The MIRAS Demonstrator Pilot Project
– Towards SMOS

M. Martín-Neira, P. Piironen, S. Ribó, E. Panaro, J. Font-Rosselló
Payload Systems Division

J. Martí-Canales, I. Zayer, A. Martín-Polegre, P. Iversen, A. Rivada
Electromagnetics Division

R. Roumeas
Thermal and Structures Division
ESA Directorate of Technical and Operational Support, ESTEC, Noordwijk, The Netherlands

M. Aguirre & P. Silvestrin
Future Programmes and Technical Studies Division, ESA Directorate of Earth Observation, ESTEC, Noordwijk, The Netherlands

Following several earlier feasibility studies, in 1998 ESA began the MIRAS Demonstrator Pilot Project within the Agency's Technology Research Programme (TRP) and General Support Technology Programme (GSTP) in an attempt to provide a technology solution to the inherent challenges of L-band radiometry. The objective was to build a representative element of the MIRAS instrument, which has subsequently been selected as the main payload for the Soil Moisture and Ocean Salinity (SMOS) mission. A second phase was initiated in April 2001 to demonstrate key end-to-end instrument performances, including antenna deployment and image validation, following approval of the SMOS mission Phase-A at the end of 1999.

Introduction

A first article about MIRAS was published in the November 1997 issue of the ESA Bulletin, in which we presented the results of the feasibility study of a two-dimensional aperture-synthesis radiometer for soil moisture and ocean salinity observations. In the meantime, the Soil Moisture and Ocean Salinity (SMOS) mission was selected in 1999 for Phase-A feasibility study as the second ESA Earth Explorer Opportunity Mission, carrying MIRAS as the sole payload on the Proteus platform. This article focuses on the technology achievements of MIRAS in the context of SMOS mission.

L-band radiometry faces the challenge of flying large apertures to achieve a spatial resolution suitable for scientific applications. Two-dimensional aperture synthesis is a solution to this challenge as it avoids mechanical scanning of a big reflector, and thus the technology research efforts of the Payload System Division at ESTEC have focused on this technique, more commonly known as 'interferometry'.

The MIRAS Demonstrator Pilot Project lumps a number of activities in various fields of expertise, to procure and test a representative part of the instrument. Some of the most relevant measurements obtained with the hardware so far are presented below, together with some of the early results of image validation tests using the first prototype MIRAS receivers and calibration methods. The instrument's evolution from the initial technology activities to its Phase-A configuration is also reviewed, and some insight is provided into the objectives and calendar for the SMOS mission itself.

MIRAS status prior to the Demonstrator Pilot Project

Figure 1 shows the MIRAS instrument as it looked back in 1997, following a major feasibility study for a large platform, a number of theoretical and breadboarding activities, and a down-sizing exercise onto a small platform, all conducted during the preceding four years. There was an array of three co-planar 5.2 m-long arms, with 27 radiating elements per arm with a spacing of 0.89 wavelengths, working in the protected part of the L-band spectrum (1400 – 1427 MHz). The main subsystems were:

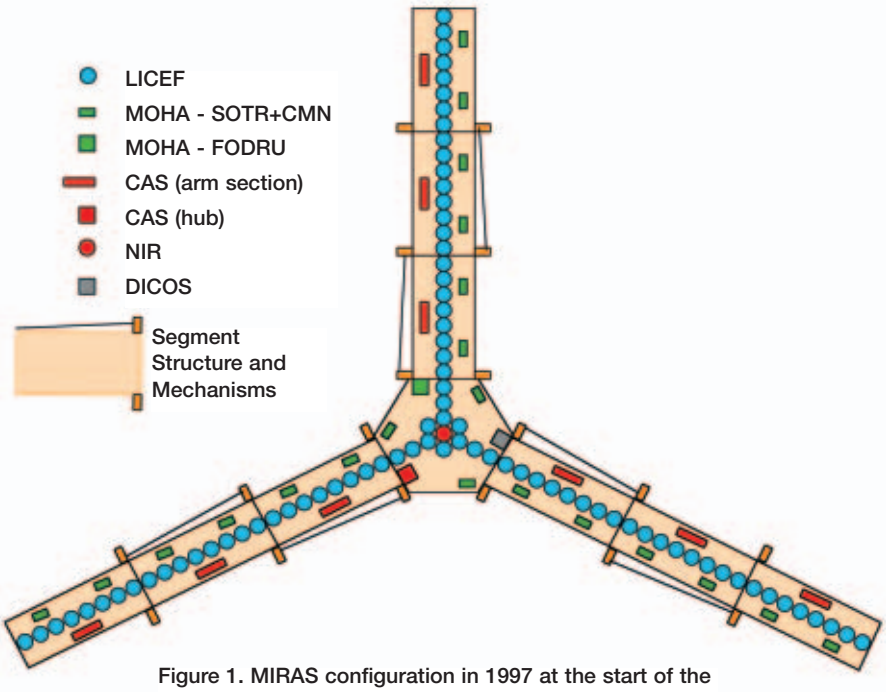


Figure 1. MIRAS configuration in 1997 at the start of the MIRAS Demonstrator Pilot Project

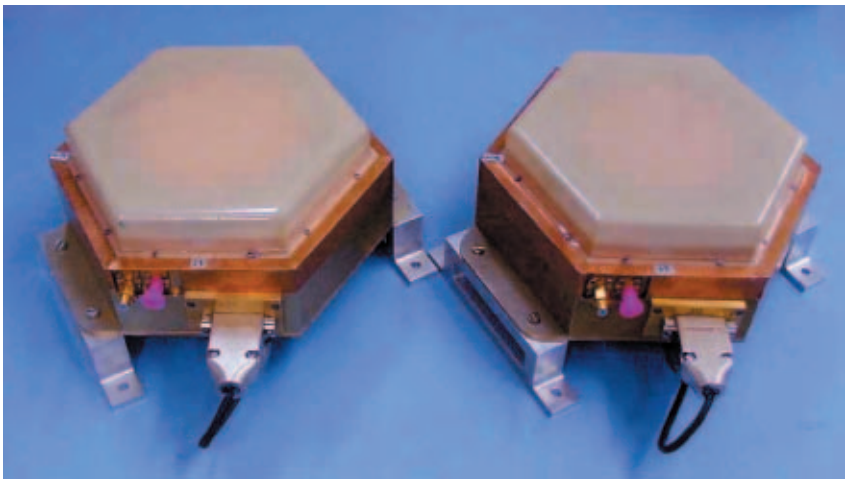


Figure 2. First-generation LICEF-1 antenna-receiver units (courtesy of MIER, Spain)

