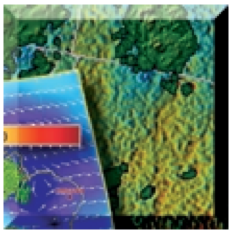

Synthetic Aperture Radar in Europe: ERS, Envisat, and Beyond

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Following the successful Seasat project in 1978, the European Space Agency used advanced microwave radar techniques on the European Remote Sensing satellites ERS-1 (1991) and ERS-2 (1995) to provide global and repetitive observations, irrespective of cloud or sunlight conditions, for the scientific study of the Earth's environment. The ERS synthetic aperture radars (SARs) demonstrated for the first time the feasibility of a highly stable SAR instrument in orbit and the significance of a long-term, reliable mission. The ERS program has created opportunities for scientific discovery, has revolutionized many Earth science disciplines, and has initiated commercial applications. Another European SAR, the Advanced SAR (ASAR), is expected to be launched on Envisat in late 2000, thus ensuring the continuation of SAR data provision in C band but with important new capabilities. To maximize the use of the data, a new data policy for ERS and Envisat has been adopted. In addition, a new Earth observation program, The Living Planet, will follow Envisat, offering opportunities for SAR science and applications well into the future. (Keywords: European Remote Sensing satellite, Living Planet, Synthetic aperture radar.)

INTRODUCTION

In Europe, synthetic aperture radar (SAR) technology for polar-orbiting satellites has been developed in the framework of the Earth observation programs of the European Space Agency (ESA). Currently, two European Remote Sensing satellites (ERS-1 and -2) carrying SAR are in orbit, and a new satellite, Envisat, is being prepared for launch in late 2000. Also, the Meteorological Operational (METOP) satellite, developed jointly with Eumetsat, is part of ESA's current program of polar-orbiting satellites. The operational Earth Watch component of the new Earth observation program, The Living Planet, and possibly the scientific Earth Explorer component will include future SAR missions. As shown in Fig. 1, the polar-orbiting program of ESA provides for continuous provision of SAR data to the scientific and operational user community. This article gives an overview of the ERS and Envisat programs, as well as plans for SAR instruments in the framework of The Living Planet Program. The history of the programs is discussed, the different SAR

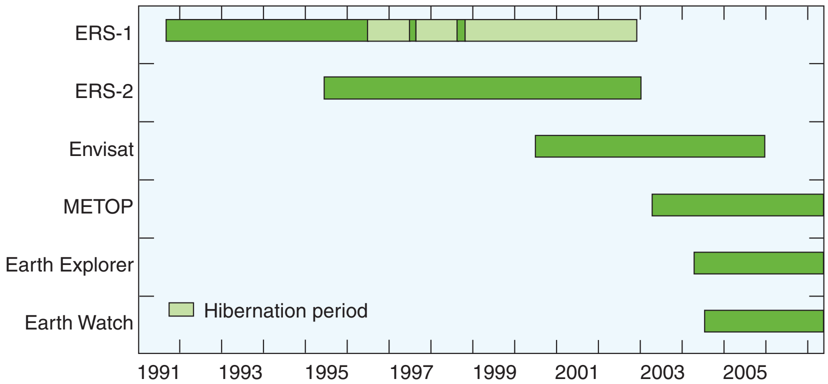

Figure 1. ESA polar-orbiting Earth observation missions (METOP = Meteorological Operational, ERS = European Remote Sensing satellite).

instruments are described, and the results of the ERS Program to date are summarized.

