The Radar Imaging Instrument and Its Applications: ASAR

M. Zink, C. Buck, J-L. Suchail, R. Torres
Envisat Programme Division, ESA Directorate of Earth and Environment Monitoring from Space, ESTEC, Noordwijk, The Netherlands

A. Bellini, J. Closa, Y-L. Desnos & B. Rosich
ESA Earth Observation Applications Department, ESRIN, Frascati, Italy

Envisat will carry an all-weather, day-and-night high-resolution radar-imaging instrument: the Advanced Synthetic-Aperture Radar (ASAR). ASAR builds on the success of the ERS-1 and ERS-/2 SARs, which have contributed to major scientific achievements and initiated pre-operational and commercial applications of radar data. The ASAR system has therefore been designed to provide continuity with the ERS instrument and to extend the range of measurement capabilities. Three new modes of operation, improved performances and new algorithms allow the generation of novel data products, including near-real-time and off-line precision image products, to be provided to scientific, institutional and commercial users, for land, ocean and ice applications.

ASAR mission objectives

The Envisat mission has both 'global' and 'regional' objectives, with the corresponding need to provide data to both scientific- and application-oriented users on various time scales. Important contributions from the ASAR to the global mission include:
– measuring sea-state conditions at various scales
– mapping ice-sheet characteristics and dynamics
– mapping sea-ice distribution and dynamics
– detecting large-scale vegetation changes, and
– monitoring natural and man-made pollution over the oceans.

ASAR will make a major contribution to the regional mission by providing continuous and reliable data sets for applications such as:
– offshore operations in sea ice
– snow and ice mapping
– coastal protection and pollution monitoring
– ship traffic monitoring
– agriculture and forest monitoring
– soil-moisture monitoring
– geological exploration
– topographic mapping
– predicting, tracking and responding to natural hazards, and
– surface-deformation monitoring.

Some of the regional objectives – sea-ice applications, marine pollution, maritime traffic, hazard monitoring, etc. – require near-real-time data products (within a few hours of sensing) generated on the basis of user requests. Others – such as agriculture, soil moisture, etc. – require fast-turnaround data services (within a few days). The remainder can be satisfied with off-line data delivery. As well as the ASAR products meeting specific operational and commercial requirements, there will be major systematic data-collection programmes to build up archives for scientific research purposes.

Land

As a result of observing the Earth's land surface with the ERS SARs, a large number of land applications have emerged, several of which are based on important developments that have been made in the field of SAR interferometry. SAR data are already being used for agricultural monitoring, forest mapping, geological exploration and flood mapping, while INSAR measurements of topography and small topographic changes are making major contributions to the assessment of environmental risks from earthquakes and land subsidence.

Ocean and ice

The original focus of the ERS missions was ocean and ice monitoring, and there have been an impressive range of scientific investigations in oceanography, polar science, glaciology and climate research, which will continue to be supported by ASAR. These include measurements of ocean-surface features (currents, fronts, eddies, internal waves), directional ocean-wave spectra, sea-floor topography, snow cover and ice-sheet dynamics. Operational systems have been developed for sea-ice mapping, oil-slick monitoring and ship detection.

Instrument operation

Measurement principle

The antenna beam of a side-looking radar is directed perpendicular to the flight path and illuminates a swath parallel to the satellite's ground track. Owing to the motion of the satellite, each target element is illuminated by the beam for a certain period, known as the 'integration time'. As part of the ground processing, the complex echo signals received during this period are added coherently. This process is equivalent to synthetically forming a long antenna - a so-called 'synthetic aperture'. Assuming a constant angular beam width along track or in azimuth over the entire swath, the achievable synthetic aperture increases with the slant range between satellite and target.

The along-track or azimuthal resolution of a side-looking radar is directly proportional to the antenna length and inversely proportional to the target slant range. Hence, the azimuth resolution of a SAR is independent of the target range, and theoretically equals half the physical antenna length. The achieved resolution is the result of a trade-off against other image quality parameters, such as the radiometric resolution.

The across-track or range resolution is a function of the transmitted radar bandwidth. Pulse-compression techniques are used to improve the performance. The fact that the end-to-end system works coherently means that both the amplitude and the phase relationships between the complex transmitted and received signals are maintained throughout the instrument and the processing chain.

Modes of operation

The ASAR instrument is designed to provide a large degree of operational flexibility. Its main instrument parameters can be selected by ground command for each of the five operational modes (Fig. 1):

– The *Image* mode generates high-spatial-resolution data products (30 m for Precision Images), selected out of the total of seven available swaths with a range of incidence angles spanning 15 to 45 deg.
– The *Wave* mode generates 5 km by 5 km vignettes spaced 100 km along-track. The position of the vignette can be selected to alternate between the centres of any two of the seven swaths.
– The *Wide-Swath* and *Global-Monitoring* modes are based on the ScanSAR technique using five sub-swaths, and each generates wide-swath products (400 km) with spatial resolutions of 150 m and 1000 m, respectively.

