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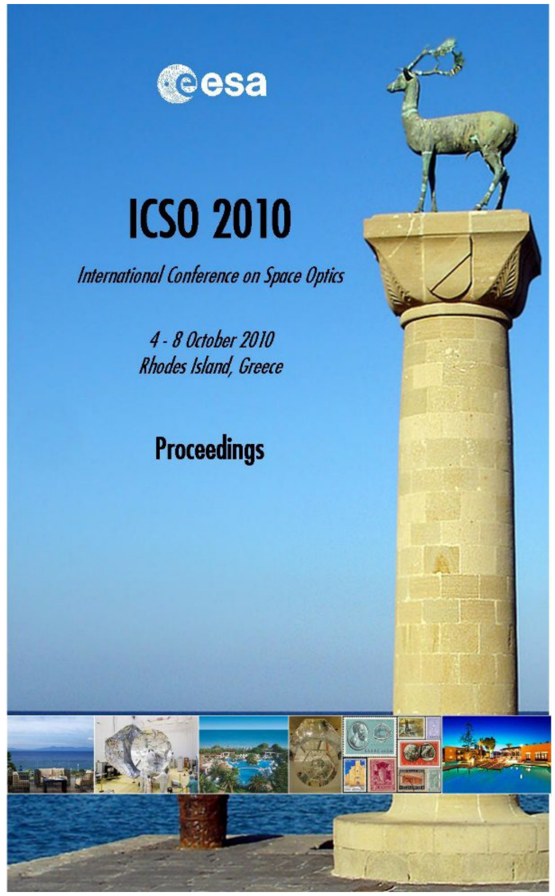

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FIBRE OPTICS IN THE SMOS MISSION

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I. INTRODUCTION

Launched on November 2nd, 2009, SMOS (Soil Moisture, Ocean Salinity) is the second Earth Explorer Opportunity mission developed as part of ESA's Living Planet Programme. It demonstrates a completely new type of instrument – a large, deployable synthetic-aperture microwave radiometer [1].

RUAG Space, Switzerland, as a subcontractor of EADS Astrium, Spain, has provided the instrument's fibre-optic harness, which interconnects the central data processor with all 69 microwave receivers, as well as 12 auxiliary units on board. For reasons explained in Section 3, SMOS is the first European mission extensively using both fibre-optic clock distribution and data transmission in space.

In Section 2, we present an overview of the scientific goals of SMOS, and describe the payload's basic function. There from we derive the rationale and the design of the fibre-optic harness (Section 3). In Section 4 all development, manufacturing, and test activities are summarised, which culminated in the successful delivery of all flight units to EADS Astrium by October 2006. We present the major test results obtained with the flight harness (Section 5), and conclude with a short summary of the higher-level activities, which lead to successful launch and commissioning of the SMOS satellite (Section 6).

II. OVERVIEW OF THE SMOS MISSION AND THE PAYLOAD

In order to advance climatological, oceanographic, meteorological, hydrological, agronomical, and glaciological science, the principal objective of the SMOS mission is to provide global maps of soil moisture and ocean salinity with high accuracy, as well as with high spatial and temporal resolution. In addition, the mission is expected to provide useful data for cryosphere studies.

Moisture and salinity decrease the emissivity of soil and seawater respectively, and thereby affect microwave radiation emitted from the surface of the Earth. The SMOS payload, also called "Microwave Imaging Radiometer by Aperture Synthesis" (MIRAS), captures images of that radiation around the frequency of 1.4 GHz (L-band).

For that purpose, MIRAS employs 69 microwave receivers, and uses the interferometry principle well-known from radio astronomy: for all possible combinations of receiver pairs, cross-correlations of the down-converted microwave signals are calculated, and the image is obtained by the two-dimensional Fourier Transform of the map of correlation coefficients. A measurement image is taken every 1.2 seconds. As the satellite moves along its polar, sun-synchronous orbit, each observed area is seen under various viewing angles (Fig. 1). Global coverage is achieved every three days.

