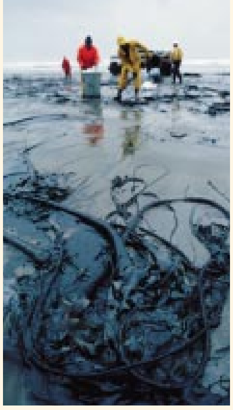
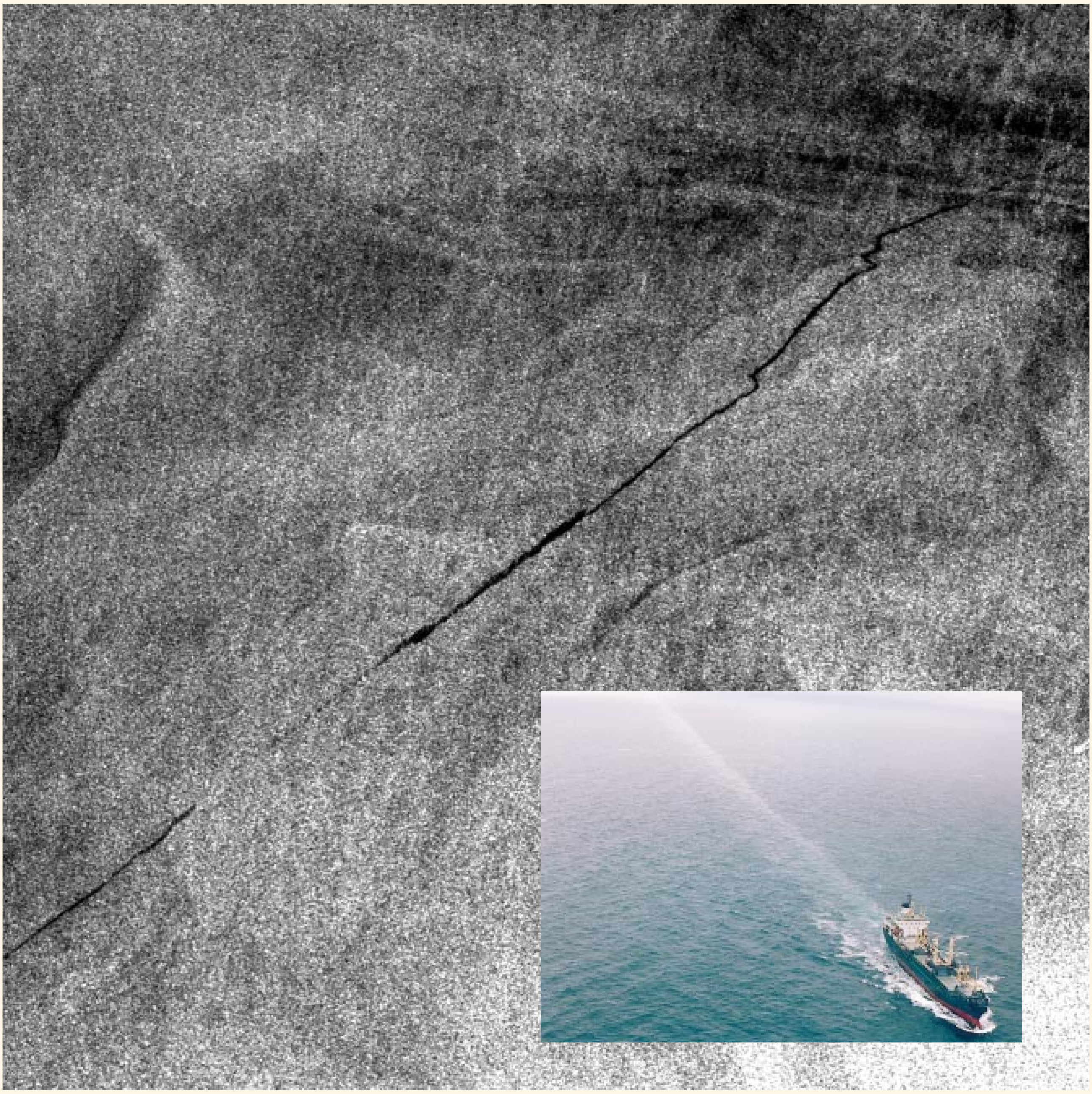
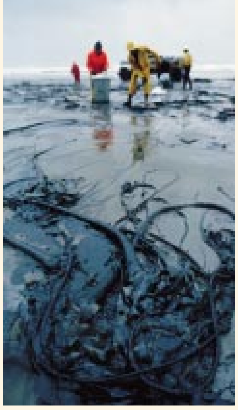


OIL POLLUTION MONITORING





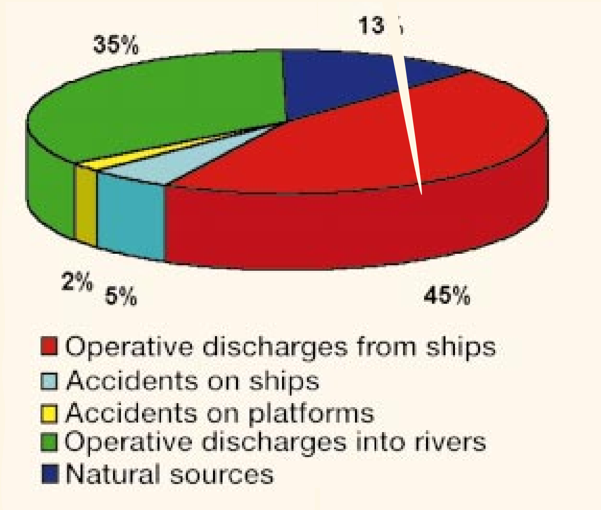
OIL POLLUTION MONITORING

The Need for Better Information

The search for oil reserves offshore is moving into deeper and deeper waters, and crude oil and oil products are being transported across the globe in increasingly larger tankers. As a result, oil spills pose a serious threat to the ecology of the World's oceans. The amount of oil spilled annually worldwide has been estimated at more than 4.5 million tons.

The biggest contributor to oil pollution in the World's oceans (some 45%) is operational discharges from tankers (i.e. oil dumped during cleaning operations). Approximately 2 million tons of oil are introduced annually by such operations, equivalent to one full-tanker disaster every week. Only 7% of the oil in the sea can be directly attributed to accidents. Land-based sources such as urban waste and industrial discharges, which reach the ocean via rivers, are also a major contributory factor.

International Commissions have been formed and Conventions agreed in an attempt to curb marine pollution. The Oslo-Paris Commission (OSPARCOM) for the environmental protection of the North East Atlantic, and the United Nations Convention on the Law of the Sea (UNCLOS) in which more than 150 countries participate, are just two examples of such co-operative efforts. All of the countries bordering the Baltic Sea and the members of the European Economic Community signed the Helsinki Commission (HELCOM) Agreement in 1992 to protect their coasts. In addition, the North Sea countries have committed themselves to intensifying the battle against oil pollution. In the framework of the Bonn Agreement (1969), almost daily surveillance is carried out to check for pollution on the North Sea Continental Shelf. The signatories of the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Agreement are obliged to ensure that ports provide reception facilities for ships' waste, and limitations are imposed to try to protect ecologically sensitive areas against oil discharges.



Estimate of the sources of oil spills at sea

Although the oil industry is fully aware of the international laws and the risks connected with marine pollution, there is still ample evidence of numerous repeat offenders. Many countries cannot afford an adequate surveillance programme. Coast-guard personnel and ship and

A ship discharging oil

aircraft crews frequently report sightings of oil spills, but the percentage of spills detected is still relatively low. Surveillance is carried out in some areas using remote-sensing aircraft. The Side-Looking Airborne Radar (SLAR) and radiometers on these aircraft detect pollution under different conditions and over wider areas than ships' observations.

National Pollution Control Authorities such as the National Coast Guard or centres for environmental protection have three main roles in terms of oil-spill detection:

- *early warning*
- *legal prosecution*
- *provision of pollution statistics.*

Identification of the discharge source and photographic documentation are required quickly both for the legal prosecution and the prevention of environmental damage.

The Limitations of Traditional Techniques

An operational pollution-monitoring scenario based only on aircraft and ship surveillance has several drawbacks:

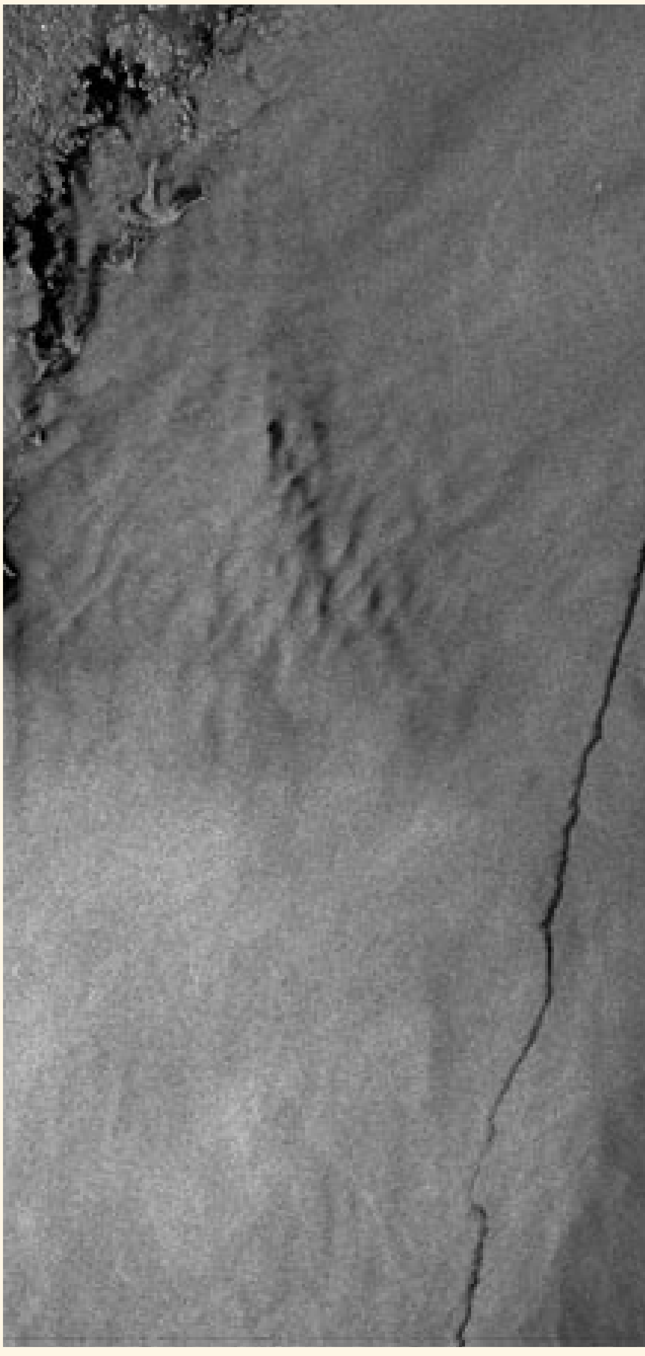
- *The time delay between an illegal discharge and its detection does not permit a successful prosecution in most of the cases, unless the culprits are caught "red-handed".*
- *Poor weather conditions can prevent an aircraft from flying over the area.*
- *The resources available for airborne surveillance often allow only a small fraction of coastal waters to be surveyed.*
- *Evidence based only on SLAR data is often deemed insufficient in a court of law.*

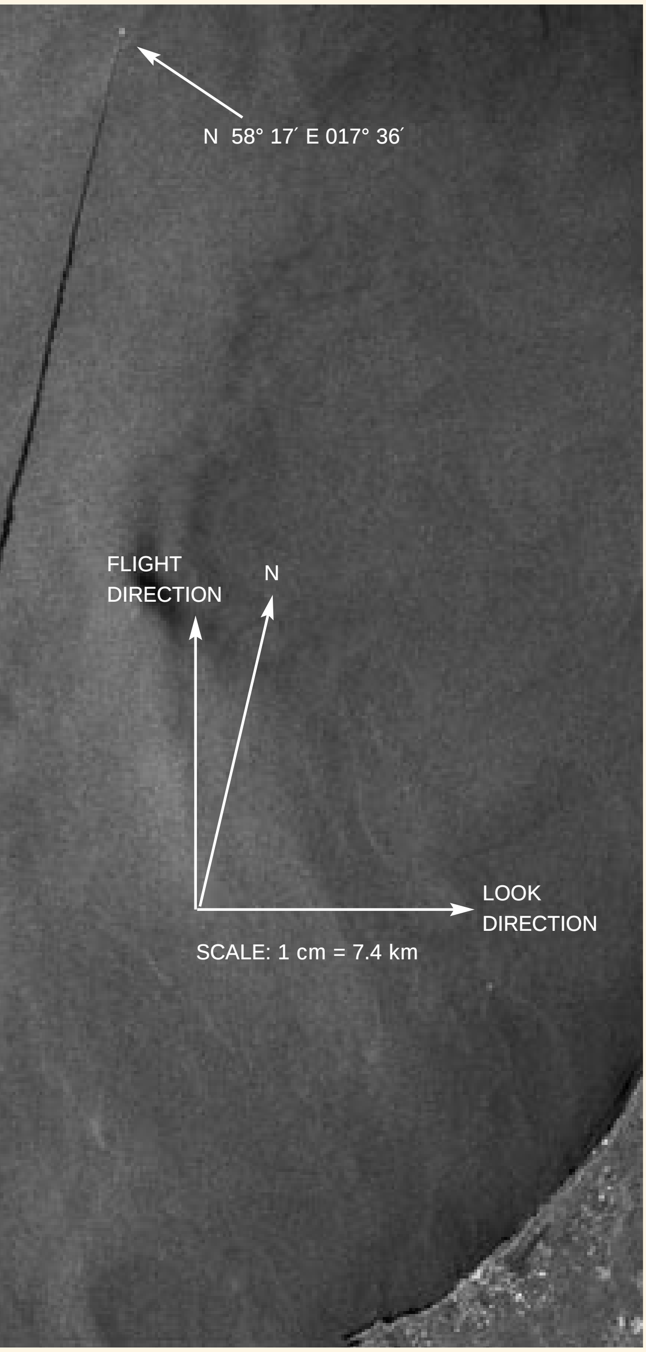
The Benefits of Space-Based Monitoring

Today, the availability of data from Earth-observation satellites offers the possibility to complement and optimise surveillance strategies, allowing a more cost-effective approach to oil-pollution monitoring. Space-acquired Synthetic Aperture Radar (SAR) data can complement current aerial surveillance strategies both by providing coverage over areas not easily surveyed with aircraft, and also by providing synoptic views of large areas. This raises the likelihood of immediate intervention being feasible, makes the operations as a whole more cost-effective, and dramatically increases the size of the area that can be routinely surveyed.

The introduction of satellite data as an additional information source has several distinct advantages:

- *The combined use of satellites, ships and aircraft for surveillance increases the chances of early detection of oil spills and fast clean-up operations, preventing further environmental damage.*
- *By regularly monitoring large areas, deeper analysis can be performed and more accurate statistics on the occurrence of oil slicks can be provided.*
- *Oil seeping naturally from the sea floor can be detected, and its occurrences carefully monitored.*
- *A better overview of oil spreading, and therefore a source of input to oil drift models, can be obtained.*





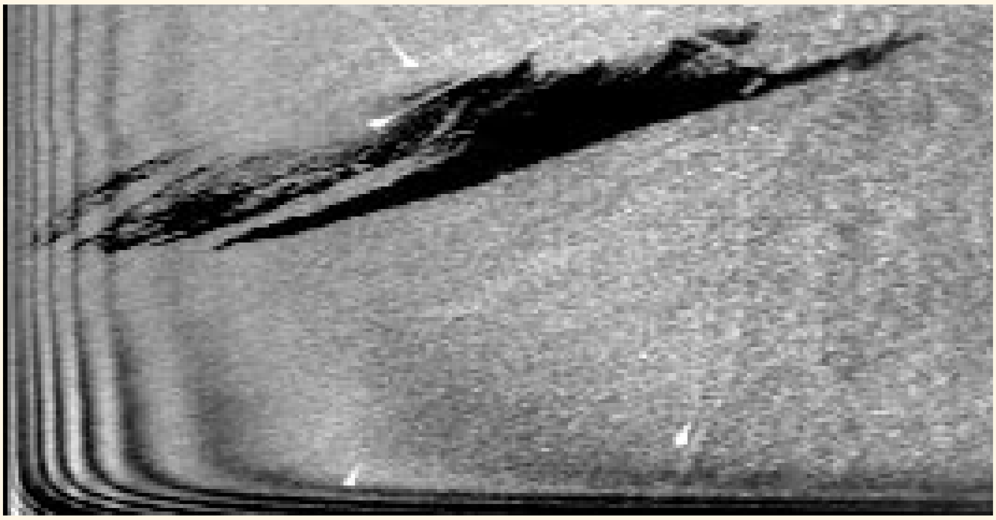
The Contribution of ERS SAR

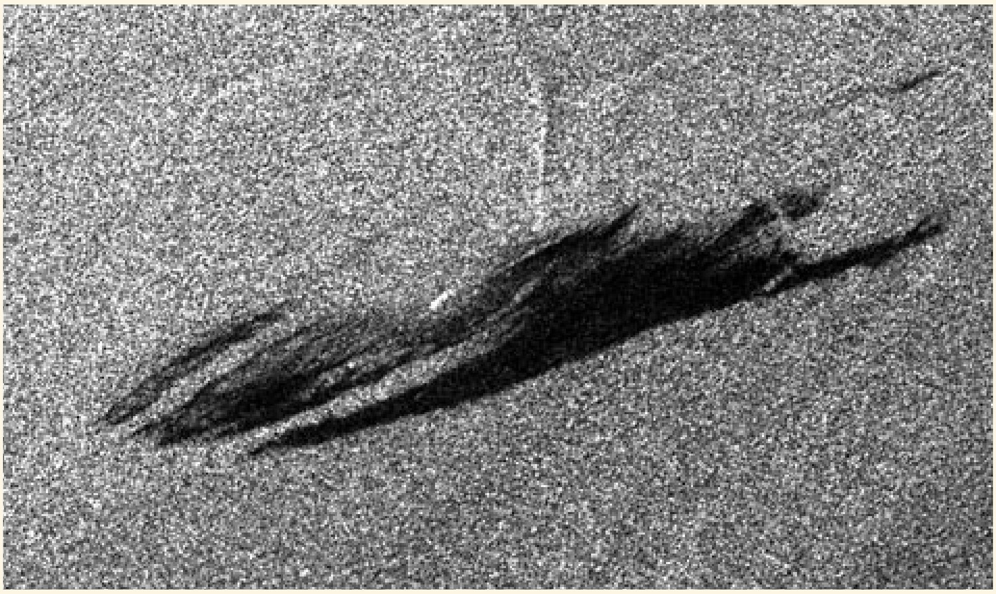
With the advent of the European Remote Sensing Satellite (ERS) missions in particular, the Earth is orbited once every 100 minutes at an altitude of 780 km. The "nominal" spatial resolution of the ERS data is 25 m x 25 m, but for oil-spill detection "low-resolution" images of 100 m x 100 m are more than sufficient, reducing the data content of each image to about 2 Mbytes. This type of image can easily be made accessible via the Internet.

Experiments have been carried out to assess qualitatively and quantitatively the potential of ERS SAR data for oil-spill detection. It can be stated as a result that the detection capability of the space-borne SAR is comparable to that of the SLAR systems used in today's maritime airborne surveillance programmes.

The presence of an oil film on the sea surface damps out the small waves due to the increased viscosity of the top layer and drastically reduces the measured backscattered energy, resulting in darker areas in SAR imagery. Use of the ERS SAR low- resolution images has demonstrated the satellites' ability to detect even very thin pollution layers for low wind speeds of 3-4 m/s and thick oil emulsions for wind speeds up to 12 m/s. Slicks as small as 0.1 km^2 in area can be detected. Pollutants that can be identified by ERS SAR include crude-oil emulsions, run-off water from acidic pitch deposits on land, drilling fluids from offshore oil rigs, waste from fish-production plants, and fish fat remaining on the sea surface from trawler catches.

Confirmed oil slicks in the North Sea detected by the ERS-1 SAR on 31 March 1996





An oil slick off the Dutch coast as observed simultaneously by a SLAR-equipped surveillance aircraft (top), and by the ERS-1 SAR (bottom). The shape of the slick appears identical in the two images

However, SAR (and airborne SLAR) scenes require careful interpretation because:

- *with low wind speeds, dark areas might not be oil slicks but merely local wind effects or natural oil films, causing false alarms unless experienced image interpreters or well-tuned classification algorithms and wind information are employed*
- *with very high wind speeds, the pollutant may mix rapidly with the sea water, leaving no surface effect to be detected.*

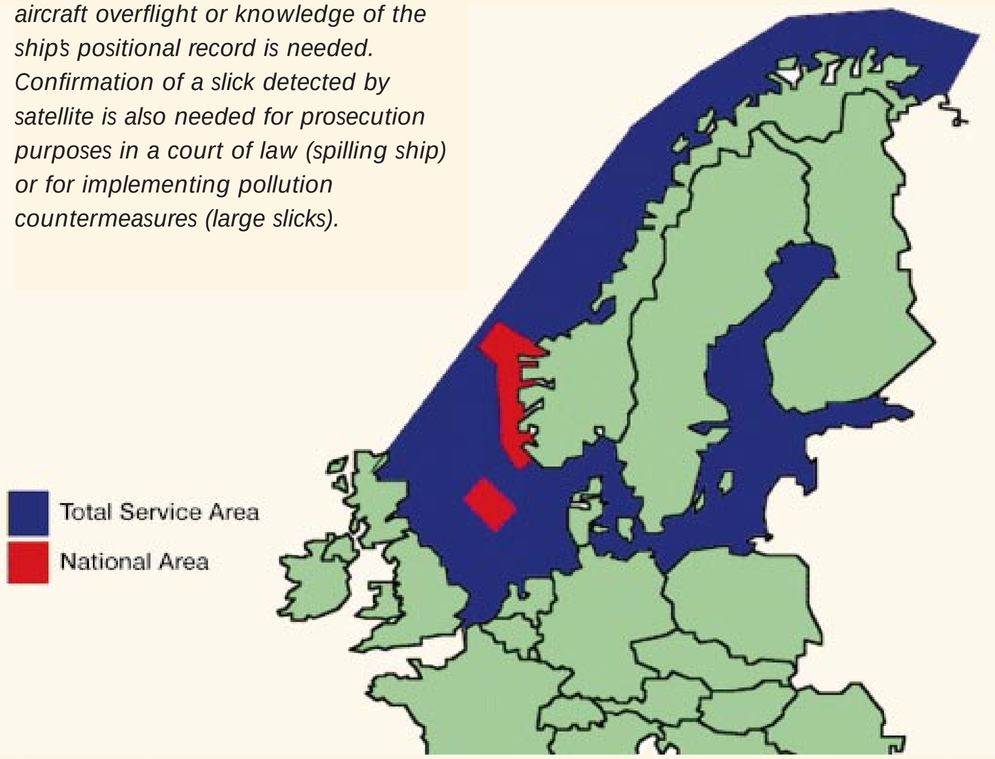
On a SAR image, a polluting ship can be spotted but not identified, for which an aircraft overflight or knowledge of the ship's positional record is needed. Confirmation of a slick detected by satellite is also needed for prosecution purposes in a court of law (spilling ship) or for implementing pollution countermeasures (large slicks).

Examples of Space-Based Applications

An operational spill-monitoring service in Norway*

Since the launch of ERS-1 in 1991, a service affording near-real-time access to ERS SAR data has been offered by the Tromsø Satellite Station in northern Norway, as part of the Norwegian Space Centre's national ERS-l programme. Based on this activity, a near-real-time oil-spill monitoring service has been established for the Norwegian Pollution Control Authority (SFT), a governmental expert agency belonging to the Norwegian Ministry of the Environment.

