The Envisat Radar Altimeter System (RA-2)

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Following on from the great success of its ERS-1 and -2 satellites, which have contributed to a much better understanding of the role that oceans and ice play in determining global climate, ESA is currently preparing Envisat, Europe's largest remote-sensing satellite to date, for launch. Its payload includes an advanced instrument complement designed to guarantee the continuity of observations started by its predecessors and to meet the global Earth-monitoring requirement on a longer time scale. In particular, the altimetry from Envisat will benefit from the improved performance of a dual-frequency Radar Altimeter (RA-2) working in synergy with the Microwave Radiometer (MWR) and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) instruments. The ground processing products that will be available in near-real-time will be as comprehensive as the off-line products, differing only in terms of the availability and quality of the auxiliary data.

The mission

RA-2 has an essential role to play in the Envisat mission, as indicated in Table 1. Operating over oceans, its data can be used to monitor sea-surface topography, thereby supporting research into ocean circulation and sea-level change, as well as providing observations of the sea floor structure or shape, and marine geoid characteristics. It will also be possible to determine near-sea-surface wind speeds and significant wave heights, data that are important for both weather and sea-state forecasting. RA-2 will also be able to map and monitor sea ice and polar ice sheets, allowing the energy/mass balances of the world's major ice sheets, including the Antarctic, to be better determined.

Table 1. Contributions of RA-2 and MWR-2 to the Envisat mission objectives

DISCIPLINES	GEOPHYS. QUANTITY	CONTRIBUTION FROM RA-2/MWR
Atmosphere	Water vapour content	MWR
	Precipitation	RA-2/MWR (research)
	Ionosphere	RA-2
Land	Surface Elevation	RA-2
Ocean	Sea Level Topography	RA-2
	Mean Sea Level	RA-2
	Waves	RA-2
	Wind Speed	RA-2
Sea Ice/Ice Sheet	Topography/Elevation	RA-2/MWR (research)
Gravity	Marine Gravity Anomalies	RA-2

In addition to operating over oceans and ice, RA-2 can also be used over land surfaces. From its observations of range and reflectivity, it will be possible to determine land surface elevations, and surface characteristics.

Because Envisat will follow the same ground track as ERS-1 and ERS-2, a continuous time series of local sea-height variations can be constructed, which will eventually span more than 15 years. This will allow the examination on inter-annual to decadal time scales of changes in: global and regional sea level; dynamic ocean circulation patterns; significant wave height climatology; and ice-sheet elevation.

We will focus here on a few of the main RA-2 mission objectives in the context of oceans, ice sheets and sea ice. A more comprehensive discussion of the Envisat RA-2/MWR instrument concept in the context of science and applications is provided in ESA SP-1224 (available from ESA Publications Division).

Oceans

The Envisat ground segment has been designed to accommodate real-time operational ocean monitoring. There are a variety of operational applications that can utilise measurements from the RA-2 system. Significant wave height and wind speed, for example, are routinely used by Numerical Weather Prediction centres. These data are made available within a few hours of satellite acquisition and are mostly independent of the quality of the satellite orbit determination.

In the coming years, mesoscale and large-scale monitoring and prediction will assimilate near-real-time altimetry into high-resolution ocean models. For instance, the goal of the Mercator project is to implement (within about 3 years) a system that simulates the North

Atlantic Ocean circulation with a primitive-equation high-resolution (~10 km) model that takes in altimeter, sea-surface temperature (SST) and in-situ data. The system will be used both for scientific research and operational oceanography. It will also contribute to the development of a climatic prediction system.

Mercator is a contribution to the Global Ocean Data Assimilation Experiment (GODAE), for which a pilot demonstration phase is planned in 2003 - 2005. GODAE is intended to demonstrate the practicality and feasibility of routine real-time global ocean-data assimilation and prediction. It will emphasise integration of the remote sensing (in particular altimetry) and in-situ data streams, and the use of models and data assimilation to extract maximum benefit from the observations.

It is clear that a more detailed understanding of ocean circulation is required in order to refine the climate-model predictions of a 13 – 111 cm increase in the average global sea level in the next century. This range implies virtually no general impact at its low end, but could have a devastating impact on low-lying countries at the high end. Most of this range of uncertainty can be assigned to lack of knowledge of ocean circulation, and especially its heat and fresh-water transport.

To advance our knowledge and prediction capabilities for the world's climate on seasonal, inter-annual, and longer time scales, it is essential that ocean-circulation processes be well observed, understood and modelled. Global and repetitive observations of ocean topography are therefore a critical element of research into climate dynamics and perturbations to the coupled atmosphere – ocean system. This is illustrated in Figure 1, which shows the altimeter observations of the 1997/98 El Niño.