These four modes may be operated in one of two polarisations, either HH or VV (in this two-

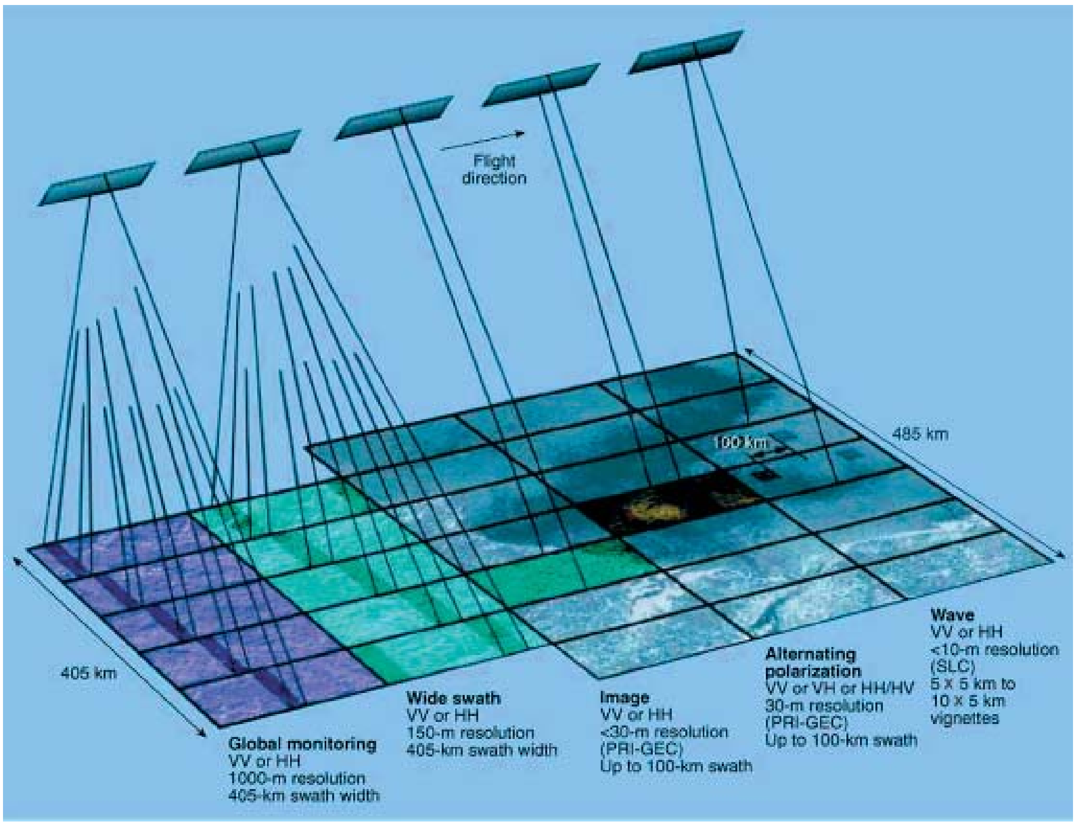


Figure 1. ASAR operating modes

letter code, the first indicates the polarisation of the transmit signal – H for horizontal, V for vertical – and the second indicates the polarisation of the receive signal).

– The *Alternating-Polarisation* mode provides two simultaneous images from the same area in HH and VV polarisations, HH and HV or VV and VH, with the same imaging geometry as in the Image mode and similarly high spatial resolution.

The ASAR instrument

The ASAR instrument consists of two main elements: the Central Electronics Sub-Assembly (CESA) and the Antenna Sub-Assembly (ASA).

Central Electronics Sub-Assembly

The CESA is responsible for generating the transmitted chirp, converting the echo signal into measurement data, as well as controlling and monitoring the whole instrument.

Compared to ERS-1 and ERS-2, which used surface-acoustic-wave devices for analogue chirp generation and on-board range compression, ASAR uses digital technologies for on-board chirp generation and data reduction. A fundamental advantage of this new approach is the inherent flexibility of such a design, which allows chirp versatility in terms of pulse duration and bandwidth, thus accommodating efficiently the various requirements associated with the high number of available operational modes and swaths of the instrument.

At reception, the echo signal is first filtered and down-converted in the RF subsystem, and then demodulated into the in-phase and quadrature components of the carrier. These two signals are then both digitised into 8-bit samples. If required, it is possible to perform digital decimation of the samples, in order to reduce the data stream, such as in Global-Monitoring mode where the transmit bandwidth is low. Following this optional step, a Flexible Block Adaptive Quantiser (FBAQ) compression scheme is applied to the echo samples.

To optimise raw data transfer, the data equipment also contains a 'science memory', where the echo samples are temporarily stored before their transmission to the on-board recorders.

Active phased-array antenna

The ASAR active antenna is a 1.3 m x 10 m phased array (Fig. 2), consisting of five 1.3 m x 2 m panels, which are folded for launch. Each panel is formed by four 0.65 m x 1 m tiles. The Antenna Sub-Assembly is divided into three subsystems: the Antenna Services Sub-System (ASS), the Tile Sub-System (TSS) and the Antenna Power Switching and Monitoring Sub-System (APSM).

The antenna is based on a mechanical structure consisting of five rigid CFRP (Carbon-Fibre-Reinforced Plastic) frames and two (one for the radar signal and one for calibration) RF distribution networks of CFRP wave guides running in parallel along the five panels. In

Figure 2. The flight-model ASAR antenna (courtesy of Matra Marconi Space, UK)

launch configuration, the five panels are stowed, folded over the fixed central one, and held in place by eight Hold-Down and Release Mechanisms (HRMs). Each HRM consists of a retractable telescopic tube levered by a secondary mechanism based on non-pyrotechnic technology (kevlar cable and thermal knife). After release, the panels are deployed sequentially around four hinge lines by using stepper motors. Locking is performed by the eight built-in latches to achieve the final antenna planarity of ±4 mm in orbit.

Each of the 20 tiles is a self-contained, fully operating sub-system, which includes four Power Supply Units (PSUs), a Tile Control Interface Unit (TCIU), two micro-strip RF distribution corporate feeds, and 16 sub-arrays of 24 dual-polarised, low-loss, dispersion-free radiating elements. Each sub-array is connected to a transmit/receive (T/R) module with independent connections for the two polarisations. The 16 sub-arrays are mounted together – although thermally and mechanically decoupled – on a single (radiating) panel, which provides structural and thermal integrity to the tile. Pre-flight studies and tests on the engineering model indicate different, but stable temperatures for each operating mode.