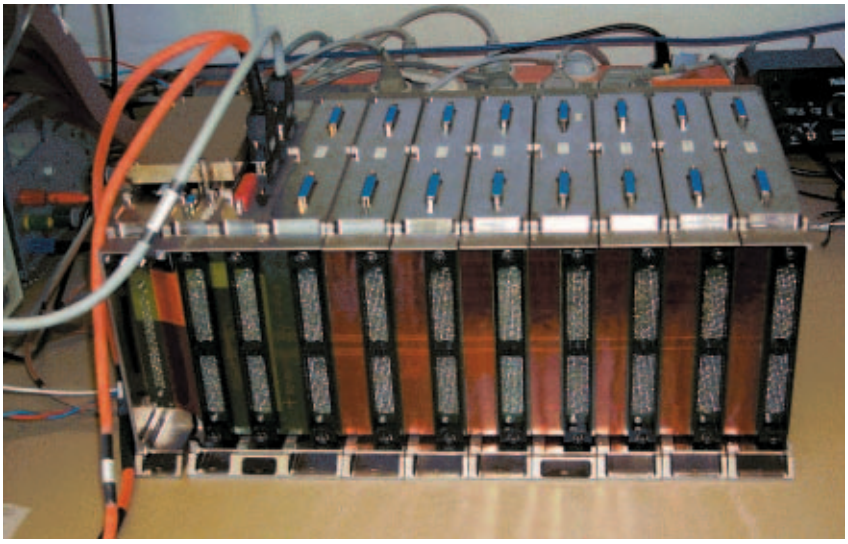


Figure 3. First-generation DICOS-1 digital correlator unit (courtesy of Astrium GmbH, Germany)

- Structure and Mechanisms (STM)
There were three arms segmented into three parts, unfolding in one plane like a solar array, with identical hinges and mechanisms at each of the nine joints. The mechanical design had to be compatible with the electrical harness running along the arm, and would serve the important role of ground plane for the antennas.

- Lightweight Cost-Effective Front-end (LICEF)
These were the antenna-receiver integrated units, responsible for receiving the thermal radiation in the two polarizations (horizontal and vertical), low-noise amplification and filtering. These receivers would down-convert the signals to their in-phase and quadrature components, providing their 1-bit digitised versions as outputs. In addition, each LICEF would also have a Power Monitoring Signal (PMS) that would provide an analogue output voltage proportional to the system temperature.

- MIRAS Optical Harness (MOHA)
The eight digital outputs from each group of four LICEF receivers plus two additional bits for alignment and error detection, would be multiplexed together and converted into an optical signal in a Serial Optical Transmitter Receiver (SOTR) unit. Every segment of the arm would have two such SOTR units, with another three units in the hub (central part of the array). The signals would be transmitted along the arms through an optical fibre to a Fibre Optic Data Receiver Unit (FODRU), which would de-multiplex them.

- Advanced Digital Correlator System (DICOS)
The digital outputs of FODRU would be routed to this central correlator, where all possible pairs of correlations between the signals from all receivers would be performed. The output correlations would then constitute the raw instrument data.

- On-board Calibration System (CAS)
The instrument would be equipped with an on-board calibration system, relying on the injection of uncorrelated and correlated noise immediately after the antenna. The correlated noise injection would be 'centralised' for the hub and 'distributed' for the arms.

Manufacture of the first-generation prototypes of the most critical subsystems, namely LICEF-1 (Fig. 2) and DICOS-1 (Fig. 3), had already begun a year earlier in 1996 and was well under way, with the correlator unit the one nearest to completion.

MIRAS Demonstrator Pilot Project - 1
During 1997, it was realised within the Payload

Systems Division that, to demonstrate the technology of a distributed system like MIRAS, a representative part of the whole instrument had to be breadboarded and tested end-to-end. That is, we had to go beyond subsystem manufacturing and move to the system level to really consolidate the technology of aperture-synthesis radiometers, including calibration. This was necessary to prove not only the electrical performances, but also the mechanical design and signal harness. It was therefore proposed to set up the MIRAS Demonstrator Pilot Project (MDPP-1) activity to manufacture one entire segment of the arm, together with some other units located in the hub of the platform needed to complete the system. MDPP-1 therefore includes:

- the SMOS parametric mission design
- the STM for a complete segment, including the deployment mechanism
- four LICEF antenna-receivers
- the CAS system to service one entire segment and the complete hub
- the MOHA to service one entire segment or the complete hub.

MDPP-1 is funded from the ESA Technology Research Programme (TRP), with the various subsystems being financed through the General Support Technology Programme (GSTP). EADS-CASA (Spain) was selected as the main contractor as Spain is providing the highest GSTP contribution for this activity. EADS-CASA has been entrusted with the technical and management co-ordination for all subsystems and is also responsible for the delivery of the fully tested MIRAS demonstrator to ESA. The activity was kicked-off in September 1998 and the contract is due to end in October 2002.

- SMOS parametric mission design

GMV and EADS-CASA (Spain) were responsible for performing a mission analysis, supported by Spain's Polytechnic University of Catalunya (UPC). This task, carried out during 1998, had the objective of sizing the main parameters of a dual-frequency MIRAS to meet a reasonable set of scientific requirements. This ensured the breadboarding of a representative part of a sound instrument, based on scientific requirements derived from previous studies, both European and American. Once SMOS had been approved as an ESA Earth Explorer Opportunity Mission, the mission analysis was repeated during the Phase-A with the full involvement of the SMOS Science Advisory Group.

An artist's impression of the results of the SMOS parametric mission design effort within MDPP-1 is shown in Figure 4.

The SMOS Mission

The SMOS mission is designed to observe two environmentally very important variables - soil moisture (SM) over land, and ocean-surface salinity (OS) - by L-band microwave imaging radiometry. SMOS will also provide information on root-zone soil moisture, vegetation and biomass and contribute to research on the cryosphere. Knowledge of the global distribution of soil moisture and ocean salinity with adequate spatial and temporal sampling is expected to significantly improve weather, climate and extreme-event forecasting.

