European development programmes, particularly those related to natural resources and environmental management. This case study shows how this has been achieved through development of local receiving stations and gives an example of how ERS has contributed to development programmes in Asia.
Acknowledgements:	J. Williams, NRI, UK L. Balababa, Asian Institute of Technology, Thailand

Data from the ERS mission, particularly the SAR data, are now received at more than 28 stations located worldwide. Of these, 17 are owned by organisations which are neither part of the ESA system nor belong to ESA member states. Data from these foreign stations have been used to support a wide range of projects outside Europe. In many cases, such as in central Africa and Antarctica, transportable stations have been used to enhance data availability.

The concept of a transportable station has now been extended further to provide a local, field based, capability to acquire high rate ERS data. This system is known as RAPIDS (Real-time Acquisition and Processing Integrated Data System).

The RAPIDS system

The value of a diverse set of SAR based Earth observation techniques is becoming more widely accepted, so there is an urgent need to make processed SAR data more easily available to meet the real information needs of less-specialist users. In many cases this requires inexpensive, reliable and timely access to local data. The RAPIDS local receiving station has been developed in the UK and The Netherlands for just this purpose, and particularly for use in developing countries where timely access to basic resource data is often both crucial and very difficult. RAPIDS has been developed by:

- BURS: Bradford University Remote Sensing Limited;
- NRI: The Natural Resources Institute (NRI) of Greenwich, UK;
- NLR: The Netherlands' National Aerospace Laboratory (NLR).

Low-cost access to SAR data: Conventional receiving stations are designed to receive data from as wide an area as possible and hence need to operate down to low elevation angles. This requires a narrow beamwidth, if multipath is not to be a problem, and hence a large antenna diameter with accurate tracking of the satellite. Such receiving stations are heavy and expensive. By limiting the data capture area to the nearest 1,000 km around the user,

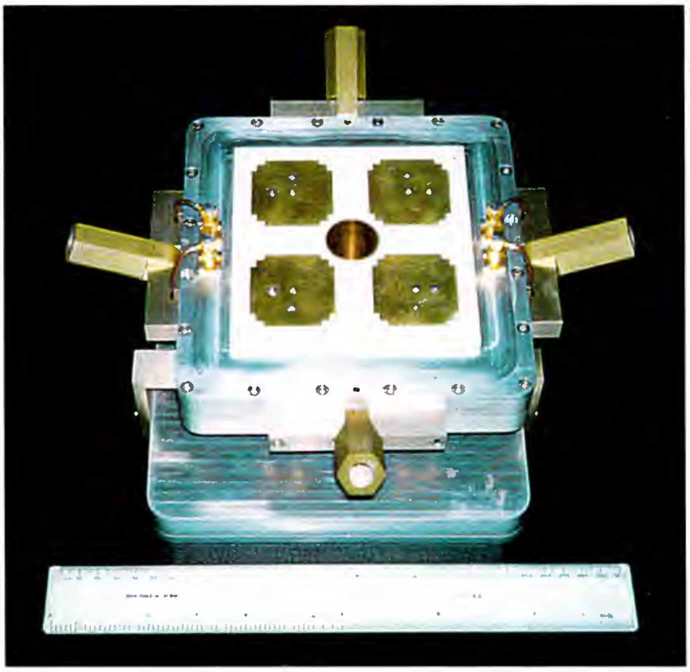


Fig. 3.41. An 8 GHz low noise amplifier mounted in the centre of four 2.2 GHz tracking signal patches (NRI)

RAPIDS only needs to operate at fairly high elevation angles and so can use a smaller (2.7 metre diameter) antenna with a relatively high beamwidth. Tracking requirements are less severe and the size and cost of the receiving system are greatly reduced. Fig. 3.41 shows the tracking head developed for RAPIDS. At the same time, the volume of data received per pass is much reduced and PC data management becomes feasible.

Decision makers are usually responsible only for their own local environment and coverage beyond national borders is not often a priority. Taking account of this, it has been possible to make RAPIDS so small, light, flexible and easy to use that it sits on a trailer (Fig. 3.42).

Fig. 3.42. The trailer mounted RAPIDS with 2.7 metre dish for data capture through a 90 degree pass (NRI)

Local data processing with high bandwidth SAR data: Since horizon to horizon coverage is not attempted, the quantities of data from RAPIDS are relatively small and manageable with only modest data processing power and storage capacity. Data from RAPIDS are received, stored and processed on a standard PC, with extra RAM. PC based SAR processing software is not expensive. High quality local outputs are available within minutes as illustrated in Fig. 3.43 and the NLR station at Marknesse in The Netherlands can produce a standard SAR scene within 90 minutes of satellite overpass.

Benefits from RAPIDS: RAPIDS provides a powerful means for monitoring local environmental change, to inform local decisions for optimal local response. Its utility lies in meeting a wide spectrum of requirements in natural resource management such as forest state, coastal zone development, environmental protection (oil slicks, fire impact areas) and disaster management (flooded areas after a tropical cyclone, volcanic or earthquake subsidence), especially in developing countries in which other sources of timely data may not exist.

Minimising costs: RAPIDS is trailer mounted for easy transport (it fits in a standard container) and local installation. This also adds to its versatility, giving it a peace keeping role, or even potentially allowing it to operate a moving ship. Its low capital and running costs, quick satellite turn-round time and self checking capability (to ensure optimal data quality) make this a viable alternative to conventional mainframe stations that typically cost ten times as much and are very difficult to operate and maintain cost effectively.

Fig. 3.43. SAR image of the Isle of Wight(U.K.), received by RAPIDS (NRI)

Application development in ASEAN countries
Through the use of foreign receiving stations, a joint European Commission (DGI)/ESA project has assisted ASEAN countries to develop ERS SAR applications by providing financial and technological support. A specific example of a project under this programme is the monitoring of rice growing in South East Asia, which has been successfully performed using ERS SAR. This project has demonstrated that:

- the normalised backscatter could be correlated with rice crop parameters including height and crop biomass;

- the normalised backscatter of the rice crop varies significantly during the growth cycle, allowing the different stages of growth to be identified.

Rice cultivation is the major agricultural activity in the Mekong Delta, known as the 'rice bowl of Vietnam'. It is largely governed by various agro-hydrological factors such as rainfall and irrigation. To accommodate the differences between the various cropping systems and cropping patterns practised by farmers, multitemporal images are required. Optical images could be useful for the purpose but rice is mostly grown during the rainy months when thick cloud cover is normal. SAR images, which have the capacity to obtain information over cloud covered areas are therefore used.

A pilot project (the CRISP-IRRI MRD project) using multitemporal ERS SAR data to delineate and map the spatial distribution of the various rice cropping systems in the Mekong River Delta, has been conducted jointly by researchers from the Centre for Remote Imaging, Sensing and Processing at Singapore, the International Rice Research Institute in the Philippines and the University of Cân Tho, Vietnam. Different cropping systems and cropping patterns have been identified in the study area which covers parts of Cân Tho, Sóc Trang and Bac Liêu provinces.

Seven multitemporal ERS SAR PRI images acquired over the period May to December 1996 were used to delineate and map areas under different rice cropping systems in the Mekong Delta. Five change index maps were generated from the six images and a 3 dB threshold was used to classify each pixel as having an increasing, decreasing or constant backscattering. These change index maps were used to create a composite image having 202 classes in which the backscatter values were subjected to hierarchical clustering analysis. The homogeneous clusters obtained were classified as single-cropped or double-cropped based on the resemblance to the known backscatter profiles of the two cropping systems. Double rice cropping was found to be the most prevalent practice in Cân Tho and Sóc Trang provinces while single-cropping was found in Bac Liêu.

A total of 39 homogeneous clusters was obtained and these were classified as either single-cropped or double-cropped, based on the resemblance of the backscatter profile to the known profile of the two cropping systems, otherwise a cluster was classified as non-rice (Fig. 3.44). The different cropping patterns under the double-cropping systems were identified at each district and then generalised to the provincial level. In Cân Tho province, Dông-Xuân/Hè-Thu (Winter-Spring/Summer-Autumn) cropping pattern is the most prevalent practice since most fields in this area are irrigated. The Dông-Xuân crop starts in November-December and ends in February while the Hè-Thu crop commences in May-June and is harvested in August-September. The Hè-Thu/Mua (Summer-Autumn/Rain season) pattern is the most widely adopted in Sóc Trang, which is mostly rainfed rice. Mua is the traditional crop that is sown in July- August and harvested in December-January. On the other hand, Bac Liêu province is divided into rice and non-rice areas. Almost 48% of the total area is divided into shrimp farming, mangrove plantations and other non-rice crops while the rest are dedicated to single and double rice cropping. The single-cropped areas are located near the coast where there are permanently saline soils. The double cropped areas are located in the more inland areas where the level of salinity is lower. Hè-Thu/Mua is still the popular cropping practice in the double cropped area. The information about cropping patterns provide ideas about the resources possessed by each province regarding rice cultivation, as well as the limitations and pressures they face to intensify cropping.

ERS SAR PRI multitemporal images are capable of detecting differences in the ground vegetation cover because of the variation of the backscatter profiles between the various acquisition dates during the year. In particular, rice areas can be distinguished because of their specific temporal signature. The information content of the ERS SAR, together with the improved accessibility offered by systems such as RAPIDS, provides benefits beyond the boundaries of Europe.

Summary
The value of ERS for applications outside Europe has been demonstrated through the ESA ASEAN project. The example shows the ability of ERS SAR to monitor rice crop growth which means that ERS SAR can be incorporated in operational agricultural monitoring programmes. The availability of systems such as RAPIDS will extend the availability of ERS data to new users in the developing world.

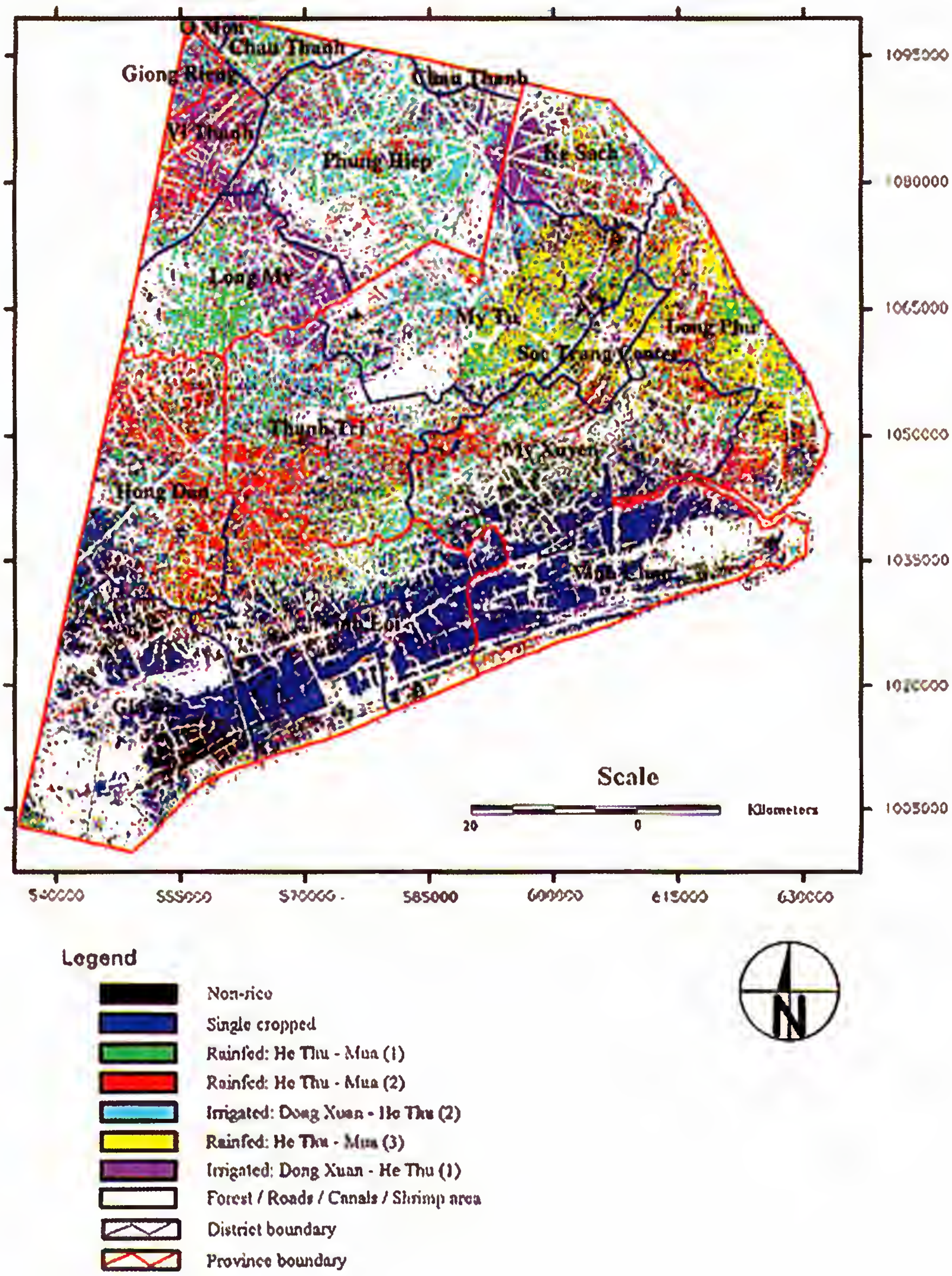


Fig. 3.44: Cropping patterns in Vietnam, derived from ERS SAR data (Asian Institute of Technology)

Case Study 11: Disaster Management

Category:	Serving operational users and enhancing industrial capability
Description:	Natural disasters are having an increasing human and economic impact because population pressures are creating increased exposure to their effects. This has two sets of consequences: the immediate human consequences and the longer term socio-economic implications. In both cases, risk management strategies are required
Acknowledgements:	Salvatore Stramondo, Istituto Nazionale di Geofisica, Italy B. Müschen, Ch. Böhm, A. Roth & M. Schwäbisch, German Remote Sensing Data Centre (DFD) Ye Xia, GeoForschungsZentrum Potsdam, Germany Bureau de Recherches Géologiques et Minières (BRGM), France National Centre for Marine Research, Institute of Oceanography, Greece Tromsø Satellite Centre, Norway

ERS data are assisting the management of natural disasters and also provide valuable support to the risk management industry. ERS data help with:

- planning for anticipated problems;
- monitoring threats such as changes in volcanic cones and fault line movements;
- assistance with relief operations;
- post disaster assessment.

Reducing the impact of life threatening events is clearly a first priority, but ERS data also contribute to the risk management industry in its efforts to handle the economic implications of disasters. Recent estimates for total worldwide economic losses due to natural disasters exceed 60 billion ECU, ten times the figure for 1960, an increase due to a greater frequency of natural disasters combined with greater human exposure to their effects. Non-natural events such as mining-induced subsidence and forest fires are also the cause of multi-billion dollar losses.

The cost of predicting, preventing and mitigating disasters amounts to one third the total cost of the losses. The risk management market offers three categories of customers for EO data:

- a risk management industry which is increasingly targeting loss prevention and fraud control;
- new customers from the manufacturing, oil and gas and civil engineering industries, in which risk management is increasingly performed in-house;
- the public sector, in which the focus is more on the effects of natural disasters and civil protection - in particular assessing the risk and effects of likely hazards, how to mitigate their effects by planning and preparation.

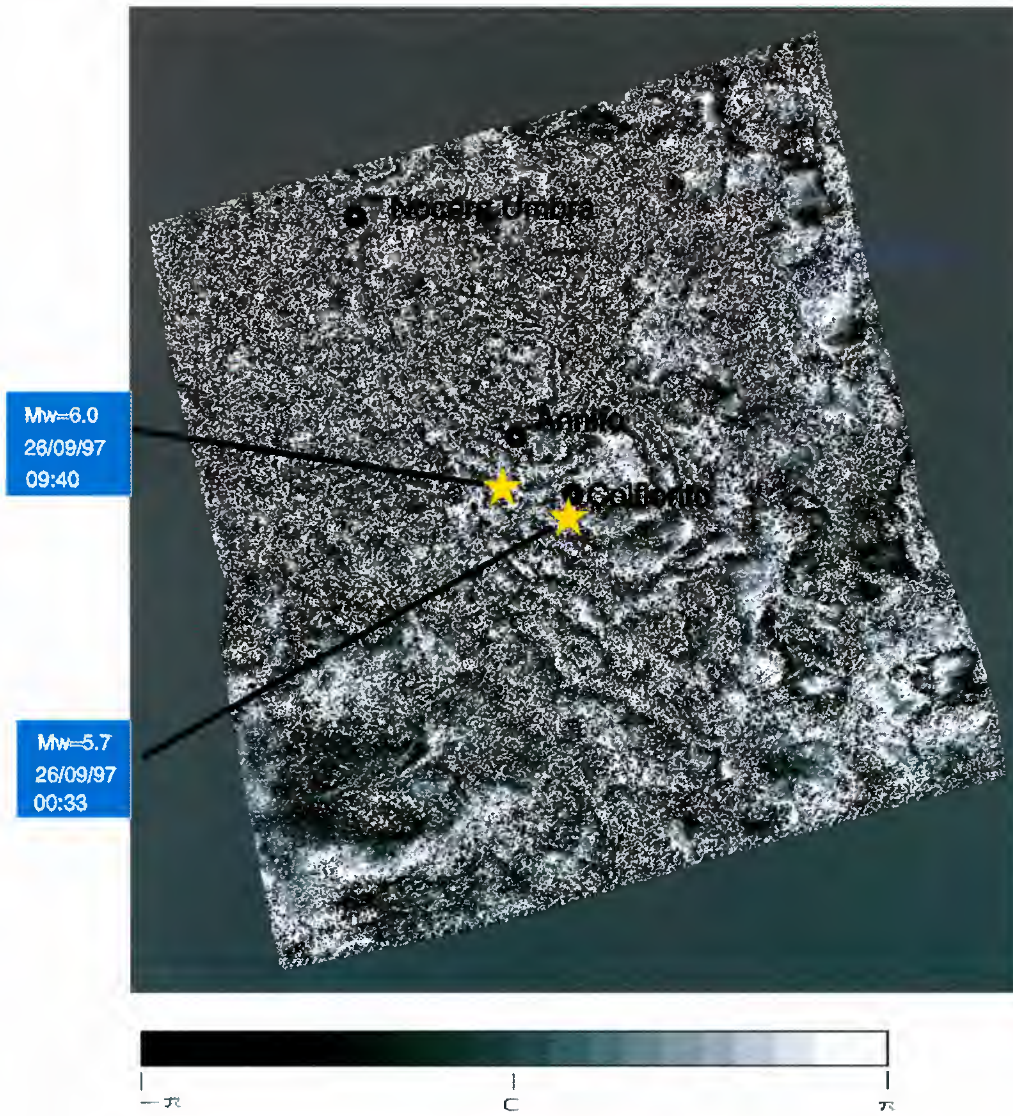
The following examples show how ERS data are being applied to the management of disasters from a range of causes.

Earthquakes
Earthquake prediction is very difficult to achieve. One way to help is to measure the land movements which occur during earthquakes, allowing earthquake models to be validated and improving our understanding of the processes involved. Using ERS SAR data to make these measurements through interferometry has been well documented. This technique has the particular advantage of measuring movement across the entire earthquake area rather than only between control points where survey equipment is located. SAR interferometry has been used to study a number of characteristics of earthquakes including:

- the distribution of surface deformation;
- earthquake cycles;
- elastic/inelastic accommodation of stresses and strains;
- seismic coupling.

Since the first major application to the Landers earthquake in California in 1992, SAR interferometry has become much more widely used. More recent examples of applications have included monitoring movements on the San Andreas fault and characterising earthquakes in Italy and in the Chilean Desert. In the case of the San Andreas fault, it was possible to identify movements along the fault over a 15 month period, observations which complemented the existing land based monitoring networks. This type of analysis is used to identify parts of the fault which are locked and which may in future become the locations of major earthquakes.

Fig. 3.45: SAR image of the earthquake area (ING)



ERS SAR data helped resolve the coseismic surface displacement occurring during the two Umbria-Marche earthquakes in Central Italy during 1997 (Fig. 3.45). The topographic information extracted from ERS data acquired 20 days before and 15 days after the main shocks, was compared. A digital elevation model with a pixel size of 20 × 20 metres was used to eliminate topographic influence on the backscattered radar signal.

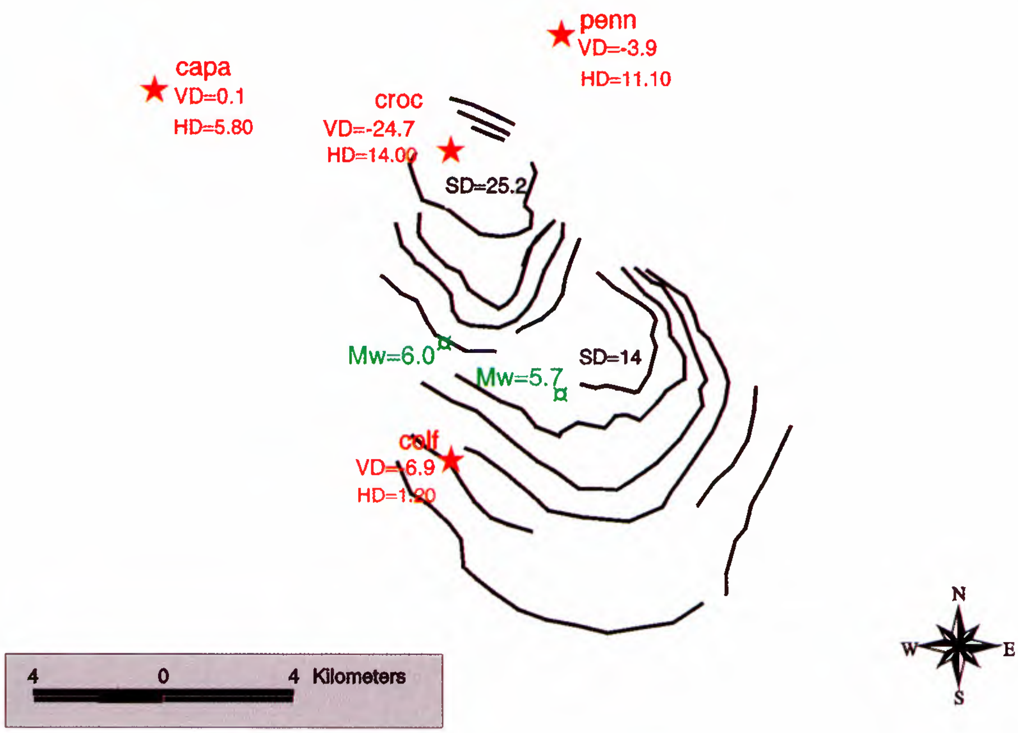


Fig. 3.46: Differential interferometric fringes of the Umbrian area (ING)

The final differential interferogram (Fig. 3.46) shows a pattern of concentric fringes corresponding to the earthquake epicentres and the areas of maximum damage. Each fringe can be seen as a contour of the surface displacement as seen from the radar pointing direction. The maximum displacement occurs in the north west part and corresponds to a subsidence of the surface of about 25 cm.