Each of the 320 T/R modules consists of two (H- and V-polarised) transmit chains and one common receive chain. For calibration purposes, a coupler (-24 dB) has been implemented at the output of the antenna module (Fig. 3).

For an active antenna, the amplitude and phase characteristics of the T/R modules vary principally as a function of temperature. To handle this, the instrument includes a scheme to compensate for temperature drifts. The temperature of each T/R module is monitored and utilised by the TCIU to compensate for the amplitude and phase variations. This approach provides the antenna with a high degree of stability.

Instrument calibration

The ASAR, unlike the ERS AMI-SAR, is an active antenna, and hence any instabilities in its gain and phase characteristics will distort the elevation beam patterns and may contribute to radiometric errors in the SAR image. For this reason, a sophisticated scheme for radiometric calibration of the ASAR has been selected, composed of three elements: internal calibration, external characterisation and external calibration.

Internal calibration

During normal operation in any of the ASAR measurement modes, a sequence of calibration pulses is interleaved with normal radar pulses. These pulses characterise the active array in both transmit and receive, on a row-by-row basis. Noise measurements are taken during the initial calibration sequences at the beginning of a mode. In the modes that have natural gaps in their imaging sequences (i.e. wide-swath and global-monitoring modes), noise measurements are also made during nominal operation throughout the mode.

External characterisation

The ASAR has a dedicated external-characterisation mode to monitor all those elements that are outside the internal calibration loop, as well as the calibration loop itself. The operation of this mode is planned every 6 months.

External calibration

Acquisitions made over high-precision transponders deployed in the Netherlands and images of the Amazonian rain forest will be used to determine the absolute gain calibration factor and the in-flight elevation antenna patterns. For the ScanSAR modes, the external calibration approach will be similar to that used for the narrow-swath mode, but will also rely on well-characterised distributed targets.

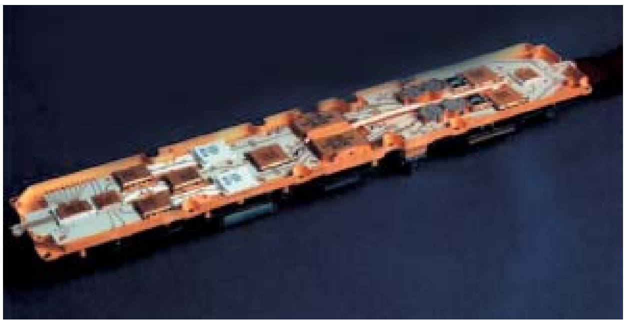


Figure 3. The ASAR transmit/receive module (courtesy of Alcatel, F)

The ASAR ground processor

The development of the ASAR processor has been based on the following concept drivers:

- The need for users to have identical products irrespective of the processing centre.
- The need to broaden the range of products, whilst still ensuring the quality of the ERS SAR high-resolution products.
- The ability to cope with the large amount of products to be generated.
- The ability to generate continuous medium- and low-resolution products along the orbit in near-real-time (strip-line processing, without radiometric or geometric discontinuity).

Following the above concepts, ESA has developed a generic ASAR processor able to handle data from any of the ASAR modes in near-real time and off-line. This ASAR processor will be installed in the ESA Payload Data Handling Stations (Kiruna in Sweden and ESRIN in Italy), in the Low-Rate Archiving Centre in Kiruna, in the Envisat Processing and Archiving Centres (PACs), and in the national stations offering ESA ASAR services. The use of a generic processor will ensure product consistency for the users, regardless of the ESA processing centre selected (same format and processing algorithm) and will simplify product validation and future product upgrade cycles.

One of the key new features of the ASAR processor is its ability to generate medium-resolution (150 m) and low-resolution (1 km) products, with their corresponding browse images, in long strips without geometric or radiometric discontinuity. These strip-line image products represent processed data from an entire acquisition segment of up to 10 min for the Image, Alternating-Polarisation and Wide-Swath modes, and up to a complete orbit for the Global-Monitoring and Wave modes. The product format allows the user to select any scene along-track within the processed segment, without any framing constraints.

To meet the high image-quality requirements, the range-Doppler algorithm is used for the Image mode precision, complex and geo-coded products, for the Alternating-Polarisation mode complex products (with few modifications with respect to the standard range-Doppler algorithm), and for the Wave-mode imagettes. The SPECAN algorithm is used for the non-complex Alternating-Polarisation products and for Wide-Swath and Global-Monitoring modes. Because of its computational efficiency, SPECAN is also used for all medium-resolution products.

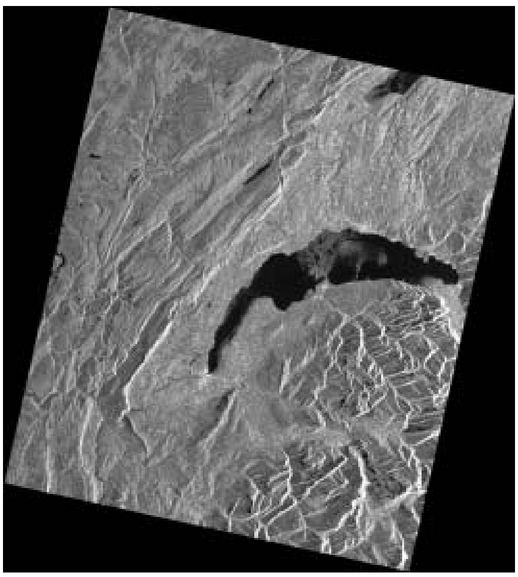


Figure 4. Example of an Image-mode geocoded product showing the Geneva area (from ERS raw data)

Wave-mode imagettes are further processed to the Image cross-spectra and to the Level-2 Wave spectra products via an inversion scheme without the use of any prior information.