Ice sheets
Recently, ERS Radar Altimeter measurements (4 million ice-mode cross-over points) have been applied to show that the average elevation of the Antarctic Ice Sheet interior (63% of the grounded ice sheet) fell by 0.9 ± 0.5 cm/year from 1992 to 1996. Moreover, when the variability of snowfall observed in Antarctic ice cores is accounted for, it can be concluded that the mass imbalance of the interior of the Antarctic Ice Sheet this century is only –0.06 ± 0.08 of the mean accumulation rate. Hence, it has been at most only a modest source or sink of sea-level mass this century. The continued availability and in particular the improved accuracy of such elevation-change data to be expected from RA-2/MWR will further enhance the value and importance of monitoring ice-sheet elevation changes. This is illustrated in Figure 2, which shows a Radar Altimeter topography map of Greenland.

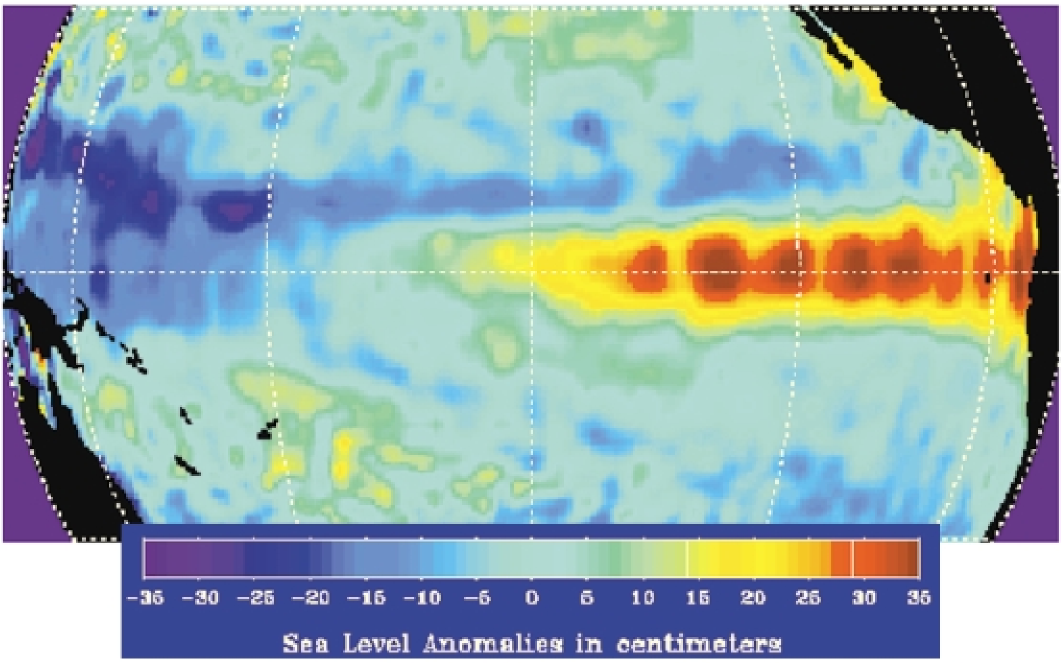


Figure 1. Sea-surface topography anomaly (red-to-yellow colours) during the 1997 El Niño event, derived from the ERS Radar Altimeter (RA) (courtesy of Delft Univ. of Technology/ESA-ESRIN)

Sea ice
A recently developed technique using data from the ERS satellites has demonstrated the potential of spaceborne radar altimetry for measuring sea-ice freeboard height (or elevation), and thereby deriving sea-ice thickness estimates (S. Laxon, pers. com.). The accuracy of these altimeter estimates is in the region of ~0.5 m compared with sonar measurements and models. RA-2 is expected to provide a significant improvement in sea-ice