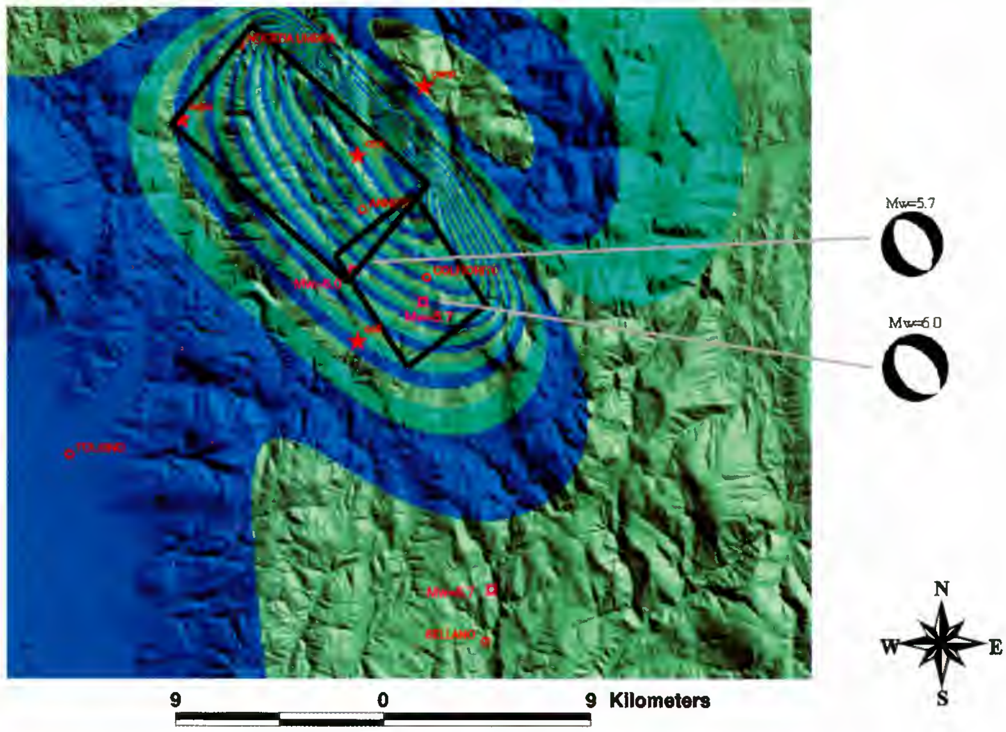


Fig. 3.47: Modelled fault lengths in relation to interferometric fringes for the two earthquakes (ING)

Post-earthquake, geodetic GPS measurements located along the fringes show an agreement with the SAR-retrieved displacements (Fig. 3.47).

Accurate spatial mapping of the coseismic deformation is fundamental for understanding the seismic source. Displacement data are used to model the fault geometry and dimensions at depth (Fig. 3.48), allowing the retrieval of important information for the continuous monitoring of the seismic hazard for Umbria-Marche.

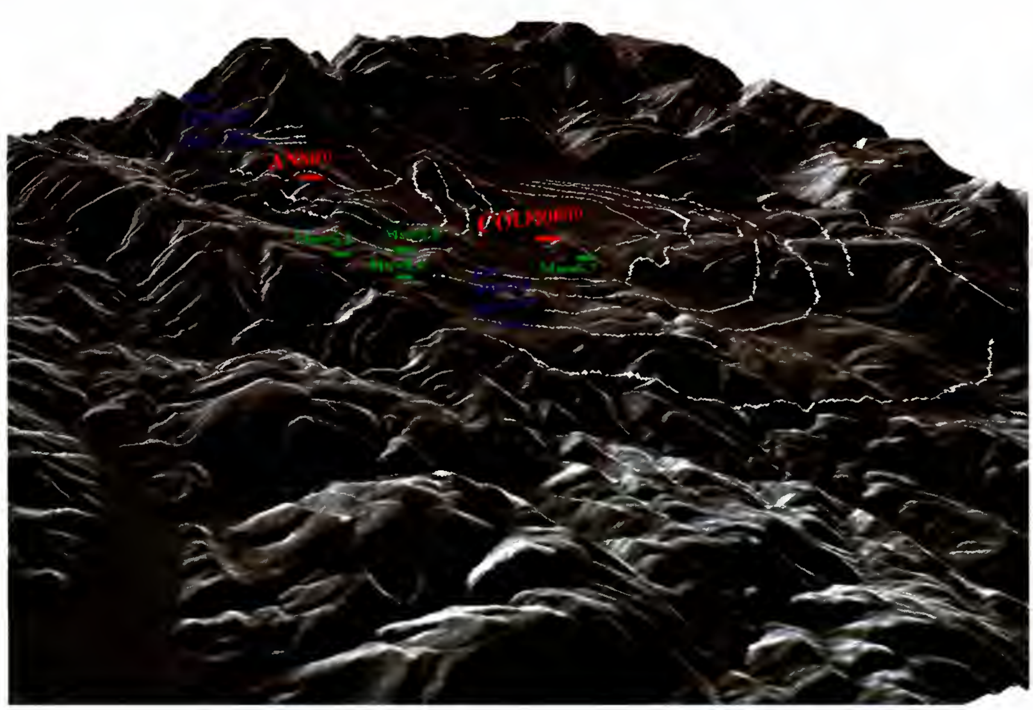


Fig. 3.48: Three dimensional view of the SAR interferometric imagery and the associated GPS fringes (ING)

The ESA project AETNA ('Analysis of problem areas and Experimental Test of possible solutions arising from the Need to Acquire and process interferometric SAR data for geodynamic purposes on a large scale basis') has included work on the Antofagasta Region located in north-central Chile along the rim of Southern America. Linking with the South American Geodynamic Activities (SAGA) project, the GeoForschungsZentrum Potsdam (GFZ) established cooperation with many partner institutions in the host countries in 1993 to 1994, leading to a network of 200 GPS stations covering the whole territory of Chile and the western part of Argentina. This network is embedded within a network of permanently operating stations in South America and worldwide which is primarily managed by the International GPS Geodynamic Service (IGS). The main purpose of the SAGA network is to observe station velocities over a period of at least ten years. In the northern part of the network a dense traverse of 72 points extending from Antofagasta to the Argentina Chaco was observed 21 months before an earthquake in July 1995 and 3 months after the event. Using more than 20 GPS receivers, about 3 days of continuous data were acquired on each site in each campaign.

Fig. 3.49 shows a normal SAR intensity image of the research site. Fig. 3.50 is an interferometric image showing deformation in the period between 14th July and 18th August 1995. The deformation is related to the coseismic elastic strain release of the 8.0 MW (moment magnitude) Antofagasta earthquake on

Fig. 3.49: Intensity (GFZ)

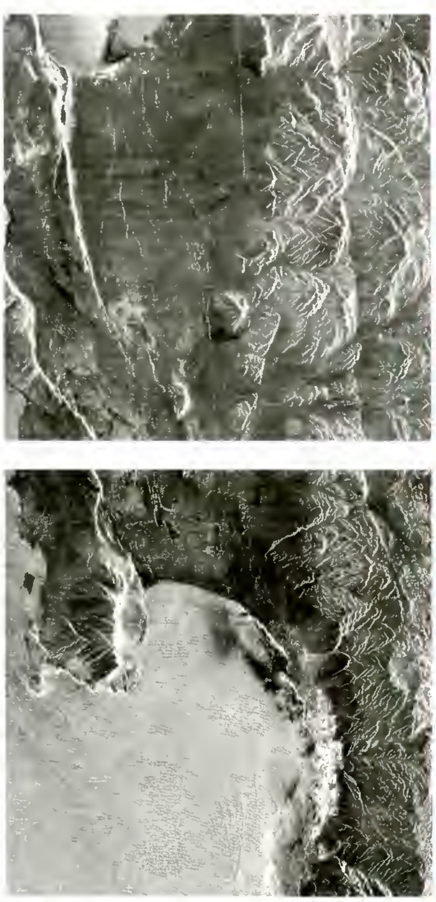


Fig. 3.50: Co-seismic displacement from 14th July 1995 to 18th August 1995 (GFZ)

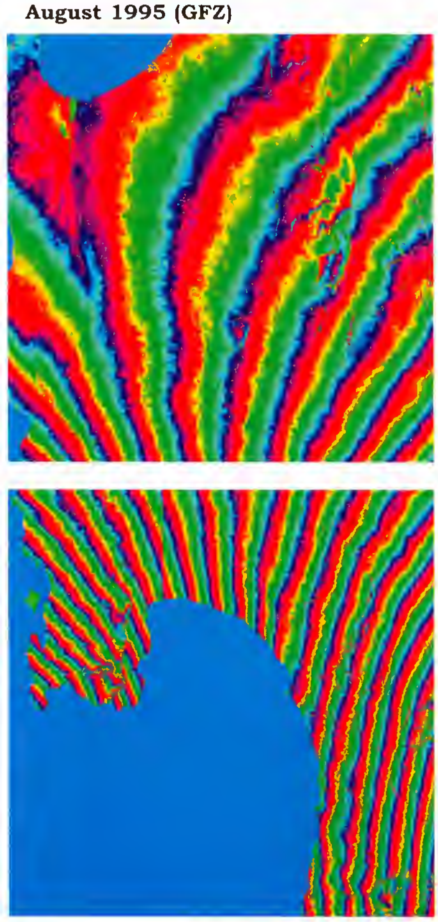
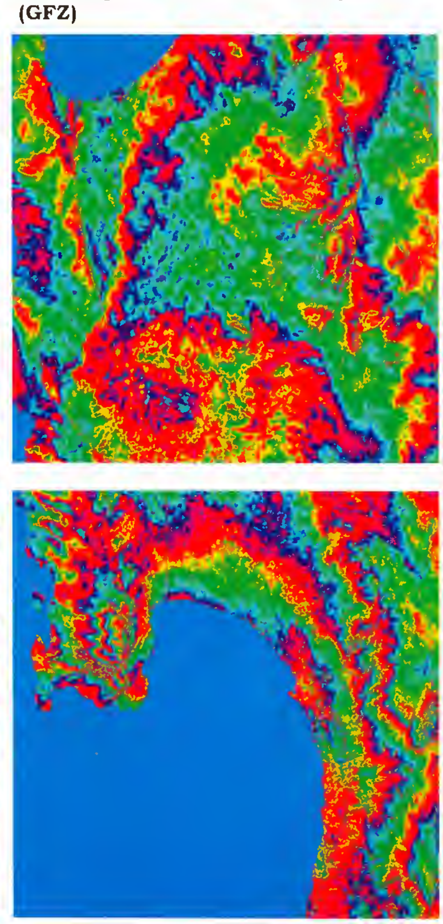


Fig. 3.51: Inter-seismic loading of 18th August 1995 to 24th May 1996 (GFZ)



30th July 1995. The distribution of fringes is very homogeneous and related displacements coincide with those derived using GPS at selected discrete points. Unlike the GPS measurement, the ERS measurements can be used to detect the areal distribution of motion. This includes motion related to lateral or vertical local inhomogeneities. Compared to the co-seismic deformation in Fig. 3.50, the inter-seismic loading of the period from 18th August 1995 to 24th May 1996 (Fig. 3.51) is more inhomogeneous. The distribution of fringes corresponds to inhomogenities and contrasts in the lithology (unconsolidated sediments versus consolidated volcanic rocks) expressed also by topographic changes at the surface. This means that differences in the surface properties (rheology) are more important. In both cases, each fringe (a colour cycle in Fig. 3.50 and 3.51) represents a relative displacement of 2.8 cm (half the wavelength of the ERS SAR) in the slant range direction.

Volcanoes

As well as its contribution to monitoring the effects of earthquakes, the ERS SAR has also proved to be very valuable in assessing the behaviour and effects of volcanoes. The full range of SAR techniques is applicable to this topic, with SAR imagery being used to identify surface and land cover changes on the volcano and SAR interferometry being used to monitor changes in cone shape which can indicate a likely eruption.

In recent years there have been a number of eruptions which have been successfully monitored with ERS. Perhaps the most spectacular of these was the subglacial eruption under the Vatnajökull glacier in Iceland. This shows the use of ERS SAR and SAR interferometry to monitor the progress of this event from the eruption itself through to the major flood event (jökulhlaup) following the release of the meltwater resulting from the eruption.

This example uses a number of ERS SAR images produced by the German Remote Sensing Data Centre (DFD) to illustrate various stages of the event. Image products and derived information were quickly supplied to the Icelandic authorities, providing very valuable information with which to plan emergency measures. From the sub-glacial eruption on 3rd October 1996 to the subsidence of the floodwave on 9th November 1996, nine SAR images were acquired - a frequency of observation made possible by the use of both ERS satellites during the Tandem Mission.

The event began with a volcanic eruption on 1st October 1996 and was first observed by ERS-2 on 3rd October. The position three days later on 6th October is shown in Figs. 3.52 and 3.53. Fig. 3.53 shows the total visible length of the fissure that was active during the eruption. The two points at which the eruption broke through the ice are marked as opening eruption fissures. It should be noted that for much of the early period following the eruption, the site was covered with dense water and ash clouds, making it inaccessible to optical observation. The ERS SAR data provide the best overall view obtainable under such circumstances.

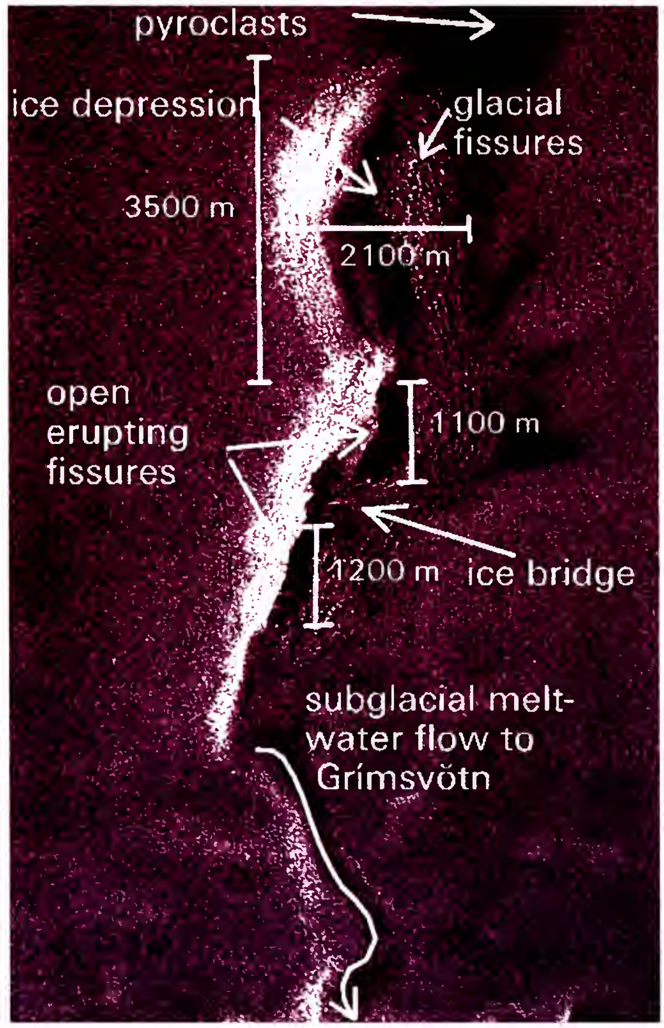
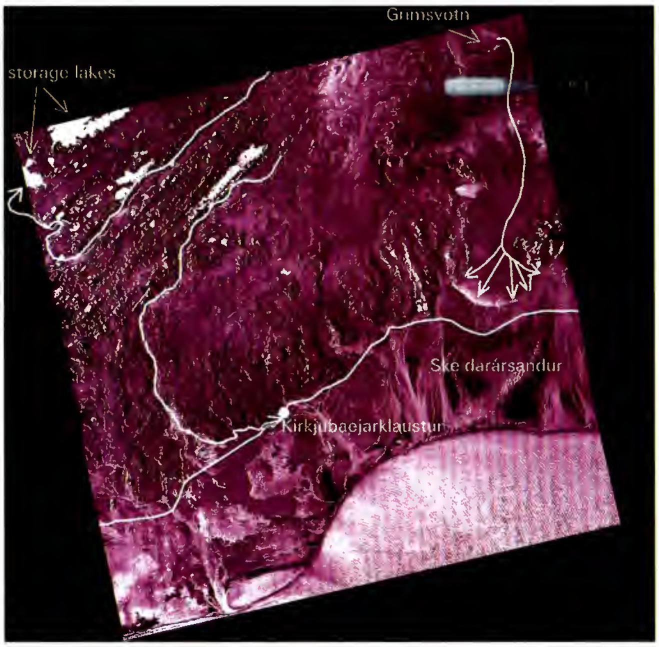


Fig. 3.52: ERS-2 data for 6th October 1996. The latest eruption is located in a north/south oriented mountain ridge under the Vatnajökull ice sheet
German Remote Sensing Data Centre (DFD)

Fig. 3.53: Extract from Fig. 3.52 showing the eruption area itself. The view extends 12 km north to south and 6 km east to west
German Remote Sensing Data Centre (DFD)



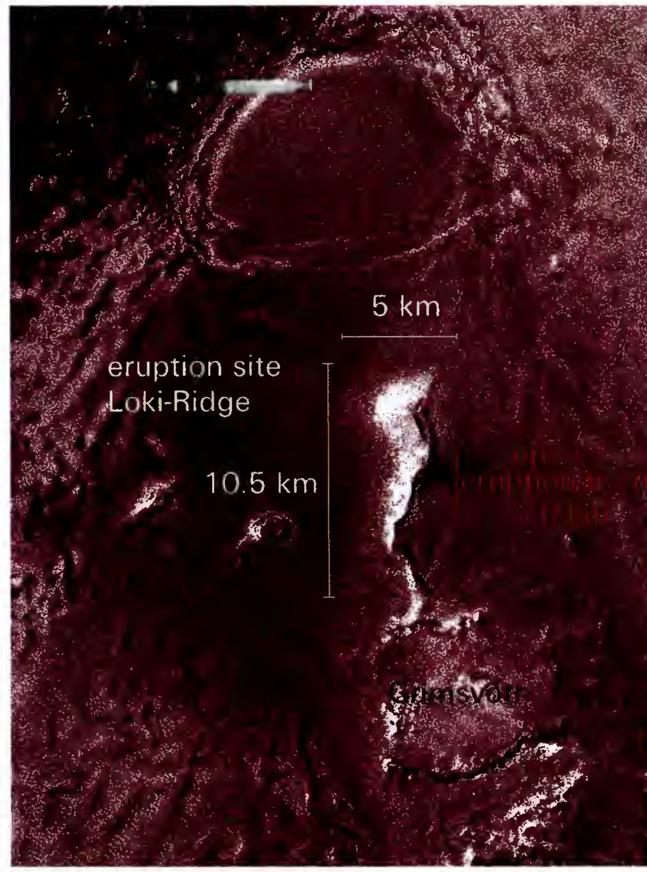
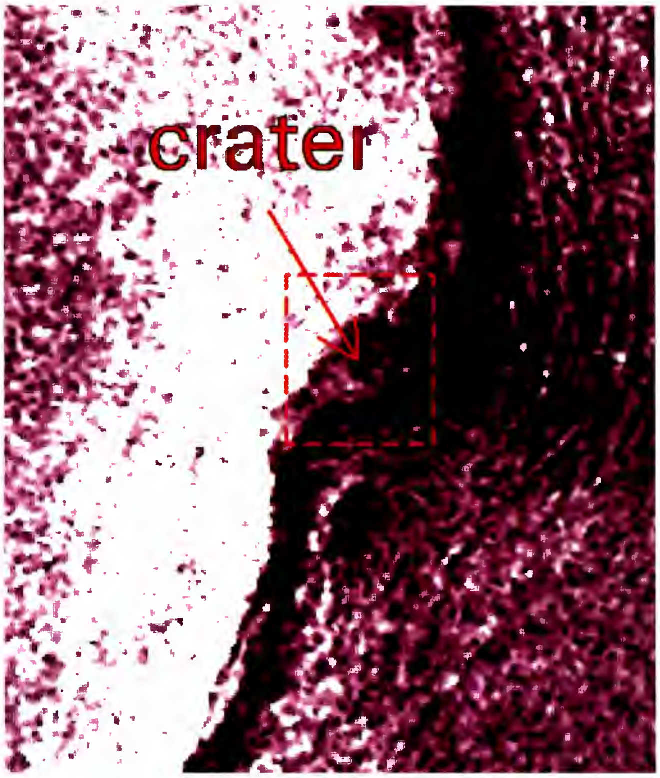


Fig. 3.54 (above): ERS-2 image for 8th October 1996 showing the possible directions for drainage (German Remote Sensing Data Centre (DFD))

Fig. 3.55 (right): ERS-2 scene for 21st October 1996 (30 km x 38 km extract) At the northern end of the eruption site, the depression which is traversed by numerous crevasses has widened (German Remote Sensing Data Centre (DFD))

Fig. 3.54 shows that the drainage of meltwater, accumulated in the Grímsvötn caldera by 8th October, is possible in three directions, each of which would endanger different forms of infrastructure. Such images can be used to plan evacuations and any counter-measures which may be possible. By 21st October the depression to the northern end of the eruption site had widened to an average width of 400 m as shown in Fig. 3.55 and in more detail in Fig 3.56.



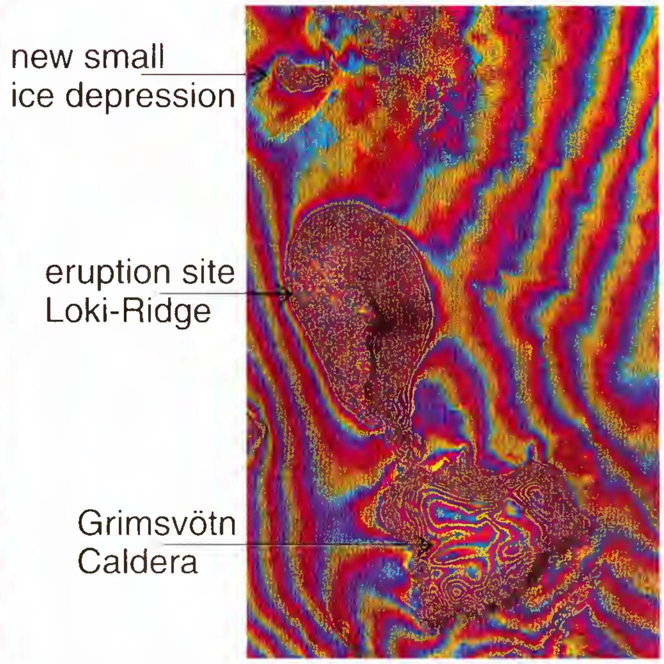


Fig. 3.56 (left): Extract from Fig. 3.55 showing the Loki Crater section (about 7 km square) German Remote Sensing Data Centre (DFD)

Fig. 3.57 (above): Interferogram from ERS-1 and ERS-2 scenes for 21st October 1996 German Remote Sensing Data Centre (DFD)

Towards the end of October, the meltwater was accumulating to form a lake containing huge quantities of water. Calculations based on known geometries and the observed changes put the volume of water in the lake at between 2.5 and 4 km^3. Fig. 3.57 shows an interferogram derived from ERS-1 & 2 images on 21st and 22nd October. This scene (approximate size 20 km by 30 km) shows three main features:

- in the centre, a pear shaped depression, which is the area still volcanically active in which no fringes are recognisable. This is because this area is was still subject to strong movements caused by subsidence, together with horizontal movements of the ice during the 24 hour period between the images used to create the interferogram;
- the Grímsvötn caldera is located towards the southern part of the image, the elevation changes here result from the accumulation of meltwater, which has lifted the ice sheet;
- to the top left of the image, a depression is visible at the southwest rim of the subglacial Bárdarbunga volcano. This indicates that a small eruption, unreported from any 'other source, took place at this location.

The final stage of the event and probably the most spectacular, was filmed from aircraft and shown on television throughout the world. The details of the release of the meltwater (jökulhlaup) were also recorded by ERS and the results are shown in Figs. 3.58 and 3.59. During this event, outflow rates, normally of the order of 50 m^3/s were raised to 25,000 m^3/s, transporting ice blocks estimated to weigh in excess of 1,000 tonnes. The effect of the outwash flood was to make significant changes to the drainage system, which needed to be taken into account when rebuilding the infrastructure lost in the event.

