

## → STAR IN THE SKY

### The SMOS payload: MIRAS

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**MIRAS is more than just the payload of SMOS. It is a radio telescope pointed towards Earth, an instrument that has challenged the fundamental theories of radio astronomy, and made a major contribution to science even before being launched.**

carried on board ESA's Soil Moisture and Ocean Salinity (SMOS) mission. MIRAS stands for the Microwave Imaging Radiometer with Aperture Synthesis.

Built by a consortium of over 20 European companies led by EADS-CASA Espacio (E), MIRAS is the single instrument

The theory behind microwave remote sensing of soil moisture and ocean salinity is based on the significant contrast between the electromagnetic properties of pure liquid water and dry soil, and pure water and saline water respectively. As the proportion of water in the soil-water mixture (or proportion of salt in the saline mixture)

increases, this change is detectable by microwave sensors in terms of the emission of microwave energy, called the 'microwave brightness temperature' of the surface.

For practical soil moisture and ocean salinity applications, using longer microwave wavelengths offers the advantage that the atmosphere, or vegetation cover, are more transparent to the upwelling signal from the surface. The radiation emitted by Earth and observed in the L-band microwave range by SMOS, however, is not only a function of soil moisture and ocean salinity. To ensure that the data derived from the SMOS mission are correctly converted into the appropriate units of moisture and salinity, many other potential perturbation or contamination effects on the signal must be carefully accounted for.

### A truly novel instrument

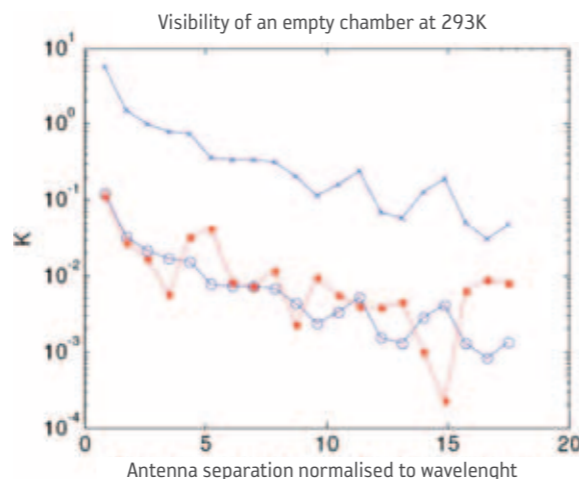
For optimum results, SMOS will measure the microwave radiation emitted from Earth's surface within the 'L-band', around a central frequency of 1.413 GHz. This microwave frequency is protected from man-made emissions and provides the greatest sensitivity to soil moisture and ocean salinity, while minimising disturbances due to the weather, atmosphere and vegetation cover above the surface.



↑ SMOS payload industrial consortium



MIRAS correlations inside ESA's Maxwell anechoic chamber (top blue line, predicted values from radio astronomy; bottom blue line, Corbella equation prediction; measurements in red)



The most challenging requirements for the mission are to be able to achieve good radiometric accuracy and stability, repeated global coverage over a short time interval, coupled with the ability to capture regional details in the quantities of interest.

Observations at this frequency and with this spatial resolution would normally require an extremely large antenna (at least 8 m diameter) to achieve the desired results. Unfortunately, this approach would lead to an extremely large payload, too big for the size of satellite available.

MIRAS's truly novel approach makes use of techniques used in radio astronomy, called 'aperture synthesis', to create a large aperture from a two-dimensional array of small passive microwave radiometers, and 'interferometry' to obtain the required spatial resolution and coverage.

Similar to the very large baseline interferometers (VLBI) used on Earth, the SMOS concept relies on a Y-shaped array of 69 elementary antennas, deployed in space, which are equivalent to a classical antenna over 8 m in diameter. This will be the first ever two-dimensional interferometric radiometer in space.

From a mean altitude of 755 km, SMOS will 'see' a considerable area of Earth's surface at any point along its orbit. The interferometric measurements will result in images from within a hexagon-like field of view about 1000 km across, enabling total coverage of Earth in under three days

### Instrument concept

MIRAS has changed the basic equation of radio astronomy. In theory, if Earth was enclosed in a gigantic sphere

## → MIRAS subsystems

### LICEF

The 66 'Light-weight Cost-Effective' (LICEF) receivers are the eyes of MIRAS. They are very sensitive total power radiometric receivers integrated with an antenna which captures radiation in both polarisations in the radio astronomy protected band of 1400-1427 MHz. Weighing only 1 kg and consuming 1W power, these receivers filter out any signals outside the protected band and are extremely 'clean', i.e. very low self-noise and no internal interference.

