MWR and DORIS – Supporting Envisat's Radar Altimetry Mission

J. Guijarro (MWR)
Envisat Project Division, ESA Directorate of Application Programmes.
ESTEC, Noordwijk, The Netherlands

A. Auriol, M. Costes, C. Jayles & P. Vincent (DORIS)
CNES, Toulouse, France

Following on from the great success of its ERS-1 and ERS-2 satellite missions, which have contributed to a much better understanding of the role that oceans and ice play in determining the global climate, ESA is currently preparing to launch Envisat, the largest European satellite to be built to date.

The Envisat altimetric mission objectives are addressed by the Radar Altimeter instrument (RA-2), complemented by the Microwave Radiometer (MWR), used to correct the error introduced by the Earth's troposphere, and by the Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) instrument. DORIS has been developed by CNES, and is already operational on several satellites. It will measure Envisat's orbit to an unprecedented accuracy, thereby serving as a major source of the improved performance that the RA-2 system will be able to achieve.

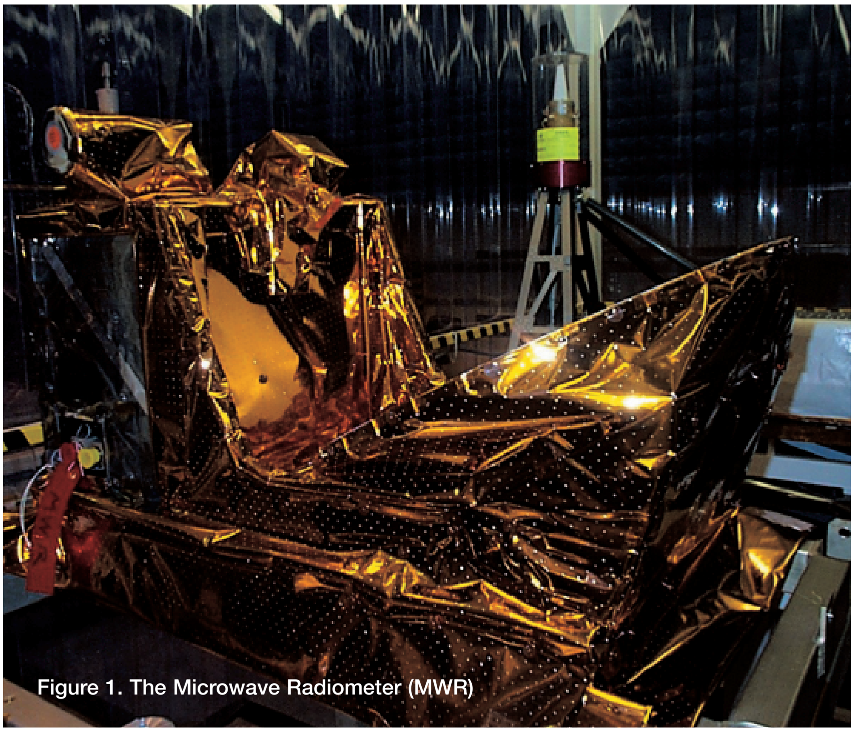


Figure 1. The Microwave Radiometer (MWR)

MWR

The mission

The Microwave Radiometer (MWR) is a two-channel passive radiometer operating at 23.8 and 36.5 GHz based on the Dicke principle. By receiving and analysing the Earth-generated and Earth-reflected radiation at these two frequencies, the instrument will measure the amount of water vapour and liquid water in the atmosphere, within a 20 km-diameter field of view immediately beneath Envisat's track. This information will provide the tropospheric path correction for the Radar Altimeter. The MWR measurements can also be used for the determination of surface emissivity and soil moisture over land, and in support of studies on surface energy budget and atmospheric and ice characterisation.

Instrument operation

The nadir-pointing antenna receives radiation at 23.8 and 36.5 GHz in linear polarisation. The antenna subsystem includes a 60-cm aluminium reflector with a focal length of 350 mm and an offset angle of 47 deg. Two feeds are used such that the 23.8 GHz channel is pointing in the forward direction and the 36.5 GHz channel in the backward direction, with a footprint of about 20 km diameter for each beam. These frequencies are separately routed into the RF front-end, where a two-point calibration scheme is adopted, with hot and cold references.

The deep cold-space measurements will be accomplished via the sky-horn feed, while the on-board calibration reference load, maintained by the thermal control system at the instrument's physical temperature, provides the hot reference.