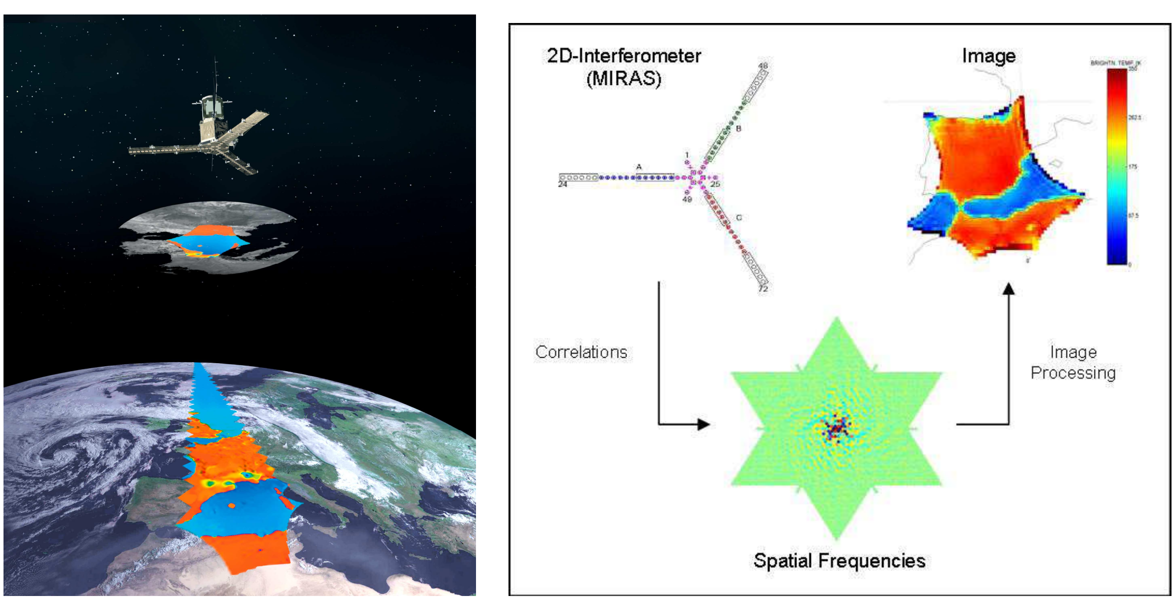

Fig. 1. Illustration of the SMOS measurement principle

From an altitude of 763 km, the SMOS receivers view an area of almost 3000 km in diameter. However, due to the interferometry principle and the Y-shaped antenna formed by three deployable arms, the field of view is limited to a hexagon-like shape about 1000 km across called the 'alias-free zone'. This area corresponds to observations where there is no ambiguity in the phase-difference.

After deployment, the diameter of the MIRAS synthetic aperture is 8 m, resulting in a spatial resolution of 35 km at the centre of the field of view. The payload is carried on a standard Proteus spacecraft bus, developed by the French space agency CNES (Centre National d'Etudes Spatiales) and Thales Alenia Space.

III. DESIGN OF THE FIBRE-OPTIC HARNESS

In order to achieve its basic function as synthetic aperture radiometer, MIRAS needs a sophisticated harness to interconnect its correlator with its microwave receivers. The two principal functions of the harness are

- to define a common time (phase) reference for all receivers, by distributing a common reference clock signal with high phase stability (both in terms of jitter and skew), and
- to transmit, in parallel, the down-converted, digitised microwave noise signals from the receivers back to the correlator.

In contrast to electrical cables, fibre-optic cables offer some key advantages for this particular application:

- Practically zero electro-magnetic emission of the cabling, which is of utmost importance because of the highly sensitive microwave receivers.
- Flexibility of the cabling (as well as its low mass), offering less resistance at the hinges, and therefore facilitating the deployment of the instrument's arms.
- Galvanic isolation between the units, as well as insensitivity to ground differential voltages.

All of this comes, of course, at the expense of the additional mass and power consumption required for the electro-optic and opto-electronic converters plugged into the individual units. Therefore, mass and power consumption have been a major driver during the course of this development.