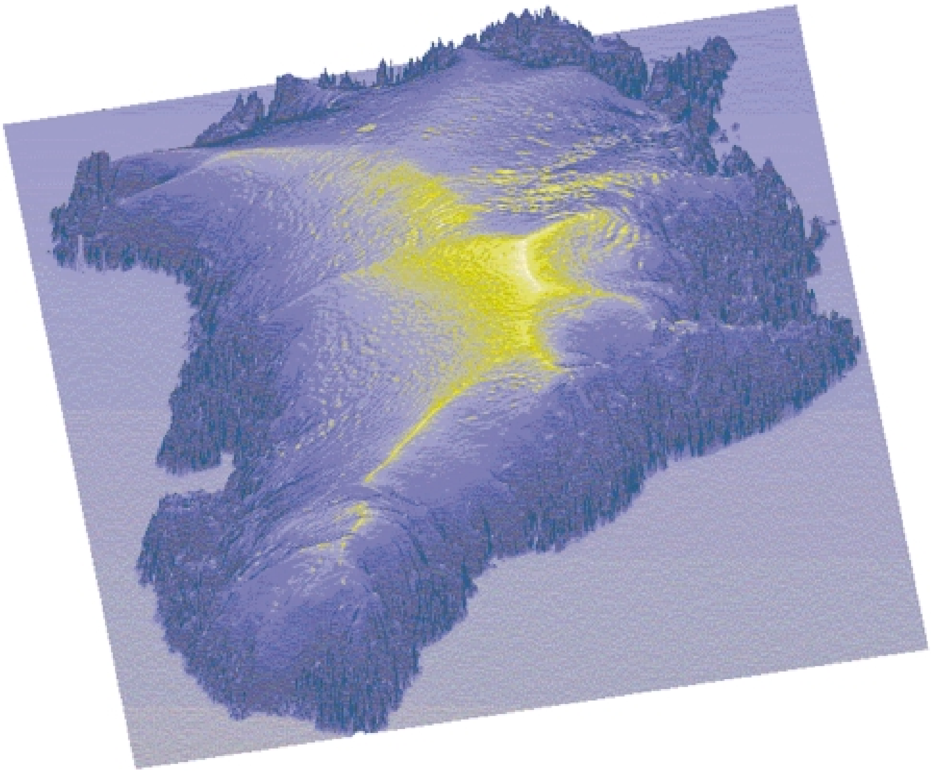


Figure 2. Radar Altimeter map of Greenland (courtesy of the University of Bristol Centre for Remote Sensing)

freeboard height determination over that provided by the ERS altimeters; the onboard tracking system will provide a much more stable record of the peaked echoes that dominate in ice-covered seas. Bearing in mind the sparse in-situ observation of temporal and spatial sea-ice thickness changes, these altimetric measurements may (although coarse in resolution and unable to cover the entire central Arctic polar region) provide valuable data for sea-ice mass fluctuation studies.

As seen from Table 1, practically all disciplinary areas of interest within the Earth system, including the ocean, the cryosphere, the land, and the planet's gravity field, are addressed by the Envisat altimeter mission in the context of scientific research, climate monitoring and near-real-time sea-state and ocean circulation forecasting. In addition, the 35-day repeat orbit at 98.5° inclination offers optimum synergistic combinations with the simultaneously operating Jason/GFO altimetric missions. The advantages of exploiting simultaneous altimeter missions with such widely different spatial and temporal samplings and inclinations have already been clearly demonstrated by the combined use of the ERS and Topex/Poseidon altimeters.

Instrument operation

The principle of radar altimetry is depicted in Figure 3. The actual altitude of the Earth's surface with respect to the reference ellipsoid can be calculated by subtracting from the satellite-to-Earth's-surface range (h) measured by the altimeter, the independently known satellite orbit height (H).

Over the oceans, the altimeter is able to measure the distance (h) between the spacecraft and the mean sea surface to an accuracy of a few centimetres (the radar actually measures the time delay of the echo reflected by the ocean surface to an accuracy of the order of 100 psec, which is then converted into a distance measurement). The reason why such a high accuracy can be achieved lies in the well-known modelling of the radar echo reflected by the ocean surface and the relationship that can be established between the waveform characteristics and the sea-state conditions (Fig. 4). The radar-echo