** The development of the service provided by the Tromsø Satellite Station has been supported by a number of institutions, including the Norwegian Space Centre (NSC), the Norwegian Pollution Control Authority (SFT), the Norwegian Defence Research Establishment (NDRE), the US Marine Spills Response Corporation (MSRC), the oil companies Statoil and ESSO, and ESA. Recipients of near-real-time data include the Dutch North Sea Directorate (NSD), SFT, and pollution-control authorities in Sweden, Finland, the United Kingdom, Poland and Estonia.*

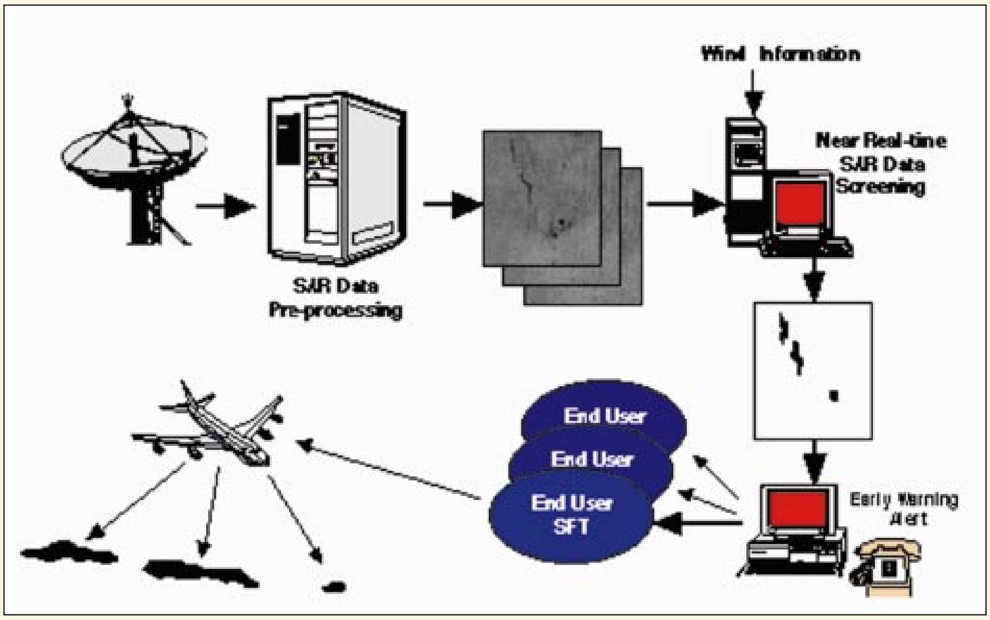


The Norwegian oil-spill-service coverage area (blue) and national high-priority area (red). ERS SAR data for the blue and red areas are analysed in near-real-time

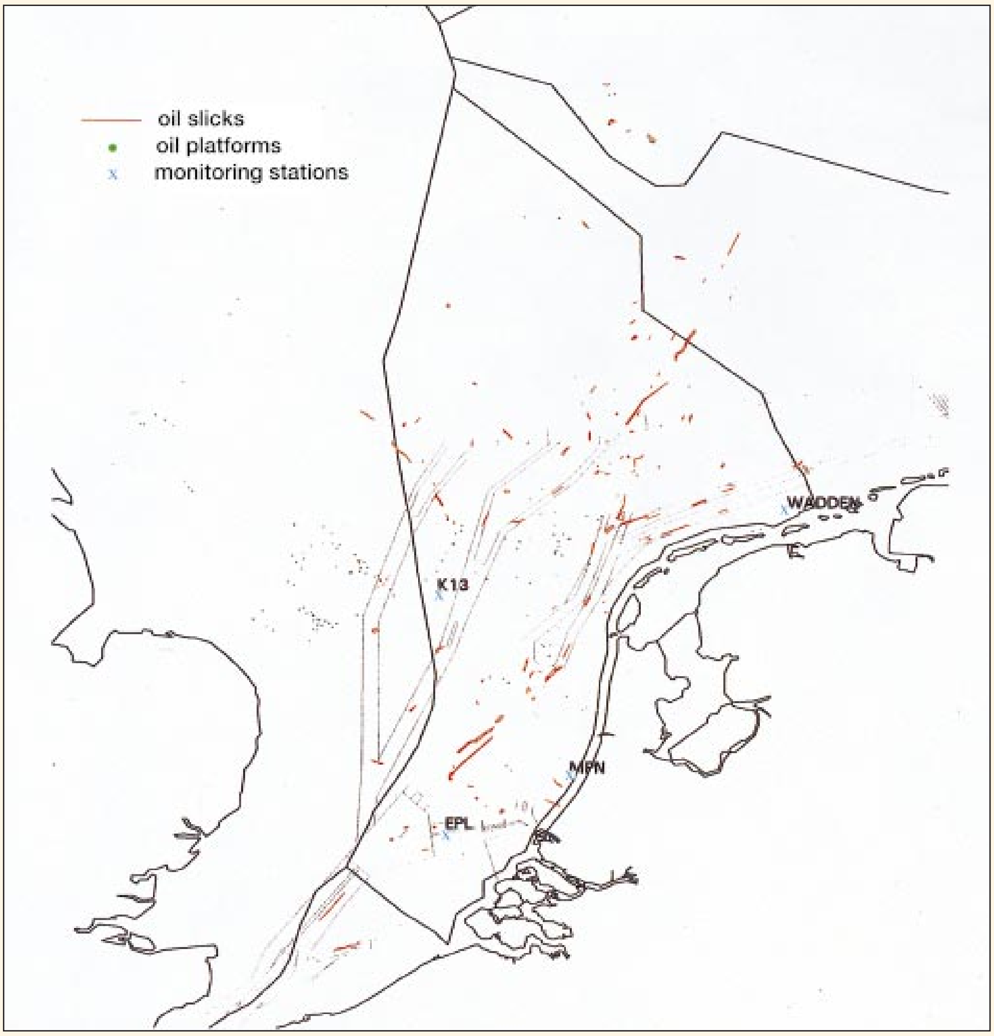
The Tromsø Satellite Station service includes the near-real-time analysis of ERS SAR data collected over Norwegian waters and the provision to the Pollution Control Authority of relevant oil-spill location information within one hour after satellite overpasses. A 100 km x 100 km SAR image is generated at the station in 6-8 minutes. An average of 300 such ERS scenes from the service area are analysed per month by the highly trained operators. The reporting is based on human, computer-supported analysis and interpretation. Reliability is further improved through the use of additional meteorological, geographical and historical information.

The Pollution Control Authority's surveillance-aircraft operations are planned and co-ordinated based on the timings of the ERS overpasses. The Station operators are in direct contact with the aircraft crew, which allows flight-path deviations to be made to verify satellite-detected slicks.

The extent of the area monitored, in combination with the near-real-time delivery of information, are just two of the advantages of the service being provided. ERS SAR data collected over the neighbouring waters of other Northern European countries are also analysed at the Tromsø Station and the relevant national authorities are notified either directly or via the Norwegian Pollution Control Authority of any oil spills detected.



The concept of the Norwegian oil-spill detection service, from reception and analysis of the data at the Tromsø Satellite Station, through early-warning alerts, and aircraft operations by the Norwegian Pollution Control Authority (SFT)



All slicks detected by ERS-1 in the Dutch North Sea during the second half of 1993 (in red). Green points mark the positions of the oil platforms, whilst blue crosses show the positions of the monitoring stations. A clear correlation is apparent between the positions and directions of the slicks and the locations of the shipping lanes

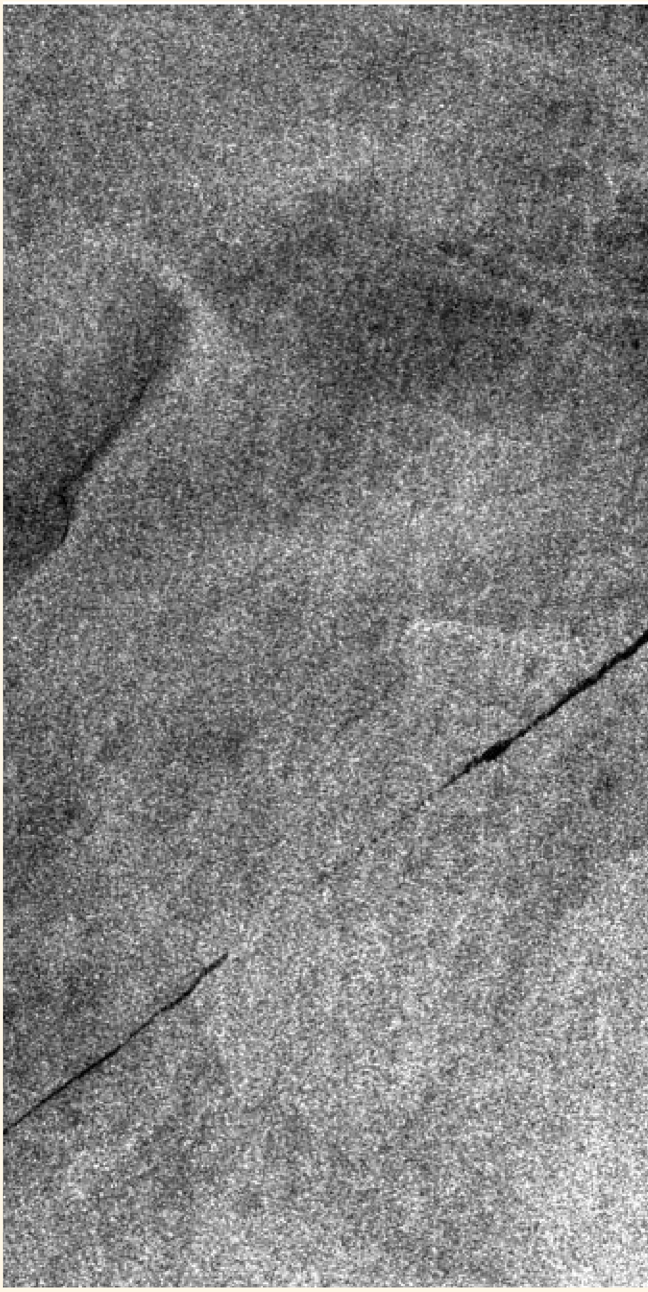
The Dutch experience

Since the nineteen sixties, the extraction of oil and gas has become an important North Sea industry. Over 450 fixed production platforms have been installed, which are connected to production wells, to distribution points and to the shore. More than 650 pipelines have already been laid, ranging in length from 100 m to 1500 km.

The Dutch part of the North Sea is patrolled daily by an aircraft operated by the North Sea Directorate (NSD) of the Rijkswaterstaat, with the aim of detecting oil spills and discharges from ships and platforms. About 1200 flight hours are typically scheduled per year, and inspections can be performed at short notice, but are also carried out randomly. Restrictions are imposed, however, by the number of possible flights, the area that can be covered, and the prevailing weather conditions.

NSD currently receives low-resolution ERS images on an operational basis from the Tromsø Satellite Station two or three times per week, with a delay of just one to one and a half hours after data reception at the Station. Such information is fundamental for coordinated intervention by modifying the flight plans of the remote-sensing aircraft to verify features detected in ERS data.

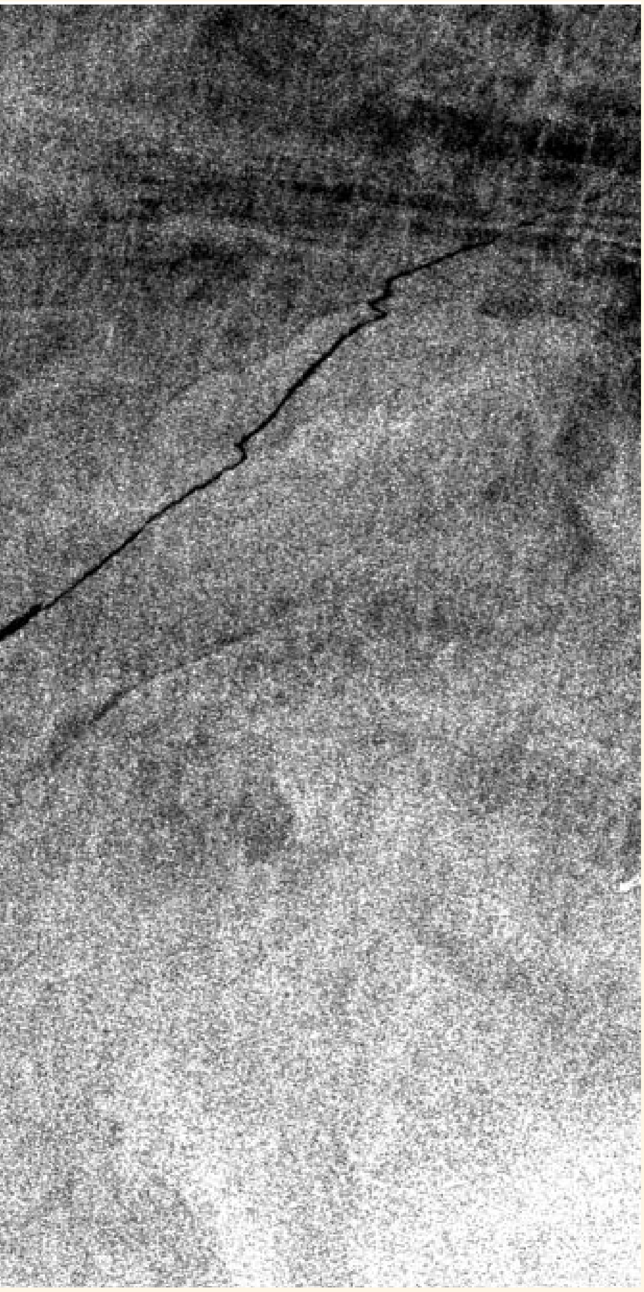
“Quick look” image derived from the ERS-2 SAR. Based on night data acquisition, the image reveals illegal oil discharges in the Mediterranean as dark linear structures



Cost/Benefit Considerations

Cost/benefit ratios and cost-effectiveness have been shown to improve when oil-pollution surveillance is based on a combination of spaceborne and airborne operations. The use of one aircraft, two aircraft, and a combination of ERS SAR data (covering 8.4 million km^2) and one aircraft (9.6 million km^2) were considered for oil-spill monitoring of the 18 million km^2 area covered annually in the North Sea. An aircraft equipped with a SLAR can monitor roughly 15 000 km^2 per hour under nominal conditions. The local weather conditions permit an average of four days of coverage per week, with approximately four flight hours per day, resulting in a daily coverage of about 60 000 km^2. The costs, the time horizon (set to twenty years), as well as the social impact have been taken into account in the evaluation. Social costs and benefits were calculated for all involved groups of service providers, end users, potential polluters (e.g. oil companies, shipping, coastal industry).

The results of conservative nett-benefit calculations show that the benefit-to-cost ratio varies from 2 to 15 using two aircraft, and from 3 to 22 for the combined satellite plus one aircraft scenario, with the most probable figures lying in the upper ranges of these intervals. The ranking of the two alternatives was confirmed by the cost-effectiveness analysis, which gave estimated costs per square kilometre of 0.09 and 0.06 ECU for two aircraft and the aircraft/satellite combination, respectively.



Future Outlook

New technologies for fast SAR processing are being developed which will reduce the delivery time for satellite imagery still further. Constant improvement of slick-detection algorithms implemented on dedicated work stations will increase the level of confidence in spill detection and hence reduce the likelihood of false alarms.

The combined use of data from the ERS satellites and Radarsat already provides daily coverage of a large percentage of the coastal oceans. ESA's forthcoming Envisat mission, carrying among other instruments an advanced SAR, will provide images covering areas of up to 160 000 km^2, both contributing to an even more cost-effective oil pollution monitoring service and securing data continuity for the years to come.

Acknowledgements

The support provided by the Tromsø Satellite Station, the North Sea Directorate of Rijkswaterstaat (NL), the Netherlands Remote-Sensing Board (BCRS), and the Munich Re insurance company (D) is gratefully acknowledged.

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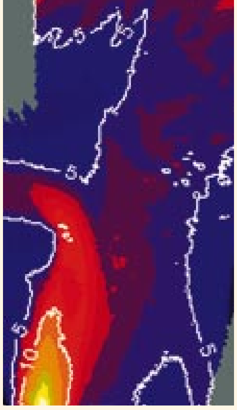
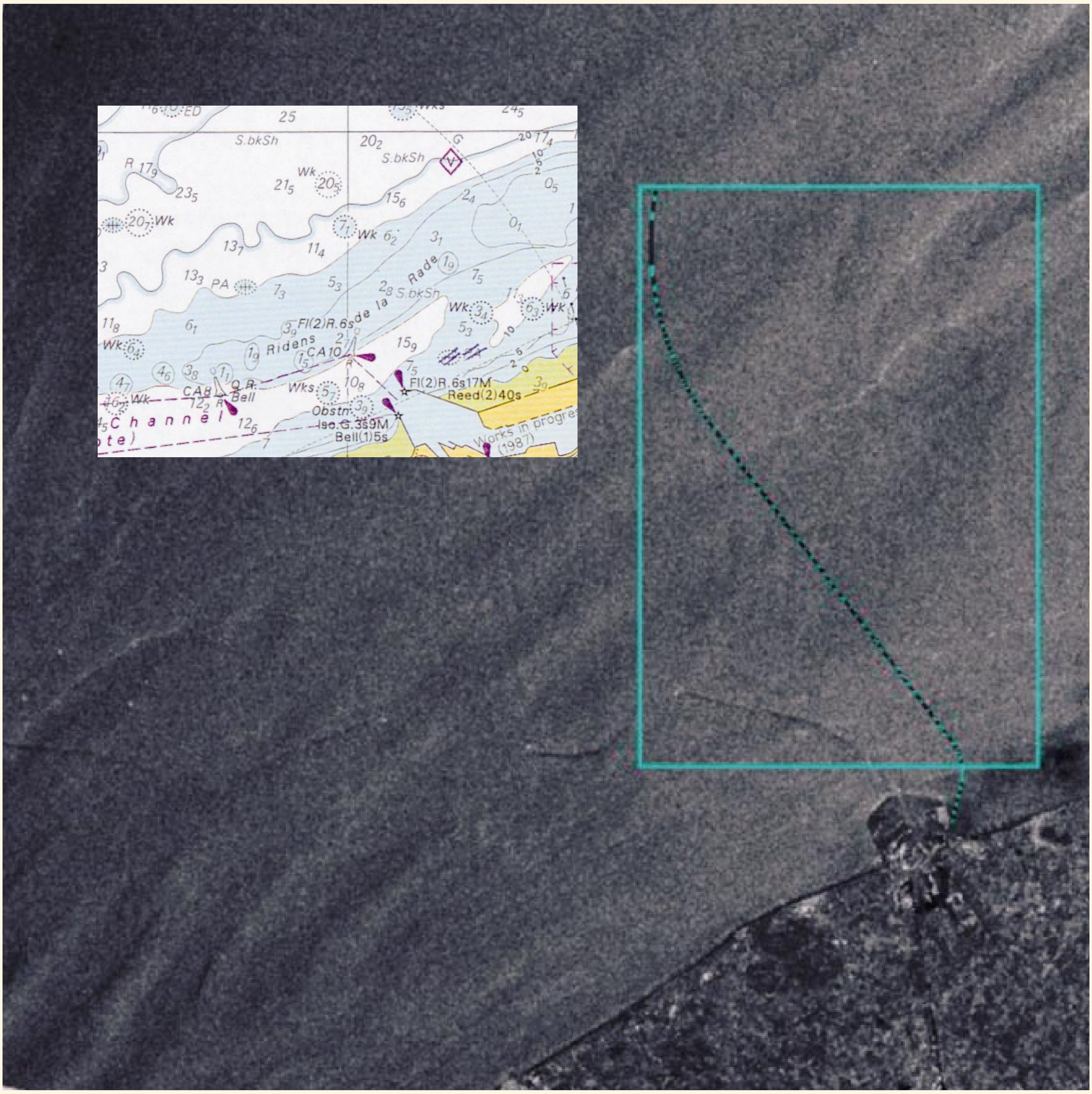


BATHYMETRIC MAPPING



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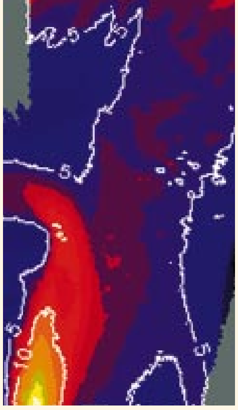


BATHYMETRIC MAPPING

The Need for Better Information

Bathymetric surveys are required for a variety of purposes at widely ranging locations. End users include construction, oil, pipeline and cable companies as well as local and national government users (harbour and shipping control authorities, resource-mapping agencies, coastal-protection agencies, etc.). The market is therefore considerable. The continuing need for accurate bathymetric information, for example by harbour-control authorities which require shipping lanes to be checked every few months, means that the demand for such services can be expected to remain high for the foreseeable future.

Typical requirements for coastal bathymetry data are:

- *Depth accuracy: better than 30 cm r.m.s. error, although for particular users this can be relaxed (e.g. 1-2 m for Admiralty charts)*
- *Position accuracy: better than 40 m*
- *Updating: dependent on particular end-user - some surveys must be repeated every four to six months, whilst others need only be repeated every few years .*

This level of performance is already attainable, but the cost to the end-user can be extremely high when using current survey practices.

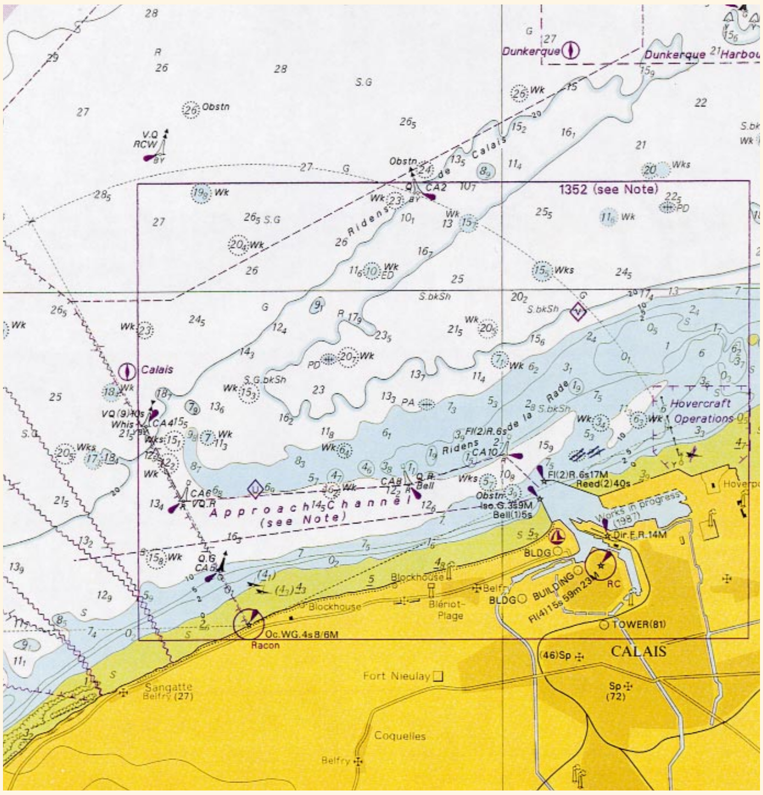
The Limitations of Traditional Techniques

Conventional sonar surveys involve dedicated vessels deploying fragile instrumentation such as sonar arrays and submersible survey vehicles, controlled by and attached to the survey ship. Operating such equipment requires sufficiently calm sea states and operations must be suspended if the weather deteriorates, leading to delays and adding to the already high overall cost. Operating close to shore, which a high proportion of surveys require, can also be dangerous, due to the lack of manoeuvring options available and the greater risk of damaging expensive survey equipment on underwater obstacles.

A survey ship engaged in a traditional bathymetric survey

To ensure that data quality is sufficient to meet customer needs, accurate positioning of both the mother ship and the various measuring instruments is necessary, which requires the use of GPS technology. In addition, accurate underwater telemetry is needed to fix relative positions between Remotely Operated Vehicles (ROVs) and the mother ship in order to accurately locate measurement points.