Soil moisture and ocean salinity need to be mapped on a global scale and with adequate spatial and temporal sampling, which the SMOS mission will do for the first time. The main requirement for mapping soil moisture from space is suitable accuracy for hydrological and meteorological models, coupled with adequate temporal sampling. Recent studies show that determining soil moisture to 4% accuracy (volumetric) every 3 days is sufficient for most purposes. The spatial-resolution requirements are linked to the specific applications, ranging from 50 - 100 km for global-circulation models, to 20 km or even less for hydrology and agronomy.

The sensitivity of L-band radiometer measurements of ocean brightness temperature to surface salinity is well-established, and it is possible to obtain ocean-salinity estimates if the other perturbing factors (roughness, wind, spume, sun glint, rain, etc.) can be accounted for. The sensitivity of the brightness temperature to salinity is about 0.5 K/psu (psu = practical salinity unit) at a water temperature of 20°C, decreasing to about 0.25 K/psu at 0°C. Given that the sensitivity of state-of-the-art radiometers is ~1K, individual observations cannot meet the requirements of the Global Ocean Data Assimilation Experiment (GODAE), which are 0.1 psu accuracy, a spatial resolution of 2 deg x 2 deg, and a 10-day revisit frequency. They can, however, be met by averaging SMOS measurements spatially and temporally, provided any systematic errors are kept very low by, for example, frequent calibration.

The SMOS satellite re-uses the generic Proteus platform developed by CNES for a variety of missions, the first of which, Jason-1, was launched earlier this year. The platform's main body is a cubic structure (sides of ~1 m) containing all of the equipment needed to store and process the on-board data, power, monitor and control the radiometer; and stabilise its operating temperature. Proteus also provides the orbit acquisition and maintenance capabilities for the planned three-year mission lifetime (extendable to five years) and for precise attitude control and determination. The platform and the radiometer each weigh approximately 300 kg.

The SMOS operational orbit is Sun-synchronous, with local solar times equivalent to 6:00h and 18:00h at the equator crossing. Such a 'dawn-dusk orbit' improves mission performance, due mainly to the more stable thermal observing conditions. The orbital altitude will be 755 km. The satellite design is compatible with several launch vehicles (Rokot, PSLV, Dnepr) and launch is planned for early 2007.

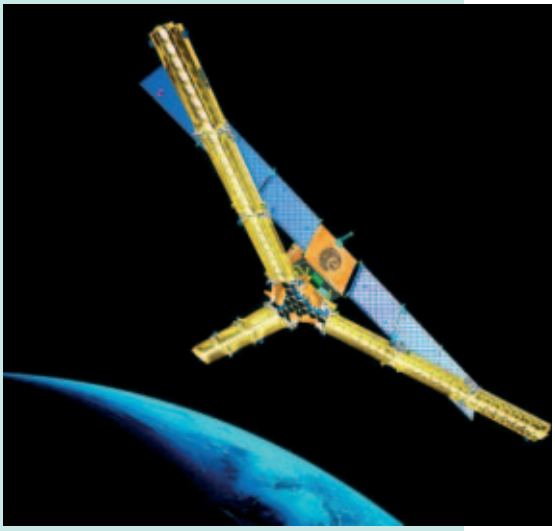


Figure 4. Artist's impression of MIRAS on Minisat following the mission-analysis performed within MDPP-1, at the end of 1998 (courtesy of EADS-CASA, Spain)

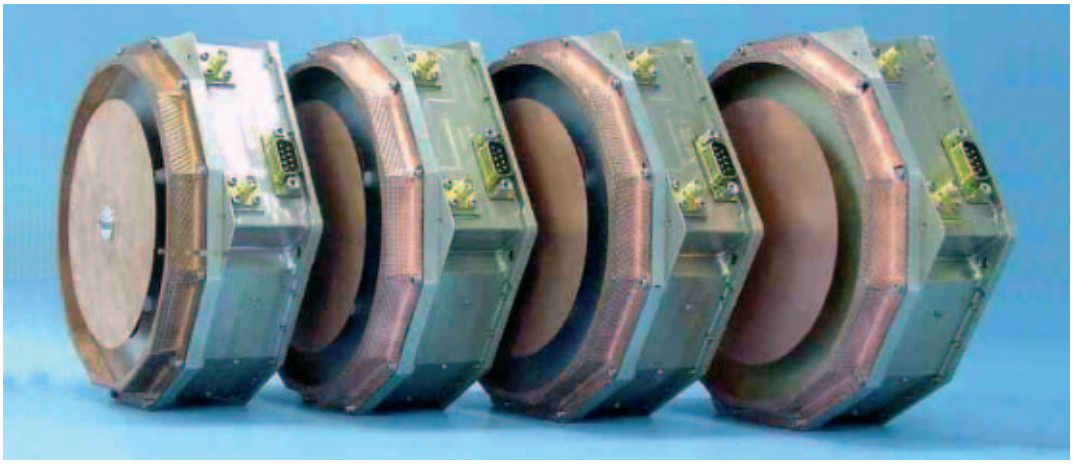


Figure 5. Four second-generation LICEF-2 antenna-receiver units produced within MDPP-1 (courtesy of MIER, Spain)

- STM-1

The structure and mechanisms developed within MDPP-1, designated STM-1 for short, have been developed by EADS-CASA. All segments of MIRAS are identical, there being only one type of mechanism. Deployment demonstrations for one segment (the first one), simulating the mechanical loading of the other two in ambient conditions, together with thermal-vacuum tests on the mechanism, have confirmed the feasibility of the proposed mechanical design and its hardware implementation.

- LICEF-2

The second-generation Lightweight Cost-Effective Front-ends (LICEF-2) have been developed based on the LICEF-1 experience (Fig. 5). MIER (Spain) has overall responsibility for this integrated antenna-receiver unit, and has manufactured its electronics. EADS-CASA has designed and manufactured the antenna and the receiver band-shaping RF filter, while UPC has provided key support in elaborating the technical specifications. MIER has delivered four end-to-end tested LICEF-2 units within MDPP-1.