Events such as the one described above are comparatively rare and tend to occur in sparsely populated areas. Nevertheless, they can have serious life

Fig. 3.58 (above): ERS-2 SAR mosaic from 7th November 1996 showing the areas affected by the flooding after release of the meltwater. Flooded areas can easily be recognised by the high reflectance from the ice blocks spread across the outwash plain
German Remote Sensing Data Centre (DFD)

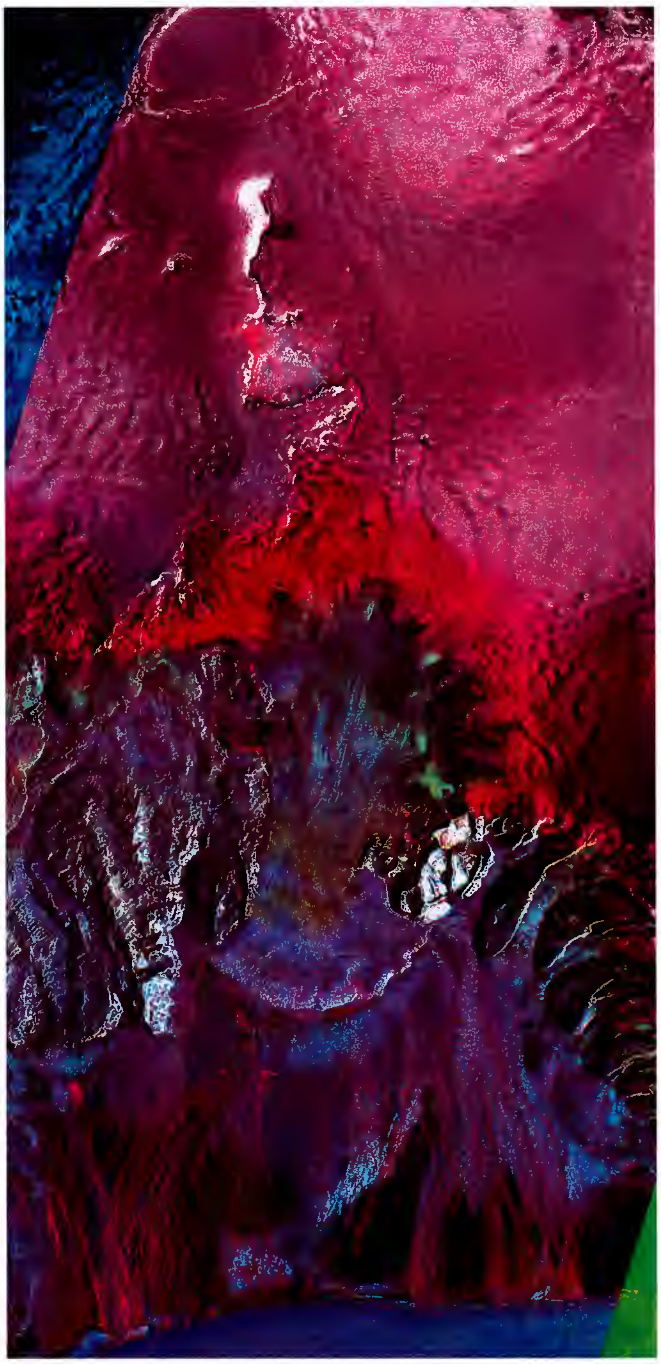


Fig. 3.59 (right): Multi-temporal composite (Blue = 21st October, Green = 22nd October & Red = 7th November) of the area affected by the flooding
German Remote Sensing Data Centre (DFD)

threatening consequences and it is important to note that, during the critical phases of the event, the cloud penetrating capabilities of the radar were vital in revealing what was happening.

Effects of the Chernobyl disaster

The explosion in one of the reactors at the Chernobyl Nuclear power plant in April 1986 was a major ecological disaster that contaminated the locality and affected the whole of Europe. A 30 km exclusion zone was designated around the site, but the effects were much more widespread than this, with contaminated material being transported within the atmosphere and water courses.

The effect of the disaster on the hydrological cycle and vegetation within the exclusion zone is important as an indicator of the magnitude of the problem and can also be used as a measure of how well the region is recovering. To monitor this area regularly with in-situ measurements is clearly too dangerous, making the use of satellite data very valuable. Accordingly historical and ongoing sequences of data from the ERS and SPOT satellites have been used to provide the necessary data.

ERS data in particular were used for the following applications:

- to provide digital elevation models using SAR interferometry;
- monitoring variations in the water surface;
- monitoring the circulation of water within the hydrological cycle.

SPOT data were used to map precisely the extent of the flooded surfaces, but often it was not possible to do this effectively because of cloud cover. On cloud affected days, ERS SAR data were used in place of the SPOT data.

Fig. 3.60 shows the use of ERS data to monitor the water surface within part of the exclusion zone. The large area in red towards the centre of the image is a lake area just to the north of the Chernobyl plant itself. The strong changes in the vicinity of the river system are interpreted in terms of changing water levels. For the analysis, data were available at monthly intervals. Images such as this allow changes in the water level to be determined, thus providing evidence of the extent to which contaminated material from the site is being removed from the exclusion zone.

Oil spill detection and monitoring

During the last thirty years, pollution of the world's oceans, particularly in coastal areas, has become a matter of increasing international concern, particularly in enclosed seas. In spite of rigorous controls, deterioration of water quality, especially in waters subject to heavy shipping, continues at a high rate. Due to the relative volumes of discharges, illegal emissions from ships represent a greater long-term source of harm to the environment than infrequent large scale accidents. Monitoring illegal discharges is thus an important component in ensuring compliance with marine protection legislation and the general protection of coastal environments.

Traditionally, this service uses airborne patrols which are expensive and often provide only patchy coverage. Fast delivery SAR products are proving to be of great value in the optimisation of air-borne surveillance resources, due to the large area they can image at any one time. Fig. 3.61 shows a comparison of an ERS image with a confirmed sighting of a slick from an airborne radar system. The ERS-1 image is on the right.

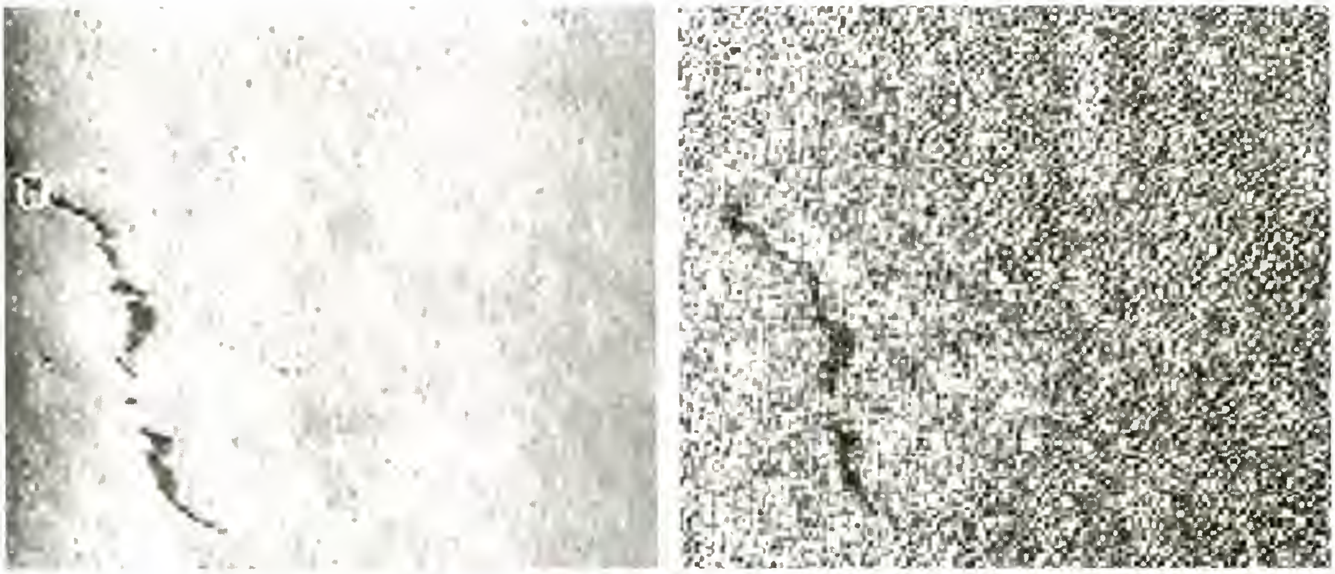


Fig. 3.61: Comparison of an ERS-1 slick image (right) with an observation of the same slick from an airborne side looking radar (Copyright: ERS raw data, ESA, 1996. Image Interpretation, TSS, 1996. SLAR data provided by Norwegian Pollution Control Authority (SFT), 1996.)

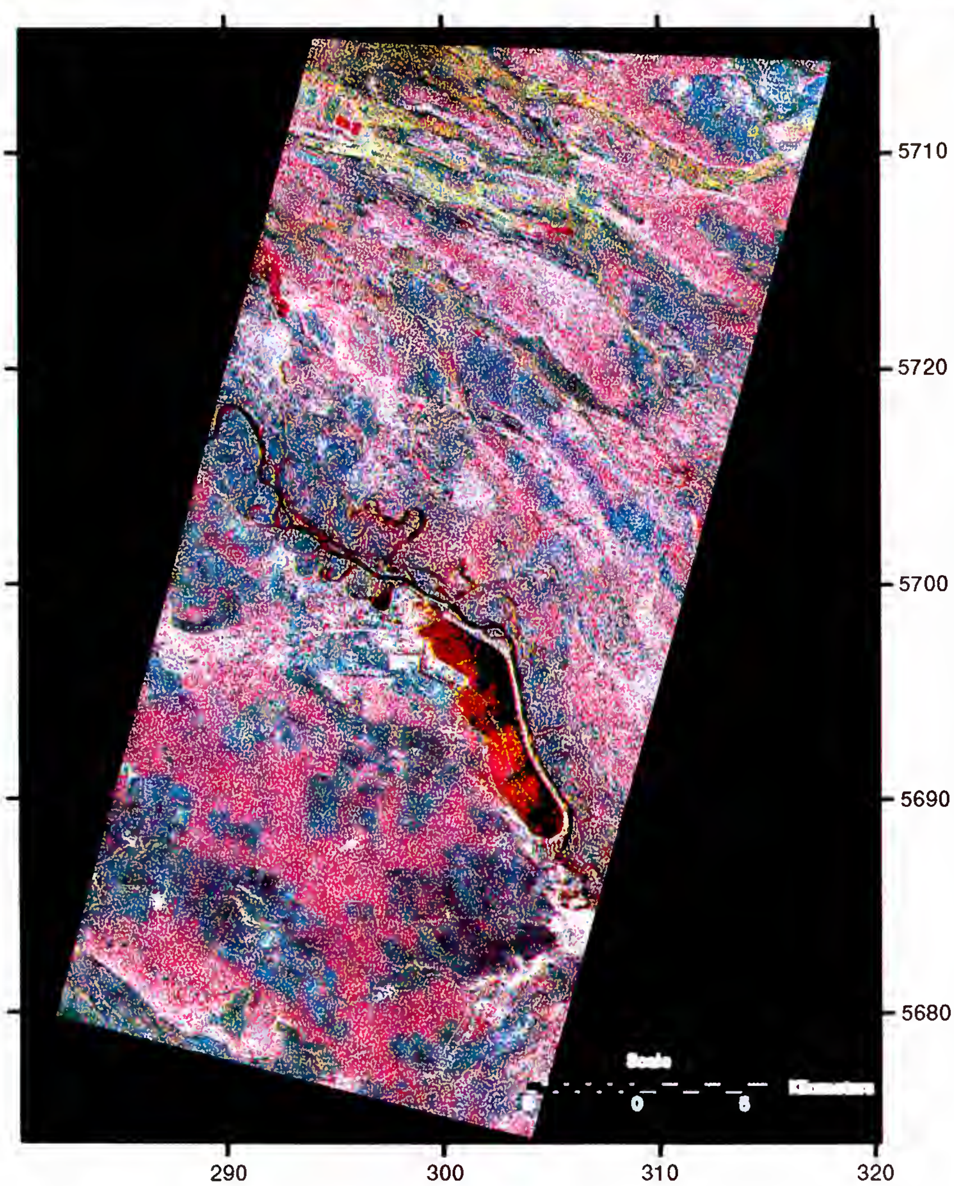


Fig. 3.60: Geocoded multi-temporal ERS SAR image showing differences between 3 dates in 1995 (BRGM).

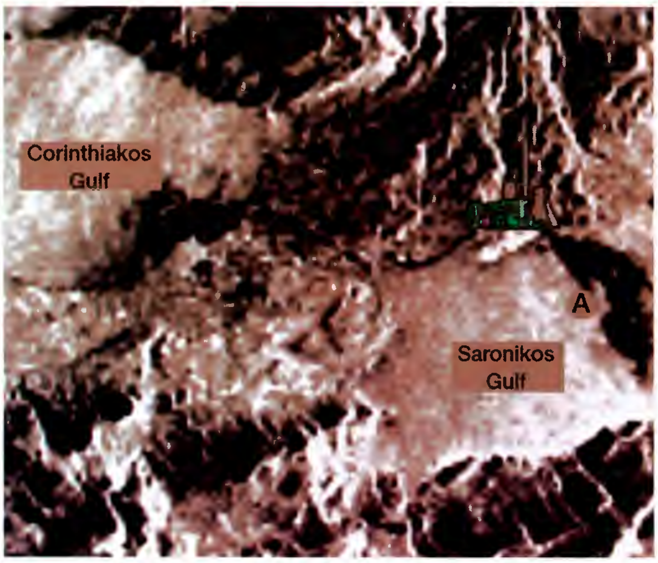


Fig. 3.62: Oil spill (A) from a refinery in Isthmia, Greece (National Centre for Marine Research, Institute of Oceanography, Greece)

Fig. 3.63: Typical shapes of detected spills on the corresponding ERS-1 SAR orbits and frames (National Centre for Marine Research, Institute of Oceanography, Greece)

Experiments show that in general, slicks larger than 0.05 km^2 can be spotted by both aircraft and spaceborne SAR with the same reliability. To illustrate the capability, Figs. 3.62 and 3.63 show examples of slicks detected by ERS SAR. Fig. 3.62 shows a discharge from an oil refinery in Isthma, Greece while Fig. 3.63, shows a number of slicks detected in the Mediterranean.

Summary

This case study shows just how wide the range of natural hazards which can be monitored by ERS has become. For volcanoes and earthquakes, the role is in monitoring changes in the lead up to and following on from specific events. In the case of oil spills there is an important role in identifying the emergence of new spills. It is also possible to use ERS data to assist with disaster relief, either through near real time image capture, or through the three dimensional elevation models derived from ERS SAR interferometry. The Chernobyl example shows how valuable the ERS data are in monitoring change in areas made inaccessible following a disaster.

Case Study 12: Weather Forecasting

Category:	Serving operational users and enhancing industrial capability
Description:	The use of the ERS scatterometer has significantly enhanced the global forecasts provided by Europe's meteorological organisations, particularly in predicting specific events such as the formation and early evolution of tropical cyclones
Acknowledgements:	L Isaksen and P Janssen, ECMWF, UK

ERS Scatterometer data have been assessed for use in operational weather forecasting models since the early phases of the ERS-1 mission. As with any new form of data in numerical weather prediction, the full impact is not achieved until the error characteristics are well understood and the assimilation procedures are optimally tuned to the data.

Following the assessments performed during the earlier parts of the mission, ERS Scatterometer data have been in operational use at ECMWF since January 1996, and have been assimilated continuously since then. Forecasters at ECMWF have found that these data have provided significant improvements in forecasting accuracy, particularly in predicting the intensity and position of tropical cyclones. The benefits of the Scatterometer in this regard can be seen in Fig. 3.64 and 3.65. Comparison of the 5 day forecast with and without the Scatterometer against the observations when the event occurred shows that without the Scatterometer, the development of an important tropical cyclone would have been missed altogether.

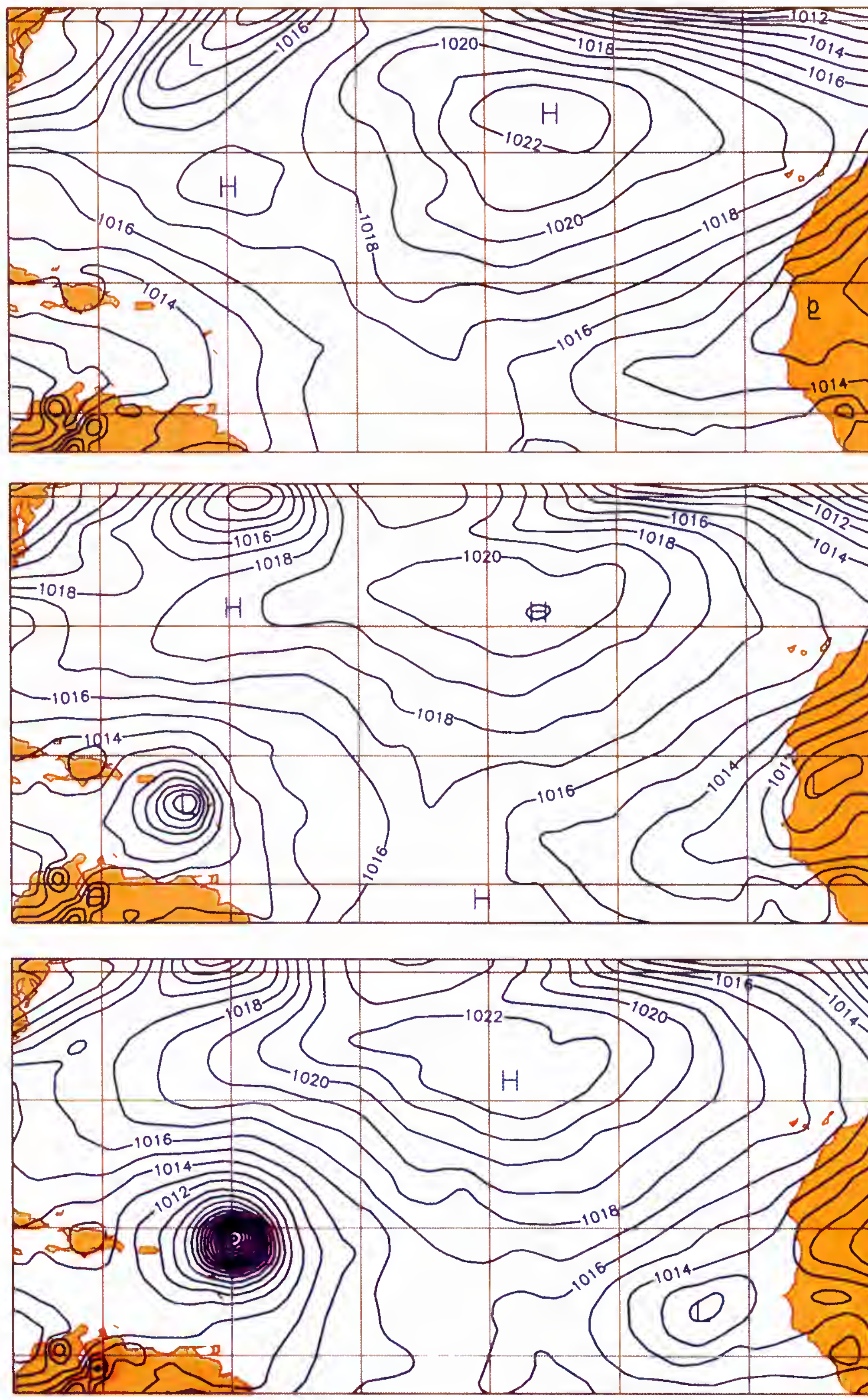
Since 1996, the benefits from the ERS Scatterometers in the ECMWF model have been further enhanced by the adoption of a 4-D variational analysis scheme which optimises the data for use in the model. This scheme, which was adopted in November 1997, enhances the impact of ERS Scatterometer data in the following ways:

- it allows the data to be used by the model at the actual time of observation, rather than referencing the observations to the nearest synoptic or sub-synoptic time (usually 00:00, 06:00, 12:00 and 18:00 hrs);

- it allows model dynamics to be included in the assimilation and thus propagates the Scatterometer wind information more effectively in the vertical dimension.

This is clearly of considerable benefit for the forecasting of near-surface wind conditions which can change rapidly during the time between synoptic hours.