One possibility for reducing the costs of traditional bathymetric mapping methods is to increase the spacing between survey tracks. However, this requires interpolation between the remaining tracks, thereby reducing the accuracy of the final product.



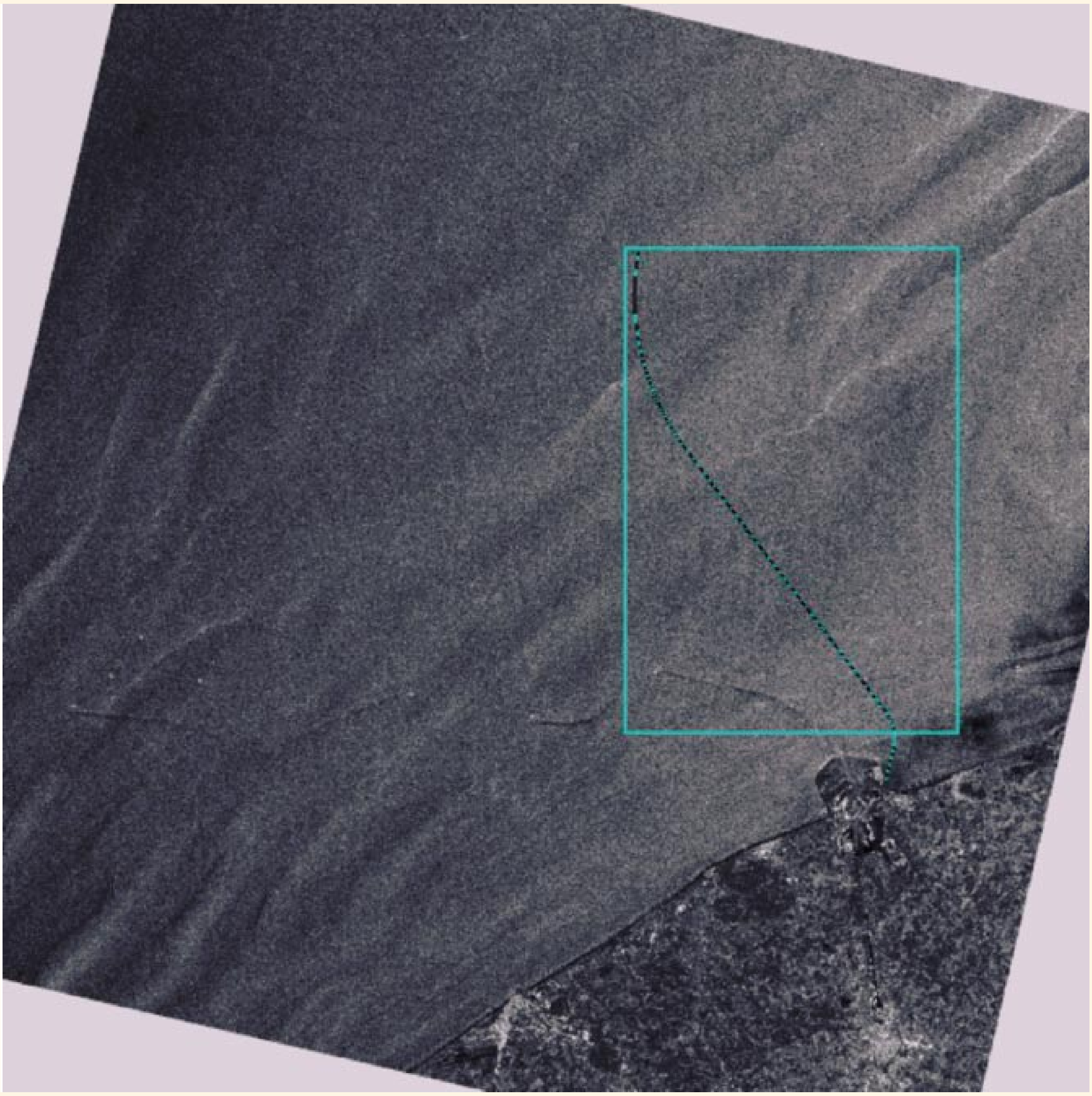
Accurate maps of sea-bottom topography like this one are used for many offshore applications, including navigation, fishing and construction. They are currently generated by conducting expensive shipborne echo-sounding campaigns

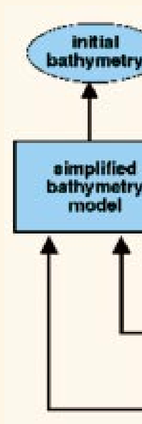
The Benefits of Space-Based Monitoring

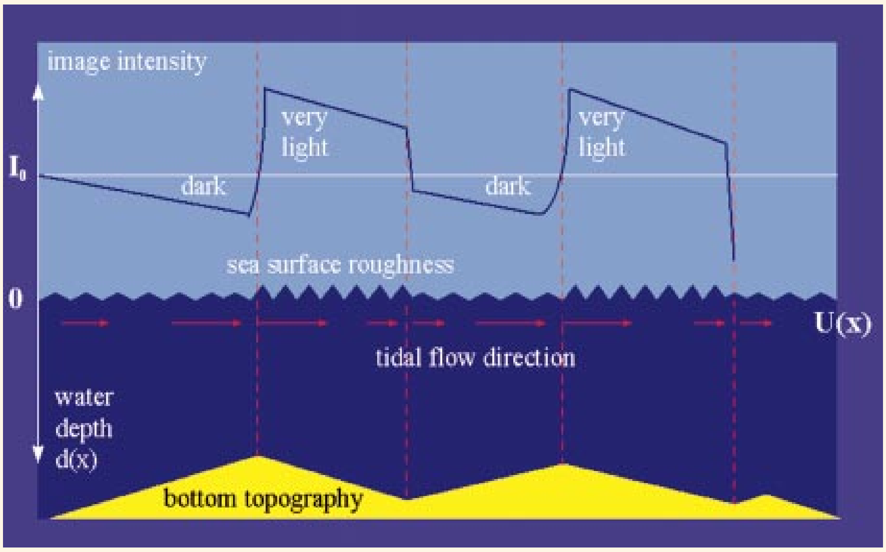
By using Synthetic Aperture Radar (SAR) images like those provided by ERS, a significant improvement in the quality of the interpolation of depth values between survey tracks can be achieved. The incorporation of SAR imagery means that surveys can be completed more quickly, leading to significant cost savings. SAR data can also be used in regions such as estuaries, where survey ships could experience difficulties. The surveys can therefore be completed with a reduced level of risk to equipment and crew.

ERS's frequent revisiting cycle allows the regular updating of maps for areas where the bathymetry is prone to rapid change, such as shipping channels subject to strong sediment deposition.

An ERS SAR image illustrating the bathymetric features of an area off the Belgian coast. The proposed route of an oil pipeline is superimposed on the image



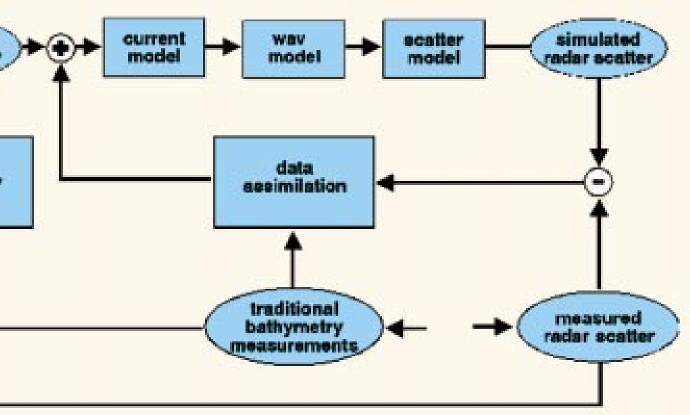




Bathymetric Imaging with ERS SAR

Variations in water depth perturb tide-generated currents, and these perturbations can propagate upwards to modulate the pattern of sea-surface roughness. If the wind speed is between 3 and 9 m/s and the magnitude of the tidal current is sufficiently large (greater than 0.5 m/s), then these surface modulations can affect the backscatter observed in SAR images of the region, allowing the observation of certain bathymetric features. The characteristic backscatter intensity pattern associated with such surface perturbations is illustrated in the accompanying figure (above) .

To retrieve water-depth values, the SAR information must be further analysed, which requires accurate models of the local hydrodynamics and wave evolution as well as information regarding the prevailing environmental conditions, such as wind speed.



Examples of Space-Based Applications

The Bathymetry Assessment System (BAS): An overview

The Bathymetry Assessment System, provided by the Dutch company ARGOSS, consists of a suite of numerical models which calculate a synthetic SAR image from a first-guess bathymetry. The difference between the synthetic image and the actual image is minimised in such a way as to generate an update of the bathymetry. This process is repeated until the depth values converge.*

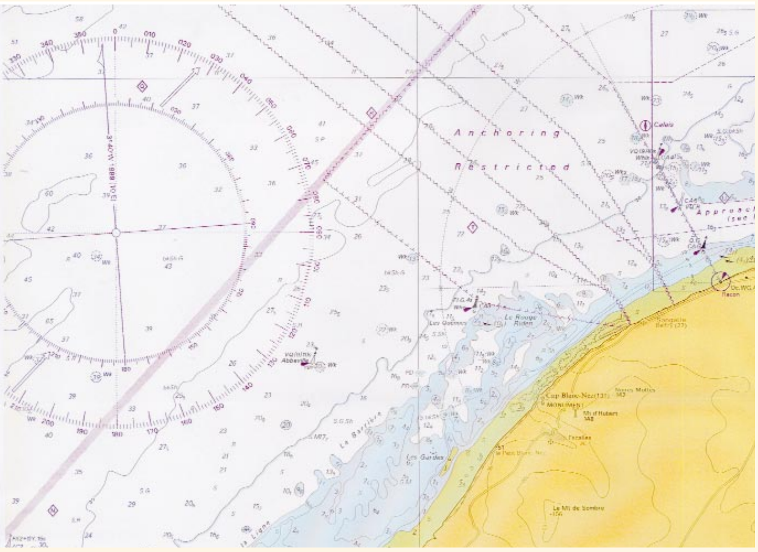
The principal models, as indicated in the accompanying diagram (bottom left), are:

- *two-dimensional shallow-water hydrodynamic equations to determine current perturbations generated by the bathymetry*
- *a current-profile model to determine how these perturbations propagate to the sea surface*
- *a wind-wave model to determine how the perturbed currents modify the sea-surface roughness*
- *a backscatter model to translate the surface modulations to a SAR image.*

The system requires the following input data:

- *sonar sounding data along calibration tracks to calibrate the system*
- *tidal data related to the acquisition time of the SAR image*
- *wind speed and direction related to the acquisition time of the SAR image*
- *SAR Precision Imagery (PRI) of the area.*

**Advisory and Research Group on Observations Systems and Services*



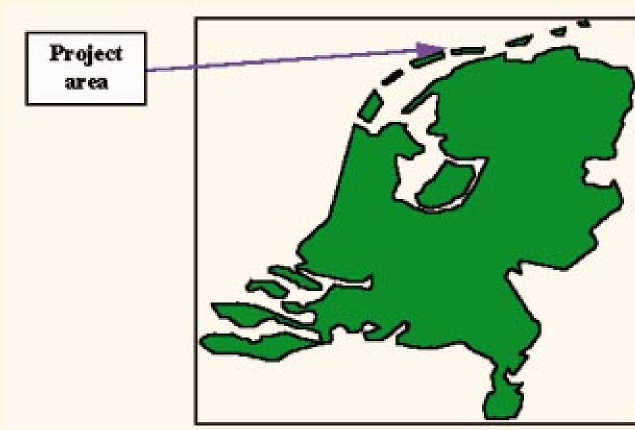
The BAS package is very flexible in terms of hardware requirements and can be run either on a PC under Windows NT or on a standard UNIX platform. An image-processing package is required to geolocate and transform the SAR data to the local projection coordinates.

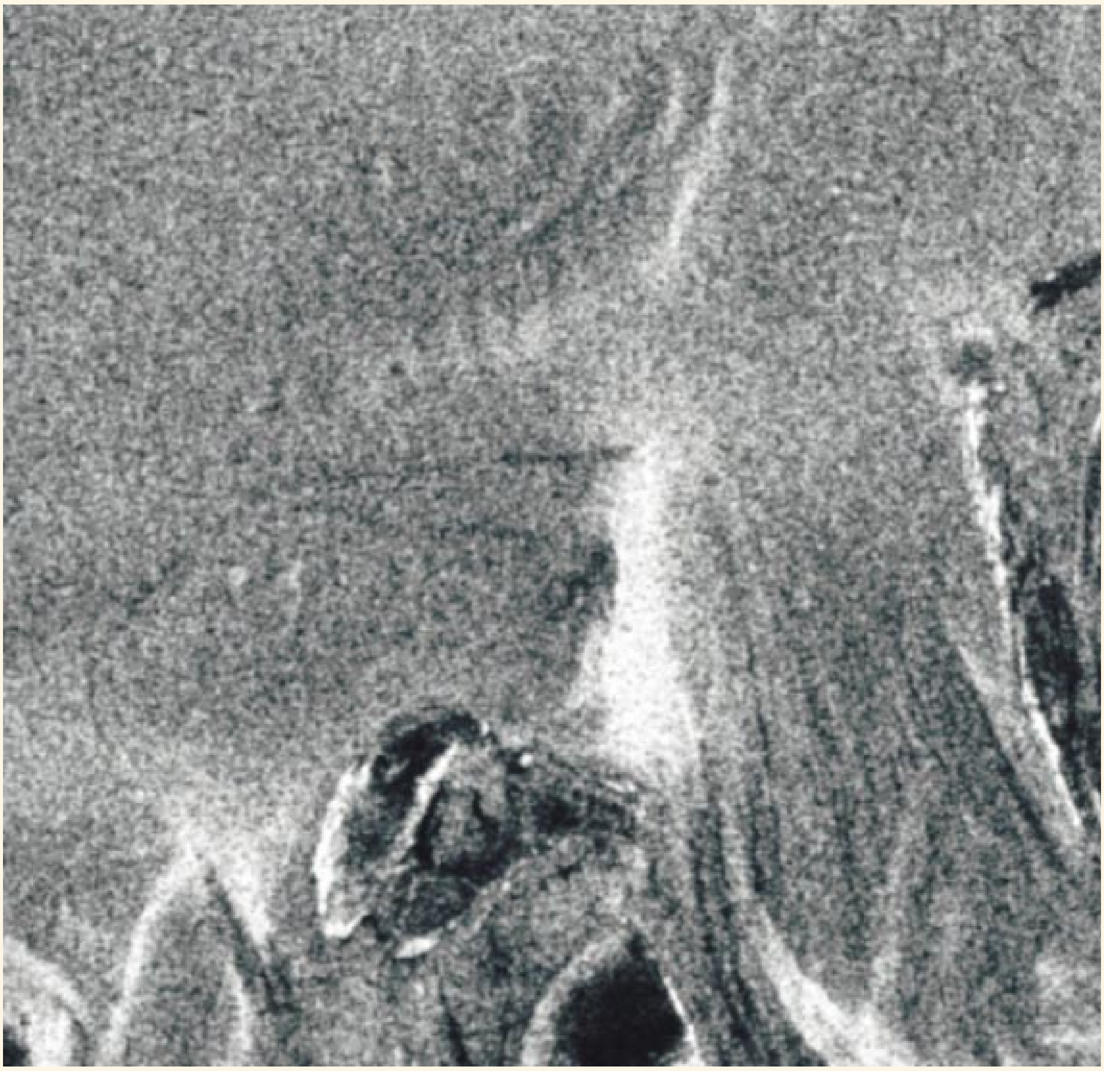
Using standard tidal and meteorological data in the numerical models, the Bathymetry Assessment System produces a chart with an r.m.s. depth accuracy of between 20 and 30 cm. This is comparable with traditional methods of depth echo-sounding, and substantially more accurate than data available from standard Admiralty charts. In addition to measurement accuracy, end users are interested in location accuracy of measurements. Using a georeferencing technique implemented by the TNO-FEL Institute in The Netherlands, each pixel within the SAR image can be located with an accuracy of better than 30 m. The BAS-provided product is therefore comparable in accuracy with conventional survey data, but is available at a fraction of the cost.

Mapping the Plaatgat Channel

The Plaatgat channel lies between the Dutch islands of Ameland and Schiermonnikoog in the Wadden Sea area off the Northern Netherlands coast. It constitutes the main shipping route between the North Sea and the harbour of Lauwersoog. Owing to natural sedimentation and erosion processes, this channel moves eastwards and silts regularly. At the same time, the neighbouring channel of Westgat gets deeper. In view of the morphological dynamics of the area, Rijkswaterstaat (responsible for managing water resources in the Netherlands) has decided to survey the bottom topography of the area every three months.

A demonstration project has been undertaken using the Bathymetry Assessment System, based on the assimilation of ERS SAR imagery. The SAR image of the Plaatgat channel shown

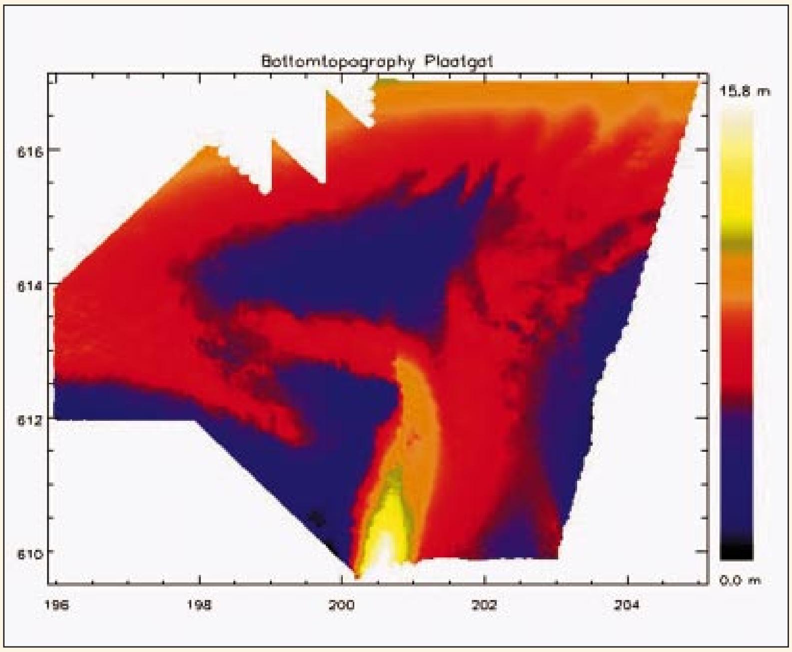


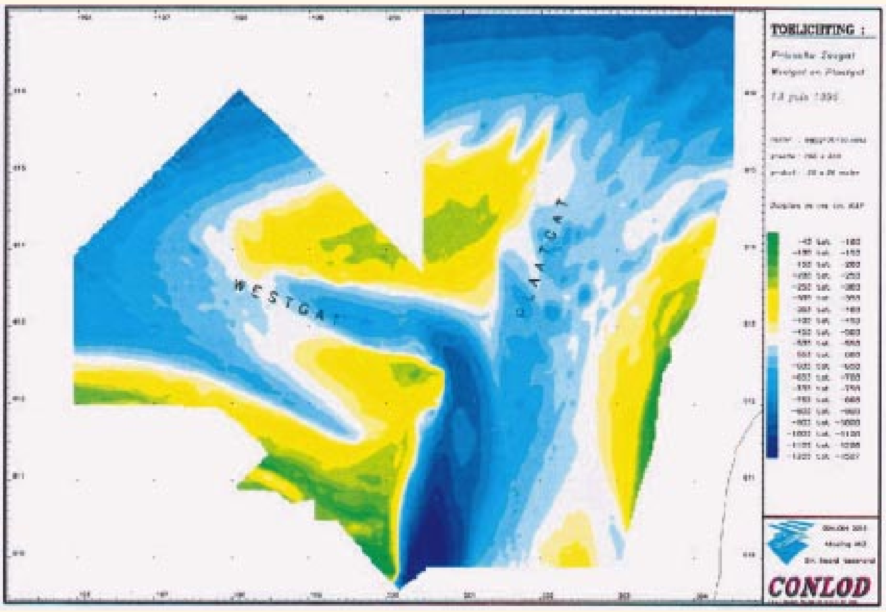


here (above) was acquired on 3 August 1995. As a first step, the image was geo-registered. Land features were identified and masked out and an “average” backscatter intensity for the entire image was then calculated and subtracted from each pixel, leaving a matrix of intensity variations.

Tidal phase data were used to calculate the displacement of the sea surface from the reference value, and hence the surface current vectors within areas of interest. Finally, echo-soundings made along a number of tracks were assimilated into the system. Although survey tracks were spaced at a nominal offset of 200 m for the purposes of the demonstration, the ERS SAR data were assimilated using a spacing of 600 m in order to illustrate the utility of the BAS. The remainder of the data were used to evaluate the system’s performance.

The area of interest was split into two regions, each corresponding to a reduced case of the two-dimensional hydrodynamic flow equations, allowing a faster inferral of the water depth. A map of data points was produced for the area (right), with a spacing corresponding to the pixel spacing within the SAR image (i.e. 12.5 m). The accuracy of the depth estimates calculated by the BAS package was compared with the depth estimates obtained from the conventional survey with a track spacing of the order of 200 m (below right). The error within the area surveyed was found to lie within the 30 cm upper limit required by the end user.





Cost/Benefit Considerations

The following comparison is based on 1995-estimated survey prices, comparing the costs of traditional survey methods with the BAS approach for an area of 300 km^2 and a survey track spacing of 200 m:

Traditional Methodology

(excl. breakdown and weather-delay costs)

Total survey line	*1500 km*
Average survey speed	*6 knots*
Total survey time	*~135 days*
Cost per day	*~US$ 5000*
Approximate total cos	*US$ 675 000*

BAS Methodology

Cost of SAR imagery	*~US$ 60 000*
(acquisition, processing, reporting, etc.)	
Field surveys	*~US$67 500*
Total survey time	*13.5 days of operation*
Approximate total cost	*US$ 127 500*

Future Outlook

The Bathymetry Assessment System has now been implemented within the Rijkswaterstaat Survey Department as a first step towards the routine monitoring of Dutch coastal waters. Further testing of the system is planned and current work centres on the development of an operational two-dimensional assimilation scheme to allow complex bathymetric geometries to be measured more precisely.

In the longer term, the incorporation of BAS output into standard Geographic Information Systems is envisaged. In this way, it will become a potential source of information for all coastal engineers, harbour authorities, etc. who are required to integrate information from different sources to ensure effective decision making. In addition, the rise in demand for digital charts is creating a further growth market for BAS applications.

A further stimulus to the operational use of SAR information for bathymetric applications will be provided by the launch at the end of 1999 of ESA's Envisat mission.

