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The ENVISAT Medium Resolution Imaging Spectrometer MERIS

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ABSTRACT - The Medium Resolution Imaging Spectrometer (MERIS), developed by the European Space Agency (ESA) for the Envisat-1 polar orbit Earth mission, belongs to a new generation of ocean colour sensors which will yield a major improvement in the knowledge of such a crucial processes as the ocean contribution to the carbon cycle.

MERIS measures the radiance reflected from the Earth's surface in the visible and near infrared part of the spectrum. Data are transmitted in fifteen spectral bands of programmable width and location. The instrument features two spatial resolution and several observation and calibration modes selectable by ground command.

The instrument development is currently carried out by an international team led by AEROSPATIALE under Envisat prime contractor ship of DORNIER. The development of the instrument has now reached a status where the instrument has been proven to be compliant with the scientific requirements.

This paper gives an overview of the instrument, its design with emphasis given to the acquisition and on-board processing chains. A summary of the recently measured performances and interface budgets is also provided

Keywords: Imaging Spectrometer, Remote Sensing, Ocean Colour, Calibration, MERIS, ENVISAT

1 - INTRODUCTION

ESA is developing the Envisat-1 satellite as a major contribution to the Earth global environmental monitoring system in space, towards the end of this decade.

An element of the Envisat-1 payload, MERIS will provide the user community with an advanced sensor for the remote assessment of marine phenomena and processes which dominate about three quarter of the Earth surface and play a crucial role in shaping its climate and ecology

The primary mission objective of MERIS include bio-geochemical oceanography such as phytoplankton biomass and productivity by measuring chlorophyll, yellow substance and other pigments concentrations.

Secondary objectives are related to atmospheric parameters such as water vapour column content, aerosols and cloud properties and to land parameters such as surface reflectance and vegetation indices.

2 - MISSION REQUIREMENTS

The multidisciplinary aspect of the MERIS mission has imposed quite a challenging set of performances requirements.

2.1 - Geometrical requirements

The MERIS output shall represent both, a significant global product and data for detailed examination of regional applications. Following this requirement an operation in two spatial modes has been established. Data acquired at 300 m resolution at sub-satellite point are mainly required in coastal zones and over land. In the second mode, MERIS produces data at 1200 m resolution continuously over the daytime part of the orbit.

A large field of view is required in order to fulfill the need for global coverage in less than three days in order to meet the oceanographic and atmospheric investigation needs.

2.2 - Spectrometric requirements

MERIS is required to acquire 15 spectral bands over the specified spectral range. This is the best compromise between the scientific needs and the platform recording storage and transmission capability.

The spectral range covers the 390 to 1040 nm wavelength region. The availability of bands in the near-infrared will considerably improve the atmospheric correction over oceans.

The spectral bands of MERIS have to be programmable from ground to enable selection of different sets of bands according to the mission plan. The location of the bands, the width and saturation levels may be changed throughout the lifetime.

The spectral width is required to be variable from 1.25 and 30 nm depending on the spectral feature to be observed. Over open ocean an average bandwidth of 10 nm is required for the bands located in the visible part of the spectrum.

2.3 - Radiometric requirements

Of particular importance are the radiometric performances of MERIS. At first the radiometric sensitivity is derived from the requirement of $5 \cdot 10^{-4}$ for NEDR (noise equivalent spectral reflectance at the sea level).

An outstanding radiometric accuracy is imperative for the atmospheric correction over ocean, which is of critical importance since typically 90% of the signal reaching the sensor originates from the atmosphere.

MERIS is required to feature low sensitivity to the polarisation of the incoming light to cope with the highly polarised atmospheric signal.

The large dynamic range of the instrument has to cover low level signals emanating from open ocean up to high level signals such as from bright clouds.

3 - INSTRUMENT CONCEPT

MERIS is a programmable imaging spectrometer which measures the radiance backscattered by the Earth in the 390 nm - 1040 nm part of the spectrum.

The imaging technique is based on the pushbroom observation principle. The scene is recorded simultaneously in the whole spectral range through a dispersive system. Only a part of the spectral range, arranged in 15 spectral bands, is transmitted to the ground. Each band is selectable in position, width and gain by ground command.

Earth scenes are imaged with a spatial resolution of 300 m at nadir and with a regular angular sampling across track. The instrument design allows to reduce the data resolution to 1200 m by combining together, on board, four adjacent pixels across track and four consecutive lines along track.

The instrument has a field of view of 68.5° shared by five identical cameras, each having a field of view of 14° . The cameras are arranged in a fan shape configuration in which the field of view overlap slightly (see Figure 1). The modular design has been specifically selected for MERIS to ensure high optical image quality over a large field of view.