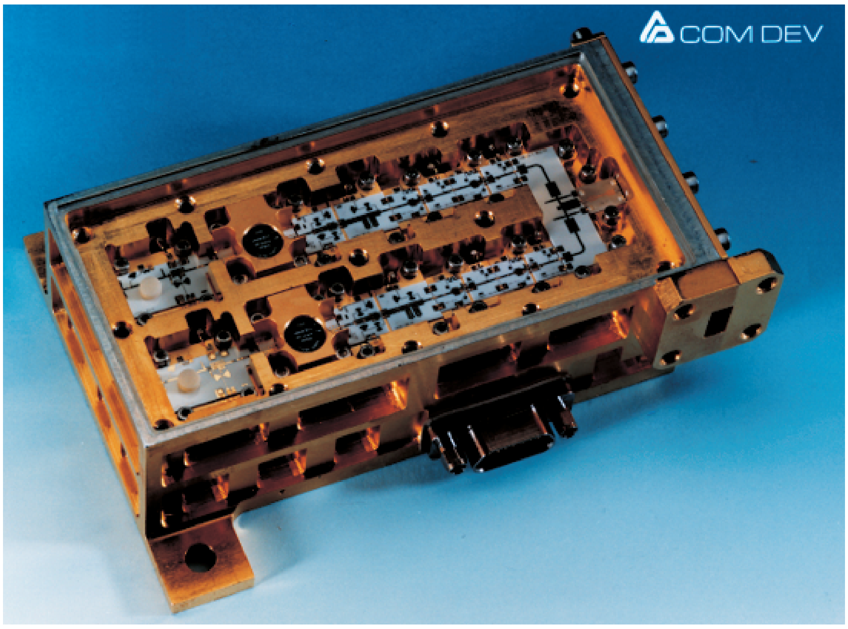
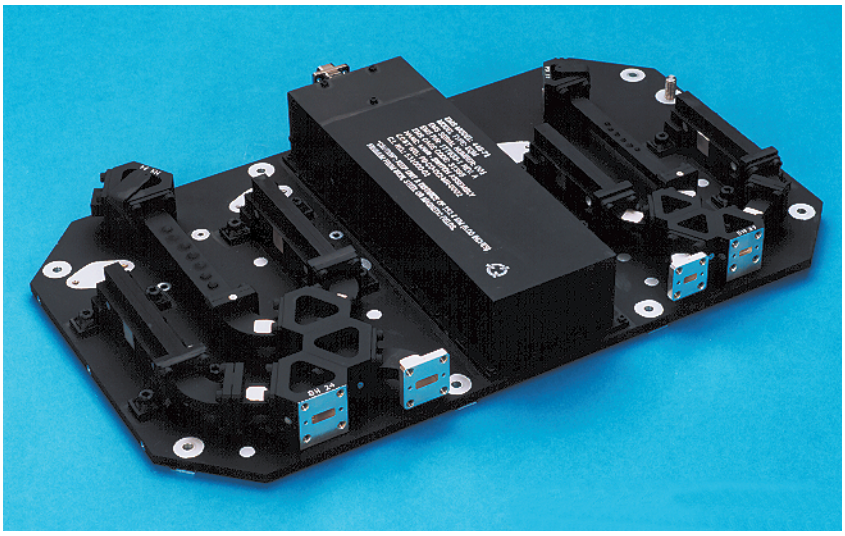


Figure 2. The 36.5 GHz Dielectric Resonator Oscillator (DRO) (courtesy of COMDEV)

The signals are down-converted in a mixer-amplifier subassembly, using the 23.8 and 36.5 GHz signals generated by Dielectric Resonator Oscillators (DROs). Both the RF front-end and the DRO's design and technology have been space-qualified for MWR. The intermediate-frequency (IF) and the analogue boards are used to process the down-converted radiometric signals; both modules are located within the Central Electronics Unit (CEU). The IF module consists of an input filter to define the bandwidth, followed by an RF amplifier chain and a square-law detector. The input signal is 500 MHz bandwidth noise, square-modulated by the Dicke frequency (1276 Hz). The analogue switches performing the detection can be opened by telecommand to avoid disturbances produced by the ASAR/RA-2 instruments. The signal is digitised in 64 bits every 150 msec.