### Noise Injection Radiometers (NIR)

Three NIRs each consist of two LICEFs connected to a noise injection control unit (NIC). 'Noise injection' radiometers are more stable than 'total power' radiometers like the LICEFs. The NIRs are used to calibrate the whole array using the on-board calibration system (CAS).

### Calibration System (CAS)

The on-board calibration system provides a correlated noise reference signal to calibrate the amplitude and phase of the LICEF receivers.

### MOHA

The transmission of the master clock signal, the local oscillator and the received digitised data is performed with an optical-fibre digital network called MOHA. This has advantages over classical electrical interfaces, such as: (a) low electromagnetic emissions, vitally important for MIRAS, (b) good phase stability by comparison with coaxial cables, over temperature and when bent, (c) insensitivity to ground differential voltages and (d) lightweight and very flexible. MOHA consists of a number of optical splitters, electro-optical converters and optical fibres. Overall, MOHA contains 74 solid-state lasers, 168 optical-receiver diodes and approximately 800 m of optical fibre cable.

### Correlator and Control Unit (CCU)

This is the instrument central computer that correlates the data received through the MOHA optical harness from all 66 LICEFs and NIR receivers. The CCU also monitors 12 thermal control loops to ensure a thermal gradient of less than 1°C across any arm segment and 6°C maximum gradient between any pair of LICEFs.

### Control and Monitoring Node (CMN)

The CMN acts as a remote terminal of the CCU. Its main functions are: handling commands from and telemetries to the CCU; analogue telemetries acquisitions like physical temperatures and LICEF voltages;

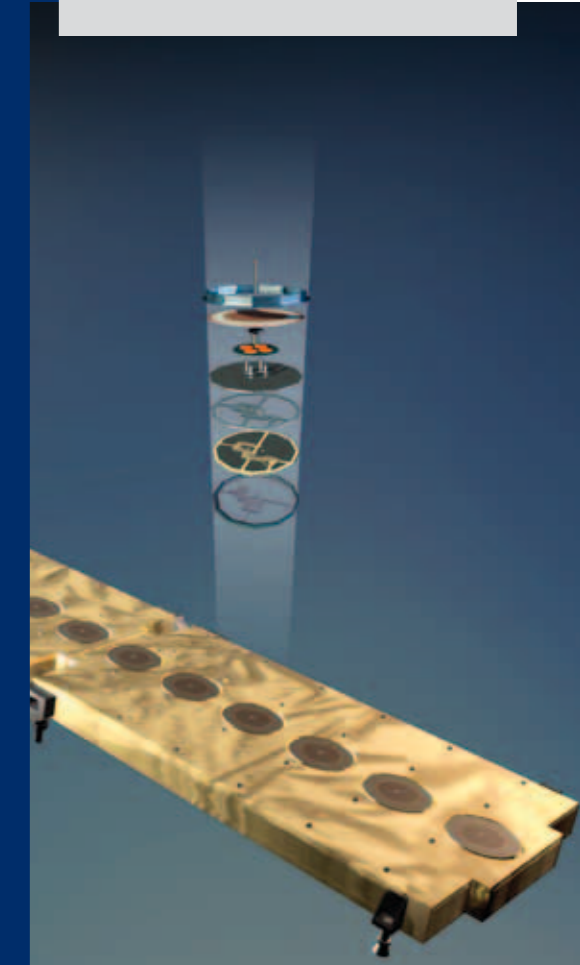
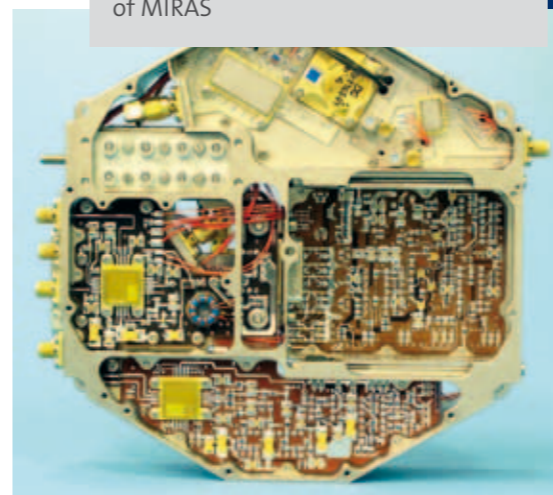
control of the LICEF polarisation and calibration; control of the CAS noise injection level switch; distributed thermal control (heaters); secondary power supply to segment units (LICEF, NIR and CAS); finally, the generation and distribution of the 1396 MHz local oscillator signal to all LICEFs.