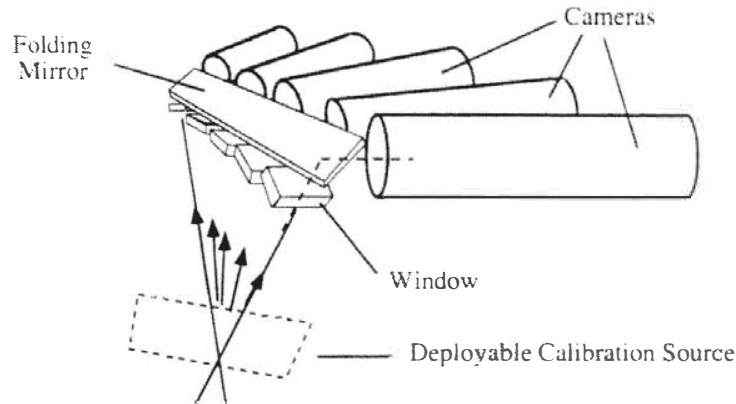


Fig. 1: Arrangement of optical modules, folding mirror and Earth viewing windows

The instrument acquisition and processing chains can be separated into four sub systems:

- The Optics
- The Detection Focal Plane
- The Video Electronic Unit
- The Digital Processing Unit

3.1 - Instrument optics

The MERIS optics consists of an external window, a folding mirror, an off axis catadioptric ground imager and a spectrometer of concentric design.

The windows are used to scramble the incident polarised light coming from the Earth, making the instrument less sensitive to light polarisation changes. The windows are made of two quartz crystal wedges with their optic axis separated by an angle of 45° . A third wedge, made of fused Silica, compensates for the deviation of the transmitted beam. A UV blocking filter is inserted in front of the window.

The ground imager is made of half-components, namely a three lenses aperture group, a concave primary mirror, a convex secondary mirror cemented on the third aperture lens and a field lens cemented on the spectrometer. The dispersive element of the spectrometer is a low grooves density concave reflecting holographic grating. A blocking filter is inserted in the corrector block to suppress the second order of the grating. The optomechanical design is based on the use of Silica and Invar where the barrels of the lenses and mirrors are in Silica and the spacers in Invar.

Table 1 summarises the instrument optical parameters. A picture of one of the flight models of the camera optics is shown in Figure 2.

Focal length	67.3 mm
Pupil area	500 mm ²
I-FOV	1.149 arcmin
Spectral sampling interval	1.25 nm
Grating grooves density	132 grooves/mm
Grating efficiency (-1 st order)	0.36 @ 445 nm

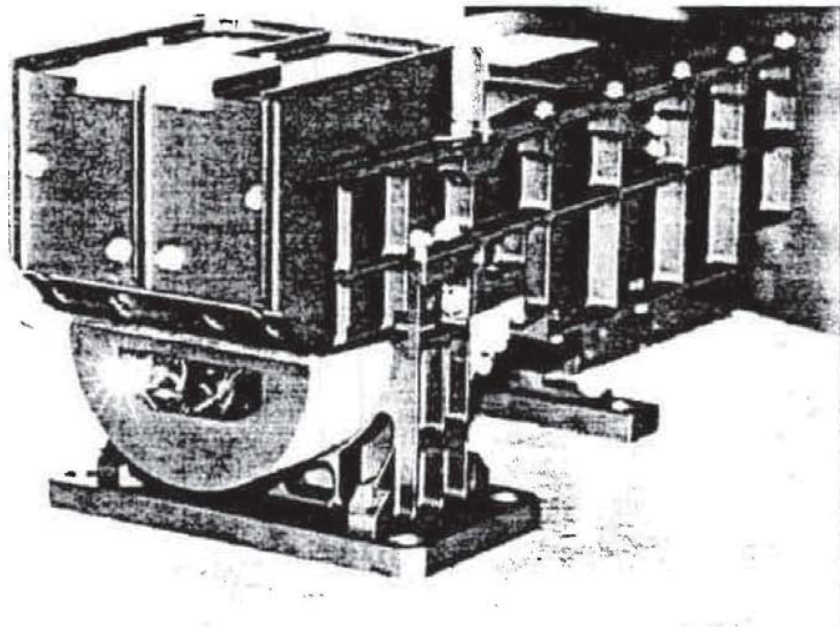


Fig.2: Camera Optics Sub-System - Manufacturer : CERCO (F)

3.2 - Detection Focal plane

The camera detectors are CCD arrays specifically developed for MERIS (Figure 3). Thinned back side illuminated CCDs have been selected which provide the required improved responsivity in the blue part of the spectral range. The imaging zone comprises 576 lines of 780 pixels, only 520 lines of 740 pixels of which are used for imaging purpose. The camera swath is imaged along the CCD line while the light dispersion take place along the CCD column. Each pixel is 22.5 μm square. The CCD covers the spectral range with a nominal 1.25 nm spectral sampling interval. The CCD layout is illustrated in Figure 4.

The CCD temperature is lowered in order to reduce the dark current and to minimise dark signal variation between two calibrations. In operation the CCD temperature is cooled down to -22.5 C by means of Peltier devices with a regulation of ± 0.35 C.

The CCDs operate in a frame transfer mode. The frame period is 44 ms. After integration, the charges are rapidly transferred from the imaging zone to the storage zone. A frame transfer is followed by a new integration period in the imaging zone, while the store zone is read out.