Figure 3. The MWR radio-frequency (RF) front-end (courtesy of EMS)



The following calibration cycle is executed every 38.4 s: Hot Load Calibration (two measurements), Sky Horn Calibration (two measurements), Offset Calibration (two measurements), Main Antenna Signal (250 measurements). Alternative calibration periods of 76.8, 153.6 and 307.2 s can be selected by command.

The instrument is controlled by the common (MWR-DORIS) Instrument Control Unit, which handles the On-Board Data Handling (OBDH) interface protocol, exchanging macro commands and telemetry data. The instrument has independent thermal-control elements (heaters and thermostats) to give its electronic circuits optimum performance.

Absolute calibration has been performed at the Remote Sensing Instrumentation Meteorological Office, in Farnborough (UK). The absolute uncertainties in the brightness temperatures of the targets used were + 0.10/-0.00 K at minimum and +0.05/-0.09 K at maximum temperatures (an improvement with respect to what could be achieved for ERS-1 and 2). A detailed model of the instrument has been developed and has been validated during the calibration campaign, at instrument radiator temperatures of 0, 10, 20, 30 and 40°C. The Fixed- and Variable-Temperature Targets were used in the ranges of 85 K and 85-300 K, respectively

The instrument performance figures are presented in Table 1, which shows that the results are better than the specifications.

The MWR instrument was the first Envisat instrument to be delivered, back in September 1997. It has since been integrated into the MWR/DORIS composite and mounted on the spacecraft. Thereafter It has performed successfully in all of the satellite tests that have been conducted.

The ground segment

The received MWR data are packaged into Level-0 products and ingested (together with the RA-2 Level-0 and DORIS products) into the RA-2/MWR processor. No separate higher level MWR products are to be generated. The MWR Level-1b (brightness temperature) and the Level-2 information (wet tropospheric path delay) is embedded as a Measurement Data Set (MDS) within the RA-2/MWR Level-1b and Level-2 products (see article titled 'The Envisat Radar Altimeter System' in ESA Bulletin No. 98).

The path correction due to the wet tropospheric component is estimated on the basis of the two brightness-temperature measurements (at 23.8 and at 36.5 GHz) from the MWR and from the σ_0 information coming from the Radar Altimeter. This gives a residual inaccuracy of 1÷2 cm (comparable to that achievable by a three-frequency radiometer).

Acknowledgement
The MWR instrument was developed under the leadership of Aleniaspazio, with equipment provided by Austrian Aerospace, ComDev, Contraves Italiana, EMS, Millitech and Schrack.
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DORIS

The system

The DORIS system (Doppler Orbitography and Radiopositioning Integrated by Satellite) was developed by CNES (Centre National d'Etudes Spatiales), IGN (Institut Géographique National) and GRGS (Groupe de Recherche en Géodésie Spatiale) to meet scientific and operational user requirements for very precise orbit determination. Beyond its initial mission objectives, the DORIS system can also fulfil other needs, such as precise ground-beacon position determination (e.g. for measuring tectonic movements), provision of Earth-rotation parameters, measurement of Earth-centre position, improvement of Earth-environment models (e.g. gravity field, global ionosphere mapping), and real-time orbit determination.

The DORIS system was designed and optimised to provide high-precision orbit determination and beacon positioning. It was developed within the framework of the Topex/Poseidon oceanographic altimetry mission and has been operational since 1990, when the Spot-2 satellite was launched with the first DORIS receiver onboard.

DORIS is an up-link radio system based on the Doppler principle. It measures the relative velocity between the orbiting satellite and a dense, permanent network of orbit-determination beacons. The core of the system is the beacon network distributed homogeneously over the Earth. The dual-frequency signals at 400 MHz and 2 GHz emitted by the beacons are used by the receivers onboard the various satellites to perform Doppler measurements. The DORIS permanent network includes 54 beacons (Fig. 4) hosted by institutes from more than 30 countries. More than 20 beacons are co-located with other precise-positioning systems to allow cross-calibration.

Each site is equipped with a beacon package that includes:
- a dual-frequency 400 MHz and 2 GHz transmitter (including an ultra-stable oscillator)
- an omni-directional bi-dual-frequency antenna, with a battery pack to provide autonomy of supply
- a meteorological package providing temperature, pressure and humidity measurements, used to correct for tropospheric effects.