THE ERS MISSION

Satellite Overview

ESA is currently operating two ERS satellites in orbit: ERS-1 and ERS-2. ERS-1 was launched on 17 July 1991 into a Sun-synchronous polar orbit, and ERS-2 was launched on 21 April 1995. ERS-2 is currently the operational satellite, and ERS-1 has been kept in hibernation since mid-1996 as indicated in Fig. 1. The ERS-1 payload consists of the following:

- *Active Microwave Instrumentation (AMI)*. Includes a SAR and a wind scatterometer, both operating in C band, having vertical polarization, using common hardware in a timesharing fashion, and providing imagery of the Earth's surface, wind speed, and direction measurements on the ocean surface. AMI also provides information about the directional spectrum of ocean waves and significant waveheight.
- *Radar Altimeter*. Provides accurate measurements of sea surface elevation, significant waveheight, sea surface wind speed, and various sea ice parameters.
- *Along-Track Scanning Radiometer and Microwave Sounder (ATSR-M)*. Combines infrared and microwave sensors for the measurement of sea surface temperature, cloud-top temperature, cloud cover, and atmospheric water vapor.
- *Precise range and range-rate equipment*. Provides accurate determination of satellite position and orbit characteristics. It is also used for geodetic applications.
- *Laser Retro-Reflector*. Enables measurements of satellite position and orbit using on-ground laser ranging stations.

The ERS-2 payload is essentially the same as ERS-1 except that it includes a number of enhancements and a new instrument, known as the Global Ozone Monitoring Experiment, to measure the chemical composition of the atmosphere. The ATSR-M has been enhanced for ERS-2 by including visible channels for vegetation monitoring.

Initially the ERS Program was not strictly user-driven, but was more oriented toward research and development because ESA is a research and development agency. However, support for the ERS satellites, and in particular the SAR, was the result of a fortunate combination of technological interests, recommendations from scientific organizations and individuals, as well as the strong belief in the observational needs and market potential for Earth observation data products.

Objectives

Science and Applications

Scientific interest in the type of oceanographic measurements that ERS-1 was designed to make began to emerge in the 1960s, and the requirement for supporting marine operations became a general driver for the development of new spaceborne observation techniques. A series of conferences brought together the observation requirements for oceanography, and these were consolidated at a conference at the Woods Hole Oceanographic Institution in 1972. This was one of the critical milestones in the development of requirements for ERS-1.

Although the objectives for the eventual ERS-1 configuration were predominantly oceanographic, it is important to stress that a wide range of possible options were considered in the period leading up to the specification of the mission. In 1974, ESA established a Remote Sensing Advisory Group, which defined user requirements for a European remote-sensing mission. Interestingly, the emphasis at that stage was on commercial applications, with disciplinary panels concentrating on areas such as agriculture, land use, water resources, overseas aid, and mineral resource exploitation.

The balance of requirements from commercially oriented applications to science was refocused in 1980 with the initiation of the World Climate Research Program. A growing public awareness of issues associated with climate dynamics and possible human influences led to the development of this major international program aimed at developing a fundamental scientific understanding of the climate system and climate processes. The potential for a European Earth observation satellite to make a major contribution to this program was recognized and taken into account during the further definition of mission objectives. A specific contribution of ERS-1 to the World Ocean Circulation Experiment was also foreseen. This major scientific program, whose observation phase began in 1990, was in the early stages of planning during the specification of ERS-1.

Official Objectives

After approval of the ERS mission by the ESA member states in March 1981, the ERS mission objectives were finalized following subsequent modifications of the payload complement in 1981 and 1982. They are reproduced verbatim below in order to facilitate a comparison of the current spaceborne remote sensing achievements and the expectations in the early 1980s.

> ERS-1 will be the European Space Agency's first satellite devoted entirely to remote sensing from a polar orbit. It will be a forerunner of a new generation of space missions planned for the 1990's which will make a substantial contribution to the scientific study of our environment. ERS-1 will provide global and repetitive observations of the environment using advanced microwave techniques which will enable measurements to be made and imaging to take place irrespective of cloud or sunlight conditions. The satellite will measure many parameters not covered by other existing satellite systems, including those of sea-state, sea-surface winds, ocean circulation and sea/ice levels. Sea-surface temperatures can also be measured to a greater degree of accuracy than with any other current space system. Much of the data collected will be from remote areas such as the Polar Regions and the southern oceans, for which there is little comparable information available to date. Data generated by the ERS-1 mission will contribute to the:
>
> - understanding of ocean-atmosphere interactions
> - knowledge of ocean circulation and the transfer of energy
> - more reliable estimates of the mass balance of the Arctic and the Antarctic ice sheet
> - monitoring of dynamic coastal processes and pollution
> - detection and management of land use change.
>
> The system has also been designed to satisfy operational requirements for data products to be delivered within a few hours of the observations being made. This is expected to make significant contributions to operational meteorology, sea-state forecasting and monitoring of sea-ice distribution which are important for shipping and offshore activities. The altimetric and precise tracking data will provide information which is valuable for geodetic applications.