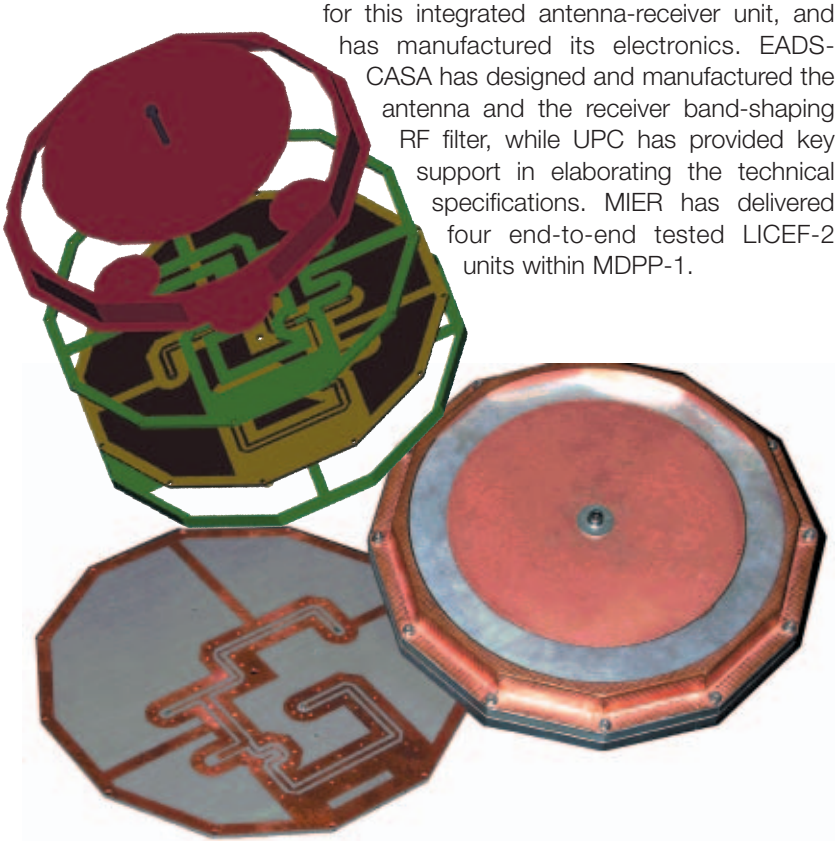


Figure 6. LICEF-2 antenna with its intermediate-layer circuit (courtesy of EADS-CASA, Spain)

(a) Antenna

The electrical design requirements for the basic MIRAS antenna element were derived from the interferometric performance expected from the instrument. The antenna was therefore designed to achieve best performance in terms of gain, bandwidth, co-polar to cross-polar ratio over the field of view, coupling between polarisation ports, and phase-centre localisation.

The requirements for phase-centre localisation and cross-polarisation performance over the field of view (33 deg around boresight) have driven the design in terms of the number of probes and their locations. The solution adopted consists of four probes balanced in pairs, located 180 deg apart and rotated 90 deg for each polarisation. This approach achieves the required 25 dB co-polar to cross-polar ratio, and confines the phase centre for both polarisations to within less than 0.5 mm around the patch's geometrical centre. The effect on the antenna pattern of using a germanised kapton foil for thermal protection has been shown to be negligible.

An intermediate layer has been included between the antenna and the RF circuitry (Fig. 6) for two reasons. Firstly, it is used to combine the received signals at the two probes with the same polarisation and to provide a single connection to the circuitry beneath. Secondly, with the three-layer design, the antenna can be rotated with respect to the receiving circuit, so that the box, the electronics and connectors remain in the same position with respect to the mounting arm, but all antennas on the three arms are aligned.

(b) Receiver electronics

The main elements of LICEF are the dual-polarisation patch antenna and the down-converter. They are integrated to form a mechanically compact sub-unit, which can be easily and separately tested before integration into MIRAS.

The receiver converts the 1.4 GHz signal from the target into two intermediate-frequency (IF) signals, I and Q, at 8–27 MHz. The IF signals are analogue-to-digital converted by 1-bit samplers at a rate of 56 Mbit/s and finally output optically for cross-correlation. These signals contain the phase information about the received signal. The local oscillator (LO) signal is fed to all LICEFs through equal-length paths to maintain phase coherency between them. In addition to the digital outputs, the total power is measured at the IF part by a Power Measurement System (PMS) for source temperature definition. To meet the radiometric-accuracy requirement, a highly linear and stable PMS is needed.

The RF and IF amplifiers, filters and mixers of an interferometric receiver are the critical parts with respect to the performance requirements. In LICEFs, custom-designed MMICs are used where applicable, as monolithic circuits diced from a single wafer are known to provide excellent uniformity. With such a customized approach, it is also possible to address low power consumption by appropriate circuit design, which is also an important issue for this system. A European foundry (Ohmic, France) has been selected to supply the GaAs MMIC chips.

The low-noise pre-amplifier (LNA) module is a conventional hybrid design to minimise losses and noise figure. Its active elements are European HEMT chips, which have a minimum noise figure of less than 0.24 dB at 1.4 GHz. The overall receiver noise figure is increased to 2 dB, however, due to several components that are necessary ahead of the LNA, such as the calibration RF switch, isolator, and antenna.

Although MIRAS operates in the protected 1.4 GHz frequency band, there are strong interfering sources such as radars operating just outside it that could be harmful for radiometry. To reduce the level of the expected in-orbit interference, therefore, very sharp filtering is required using a Chebyshev comb-line design with eight tunable resonators. The RF filter's other important role is to make the frequency response of all receivers as identical as possible, which translates into a good fringe-washing function.

The PMS in the LICEF performs the power-to-voltage conversion of the received signal. Although the PMS could, at its simplest, be a single diode, considerable effort has been invested in designing a PMS that is highly stable over a wide temperature and dynamic range, in striving for the optimum solution.

- CAS-1

The MIRAS onboard Calibration System in MDPP-1 (CAS-1) is the responsibility of the Helsinki University of Technology and of Ylinen (Finland). This system is based on the injection of correlated and uncorrelated noise into all the receivers of the MIRAS array. Matched loads inside the LICEF receivers provide the uncorrelated noise, while the injection of correlated noise is centralised within the hub and distributed along the arm arrays, as proposed by UPC in earlier studies.

CAS-1 is made up of noise-source and power-divider housings, control and monitoring nodes and phase-matched cabling to service the LICEF receivers. The hardware has been built and completely characterised at subsystem level. Figures 7 and 8 show the control and monitoring node, as well as the hub noise source and power-divider housings.

- MOHA-1

Verhaert, Siemens Atea and Nexans (Belgium) are responsible for the MIRAS Optical Harness in MDPP-1 (MOHA-1). Verhaert is the subsystem prime contractor, responsible for space issues and mechanical design, Siemens designed and manufactured the hardware, and Nexans provided the optical fibres.