Table 1. MWR performance summary

Performance	*Requirement*	*Achievement*
Radiometric Sensitivity	< 0.6 K	0.4 K
Radiometric Stability	< 0.6 K	0.4 K
Radiometric Accuracy (after calibration)	< 3 K at Ta = 300 K	1 K at Ta = 300 K < 3 K at Ta = 85 ÷ 330 K
Dynamic Range	3 K to 300 K	3 K to 330 K
Non-Linearity	< 0.5 K	0.35 K
Centre Frequency Stability	< 0.75 MHz / °C	< 0.2 MHz / °C
Antenna Radiation Efficiency	> 93 %	97 % worst case
Antenna Main Beam Efficiency	> 89 %	94 % worst case
Antenna 3 dB Beamwidth	< 1.7 °	1.5°
Instrument Mass	< 30 kg	24 kg
Operational Power	< 50 W	18 W

The beacons transmit a narrow-band ultra-stable signal plus auxiliary data: beacon identifier, housekeeping data, meteorological data, and time-tagging reference data. Presently, two master beacons located in Toulouse (F) and Kourou (Fr. Guiana) are connected to the control centre to allow data uploads to the onboard package. They are also linked to an atomic clock to allow synchronisation of the DORIS system with international reference time.

The DORIS onboard package for Envisat includes: a receiver performing Doppler measurements and receiving auxiliary data from the beacons, a dual-frequency omni-directional antenna, an ultra-stable oscillator, and a two-channel receiver (with DIODE navigator capability as part of the onboard software). The dual-frequency receiver allows ionospheric corrections to be made.

The DORIS control and processing centre, also located in Toulouse (F), is responsible for beacon network monitoring, onboard package monitoring and programming, science telemetry acquisition and pre-processing, technological archiving, precise orbit determination, and beacon positioning. This centre is included in the SSALTO (Orbitography and Altimetry Multi-mission Centre) CNES ground segment. The interfaces between SSALTO and the Envisat Flight Operations Segment (FOS) and Payload Data Segment (PDS) have been defined to meet all of the Envisat mission requirements.