Figure 5. Example of an Image-mode medium-resolution product, showing the Ellsworth Highland, Antarctica (from ERS raw data)

The processor computes the replica of the transmitted pulse from the calibration pulse measurements, the row patterns as characterised on the ground, and the external characterisation data. The reconstructed replica tracks variations in the transmit and receive chains and is used to determine the range reference function for compression processing

Noise samples are available in the ASAR source packets at the beginning and end of any acquisition segment and, depending upon the mode, also at regular intervals during the acquisition. They are used to estimate the noise power, which is annotated in the product. No noise subtraction is performed at this stage.

The auxiliary information required by the ASAR processor to perform data decoding, chirp reconstruction and any other correction during the processing (such as the elevation antenna-pattern correction) is provided through auxiliary files. The ASAR auxiliary files are available as standard products, with a certain period of validity (which is annotated in the product) and are generated by dedicated calibration facilities.

The ground processor includes a Doppler Centroid Estimator with a specified accuracy of 50 Hz for the Image and Wave modes, as for ERS, and 25 Hz in the ScanSAR modes in order to limit radiometric errors in azimuth.

The ASAR processor will be used to ensure systematic processing in near-real time of all received high-rate data to generate medium-resolution and browse products. All Wave and Global-Monitoring mode data will also be systematically processed in near-real time.

Furthermore, the ASAR processor will allow high-resolution products to be processed from Image or Alternating-Polarisation acquisitions (Precision Images, Single-Look Complex or Ellipsoid Geo-coded products) in near-real time or off-line, depending on user requests. Figures 4 and 5 show examples of an Ellipsoid Geo-coded Image of Geneva and a Medium-Resolution Image over Ellsworth Highland (Antarctica).

The different products, their coverages and qualities are presented in Table 1.

Applications

Important applications of SAR, like *ocean monitoring and ship routing*, can be satisfied with amplitude images. Figure 6 shows oil spills around oil platforms in the North Sea. The spills

Table 1. ASAR product characteristics

Mode and Product Name	Nominal Resolution (m)	Pixel Spacing (m)	Coverage (km)	Product ENL
IM precision IMP	30 x 30	12.5 x 12.5	56-100 x 100	3.9
IM single look IMS	9 slant x 6	natural	56-100 x 100	1
IM geocoded IMG	30 x 30	12.5 x 12.5	100 x 100	3.9
IM medium resolution IMM	150 x 150	75 x 75	56-100 x 100	40
IM browse IMB	900 x 900	225 x 225	56-100 x 100	80
AP precision APP	30 x 30	12.5 x 12.5	56-100 x 100	1.9
AP single look APS	9 slant x 12	natural	56-100 x 100	1
AP geocoded APG	30 x 30	12.5 x 12.5	100 x 100	1.9
AP medium resolution APM	150 x 150	75 x 75	56-100 x 100	50
AP browse APB	900 x 900	225 x 225	56-100x100	75
WS medium resolution WSM	150 x 150	75 x 75	400 x400	12
WS browse WSB	1800 x 1800	900 x 900	400 x 400	57-62
WV imagette & cross spectra WVI	9 slant x 6	natural	5 x 5 to 10 x 5	1
WV cross spectra WVS	-	-	5 x 5 to 10 x 5	n/a
WV spectra WVW	-	-	5 x 5 to 10 x 5	n/a
GM image GM1	1000 x 1000	500 x 500	400 x 400	12
GM browse GMB	2000 x 2000	1000 x 1000	400 x 400	18-21

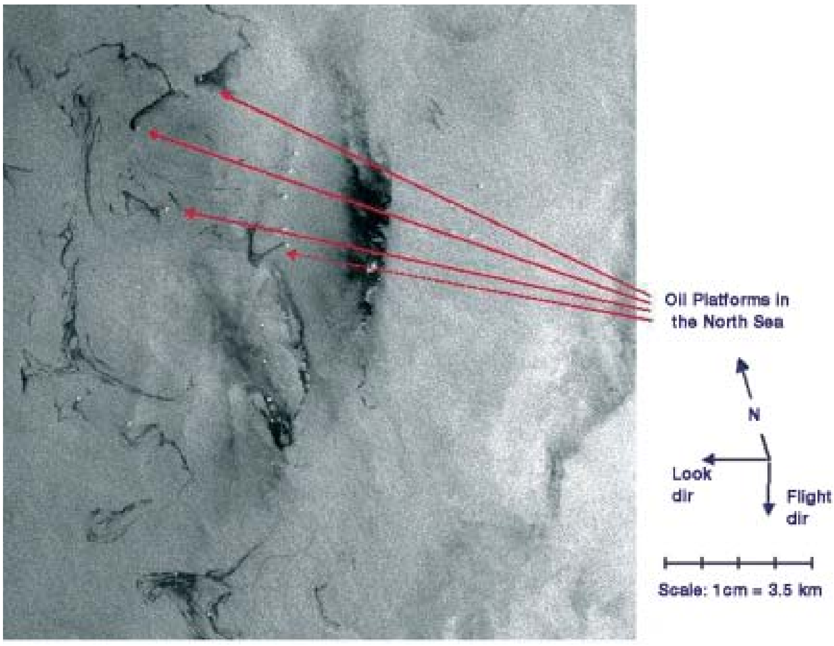


Figure 6. Oil spills detected by ERS-1 (courtesy of the Tromsø Satellite Station, Norway)