MOHA-1 is an optical connection that brings the digital I and Q samples from all LICEF receivers down to the central correlator unit (DICOS). The optical harness consists of multiplexer boxes along the arm and a demultiplexer close to the central correlator. This multiplexing into groups of four receivers, together with the use of optical fibre, reduces

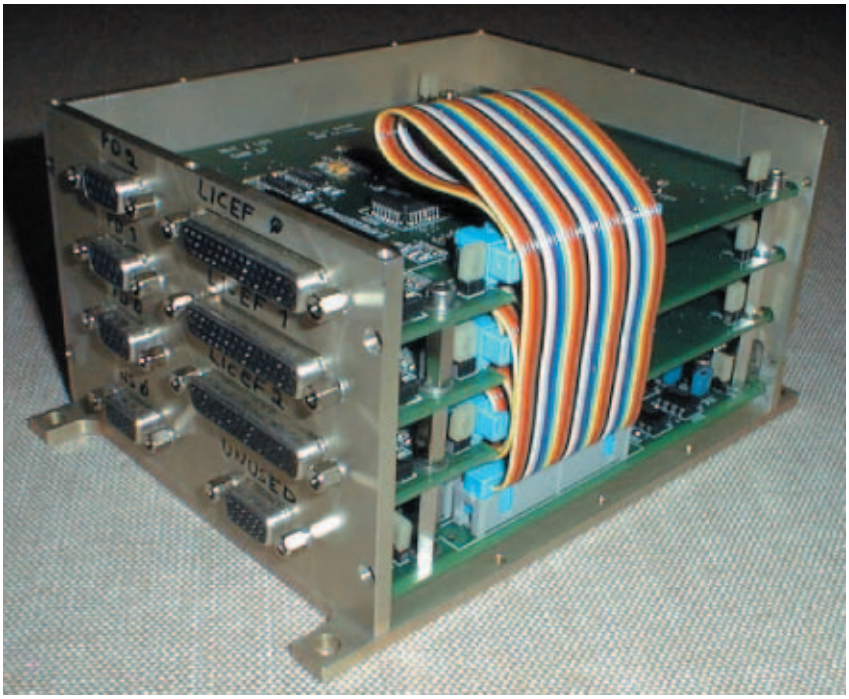
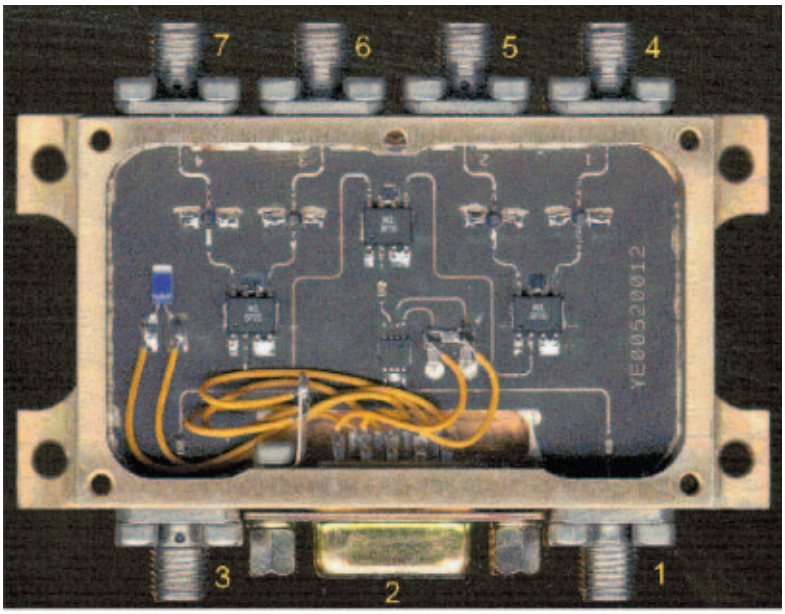


Figure 7. Control and Monitoring Node (CMN) of the CAS on-board calibration system (courtesy of HUT, Finland)



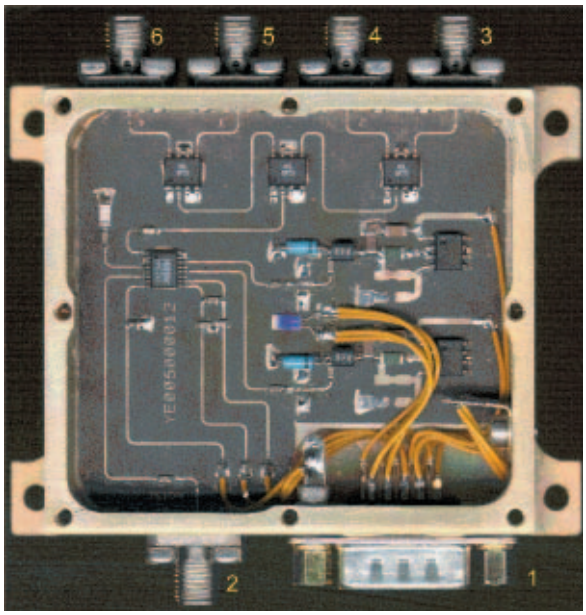


Figure 8. On-board calibration system (CAS) hardware, with the Power-divider (left) and Noise-diode (right) housings (courtesy of Ylinen, Finland)