Acknowledgements

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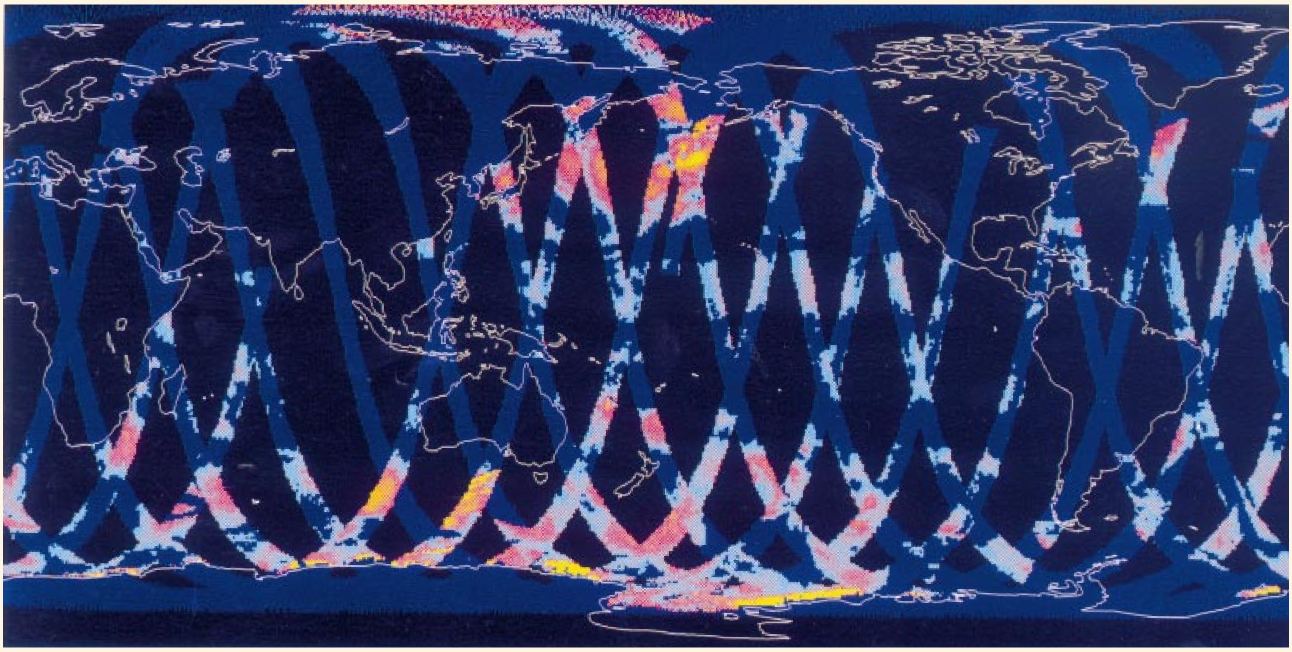
WIND & WAVE FORECASTING



WIND & WAVE FORECASTING

A fishing trawler in high seas. Precise wind and wave information are essential for these kinds of operations

The Need for Better Information

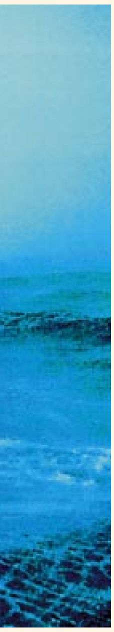
In many areas of marine activity, including the domains of ship navigation and routing, deep-sea fishing, oil and gas exploration, etc., the availability of timely wind and wave forecasting can be crucial to safe and economic operation.

With global reserves of oil and gas forever diminishing and demand increasing, exploration companies are looking to frontier areas offshore to provide new and viable sources of hydrocarbons. The wind and wave forecasting is often sketchy to say the least in such areas due to the lack of reliable meteorological data. Unanticipated downtime during seismic surveys to pinpoint sites for exploratory drilling can result in considerable financial loss.

When a rig is deployed at a newly discovered reserve, it is essential to be aware of any imminent extreme conditions such as unusually large swell waves, etc., which can result in dangerous resonant motions. Many of the associated operations such as crane lifts, tanker loading and drilling, involve the coupling of structures or unevenly distributed weightings. Excessive wave-induced motion can easily cause collisions and capsizes. During pipeline-laying operations, for example, which can only be carried out when there will be waves no higher than 3 m for at least 6 hours, the costly crane lifts needed are totally at the mercy of the elements.

All types of ocean vessels are vulnerable to wave-induced damage. There is significant growth in both the size and number of ships navigating key routes across the North Atlantic, around the Pacific Rim and in the Persian Gulf. Currently, an average of three ships with displacements of over 500 tons are sunk every week. The dry-dock refit costs for repairing wave-induced slamming fatigue in those that survive such incidents can be enormous.

As coastal fish stocks become further depleted due to pollution and over-fishing, the fishing industry too is having to move into more inaccessible and hostile waters.



Crane heavy-lifting activities around an offshore oil rig

Limitations of Traditional Techniques

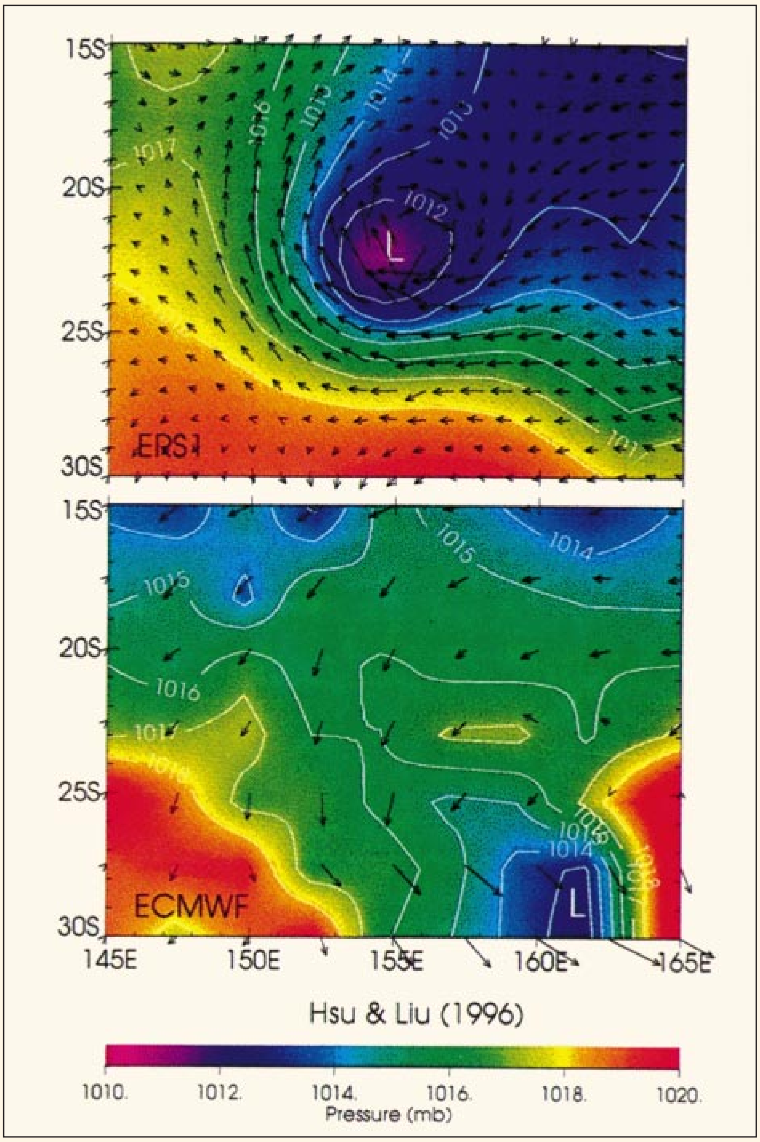
Forecasts of marine wind conditions are traditionally provided by national meteorological agencies. Atmospheric models are usually driven by the few in-situ measurements available, which are gathered either by ships navigating along major routes or by dedicated networks of buoys. Consequently, these atmospheric models may well not accurately represent atmospheric cyclonic features characteristic of storms that have not been measured directly. In order to generate accurate wave forecasts, precise wind information is needed. As a complement to the wave models used for the sea-state forecasting, reliable information on wave height, period and direction is required if the wave fields are to be accurately represented.

Expensive buoy network systems are commonly used in areas with dense ship traffic, such as Europe's northwest shelf, to measure both winds and wave heights with the spatial and temporal sampling needed for modelling. Besides their high cost (over 1.5 million ECU per annum for a ten-buoy network), such networks suffer from incompatibilities (i.e. the measurements are not standardised) that prevent neighbouring countries from sharing the data, seriously limiting the system's usefulness. Even with these dedicated buoy networks, large parts of the oceans remain unobserved, including key frontier areas where marine activities are experiencing rapid development.

Today's wind and wave information requirements are also rather diverse, depending on the specific application. Sometimes a "point-to-point" forecast along a particular ship route may be needed for a specific time period; in other cases regular forecasts are required with a precise frequency of updating.

The Benefits of Space-Based Monitoring

Clear benefits in the domains of marine wind and sea-state forecasting are obtainable through the use of the information collected from modern and sophisticated space instrumentation such as that carried by the European Remote Sensing Satellites (ERS). Homogeneous, global and continuous coverage as well as an improved resolution are some of the advantages over conventional observations from ships and buoys that active microwave sensors operating from space (i.e. ERS's Altimeter, Scatterometer and Synthetic Aperture Radar (SAR)) can provide.



Surface wind vectors (dark arrows) and surface pressures around tropical cyclone Oliver, derived from ERS-1 Scatterometer data and from ECMWF data at 12 UTC on 11 February 1993. The cyclone was located in the Southern Pacific, where in-situ observations are sparse. The improvement with ERS data in describing such features is self-evident

The Contribution of ERS

Owing to the high revisit frequency of ERS, the global wind fields derived from its Scatterometer are likely to allow the detection of at least three or four of the ten or so major cyclonic depressions affecting the Earth's surface at any given time, thereby improving both the atmospheric and resultant wave-field forecasts.

Wave-height observations provided by ERS's Altimeter, and measurements of the period of swells generated by even distant storms thousands of kilometres away, can be used to substantially improve local wave forecasting. The high quality and reliability of ERS's data products, which have been thoroughly validated, are important factors when accurate metocean and sea-state forecasts that provide a true representation of anticipated wind/wave fields have to be generated.

Examples of Space-Based Applications

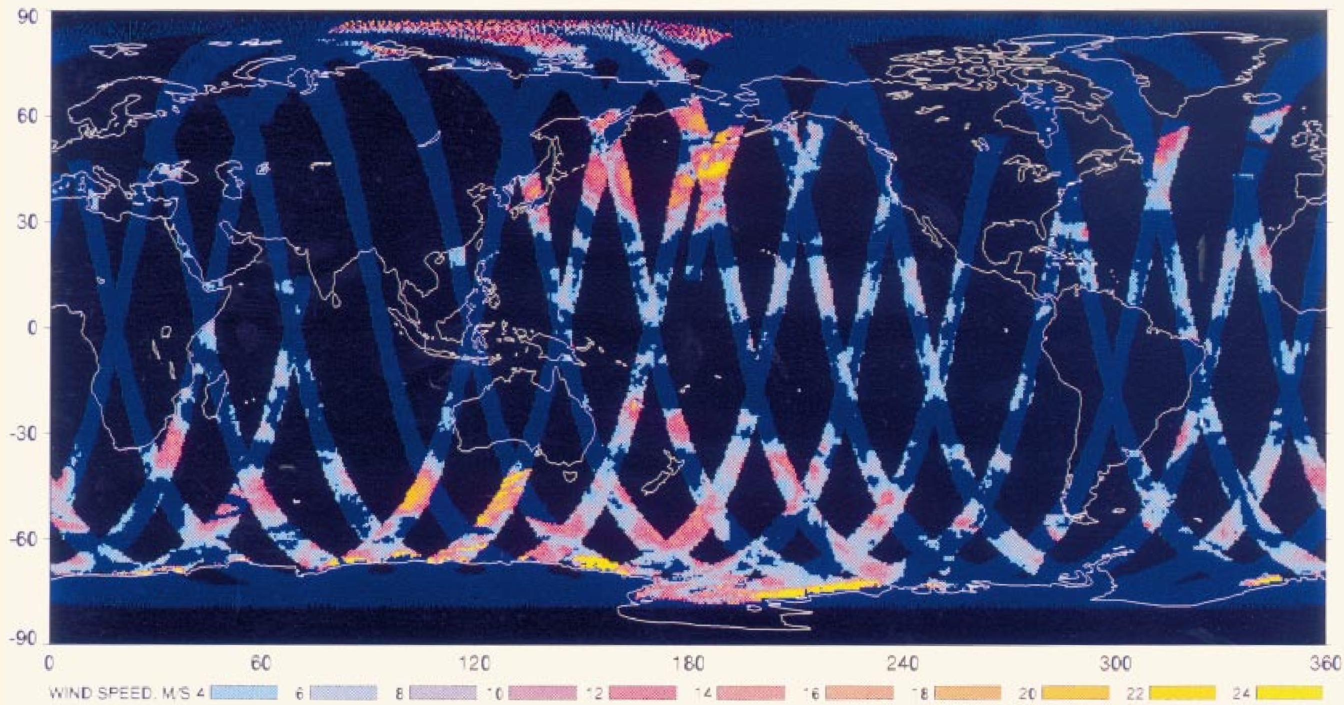
Improving meteorological forecasts

In various studies by the UK Meteorological Office (UKMO) and the European Centre for Medium-Range Weather Forecasts (ECMWF), assimilation of Scatterometer data was observed to produce a marked improvement in meteorological forecasts. Weather forecasting reliability measures showed an improvement of 6-10% in surface pressure fields and 2-4% in temperature and wind-fields in the four-day forecast compared with the global models derived without the Scatterometer data.

Producing wave forecasts

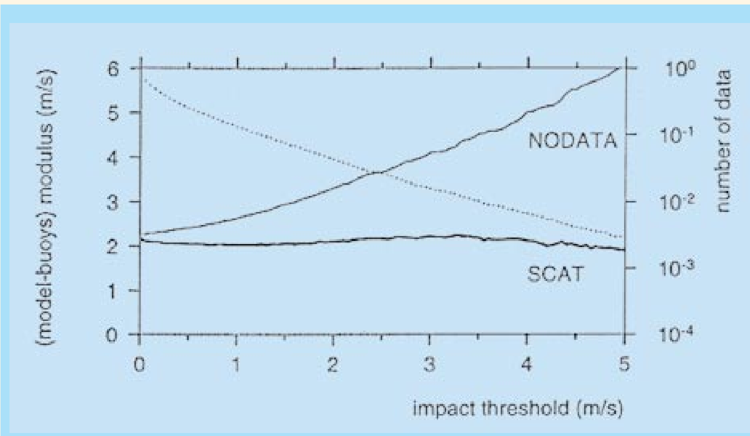
Every wave forecast is produced using an initial state obtained by assimilating (blending) wind and wave data into a numerical model. The data are usually gathered into six-hour windows centred around the assimilation times. At each time increment, sea spectra are calculated, using an action balance equation where the evolution of the energy spectrum of the waves is driven by three contributory effects: energy input from wind forcing (produced by an atmospheric model), nonlinear wave-wave interaction which transfers energy between long and shorter wavelength waves, and energy dissipation from breaking waves. The wave-model output is then corrected locally with measurements of wave height using an optimal interpolation scheme.

Wind measurements made by ships and satellites. Above: Ship in-situ wind measurements for the three-day period 31 October - 3 November 1990, each dot representing one wind-speed/direction report. Below: One day of ERS-1 Wind Scatterometer measurements in March 1992



Impact of the inclusion of Scatterometer wind-field data on wave-forecasting accuracy. The output from a wave model when using Scatterometer wind fields and wind vectors derived from the Meteo-France operational weather model was compared with wind vectors from drifting buoys and Altimeter wave heights. The error curves obtained indicate a clear improvement due to the inclusion of the Scatterometer input

The availability of global high-quality wind- and wave-field data in near-real-time from ERS means that a suitable scheme is needed for assimilating this very large volume of data within the life cycle of the operational forecast. In contrast to conventional observing systems which provide wind and wave data at fixed times and locations, satellite data are generated continuously at variable locations, requiring a four-dimensional (both space- and time-dependent) assimilation technique and the assignment of weightings to the various types of data. ERS Scatterometer data are already being used to correct the wind- field inputs for the atmospheric models of several meteorological offices around the World, and the accuracy of wave forecasts has been greatly increased.



Correcting wave fields with ERS wave heights

The slope of the increase in the SAR backscatter signal from 10% to 90% of full energy correlates with the roughness of the sea as measured by the satellite. It can therefore be used as a tool for significant-wave-height measurement.

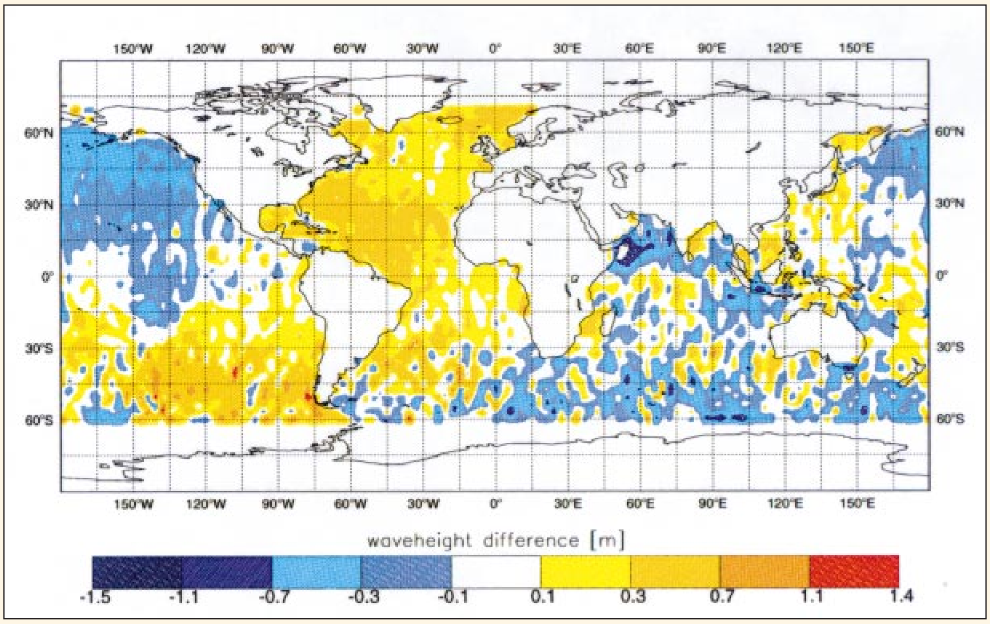
Altimeter and Scatterometer data are assimilated into the ECMWF's wave model (WAM) in order to produce its wind and wave forecasts.

Satellite data must be carefully cross-calibrated against in-situ wave-buoy and weather-station measurements

Operational use of ERS data

Since 1992, a number of customers, predominantly shipping operators and offshore oil-production companies, have availed themselves of information derived from ERS in the form of products tailored to their needs and regularly provided by the UK Meteorological Office (UKMO).

Scatterometer, Altimeter and SAR Wave-Mode data are incorporated into the general forecasting products such as the five-day ocean weather forecast. These data are assimilated into numerical models which provide initial analysis fields of wind and wave data, upon which the forecasts are subsequently based.



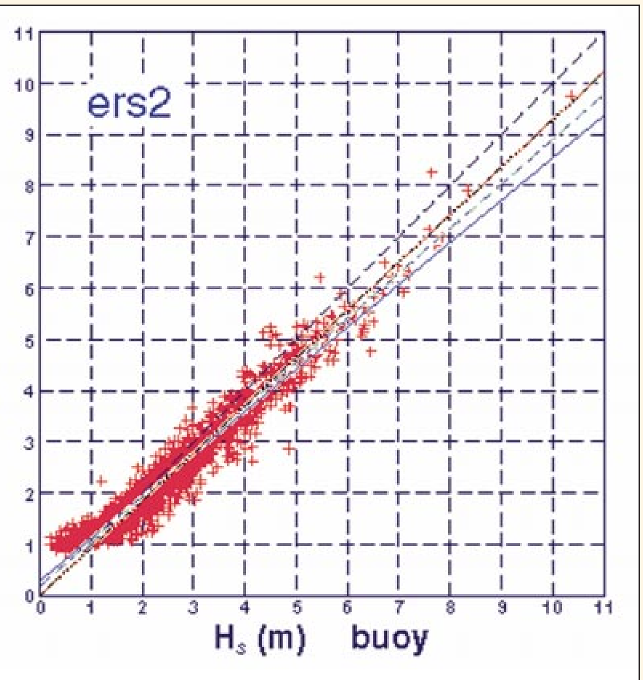
Differences between wave-height outputs from the WAve Model (WAM) derived using simulated wind fields (no Scatterometer data used), and the measured significant wave height from the ERS-1 Altimeter for July 1993. This chart illustrates the magnitude of the corrections needed. The new wave field produced with Altimeter data included was validated with wave-buoy data; a reduction in standard deviation of 3% in the Western Atlantic, increasing to 15% in the Eastern Pacific where there are fewer in-situ observations, is apparent

In addition to its general marine forecast products, the UKMO provides specific support for ship routing, with around 1000 such contracts serviced annually and with 30-40 customers at any one time. The modelling predictions are analysed by experienced master mariners and the optimal routes recommended to the ships' masters.

For the oil industry, the model outputs are extrapolated to the shallow waters around the UK to provide operational support in the planning and execution of such tasks as drilling and lifting operations.

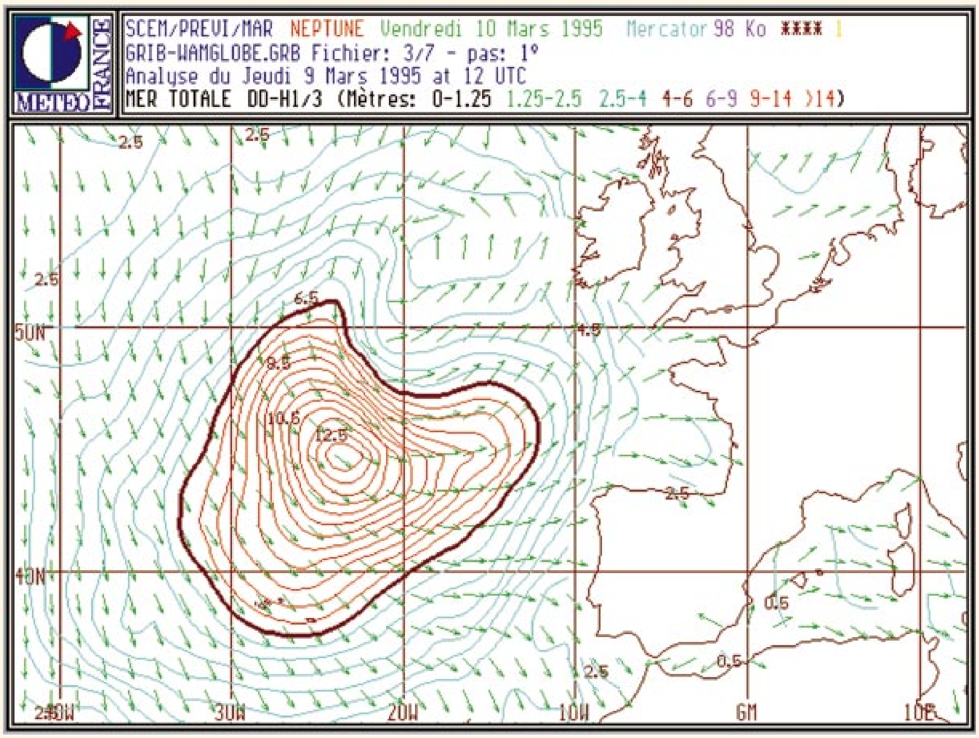
A third customer area is the coastal protection and engineering industry, where users are supplied with data extrapolated from the nearest grid point to the location of interest via a transform incorporating the local coastal bathymetry. Companies operating in this domain, such as Delft Hydraulics and HR Wallingford, buy such products from the UKMO in order to provide sea-defence design services to local authorities.

The "Neptune" service operated by the French national weather service Meteo-France is based on its own numerical wave forecasts and those from the ECMWF, both of which incorporate ERS Altimeter and Scatterometer data. The Meteo-France forecast is generated using its own model of the atmosphere, ARPEGE, which ingests data from ships and buoys and infrared satellite data. ERS Scatterometer data are used to correct the wind fields.



Calibration of ERS-2 wave heights with in-situ measurements. A comparison with buoy data for the period June 1995 to August 1996 shows that ERS-2 underpredicts wave heights by about 8%, which is easily corrected for before assimilation of these data

Northeast Atlantic wave swell (left) and pressure and wind (right) forecasts provided as part of the “Neptune” service



The data are transmitted via the Inmarsat-C satellite to an onboard desktop computer equipped with the appropriate interpretation software. The information can be viewed either in the form of a chart, or in a user-defined format if the extraction of particular information, such as waves exceeding a particular height, is required.

Depending on the customer’s particular requirements, the “Neptune” service provides pressure, wind speed and direction, swell height, direction and period, and sea-surface temperature analyses. Forecasts are provided with a spatial resolution of 0.5 deg longitude for a five-day period. A chart of fronts and isobars containing both an analysis of the current situation and a forecast for the following three-day period is provided.