Synthetic Aperture Radar

Selection

Although the final selection of the ERS-1 payload was influenced by Seasat, interest in microwave observation techniques had already emerged in Europe in the early to mid-1970s. This interest was reflected in ESA studies that demonstrated the feasibility of building a SAR in Europe. Three possible missions were proposed: GOMSS (Global Ocean Monitoring Satellite System), LASS (Land Applications Satellite System), and COMSS (Coastal Ocean Monitoring Satellite System), all of which included a SAR instrument as part of the payload. The end of the initial Phase A studies coincided with the untimely failure of Seasat, but the period of Seasat's operation was sufficient to generate considerable interest in the measurements it had started to make.

As a result, pressure developed to modify the COMSS concept, which formed the basis for ERS-1, to include a radar altimeter and a scatterometer. The proliferation of instrument options meant that trade-offs were inevitable in order to select a payload complement compatible with mass, power, and physical accommodation constraints of the selected ERS platform and with the program budget. When decisions had to be made about the final payload, studies were conducted to consider the possibilities of both wind and wave scatterometers. It was then realized that it would be possible, given an appropriate design, to include a wind scatterometer and to use the SAR to provide the functionality of a wave scatterometer. This was achieved through the inclusion of the wave mode for the SAR, which operated in an interleaved mode to provide both wind and wave information. This option, chosen for the final payload, brought the SAR onboard the ERS satellites.

Characteristics

The SARs on the ERS satellites are part of the AMI, a multimode radar operating at a frequency of 5.3 GHz (C band), using vertically polarized antennas for both transmission and reception. In image mode, the AMI is configured as a SAR and provides telemetry data, later to be processed into radar images of ocean, ice, and land 100 km in width, 250 km to the right of the subsatellite track, and with a mid-swath incidence angle of 23°. The spatial resolution is about 25 m across track and 6 m along track. In order to reduce speckle, a typical SAR processor averages the intensity of individual pixels to improve image quality at the expense of spatial resolution. This is called "multilooking." A typical standard three-look image is 100×100 km in size and has a 25×25 m spatial resolution. The output data rate in this mode (105 Mbit/s) is too high to be recorded onboard; this mode can therefore be used when within the visibility pattern of a ground station equipped for reception of ERS SAR data. Through bilateral agreements with a large number of stations worldwide and with the use of a number of transportable receiving stations, full global coverage of the land surface and major portions of the ocean was achieved.

In wave mode, the AMI is also configured as a SAR, as in the image mode. The important difference is that the data rate at the output is reduced to 345 kbit/s, which makes it suitable for onboard recording and, consequently, the wave mode can be operated globally. The reduction of the data rate is achieved through reduction of the image size and the resolution of the digitizer of the detector. When in the wave mode, an image of typically 10 × 5 km is taken at 200-km intervals along the orbit. The spatial resolution of the wave mode is identical to that of the image mode. Normally the wave mode is operated in multiplex with the wind scatterometer. The main purpose of this mode is to take radar "snapshots" over the ocean to measure the ocean wave patterns in terms of the directional spectrum of the ocean waves; however, this mode can also be used over land. The wave mode "imagettes" can be positioned anywhere within the image mode swath.