Fig. 3.64: 5 day forecast with and without Scatterometer



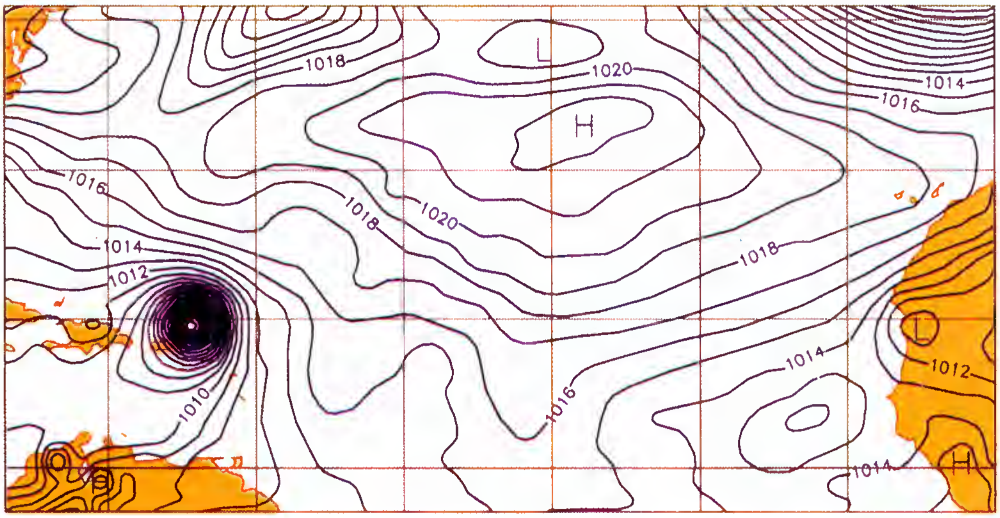
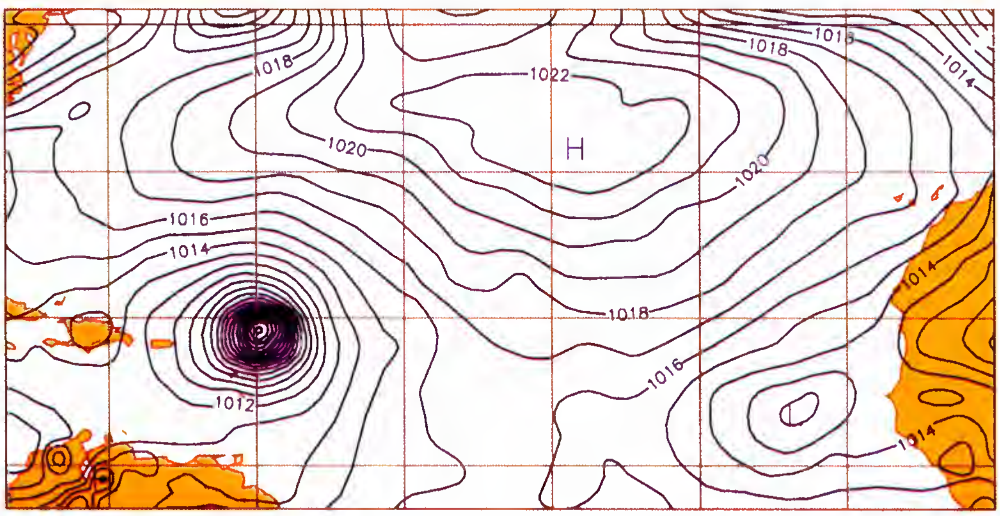


Fig. 3.65: Actual situation after 5 days (for comparison with the forecasts)



In assessing the performance of the Scatterometer, the ECMWF has made a number of observations. These include the following:

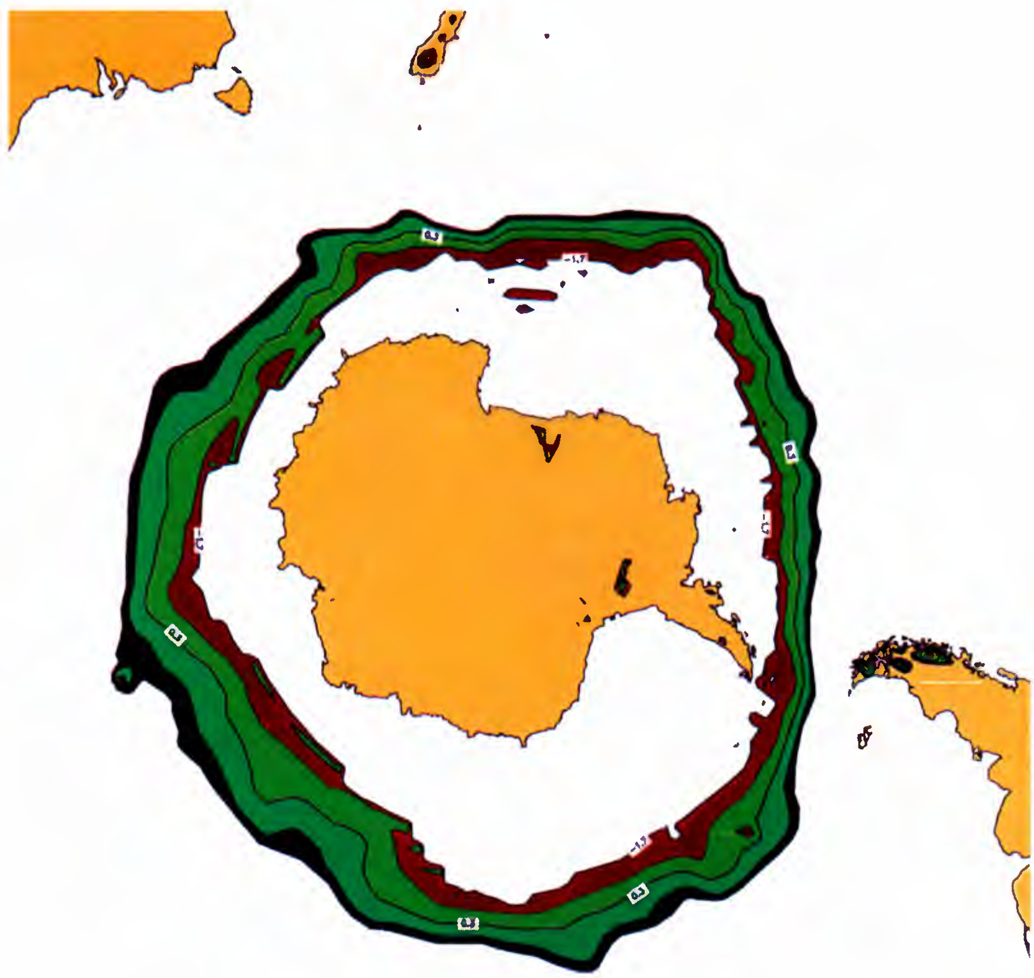
- 'The ERS-1 Scatterometer performance proved to remain remarkably stable in time';

- 'The wind product from ERS-2 was of a similar quality to those of the ERS-1 instrument'.

In addition to the direct observations about the quality of the data from the scatterometers, there are also a number of service improvements offered by ERS operations that support the operational users at ECMWF. Users are now informed well in advance of events such as orbital manoeuvres which can affect instrument availability and, as a result of user lobbying, greater use of the Scatterometer rather than the SAR is offered, especially when the formation of tropical cyclones is thought possible.

In parallel with the operational use of the instrument, there has also been the opportunity to continue with research which will benefit future Scatterometer designs and data exploitation. For example, the Tandem Mission, in which ERS-1 & 2 were flown in coordinated orbits, provided an opportunity to

Fig. 3.66: Diagrams from the ECMWF showing new areas covered



consider the likely impact of double or multiple swath scatterometers. These assimilation experiments were carried out in April 1996.

The successful use of the Scatterometer has led to work which increases the amount of data which can be used from it. The use of the Scatterometer has been limited, close to the Antarctic sea ice margin, because false readings are obtained if sea ice is present in the Scatterometer footprint. This has been an important limitation because many important storm tracks develop in the vicinity of the sea ice margin. Work at ECMWF has used data from the SSM/I instrument on the US DMSP satellite, which provides regular coverage of the sea ice margin to fine tune the cut off point for the Scatterometer. This has led to the availability of data in new areas, as shown in Fig. 3.66.

Summary
The ERS Scatterometer has been under evaluation by Europe's meteorological centres since its earliest days. This evaluation was necessary because apart from the short Seasat mission, this is the first spaceborne scatterometer available to supply data. In the last two to three years, after successful evaluation reports, it has come to be adopted as an operational instrument by major meteorological centres, providing data into the assimilation schemes for numerical forecast models. One specific benefit of the scatterometer is in its ability to provide more accurate forecasts of tropical cyclones, up to 5 days ahead.

Case Study 13: Commercial Services for Offshore and Marine Industries

Category:	Serving operational users and enhancing industrial capability
Description:	ERS has made significant contributions to the provision of commercial services for the offshore and marine industries. An important example of this contribution is the supply of bathymetric information derived from ERS SAR data
Acknowledgements:	ARGOSS, The Netherlands NDRE, Norway

Bathymetric information

Accurate depth charts of shallow seas are of great importance for shipping traffic and for off-shore activities like pipeline routing, dredging and construction works. The global demand for this information is estimated to generate revenues in excess of 1 Billion ECU per annum. Traditionally this information is gathered by ship-borne echo sounders. Such surveys are expensive and time consuming.

It is possible to map shallow coastal areas very cost effectively and accurately by integrating the ERS SAR imagery with a limited number of conventional soundings.

ARGOSS, a company in the Netherlands, has developed a bathymetric mapping service and is successfully selling this to provide commercial mapping services worldwide. In 1997 a total annual revenue in excess of 800,000 ECU has been generated with this service. At the moment these new services are provided on a relatively small scale in Europe, the Middle East and Africa. However, in cooperation with industrial partners, new initiatives have been taken to develop complete end-to-end services and to expand the services into the Asian market.

Fig. 3.67 is an ERS SAR image of the Dutch Wadden Sea and Fig. 3.68 shows an example of a bathymetric map derived from it.

Ship detection in coastal regions

Knowledge of the whereabouts and activities of ships in coastal regions is useful to a range of government and law enforcement agencies, such as those concerned with enforcing fishing legislation in exclusive economic zones, and environmental protection agencies to support pollution control. The information is also valuable to coastguards for search and rescue operations and law enforcement activities where it supplements land-based coastal surveillance radar whose maximum range is under 100 km.

It has long been recognised that satellite-based radar has the ability to detect and monitor ship traffic. Due to the nature of radar, monitoring can take place through cloud cover and at night thus proving an advantage over optical data. As well as the detection of vessels, it is also possible to derive information on each vessel's location, speed, heading, and class.

Fig. 3.67: SAR image of the Wadden Sea, The Netherlands, acquired on 3rd August 1995 (ARGOSS)

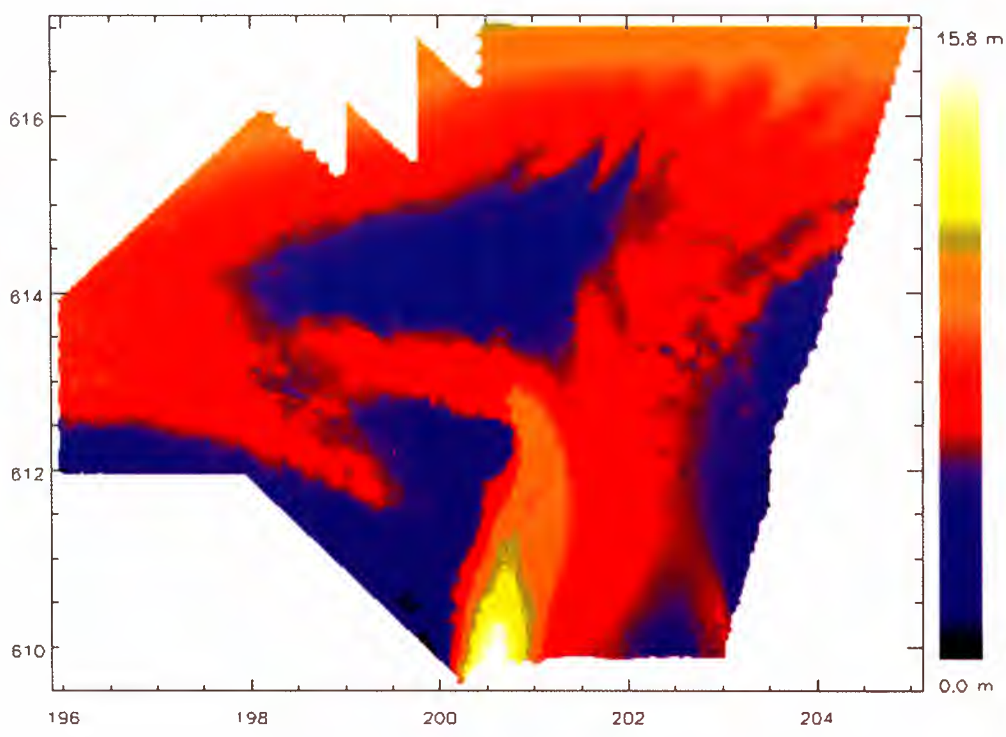


Fig. 3.68: The bathymetric map based on the ERS SAR image (ARGOSS)

Fig. 3.69 shows some of the work carried out by the Norwegian Defence Research Establishment on ship detection using ERS SAR. The incidence angle of the ERS SAR is not optimum for this application, but nevertheless it is performing a function which assists in the monitoring of the large areas of open sea for which the Norwegians are responsible.

Sea ice monitoring and navigation for Arctic operators
Much progress has been made with operational ice monitoring services based on ERS data. Daily sea-ice information is required for navigation during winter throughout the northern Baltic, around Svalbard, the Greenland Sea, along the eastern coasts of Canada, the northern USA, the Great Lakes, and during summer in the European, Russian and Canadian Arctic. Three to seven day forecasts are also needed for strategic planning. The type of information required includes location of the ice edge, and estimates of ice type and ice concentration. Also important is measurement of ice drift and speed.

The value of Fast Delivery ERS SAR data has been demonstrated within well-established national sea-ice services. This use is based mainly upon manual interpretation and is used as a complementary data source to traditional satellite sources such as Passive Microwave Radiometry and low resolution optical data. In parallel, a number of value-adding companies within Europe are developing next generation workstations which incorporate new techniques from the science community, which automate feature interpretation and tracking. Additionally, demonstrations are being made of the use of ERS SAR data for shipping and offshore activities close to the ice edge.

Summary
ERS contributes to a number of important marine information services which are increasingly provided as commercial ventures. The bathymetry example is particularly important for pipe laying and for port maintenance while wave climatologies from the ERS radar altimeters are used for many marine activities sensitive to the sea state.

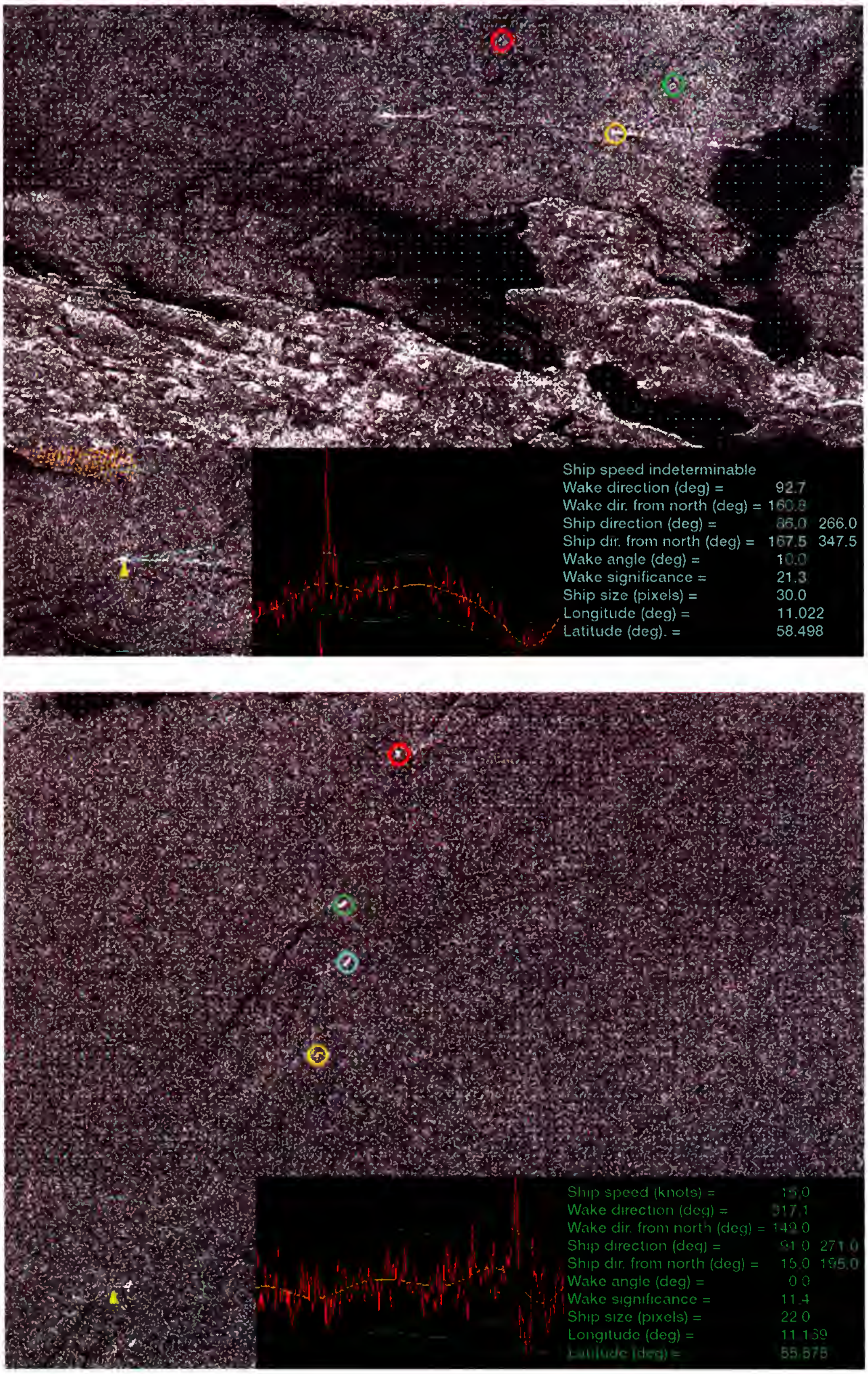


Fig. 3.69: Ship detection examples from the Norwegian Defence Research Establishment

Case Study 14: Making a Contribution to Water Resource Management

Category:	Serving operational users and enhancing industrial capability
Description:	Water resources are of fundamental importance to maintaining life. Water can also pose a threat to life through flooding, avalanche and landslide. ERS data contribute to water management in a number of ways, examples of which are given in this section
Acknowledgements:	German Remote Sensing Data Centre (DFD) ESA ESRIN, Italy

Water is the fundamental resource for civilisation. A lack of water can lead to regional tensions while a surplus of water can cause major loss of life and property. As well as its immediate effects, the hydrological cycle is an important component of the global climate system.

Making spatial measurements in hydrology has never been easy at any scale, but ERS has brought some major advances. In particular, ERS measures:

- flooded areas, for use in flood assessment, modelling and claims assessment;
- soil moisture, for climatology, trafficability and flood prediction;
- topographic profiles, which are an essential component of hydrological models;
- additional ground features, including land cover and other spatial data which are important components of hydrological models.

The contribution of ERS data in hydrology, both directly and through spatially distributed models, is illustrated in Fig. 3.70.

Progress has been made in many applications of ERS data over the last three years.

In the measurement of soil moisture:

- European researchers have established a sound theoretical basis for deriving soil moisture content from SAR data. The method has been complemented by the use of physically based scattering models;
- improved methods have been developed for overcoming surface roughness and vegetation effects, including the use of coherence assessments to identify surface change.

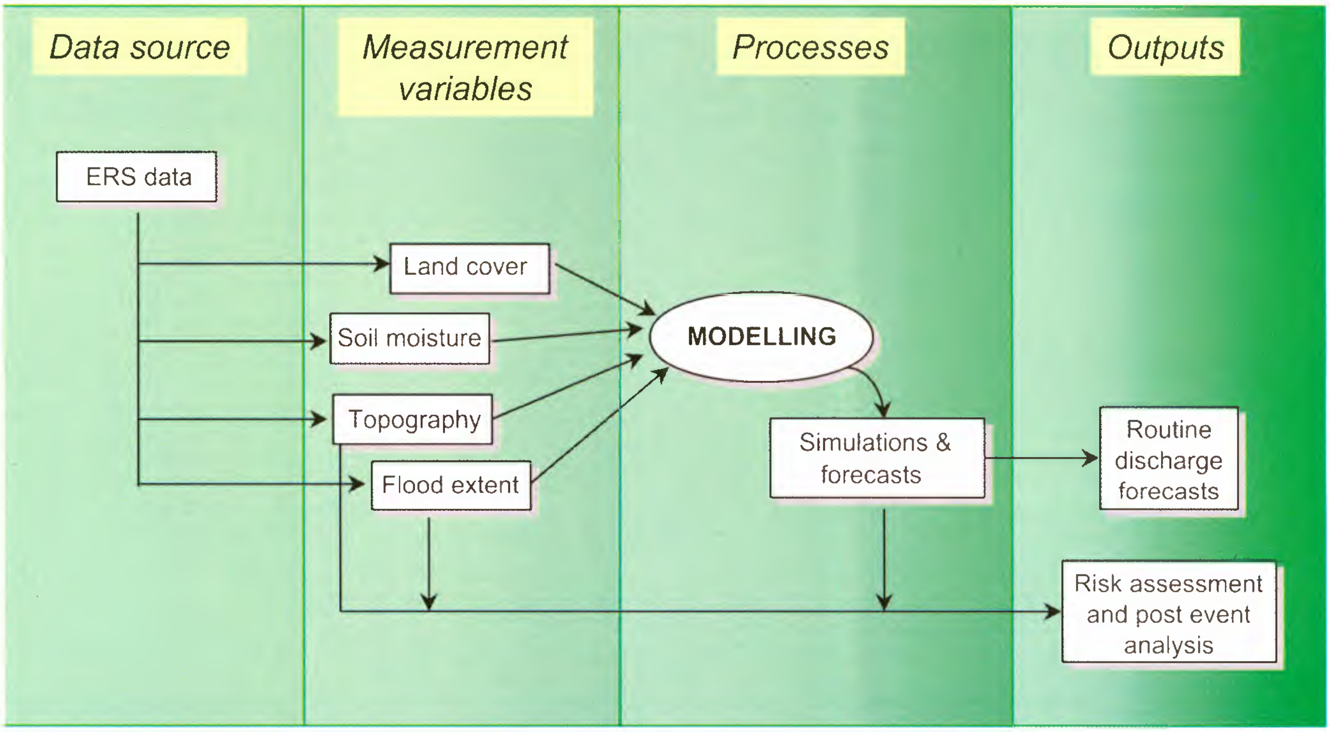


Fig. 3.70: The role of ERS data in hydrology

The use of ERS SAR data is now an established tool for flood monitoring. In most cases, the floods are visible with sufficient contrast in the imagery to avoid the need for complex retrieval algorithms. This makes the technique much easier and cost effective to use. A growing number of examples are available that show the continuing successful use of ERS data for identifying flood extent.

Flood monitoring is a good visual example of the use of SAR data in hydrology. During flood emergencies it is often difficult to obtain a comprehensive assessment of the flood extent because of difficult weather conditions.

The ERS SAR which can operate independently of weather and light conditions has made a valuable contribution to characterising the catastrophic winter floods that occur each year in Europe. The contribution of the SAR has been twofold:

- for large and prolonged events, it has been used to monitor the progress of the floodwave at a number of stages along the river;
- for smaller events, where only a single 'snapshot' has been available, the data are still going to be very valuable for assessing damage claims and planning future prevention measures.

As well as monitoring floods, a number of other techniques have been developed for using ERS data in hydrology. For example, the use of elevation data derived from interferometric SAR data can be very valuable in support of distributed modelling, which can simulate the effects of significant changes to the catchment.

Portugal 1997

After several days of heavy rain, the area neighbouring the Guadiana river along the Portugal-Spain border was subject to violent and very fast flooding from November 6^{th} to November 8^{th} 1997. ERS-2 passed over the area on November 7th 1997, over the final part of the Tagus river course (Portugal). The same day a fast delivery transmission was planned from the acquisition station at Fucino Italy. A further comparison with an ERS archive frame allowed a more accurate definition of these flooded areas at a later date.

The SAR image shown in Fig. 3.71, acquired at 11:18:49 GMT, shows the Ribatejo region from Lisbon (lower left) to Abrantes (upper right). Some flooded areas are visible in dark grey tones at the image centre between the towns of Golega (North) and Santarema (South), where some villages could be reached only by boat.

Fig. 3.71: ERS SAR image of the Ribatejo region of Portugal from Lisbon (lower left) to Abrantes (upper right)

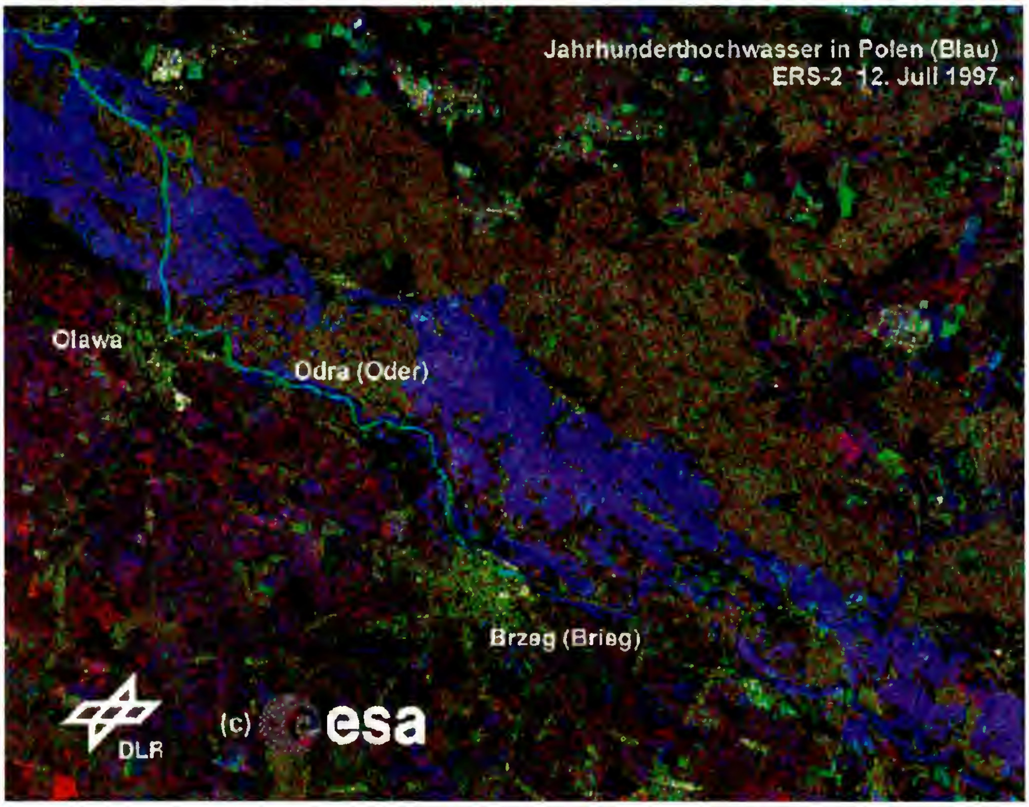
Austria, Czech Republic, Poland and Germany Flooding
July - August 1997
The worst flooding in decades in the Czech Republic, Poland and eastern Germany destroyed farmland and killed at least 52 people in Poland and 39 in the Czech Republic. In Poland, 300 towns and villages were under water. In the Czech Republic, the government reported that nearly 2,700 homes were destroyed by the flooding. Many thousands of people had to be evacuated.