During the frame transfer, the CCD integrates over the entire spectral range a additional signal which is superimposed onto the useful signal. In the case of MERIS, this smear signal creates an offset which needs to be corrected. Because this smear signal is scene dependent, it has to be recorded and corrected for each frame. This has been made possible thanks to the optimisation of the CCD design. The shield covering the storage zone has been slightly extended over several lines of the imaging zone. The so-called smear lines record the smear signal. After summation of the smear lines in the shift register, the resulting smear band is read out and transmitted to the ground at every frame in addition to the 15 spectral bands.

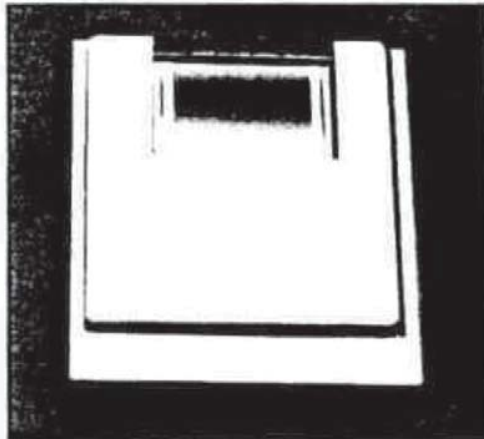


Fig.3: CCD - Manufacturer : EEV (GB)

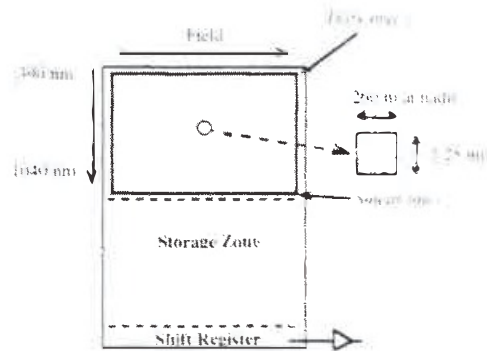


Fig.4: Basic layout of the CCD

Included on either side of the 740 pixels line are dark reference pixels which are also covered by the shield. These pixels are used in the Video Electronic Unit for offset compensation. This compensation is required to ensure the stringent required signal stability along the orbit and in between two calibrations.

A specific coating has been developed and deposited on the CCD surface. The coating features a wedge along the CCD column to ensure an optical thickness of $\lambda/4$ for all wavelengths in the spectral range. This contributes to lower straylight ghost images to acceptable levels.

The CCD plays an important role in the programming of the MERIS spectral bands. Due to the large storage capacity of the readout register (4 times the pixel capacity), several lines can be accumulated in the shift register before to read out the information. This process is termed spectral relaxation. The programmed spectral width is obtained by summing the necessary number of CCD lines in the shift register. For the spectral bands located in the blue-green part of the spectrum, the total integrated signal is high and would exceed the shift register capacity. In this case the spectral relaxation is completed in the Digital Processing Unit. The CCD lines which fall outside the 15 selected spectral bands are dumped at shift register level.

The width and position of the MERIS spectral bands can be modified in-flight through a dedicated management of the CCD programming. Apart from allowing the selection of different sets of spectral bands during the mission, the CCD programming serves also the purpose to compensate for any spectral drift which may occur during launch or in flight.

Quantitative design and performance parameters of the CCD are listed in Table II.

Table II: CCD parameters		
Architecture	Frame transfer	
Technology	- Thinned CCD (thickness 20 μm) - Back side illuminated	
Size (imaging & storage zone)	780 (H) x 576 (V)	
Pixel size	22.5 μm x 22.5 μm	
Full well capacity	Pixel	$> 6 \times 10^5$ electrons
	Shift register	2.4×10^6 electrons
Frame rate	22.8 Hz	
Operating temperature	-22.5 $^{\circ}\text{C}$	
Responsivity	see Figure 5	
Dark current at operating temperature	$< 1.4 \text{ pA/cm}^2$	

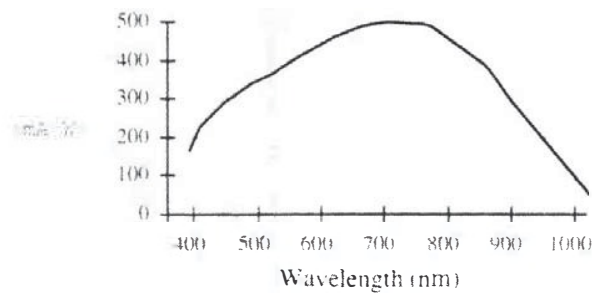


Fig.5: CCD responsivity - Averaged value over the five CCD flight models

3.3 - Processing chain

Each camera has its own dedicated image processing chain. The analogue processing is undertaken by the Video Electronic Unit, whose functions are to:

- extract the useful signal by correlated double sampling
- compensate the offset variation by using the dark reference pixels
- amplify the signal
- digitize the video signal on 12 bits

The overall instrument acquisition and on board processing is illustrated in Figure 6.