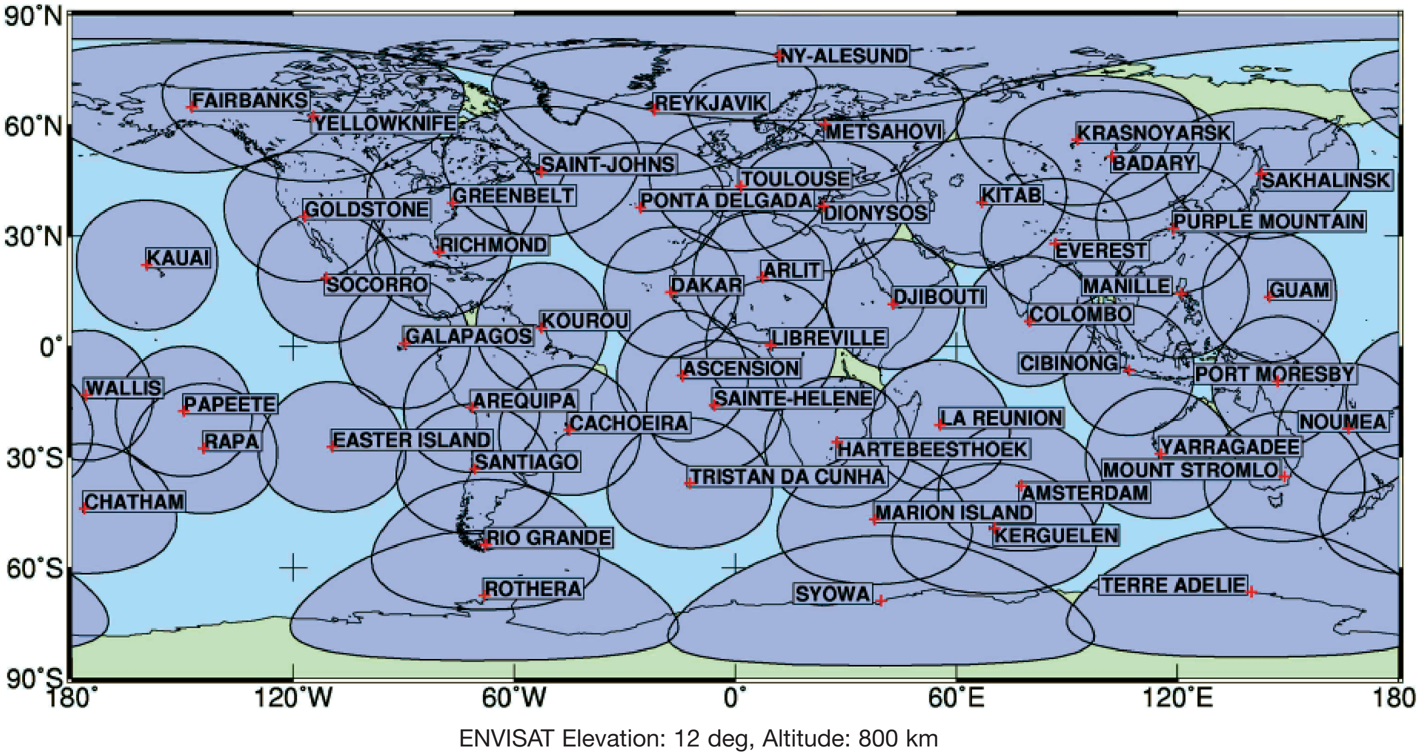


Figure 4. The DORIS ground network

Instrument performance
For Envisat, the accuracy of the real-time orbit provided by the DORIS/DIODE onboard software has been specified as 1 m (three axes). The performance of the DIODE software already flying on Spot-4 and the improvements that have been tested on the ground indicate that this level of accuracy should be achieved without any difficulty. Indeed, the performance of the onboard DIODE real-time navigator has already been estimated at 40 cm from various simulations of the radial component of Envisat's orbit. The 30 cm-level is expected to be reached using an upgraded version of the software (see below).

The accuracy for the radial component of the offline precise orbit has been specified as 10 cm, with the even more challenging figure of 3 cm often quoted as a goal. Experience gained with the Topex/Poseidon and Spot satellites and appropriate simulations indicate that the 10 cm specification can be achieved without major difficulty, whereas the 3 cm goal is a challenge that the Envisat Precise Orbit Determination team will actively pursue.

The DORIS/DIODE onboard capability
The version of DIODE that will fly on Envisat is improved with respect to the Spot-4 version in that it takes into account: the Earth's gravity field up to 40°x40°, the Sun's and the Moon's attractions with a simplified ephemeris model, the solar radiation pressure using a simple model of the spacecraft, and empirical and adjustable once per revolution accelerations to absorb residual errors.

In addition, several new functions have been designed and already extensively tested on the ground:

– *Self-initialisation:* Without any orbital information, the DORIS receiver can perform measurements by simply scanning around an average frequency. DIODE will be able to estimate the spacecraft's position without needing initial conditions sent from the ground ('lost in space' scenario). The non-linear behaviour of the equations of motion is solved by using two separate filters, which process the measurements from four passages. The two filters are based on two different (one crude and one more accurate) models. The resulting orbit (generally with an accuracy of a few metres) is then provided to the standard filter for the final convergence.
– *Self-programming:* Normally, DIODE uses its estimation of the orbit to inform the DORIS receiver about the next visible station and its Doppler shift every 10 s. The accuracy is such that these predictions can be used by the receiver itself to self-programme the next station to be received. A selection algorithm is added for the cases in which several beacons may be visible simultaneously.

Also, a time-determination function now exists for all versions of DIODE that is accurate to within a few microseconds and can therefore be used on the ground and/or by the spacecraft's payloads and central flight software. The Envisat ground segment will therefore use DIODE outputs for accurate real-time product generation.

The ground network

The next generation of DORIS beacons (third generation) will have the ability to transmit their signals on slightly shifted frequencies with respect to the nominal system frequencies. This will avoid the risk of 'Doppler collisions' when the DORIS system is used from high-altitude orbit, and will allow more DORIS beacons to be used in a given region.

Another major feature of these third-generation beacons is that they broadcast the current date (year/month/day/hour/minute/ seconds) in Time Atomic International (TAI) format. It allows the in-flight DORIS instruments to perform their initialisation process – from equipment turn-on to satellite position, velocity and time estimation – fully autonomously, without any ground commanding or uploading.

Beacon data transmission (synchronisation word, auxiliary data, uploading in case of master beacons) is performed according to a 10 s sequencing. This sequencing is synchronised with respect to TAI to within ± 1 s to guarantee correct reception of these beacon data by the in-flight instruments.