A second wave of flooding occurred on 21st July as falling rain continued to enlarge the flood leading to final damage estimates as high as 2 BECU. A number of ERS SAR images were acquired, showing various stages of the flood event. Fig. 3.72 provides an overview of the total area affected.

Figs. 3.73 and 3.74 illustrate the capability of the ERS SAR to provide an important overview of the flood event. The extent of the flood has been evaluated from the SAR images and is shown coloured blue. The limits of such a major event are not easy to determine by any other means, optical instruments and visual inspection is often limited by cloud cover while the wide, flat floodplains make estimation using elevation models very imprecise. Images such as these are therefore very valuable when considering how to ensure that future events are much less damaging.

Fig. 3.72: Location of the major floods in central Europe, Summer 1997 (DLR)

Fig. 3.73: ERS SAR view of the flooding on the Oder river in Poland, 12th July 1997. The normal river course is in light blue, with the flooding shown in dark blue. (German Aerospace Centre, DLR)



Summary
Water is of vital importance. Population growth and increased use per head mean that shortages are a growing problem in many places. Conversely, the same population growth often leads to development in unsuitable areas, with increased risk from flooding. The ERS SAR provides valuable information for water management by allowing the extent of floods to be determined and assists with modelling activities through its measurements of soil moisture conditions.

Fig. 3.74: ERS SAR view of the flooding on the Oder river in eastern Germany. (DLR)

Case Study 15: Business success with ERS

Category:	Serving operational users and enhancing industrial capability
Description:	This case study shows how an organisation which has been selling services based on the use of ERS SAR for a number of years is now finding that the market for the data and derived applications is increasing considerably
Acknowledgements:	A Sowter, NRSC, UK

The SAR business at NRSC has grown considerably in last few years. This has been due to advances in the operational capability within NRSC in two main markets: agriculture and the oil industry.

In the case of the agriculture market, the use of ERS SAR data was first introduced to the UK Control of Subsidies contract in 1995, and proved a success. During this time frame a tool (TSAR) was developed at NRSC, for the operational radiometric and geometric correction of SAR data. This greatly enhanced capability by integrating the ERS SAR data with other datasets, including optical data, within a GIS for data analysis and for removing the radiometric and geometric distortions due to terrain effects. This makes SAR data very easy to handle. The development of TSAR was a springboard to the operational capability of using SAR data for various agriculture applications. Of particular interest to EU DG VI (Agriculture) was the capability to provide early season crop area estimates. Large scale contracts were undertaken, in 1996/97 and 1997/98, to provide area estimates prior to the growing season based on the sensitivity of SAR to soil moisture and roughness and its relationship with ploughing and tilling activities. The date when a field is ploughed or tilled will vary according to the type of crop. This means that broad crop classes can be identified much earlier in the season using SAR data than through optical based instruments. An example of this work is shown in Fig. 3.75 and Case Study 7 on agricultural monitoring provides more detail.

In the oil and gas exploration market, ERS SAR has provided the optimal data for detecting and characterising natural undersea seepages of oil since its launch in 1991. The availability in some cases of 'Tandem pairing', i.e. scenes acquired one day apart, provides a better chance of selecting optimal scenes for slick analysis. An increasing interest in seep screening studies around the world by oil and gas exploration and production organisations has promoted the need for extensive but inexpensive multi-coverage data orders. An agreement between NRSC and Eurimage permits, in certain circumstances, a screening inspection order, which reduces final costs considerably. This helps NRSC to win work in a highly competitive market. Fig. 3.76 shows an example of a natural slick image from ERS SAR.

In addition to the two main markets for SAR, NRSC has now acquired significant experience in using SAR data for a diverse range of applications including forestry, urban development and geology and has provided

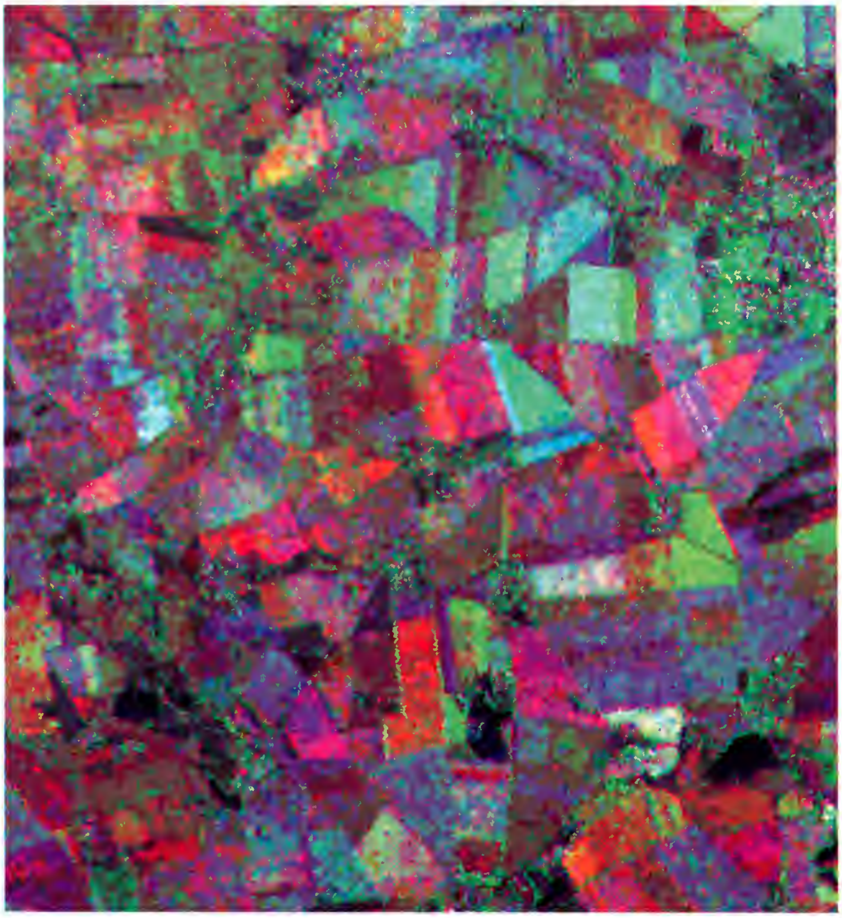


Fig. 3.75: Example of a winter/early season ERS-2 multi-temporal SAR image showing changes due to farmer activity.
Blue = 1th October 1996, Green = 10th December 1996, Red = 18th February 1997 (NRSC)

Fig. 3.76: A dramatic example of a swirling natural seepage slick (NRSC)

significant inputs to projects such as SAFE (Study of the Cost-Benefits of a SAR Mission for Agriculture and Forestry in Europe). This experience, coupled with extensive internal resources to manage large volumes of SAR data and the TSAR tool for geometric and radiometric correction of SAR data, provides a unique facility for the completion of large operational projects, research and development projects, and specialised consultancy and training services in both radar theory and applications. Indeed NRSC is currently delivering SAR applications training for the South Korean Government Research Agency.

Summary
This case study demonstrates that applications of ERS data have now achieved commercial sales. ERS SAR data have always been seen as a supplement to optical data, but increasing reliability, improved levels of service from the ERS ground segment and advances in data interpretation mean that they are now commercially viable in the same way as optical sources.

Case Study 16: SAR interferometry

Category:	New and refined techniques to improve information content
Description:	The progress of the interferometry technique is one of the success stories of the ERS programme. This section examines how the technique was developed, supported by the Tandem Mission, used in a range of applications and to develop future markets.
Acknowledgements:	CSL, Liège, Belgium Marconi Research Centre, UK Dornier Satellitensysteme, Germany ESYS Limited, UK

The technique of radar interferometry was not originally foreseen as a major means of using ERS data, but research into the topic has spawned a wide range of valuable applications. Optical interferometry has been established as a measurement technique with a wide range of applications for many years. The method for radar is broadly similar and requires two SAR images taken from points separated by a known baseline. These are coregistered and the phase differences between the images are displayed in an image known as an interferogram. The interferogram is then checked for coherence. Areas with sufficient coherence can be used to provide a digital elevation model through a process known as phase unwrapping (i.e. converting the fringes on the interferogram into height intervals). The distribution of coherence can also be used for applications such as land cover mapping and assessing surface changes.

Fig. 3.77 summarises the main events in the development of SAR interferometry which is now starting to be exploited commercially. This case study presents a number of aspects of interferometry development:

- applications of SAR interferometry to digital elevation modelling, concentrating on how the technique has been developed to overcome accuracy limitations;
- applications of SAR interferometry to monitor the extent of mining subsidence - an example of a demonstration project;
- the Tandem Mission - in which ERS-1 and ERS-2 were flown in coordinated orbits with a 24 hour separation, specifically to acquire images for SAR interferometry. The unique dataset which resulted has global coverage and provides Europe with a unique and marketable capability;
- the business case for InSAR, which summarises the market potential for the technique.

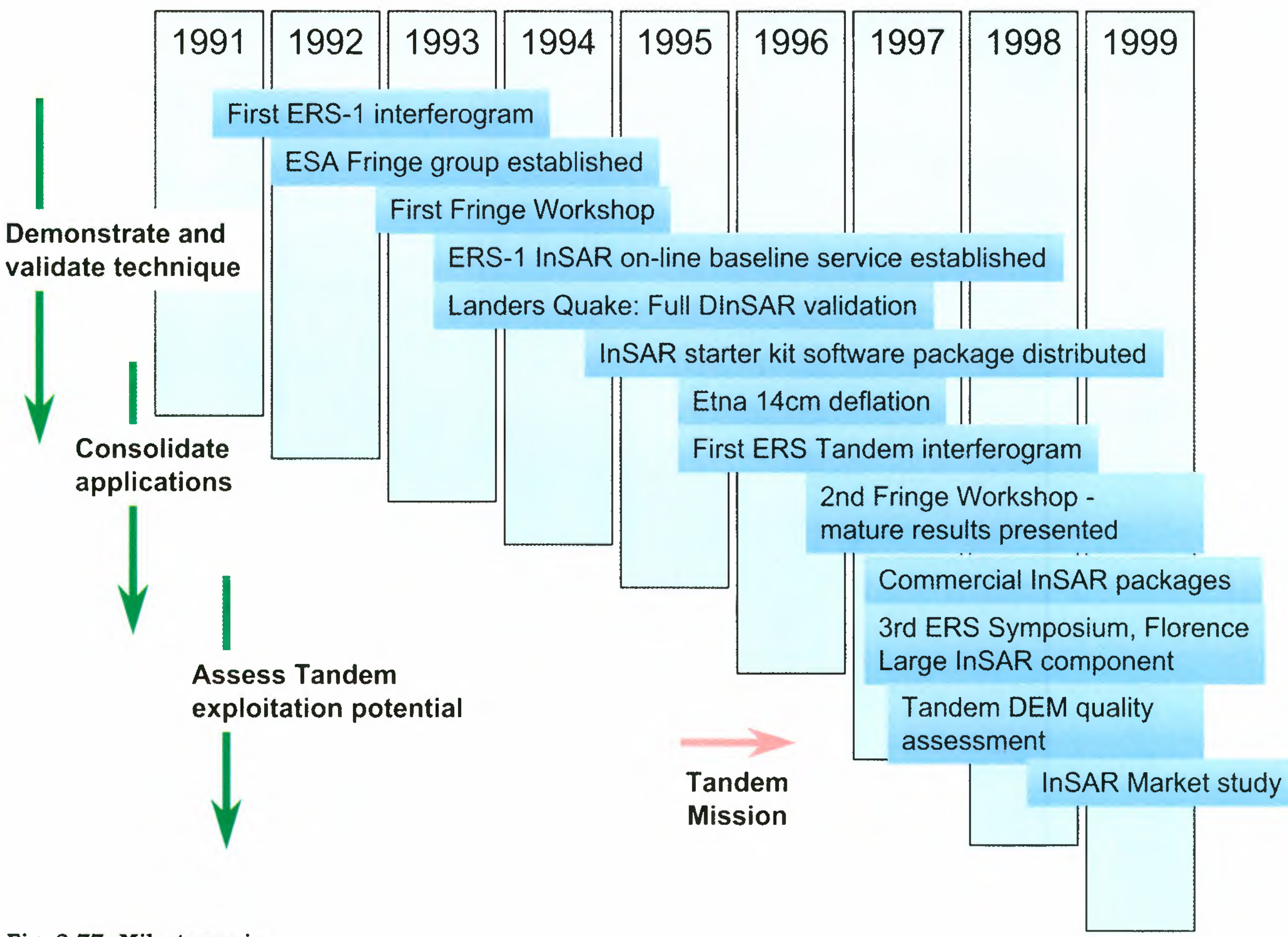


Fig. 3.77: Milestones in the development of radar interferometry with ERS SAR (Mark Doherty, ESA ESRIN)

Mapping elevation and elevation change

One of the best known applications achieved using ERS SAR data for interferometry is the creation of elevation models or topographic maps. Using SAR interferometry, the elevation of the majority of the Earth's land surface can be mapped at a resolution not available from other sources. This in turn has led to a wide range of important Earth science investigations, which include:

- ice mass balance studies;
- climate change history through the tilting and orientation of alluvial fans;
- coastal uplift and inland subsidence associated with tectonic movements in Chile;
- volcanic subsidence through 3 year differential InSAR in California.

Considerable work has been needed to evaluate the performance of the technique on the wide range of surfaces on which results may be required,. Radar signal penetration into dry snow, ice and alluvial material will all be very different.

The effects of differing atmospheric conditions on the phase relationships between the radar signals are also important because they affect the accuracy of the final result. A number of approaches have been explored to quantify and control this effect. Firstly, the meteorological conditions affecting interferometric results have been assessed. These can be monitored by independent data sources and are used to eliminate unsuitable days. Secondly, a technique has been developed to calculate the best consensus DEM from a set of 5 or 6 pairs. This technique calculates a DEM error map and uses this to calculate automatically the best DEM for the full set of images. In addition to these developments, the increasing availability of both ascending and descending passes allows areas of shadow and layover to be filled in and also results in a reduction in the height error.

Studies are continuing to refine the process further. For example, recent work by CSL, Liège, Belgium has shown that taking the following precautions when preparing a DEM using InSAR can further improve accuracy:

- if the area is agricultural, images should be acquired early in the season, before crop emergence or agricultural activity;
- meteorological satellite images and data should be acquired at the same time as the SAR images, to assist with quality control;
- if unfavourable atmospheric conditions are unavoidable, careful baseline selection can help to minimise atmospheric effects

Validating the final accuracy of DEMs is never easy because:

- in many cases, the DEM is unique;
- where it is not unique, the spatial error characteristics of the reference source may themselves be poorly known;
- the scale may not be comparable with other sources.

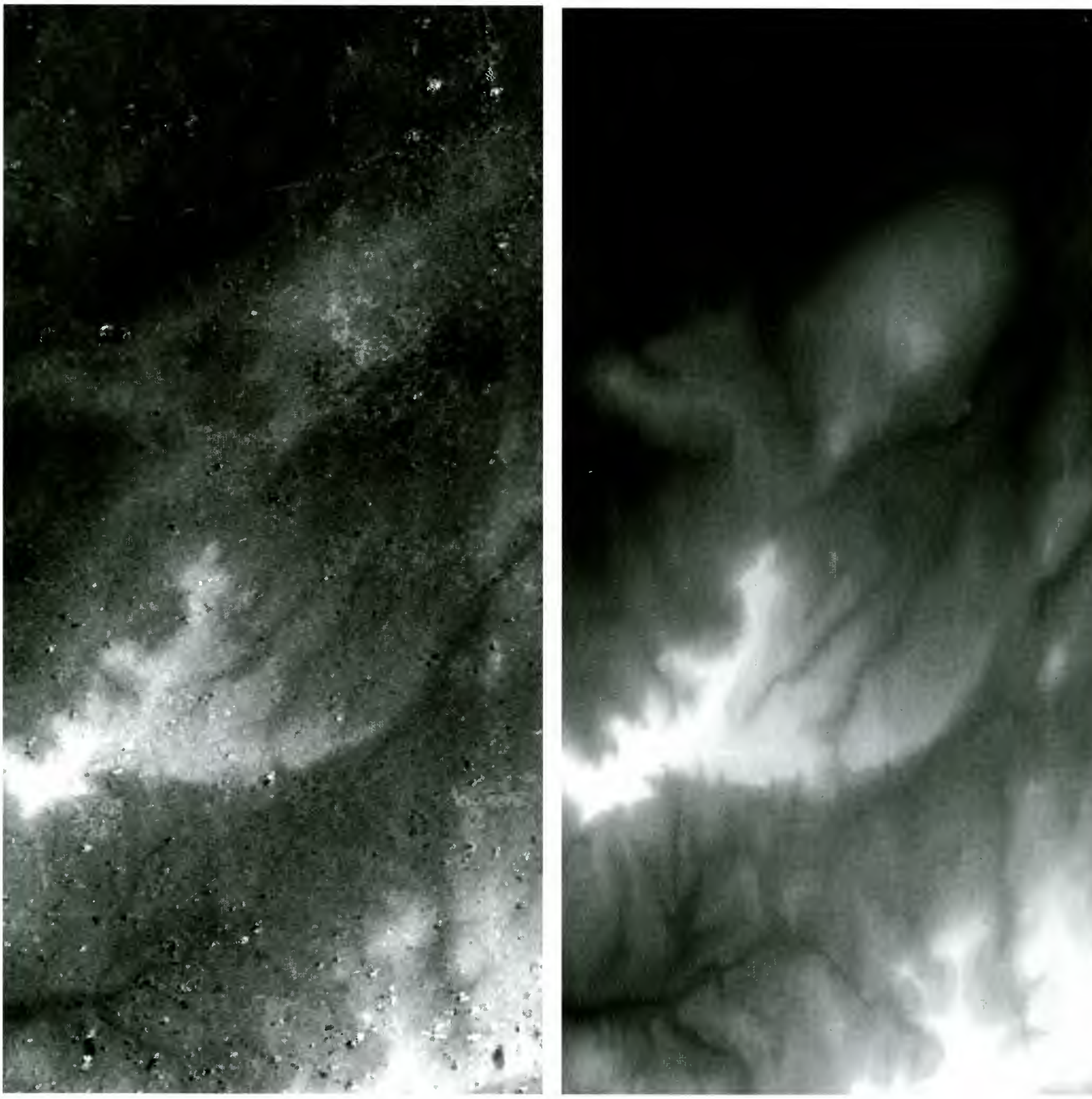


Fig. 3.78: Comparison of the existing (left) and InSAR DEMs for the Bruges area of Belgium (CSL, Liège, Belgium)

In particular it is important to remember that the accuracy of the 'normal' elevation maps cannot be measured in terms of their spot heights alone. The accuracy of these heights are often measured to within centimetres, but the accuracy of the map in between these is often much poorer. Fig. 3.78 shows a comparison between an InSAR DEM of the area around Bruges and the existing DEM of the Belgian mapping authority. The close similarity between the two can clearly be seen, showing the potential of the technique in unmapped areas.

In a similar study to evaluate the possible use of ERS SAR based DEMs in the UK, the UK National Mapping Agency (The Ordnance Survey) found that it was possible to detect in the InSAR DEM a narrow cutting of the M25 motorway which is not present in the high resolution Ordnance Survey elevation model. It was also possible to produce DEMs over a highly vegetated and cluttered scene even with a 35 day repeat. No atmospheric effects were detected and no detectable difference in accuracy even with the baseline separations differing by one third.

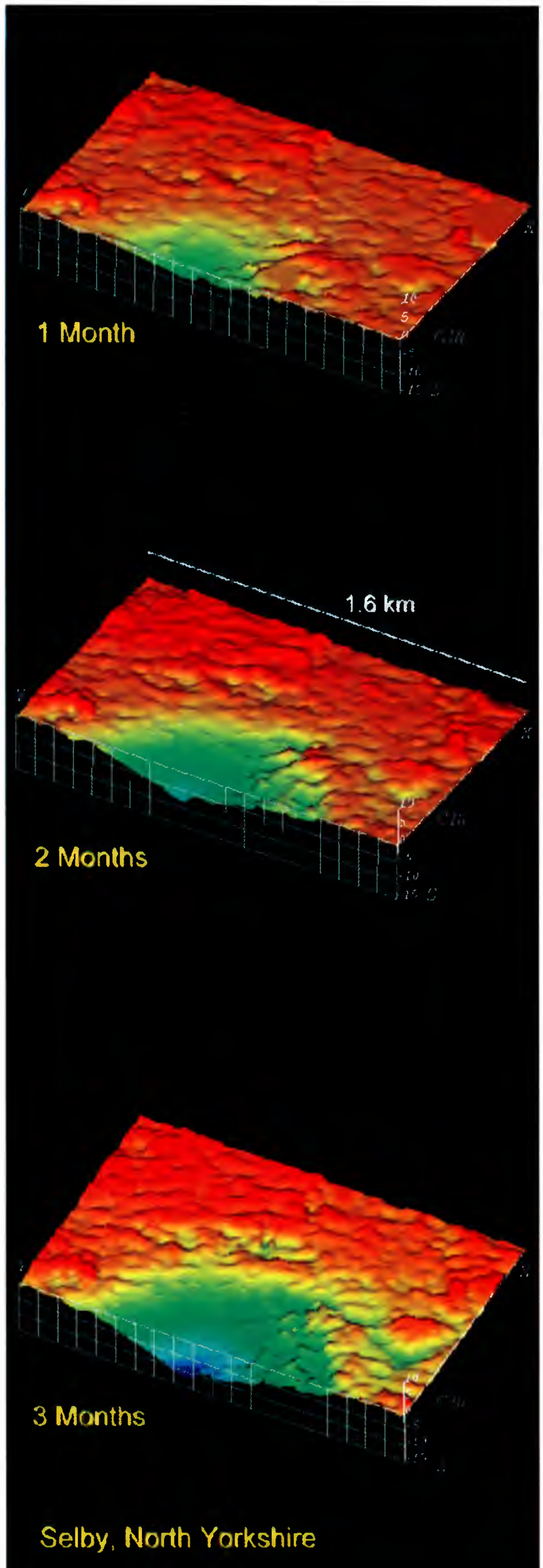
Using InSAR to identify and monitor mining subsidence

Marconi Research Centre have undertaken a project to improve the accuracy of subsidence prediction models implemented in the mining industry, through the use of satellite radar images. The project used SAR interferometry with data from both ERS-1 and ERS-2 to provide extremely sensitive maps of surface deformation over intervals of 35 days.

Subsidence models are used to help mine management by providing information on productivity, assessing regulatory conformance and minimising environmental and economic impacts. By improving the accuracy of these models, the mining companies can improve the information used to manage their business.

Validation of the technique is currently being conducted against maps of active coal panels and traditional surface surveys at a test site at Great Driffield in Yorkshire, UK. Fig. 3.79 shows the type of subsidence information which can be provided using SAR interferometry. Modelling of radar interactions is being done with a computer simulation created at the Marconi Research Centre using a second-order radiative transfer model for radar scattering. The project is also developing the application of the technique at the Selby Coalfield in Yorkshire, UK and the Silesian Coalfield near Ostrava, Czech Republic.