The signal amplification is done by selecting one of the 12 fixed gains defined in the range [1 to 3.75]. The selection of the amplification gain is done separately for each spectral bands in order to minimize the noise contribution of the processing chain.

The digital output of the Video Electronic Unit is subsequently processed by the Digital Processing Unit in three major steps:

- Complete the spectral relaxation up to the requested band width.
- Subtract the offset, smear components and compensate for gain non uniformity and ageing.
- Reduce the data spatial resolution when required.

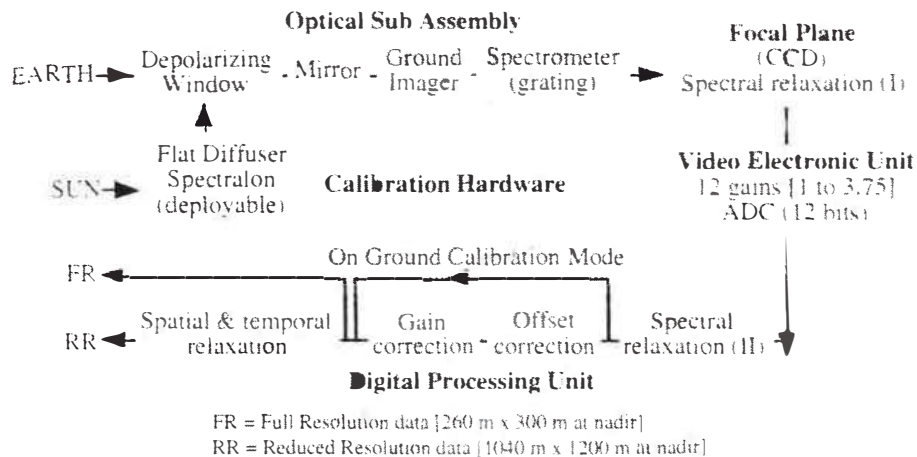


Fig. 6: Acquisition and on board processing chain

The instrument design offers the flexibility to have these corrections applied either on board or on ground. In the latter case offset, smear and gain correction are bypassed in the on-board processing flow.

4 - OPERATION CONCEPT

Since MERIS is based on solar reflected radiation, appropriate illumination conditions of the scenes for the image acquisition process has to be ensured. The instrument Observation mode is thus defined for the day zone of the orbit equivalent to a sun incidence angle of 80° at the sub satellite point, corresponding to measurement time of approximately 45 min per orbit. Calibration is carried out when the spacecraft flies over the south orbital pole and the sun illuminates the instrument in a direction orthogonal to nadir. For the rest of the orbit, MERIS is in non-observation modes. Figure 7 illustrates the basic operation timeline.

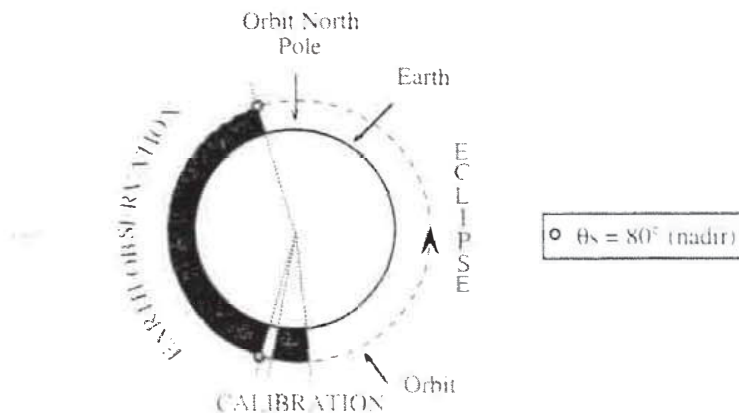


Fig. 7: MERIS Operation Profile

Four operation modes are defined:

- Observation modes - **Averaging**
 - **Direct and Averaging**

In both modes data can be corrected from offset, smear and gain non uniformity either on board or on ground. In the later case, raw data are transmitted and radiometrically corrected on ground.

- Calibration modes
 - **On-board Calibration**, where calibration coefficients are computed on board, stored and as well transmitted to the ground
 - **On-ground Calibration**, where only raw calibration data are transmitted to the ground. Calibration coefficients are computed on ground.

In Averaging Mode MERIS continuously delivers Reduced Spatial Resolution (RSR) data. When MERIS is switched to the Direct and Averaging Mode, the instrument delivers in addition to the RSR data, Full Spatial Resolution (FSR) data in the same 15 spectral bands. These Full Resolution data will be available for up to 20 minutes per orbit, limited by the platform capability.

5 - CALIBRATION CONCEPT

To meet the stringent requirements on accuracy the measurement data need to be corrected for non-uniformities and distortions introduced in the overall measurement system, as well as to convert the MERIS data into radiance values. In-flight, four calibration sequences are defined:

- Dark calibration
- Radiometric gain calibration
- Diffuser ageing characterisation
- Wavelength referencing

During the dark calibration, signal is recorded with the Earth and Sun aperture closed. Multiple frames are acquired and averaged in real time yielding the Dark Current Offset coefficients which account for pixel dark current and electronic offset.