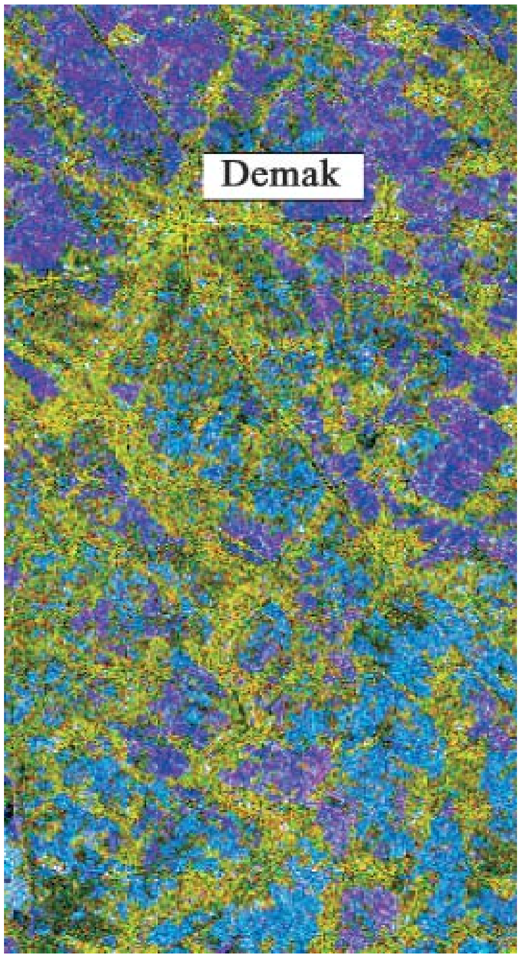


Figure 7. Rice map generated from multi-temporal ERS acquisitions over an area of Java: early rice (magenta), late rice (cyan) and non-rice (yellow) (courtesy of CESBIO, F)

are easily recognised because of their low backscatter, making them appear very dark in the image. Use of lower resolution modes (Wide-Swath and Global-Monitoring modes) provided from ASAR will offer the possibility to monitor larger areas with more frequent revisits.

Another application of high economic importance is sea-ice navigation. Radar-extracted *sea-ice information* can satisfy operational needs for navigation, offshore operations and weather forecasting. Radar images downloaded via the Internet are already being used in real time to organise ice-breaker interventions and to address vessel routes. The variable incidence angle can be used to enhance sea-ice edges. Changing polarisations will allow improved ice-type discrimination and will probably help in the forecasting of leads or ice-pack development.

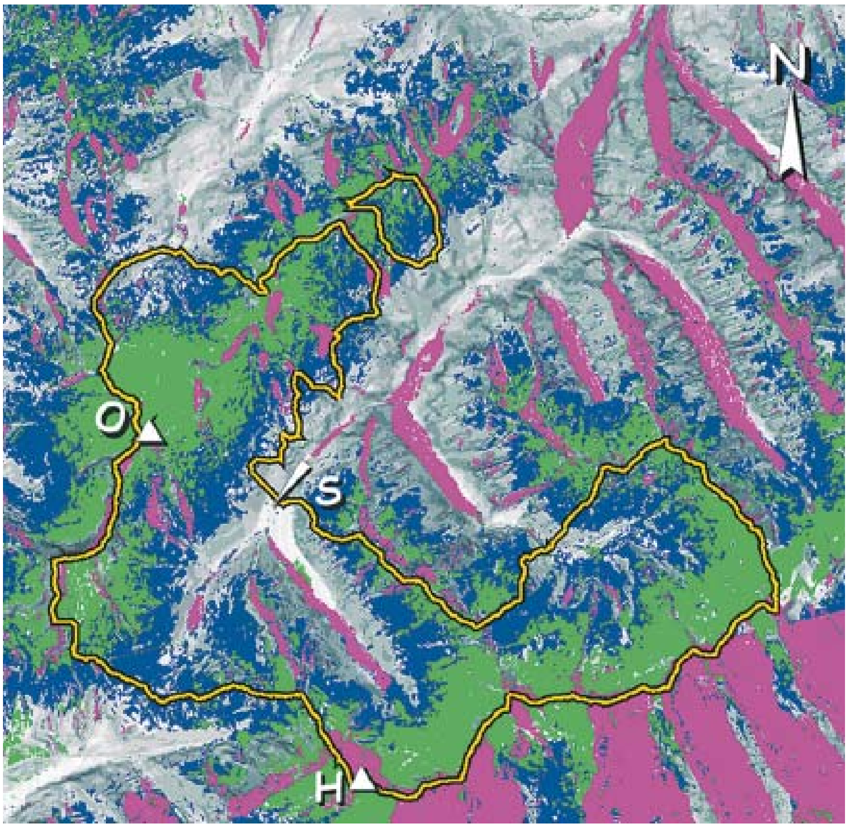


Figure 8. A snow map derived from ERS-2 ascending and descending passes over the Tyrolean Alps

Earth-surface classification is another important SAR application. Most agricultural crops, for example, show a very pronounced change in backscatter as a function of the plant's development. Figure 7 shows a colour-composite generated from multi-temporal ERS-1 SAR acquisitions over Java. Three classes can be easily separated: early rice (magenta), late rice (cyan) and non-rice (yellow). Similar techniques can be used for vegetation, snow and ice monitoring.

The *extent of snow-covered areas* is a key parameter for snow-melt run-off modelling and forecasting. Because SAR sensors provide repeat-pass observations irrespective of cloud cover, they are of particular interest for this application. At C-band, dry snow is transparent and backscatter from rough surfaces below the snow pack dominates. This is why the return signals from dry snow and snow-free areas are very similar. When the snow becomes wet, the