Fig. 3.79: Subsidence in the North Yorkshire coalfield as measured by ERS SAR (MRC)



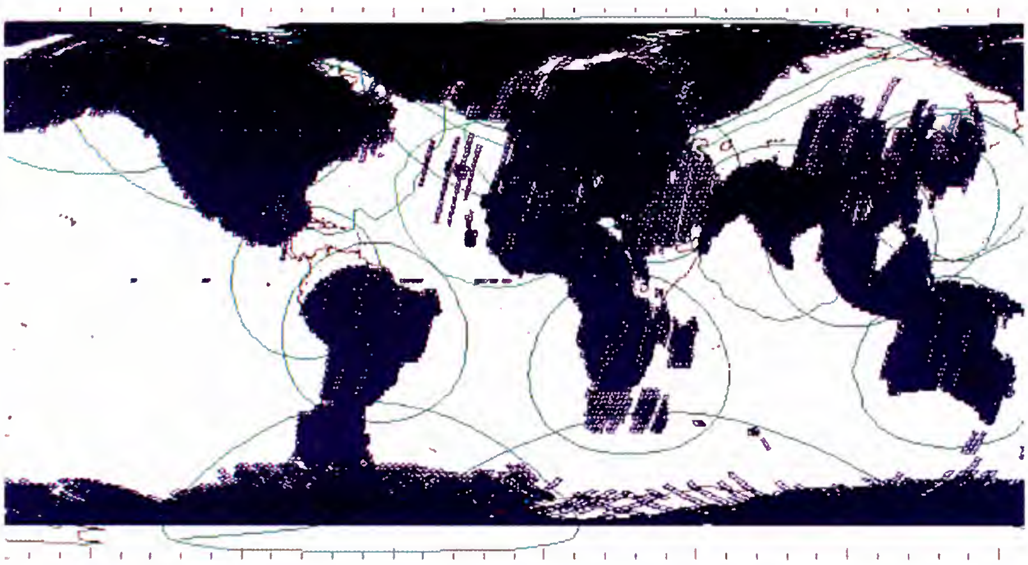


Fig. 3.80: ERS-1/ERS-2 SAR Tandem acquisition pairs with optimum baseline values for DEM generation (ESA)

The Tandem Mission

During the Tandem Mission, the ERS-1 and ERS-2 satellites were flown in identical orbits with a 24 hour separation. The mission was completed after 9 months of successful operation. The objectives were to collect SAR image pairs for use in interferometry and other synergistic applications. The result is that SAR pairs with an offset of one day have been acquired over practically all global land surfaces.

Close and efficient cooperation between all the ERS ground-segment entities enabled ESA to collect this unique global dataset. It provides the basis for many years of scientific and technological exploitation and spin-offs, ranging from the development of new, fast, processors and methodologies in interferometry, to applications in such disciplines as global mapping, hydrology, ice and glacier monitoring and risk management. The long term market prospects for resulting products are also rated highly (see below).

About 110,000 ERS SAR pairs were acquired during the Tandem Mission, covering nearly the whole global land surface. Whilst over South America and parts of Southeast Asia just one data pair was acquired, as many as five or six interferometric pairs (1 day offset) are available for Europe and North America, allowing greater accuracies to be achieved. 73% of the acquired data meet the optimal baseline requirements for DEM generation of 50 to 300 m and cover the global land mass (Fig. 3.80). This is a much higher percentage than was originally expected, thanks to the precise orbit maintenance during the Tandem Mission. Another 6% of the acquired data with baseline values between 300 and 600 m are still usable for DEM generation. The remaining 21% of the data with baseline values below 50 m can be used for other applications like change detection and differential interferometry. It should be noted that almost all the areas with limited coverage in Fig. 3.80 have now been completed.

The business case for InSAR

Given the wide range of useful applications which can be achieved with SAR interferometry, ESA has initiated studies to define the market for interferometric products and services in the period to 2020. This study considered:

- the information products which could be derived from both current (ERS) and future radar interferometry missions;
- the current demand for such products and how this will evolve in the period from 1998 to 2020;
- a mission specification which will allow the expected demand to be met within a viable business venture.

The market information was obtained using information from over 100 interviews with potential customers and the results were scrutinised by a panel of market experts. Table 3.1 lists the 35 InSAR products defined as the basis for the study, indicating the wide range of applications of interferometry.

The market survey predicts significant potential revenue for InSAR derived products and considerable growth over the next 20 years as shown in Fig. 3.81. This shows the predicted growth in the addressable market over the analysis period at which the applications market can aim. The revenues measured are for the supply of information services in a format suitable for direct use by the user, i.e. they include any value added component and, where required, fusion with other data. The curves assume that by about 2005 most organisations will routinely be using high capacity networks with desktop GIS and that it will be possible to produce and deliver the entire range of information products and services listed in Table 3.1. Three price scenarios are depicted, which take account of reduced sales volume in response to price increases and vice-versa.

Primary Services *(Unique to InSAR)*		**Secondary Services** *(Some competition from other technologies)*	
Fault movements	•	Digital Elevation Model	o
Surface deformation	•	Slope angle models	•
Quake fringes	•	Land cover, general and rural	•
Location and movements of icebergs	•	Snow covered areas	•
Glacier movements	•	Changes in cultivated land	o
Deforestation progress	o	Flood forecast, detection and monitoring	o
Location of landslides	o	Environmental infrastructure	o
Building location and changes	o	Snow type	o
Structure deformation	o		
Object displacement	o		
Land subsidence	o		
Soil erosion	o		

Legend: • can be achieved with ERS system, o can be achieved with ERS system, but with some constraints

Table 3.1: ERS contribution to the provision of InSAR information products (Dornier)

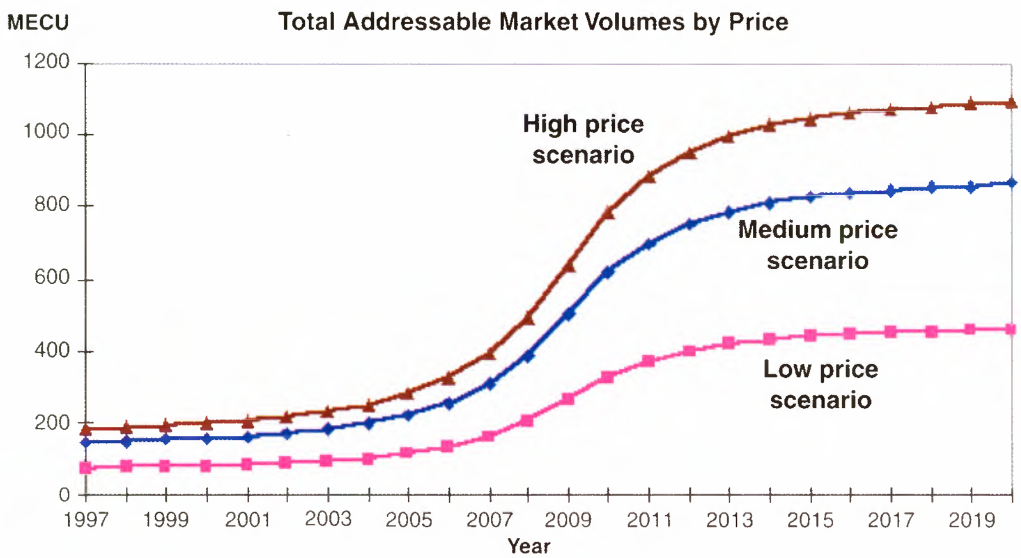


Fig. 3.81: InSAR market projections (addressable markets) (Dornier/ESYS)

Summary
The InSAR technique has been developed to improve its accuracy and pilot studies have established its value. With the major asset of the Tandem Mission dataset, Europe is well placed to exploit the significant commercial potential of this technique.

Case Study 17: Improving the Return from ATSR Data

Category:	New and refined techniques to improve information content
Description:	The ATSR instrument is primarily intended for long term monitoring of sea surface temperature. The retrievals of sea surface temperature continue to be refined. New applications including detection and monitoring of forest fires are also being developed taking advantage of the new visible channels on the ERS-2 instrument, such as the examples in Indonesia presented below
Acknowledgements:	Chris Mutlow, RAL, UK ESA ESRIN, Italy Eurimage, Italy

Three of the main recent developments with the use of ATSR data have been:

- Improvements to the cloud information retrieved by RAL from the visible channels on ATSR-2: information is now being retrieved on cloud phase, particle size and optical depth. In addition, the polycrystal structure of ice clouds is being evaluated.

- Work by RAL on sea surface temperature retrievals has continued and has confirmed the effectiveness of the dual view approach applied by the instrument in providing very accurate sea surface temperatures. Specific developments include a new algorithm which overcomes many of the problems associated with atmospheric aerosol signals.

- ESRIN has been working with IGBP to develop a system for detecting forest fires using ATSR-2 data. ATSR-2 is particularly well suited for fire detection and burnt scar monitoring and this is the basis for the development. This programme has been responsible for monitoring the recent major fires in Indonesia, an application which is now described in more detail.

The exceptional fires which occurred on the island of Borneo and generated such severe haze, have resulted in one of the worst environmental disasters experienced by this region. The impact on normal life has also been very serious: fatal accidents, serious air pollution, marine and road transportation disruption, economic losses and food shortages, among others.

In normal climatic conditions, the fire season in this region begins at the end of July and continues to the end of October. Due to the influence of the 'El Niño', South-East Asia is suffering its worst drought in five decades. In the absence of seasonal rains to extinguish the fires, they have burned for extended periods and have spread over a much greater area than in previous years.

Satellite data from geostationary or polar orbiting weather satellites have been used to monitor the evolution of the smoke and fires. The ERS-2 satellite, with the ATSR-2, was able to provide specific information for locating fires and on the levels of trace gases over the region.

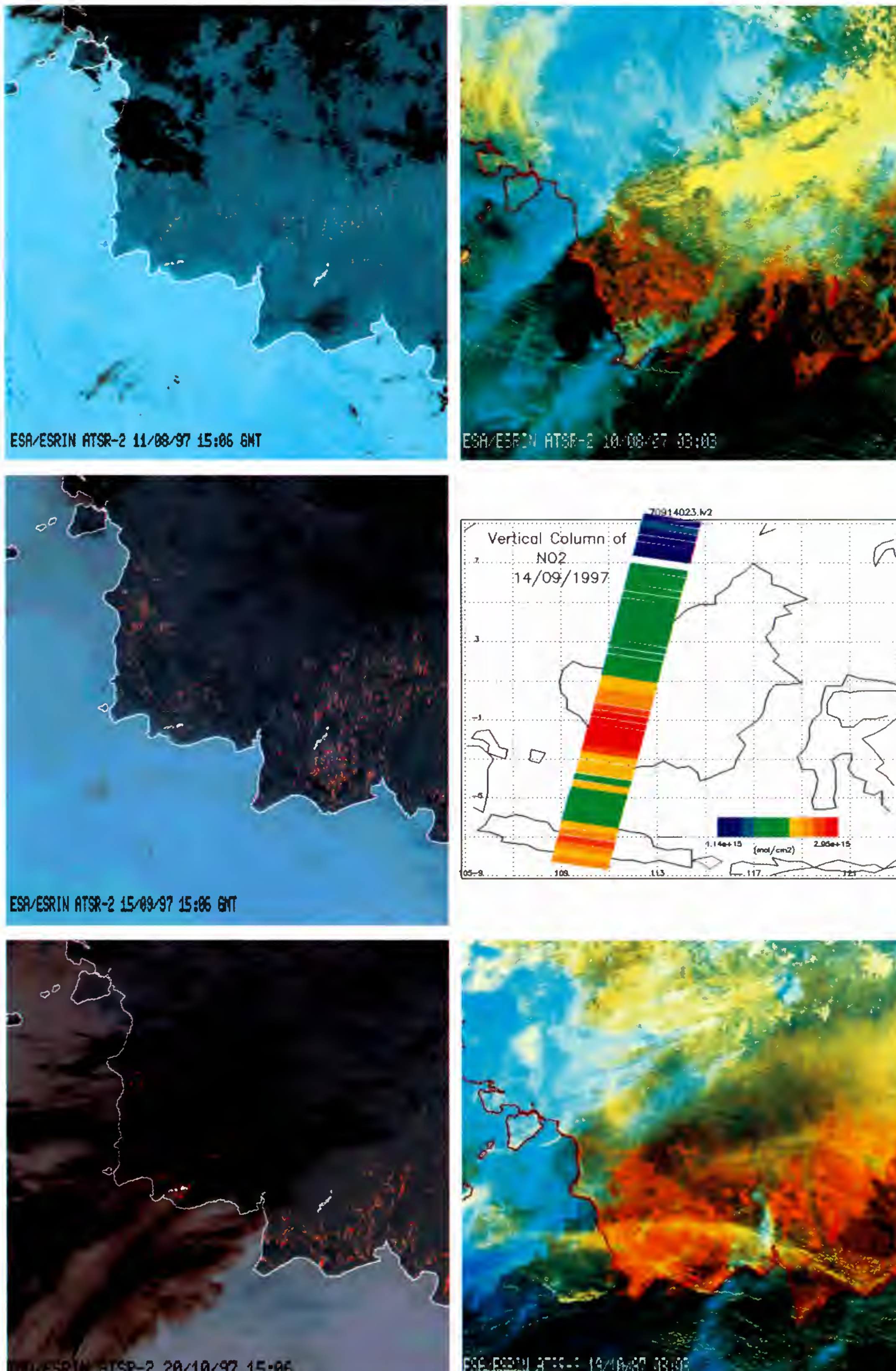
At the request of the international user community, ready-to-use fire products (hot-spot images and localisation files) from ATSR have been processed and made available through a dedicated WWW server within two days of sensing. In addition to the ATSR, the GOME capability in atmospheric chemistry adds additional information to our understanding of these events. These two instruments pave the way for the future Envisat mission, in which instrument continuity is assured through the Advanced ATSR (AATSR) and SCIAMACHY instruments. In particular the very positive feedback received from this initiative demonstrated the importance and need for a fast-delivery service of ready-to-use products to end users.

Figs. 3.82 and 3.83 both show examples of the fires detected by the ATSR. The instrument is highly sensitive to surface temperatures and accordingly is very capable of detecting the thermal gradients associated with the fires.

The ESA/ESRIN service, named 'Rush ATSR Fire Products', follows the progress of all the fires detected by the ERS ATSR instrument. This service aims to demonstrate that fire monitoring will benefit from the ERS / ATSR fire products. The processing capacities allows 2 to 3 subcontinents to be monitored at any one time and depending on the season and the fire event location, a medium term processing plan is set up. From 1st June 1998 up to end September 1998, it is intended to survey the European land masses to produce a European Fire Atlas for 1998. Potential users may require the demonstration to be done on a specific test site. This activity prepares the way for a Forest Fire Earth Watch mission proposed as a post Envisat EO mission.

The topic of monitoring the effects of forest fires with the ERS SAR was covered in Case Study 6 on global forest monitoring. It is interesting to note the comparison between the areas identified as hot spots by ATSR in Indonesia and the ERS SAR classification of the same area based on coherence mapping from Tandem images. Fig. 3.84 shows such a comparison for a site in Indonesia. The boundaries of the two images are the same, and the close linkages between the areas identified is clear. This demonstrates the power of synergy between the different ERS instruments

Fig. 3.82: Examples of forest fires detected by ATSR over Indonesia (ESA / Eurimage)



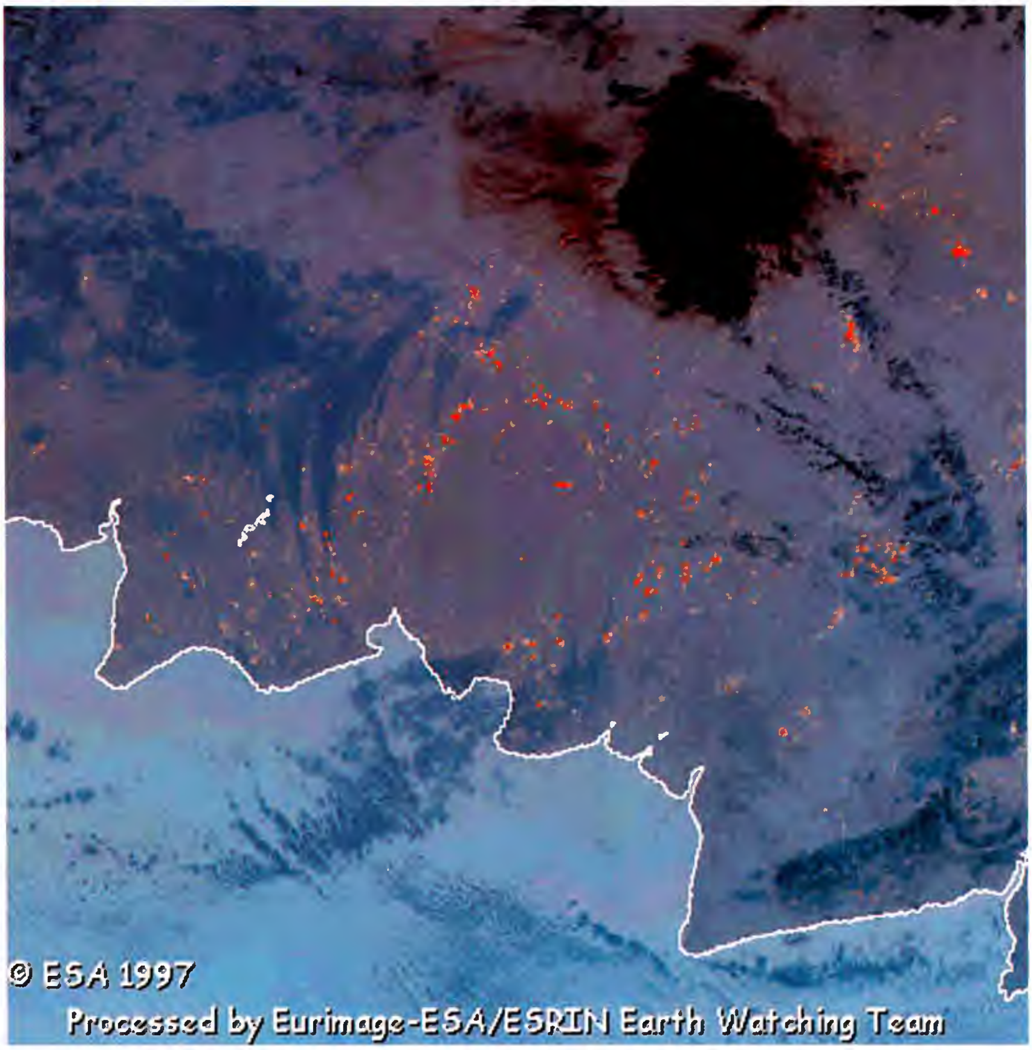


Fig. 3.83: Forest fires observed by ERS-2 ATSR-2 over Indonesia, September 1997 (ESA/Eurimage)

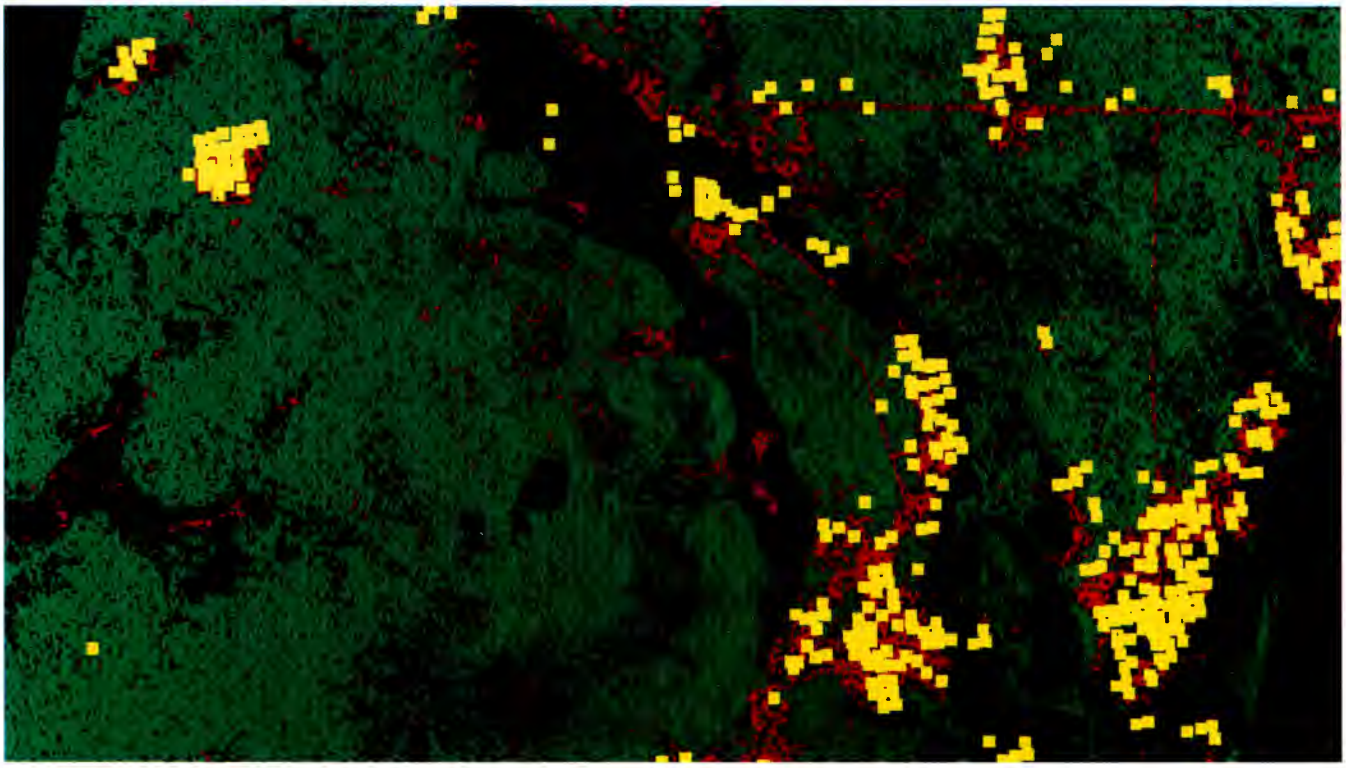


Fig. 3.84: Comparison of ERS ATSR hot spots over Indonesia with ERS Coherence mapping of the same area (ESA).

Summary
The detection of forest fires with ATSR is a very visual example of how useful the instrument can be over land areas. This value is emphasised when the users request the information to be made available as rush delivery products. The sensitivity of the instrument, designed for sea surface temperature measurement, is also of value in this application.

Case Study 18: Developing Radar Technology After ERS

Category:	New and refined techniques to improve information content
Description:	The industrial groups involved in the development of ERS have used the experience gained to develop new and innovative products which will help to ensure that Europe retains a competitive position on the World stage
Acknowledgements:	Joerg Herrmann, Dornier Satellitensysteme, Germany Kevin Morgan, MMS Portsmouth, UK Andrew Ballard, DERA, Farnborough, UK

The technology in the ERS Active Microwave Instrumentation (AMI) (i.e. SAR and Scatterometer) dates from the mid 1980s, with a number of components derived from earlier applications such as military radar, sonar and broadcast TV. The experience gained in the development and construction of this instrument has been fed into the Envisat ASAR and the METOP ASCAT and provides the basis for commercially oriented missions in the future. ERS has enhanced the prospects for European satellite radar business in a number of ways:

- the science of radar imaging is now much better understood, especially in Europe, allowing application requirements to be specified much more precisely;

- the basis of a commercial market for satellite radar imagery has been established with ERS - there are now customers anticipating more advanced products;

- the experience gained by European industry in the development of the AMI has provided a strong technological basis, allowing it to take advantage of the opportunity created.