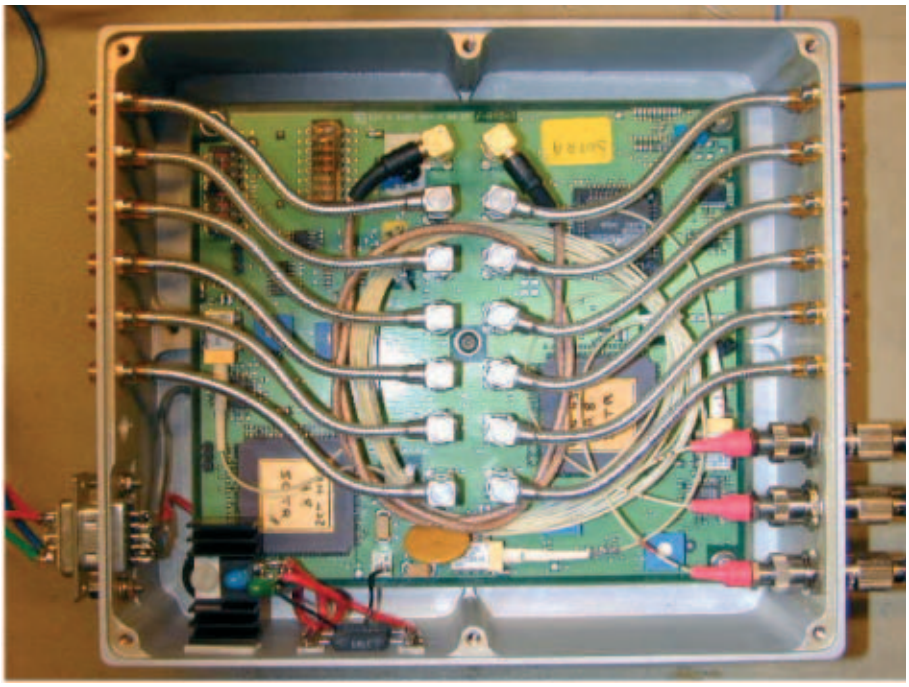
the number of lines needed and the mass of the harness, which is very important for its routing and its impact on the deployment mechanisms. The data rate is 10 times the sampling clock (about 560 Mbit/s). Two very similar ASIC circuits, one for the multiplexer and the other for the demultiplexer, have been developed in MOHA-1. The optical harness also serves to generate and distribute the reference clock signal, the heart of the instrument, as its operation must be fully coherent. This uplink goes through one optical fibre per multiplexer. Each multiplexer then distributes it to four LICEF receivers. LICEF uses a Phase Lock Loop circuit to lock its voltage controlled oscillator to this reference, thereby achieving coherent operation throughout the array.

Figure 9 shows the Serial Optical Transmitter Receiver (SOTR) unit.

- DICOS-1

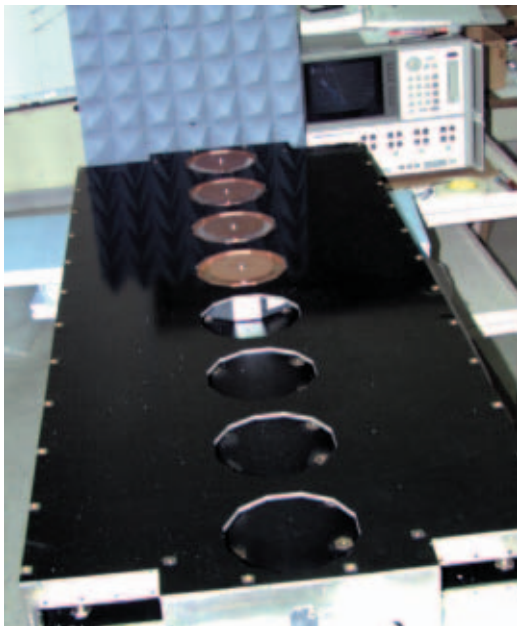
The advanced MIRAS Digital Correlator System (DICOS-1) was developed under a contract with Astrium GmbH (Ottobrun, Germany) prior to MDPP-1. This unit, which has 18 000 correlators working at 1-bit and 56 MHz, performs onboard cross-correlation of the signals between any pair of antenna elements in the array. These correlations are samples of the so-called 'visibility function', which is essentially the Fourier transform of the image's brightness distribution. This raw MIRAS data (order 100 kbit/s) is downloaded to Earth for image processing. DICOS has been built around a 17x17 (289) correlator ASIC circuit, with each ASIC having about 100 kgates in 1.0 micron-gate-length 3.3 V CMOS technology.

Figure 9. Serial Optical Transmitter Receiver (SOTR) unit of the MOHA optical harness (courtesy of Verhaert and Siemens, Belgium)



MIRAS Demonstrator Integration and Test

All LICEF subsystems, MOHA, CAS and DICOS have been delivered to EADS-CASA and the MDPP-1 activity has now entered its final phase, namely assembly, integration (Fig. 10) and testing of the complete MIRAS demonstrator. The companies responsible for the different subsystems developed their own particular Electrical and Mechanical Ground-Support Equipment (EGSE and MGSE) to perform the subsystem-level testing. The division of responsibilities at system level is as follows: EADS-CASA for MGSE and HUT for EGSE and the execution of full system end-to-end electrical tests, already performed in an anechoic chamber at the Technical University of Denmark (DK).



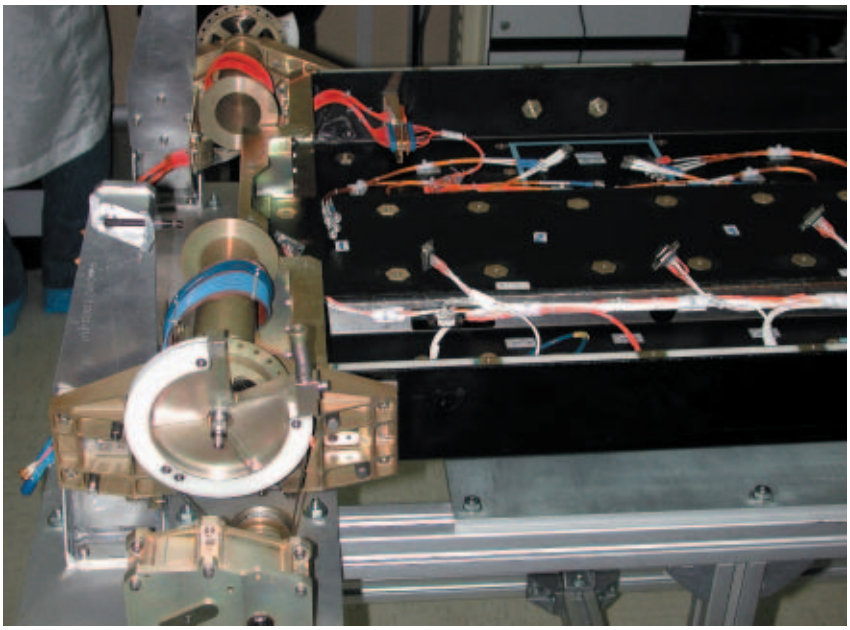


Figure 10. First steps in the integration of the MIRAS demonstrator in MDPP-1. Left: integrating the LICEF-2 receivers. Right: wiring the harness. (courtesy of EADS-CASA, Spain)

MIRAS Demonstrator Pilot Project - 2

Early in 2000, an MDPP-1 follow-on activity was prepared under the title 'Validation of L-band Image Radiometry', known as MDPP-2 for short, the objectives of which are to advance the demonstration of the technology feasibility of MIRAS through:

- a Deployment Demonstration Test for one complete arm (three segments)
- an Image Validation Test using a 12-LICEF MIRAS array
- three proof-of-concept activities involving: a Noise-Injection Radiometer (NIR), an advanced correlator unit (DICOS-2), and an advanced band-pass filter (BFP-2), and
- the breadboarding of the optical harness from SMOS-Phase-A (MOHA-3).