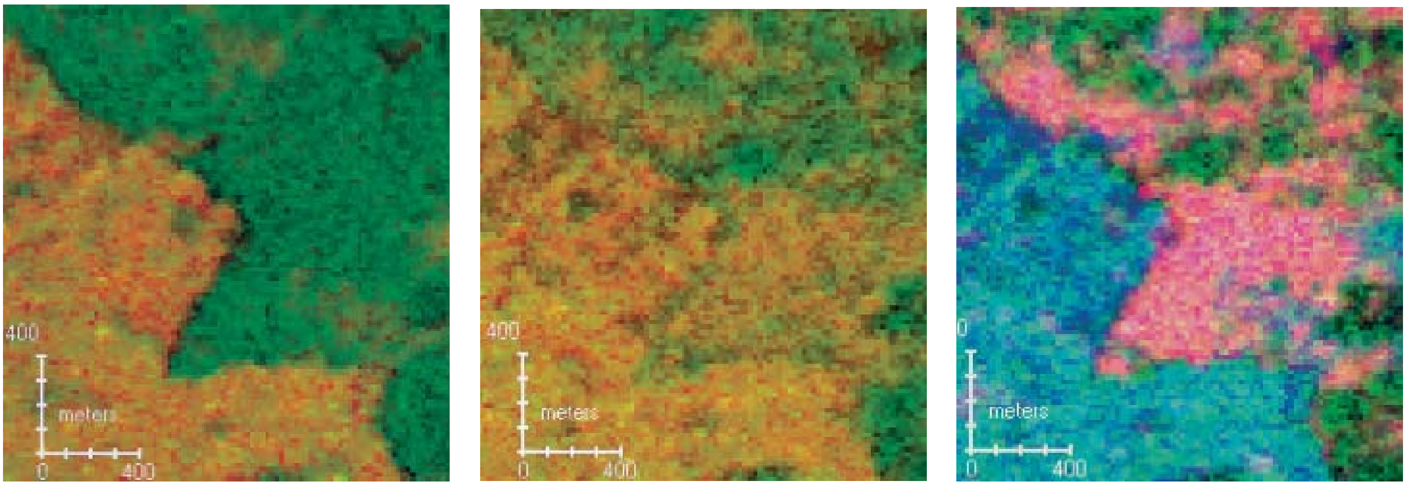


Figure 9. ERS tandem coherence before (left) and after (centre) a storm and the coherence change (right): damaged areas appear in pink tones (courtesy of SERTIT, F)

backscatter decreases significantly. Hence, wet snow can be detected by the temporal backscatter changes when compared to dry snow or snow-free conditions. An example of a snow map derived from ERS-2 ascending and descending passes is shown in Figure 8.

The ASAR's new Alternating-Polarisation mode will increase the number of independent measurements and further enhance the classification capabilities.

Interferometric coherence depends on the stability of the geometric distribution of scatterers, and is therefore very sensitive to surface changes and hence very useful for change detection. The fact that coherence is highly dependent on canopy depth (high for bare soil and low for dense forests) is exploited for vegetation classification.

Storm impacts on forest patches result in an increased level of coherence. By comparing the coherences before and after the storm, the affected areas can easily be identified (Fig. 9). This technique allows *forest-damage assessment* following disastrous storm events.

Floods represent one of the most severe risks for human life and property (Fig. 10). The forecasting, mapping and simulation of floods is therefore essential for the successful planning and operation of civil-protection measures (e.g. for dams, reservoirs) and for early flood warnings (evacuation management).

Hydrological modelling for flood forecasting makes use of interferometrically derived elevation models, soil maps and *soil-moisture* information derived from SAR data. Soil-moisture information is relevant for run-off modelling because it determines the extent of saturation of the watershed, and hence the partitioning of rainfall into surface run-off and infiltration.

The ERS-1/2 missions have successfully demonstrated that the radar cross-section measured over the oceans can be related to wind field. When the ASAR is operated in Wave mode, small areas of the ocean are imaged at regular intervals along the swath and high-resolution complex vignettes are gathered. The retrieval of wind and wave fields is based on dividing the SAR image into a non-linear and a linear part, where the non-linear part is mainly wind-driven and the linear part mainly swell-driven.

The new wind-retrieval methodology is based on using an inter-look processing technique. The time de-correlation measured from the azimuth cut-off of the cross spectrum can be shown to be related to the local wind speed,

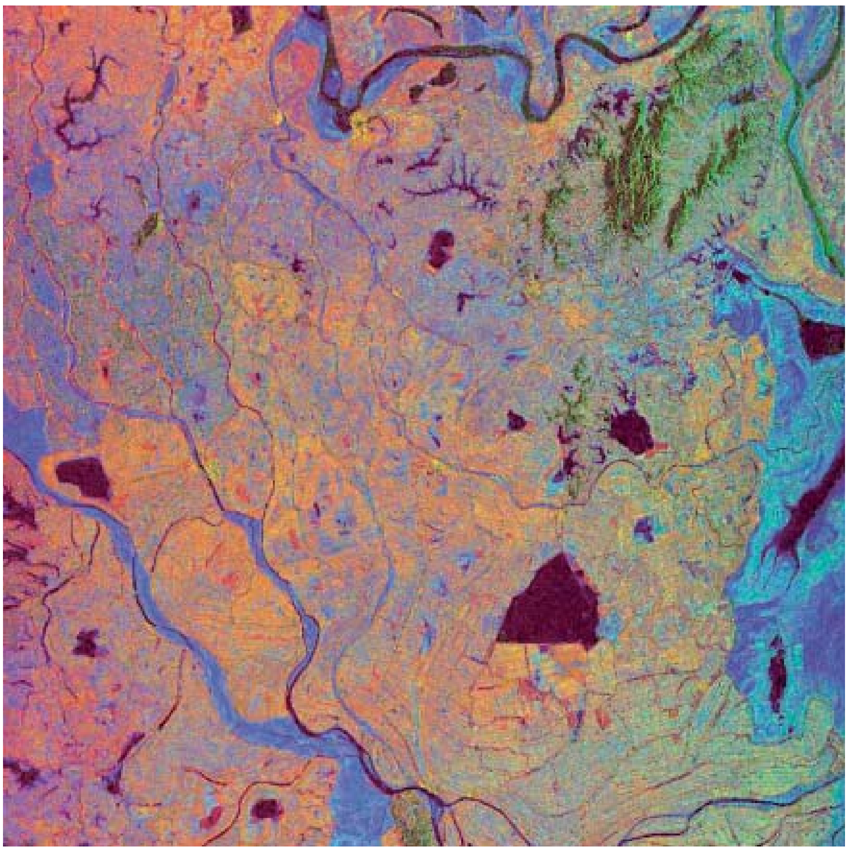


Figure 10. Extent of flooding (blue) around the Yangtze River, highlighted by comparing the coherences of two ERS images from 1995 with two from August 1998
R = coherence in 1998, G = intensity, B = difference in coherence 1998-1995