In the gain calibration mode, a white diffuser plate, sun illuminated, is inserted into the field of view of MERIS at the cross over point of the five cameras fields of view. The diffuser provides a reflectance standard across the entire spectral range and field of view. In this way a full aperture instrument calibration which follows the same optical path as in the observation modes is performed. During the calibration the signal is recorded during 512 frames. Each frame is corrected from offset and smear components. The averaged signal is then divided by the diffusers BRDF obtained from on ground characterisation and stored on board, yielding the Absolute Radiometric Gains. During the on-ground calibration mode the on-board processing is limited to the averaging over the 512 frames. The gain coefficients are calculated on-ground.

The calibration diffuser is exposed to the sun for a cumulated period of about 1 hour during the MERIS lifetime. Some limited degradation caused by radiations (UV and particles) exposure may be expected. A second white diffuser is therefore provided to evaluate changes in the BRDF of the commonly used diffuser. This diffuser will be used infrequently and will thus not degrade at the same rate as the first diffuser. The ageing of the diffuser is monitored by comparing the data acquired with both diffusers.

Spectral calibration is achieved by using another diffuser featuring well known absorption peaks. MERIS will be reprogrammed to sample adequately the absorption features. From this calibration the spectral position of any spectral band can be derived. It is also envisaged to use as an alternative the solar Fraunhofer absorption lines when observing the sun illuminated white diffuser.

6 - ON BOARD CALIBRATION HARDWARE

The required calibration performances for MERIS are quite severe. A very accurate band to band calibration relative to the solar spectral irradiance is required for ocean colour applications. The imaging principle of MERIS imposes, in addition, a need for detector elements to be accurately normalised.

The basic hardware requirements for an on-board calibration system offering both a uniform reference signal over a large field of view and a stable absolute spectral reference signal has led to the preferred solution which utilises flat diffuser plates illuminated by the sun.

The calibration hardware is implemented on a selection disk (Figure 8). A stepper motor allows to select alternatively any of the five positions of the disk as required by the instrument mission requirements:

- Gain calibration: a well characterised flat plate white diffuser is inserted into the field of view of MERIS.
- Dark calibration: the Earth and Sun optical paths are blocked.
- Diffuser degradation monitoring: the nominal and redundant diffusers are alternatively inserted into the field of view of MERIS.
- Spectral calibration: the wavelength diffuser is inserted into the field of view of MERIS.

The selection disk also includes a diaphragm which is introduced in the field of view for the Earth Observation modes.

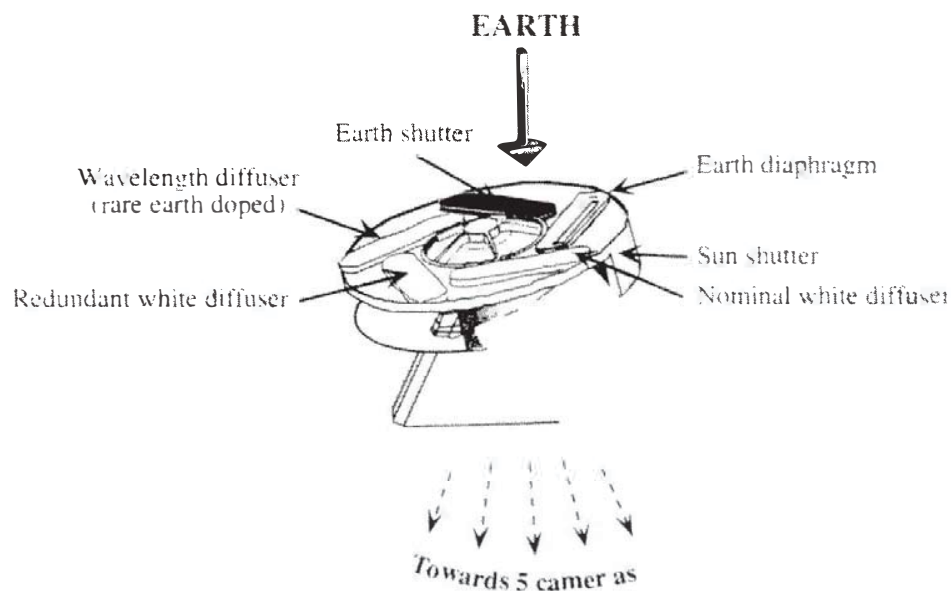
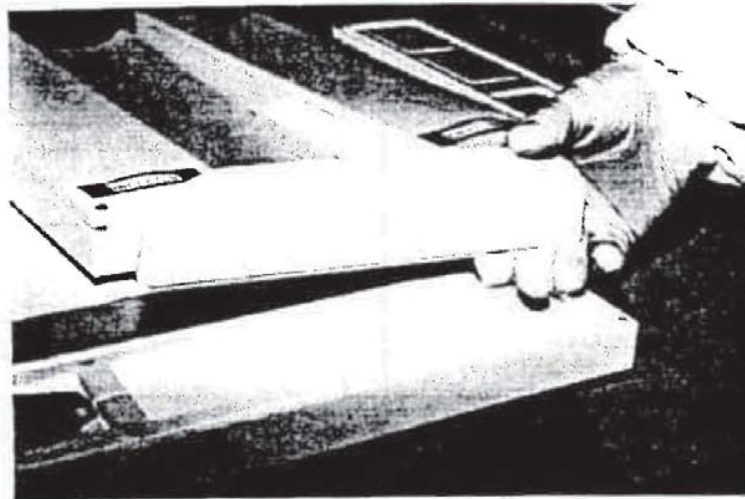