Fig. 2 shows the block diagram of the MIRAS Optical Harness (MOHA). The Subsystem has plug-in-interfaces to the following units, all developed by other subcontractors of the SMOS Consortium:

- The Control and Correlator Unit (CCU), which performs correlation, data processing, and instrument control.
- In total 72 microwave receiver channels (Light-weight Cost-Effective Front-end, LICEF), which perform reception of the microwave signals, as well as down-conversion into in-phase and quadrature components, quantisation, sampling, and multiplexing into so-called I/Q data streams.
- 12 Control and Monitoring Nodes (CMN), which derive the local oscillator for 6 LICEFs from the reference clock (by multiplication of 25), and perform other control and monitoring tasks.

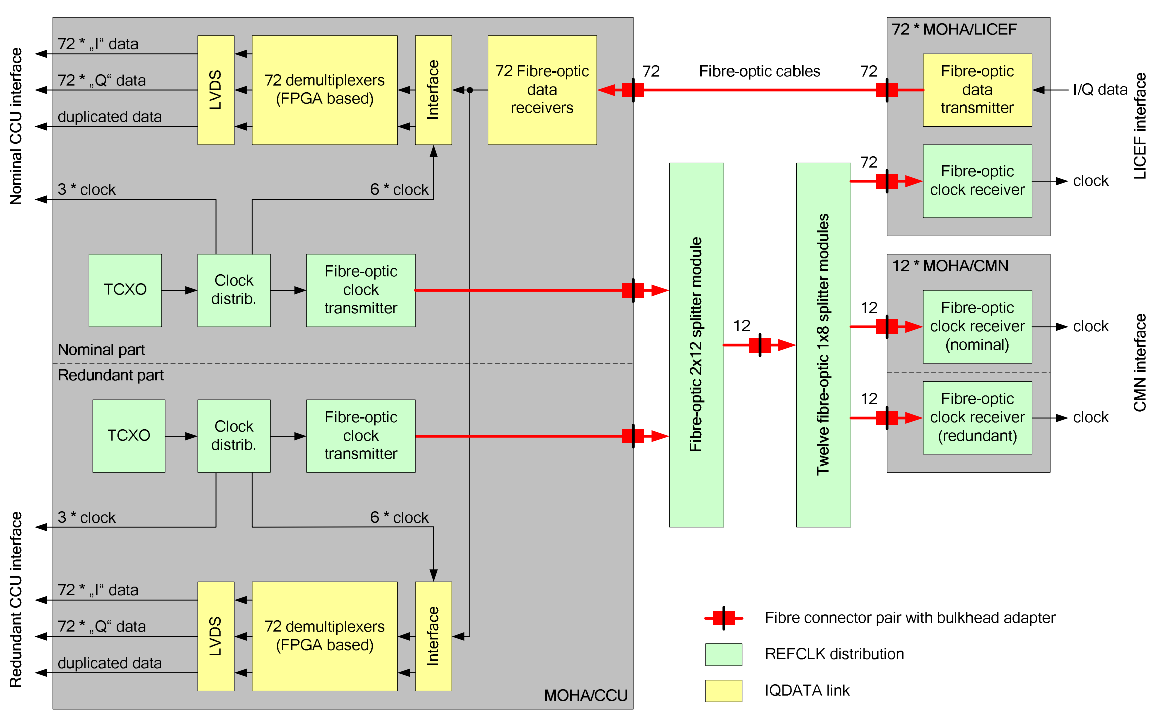

Fig. 2. Block diagram of the MIRAS Optical Harness

The functionality of MOHA can be split into two parts, identified by different colours in Fig. 2: Reference clock distribution, and I/Q data transmission/de-multiplexing.

The 55.84 MHz reference clock of SMOS is generated within the MOHA part of CCU. It is distributed electrically to the correlator part of CCU, to the MOHA/CCU internal data recovery, as well to a fibre-optic clock transmitter. The transmitter comprises a laser driver integrated circuit, and a 1310 nm single-mode fibre coupled Fabry-Perot laser diode with a nominal output power of 1.5 mW. The optical reference clock signal is then split into 96 equal parts by a cascade of passive optical splitters. Together with optical excess losses, the nominal power at each clock receiver is -20 dBm.