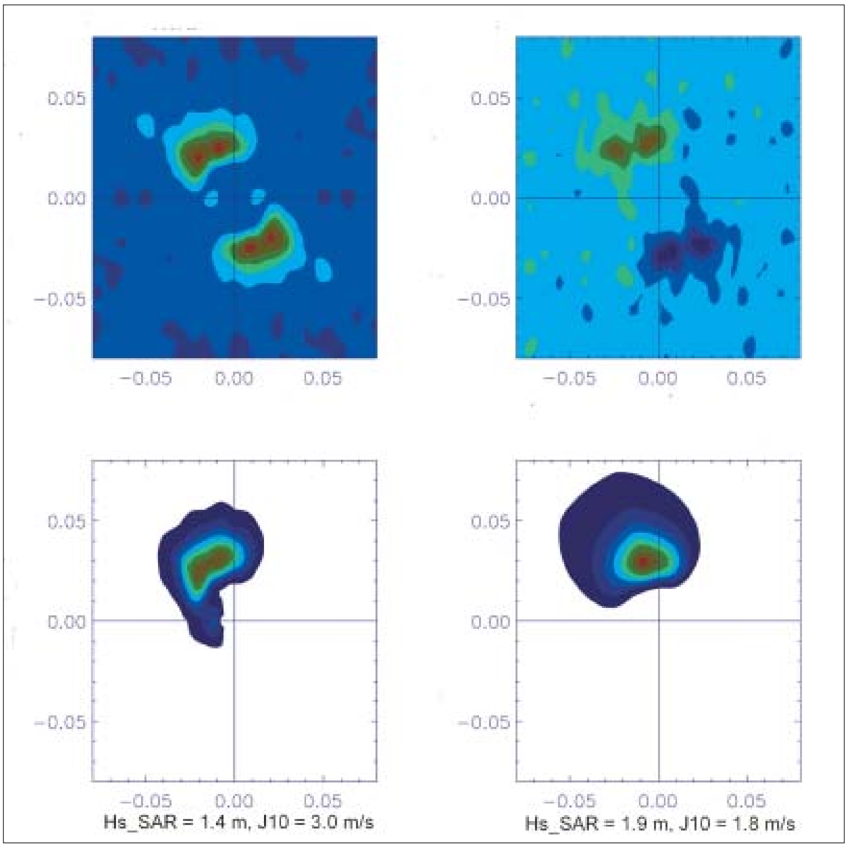


Figure 11. Real (top left) and imaginary (top right) parts of an image cross-spectrum (from ERS data), retrieved wave spectrum (lower left) and modelled spectrum (lower right) for comparison (Hs_SAR = wave height, J10 = wind speed) (courtesy of NORUT, N)

and the phase spectrum of the non-linear part can be used to approximate the wind direction (Fig. 11). These new methodologies will provide meteorological users with wave directional and geophysical parameters and wind parameters, and can also constitute the basis for a future wind-retrieval algorithm tailored to the high-resolution Image-mode data of the ASAR instrument.

Interferometry represents one of the most innovative applications of SAR, and ERS-1 and ERS-2 have made a crucial contribution to the demonstration of this technique. The ERS tandem dataset covers most of the Earth's land and ice surfaces. Digital Elevation Models (DEMs) can be extracted from the interferometric data with an accuracy of up to 5 m, depending upon the terrain's topography and surface-cover coherence (Fig. 12).

Differential interferometry also allows the quantification of surface dislocation and subsidence due to earthquakes and mining activities on a regional scale and with millimetre accuracy. This highly sensitive technique requires acquisitions before and after the surface deformation, and a third image to obtain a reference DEM (existing highly accurate topographic data may also be used).

Figure 12. High-precision Digital Elevation Model of Bachu (China), derived from ERS tandem data (courtesy of DLR, D)