Fig.8: Implementation of the calibration hardware onto the selection disk

Following extensive environmental tests, Spectralon™ has been selected as diffuser material. Diffusers manufactured with this material offer the required uniformity over the field of view and a remarkable stability once they have been cleaned according to a procedure specifically established for the MERIS programme.

White Spectralon™ diffusers (Figure 9) and Spectralon™ diffuser doped with rare earth oxide are used respectively for the gain and spectral calibration.



(Photo courtesy of Aerospatiale)

Fig.9: Diffuser plate in Spectralon™ - Manufacturer : LABSPHERE (USA)

Both diffusers have been characterised on ground:

- The BRDF characterisation of the white diffusers is reported in [Oli] 97]
- The hemireflectance characterisation of the rare earth doped diffusers is shown in Figure 10.

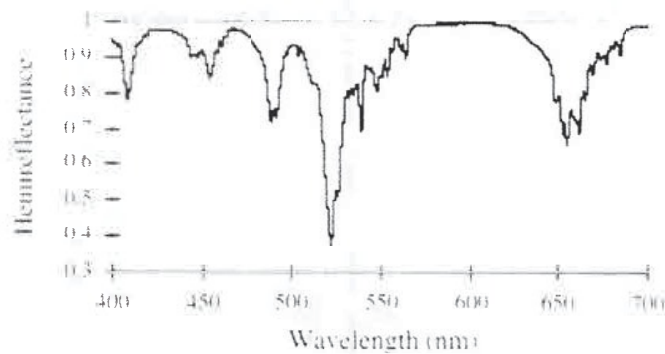


Fig.10: Earth doped diffuser hemireflectance as a function of wavelength.

7 - PERFORMANCES AND INTERFACES TEST RESULTS

Testing of MERIS is done at unit, camera and instrument level. A simplified performance verification matrix is provided below

Performance	FPA	AIC	OSA	Camera	Instrument
Field of View			X	X	X
Inter Band Registration			X	X	X
Spectral Range	X		X	X	
Spectral sampling interval			X	X	
Spectral Resolution			X	X	
Spatial Registration			X	X	X
Polarisation	X		X	X	
Linearity	X	X			
MTF	X	X	X	X	X
Signal Dynamics	X				
S/N or NEDL		X			X
Accuracy					
Orbital signal stability		X			
Straylight				X	X

OSA: Optical Sub Assembly

AIC: Analogue Imaging Chain = FPA + VEU

7.1 - Performances budgets

All the performances parameters have been measured on flight models, except for these verified at instrument level which have been so far measured on the Engineering Model, as the Flight Model is presently in integration phase.

	GEOMETRIC IMAGE QUALITY
Field of view	68.5° centered about nadir
Swath width	1150 km, from the Envisat-1 orbit
Localisation accuracy	< 2 km
Pixel size	See Figure 11
Inter band registration (1)	< 0.15 pixel (1)

(1) averaged value over all bands combinations

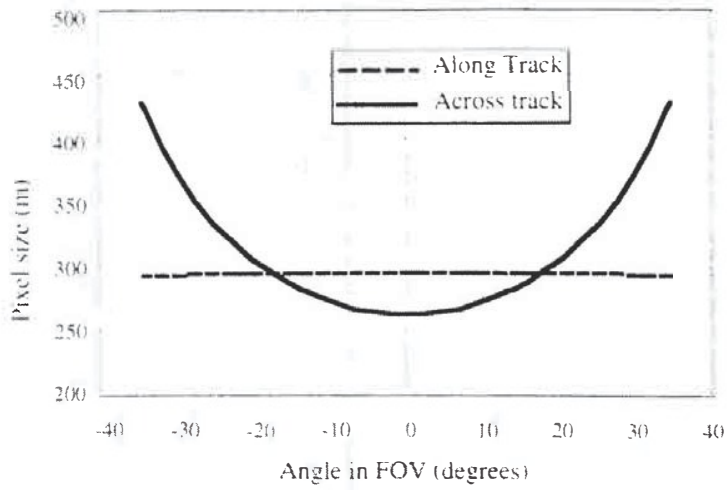


Fig.11: Pixel size (Full Resolution data) along track and across track as a function of angle in the field of view