DORIS's impact on Envisat mission objectives

Precise orbit determination

When designing an observing system, one has first to identify the signals within the scope of the observation. Focusing on ocean dynamics, it is clear that the corresponding signal has a wide spectrum in both space and time:

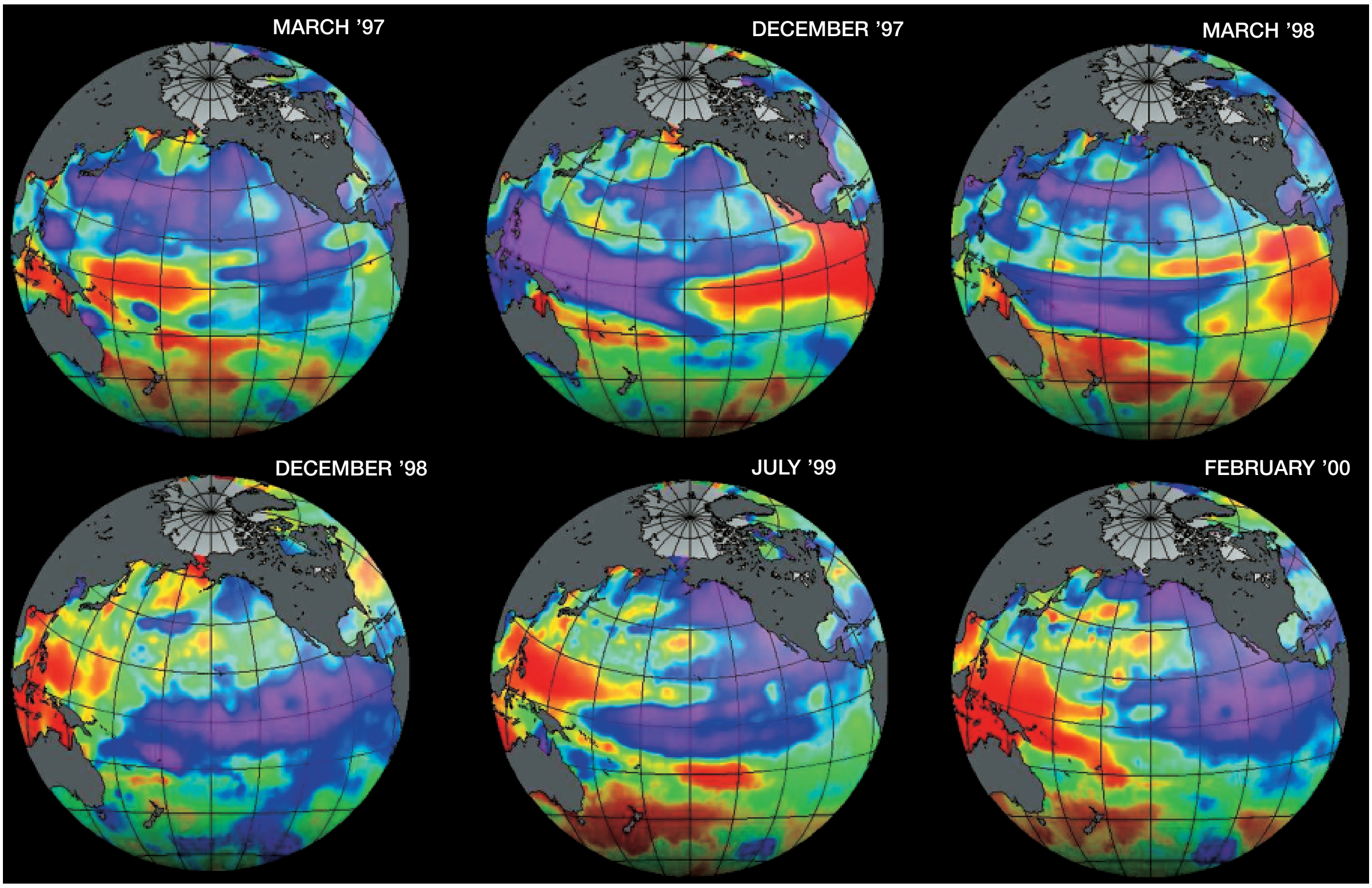
- Mesoscale eddy features, with a typical amplitude of the order of 5 to 20 cm, a spatial scale of the order of 100 to 300 km, and an associated temporal scale from a few days up to months or years.
- Seasonal signals of the order of 10 to 15 cm, varying mainly on a hemisphere basis.
- Inter-annual signals such as the El Niño phenomenon, with a typical amplitude of 20 cm and time scales ranging from several weeks to months (Fig. 5).
- Very long time scale variations in mean sea-level, with magnitudes of some 1.5 mm/yr.