Unlike MDPP-1, the core funding for MDPP-2 comes from the GSTP budget, which covers the deployment demonstration, the image validation and NIR. DICOS-2 and BPF-2 are TRP-funded subsystems. The industrial companies involved in the GSTP share are the same as in MDPP-1, except for the addition of Toikka (Finland) and Contraves (Switzerland). The subcontractor selected for DICOS-2 is Astrium GmbH (Germany), with EADS-CASA responsible for BPF-2. The MDPP-2 contract was kicked-off April 2001, with a planned end-date of June 2003.

- Deployment Demonstration Test

This test implemented by EADS-CASA involves, in addition to the available first segment from MDPP-1, the manufacture of:

- the structures of the second- and third-arm segments
- the mechanisms (except for the hold-down and release mechanisms)
- the synchronisation hardware, and
- the mechanical dummies of the electronic units.

- Image Validation Test

This test is the responsibility of EADS-CASA, strongly supported by UPC and with the participation of the subsystems companies as indicated below. Its objective is the recovery of a known brightness-temperature scene within the specified spatial resolution, radiometric resolution and accuracy. The reference scene will be taken inside an anechoic chamber at INTA's facilities in Spain, in two different situations: when there is a constant brightness distribution provided by the chamber absorbers at ambient temperature, and when there are two point sources simulated by two probe antennas placed within the useful instrument field of view.

- NIR

The Noise-Injection Radiometer (NIR), which is being developed by HUT, Ylinen and Toikka, performs the following functions:

- measurement of the antenna temperature with fully polarimetric capability, needed for the retrieval of the polarimetric brightness temperature maps
- measurement of the output power of the hub centralised noise source of CAS, required to perform amplitude calibration.

The NIR is a pulse-injection radiometer operating with a Dicke reference load. Its core electronics and antenna are identical to those of LICEF, as both units must be as similar as possible to achieve the best performance. The NIR successfully completed its Critical Design Review in June 2002. For redundancy reasons, the MIRAS Phase-A configuration includes two such NIR units.

- DICOS-2

Astrium GmbH is responsible for the manufacture of MDPP-2's advanced second-generation Digital Correlator System, DICOS-2, which also passed its Critical Design Review in June 2002. Its new features compared to DICOS-1 are:

– new DICOS ASIC development, in a technology suitable for space application
– fringe-washing capability
– dual-polarisation and full-polarisation operation, and
– enhanced redundancy.

- BPF-2

The development of an advanced RF Band-Pass Filter in MDPP-2 (BPF-2) is being carried out by CASA-EADS. BPF-2 is an optimised design based on the one already produced for the LICEF-2 receivers. A slightly lower mass, a more robust connector fixing, and venting holes are some of the improved features. The Test Readiness Review is planned for July 2002.

Image validation using the HUT-2D radiometer

HUT, together with Ylinen, started the development of an airborne 36-element U-shaped two-dimensional interferometric radiometer back in 1996, financed by the Finnish National Research Technology Programme. Within the MDPP-1 calibration activities described above, the Finnish team became involved in the implementation of the MIRAS onboard calibration system in their airborne instrument. By 2000, the development of the HUT-2D instrument had slowly progressed and a new contract was placed by ESA's Earth Observation Directorate to finally push the instrument towards completion. A two-step strategy is currently being followed, first performing tower-based tests with only eight receivers, before the final production of the 36 receivers for the aircraft flights.

Image validation using the LICEF-1 receivers

Several image-validation test campaigns were carried out using the LICEF-1 receivers (cf. Fig. 2) within the Payload Systems Division at ESTEC and by the University of Valencia, the objective being to obtain absolutely calibrated images of the Sun, Moon and cold sky. A small version of MIRAS was built with eight-element-long arms and a Y-shaped structure. A simple 12-correlator unit (DICOS-3) developed specially by Astrium GmbH was used for this particular experiment, which was performed in the Dwingeloo (NL) radio observatory's premises to avoid interference.

Figure 11 shows the image of the Sun. Absolute accuracies in the 4% range were achieved, which was well within the error bars of the relatively simple setup and signal processing applied.

From technology research to Phase-A: instrument evolution

As explained above, the instrument configuration for the MIRAS Demonstrator

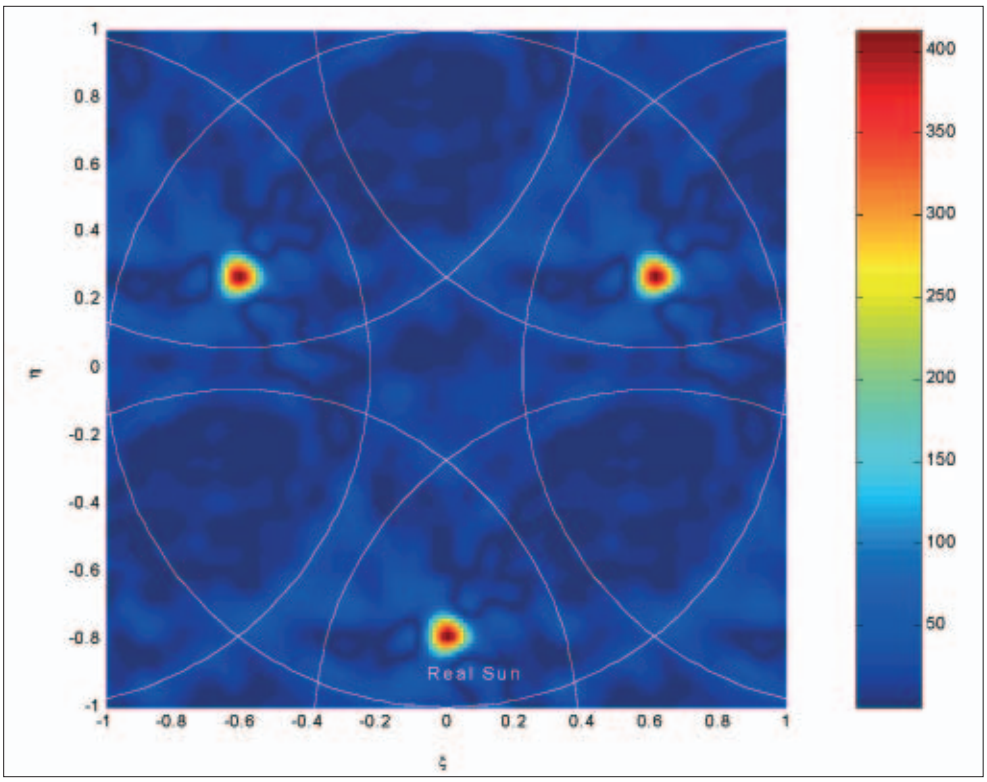


Figure 11. Solar image acquired using the LICEF-1 receivers and the DICOS-3 correlator unit. The real Sun is at 6:00; those at 10:00 and 2:00 are aliases, as expected