SPECTROMETRIC IMAGE QUALITY	
Spectral range	390 - 1040 nm
Spectral sampling interval	1.25 nm
Spectral resolution	1.7 nm (see Figure 12)
Band transmission capability	15 bands programmable in location
Spectral bandwidth	programmable from 1.25 nm to 30 nm
Band center knowledge	0.6 nm

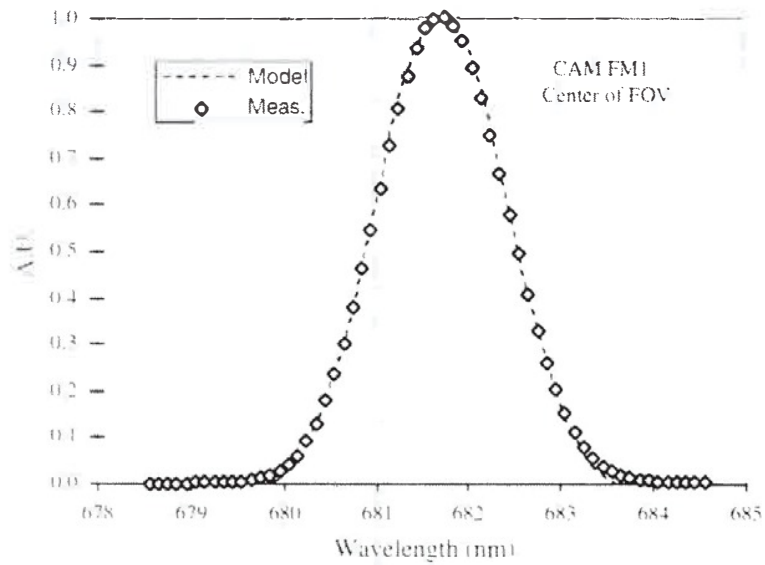


Fig.12: Instrument line shape function

RADIOMETRIC IMAGE QUALITY	
Polarisation sensitivity	< 0.3 % over the full spectral range
Signal dynamics	From noise level to bright clouds signal (reflectance 1.0) (max. radiance = $620 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$)
Radiometric resolution - NEDL	See Figure 13
Radiometric accuracy	2 % to 4 % relative to the sun irradiance
Orbital signal stability	0.2 %

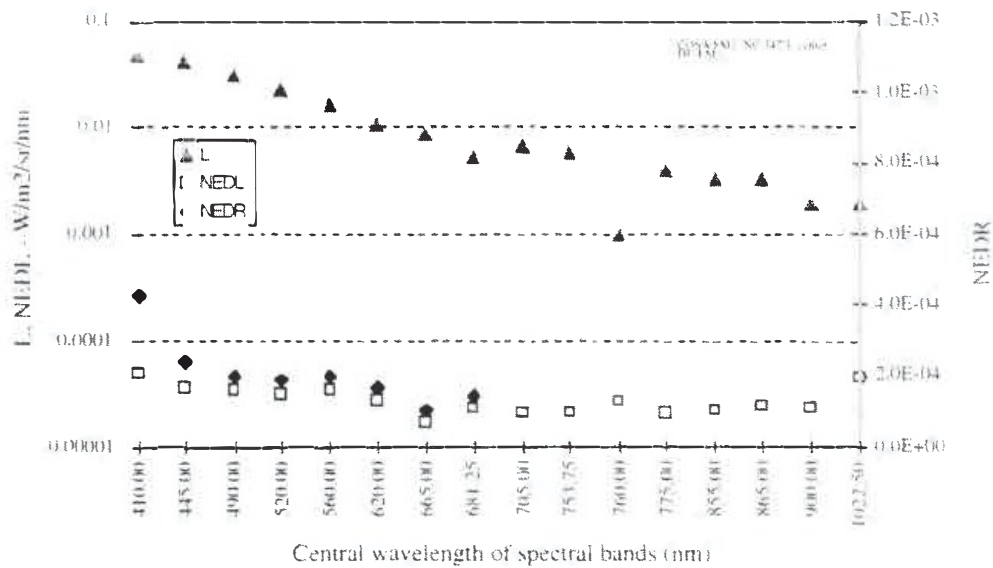


Fig.13: Radiance L and radiometric resolution (Noise Equivalent Spectral Radiance top of the atmosphere NEDL, Noise Equivalent Reflectance at sea level NEDR) as a function of wavelength.
 - Ocean scene (case I waters)
 - Pixel position: center of field of view with sun zenith angle = 60
 - Reduced Resolution data

7.2 - System and interface budgets

Lifetime		4 years
Data Rate	Reduced resolution data	1.6 Mbits/s
	Full resolution data	24.0 Mbits/s
Mass		200 kg
Power		200 W
Dimensions (L x l x h)		1.8 m x 0.9 m x 1.0 m

The overall mechanical layout is illustrated in Figure 14.