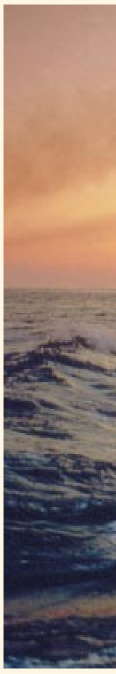
The “Neptune” service also allows mariners to receive forecasts for a specific sea area, for example for delicate offshore operations (test drilling, pipeline deployment) or for fishing purposes. It can also provide ship operators or yacht racers with “point-to-point” forecasts in near-real-time during the course of a voyage.

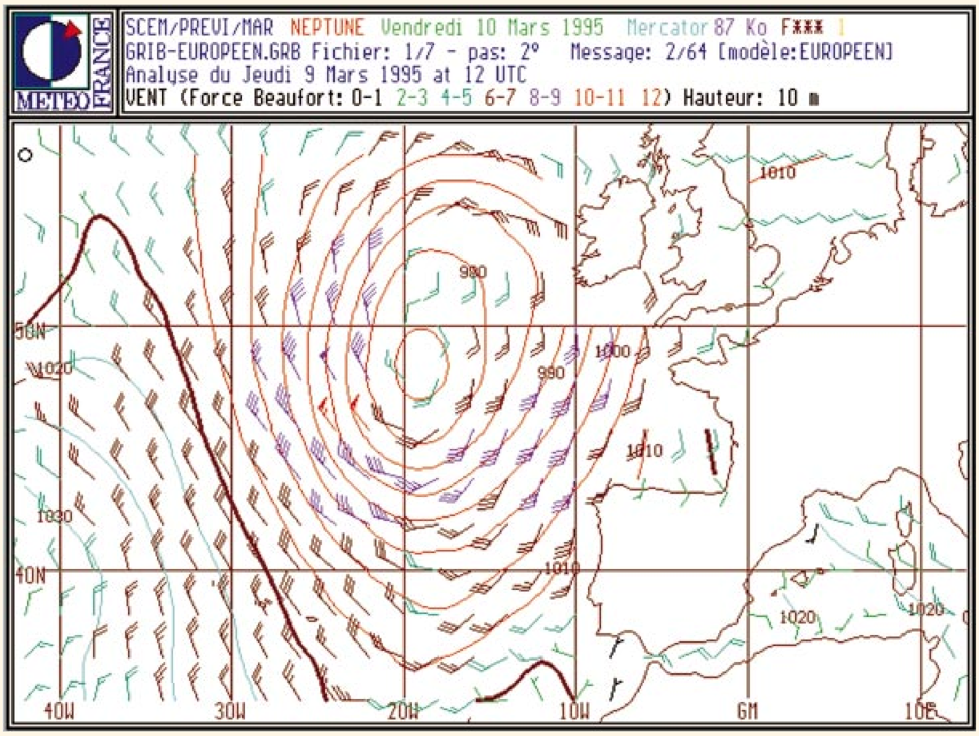
Offshore-operations support

Offshore heavy-lifting operations can only be carried out if wave heights remain reasonably low for the duration of the operation. In addition, the period of the swell must be sufficiently different from the natural periods of oscillation of the vessels involved.

Correct decisions about the suspension of work, for example if the risks to man and equipment are becoming too high, can only be taken if accurate short- and medium-term wave forecasts are available, particularly for the directional wave spectra at the site of the operation. This is only feasible if both the temporal resolution and quality of the forecast are sufficient.

As a demonstration of the operational applicability of space-gathered information, sea-state forecasts based on satellite data were provided to the Dutch



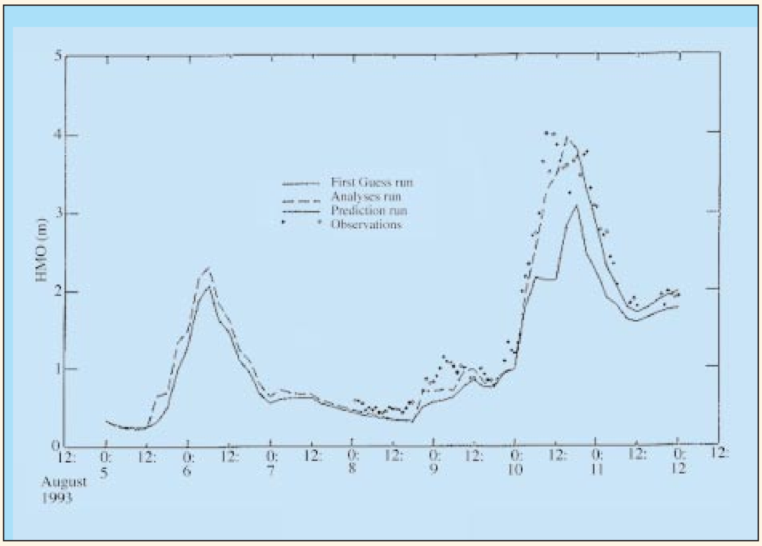


offshore-engineering company Heeremac Engineering Services for a Delft Hydraulics and Netherlands Remote Sensing Board project involving heavy lifting and exploratory drilling operations. ERS-1 Altimeter and Scatterometer products were used to correct "first-guess" wave and wind fields (from the UKMO) for the PHIDIAS numerical sea-state forecasting model covering the North Sea and the Northeast Atlantic. An improved forecast was thereby generated, which was validated using waverider and directional wave-buoy measurements. The assimilation of ERS significant-wave-height data was found to be particularly useful in the presence of strong swells.

The forecast contained information on significant wave height, period, wave length and direction, as well as wind direction and strength. In addition, longer term forecasts on approaching swells were provided. These data were then used to compute parameters such as crane tip motions for lifting operations, to prevent pronounced tension variations within the lifting equipment and dangerous impact forces between the objects being lifted and the other vessels. In one particular case, the improved forecast predicted a peak in crane-tip motions which was missed by the "first-guess" fields which did not include ERS data.

Crane barge hoisting drilling and accommodation facilities into place

The further development of the wave forecasting system is currently being carried out by ARGOSS (Advisory and Research Group on Geo-Observations Systems and Services) and is aimed at providing fully operational systems and services. To reduce the risk of damage to vessels and platforms etc. under tow, an onboard decision support system is also under development that includes both traditional onboard measurements and satellite data



Effect of the assimilation of ERS Altimeter data on wave prediction: the forecast provided matched the reality very well

Cost/Benefit Considerations

The scale and immediacy of the risks facing industries which depend on the sea creates enormous potential for the application of accurate meteorological and sea-state forecasts. However, like all private-sector industry, these customers are extremely cost- and service-sensitive and will only invest in the necessary infrastructure if the data products being provided meet their needs in terms of accuracy, reliability, timeliness and cost.

Where satellite data really comes into its own as a source of information is in frontier regions for offshore operations such as the North Western Approaches or Southeast Asia, or for fishing activities in the Southern Oceans. In areas where there are insufficient in-situ measurements being made, ERS-2 data are an essential element for the production of accurate wind and wave forecasts.

Accurate wave forecasts are crucial for the avoidance of extreme wave heights and certain dangerous wave periods when planning so many critical marine operations. The true benefits from the availability of such services are still hard to quantify, however, as dangerous conditions do not occur during every operation. They are therefore often not fully accounted for in cost-benefit analyses. Nevertheless, the human safety aspect alone provides a substantial justification for the economic investment, and the tangible financial cost-saving benefits of using wave-forecasting services are comparatively easy to assess.

Future Outlook

The efficiency of the assimilation of the satellite-provided data is improving steadily. The European Centre for Medium-Range Weather Forecasts (ECMWF), which produces wave forecasts based on the assimilation of ERS data using the WAM model, has improved the output resolution of its global model from 1.5 to 0.5 deg by means of technical advances within the system. This new resolution extends the wave forecasts from the open ocean to the coastal regions without the limitations of regional models.

Currently, ERS-2 satellite data is the only source of wide-area wave information in near-real-time. ESA's next generation of Earth-observing satellite Envisat, to be launched in 1999, will have the ability to measure wave height, period and direction using advanced versions of the ERS SAR and Radar Altimeter sensors. The Scatterometer measurements presently being made by ERS-2 will be continued by the ASCAT instrument to be flown on the METOP spacecraft due for launch in 2001 for Eumetsat.

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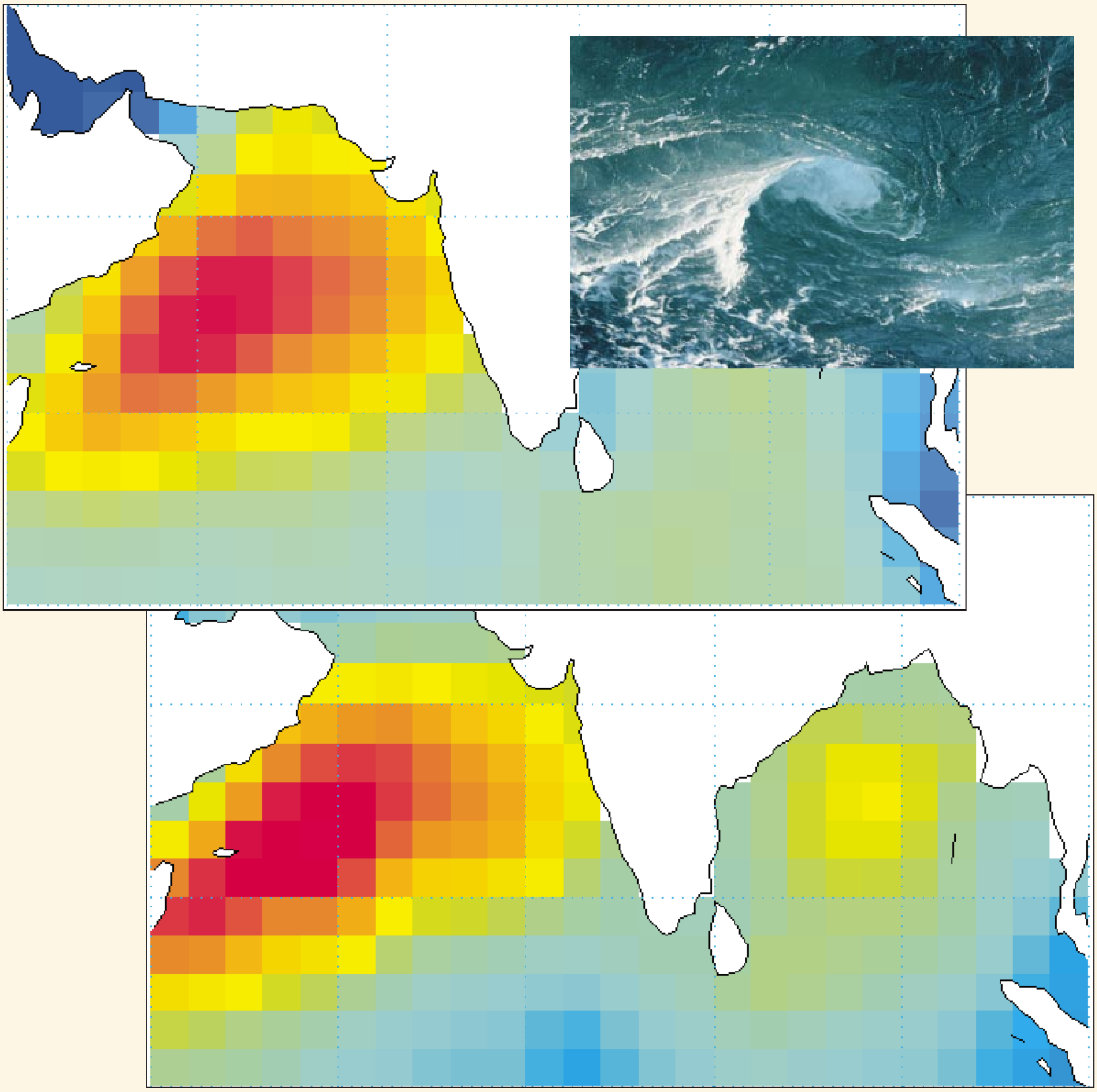
MARINE CLIMATOLOGY



MARINE CLIMATOLOGY

The magnitude of the forces at work on the Brent Charlie rig during a storm. Severe damage can be caused to offshore structures if marine climate information is not adequately considered in their design

The Need for Better Information

A wide range of users take advantage of the information contained in charts such as those on the front page of this folder. They are just one example of the kind of services provided for many locations around the World by specialised companies which produce estimates of wave height and wind-speed climatology from satellite data.

Climatological information is important for marine activities and operators worldwide. Recent research conducted by the Southampton Oceanography Centre (UK), for example, has shown that average wave heights over much of the Northeast Atlantic have increased considerably in the past decades. In areas where marine activities are increasing, such as Southeast Asia and the east coast of South America, the need to improve on today's sparse knowledge of climatological conditions is critical.

In such activities as offshore oil exploration (ship surveys, exploratory drilling) and production (pipeline laying, jacket installation), bulk cargo shipping and trans-ocean towing, the largest forces suffered by the ocean-going vessels involved are the result of wave activity. Knowledge of prevailing environmental conditions is therefore crucial for sound decision-making regarding the type of vessel to be assigned to a specific operation and the manner in which that operation is to be carried out. This is particularly important when there are likely to be extreme weather conditions, for instance during the winter months or during the monsoon season.

Marine warranty companies also rely on climatology information for a particular operating area when they have to certify offshore structures and vessels for operation. Certification involves ensuring that a vessel is capable of operating safely under any conditions likely to be encountered, both nominal and extreme, and in compliance with local/national

regulations. The statistical criteria applied usually include the highest wave heights to be expected over a period of 100 years, over a one-year period, or for the duration of the operation.

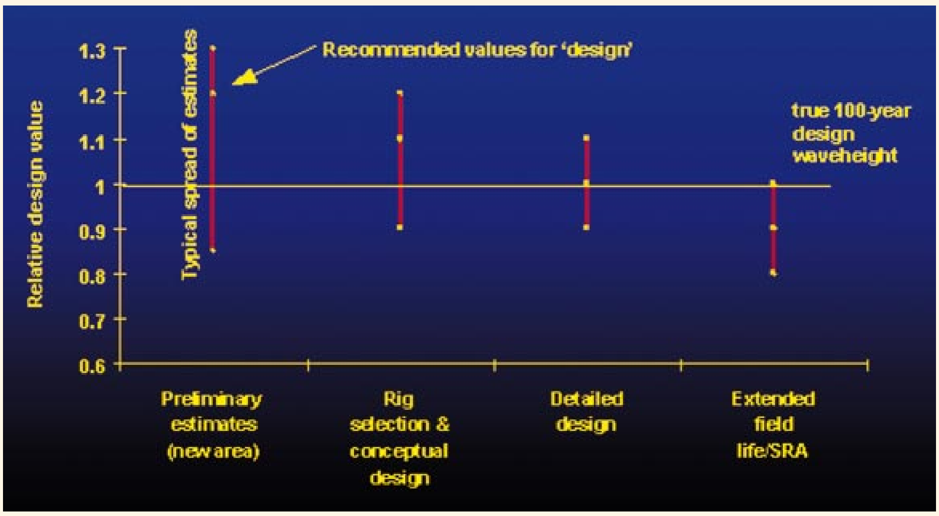
Being able to rely on precise marine climatology information in new frontier regions is vital to the oil and gas industries, in order for them to plan all phases of their operations safely and cost effectively, including:

- *initial exploratory seismic surveys, where a day lost can represent a financial loss of thousands of ECUs*
- *engineering and maintenance work on drilling rigs and production platforms*
- *establishing design criteria for offshore installations, where costly over-engineering can be avoided if precise climatological information is available at an early stage.*

Reliable and accurate climatological information brings direct economic benefits as well as improved safety and efficiency. Pipeline contractors, for example, who have to cease operations in bad conditions, cost in a percentage of down-time when they bid for fixed-price work. Overestimation of anticipated down-time raises the bid price, whilst under-estimation reduces the profit margin.

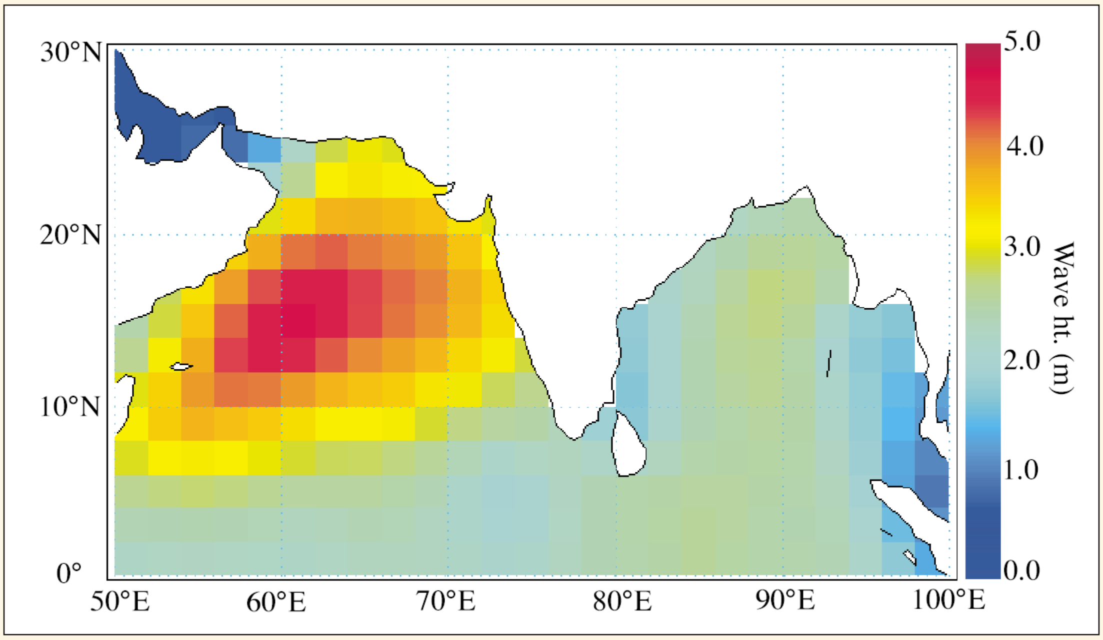
The Limitations of Traditional Techniques

In order to derive information about the climatology of a particular marine area, a statistical analysis is performed on a long time series of data on wave height, period, and direction, as well as wind speed and direction. Using these data, the climate of the area can be derived in terms of the statistical likelihood of encountering winds and waves of a particular size, direction or period on a monthly or seasonal basis. Also derived are the properties of the average wave expected at a particular time of the year, and the maximum wave recorded in a 50 or 100 year period. The longer the time series of observations, the more confidence engineers can place in the predicted climatology.



The spread in design criteria for offshore structures caused by lack of reliable climatological data, which means that large margins must be incorporated

Average significant wave height (left) and wind speed (right) in the north Indian Ocean during July, derived from ERS-1, Geosat and TOPEX data obtained between 1986 and 1996. Careful calibration of each of these altimeters against US NDBC buoys ensures their mutual accuracy



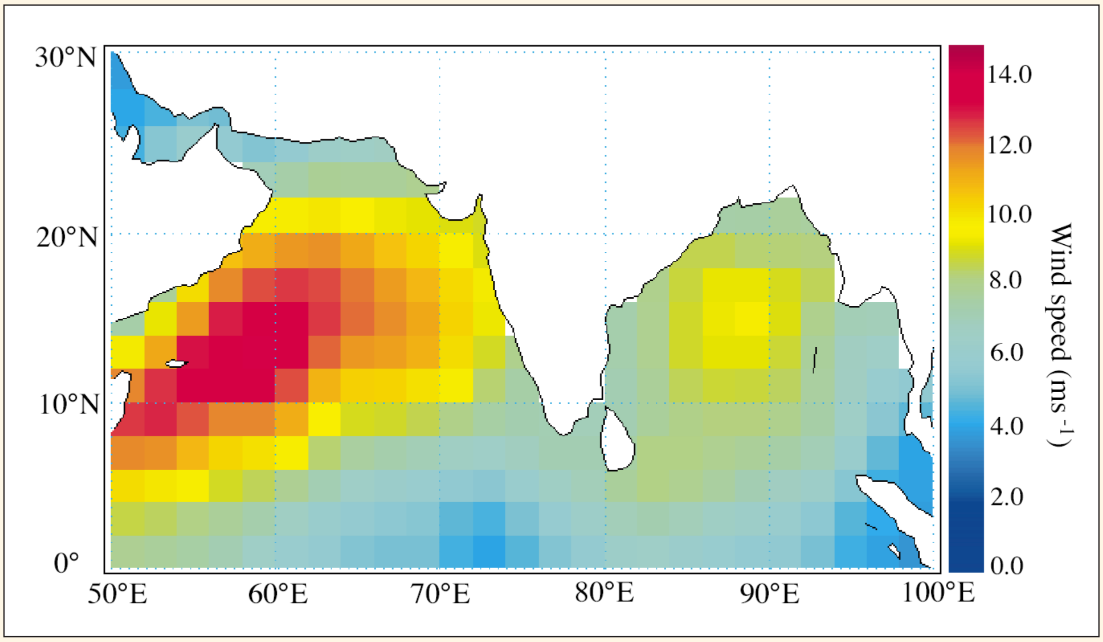
In some cases, it is possible to split the seas and the oceans into "climate-coherent" areas which have a particular prevailing climate in terms of winds and waves, so that measurements at one location can be considered representative for the whole area. How large these areas are depends on their geographical location and their proximity to currents and coastlines. However, in some areas there can be great variations over just a hundred kilometres, putting into question the validity of the climatological information supplied to a customer if the wave measurements were not made close to the location of interest.

As with forecasts of sea state, until recently wave data used in the extraction of climatological information have been largely unavailable outside the major shipping routes, where a ship's master would stand on deck and estimate the size of the waves. Subjective observations gathered in this way make the quality of the data, and thus the quality of the climatological information derived from it, difficult to assess. One means of improvement is the extended deployment of wave-measuring buoys, but their measurements are still highly localised and they are expensive to operate.

Another major drawback of conventional data sets is that the measurements are highly localised in time as well as space, and extrapolations for extended periods or for extreme values can be unrepresentative. Moreover, wave climatology information has traditionally been provided in atlases or maps for a specific area, based on data from in-situ observations. Increasingly, information is required on frontier areas for which these atlases have inadequate accuracy.

The Benefits of Space-Based Monitoring

The principal advantage offered by a satellite system is the greatly improved spatial and temporal coverage that it provides. Space-based observations include every ocean, with frequent revisits (periodicity depending on the orbit configuration of the satellite), allowing global archives to be built up. In addition, the greater accuracy of the data ensures the reliability of the climatological information that is ultimately produced.



The Contribution of ERS SAR

A substantial contribution has been provided since 1991 by the radar instrumentation onboard the European Remote Sensing (ERS) satellite series, specifically the Radar Altimeter, the Wind Scatterometer, and the Synthetic Aperture Radar (SAR). These instruments have been continuously providing not only wide-area wind speed and direction (Scatterometer) data, but also wave-height (Altimeter), period and direction (SAR) measurements, even over regions never previously explored.