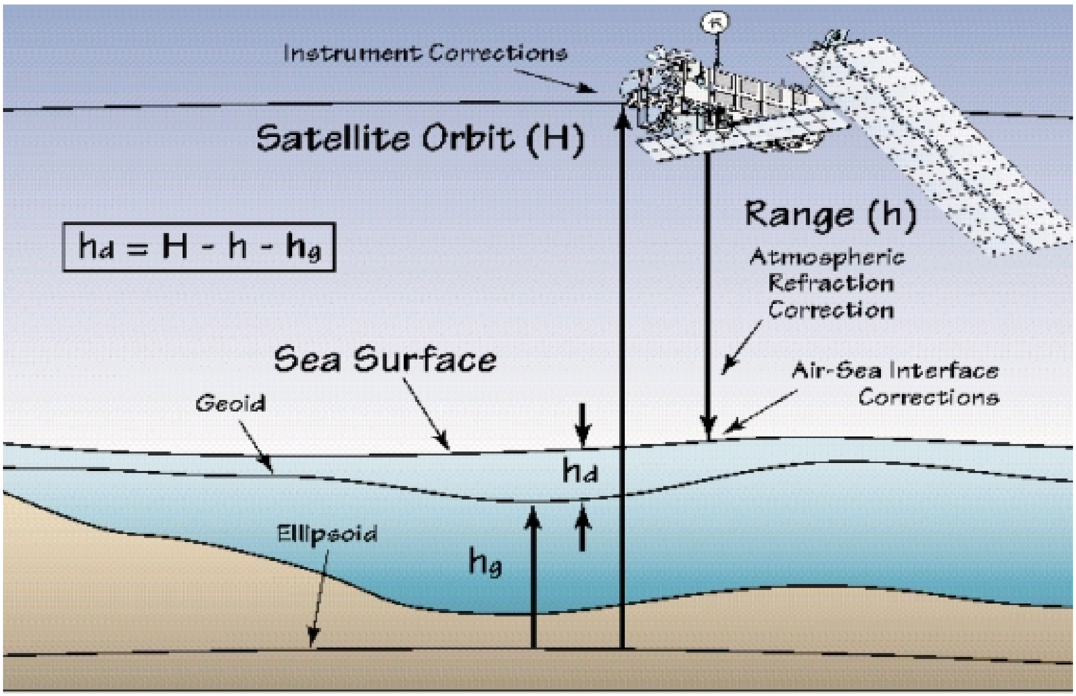


Figure 3. The principle of altimetry measurements

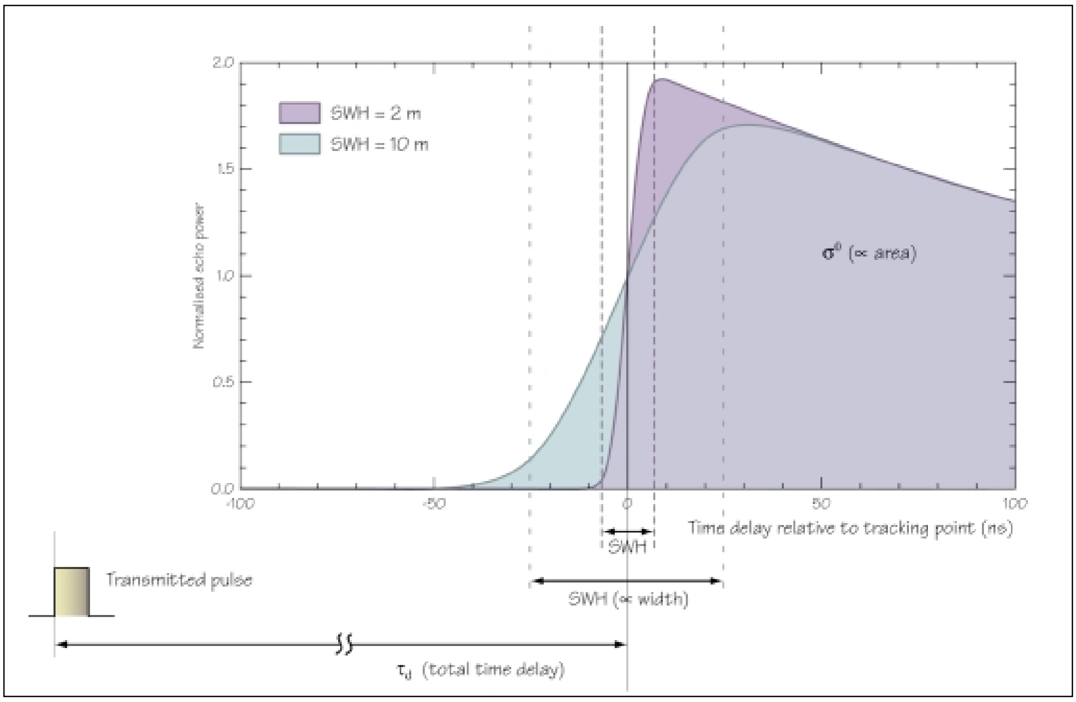


Figure 4. The transmitted pulse, the shape of the echo from the ocean, and the parameters derived from it

waveform can be analytically described by the so-called 'modified Hayne model', which has been well-validated by earlier altimetric missions. The satellite-to-Mean Sea Surface (MSS) distance h (in metres) can be calculated from the time delay τ_d between the transmitted pulse and the reception of the mid-point of the waveform's leading edge. The measured delay is translated to a distance via the relationship h (cm) = $15\tau_d$ (ns). The Significant Wave Height (SWH) is related to the spreading of the waveform leading edge (the smoother and longer the leading edge, the higher the waves are) and can be retrieved via the relation SWH (m) = $4\sigma_S$ (m) (σ_S inversely proportional to echo leading-edge slope). The backscatter coefficient (σ_0) is related to the received echo power (waveform amplitude). The wind speed at the sea surface can be related to σ_0 via established models.

The RA-2 mission objectives are not limited to ocean surfaces. The instrument has been conceived such as to maximise the coverage and the tracking of non-ocean surfaces also (within the capabilities of the pulse-limited technique). To achieve this, a clear separation has been made between two main functions, namely: the collection of meaningful radar echoes without any extraction of geophysical parameters is accomplished on-board; and the estimation of the relevant geophysical quantities is only implemented on the ground. Previous altimeters had these two functions merged on board, thereby increasing the constraints on their optimisation. Their clear separation for RA-2 has made it possible to dedicate onboard processing resources to achieving more robust and autonomous instrument operation over different types of surfaces.