Absolute radiometric calibration. Absolute radiometric calibration, vital to many applications of SAR, has been an objective throughout the development of the program. This calibration was achieved through a design that ensured excellent instrument stability and minimized the effect of signal distortions and the level of spurious signals. In addition, the SAR ground processors are equipped with tools to correct system imperfections, as required for the specified image quality. The information necessary to provide these corrections is derived from prelaunch characterization of the instrument from an onboard internal calibration system measuring the gain drift during each imaging sequence and from receiver noise measurements.

To complement this activity, the performance of the instrument must be assessed as a whole by measuring the absolute system gain and by monitoring gain variations outside the internal calibration loop. This is achieved by imaging reference targets. For ERS, high-precision active radar calibration (ARC) units were developed. These units act as a transponder receiving the SAR signal and returning an amplified and delayed replica back to the satellite, which appears in the image as a bright spot of known radar cross section while standing out well against the background of the surrounding area. The transponder calibration gives excellent absolute gain calibration and also provides data for the estimation of antenna beam-pointing biases.

The limited number of locations of the transponders across the image track means that it is necessary to supplement this work by considering the images of areas that have been found to be stable, distributed scatterers of C band at vertical polarization through airborne campaigns. The best area of this type was found in the South American rain forest and, accordingly, this has been chosen to determine variations in the SAR antenna pattern.

Finally, by including analogue-to-digital converter nonlinearity corrections, the ERS image products achieve a radiometric stability of 0.2 dB (standard deviation) with an absolute bias of less than 0.2 dB, which is largely determined by the calibration accuracy of the ARC units (0.14 dB). In view of this, the calibration constants are given within maximum bounds of ±0.4 dB, well within specification.

Geophysical data products. At the time of the ERS program approval, the ESA project commitment was restricted to the so-called level 1b SAR products, calibrated images from the image mode, and two-dimensional image spectra from the wave mode. The reason for this restriction was that retrieval algorithms used for the estimation of geophysical parameters from radar images, including the "real" spectrum of ocean surface waves, were still subject to scientific debate. Therefore, there was only limited geophysical validation for the SAR, unlike for the wind scatterometer for which an operational wind retrieval model was developed. This model was supported by extensive validation using both dedicated campaigns of correlative measurements and data assimilation in numerical weather prediction models. In the meantime, retrieval algorithms have been developed and validated for directional ocean wave spectra. These algorithms are based on iterative data assimilation into global wave models to account for distortions of the spectra due to the SAR imaging mechanism of the ocean surface.

ERS SAR interferometry. In addition to radiometric stability, a SAR instrument has to have good inherent phase stability because the image formation process of a SAR involves coherent processing of echo signals to produce well-focused imagery. Thus, two or more complex SAR images retaining both amplitude and phase of the echo signals are, in principle, suitable for SAR interferometry. However, this requires good phase performance of all system components, sufficient frequency stability of the internal reference clock, and good platform stability. Although not a mission objective, the ERS SARs have proved capable of supporting SAR interferometry very well, thereby opening up an entirely new field of SAR applications. This capability was demonstrated when both ERS-1 and -2 were used in tandem to provide 1-day repeat observations globally.

Results

Following the excellent instrument performance of the ERS SARs, which have greatly exceeded the projected 3-year lifetime, the ERS Program has created exciting new opportunities for scientific discovery within the international science community and has initiated commercial applications of SAR data. The original focus was on oceans and ice monitoring, and an impressive range of scientific investigations has been carried out in oceanography, polar science, glaciology, and climate research. However, operational systems have since been developed for sea ice mapping, oil slick monitoring, and ship detection.

Additionally, a large number of land applications have emerged, several based on important developments in SAR interferometry. SAR data are also being used for agricultural monitoring, forest mapping, geological exploration, and flood mapping, while SAR measurements of topography and small topographic changes are making major contributions to environmental risk assessment involving earthquakes and land subsidence.

Scientific data exploitation and application demonstrations were supported by ESA in the framework of a series of Announcements of Opportunity. Since the launch of ERS-1, approximately 32,000 free SAR scenes have been delivered to scientists, and approximately 8,000 have been delivered to the leaders of application demonstration projects. The attendance and the number of papers at dedicated ERS symposia and workshops (Fig. 2) also reflect the success of the ERS SAR mission.