Examples of Space-Based Applications

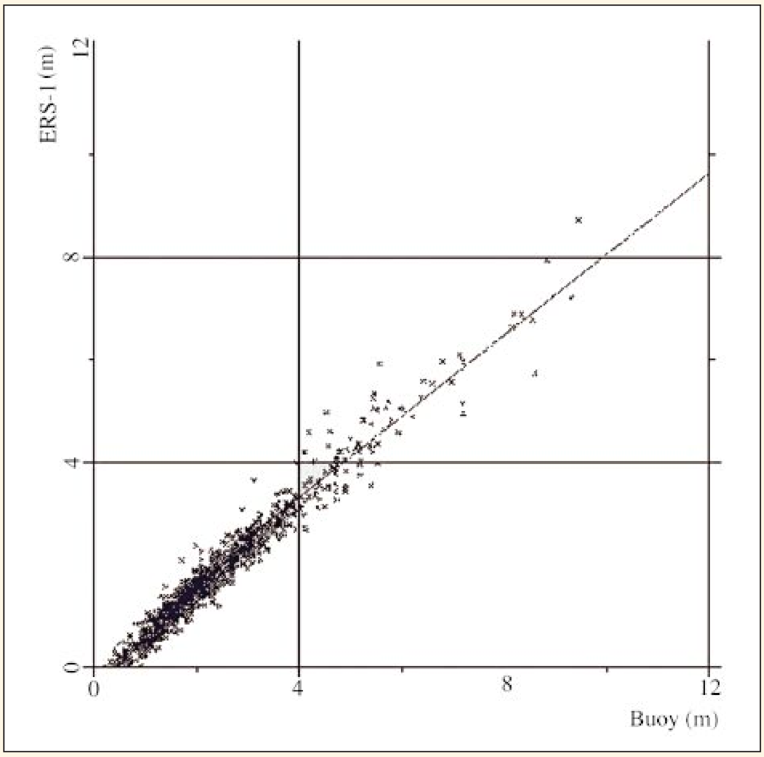
The on-line climatology database

With other satellite missions operating in parallel with ERS, such as Geosat and TOPEX/Poseidon, a time series of ten years of significant-wave-height measurements has now become available. Each of the three altimeters onboard the above missions has its own bias, requiring calibration with other data sets.

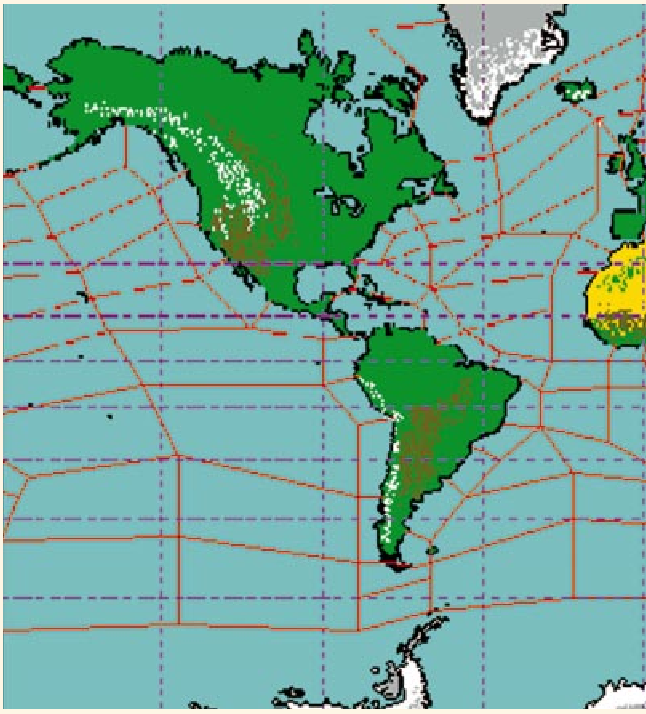
These data are sorted by geographical area for ease and speed of extraction, and stored as an on-line database, which is regularly updated with new data.

In addition, a global atlas of ready-made products can be generated and stored on a CD-ROM or floppy disk. The climatology can be presented as histograms or scatter diagrams to illustrate the distribution of different measured values, or as maps and charts similar to traditional atlases.

An example of calibration of ERS significant wave height with buoy data for the Norwegian Sea performed by Oceanor, the Norwegian oceanographic company



Pre-defined areas of quasi-homogeneous climate, for which CLIOSat provides climatology information



The quality of the derived climatology is heavily dependent on the accuracy and reliability of the data, with an additional reliance on the coherence of the measurements, related to the length of time series these data represent. Both averages and the extrapolation to extreme values can be valid only when the data are representative enough to point to a consistent result.

CLIOSat - a PC-based wave atlas

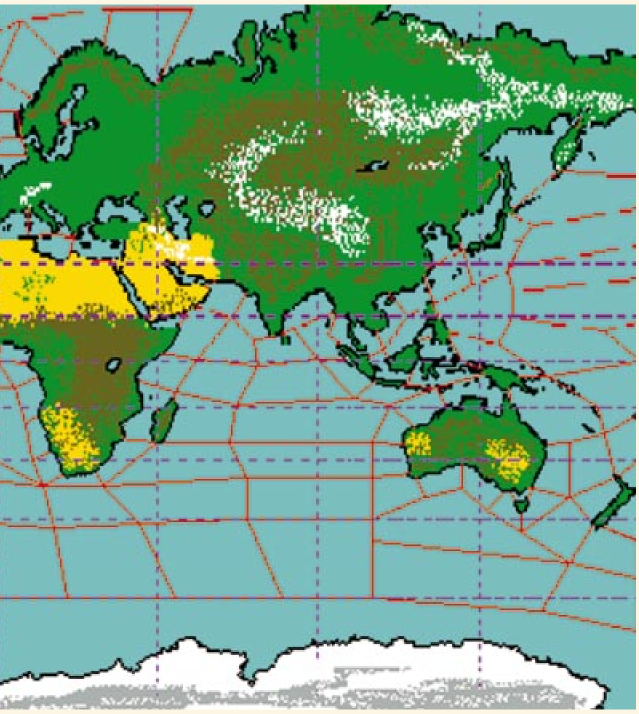
One example of the operational use of satellite-derived information is CLIOSat, a PC-based system developed in France by MeteoMer (a meteocean information company) and the National Marine Research Institute.

CLIOSat makes available worldwide marine climatology information in the form of a floppy disk or CD-ROM with a "point-and-click" interface. Histograms for pre-defined areas of reasonably homogeneous climate are provided.

CLIOSat provides a number of different data products and two main presentation formats: histograms and scatter diagrams. The products are derived from an archive and retrieval system which stores all existing ERS Altimeter, Scatterometer and SAR Wave Mode data in processed form, and which is updated on a regular basis (daily in the case of ERS-2 altimetry). Climates have been elaborated using measurements from Geosat, ERS-1 (ERS-2 for updates) and TOPEX/Poseidon. All of these measurements have been calibrated and validated with in-situ measurements, including those from Meteomer wave buoys.

A variety of parameters can be selected from the CLIOSat data, including wind speed, wind direction, significant wave height (Hs), wave period and direction. The user is provided with either histograms of the distribution of these wind/wave parameters or with extremal values of wave height. These values are only indicative (pre-project information) but offer a first impression of the range of estimated extreme Hs values that could be encountered within an area of interest.

Users can obtain similar basic statistics (except extreme Hs values) on an area of interest (specified location and size) for a particular period (year, season, month, combination of months) within 48 hours via the CLIOSat on-line service, using the fully up-to-date satellite database. To determine the precise metocean conditions (extreme Hs value, wave statistics) at a specific location (e.g. an offshore or coastal site), more involved analysis methods are necessary, such as the combination of satellite data with stochastic and meteo-oceanic models.

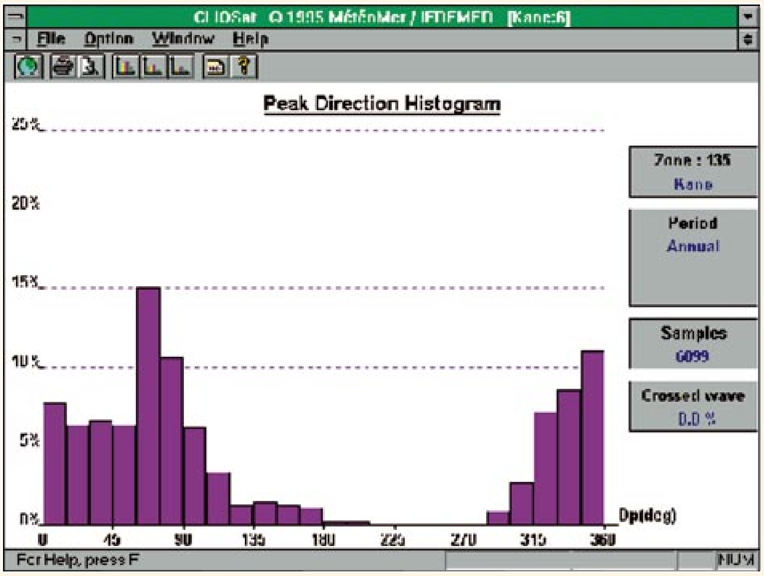


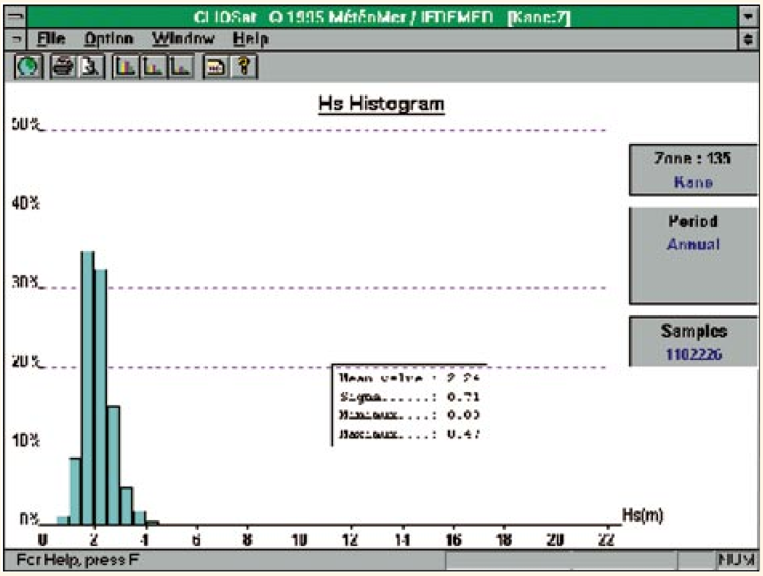
Both the CLIOSat software and the on-line service have a wide customer base that includes the major oil companies such as Total (France), Shell (USA), ELF-Aquitaine (France) and Chevron Oil (USA). The CLIOSat service has also provided data for frontier areas such as Southeast Asia and West Africa, as well as for such shipping routes as Taranto - Istanbul.

WAVSAT - an operational service

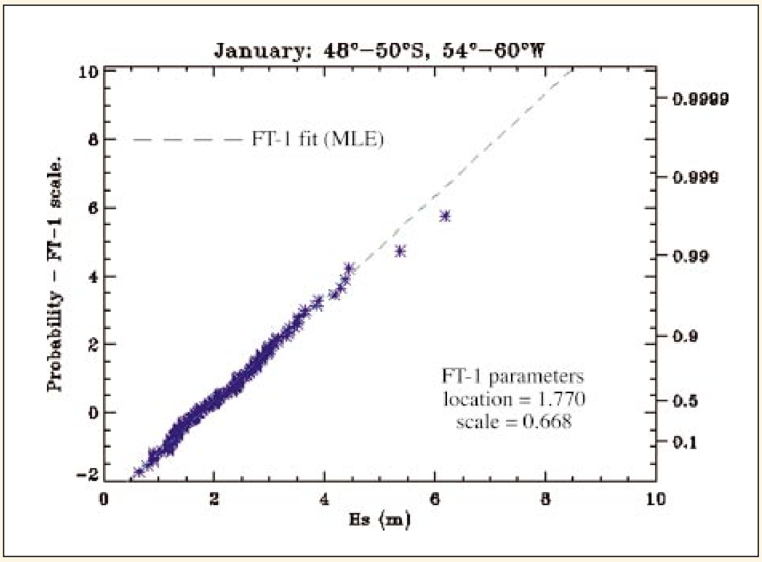
Companies engaged in offshore design and operational planning work can take advantage of the marine climatology information provided by WAVSAT, a service set up in the United Kingdom by Satellite Observing Systems (SOS) to meet specific user needs.

From the WAVSAT database, which presently holds over 10 Gbytes of data with regular updatings from new measurements, estimates of wave height as well as wind-speed climatology derived from satellite altimeter data can be obtained. The combination of data storage by geographical location and permanent on-line access facilitates information extraction by the users around the World. A wide range of other statistics are also readily available from the WAVSAT database.





Two sample products from CLIOSat: a histogram of the distribution of the wave direction on an annual basis for an area in the Central Atlantic (above) and a histogram of the wave heights for the same area on an annual basis (below)



A cumulative probability distribution of wave height during January for an area north of the Falklands (48-50°S, 54-60°W), one of a range of products supplied to Shell International Exploration and Production. The Falklands is a frontier region where little data exists apart from satellite measurements. The line drawn on the cumulative distribution plot is the fit to the data, estimated by maximum likelihood; the point at which it intercepts the top of the plot is the 100-year return value for that month

Cost/Benefit Considerations

Climatology information is primarily of use in optimising the decision-making process regarding the design of structures for, and the planning of operations in the global marine environment. Although it is hard to separate the benefits of meteocean data from those deriving from other information sources, it is clear that an engineering design team requires a precise and reliable source of climatological information if it is to function efficiently. Without it, an offshore structure may be over-engineered or, far worse, may not be sufficiently resilient to withstand the winds and waves to which it will eventually be exposed.

Especially in new frontier areas, access to satellite-derived climatology information is undoubtedly a cost-effective tool for companies involved in the design and safe operation of engineering structures. In the long term, the benefits of avoiding mishaps and unnecessary financial outlays by taking advantage of modern satellite-derived information sources far outweigh the cost of the information itself.

The users of this service include such public bodies as the French Marine Hydrographic Service and the UK Defence Research Agency. Both provide oceanographic information to their respective navies and to other bodies such as the French Maritime Insurance Council and the French Petroleum Institute.

Future Outlook

As the reliability of all wave climatology information increases with the time series of the measurements, continuity of data is important. In addition, as the climates of some areas are clearly changing, regular updates for already reasonably well-known areas are required, making continuity of measurement all the more important.

The next generation of ESA Earth-observing satellite Envisat, carrying besides other instruments a Radar Altimeter and a Synthetic Aperture Radar, will be launched in 1999. Until then, continuity is being assured by ERS-2, which is making observations of wind fields and wave heights and spectra, and by the wave-height measurements from the TOPEX/Poseidon altimeter. The eventual availability of wave heights also from TOPEX and Geosat follow-on missions will mean that we will be able to rely on a much greater density of sampling measurements in the future, and thus on an improved quality for the end products.

Acknowledgements

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ESA gratefully acknowledges their contributions.*

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ESRIN

SEA–ICE MONITORING

SEA–ICE MONITORING

The Need for Better Information

Sea-ice information is required by a wide spectrum of users involved in maritime operations at high latitudes. Greater exploitation of Arctic offshore oil and gas reserves has led to a requirement not only for accurate and timely ice monitoring, but also for reliable design inputs in terms of ice statistics for offshore constructions. Other users, specifically in coastal regions, include coast-guard and harbour authorities. Operational information on sea-ice status is also required by the fishing industry for such areas as the Barents Sea and the region around Svalbard, and by merchant vessels crossing ice-infested regions in the Baltic or the Canadian, Alaskan and European Arctic.

Ice-breakers play an essential role in ice-infested waters by keeping the Baltic-Sea ports open in the winter months and chaperoning vessels not adapted to icy conditions. These services are often provided free-of-charge, but sometimes also on a fixed-price basis so that optimisation of the routings can directly benefit both operators and customers.

The ice-monitoring requirements for supporting each activity overlap considerably, but differ in detail. The extent of the ice provides safety limits for those concerned with avoiding ice altogether. Ice-strengthened vessels risking navigation within the ice pack require information on the ice-age distribution and on pack motion in order to avoid high-pressure ridges and identify navigable leads. The end-product required is therefore a service that incorporates all available data and combines it with expert analysis.

The Limitations of Traditional Techniques

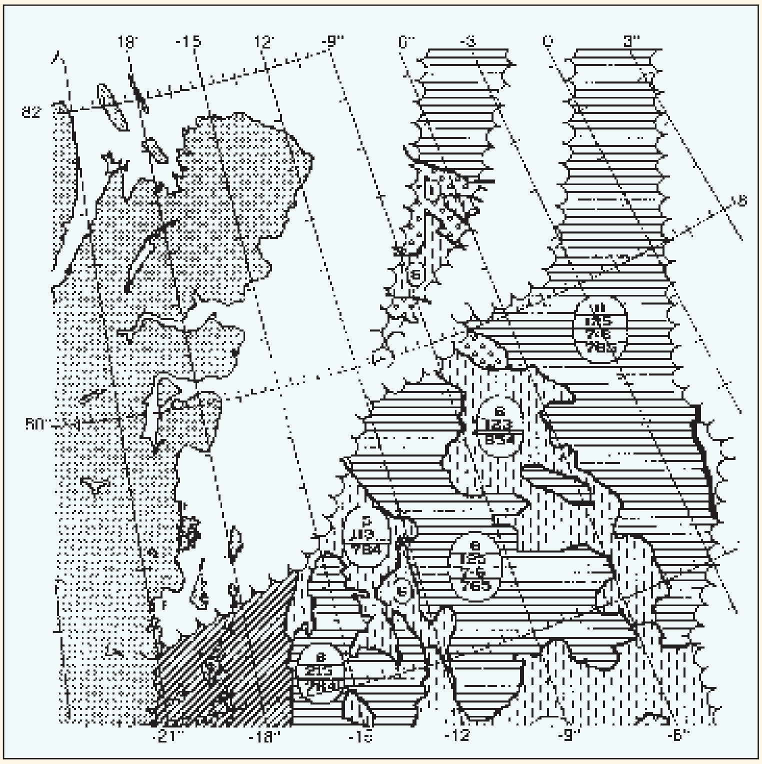
Many countries already maintain ice-monitoring and forecasting services, including China, Russia, the USA, the Scandinavian countries, Canada and the Baltic States. These services are essentially tactical in nature, providing information on conditions for planning within current operations and for the optimal routing of ice-breakers. A typical forecast service consists of daily regional (500 km^2 coverage) surveys in the form of ice type and concentration maps. However, many critical requirements such as strategic information prior to operations in ice-infested waters, multi-temporal information on ice-pack drift, and spatially detailed nowcasts and forecasts for critical areas such as straits are not met by these services.

Useful but sparse information is provided in the form of reports from vessels already in the ice, and from ice-breakers and weather stations. Other data sources include airborne-radar surveys, but these are expensive and still provide only limited coverage. Although the radar sensor itself may be insensitive to the prevailing weather conditions, the aircraft upon which it is flown can be grounded for days or even weeks at a time by adverse weather.

Precise knowledge of sea-ice conditions is vital when offshore operations at high latitudes are involved

The Benefits of Space-Based Monitoring

Satellite image data have proved to be of major benefit for regional ice surveillance. Large-scale monitoring of sea ice is routinely performed using Special Sensor Microwave Imager (SSM/I) data, which have a coarse spatial resolution of around 50 km. These data are independent of cloud cover and the whole Arctic region is covered twice daily. The NOAA infrared/optical Advanced Very High Resolution Radiometer (AVHRR) has a higher ground resolution (1 km), but both cloud cover and darkness impose constraints on its operation.



Ice chart derived from NOAA AVHRR imagery, illustrating the impact of cloud cover (white areas)

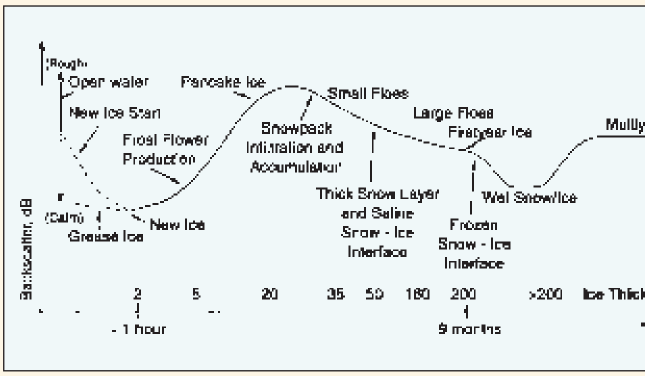
The Contribution of ERS SAR

The ERS Synthetic Aperture Radar (SAR) instrument provides imagery of the Earth up to a latitude of 84ºN. It maintains a high radiometric accuracy at 100 m spatial sampling, which constitutes the optimal trade-off between image properties and data size. This resolution is also comparable to the Side-Looking Radar (SLR) data obtainable from aircraft. For ice monitoring, therefore, the SAR represents a vital bridge between coarse-resolution satellite data and airborne radar, allowing leads and other features important for successful navigation at high latitudes to be resolved. It operates perfectly in all weathers and is unaffected by the long dark polar winter. In generating daily ice maps of regions that are typically 500 km by 500 km in extent, it can be useful to combine the SAR's detailed high-resolution information output (delivered just 2-3 hours after acquisition) with other data sets such as SSM/I and AVHRR, when available.

Since the ERS SAR is an active microwave instrument that measures the energy backscattered from the Earth's surface, one can distinguish the different ice types and map leads, polynyas, shear zones, land-fast ice, drifting ice and the location of the ice edge in the ERS image products now commonly used for ice applications.

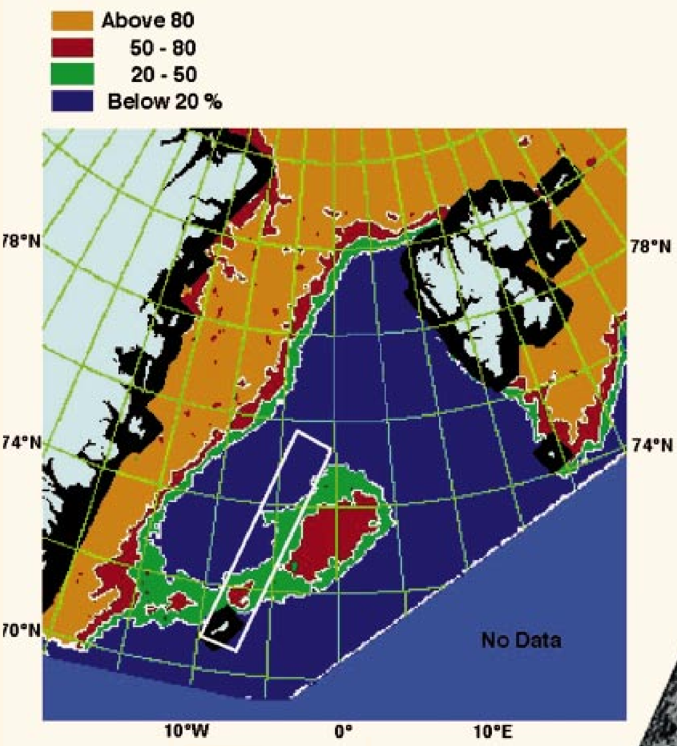
The SAR can accurately identify the state and condition of sea ice from the combination of the backscatter from the ice, the nature of the surrounding ice, the texture and the shape of the floes. Any ambiguities arising in this classification process can be resolved through the use of expert regional knowledge and auxiliary data sets, such as meteorological information, ship and shore observations, aircraft and other satellite data.