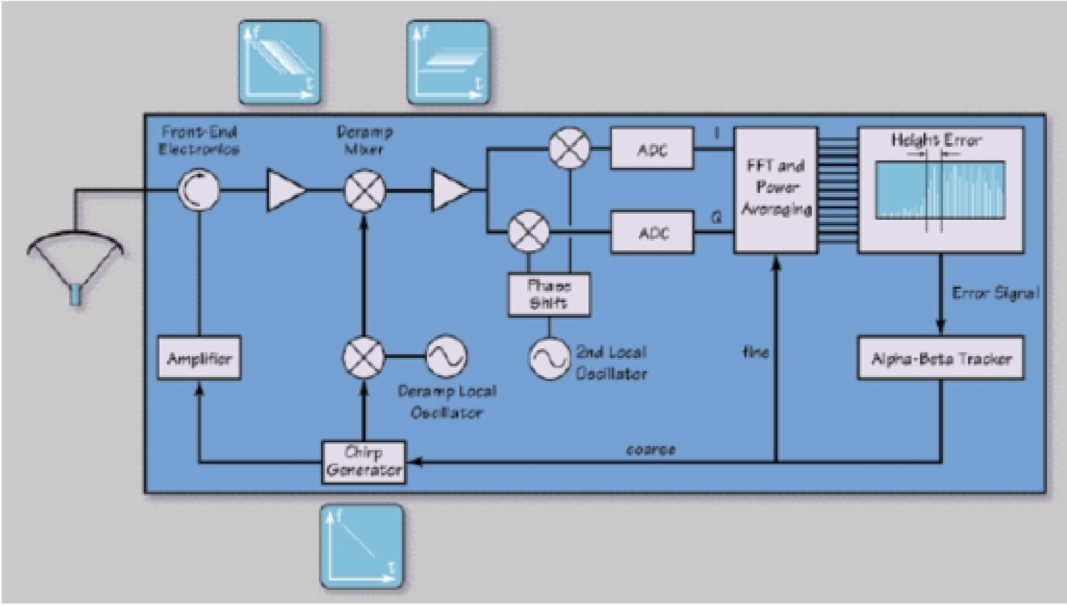
RA-2 is a fully redundant, nadir-pointing, pulse-limited radar operating via a single antenna dish at frequencies of 13.575 GHz and at 3.2 GHz, enabling the correction of height-measurement errors introduced by the ionosphere. It is designed to operate autonomously and continuously along the orbit to collect, on a global scale, calibrated samples of the earliest part of radar echoes from ocean, ice, and land and from their boundaries, without interruption.

The radar's functioning is illustrated in Figure 5, where only the 13.575 GHz chain is shown. RA-2 exploits linearly frequency-modulated pulses called chirps to achieve high range resolution and low peak-power demands.

During transmission, the pulses produced by the chirp generator are amplified by either Ku-band (13.575 GHz) or S-band (3.2 GHz) chains. For every four pulses transmitted at Ku-band, only one pulse is radiated at S-band. The amplifiers exploit travelling-wave-tube technology at Ku-band, and bipolar transistors at S-band. The front-end electronics route the signals to the dual-frequency, centre-fed parabolic antenna, and prevent the transmitted power from damaging the sensitive receiver designed to process very weak signals.

In reception, the front-end electronics route the echoes to the receiver. Each echo is the superposition of transmitted chirp replicas, backscattered by the many reflectors on the surface below, delayed by the time (about one five thousandth of a second) that the chirp

Figure 5. Block diagram of the Radar Altimeter



pulse has taken to travel back and forth across the radar-to-reflector distance. At this point in time, the onboard processor triggers the generation of a new chirp signal to down-convert the incoming echo. This operation, called 'de-ramping', transforms the various received replicas into different tones of constant frequency and converts the height differences between the various surface reflectors into frequency differences, which can be more accurately resolved by spectral filtering. After further amplification, the signal is converted into its in-phase (I) and quadrature (Q) components and is sampled. A 128-point complex Fast Fourier Transform is implemented to resolve echo details with a resolution that is inversely proportional to the transmitted chirp bandwidth. Square-modulus extraction and averaging are applied to the samples to reduce fluctuations and data rate.

The onboard processor is programmed to run all RA-2 operations autonomously, although it can be bypassed by ground commanding if necessary. Operations start with the automatic detection and acquisition of the surface echoes by the main channel (13.575 GHz). As soon as the acquisition is successfully accomplished, RA-2 automatically starts the tracking phase. During this phase, a tracking window is locked on the earliest part of the echoes and its position, gain and resolution are updated by the new on-board processor. The Model-Free Tracker (MFT) software allows interruption-free collection of the echo samples around the complete orbit, irrespective of surface type. Three range resolutions are available, corresponding to the three transmit bandwidths of 320, 80 and 20 MHz. Over open ocean surfaces, where the echo shape can only have smooth variations for periods of seconds, RA-2 always uses its highest resolution. Over coastal zones, ice and land where the tracking could be lost due to the unpredictable and fast-changing echo shape, RA-2 can autonomously switch to a coarser resolution. If tracking is indeed lost accidentally, an automatic procedure re-starts operation from detection and acquisition. Internal calibration data are routinely collected every second without interrupting echo sample collection. Those data are processed on the ground to compensate instrument time-delay and gain variations with respect to pre-launch calibration, due for instance to ageing or in-flight temperature conditions.