Satellite orbit error has been the bane of oceanographers, who analyse altimetry data quantitatively. To overcome this difficulty, altimeter users have pinned their hopes on very efficient error-reduction methods, particularly for ocean mesocale recovery. For long-wavelength ocean signals, however, even the most sophisticated orbit error-reduction methods are not satisfactory, and will never replace very precise orbit measurements, in which DORIS can play a major role.

Climate-change studies

Within the climate-change research framework,

Figure 5. The El Niño/ La Niña 1997-2000 events as seen by altimetry



today's rate of global sea-level change is a crucial measurement, for which altimetry has been widely used. From their analysis of collections of tide-gauge measurements, several researchers are already quoting figures of about 1.5 mm/yr. In the framework of geodesy/altimetry, it is important to focus on how such tide-gauge and space-altimetry data can complement each other to arrive at a reliable estimation of global sea-level change. DORIS will contribute significantly in this context, providing a reliable terrestrial reference frame over time.

One crucial advantage of altimetry from space is that observations are performed on a global scale in a centre-of-mass fixed reference frame. The positions of the stations tracking the satellite define the orbit reference frame, and consequently the ability to precisely determine their locations within a co-ordinate system whose origin is located at the Earth's centre of mass is of considerable importance. It is widely agreed that the international network of satellite laser ranging systems is an important contributor to the reference-frame definition. The permanent orbitography network of DORIS beacons is the other major contributor. Indeed, since Topex/Poseidon's launch, knowledge of the co-ordinates of the ground beacons has greatly improved, allowing the DORIS system to be included in the IERS reference-frame computations.

Because a primary goal of altimetry is to contribute to a continuous ocean observing system on a long-term basis, it becomes extremely important to manage the evolution of the terrestrial reference frame. Use of the 2nd generation of DORIS instruments onboard Envisat and Jason will allow the DORIS station motion analysis to be pursued with even better accuracy, since the instrument noise of the DORIS receiver will go down to the order of 0.1 mm/s, compared with 0.3 mm/s for Topex/Poseidon-like receivers.

Another subject of careful study has to be the stability of the reference frame in which sea-levels are computed. It is known that geo-centre variations are affected by the nature of the reference system adopted, and in particular its origin. Sea-surface heights are related to the Earth's centre of mass, since the satellite orbit is defined in an inertial reference frame with that at its centre. In practice, tracking data involved in the orbit computation are collected by stations that are distributed over the Earth's surface, which contributes to the Earth-fixed reference frame definition, the so-called ITRF (International Terrestrial Reference Frame). Hence motions of the ITRF centre relative to the centre of mass should be taken into account in resolving the global mean sea-level equations.

Sea-level monitoring

Observation of the ocean is now thought of by oceanographers in terms of a global and an 'integrated' system. Indeed, there is now general acceptance that space and in-situ techniques are complementary in terms of the characteristics of their sampling, precision and accuracy, and that they must be exploited jointly to provide the optimum observing system. The same concept is valid for the sea-level-change problem, and GPS and DORIS geodetic techniques have been used for several years together with altimetry and tide-gauges data to estimate the rate of sea-level change. Continuous enhancement of the DORIS ground network by increasing the co-location of DORIS beacons with tide gauges is very attractive. Upgraded versions of the DORIS system, for instance with the multiple channel capability, now offer the possibility to design an efficient integrated tide gauge + GPS + DORIS + altimetry + laser sea-level monitoring system.

Conclusion

From its 'probationary' status on board Spot-2, the DORIS system has evolved to become a major contributor to oceanographic and geodetic science and applications. On Envisat, DORIS will contribute significantly to the fulfilment of the altimetry-mission objectives, as well as more generally supporting the instrument payload data processing, in near-real-time and off-line, with orbital information.

An International DORIS Service (IDS) is currently being created, to support the use of the DORIS system and products, to define standards, to promote research and development activities to improve system performance, operationality and applications, as well as to interact with the user community. DORIS data and expertise from the Envisat mission will be of great value for the new IDS.

Acknowledgement

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