All 96 clock receivers, either part of LICEF or of CMN, are of identical design. Each receiver consists of a single-mode fibre coupled pin-diode / trans-impedance amplifier (pin-TIA) module, an optimised band pass filter, and a discriminator integrated circuit which finally delivers a rectangular clock signal. In order to achieve the required RMS jitter of less than 50 ps, at least -27 dBm are required at the clock receiver inputs. This results in a link margin of 7 dB and a nominal RMS jitter of approx. 10 ps.

Triggered by its own reference clock output, each MOHA module in LICEF is fed with a multiplexed I/Q data stream of 111.68 Mbit/s. The optical I/Q data transmitter is of the same design as the reference clock transmitter of MOHA/CCU, but operates only at 0.75 mW, still ample power to perform practically error-free data communication.

After transmission via fibre cables of 7 m length, the 72 optical I/Q data signals arrive at the MOHA module in CCU (Fig. 2). There, pin-TIA modules perform opto-electronic conversion, and each channel is split into a nominal and a redundant part. LVDS receivers perform data discrimination and conversion to CMOS level. Field-programmable gate arrays (FPGA) perform de-multiplexing of the I/Q data streams, duplication of some signals, and parallel delivery to the CCU correlator via LVDS drivers. The connector interface at the CCU side comprises in total more than 1200 pins.

The redundancy concept of the MOHA modules is tightly coupled with the redundancy concept of their host units. There is actually no redundancy within the 72 science channels – failure of one channel can be accepted without significantly degrading the imaging performance of the instrument. As soon as a component affects more than one channel, however, cold redundancy is implemented in order to avoid single-point failures. Passive optical splitters are an exception to this rule, since they are very reliable.

Special attention had to be put on the I/Q data receivers, since they are supplied by both the nominal and the redundant supply voltage of CCU. A single short-circuit would result in a complete instrument failure, and therefore individual short-circuit protection circuits have been implemented to eliminate this failure mode.

Due to the large number of parallel channels, the physical implementation of the MOHA module in CCU is split into one transmitter module and six identical receiver modules, each comprising 12 channels. Redundancy is implemented within each module. Fig. 3 shows the partially assembled box with all optical connectors in the front.

Figs. 4 and 5 depict a fibre-optic splitter and a MOHA module in LICEF, respectively. The latter is to be plugged into the slot of a cylindrical LICEF unit. The two optical connectors can bee seen on the module’s front panel.