How each LICEF fits on the arms of MIRAS



A LICEF radiometric receiver: the eyes of MIRAS



of microwave absorbing material, at uniform physical temperature (a 'black body'), radio astronomers would not be able to image such a simple uniform target. MIRAS broke this barrier apart.

MIRAS is based on the 'Corbella' equation, which is a fundamental variation to the Van-Cittert Zernike theorem used in radio astronomy. The Corbella equation relates the behaviour of a radiometer inside a black body with another well-known microwave theorem, the 'Bosma' theorem. The Corbella equation was derived by the Polytechnic University of Catalonia (E) during the pre-development activities that led to the SMOS mission and can be considered as a major contribution of SMOS to science already before being launched.

MIRAS captures the noise radiated by the target through its small apertures and performs the cross-correlation of the

$$V_{ij}^{pq}(u, v) = \iint_{\xi^2 + \eta^2 \leq 1} F_{n,j}^{\alpha,p}(\xi, \eta) F_{n,j}^{\beta,q*}(\xi, \eta) \frac{T_B^{\alpha\beta}(\xi, \eta) - \delta_{\alpha\beta} T_r}{\sqrt{1 - \xi^2 - \eta^2}} \tilde{r}_{ij} \left( -\frac{u\xi + v\eta}{f_o} \right) e^{-j2\pi(u\xi + v\eta)} d\xi d\eta$$



The Corbella equation

signals from all possible pairs ('baselines') of antennas. This set of cross-correlations constitutes the raw measurements provided by the instrument. According to the Corbella equation, each cross-correlation is a Fourier component of the difference (contrast) between the brightness temperature of the target and the physical temperature of the instrument. No contrast leads to zero correlations, which is the case of an interferometer enclosed in a black body in thermal equilibrium conditions (Bosma theorem).

So MIRAS does not measure the brightness temperature of the scene directly, but its Fourier spectrum. It is therefore necessary to apply an inverse transformation to the basic measurements of SMOS to retrieve an image. System non-idealities mean that the relationship between target and cross-correlations is not an exact Fourier transform, and the image reconstruction has to take this into account.

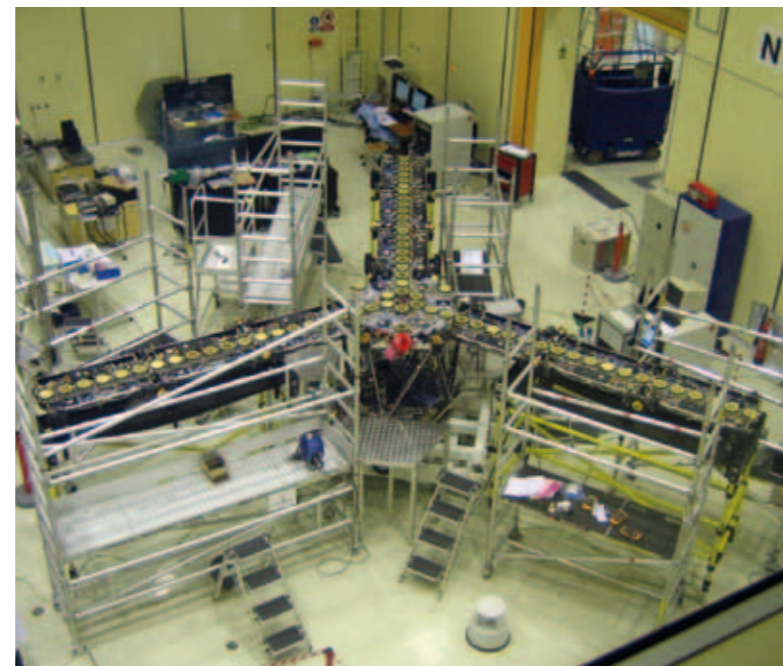
### MIRAS mechanical features

MIRAS's unusual three-pointed star shape is due to the hexagonal sampling that the instrument performs of the spectrum of the image. The small apertures (69 in total) are arranged along three arms evenly spaced at 120°. This represents a saving of 15% in the required number of receivers by comparison with rectangular sampling (which would lead to a cross shape instead of a star). Less visible to the eye is MIRAS's main architectural feature: the replication of the same basic electrical, mechanical and thermal functions across its large array. The modularity of its design has been the key to split critical requirements across different subsystems optimally, to ease their manufacturing and integration, and to allow instrument testing on ground.