The Pulse Repetition Frequency (PRF) of the main channel has been increased to about 1800 Hz, in order to collect a higher number of independent observations per second and thereby improve the measurement accuracy.

The data from the S-band channel, highly sensitive to ionospheric effects, allow the accurate correction of these effects on the main-channel height measurements. Corrections are applied to both the near-real-time and the offline products. Single-frequency altimeters have to rely instead on ionospheric models that are less accurate and do not account for small-scale spatial variations. The echoes received by the secondary channel are always sampled at a fixed resolution, corresponding to the 160 MHz band, in a window whose position and gain are related to those of the main channel.

The averaged echo samples are sent to ground via time-tagged source packets. Internal calibration and ancillary data are also added. Furthermore, a new RA-2 feature allows the storage, by ground command, of up to 2000 unaveraged individual echo samples and their transmission to ground in several source packets. Individual echo collection is made available as a dedicated data product for research purposes.

A summary of RA-2 design parameters is provided in Table 2.

The RA-2 development programme has been successfully completed and the instrument is now being integrated onto the satellite. Figure 6 shows the RA-2 flight-model panel after the completion of its acceptance-test programme.

RA-2 operation and performance verification has been carried out extensively on the ground by using an RA-2 Return Signal Simulator connected to the antenna port, to produce echoes representative of complex combinations of ocean, land and ice, and their boundaries. The rms accuracies measured during the ground testing over open ocean for the three engineering parameters – time delay τ_d (ns), radar cross-section σ_0 (dB), and echo leading-edge slope σ_s (cm) – are summarised in Table 3 as a function of σ_s.

The accuracy contributions achievable by the altimetry system are summarised in Table 4.

The data products

Based on the experience gained from the ERS missions, significant improvements have been built into this new generation of altimetric products, particularly in terms of the enhanced quality of the near-real-time observations, which are now nearly as good as the final precise product. The product specification process has included wide consultation with users of ERS and Topex/Poseidon altimetric data. Further product refinement and state-of-the-art algorithm specification have been elaborated by three European Expert Support Laboratories. Moreover, the RA-2 and MWR products and algorithms are being peer-reviewed by independent experts.

The Envisat RA-2 and MWR data products will be globally processed in both near-real-time

Table 2. Summary of RA-2 design parameters

Orbit range (km)	764, 825
Operative frequencies (GHz)	13.575, 3.2
Pulse length (microsec)	20
Ku chirp bandwidths (MHz)	320, 80, 20
S chirp bandwidth (MHz)	160
Ku transmitter peak power (W)	60
S transmitter peak power (W)	60
Ku-PRF (Hz)	1795.33
S-PRF (HZ)	448.83
I/Q A/D conversion bit number	8 + 8
Number of FFT points	128
Max. data rate (kbit/sec)	91
Antenna diameter (m)	1.2
Measured power consumption (W)	126
Mass (kg)	112

Table 3. RA-2 rms retrieval accuracies for the three engineering parameters

rms	σ_s =0.5 m	σ_s =1 m	σ_s =2 m	σ_s =3 m
τ_d (ns)	0.15	0.16	0.24	0.39
σ_o (dB)	0.49	0.52	0.52	0.52
σ_s (cm)	3.1	4.1	5.4	6.7

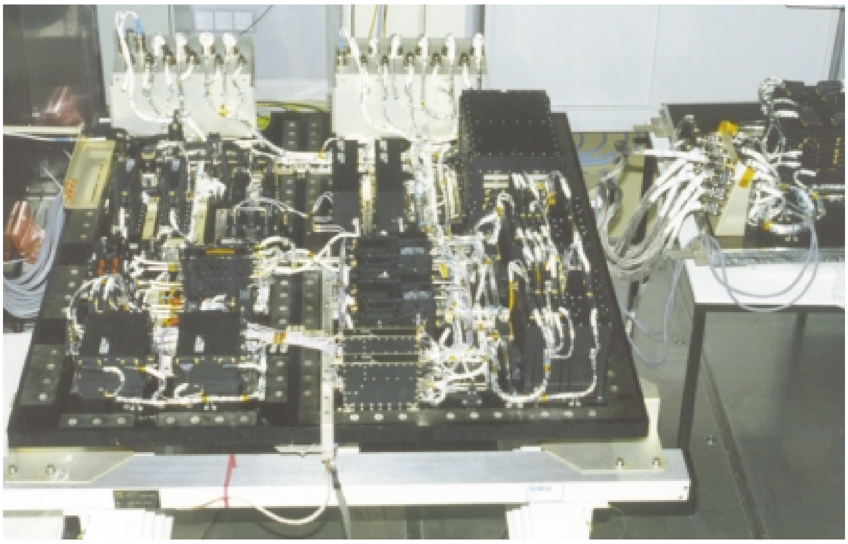


Figure 6. RA-2 flight-model panel after the completion of its acceptance test programme