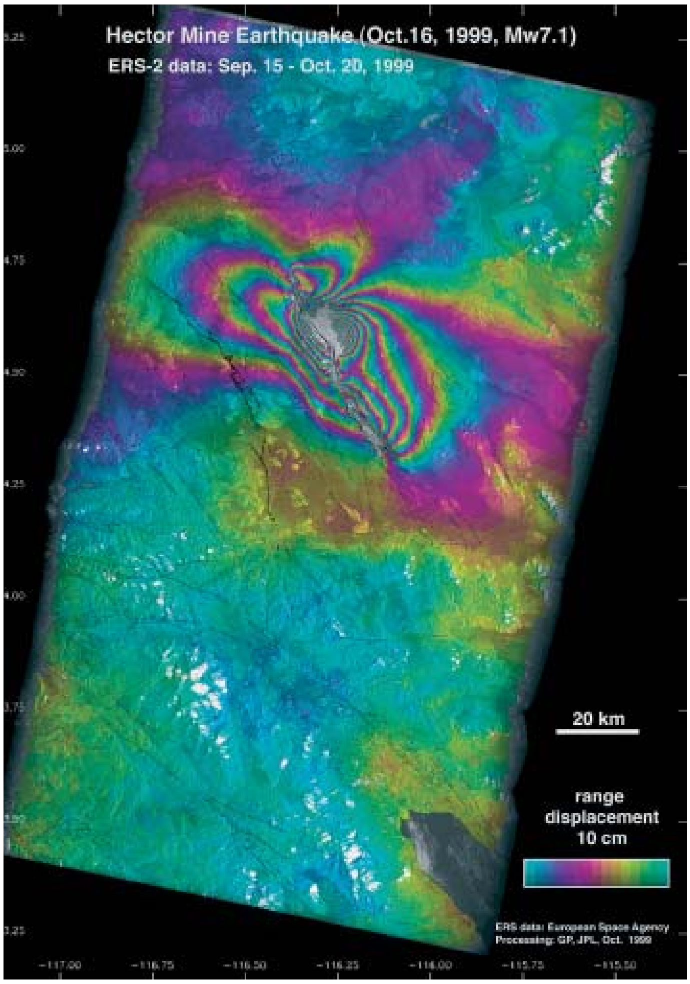


Figure 13. Interferometric map of the Hector Mine earthquake (1999) area in California showing the ground displacement along the radar line of sight. One full colour cycle represents 10 cm of range displacement (courtesy of JPL, USA)

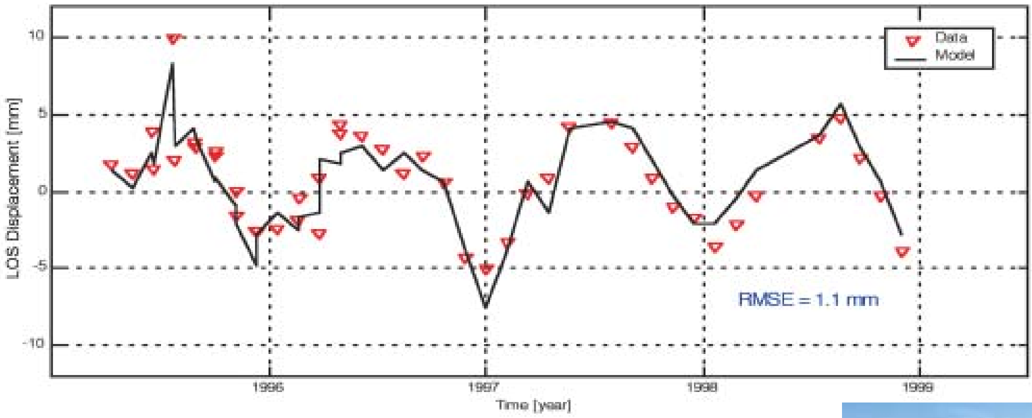


Figure 14. Measured line-of-sight displacement of the La Vilette Science Museum in Paris, compared to the modelled displacement due to temperature variations (courtesy of Politecnico di Milano, I)

This technique has also been applied to the monitoring of glacier movements and to the estimation of the ice flow rates.

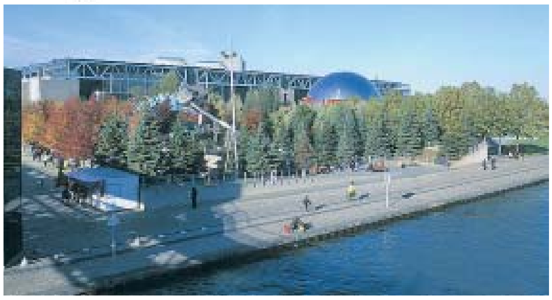
Figure 13 is an interferometric map of the Hector Mine earthquake area in California in 1999, showing the ground displacement along the radar line of sight. One full colour cycle represents 10 cm of range displacement. Dotted lines depict California faults, and the thick, solid lines indicate the Landers surface rupture in 1992. Thin, solid lines within zones of dense fringes are surface breaks inferred from azimuth and range disparities (offsets) between before and after images, and phase discontinuities. Co-seismic motion maps could be useful in the emergency response phase of disaster management in order to locate the areas with greatest potential damage (bigger measured ground deformation).

Almost ten years of ERS data made it possible to develop the so-called 'permanent-scatterer technique', which allows one to monitor any movement of these scatterers over several years. Typical permanent scatterers are buildings or other large man-made structures, which are coherent over very long time periods. Figure 14 shows the measured line-of-sight displacement of a large building (steel construction) in Paris, and in comparison the modelled displacement due to temperature variations. The RMS error is 1.1 mm.

Long-term availability of ASAR data will guarantee further exploitation and development of such applications. Interferometric combinations of the ASAR Image and Wide-Swath modes will allow co-seismic motion retrieval by means of low-resolution interferometry.

Conclusion

The ASAR instrument is characterised by extensive flexibility thanks to its five operational modes, its ability to image in horizontal and vertical polarisations, the wide range of incidence angles covered, and the possibility to shape the antenna beam in both transmit and receive by controlling the amplitudes and phases of each of the 320 transmit/receive modules individually.



In order to achieve the required performance and operational flexibility, a large number of new technologies, processes and components have been qualified.

All acquired data will be processed in the ESA ground segment by a generic processor to ensure product consistency irrespective of the processing centre. A large number of ASAR products will be routinely produced and will be made available to the users. ASAR will therefore be an invaluable tool for Earth observation, capable of supporting the following principal applications:
– agricultural, forest, and soil-moisture monitoring
– detecting land-use changes
– responding to natural hazards
– geological exploration
– topographic mapping
– surface-deformation measurements

This large number of applications qualifies ASAR as a precursor to future Earth Watch missions.

Acknowledgements

Many European industries have participated in the efforts required to develop the largest single instrument (and associated ground-processing chain) ever built in Europe for remote-sensing applications. We must limit ourselves here to mentioning only the major industrial contractors: Astrium-Ltd (Instrument Prime), Alcatel Space Industries (Tile Sub-System), Alenia Aerospazio (CESA) and, for the ASAR Ground Processor, MDA as a sub-contractor of Alcatel Space Industries (PDS Prime Contractor).