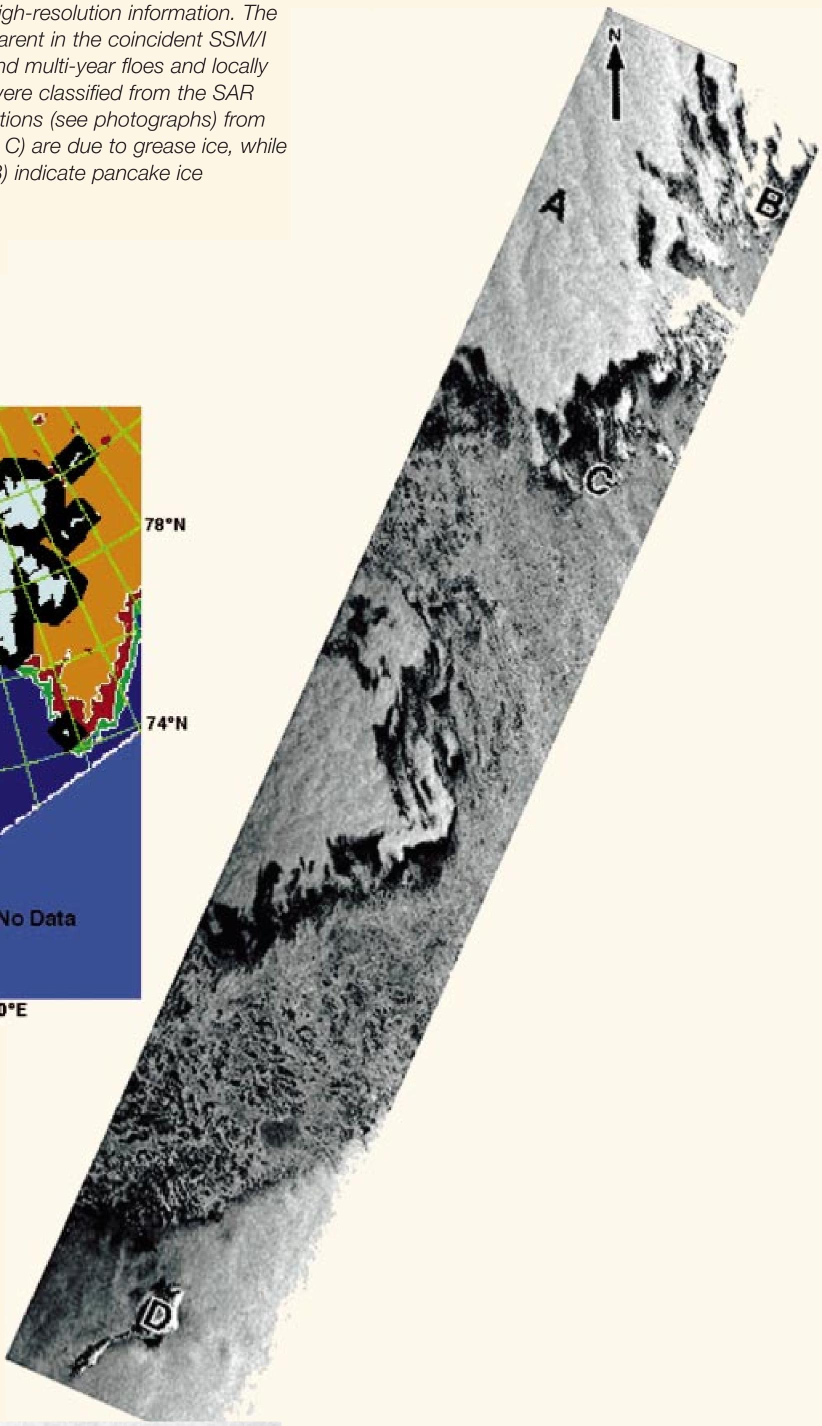
In addition to allowing the classification of ice type, the delineation of the ice edge, the accurate determination of ice concentration and the identification of leads, the frequent repeat coverage provided with the ERS SAR facilitates the detection and monitoring of ice movements and floes, enabling the tracking of pack-ice and ice at the edge of the Marginal Ice Zone.



The radar backscattering properties of ice vary with its age. The response from the ice is related to both surface and volume scattering properties such as roughness, presence of melt ponds, frost flowers and salinity and different snow/ice types

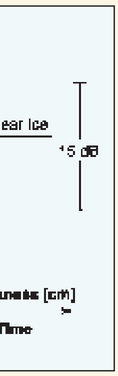
This figure illustrates the SAR's ability to provide high-resolution information. The SAR swath cuts across the Odden ice tongue apparent in the coincident SSM/I ice chart. This tongue consists of small first-year and multi-year floes and locally formed grease and pancake ice. These ice types were classified from the SAR imagery and documented with in-situ ship observations (see photographs) from around area B. Dark signatures (above both B and C) are due to grease ice, while brighter signatures (below and around C, around B) indicate pancake ice





pancake ice

grease ice

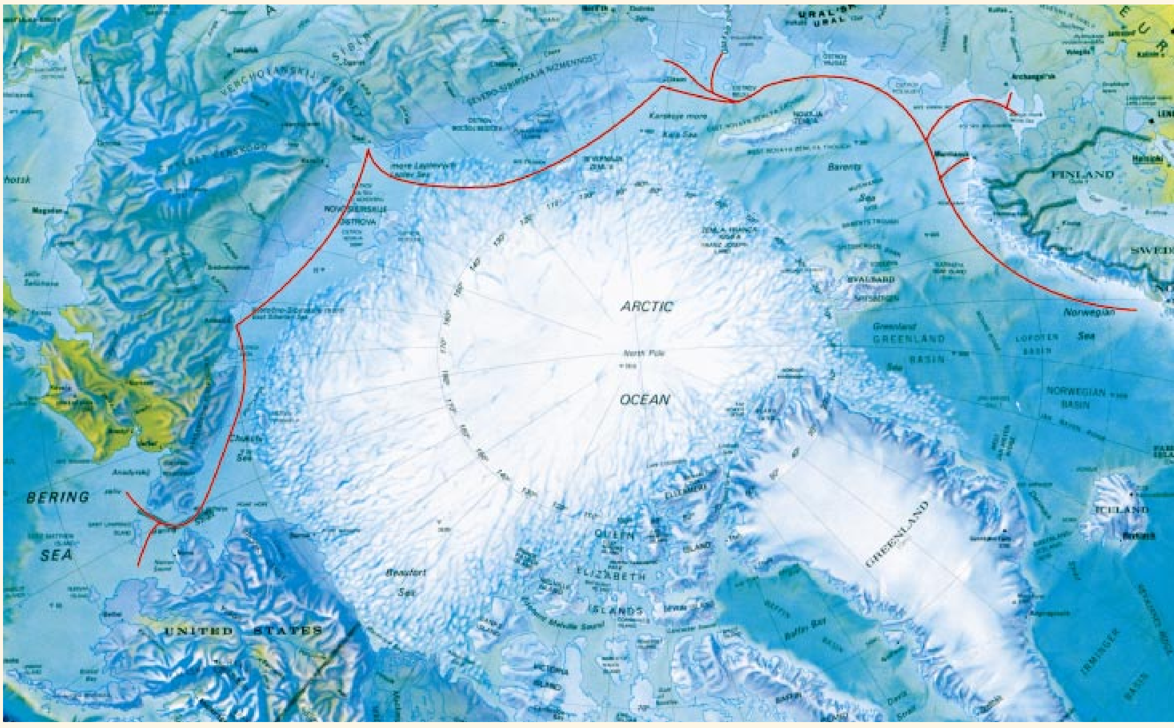


Examples of Space-Based Applications

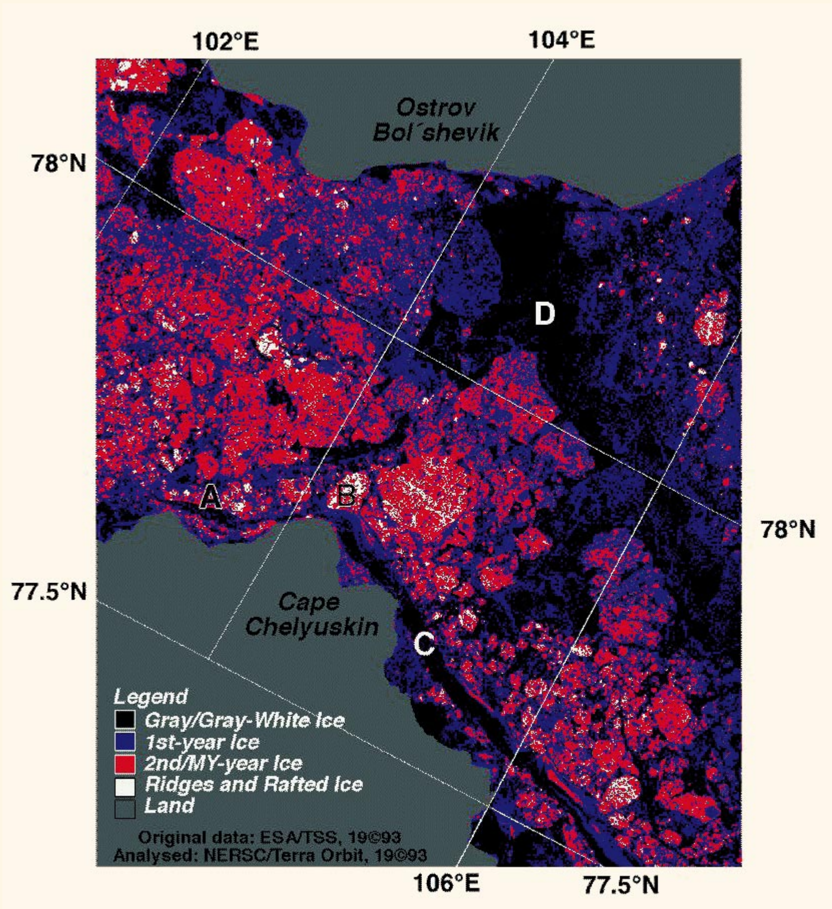
The "Icewatch" Service: Mapping the Northern Sea Route

The Northern Sea Route is the navigational route along the north coast of Russia from the Barents Sea in the west to the Bering Strait in the east (see below). Taking this route can reduce the transit time between Europe and the Pacific by approximately 10 days. However, the prevailing ice conditions in the region restrict sea transportation to ice-class vessels, as well as requiring ice-breaker assistance throughout the year. In summer, vessels ply the whole route, whereas in winter it is mainly the western part that is used to serve the ports on the Yenisei River. In addition, companies involved in the offshore oil exploration and production activities in areas such as the Eastern Barents and Kara Seas require information on ice conditions for facility (rigs, etc.) structural design and for monitoring purposes.

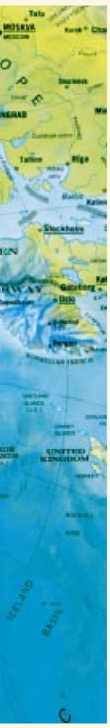
An extensive ice monitoring and forecasting service has been built up over the past 50 years in Russia for the Northern Sea Route in order to provide the ice-breakers with information. Recently, a first joint project in Earth observation between the Russian Space Agency (RKA) and ESA known as



The Northern Sea Route, opened to western shipping in 1991

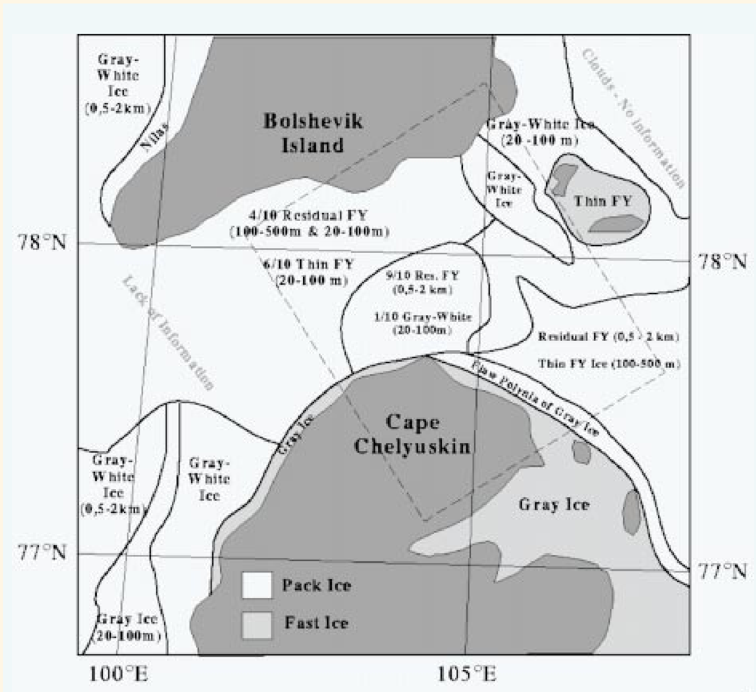


Ice map derived from an ERS SAR image and the coincident ice chart from the Russian Ice Service derived from SSM/I and NOAA AVHRR data. Note areas affected by cloud in the chart



"Icewatch" has been initiated. Its aim is to implement satellite monitoring of the Northern Sea Route, relying on the combined use of ESA ERS SAR, RKA OKEAN SLR, and other remote-sensing data. A pre-operational service has been set up that provides users with ERS SAR images via NIERSC, an organisation based in St. Petersburg that includes the Murmansk Shipping Company, the Dickson Operational Centre and several oil companies among its members. Several customers have already placed orders for regular satellite data, and operational use of this promising application is expected to grow considerably, helped by the European Union's taking an interest in "Icewatch".

The use of ERS-1 SAR data for near-real-time ice mapping in the Northern Sea Route was demonstrated for the first time by the Nansen Environmental and Remote Sensing Center (NERSC) in August 1991, just a few weeks after the satellite's launch. SAR-derived sea-ice



maps were sent by telefax to the French polar-research vessel "L'Astrolabe" during her voyage through the Northeast Passage from Norway to Japan.

Other demonstrations have been carried out by the Nansen Centers in Bergen and St. Petersburg with several of the Russian ice-breakers operating ice-convoy services along the Siberian coast and rivers. A scientist from the Nansen Center in St. Petersburg travelled onboard the ice-breakers and analysed the SAR images in co-operation with the vessel's captain and the ice pilots.

The Inmarsat-A communications satellite has been used to test new methods for the near-real-time distribution of data to ice-breakers operating in the Northern Sea Route. One of these experiments was performed on 25/26 January 1996, when the ice-breaker "Taymir" was sailing from Dikson to Beliy Island (70-80º E) in 100% ice. Using a PC and a modem connected to the Inmarsat station onboard the vessel, processed ERS-1 SAR images were received just 5 hours after the satellite overpass. In these images it was possible to clearly distinguish areas of rough ice and hummocks (brighter signatures) from smooth undeformed ice (darker signatures), allowing the ice-breaker to change course accordingly and select both a faster and safer sailing route.

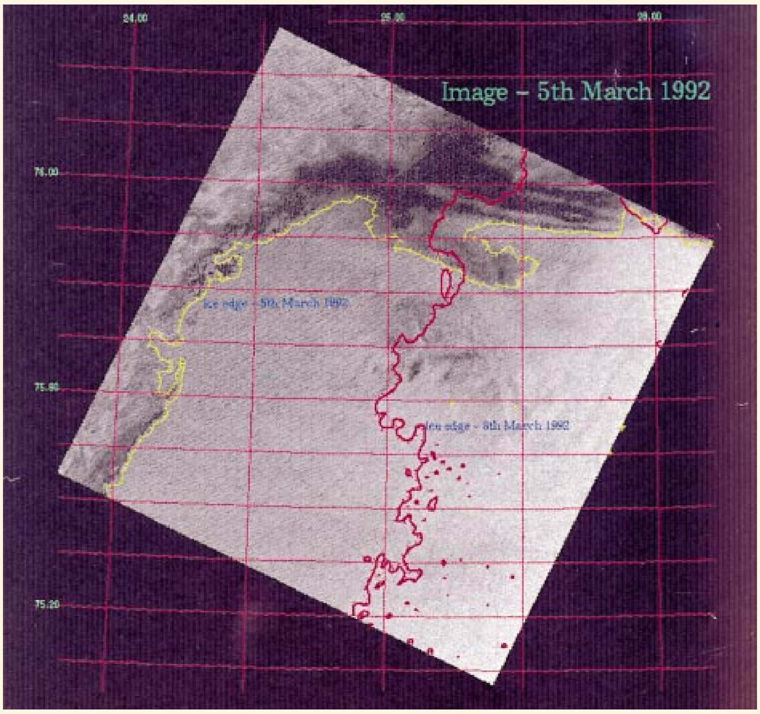
The UK Sea-Ice Workstation experiment

In the field of ice-charting, the most common requirements that an operational service has to meet are:

- *the production of precise and reliable ice information derived from an efficient system capable of handling and merging heterogeneous data sets*
- *the dissemination of such information through optimal mechanisms tailored to user needs.*

As an example of the efforts in this direction, a Sea-Ice Workstation has been developed by Earth Observation Sciences Ltd. (UK) with the support of the British National Space Centre (BNSC) and the Defence Research Agency (DRA). The aim was to prove the concept of usefully combining different types of satellite data. Most of the processing was targeted at the classification of ice into three categories: open water, first-year ice and multi-year ice. Contextual information was provided by data from the SSM/I and AVHRR sensors, but the detailed analysis of local areas was achieved using ERS SAR data.

The Sea-Ice Workstation was tested between 1994 and 1996 by supplying products to operators engaged in offshore activities in ice-infested waters. Charts were generated displaying ice-motion vectors, ice types, ice concentrations and ice-edge locations, depending on the user's requirements. The users to which the charts were supplied, in digital form via Inmarsat or



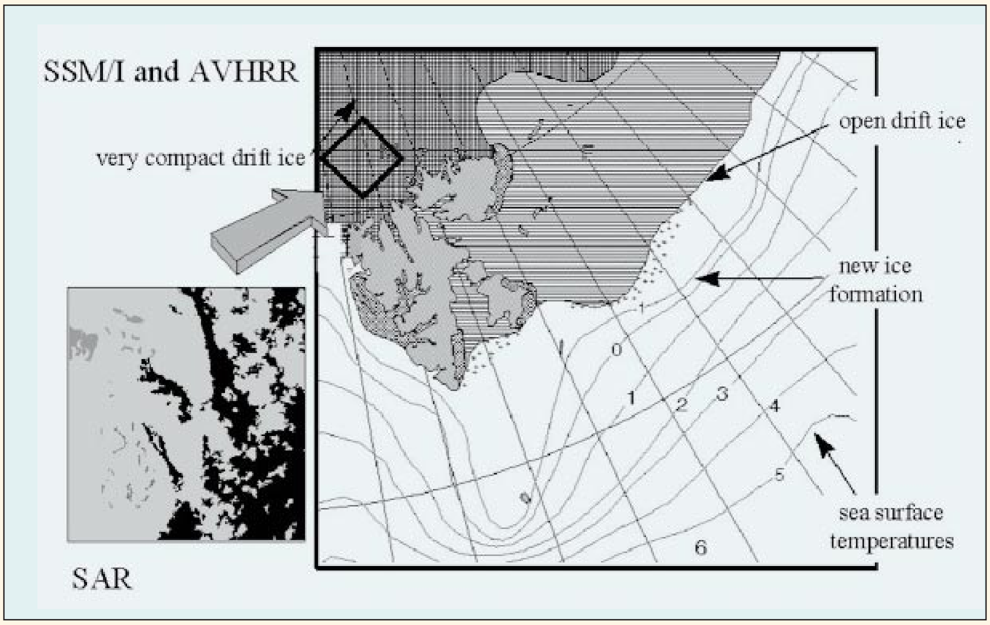
Typical ice-edge product from the Ice Prediction and Analysis Platform (IPAP) experiment. The area to the west in the image consists of first-year ice with a fringing of grease ice. The image is overlaid by two edge lines, one generated from the displayed image, and one from the next overpass of the satellite three days later

Orbcomm receivers, included: an oil production platform operating in the Barents Sea; meteorological organisations, for inputting into forecasting models; and shipping operators for route planning. A Royal Navy submarine also received coded ice charts on a regular basis whilst submerged beneath the ice.

The result of these tests, a "ready-for-use" tool for ice pilots, is presently being tested by weather-service authorities like the VNN in Norway as a basis for modelling the movement of vessels through sea ice.

The Ice Prediction and Analysis Platform experiment

An interesting experiment took place in August 1994, when Nuna Oil conducted a seismic survey in the ice-infested Greenland Sea. Maps of local ice concentrations and movements derived from ERS SAR images were delivered in near-real-time by fax to the vessel carrying out the survey, by GEC-Marconi Research Centre (UK). The Canarctic Shipping Company was also involved in the experiment and had the task of evaluating the satellite products from an operational-user point of view.



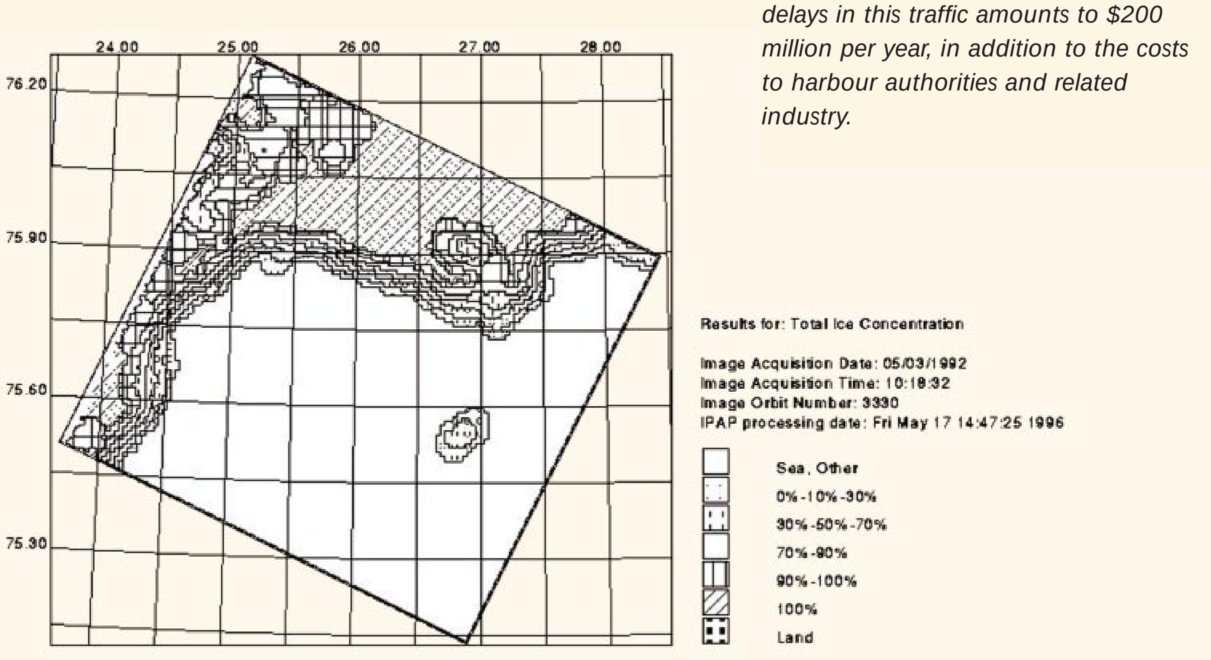
SSM/I and NOAA AVHRR-derived ice chart, with coincident classified SAR imagery

The ERS-1 SAR images were received at the West Freugh ground station in Scotland and transmitted via conventional land lines to the GEC-Marconi Research Centre, where they were processed automatically on a dedicated system, the "Ice Prediction and Analysis Platform" (IPAP). Ice-concentration and ice-movement maps were derived and all data were stored for further use as multi-temporal ice edge and pack-ice motion products. A validation study of the supervised classification algorithms available within IPAP using coincident in-situ information from the Canadian ice-breaker "MV Arctic" showed an accuracy of better than 98% for the area around the Bent Horn oil terminal

Cost/Benefit Considerations

The ice workstations generate accurate and timely ice information that constitutes an immediate and tangible contribution to the activities of the standard ice-charting service. When operations have to be undertaken for extended periods in ice-infested waters, knowledge on pack movement and routes through leads is crucial to speed up transfers and minimise fuel consumption. It also allows one to avoid using ice-breakers unnecessarily.

In the Baltic Sea, for example, where ice-breakers are used extensively to keep harbours open in winter, approximately 4000 ships visit the 23 Finnish harbours alone, each spending an average of four days in ice-infested waters. The cost of delays in this traffic amounts to $200 million per year, in addition to the costs to harbour authorities and related industry.



Typical ice-concentration charts output as part of the IPAP experiment. These ice-concentration (and ice-motion) maps were faxed to the master of the ship via the Inmarsat communications satellite within 3 hours of the satellite overpass. This allowed sufficient time to revise operational decisions regarding the survey route and the deployment of the hydrophone arrays

Future Outlook

Operational ice services need continuity of information flow and this is now ensured by the presence in orbit of both the ERS and Radarsat satellites. In addition, the flow of satellite data will increase considerably in 1999 with the launch of Envisat, the new ESA mission carrying among other instruments an advanced SAR instrument operating in a wide-swath mode, which will be ideal for regional ice monitoring.