Developments in European satellite radar technology since ERS have addressed a number of important areas, including:

- the overall approach to producing SAR instrumentation;

- the antenna designs;

- the central electronic systems;

- the data handling systems.

Two of the main contractors involved in the development and production of the ERS AMI were MMS-Portsmouth and Dornier Satellitensysteme (DSS). This case study shows how these companies, using experience gained on ERS, refined through national and ESA programmes, are now establishing commercially oriented SAR missions.

Approach to SAR production

Perhaps the most important development for any commercial mission is the ability to produce a system at a cost which can be recovered through sales derived from mission data. During the late 1980s it became evident that the standard way of producing a spaceborne SAR system was too expensive, partly because there was little component reuse. This was to be expected because the ERS system was a first for European industry, but it was important to move forward and a number of programmes were established at ESA and national level to ensure that this happened. Examples of such market driven programmes are the CORE Radar programme in the UK (with MMS as the lead company) and the SmartSAR initiative in Germany (with DSS as the lead company).

The MMS CORE Radar programme in the UK is a third generation development of radar related products intended to satisfy the requirements of a wide variety of applications and customers (ERS SAR is considered the first generation, Envisat ASAR the second and developments discussed in this section the third). While the initial motivation was aimed at spaceborne SAR, many parts of the system are also applicable to other instrument types and non-space missions. The main drivers used to define the CORE Radar programme were:

- applicability to small and large SARs;
- affordability;
- short timescales for development;
- volume, mass and cost efficiency;
- modularity;
- expandability and flexibility.

The result of the programme was a system with the following capabilities, capable of being produced for launch early in the next century.

- operation on different frequencies (Ku, X, C, S and L-band);
- a variable number of transmit and/or receive channels (for different polarisations, multiple frequencies and different operating techniques);
- suitability for wide bandwidth signals (currently up to 300 MHz);
- interfaces to a range of platform standards and a range of active antenna types.

These capabilities combine to ensure that the system can be tailored to meet user requirements precisely, allowing very high quality results. In addition, the flexibility for platform mounting and interfacing allows the technology to be exported with greater ease.

Antennas

The design challenge for the antenna is to overcome the conflict between a need for low mass and low cost, while meeting user requirements for higher resolution, precision and adaptability. To this end, DSS is undertaking the following developments associated with the SmartSAR programme:

- production of a demonstrator for an X-band antenna front end (known as DESA) which provides a ground resolution of 1.6 m. The slotted waveguide array used within this design is derived from the AMI SAR antenna used on ERS and from the DSS X-SAR antenna flown on the Shuttle Imaging Radar missions. Using Carbon Fibre Reinforced Plastic (CFRP) waveguide radiators for dual polarisation, a low mass system is combined with low loss performance (Figs. 3.85 and 3.86). The transmit/receive modules which form part of the active phased array in this design were developed by DASA Ulm (Fig. 3.87).

Fig. 3.85 (left): DESA mock-up in front side view (DSS)

Fig. 3.86 (right): DESA panel feed network (DSS)

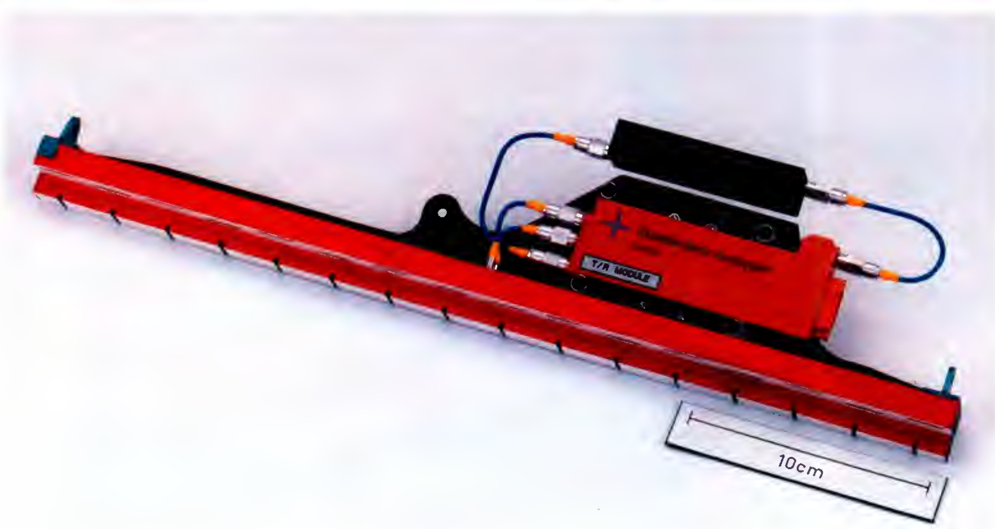
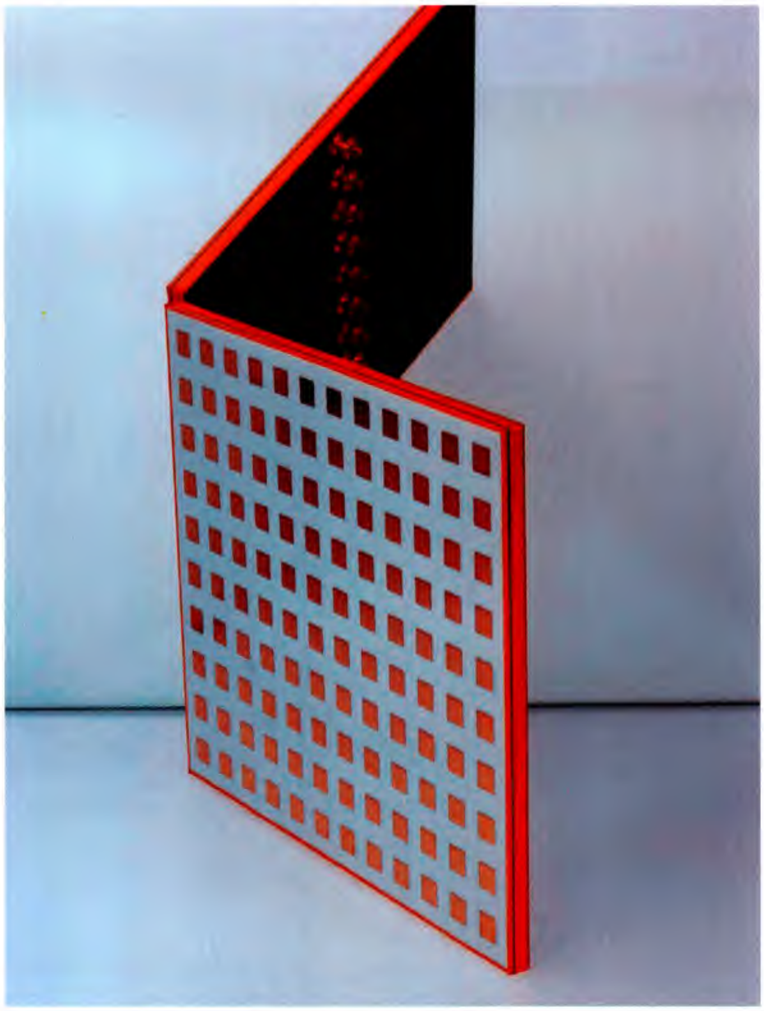


Fig. 3.87: DESA transmit/receive module (DSS)

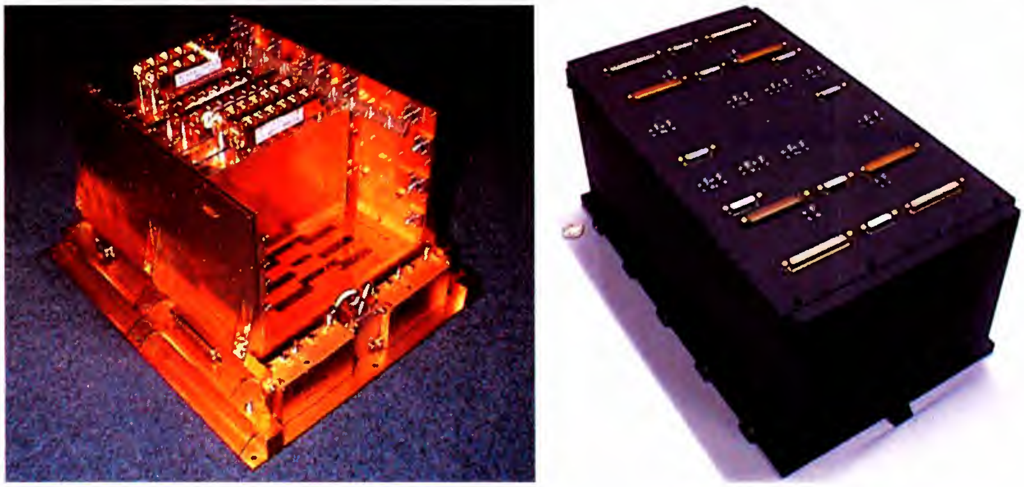
Fig. 3.88: X-band microstrip patch radiator (DSS)



• A patch array antenna design has also been produced as an alternative to the use of CFRP, in this case making use of novel materials. Technical problems such as layer bonding have been overcome and the result is low loss combined with very high bandwidth in X-band as well as excellent cross polarisation separation (Fig. 3.88). This development will allow the construction of an ultra lightweight antenna radiator and can be scaled to enable the requirements for the longer wavelength L-band systems to be met at acceptable mass (and acceptable cost).

The CORE Radar programme has also considered antenna design. This component is a wide bandwidth slotted waveguide design which can be used as the basis for X, C and S band antennas. The aim of this development is to provide a technological basis for developing low cost export missions.

Central electronics
The antenna is the most visible part of the radar system and, with active phased array technology, performs more functions than was the case with ERS. Despite this, the central electronic systems remain essential components in which the requirements for lower mass and greater modularity must be satisfied.



Core Radar Intermediate Frequency Equipment Core Radar Base Band Equipment

Fig. 3.89: IF and baseband equipment from the CORE Radar programme (MMS, Portsmouth)

The CORE Radar programme has addressed this area of the SAR and the resulting IF and baseband equipment is illustrated in Fig. 3.89. The two elements perform the following functions:

- IF equipment: provides frequency generation, upconversion and downconversion for wide bandwidth, multi frequency and multi polarisation radars;

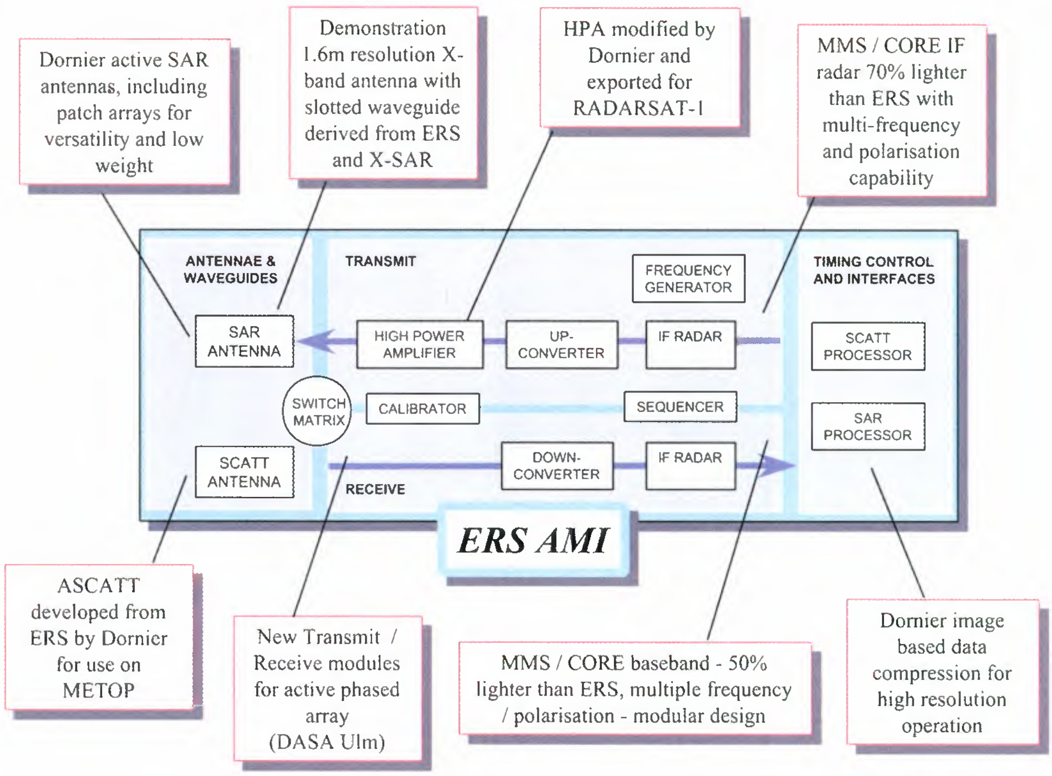
- Baseband equipment: provides high speed control, signal generation and processing for wide bandwidth, multi frequency and multi polar radars.

Both sets of equipment are highly integrated and replace several equivalent units used on the ERS and ASAR missions, providing mass savings of more than 70% and 50% respectively. The modular and flexible design allows the equipment to be used in a variety of configurations for a wide range of radar and other types of instrument. This in turn allows development costs to be spread over a wider range of missions.

Data handling

SARs have always been considered as instruments with very high data rates, although the rate of over 100 Mbit/s output by the ERS SAR, which was considered daunting ten years ago, is now seen as less dramatic. The new generation of instruments will produce data at a rate of approximately 1.5 Gbit/s. As a result, DSS have undertaken research into on-board SAR processing to filter and compress the SAR data, thereby reducing the data volumes. This research is considering compression algorithms based on images rather than raw data. Advanced systems for on-board data storage are also being considered in parallel with developments on other ESA programmes.

Fig. 3.90: Some European developments in SAR technology since ERS examples from DSS and MMS)



The way forward

Some of the work undertaken on the technology programmes defined above is summarised in Fig. 3.90 against a background of the ERS AMI system. It should be noted that these are only examples chosen to represent the work being undertaken throughout Europe.

All of this technological development begs the question - why ? The reason is that the work is achieving the aim set out at the start of the case study, namely to achieve better performance at much lower costs, the sign of technical maturity. To illustrate how the above work is being used to good effect, the example of the TerraSAR can be cited.

The TerraSAR concept is a submission for the ESA Earthwatch programme which combines the experience of DSS and MMS, together with other European partners. The aim of this programme is to produce a cost effective, high resolution land monitoring SAR which capitalises on the requirements experience described in the earlier case studies and the technological work described above. The system, which could be installed by 2003, will be operated by a private entity that will maintain system and service continuity on the basis of a sustainable business.

The services will be based on a dual frequency (X and L band) SAR with multiple polarisation capabilities. The X-band sensor will provide data with resolution of about 1 m for land mapping while the L-band sensor will provide land monitoring for variables such as soil moisture. The sensor capabilities will include stereo SAR in X-band and repeat pass interferometry in L-band.

The work carried out at DSS in this context is on an X-band high resolution SAR antenna front end which complements the CORE Radar work on central electronics from MMS-UK.

Summary
Developing the AMI instrument on ERS was a complex task and many lessons were learned on the way. One of the positive outcomes of this is that these lessons have been valuable in the development of the more advanced ASAR and that European industry is looking beyond this to the next generation of missions. With smaller, lighter satellites the consolidated European industry of the future is well placed to exploit the use of future SARs.

Case Study 19: ERS Exploitation Within GIS

Category:	New and refined techniques to improve information content
Description:	ERS data can be used more effectively for everyday problem solving if they can readily be merged with other data sources and spatially analysed. These capabilities are enabled by Geographic Information Systems (GIS). This case study shows how ERS SAR data have been used to develop a prototype GIS flood monitoring product.
Acknowledgements:	Giovanni Sylos-Labini, Planetek Italia, Italy

One of the most important developments in the use of ERS SAR data has been the drive to make the data readily available for use in everyday applications. Since the launch of ERS-1, a number of developments have helped to make this possible, including:

- increasing computer power - effective SAR processing can now be carried out on PCs;
- availability of relatively inexpensive processing and image manipulation software;
- convergence of data formats making importing the data easier than in the past.

For many applications the key is to use ERS data effectively with other sources and perform spatial analysis without specialist capabilities. This ability is increasingly provided by commercial PC- or network-based Geographic Information Systems (GIS). These systems are used extensively by actual and potential users of ERS data such as local authorities, utilities and environmental management organisations, so making ERS derived information compatible with these systems has been a priority.

To illustrate how ERS SAR data are being used to develop GIS products, an application by Planetek Italia is presented which shows how the extent of a flood affected area was determined automatically from ERS SAR and delivered in a standard GIS format. Such products are used directly by responsible authorities, unlike the original image data which would be too difficult for untrained personnel to handle and interpret.

The region around Beziers in Southern France was affected by severe flooding on the night of January 28th 1996. To analyse this event and identify the optimum product characteristics, ERS SAR images were used from ERS-2 on August 7th 1995 (a reference image), ERS-1 on January 28th 1996 (just before the event) and ERS-2 on January 29th 1996 (immediately after the event).

Fig. 3.91 shows an image formed by taking the difference between the two

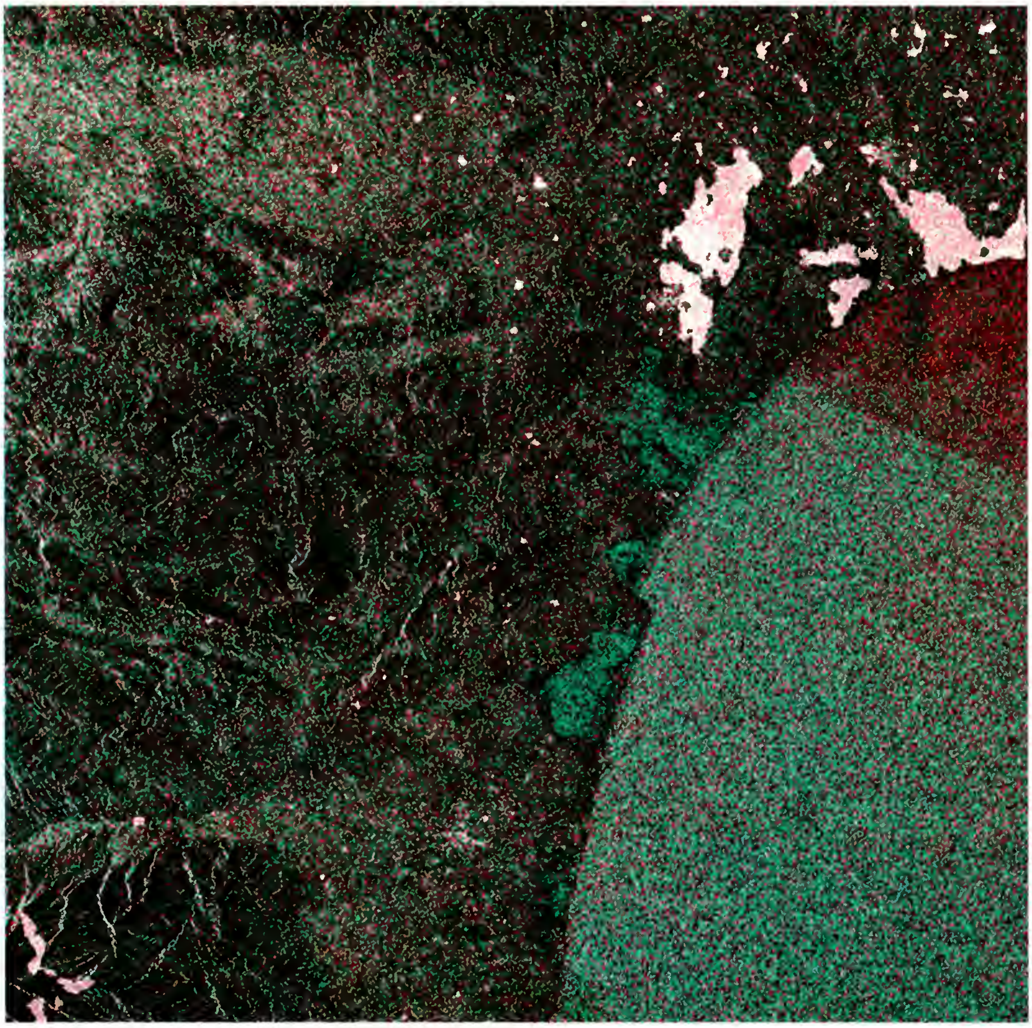


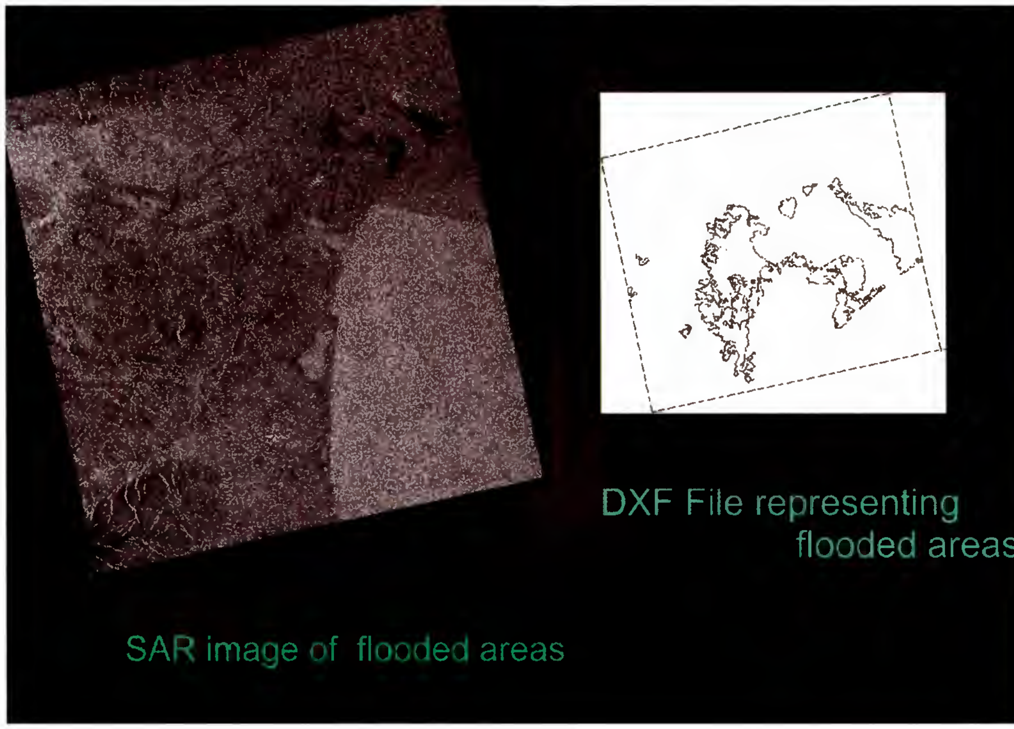
Fig. 3.91: An assessment of the Béziers flood, based on SAR images from 28th January 1996 (before the event) and 29th January 1996 (after the event)

ERS images taken on 28th and 29th January 1996. The area shown in white represents the flooded region. Changes observed off the coast, which would normally appear in white are excluded using coastline information. It is interesting to note that a small central part of the river bed (located in the centre between the two biggest white areas) is not properly covered. This is because the flood event had just begun at the time the first image was taken, showing the sensitivity of the image data to the local conditions.

By adding information from the third reference image of five months earlier, it was possible to refine the analysis of the flooded area. Having explored a number of approaches to extract the flooded area from the SAR imagery, including those shown above and the use of interferometric coherence, the next stage was to finalise the product characteristics. The aim of these was make the results even more accessible to the user community.