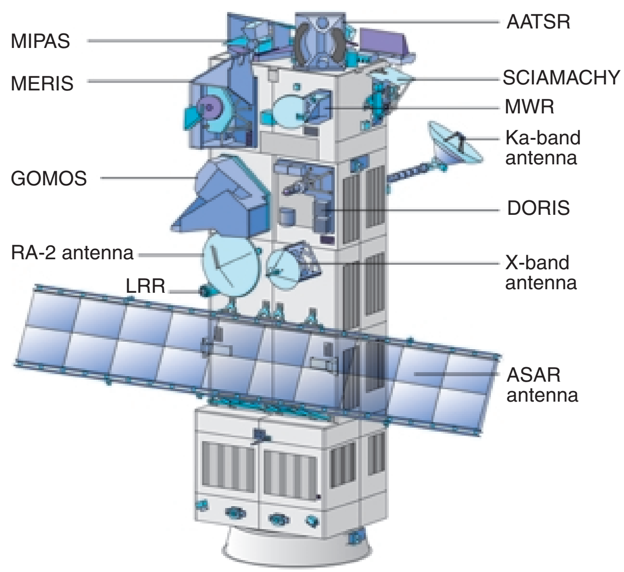

Figure 3. Envisat and its 10 major instruments.

THE ENVISAT MISSION

Envisat and METOP emerged as viable ERS follow-on missions after a critical review of even more ambitious concepts involving international polar platforms docking at a manned space station for in-orbit refurbishment. Envisat is an advanced, Earth-observing satellite designed to provide measurements of the atmosphere, ocean, land, and ice over a 5-year period. It will provide direct continuity of measurement with most ERS instruments (except the advanced scatterometer, which is on METOP), thereby extending to more than 10 years the long-term data sets critical for global environmental monitoring, and furthering many operational and commercial applications. Envisat will be launched in late 2000 from the Kourou Space Center in French Guiana by an Ariane-5 launch vehicle. It has a payload mass of over 2000 kg and includes the following 10 major instruments (Fig. 3):

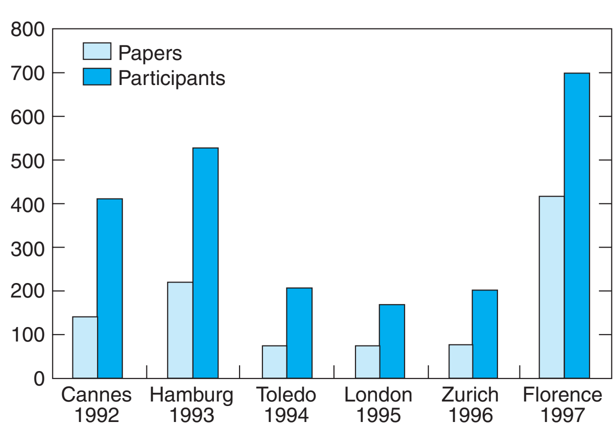

Figure 2. ERS symposia and workshops (1992–1997).

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

The Envisat mission has both global and regional objectives, which make it necessary to provide data to scientific and application users on various time scales. Some of the regional objectives (e.g., sea ice applications, marine pollution, maritime traffic, hazard monitoring) require near–real-time data distribution within a few hours from sensing; others, such as agriculture and soil moisture mapping, require data turnaround in a few days. The remainder can be satisfied with off-line data delivery a few weeks later. Important contributions of 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
- Monitoring natural and man-made ocean pollution

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

Compared with the ERS SAR, which is a single-channel, fixed-geometry instrument, ASAR represents a step forward in both system flexibility and the scientific value of its data sets. It offers several major technical features:

- Instrument enhancements include a digital chirp generator and an improved linear dynamic range.
- Flexible swath positioning offers the choice among several image swath positions at various distances from the subsatellite track, with different incidence angles.
- Dual polarization offers simultaneous operation at horizontal, vertical, and cross-polarization combinations (horizontal and vertical, horizontal and horizontal–vertical, or vertical and vertical–horizontal).
- Wide swath coverage offers a 405-km swath with 150-m or 1-km resolution.
- Enhanced wave mode acquires imagettes at 100-km intervals along track.
- Extended operating time is available at high resolution (30 min of operation, 10 min in eclipse).
- Global SAR coverage is possible using a solid-state recorder and a data relay satellite.