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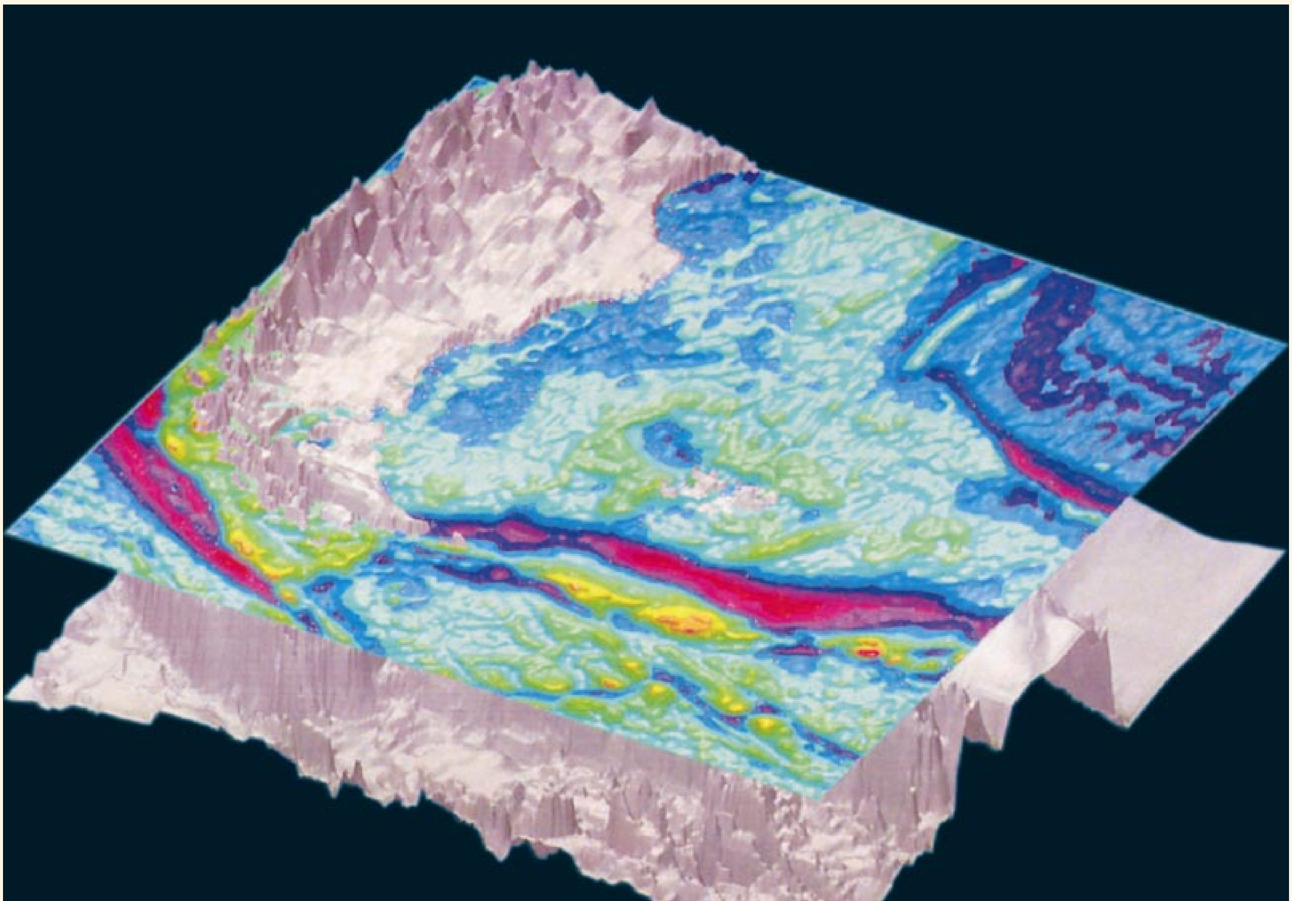
OFFSHORE OIL AND GAS EXPLORATION



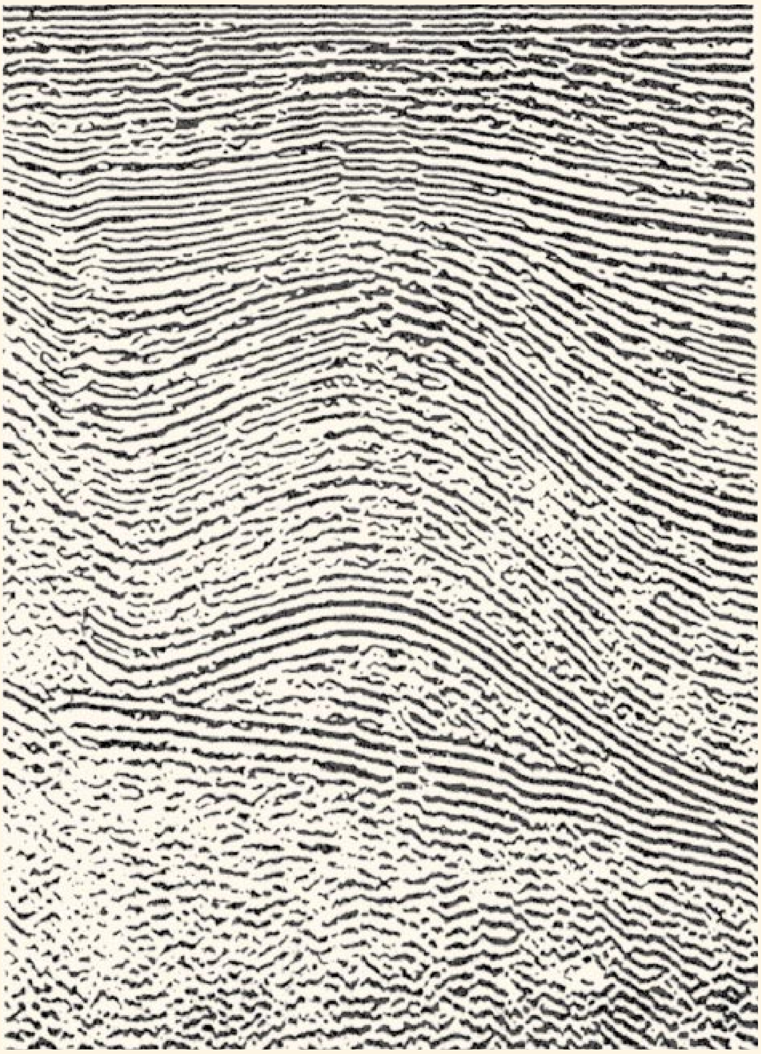
OFFSHORE OIL AND GAS EXPLORATION

The Need for Better Information

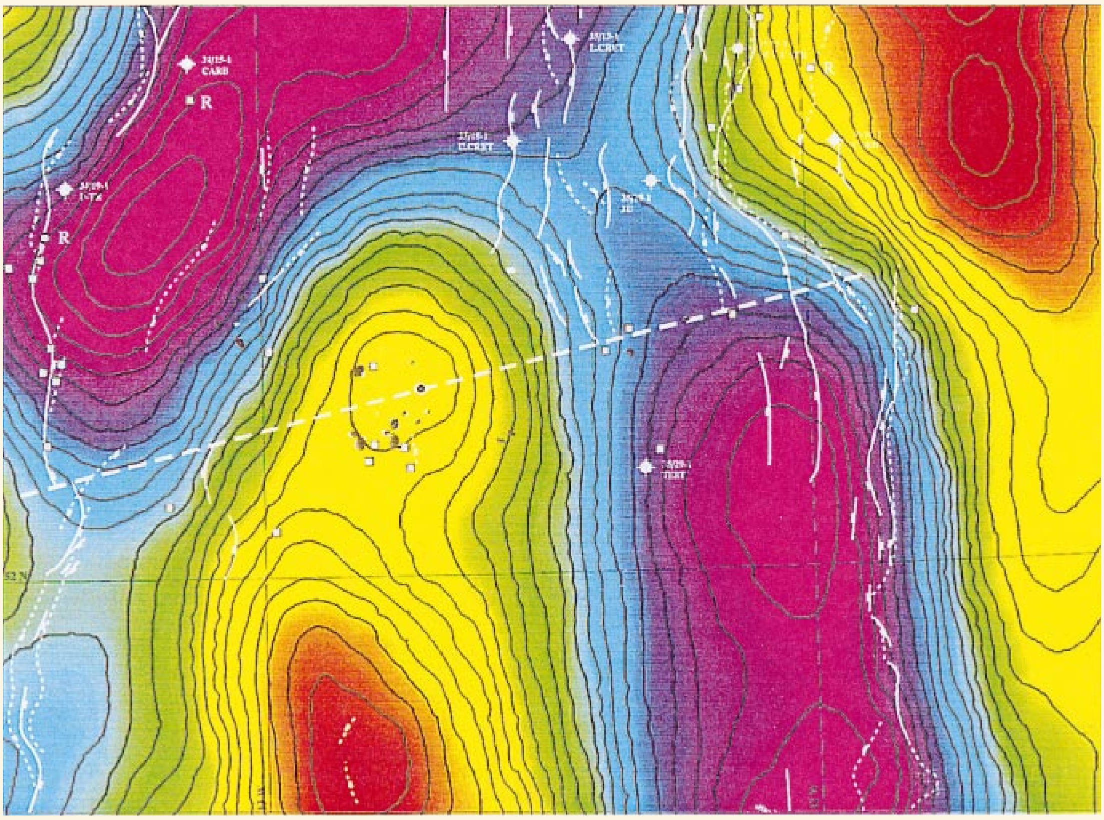
The Earth's dwindling reserves of natural hydrocarbons are obliging oil and gas companies to expand their activities to ever more remote and inhospitable areas of the globe. Harsh environmental conditions and the lack of any survey support infrastructure combine to make conventional prospecting techniques - marine seismic surveying, gravity- and magnetic-anomaly mapping and test drilling - extremely expensive in these new frontier areas. These methods of data collection are also very labour-intensive. The future viability and profitability of the oil and gas industry is therefore strongly intertwined with the search for ever more efficient prospecting and surveying techniques that are operable on a global scale.

The Limitations of Traditional Techniques

The costs associated with the identification of new sources of oil and gas using traditional means are immense even in relatively accessible areas such as the North Sea and the Northwestern Atlantic. Additional costs must be met when tackling the more remote areas such as the Arctic Ocean and in Southeast Asia where hazards such as ice floes or severe storms can cause expensive delays. Today, however, the deployment of the such expensive surveying resources can be optimised by the judicious application of remote-sensing data.



Seismic profiles like the one shown here related to an area of the North Sea, reveal anticline structures which may indicate the presence of oil traps.

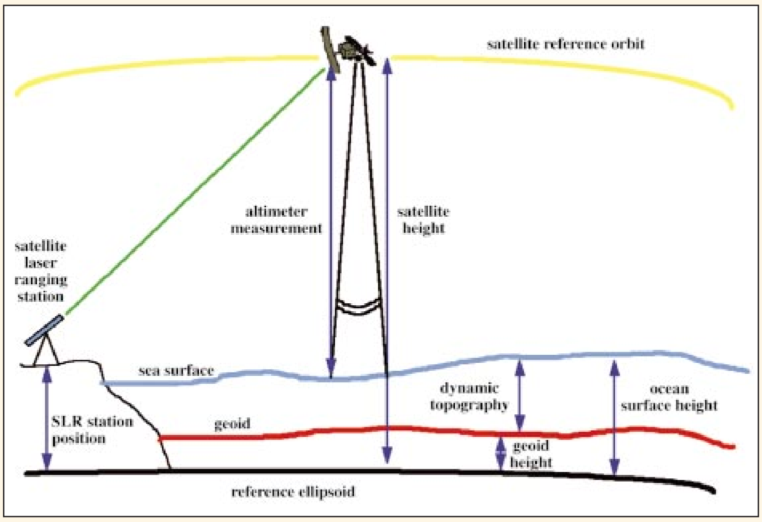


Gravity-anomaly variations over the Porcupine Basin area in the Atlantic as derived from ERS-1 Altimeter data. These data clearly show a major transcurrent fault (white dotted line) which would be difficult to detect in conventional seismic data

The Benefits of Space-Based Monitoring

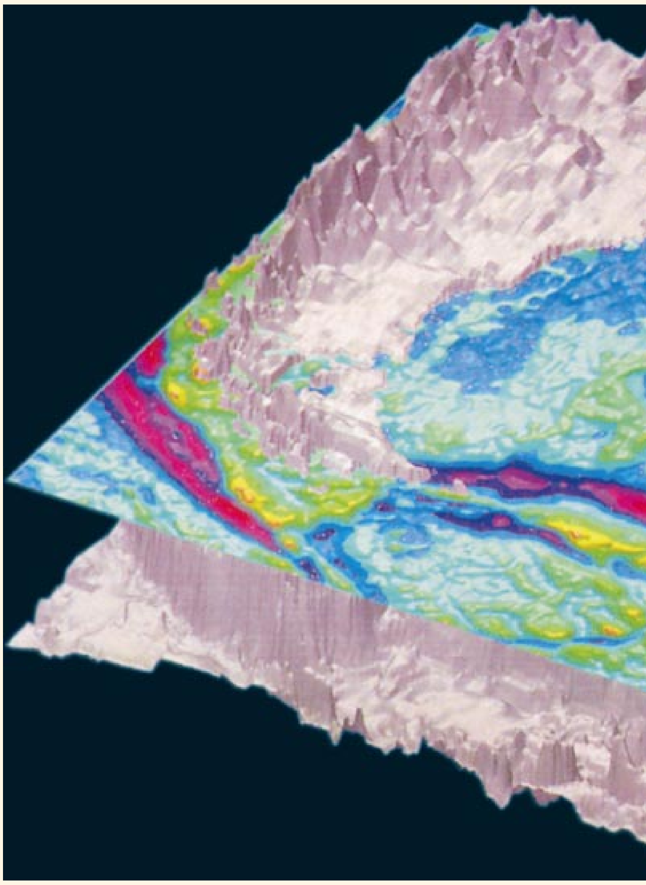
In the oil-prospecting domain, gravity-anomaly measurements are important indicators of the presence of potentially oil-bearing structures beneath the sea surface due to the characteristic perturbations induced in the gravity field by the different rock types. These variations in the gravity field cause variations in the shape of the sea surface, which represents a surface of constant gravity. Thus by precisely measuring the shape of the sea surface it is possible, once unwanted effects such as current features have been removed, to extract gravity anomalies and detect the presence of hydrocarbon trap structures.

Satellite-borne radar altimeters, in combination with orbit-tracking data, allow such precise measurements of the sea surface to be made. The global ocean-surface height can be determined by combining this measurement with the satellite position data obtained from a worldwide network of tracking stations. In addition, the effects of tides, currents and bathymetry on the sea-surface height are determined and removed. The resulting mean sea-surface height is then converted into variations in the gravity field.



Instantaneous measurement of satellite height above the sea surface provided by the ERS-1 and ERS-2 Radar Altimeter

Gravity field over the Falkland Islands, in the South atlantic, derived from Altimeter measurements. Approximately 200 000 sq. km of the offshore area includes sedimentary basins with significant hydrocarbon potential.



The Contribution of ERS

The ERS spacecraft carry a suite of microwave instruments capable of providing geophysical exploration companies with valuable and timely information, allowing them to achieve considerable reductions in their survey costs. The two main ERS instruments relevant for hydrocarbon exploration are the Synthetic Aperture Radar (SAR) and the Radar Altimeter.

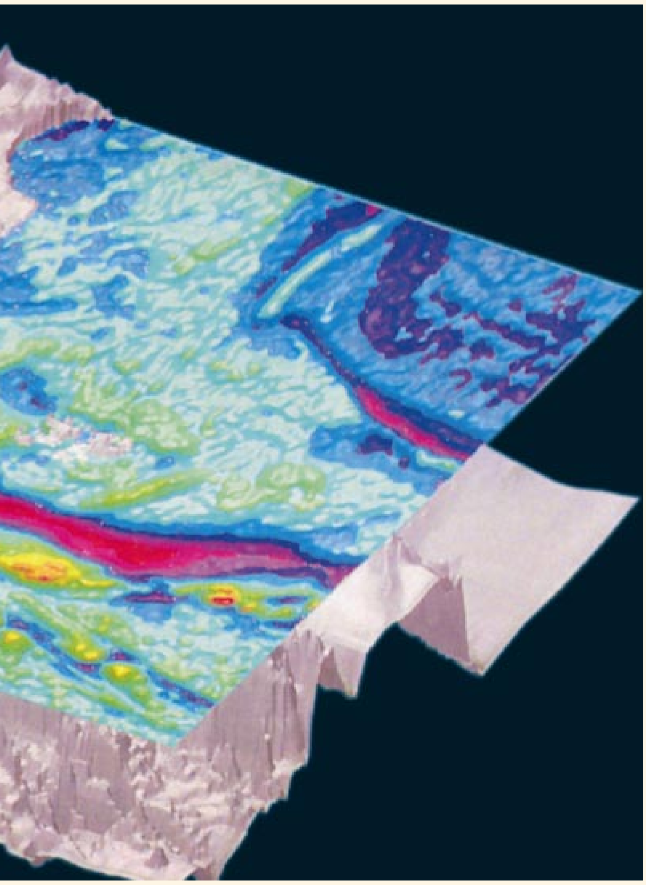
The SAR provides an image of approximately 100 km x 100 km with a spatial resolution in the order of 25 m. It allows the detection of oil slicks on the sea surface originating through seepage from subsea hydrocarbon deposits, thereby permitting the identification of promising areas for more extensive surveying.

The Radar Altimeter measures the height of the satellite above the sea surface to an accuracy of approximately 10 cm, allowing the inferral of gravity anomalies arising from subsea geological structures with oil-bearing potential.

Examples of Space-Based Applications

Marine gravity maps (Gravsat)

Marine gravity maps based on Radar Altimeter data are already being produced for certain areas of the globe, including the Gulf of Thailand, the Gulf of Mexico, the East China Sea, the Bay of Bengal, the Falkland Islands and the northern seas off the coast of Russia. They are being generated and made available to a number of oil and gas companies, as well as to the British Geological Survey, by Satellite Observing Systems (SOS) Ltd. (UK). The measurements also incorporate Seasat and TOPEX/Poseidon data and the recently declassified Geosat archives. Once the gravity anomalies have been determined, the necessary geophysical interpretations are performed and features of interest highlighted for the customer.



Subsea hydrocarbon-deposit location

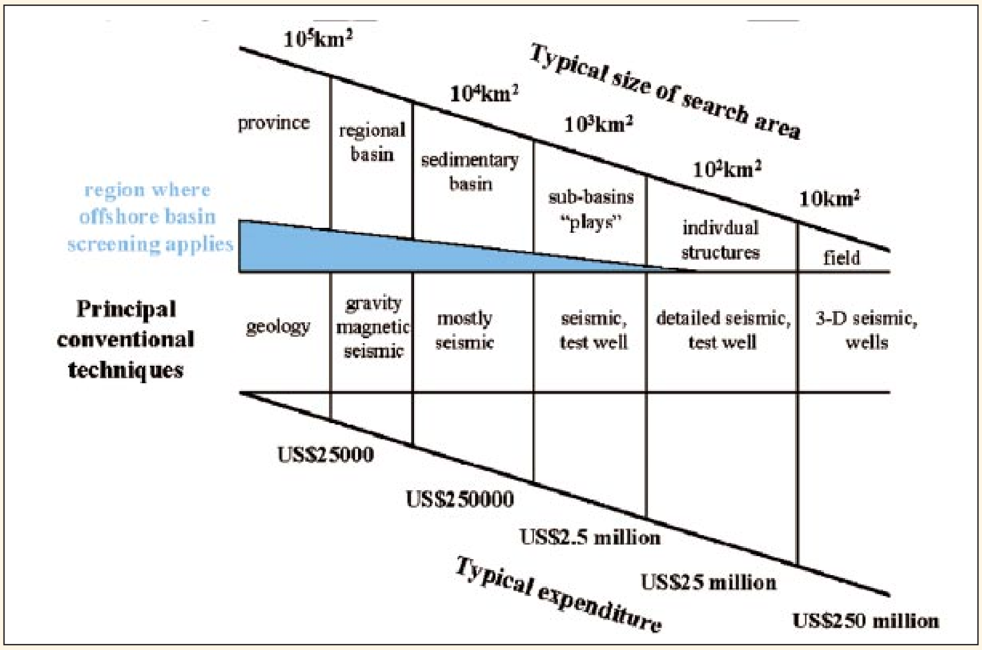
Small amounts of oil leak into the ocean from subsea deposits giving rise to detectable surface slicks which can serve as an indicator of the presence of oil-bearing structures. Until now, there has been no generally available, low-cost method for identifying these seepage clues. During times of low to moderate wind speeds, the ERS SAR can systematically detect these slicks over large swaths of ocean, regardless of the prevailing cloud or lighting (day or night) conditions. The backscatter levels detected by the SAR depend on small capillary waves on the sea's surface which are smoothed out by the presence of oil, causing a decrease in the surface roughness and making the slick areas appear darker than the surrounding ocean in the SAR imagery. Compared to other oceanic surface features, these seepage-slicks often persist over time, so that multiple SAR images acquired months apart during low-wind conditions can be extremely informative.

SAR image acquired over the Gulf of Mexico. The naturally occurring seepage slicks have a characteristic "dog-leg" appearance. This image is part of a data set acquired and analysed by the GOSAP Consortium as part of a major initiative in the USA to exploit satellite remotely sensed data in the oil exploration and production industry*

** A cooperation between universities (e.g. Texas A&M), national research institutions (e.g. NOAA) and the oil companies (e.g. Shell and Marathon Oil).*

Although in principle such seepage-slick detection is also feasible with optical instruments such as the SPOT HRV, in practice the need for cloud-free imaging and observation-geometry constraints lead to the ERS SAR being identified a significantly better tool for detecting and mapping such phenomena.

Offshore basin screening usually takes a few weeks and costs less than 0.5 ECU per km^2. Oil companies use the service to select/rank exploration blocks offered by governments and to prioritise the acquisition/purchase of seismic data



The offshore basin screening service

This is a service offered to the offshore oil-exploration industry, by Nigel Press Associates and TREICoL in the UK, which saves time and money by prioritising seismic expenditure and focusing attention on the most prospective basins.

Radar Altimeter data from ERS-1/2 are combined with similar data from other missions, resulting in a track spacing that can be as close as 1 km. Other geophysical information is also incorporated where available. The altimetry is converted to a gravity map that can outline the basins in which oil might be present. These gravity maps are combined with a map of sea-surface slicks resulting from natural oil seepages, as detected and analysed in SAR images.

Cost/Benefit Considerations

The space-based services currently provided to the oil-exploration industry are not intended to replace conventional techniques such as seismic mapping and ship-borne gravity-anomaly studies. The accuracy possible with conventional surveying techniques is presently several times better than is possible with satellite measurements given that the ground-track resolution for Altimeter-based gravity-anomaly studies is still in the region of 7 - 10 km. With ship-borne gravity-anomaly mapping, the track spacing can be made as close as one wishes. The advantage of the satellite-based techniques is that the costs are many times lower than with conventional methods, offering exploration companies the opportunity to perform a preliminary analysis of a region before committing expensive resources to any survey. In addition, the satellite coverage provides easy access to remote basins without the need for an expensive support infrastructure.

Future Outlook

Although there has been considerable interest from the oil industry in the exploitation of remote-sensing data for several years, it is only now, with the availability of the ERS data products, that the services provided to the industry are beginning to meet its requirements in terms of precision and coverage. Many oil and gas companies are already actively using ERS data in their day-to-day activities - including British Gas, Statoil, Exxon, Shell, Marathon, Mobil, Amoco, Pecten, and Chevron - and their number can be expected to grow substantially in the coming years.

Together with the anticipated progressive improvement in terms of quality, the services already available will benefit from the continuous provision of data that will be ensured by the launch of ESA's Envisat spacecraft at the end of 1999, carrying among other instruments both an Advanced SAR and a Radar Altimeter.

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