The product format adopted consists of a descriptive component which is added to the actual data files. The descriptive part is an ASCII file which can be read by operators as well as computers. It provides information to assist with understanding the data and to help with ingestion into commercial software packages. It also contains pointers to WWW sites containing more detailed information and support.

Fig. 3.92: SAR image and vector file used to produce the final Flood Map.



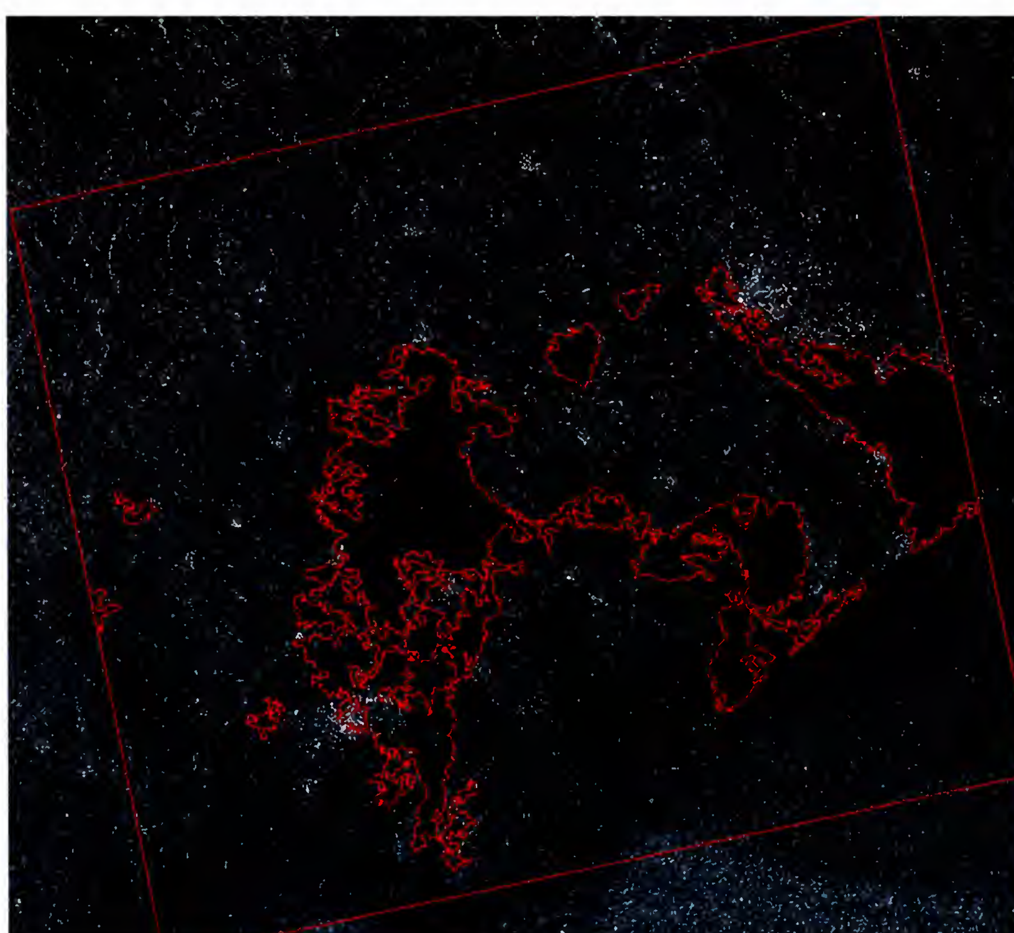


Fig. 3.93: Prototype product with flooded area near Béziers are delineated in red. The image under the red vector map is the SAR scene. (Planetek Italia)

The format of the data layer was chosen to be as universal as possible. De facto industry standards were preferred to more complete, but restricted formats. DXF format was chosen as the standard format for vector files, and GeoTIFF format was used for raster files. The two layers shown in Fig. 3.92 were used to generate the final product.

The final flood map is shown in Fig. 3.93. The result is a vector map of the flooded zones in a format which can be immediately employed by end users.

The key aspect of this work is producing output that can be used directly by the customer's GIS, combined with on-line assistance to provide the user with greater confidence. Typical functionality offered by popular GIS packages such as ArcView could then be employed to combine such a product with standard digital mapping of the region including population, land use and infrastructure, to help determine appropriate remedial action and damage estimation. This approach allows the ERS data to be used cost effectively and without concerns about the complexity of data handling.

Summary

ERS data are only of general use if they can be made relevant to those undertaking everyday tasks. The best way to do this is to make them easy to use, easy to understand and easy to integrate with other spatial data sources. It is through the use of GIS that this can be achieved since desktop GIS is increasingly the everyday tool of those working professionally with spatial data. This case study provides an innovative approach which has been welcomed by users. It opens up different possibilities for the future in terms of how multimedia approaches including EO products could stimulate greater demand.

4. Business Development With ERS

4.1 Introduction

The sales of data and information derived from ERS missions are a growing European business. There are positive supporting signs that:

- substantial niche markets are being established within a wide range of global industries;
- the volume of ERS data sales is increasing;
- commercial services are becoming operational;
- new techniques are emerging to provide quick access to substantial private sector markets.

Fig. 4.1 illustrates clearly the growth in demand for ERS products by showing average monthly sales of SAR data from early 1993 to the first quarter of 1998. In this period, demand has increased threefold with the cumulative total reaching over 8,000 individual products. As customer awareness and confidence grows, the rate of growth should, for the foreseeable future, remain at, if not exceed, current levels.

Over the same time period, sales of Low Bit Rate (LBR) data have also increased at a dramatic pace. The number of LBR products sold increased by 28% in the period 1993-94 and 80% in 1996-97. The figures for the first quarter of 1998 do not show any sign of slowing down, with 403 products already supplied and ATSR in particular showing a marked increase.

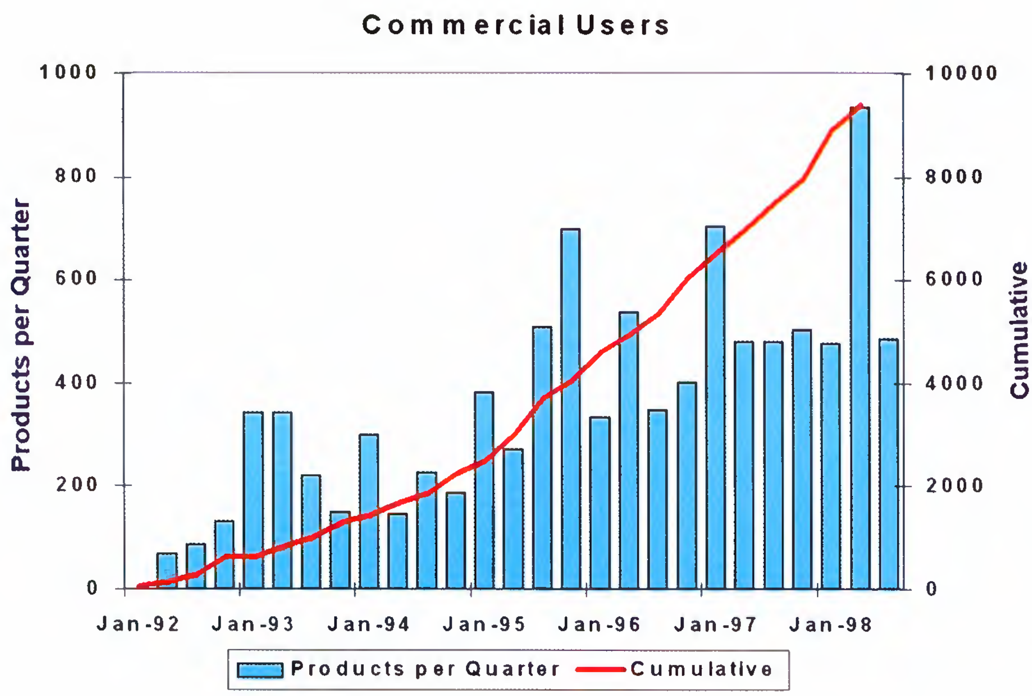


Fig. 4.1: Development in sales of SAR products

The number of applications and industry sectors that have already developed is impressive, illustrating not only the versatility of the data, but also the tenacity and foresight of the growing number of small and medium sized companies capitalising on the opportunities afforded to them. Table 4.1 summarises the range of market sectors into which ERS related products and services are being commercialised, as well givingas an indication of the type of applications of interest, the sensors used and examples of known private sector companies operating in each field. It should be noted that many organisations which are working effectively in these areas are not companies, but government institutes or research organisations. Accordingly, representation in the table reflects partly the extent to which these activities are handled in the private sector in different European countries.

Table 4.1: Operational users and applications for ERS products.

Market	Main applications	Sensors/ Technique	Example VA companies
Oil and gas exploration	Offshore basin screening	SAR, Altimeter	Nigel Press Associates/Treicol, UK National Remote Sensing Centre, UK
	Slick detection	SAR	Nigel Press Associates, UK Tromsø Satellite Station, Norway Earth Observation Sciences Ltd, UK
	Geology mapping	SAR, Altimeter	BGR, Germany Nigel Press Associates, UK National Remote Sensing Centre, UK
	Seismic survey planning	Altimeter	Nigel Press Associates, UK Satellite Observing Systems UK
	Pipeline monitoring	SAR	Kayser Threde, Germany GAMMA, Switzerland
Environmental Monitoring	Oil/chemical slick detection	SAR	Nigel Press Associates, UK National Remote Sensing Centre, UK Tromsø Satellite Station, Norway Earth Observation Sciences Ltd, UK
	Flood mapping	SAR	DSS Dornier, Germany GEOIMAGE, France GAF, Germany Planetek Italia, Italy Synoptics, The Netherlands
	Flood Modelling and Forecast	SAR	Vista, Germany
	Large scale climate parameters	Scatt	IFARS, Germany
	Ozone Monitoring	GOME	DFD, Germany DWD, Germany

Market	Main applications	Sensors/ Technique	Example VA companies
Marine and Coastal Zone Management	Bathymetry mapping	SAR	Aerosensing, Germany ARGOSS, The Netherlands
	Oil/chemical slick detection	SAR	Nigel Press Associates, UK National Remote Sensing Centre, UK Tromsø Satellite Station, Norway Earth Observation Sciences Ltd, UK
	Ocean vessel tracking and navigation	SAR	Anite, UK
	Sea ice monitoring	SAR, Altimeter	BSH, Germany VTT, Finland Tromsø Satellite Station, Norway Anite, UK Earth Observation Sciences Ltd, UK
	Wave height mapping	Altimeter, Scatt	Satellite Observing Systems, UK Oceanor, Norway
Risk Management & Insurance	Earthquake assessment, monitoring and prediction	InSAR	GFZ Potsdam, Germany Nigel Press Associates, UK (CivInsar)
	Subsidence mapping	InSAR	GFZ Potsdam, Germany Nigel Press Associates, UK (CivInsar) Planetek Italia, Italy Atlantis Scientific, Canada
	Flood mapping	SAR	DSS Dornier, Germany GAF, Germany Planetek Italia, Italy
	Wave height mapping	Altimeter, Scatt	Satellite Observing Systems, UK
Agriculture	Crop identification and verification	SAR	DASA Jenoptik, Germany GEG, Germany National Remote Sensing Centre, UK Remote Sensing Applications Consultants, UK Synoptics, The Netherlands SCOT Conseil, France SERTIT, France
	Yield prediction	SAR	National Remote Sensing Centre, UK Remote Sensing Applications Consultants, UK

Market	**Main applications**	**Sensors/ Technique**	**Example VA companies**
Forestry	Change detection	SAR	DSS Dornier, Germany Earth Observation Sciences Ltd, UK RSS, Germany Spot Image, France
	Forest mapping	SAR	VTT, Finland National Remote Sensing Centre, UK
	Deforestation	SAR	GAF, Germany Kayser Threde, Germany
Cartography	General mapping	SAR	Spot Image, France National Remote Sensing Centre, UK Remote Sensing Applications Consultants, UK
	Land use mapping	SAR	National Remote Sensing Centre, UK Remote Sensing Applications Consultants, UK
	3-D model generation and visualisation	SAR, Altimeter	Atlantis Scientific, Canada Aerosensing, Germany DSS Dornier, Germany Planetek Italia, Italy Nigel Press Associates, UK National Remote Sensing Centre, UK
Water Resource Management	Channel mapping	SAR	Spot Image, France
	Land use mapping	SAR	Spot Image, France Kayser Threde, Germany
	Geology mapping	SAR	BGR Germany Nigel Press Associates, UK Spot Image
	3-D model generation and visualisation	SAR, Altimeter	DSS Dornier, Germany Nigel Press Associates, UK Matra Cap Systemes, France Synoptics
Civil Engineering	Subsidence mapping	SAR	GFZ Potsdam, Germany Nigel Press Associates, UK
General	Training	SAR	DFD, Germany DSS Dornier Germany GAF, Germany Planetek Italia National Remote Sensing Centre, UK

Eurimage SPA of Rome, Italy is the major commercial supplier of ERS data in Europe operating a network of some 50 Application Providers. With the sales of ERS data growing at an average rate of 25-30% per annum over the last 5-6 years, it is easy to see why they are so optimistic about the future. 'We are expecting another 25% growth in sales this year', explains Luciana di Domenico, ERS Business Manager at Eurimage, 'illustrating that ERS applications are moving into the commercial mainstream. We are seeing expansion in significant areas such as oil and gas exploration, digital elevation modelling with interferometry and coastal zone management, encouraging us to become more global in our vision'.

While sales of ERS data stand at about 1.2 MECU per annum, this does not account for the value added business generated by the private sector companies around Europe. It is these companies that turn complex scientific achievement into commercial reality. Their activities can be broadly divided into those in a marine environment and those on land.

Marine markets

The marine market has been an obvious target for commercial sales of ERS data as the mission was designed to emphasise oceanographic applications. Commercial operations fall into the following categories:

- sea ice monitoring systems and services;
- ocean vessel tracking;
- navigation;
- insurance;
- emergency response;
- off-shore exploration.

The last 5 years have seen the consolidation of commercial services in areas such as sea ice mapping and ocean navigation in which the use of ERS data is being fully integrated into national public services, while newer techniques, such as bathymetric assessment, have been discovered and marketed successfully.

A prime example of innovation and early success in developing saleable services based on ERS data is ARGOSS, established in 1995 and based at Marknesse in The Netherlands. Han Wensink, Managing Director of ARGOSS, describes the company as being 'at the leading edge of commercial coastal and offshore remote sensing in Europe', although their customers are found beyond European boundaries, with business coming from parts of Africa, the Middle East and South East Asia. In a little over 2 years, the ARGOSS Bathymetric Assessment System is generating revenues of more than 800,000 ECU per annum. ARGOSS has published papers in journals such as Hydro International and is now forming commercial partnerships to ensure the continued global success.

Off-shore basin screening was an unknown application 10 years ago. Nigel Press Associates (NPA) in the UK, however, has very successfully carved a new niche market within the oil exploration industry worth in the region of 3 MECU per annum. With support from The Really Easy Imaging Company (TREICoL), UK and the British National Space Centre, this innovative technique involving data from both the SAR and Altimeter instruments is becoming a standard procedure. To date, over 120 surveys have been completed and at least 2 other companies have entered the market to compete for their own share of this business.

Land

The original ERS objectives included experimental land applications, but progress with land applications has gone considerably beyond what was expected. Commercial operations fall into the following categories:

- cartography and land use mapping;
- 3-D modelling and visualisation;
- emergency response;
- natural hazard monitoring and prediction;
- subsidence mapping;
- geological mapping and on-shore exploration;
- agricultural statistics;
- forest management.

One of the most exciting developments in land applications has been the ability to use interferometric processing on separate SAR images to produce vital information on land surface change and elevation. The substantial business possibilities are beginning to be realised in areas such as insurance, real estate, natural hazard monitoring and mining to name but a few. Nigel Press Associates is one of the companies pioneering this technology and starting to realise return on its investment. Projects have already been completed which assess the effects of subsidence caused by mining activities in the UK and earthquake impact assessment in Greece.

The issue of subsidence is extremely emotive and has required, until recently, a confidential approach by NPA. However, the recent signing of a deal with Cartograph, a geographic services and data provider to the Insurance industry signifies the maturing of this complex technology into a fully commercial context.

Atlantis Scientific Inc. is a Canadian company, founded in 1981, that has been developing techniques and software for the creation and application of radar remote sensing, including interferometric SAR. A new commercial aspect of the business began in September 1996 under the name EOServ and has generated almost 1 million ECU revenue in its first year selling Atlantis' radar expertise to customers in government, space and the oil and gas industries. Indeed, ESA became a major client when Atlantis was awarded the contract to validate data from the ERS Tandem Mission over North America.

The most promising recent development from Atlantis is the creation of a new company, set for launch in September 1998, to pursue the development and marketing of a global digital elevation model archive created from their own EOServ archives, relying heavily on ERS Tandem Mission data. With an estimated global demand for DEM of approximately 77 MECU per annum by the year 2001 and access to a distributor network of some 300 established companies, Atlantis expects to reap rich reward from the venture. Dennis Nazarenko, Vice President at Atlantis, states clearly 'Atlantis understand that interferometry is truly a very cost effective method of creating high resolution DEM. This means that ERS is essential to the quality of our final product and central to our whole business strategy'.

GAF, Germany has been most involved in developing techniques for emergency response to major flooding. The past few years have seen some catastrophic flood events in central Europe, especially in Poland and Germany. GAF has worked closely with the civil authorities responsible for the Rhine and Oder river basins, identifying input to fast response systems. Current GAF work is being funded by the EU to develop application software dedicated to flood preparedness.

The synergistic use of ERS SAR data with optical forms of remotely sensed imagery has long been realised, although the drive for integration into commercial applications is only now being exploited. The worlds largest supplier of space-borne optical imagery, Spot Image of France, have recognised the benefits of ERS SAR when used in addition to their own sources for a whole range of projects including water resource exploitation, forestry management and topographic mapping. 'Not only does ERS SAR imagery help solve the problem of cloud cover', explains Louis-François Guerre, Head of Radar Applications at Spot Image, 'but its high geopositional accuracy allows more reliable image referencing in remote regions where ground control is a problem. We intend to capitalise upon these advantages and are already pursuing a vigorous programme of training and education among both our internal sales staff and international distributor network'.

Such is the utility of the ERS imagery in tandem with their own sources, Spot Image is committed to developing the market for ERS SAR on a global basis with partners and staff in France, USA and the Far East having already attended presentations and training sessions.

Training in SAR applications is an area in which companies such as Planetek Italia can generate further business. Having equipped ESA with a fully functional SAR training laboratory, Planetek runs regular training courses and events designed to introduce new users and customers to the benefits of what is often seen as daunting technology.

The real benefit of ERS to companies throughout Europe is extremely difficult to evaluate. In many cases, the value to human life and the physical environment of the applications being developed far outweighs any financial return and it is inappropriate to judge only by monetary measures. However, companies such as those referred to here still have to survive in a harshly competitive world. ERS products are helping them to do more than survive, opening up new markets and offering opportunities for growth that will develop further with the advent of Envisat.

The future
The future for commercial applications of ERS-derived products seems bright. Techniques such as interferometry are creating new possibilities that were unforeseen 20 years ago. More established services such as sea ice monitoring are becoming entrenched in mainstream activities and becoming vital elements of successful global navigation.

Commenting on the future for ERS data in the commercial world, Helmut Hoensch, Radar Specialist at GAF, Germany's leading supplier of earth observation products and services, comments 'Only a few people have thought that ERS could have so many applications on land. Therefore I'm sure that this market will evolve further, especially when Envisat becomes available'.

Further encouragement for the future of remotely sensed imagery lies in the phenomenal growth of the geographic information systems (GIS) industry. Some commentators already value this industry at approximately 6 Billion ECU for 1997 with growth rates in the region of 10-15% per annum. While data from the ERS missions will not apply to all uses of GIS, the general trend towards the Information Society based upon digital technologies will ensure a future demand for the myriad value added products available and yet to be discovered.

Major new techniques set for high growth include:

- interferometry;
- off-shore basin screening;
- bathymetry mapping;
- land use mapping;
- agriculture and forestry management.

5. The Way Forward

Links to the future from ERS instruments are shown in Table 5.1. This demonstrates that the progress made with ERS has provided a solid foundation for these future programmes by building scientific understanding, developing applications techniques and by helping to create industrial structures through which data from the future missions will be applied.

ERS instrument	Legacy and future plans
SAR	Mature applications developed, including land in addition to the ocean and ice originally emphasised. SAR interferometry established as a major field of scientific enquiry and application technique. Follow-on mission on Envisat (ASAR) will build on the ERS SAR foundation with multiple polarisation capabilities. Future SAR missions also include Radarsat 2 with proposals for InSAR mission and for LightSARs, providing greater opportunities for repeat monitoring
Scatterometer	ERS Scatterometer is now in operational use (e.g. at ECMWF since early 1996) 4-D variational analysis scheme uses Scatterometer data more effectively, enhancing its operational contribution. Operational Scatterometer (ASCAT) to fly on Metop
Radar altimeter	Follow on mission on Envisat will continue and refine the dataset created by ERS Other, complementary altimetry missions to fly (e.g. Geosat Exact Repeat Mission and the Jason TOPEX/POSEIDON follow on).
ATSR	AATSR to fly on Envisat Increasing appreciation of the importance for long term weather forecasting of high accuracy SSTs.
GOME	GOME-2 to fly on Metop

Table 5.1: Future plans based on the achievements of ERS instruments

In considering where European EO might go, it is important to consider where the ERS missions have brought us.

In the early 1980s, Europe had little expertise in space radar applications. Through successful cooperation at the scientific and technical levels, the ERS programme designed and built two satellites which have:

- provided accurate, reliable and policy relevant measurements of phenomena from the mesoscale to the global scale;
- provided long operational lifetimes which ensure long term and thus relevant datasets;
- fostered effective cooperation at the European level;
- formed the basis for a great increase in skills available for producing future missions and to make effective use of their data.

The fact that the mission objectives have been exceeded, and continue to be further exceeded is an effective demonstration of the programme's success.

The scientific origins of the ERS programme can be traced back to the early 1970s. Since then, it is interesting to note the changes in the terminology in which the mission objectives have been expressed. The emphasis has moved between scientific understanding of the Earth system and the need to support commercial developments of EO, with a greater emphasis on short term solutions.

Given these changes, it is important to recognise that the successes of the ERS programme support both cases, as has been shown in the pages above. High quality monitoring is always relevant and the long term records provided by ERS have made demonstrable contributions to Earth system science. Similarly, the contributions of ERS to applications needing rapid response, such as flood monitoring and ship routing, emphasise the relevance of ERS to everyday activities.

There is now a need to build on the high quality datasets established by ERS, a function which is now placed in the hands of Envisat. The SAR mission will be continued by ASAR, the ATSR by AATSR, the RA mission by a similar instrument and GOME with SCIAMACHY on Envisat. The Scatterometer is now considered fully operational and a successor (ASCAT) will take its place with the more familiar operational instruments on Metop, together with a GOME-2 to provide continuity and complement SCIAMACHY.

Beyond Envisat, proposals for future missions are classified into Earth Explorers and Earthwatch missions. This recognises the need to evolve some of the instruments towards a full operational service while continuing to develop new capabilities.

The skills which have been developed by Europe's scientists and engineers as a result of the ERS programme will allow these new ventures to develop in a new way. Features of these missions can thus include:

- smaller, more dedicated mission profiles based on the improved data requirements now available;

- shorter gestation times in keeping with the smaller payloads;

- greater re-use of existing developments where appropriate in the face of technological progress;

- greater partnership between institutions and industry in the funding of the more operational missions.

One of the most important lessons of the ERS programme has been the importance of data quality, not only to the applications anticipated at launch, but also to new applications and analysis procedures. The challenge is to achieve this quality cost effectively - no small task for Europe, but one for which ERS has prepared us well.

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