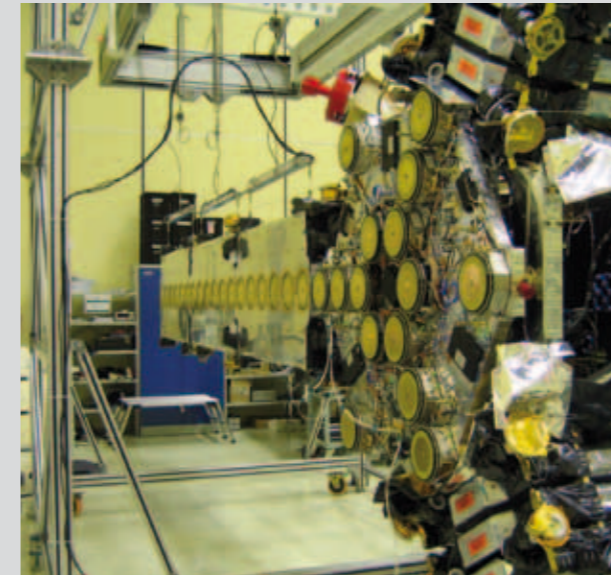
**MIRAS has changed the basic equation of radio astronomy.**

To fit on the launcher, the MIRAS arms are divided into three segments separate d by spring-hinged deployment lines. The deployment of the three arms happens simultaneously thanks to a speed regulator in the root hinges and a system

of pulleys and ropes interconnecting this to the two outer hinges. The deployment takes about three and a half minutes.



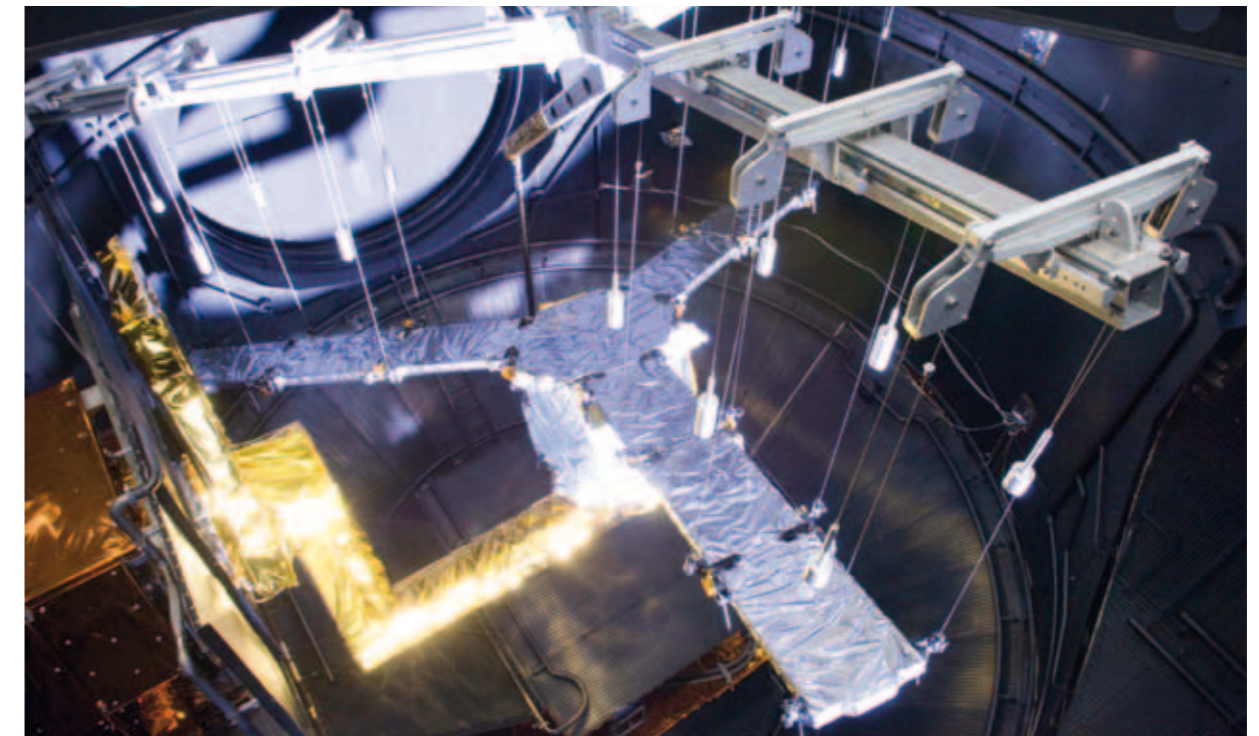
MIRAS during its assembly and integration



Arm deployment test

The arms are made of carbon-fibre reinforced polymer with some aluminium-reinforced areas near the deployment mechanisms. The carbon fibre ensures a high thermal structural stability, important for keeping a constant distance between L-band receivers during the mission. The width of the arms was chosen to reject signals coming from behind the array as well as to host the electronic boxes and harness inside.