The operating modes and observation geometry of ASAR are depicted in Fig. 4. ASAR will provide continuity of the ERS SAR image and wave modes, but with the opportunity for better temporal frequency of coverage. The nominal 30-m spatial resolution and swath coverage of ASAR image mode (100 km) and wave mode (5 km) are the same as the ERS image mode, and ASAR will also be in a 35-day repeat orbit. However, using beam steering, it will be possible to obtain images of the same area on the ground from

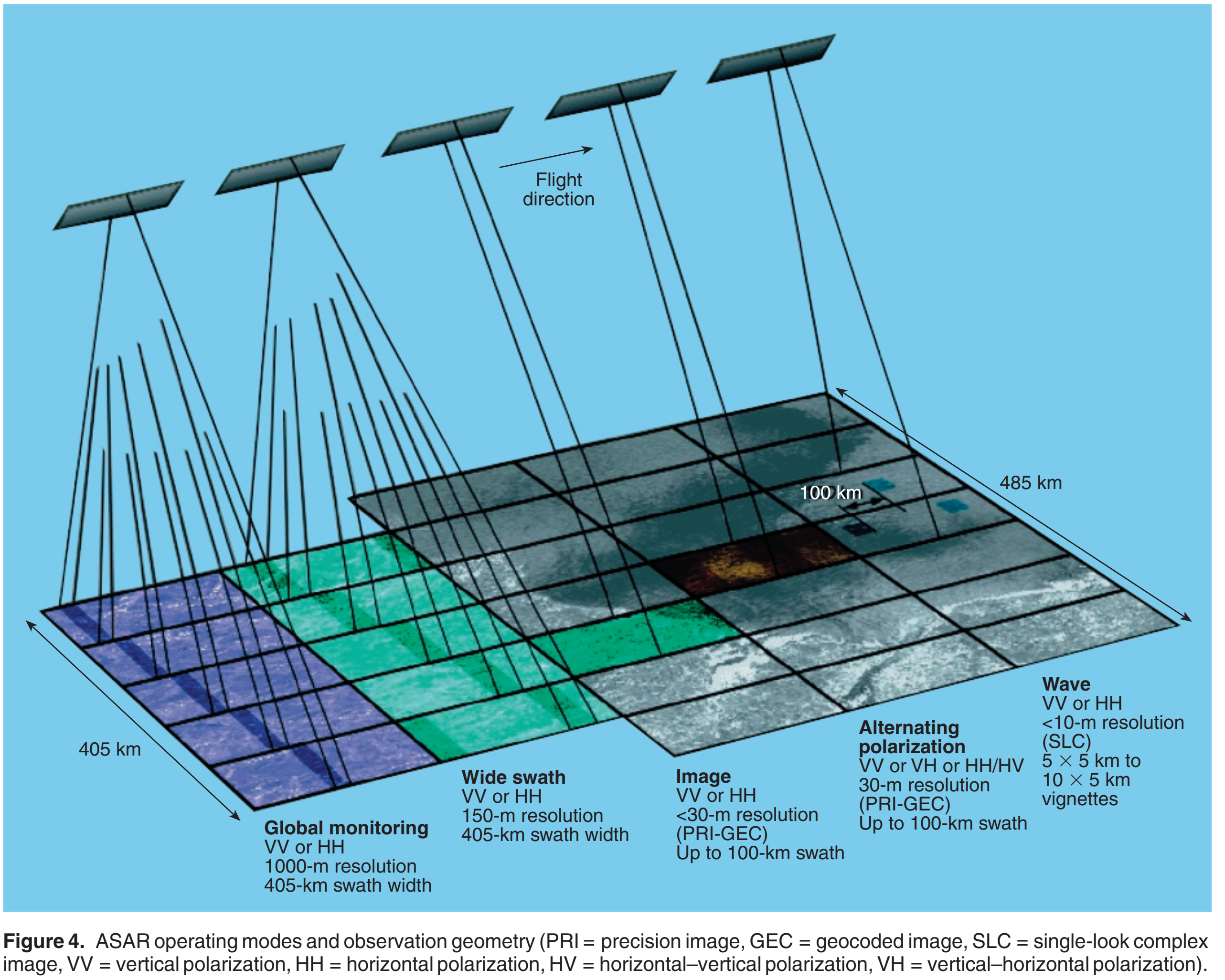

Figure 4. ASAR operating modes and observation geometry (PRI = precision image, GEC = geocoded image, SLC = single-look complex image, VV = vertical polarization, HH = horizontal polarization, HV = horizontal–vertical polarization, VH = vertical–horizontal polarization).

different orbits. This gives a revisit frequency varying from daily coverage near the poles to weekly coverage at the equator.

ASAR has dual-polarization capabilities, and a special alternating polarization mode has been implemented that enables half of the looks at a scene to be acquired with horizontal polarization and half with vertical polarization. This mode considerably increases the target classification capability (especially if used with multitemporal imaging). Wide-area coverage will be achieved by switching between different swaths using the ScanSAR technique. This switching will allow 405-km coverage at resolutions of either 150 m or 1 km. At the 1-km resolution, the data rate is low enough for tape recording onboard the spacecraft, and the recording capacity will be sufficient for downloading low-resolution global coverage through a single receiving station.

Special attention has been focused on the Envisat ground segment in order to provide consistent, high-quality data products and rapid turnaround times. Data services will include on-line data search, browsing, and ordering. A system will be established for delivery of large, near–real-time data products.

In view of the new technology necessary for the ASAR's distributed power antenna concept, it has been a challenge to design ASAR with the same accuracy and stability specifications as ERS. Although the same basic approach to calibration was followed, completely new ARC units were developed to deal with in-orbit antenna characterization after possible instability or failure of one of the antenna transmit/receive modules. Current performance predictions, based on prelaunch measurements, indicate that the ASAR's performance will be comparable to the AMI over a much wider range of incidence angles.