Table 4. Altimetry error contribution budget

CONTRIBUTION	NON-CORRECTED EFFECT (CM)	RESIDUAL ERROR AFTER CORRECTION (CM)	COMMENTS
Instrument Error		2.4	Measured . (Table 3 for σ_s =1 m (SWH=4m)). h(cm) = 15τ_d(ns)
Orbit		~ 3	DORIS precise orbit
Sea-State Bias	0-20	~ 2	
Dry Troposphere	~230	0.2-2	
Wet Troposphere	0-30	1-2	Real-time use of MWR data

and offline with an identical processing algorithm, including the wet tropospheric correction from the microwave radiometer and the ionospheric correction from the two frequencies, as well as many other improvements originating from the novel design of this second-generation Radar Altimeter. The near-real-time processing is therefore comprehensive and the same as for offline products; only the availability and quality of the auxiliary data differ.

The suite of RA-2 products is based on the principle of one main Geophysical Data Record (GDR). The Envisat product's general format is exploited to add substructure inside the product to hold such additional data as the averaged waveforms (at 18 Hz), the individual waveforms (at 1800 Hz), and the Microwave Radiometer data set. Thus, the same product covers the standard once per second data (GDR) and the waveform data (SGDR). Moreover, this product is global and independent of the subsatellite terrain and of the Radar Altimeter measurement resolution mode, thereby avoiding artificial boundaries between geographical features like land/sea or land/lake transitions and ensuring that lake or wetland data always end up in the same data product.

The Fast Delivery GDR (FDGDR) product is delivered in less than three hours, for weather-forecasting, sea-state and real-time ocean-circulation applications. A subset of the FDGDR, called FDMAR (Marine Abridged Record) is extracted to reduce the volume of online data transfers. This product is then delivered again in less than 3 days for ocean-circulation monitoring and forecasting applications, substituting the meteo predictions for the more precise analyses and the preliminary orbit for an improved orbit solution. The final products containing the most precise instrument calibrations and orbit solutions are delivered within 3-4 weeks. The schematic in Figure 7 summarises the organisation and latency of the product generation. One of the major differences is constituted by the quality level of the orbit, thanks to the DORIS system. The expected orbit accuracy is:

– better than 50 cm for the Orbit Navigator, used for FDGDR production
– around 10 cm for the DORIS preliminary orbit, used for IGDR (Interim Geophysical Data Record) production
– around 3 cm for the DORIS precise orbit used for GDR production.

The Envisat products are categorised into three distinct levels:

– Level 0 (raw): unprocessed data as it comes from the instrument.
– Level 1b (engineering): data converted to engineering units, with instrumental calibration applied (IF filter – corrects power distortions of echo waveforms – internal range calibrations, corrections for possible drift of reference timing source, no retracking); the product segmented in half-orbit (pole-to-pole) mainly contains datation (conversion of satellite time to UTC) geolocation, time delay, orbit (<50 cm NRT to ~3 cm offline with DORIS precise orbit), sigma-zero, averaged waveform samples at 18 Hz data rate, individual waveform at full pulse-repetition frequency and MWR brightness temperatures.
– Level 2 (geophysical): data converted to geophysical units (with retracking); the product mainly contains datation, geo-location, output from retrackers (range, wind speed, significant wave height, etc.), at 1 Hz plus some 18 Hz parameters (range, orbit). All geophysical products, including the near-real-time products, are retracked (waveform data are fully processed in the ground processor to extract the geophysical parameters).

In order to retrieve the geophysical parameters over all types of surface (ocean, ice or land, sea-ice, etc.), four specialised retrackers are run continuously in parallel over all surfaces:

– Ocean retracker: optimised for ocean surfaces, it is based on a modification of the Hayne model
– Ice-1 retracker: optimised for general continental ice sheets, it is a model-free retracker called the Offset Centre of Gravity echo model; it is used for ERS and will ensure continuity of the measurements
– Ice-2 retracker: optimised for ocean-like echoes from continental ice sheet interior, it is a Brown-based model retracking algorithm
– Sea Ice retracker: optimised for specular returns from sea-ice, it is a threshold retracking scheme for peaky waveforms.

The usual necessary geophysical corrections are available in the product. The ionospheric correction will come from the dual-frequency altimeter, backed up by the measurements from DORIS and the Bent model. The wet tropospheric correction will come from the on-board microwave radiometer, backed up by a value computed from ECMWF fields.