The arms fold flat over three of the sides of a 1.2 m high strutted hexagonal prism that constitutes the hub of



MIRAS inside ESA's Large Space Simulator undergoing thermal-vacuum tests

the payload. The other sides accommodate the X-band transmitter to send the data to ground and the star tracker to determine the pointing of the instrument accurately. The top and bottom bases of the hub prism serve as trays to which attach the electronic equipment. The hub interface to PROTEUS is through fixing points at the four corners of the platform upper side.

The thermal control in MIRAS is designed to minimise the temperature differences across receivers. This is achieved by placing all these units on thermal doublers actively controlled in temperature by heaters. The temperature sensors are built into the receivers themselves, providing the feedback for the thermal control software in the on-board computer. Externally, the temperature equalisation of the receivers is assisted by a radio-transparent foil placed on all the antennas.

### MIRAS electronics

The level of power radiated by Earth that can be collected within the protected L-band (brightness temperature) is very low. Hence the receivers of MIRAS are highly sensitive microwave receivers (LICEFs) that amplify the signal several billions of times up to detectable levels.

The digital output signals from the receivers are sent to a central correlator through an optical harness (MOHA). Optical fibres have proved essential in achieving MIRAS's formidable performance, absent of any bias in the majority of the correlations. Errors caused by internal signals leaking towards the very sensitive receivers are difficult, if not impossible, to calibrate out properly given the tight scientific requirements. Optical fibres do not radiate nor pick up any electrical signal, leading to the verified result of extremely clean measurements. SMOS is the first mission on which ESA will launch an optical harness into space.

## → Interferometry in remote sensing

The origins of radio astronomy date back to the 1940s and 50s, but applications to Earth observation were only suggested in the late 1970s by the University of Berne. It was practically proposed in the 1980s by engineers at NASA's Goddard Space Flight Center in collaboration with the University of Massachusetts at Amherst, with the objective of mapping Earth's soil moisture and ocean salinity, two important geophysical parameters never measured before at global scale.

developments followed elsewhere with different variations such as using the motion of the platform to reduce in the required number of receivers, this being equivalent to the use of Earth rotation in radio astronomy.

Aperture synthesis in two dimensions was developed in Europe during the 1990s. The Technical University of Denmark constructed a laboratory demonstrator and ESA started the research for the spaceborne L-band MIRAS radiometer.

ESA's study involved French scientists at the Centre d'Etudes Spatiales de la Biosphère (CESBIO), who had already started the research in this area, and benefited with the participation of radio astronomers from the Observatoire du Midi Pyrenees. The Polytechnic University of Catalonia (UPC) in Barcelona played an important role in defining the requirements and calibration strategy for MIRAS.

Even more crucial was UPC's research on the completed ESA MIRAS demonstrator, which led to the Corbella equation in early 2003, a fundamental correction to the formulation used by radio astronomers. The Helsinki University of Technology (HUT) manufactured the HUT-2D, the first airborne two-dimensional aperture synthesis radiometer to provide good quality images of Earth surface. The calibration strategy of SMOS was first tested on HUT-2D.

In 1999 the SMOS mission was selected by ESA as the second Earth Explorer Opportunity Mission,

carrying MIRAS as the only payload instrument. In 2009, SMOS will demonstrate these new techniques and pave the way for applications in other areas. In fact, aperture synthesis has been proposed from geostationary orbit and higher frequency interferometers are now considered viable for Earth observation satellites flying in low Earth orbit.

Several other ground-based and airborne microwave interferometric radiometers have been developed by different groups around the world, such as NASA's ESTAR-2D, JPL and ESA geostationary sounder demonstrators, and the C- and X-band interferometers of the Chinese Centre of Space Science and Application Research.



AMIRAS: the Airborne MIRAS demonstrator on the HUT Skyvan



Helsinki University of Technology's HUT-2D interferometer



The first interferometric radiometer built had a synthetic beam in only one dimension, using the real aperture antenna pattern in the other. This was NASA's Electronically Steered Thinned Array Radiometer (ESTAR), an aircraft demonstrator of such a hybrid instrument. Subsequent

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