THE LIVING PLANET

The ESA member states have recently approved a new Earth observation program, The Living Planet, which covers the whole spectrum of user interests ranging from scientific research through applications. The research-driven Earth Explorer missions will be paralleled by applications-driven Earth Watch missions designed to focus on specific Earth observation applications and service provision. SAR missions have been proposed in both the scientific and applications parts of the program. The emphasis of the science element is global biomass mapping using long-wavelength SAR at P band; in the applications aspect, studies have been initiated to explore the market potential and the technical feasibility of an operational SAR.

CONCLUDING REMARKS

The ERS and Envisat projects can only satisfy their mission objectives of scientific research and application demonstration, operational and commercial use of the data, and development of the market if the data products reach scientists and the operational and commercial users. Considering this fact, ESA member states (plus Canada) adopted a new data distribution policy for ERS and Envisat. The objectives of this policy are to maximize the use of the data and to stimulate a balanced development of science, public utility, and commercial applications.

The conditions for the distribution of data depend on the use of the data: category 1 (research and application development) or category 2 (all other uses, including operational and commercial use). The policy for data distribution is open and nondiscriminatory. ESA is responsible for the distribution of data for category 1 use and delegates to third parties the responsibility for marketing and distributing of data products for category 2 use. For category 1 use, ESA will fix the price of all ESA-generated products at or near the cost of reproduction with special waivers for Announcements of Opportunity. For category 2 use, ESA will fix the price of all ESA-generated products that are provided to selected distributing entities at a level comparable to the price for category 1 data. Distributing entities will be free to set prices for category 2 use. It is to be expected that category 2 data products will include value-added products in addition to SAR scenes.

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