The FDGDR will be processed in the receiving stations and delivered in less than 3 hours. The IGDR and the final precision GDR products will be processed off-line at the Processing and

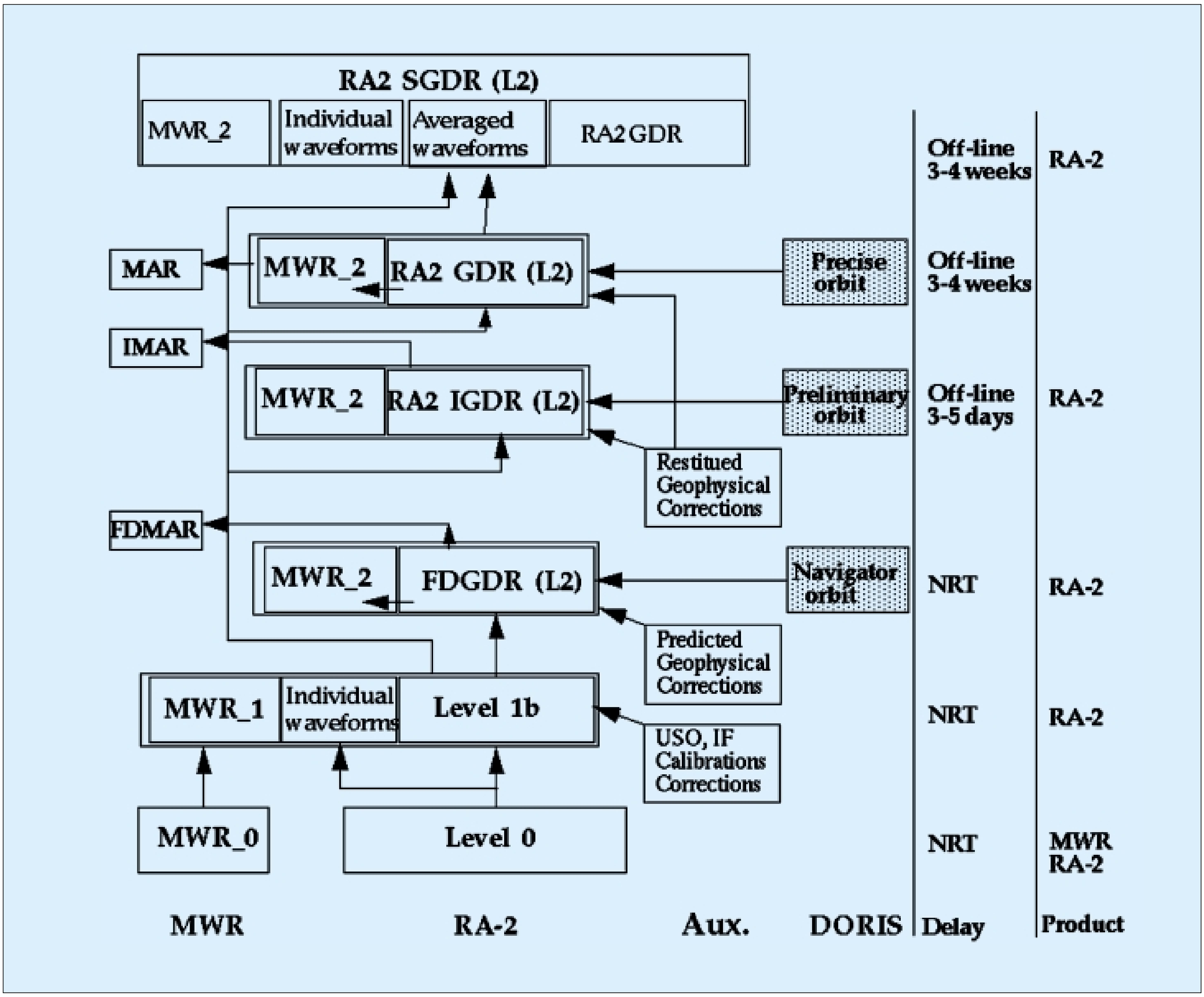


Figure 7. Envisat Radar Altimeter and Microwave Radiometer product tree

Archiving Centre in Toulouse, France, using the same algorithms as the Fast Delivery processor.

In summary, the GDR products will be built from four specialised retrackers running in parallel over all surfaces. The data coverage will be up to 81.5° N and S in a dense ground-track layout (35-day repeat cycle). The Envisat ground system will deliver global NRT data in less than 3 hours. These will already be of near-GDR quality as they will be built with the same algorithms and will contain the good-quality orbit produced in real time by the DORIS navigator. The full exploitation of the data from RA-2 demands high-quality absolute calibration at Ku- and S-bands for the three instrument parameters, as well as a very accurate cross-calibration with other altimeter data during overlapping flights, to provide the user community with a continuous and consistent altimetric time series.

The Envisat User Service is the unique interface to the user community. It will register data requests, both fast-delivery and offline, and organise the acquisition, processing and product delivery. It is accessible using a WWW browser via a Unified User Services Interface. This means that users will be able to access Envisat data services at any station or centre via an identical user interface.