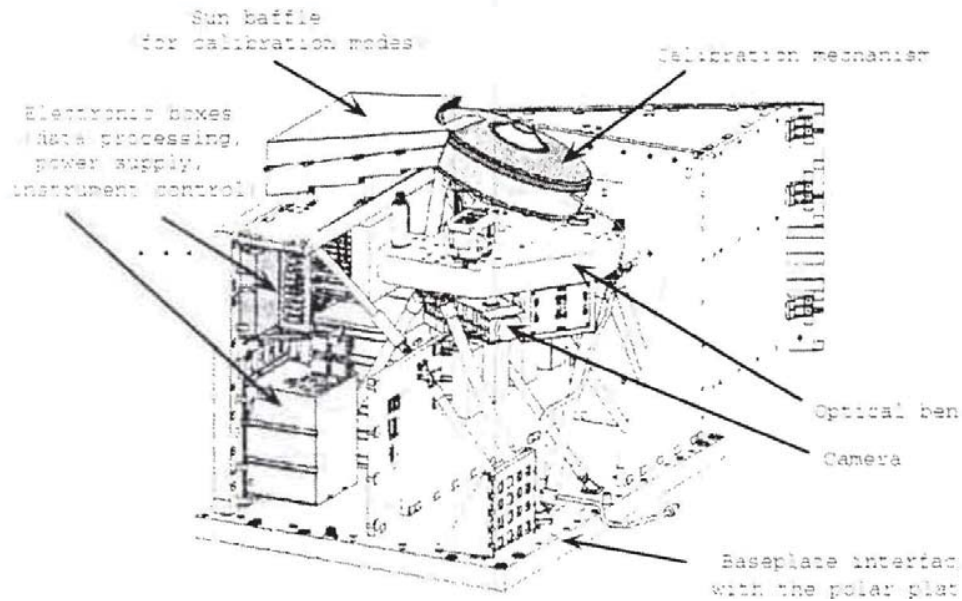
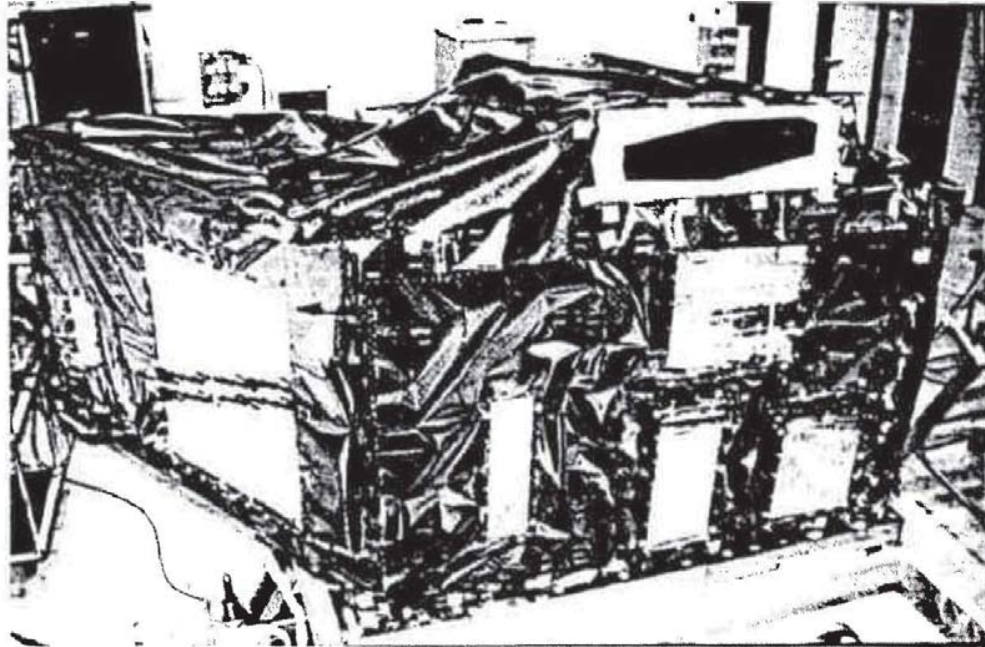


Fig.14: Mechanical layout of MERIS

8 - OUTLOOK

The instrument Engineering Model (Figure 15) programme has been successfully accomplished. The model has been integrated on the polar platform Engineering Model and is currently under testing at satellite level. Flight model manufacturing at unit and subsystem level is completed and the instrument integration is under way. The Flight Model instrument will become available in 1998 for integration on the ESA Envisat-1 satellite.

MERIS will provide the user community with a highly flexible ocean colour instrument featuring both programmable spectral and spatial characteristics as well as excellent radiometric performances.



(Photo courtesy of Aerospatiale)

Fig.15: MERIS Engineering Model

REFERENCE:

- [Olij 97] C. Olij, J.G. Schaarsberg, H. Werij, E. Zoutman, G. Baudin, B. Chommeloux, J.-L. Bézy, G. Gourmelon: "Spectralon Diffuser Calibration for MERIS". *The European Symposium on Aerospace Remote Sensing*, London, United Kingdom, September 1997