Pilot Project responded to the objective of technology-feasibility demonstration, rather than to meeting specific scientific requirements. Late in 1998, however, a proposal led by Y. Kerr (CESBIO, France) and J. Font (ICM, Spain) for the SMOS mission was submitted to ESA, and approved as the second Earth Explorer Opportunity Mission one year later. The SMOS Phase-A was started in September 2000 and, within this framework, a proper sizing of the MIRAS instrument was then performed by industry with a thorough mission analysis. The industrial study was guided by the SMOS Science Advisory Group, established specially for the purpose.

The resulting refined scientific requirements, together with the technical constraints on the mission, led to a somewhat smaller MIRAS instrument than that of MDPP. There were also some changes to the detailed architectures of the various subsystems, the optical harness being the most modified because the signals were no longer to be multiplexed. The MOHA-3 activity at Contraves (CH), mentioned earlier, is aimed at breadboarding the new optical harness within MDPP-2. The MIRAS configuration at the end of the SMOS Phase-A is shown in Figure 12.

The MIRAS Demonstrator Pilot Project provided invaluable experimental data during the SMOS Phase-A, continues to do so during the present Pre-Phase-B, and will do the same again during SMOS Phase-B, which has been approved with a planned start around November 2002.

Conclusion

The Demonstrator Pilot Project has brought together the development of the various subsystems to demonstrate MIRAS's feasibility and imaging performance right up to system level. The progress in the development of the HUT-2D airborne radiometer, the results of a Sun image validation test and an overview of the SMOS mission have also been presented here. Based on the results that have been achieved, in summarising the status of technology readiness of MIRAS for the SMOS mission, we can state with confidence that all critical areas have been successfully covered. We look forward to reporting on the first images from SMOS in the ESA Bulletin some five years from now!

Acknowledgements

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The contributions to the project from the Spanish Trainees who spent time with the ESTEC Payload Systems Division in the last four years also deserve a special mention.

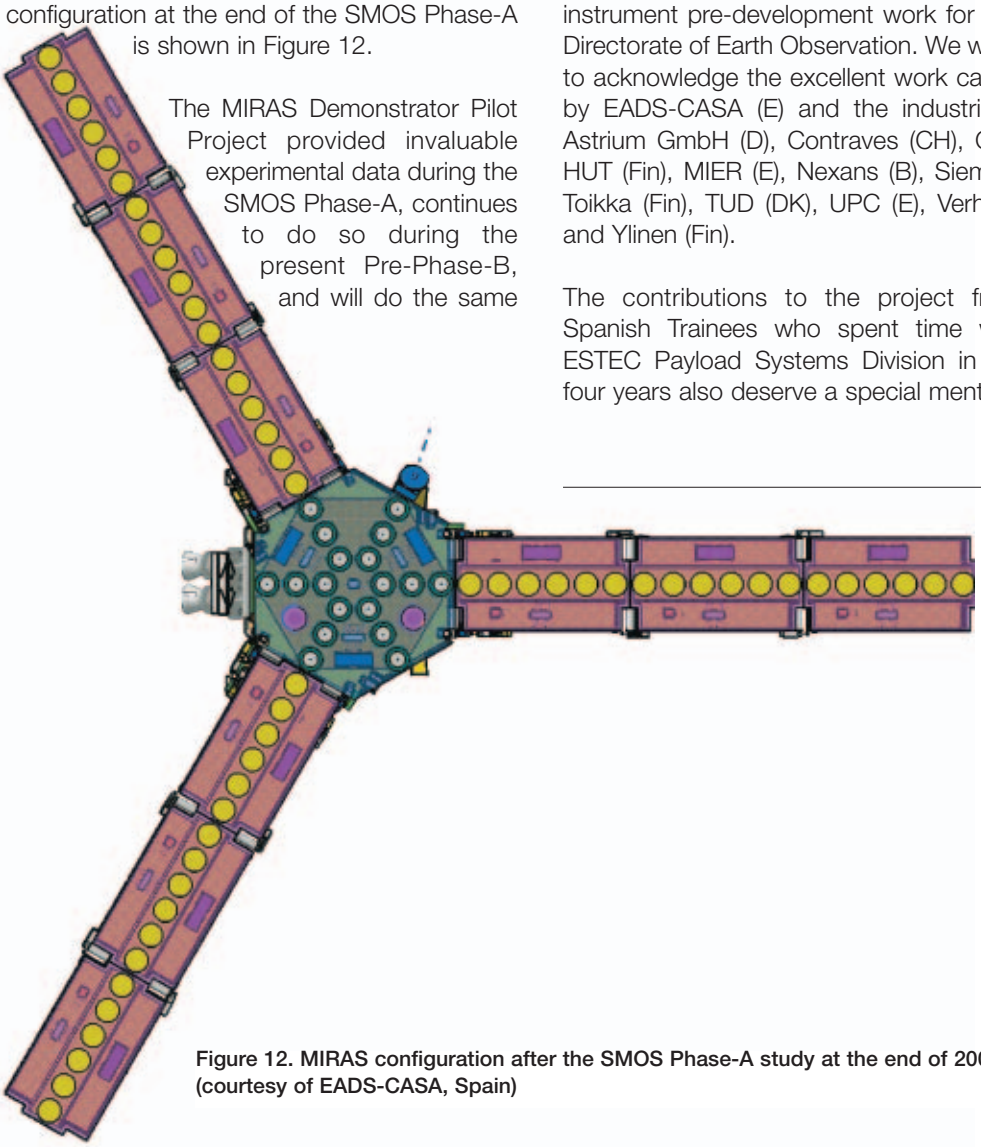

Figure 12. MIRAS configuration after the SMOS Phase-A study at the end of 2001 (courtesy of EADS-CASA, Spain)