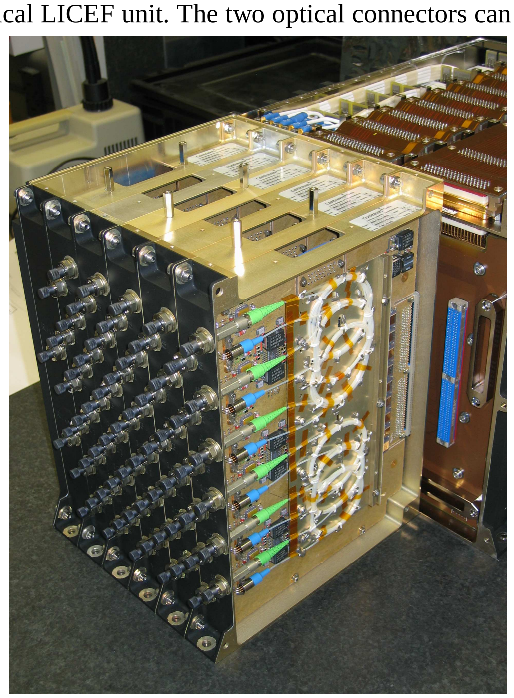

Fig. 3. MOHA module in CCU, flight model, during integration with CCU

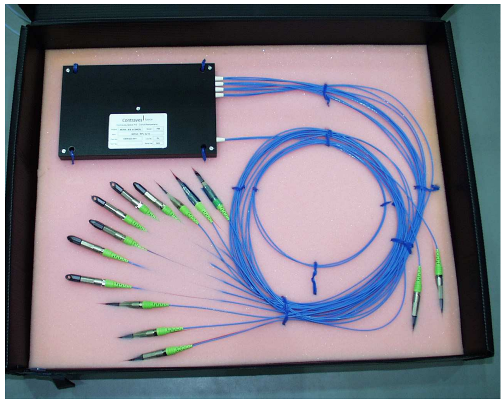

Fig. 4. MOHA fibre-optic 2x12 splitter, flight model

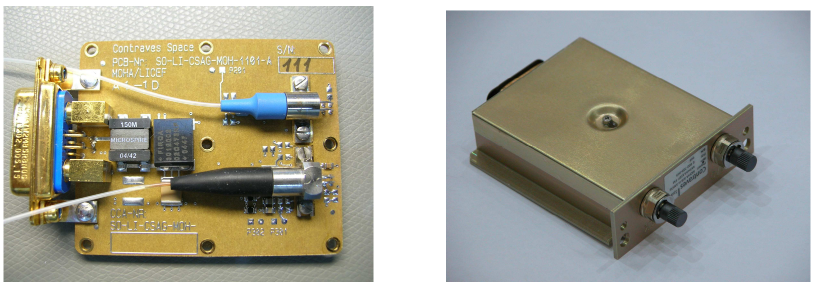

Fig. 5. MOHA module in LICEF, flight model

IV. SUMMARY OF THE DEVELOPMENT AND VERIFICATION PROGRAMME

The development of the MOHA proto-flight model has been performed in three major phases.

In MOHA Phase A (second half 2002 / 2003), the basic concept has been elaborated, trade-offs have been made, and the major performance parameters (clock jitter and skew, power consumption, bit error ratio) have been verified by breadboard experiments.

In MOHA Phase B (2004), the preliminary electrical, mechanical, and thermal design of the harness has been established in parallel with that of the complete instrument. Interfaces and budgets have been frozen. An Engineering Model with 4 LICEF modules and a CCU module comprising 12 channels has been built, tested, and delivered to the prime contractor for instrument level tests.

In MOHA Phase C/D (2005 / 2006), the flight model design has been frozen, and the complete set of hardware has been manufactured, integrated and tested. Due to the tight clock skew requirements, every module had to undergo a sequence of adjustment steps for accurate control of optical parameters, as well as delay. The latter has been adjusted by trimming fibre pigtail lengths.

Full functional and environmental testing (vibration, thermal vacuum) has been performed on all modules. Electro-magnetic compatibility has been verified on a reduced set of modules. Furthermore, subsystem-level verification of the complete harness (in terms of bit error ratio) has been performed both on proto-flight modules and on qualification / spare modules.

Due to the relatively large number of individual modules and a highly interleaved integration and test flow, the Phase D campaign has been very challenging from a logistic point of view. In October 2006, Phase D has been finalised by the delivery and acceptance of the last qualification / spare MOHA modules by EADS Astrium.

In parallel to these standard development and verification activities, a component qualification programme has been executed during Phases A through C, due to two reasons: In the first place, fibre-optic and opto-electronic components (splitters, receiver modules, laser diode modules) are not available off-the-shelf with a suitable qualification. Furthermore, the stringent power consumption and mass requirements required the use of reasonably recent commercial integrated circuit technology for two electrical component types (laser driver and discriminator).

All the above-mentioned commercial components therefore have been subject to a dedicated campaign, composed of the following activities:

- Commercial component evaluation testing, to find out – among several candidates – the component most suitable for the application.
- Qualification testing, to demonstrate that each component can meet its performance requirements for the specified lifetime.

- Procurement of the flight components and their constituents from a single production lot, in order to eliminate as far as possible any process variations.
- 100% screening and burn-in of the flight components, in order to stabilise their characteristics and to detect early failures.
- Lot acceptance testing on samples of the flight lot, to ensure that it meets the defined quality requirements.

V. TEST RESULTS

Table 1 summarises the main performance test results of the MOHA proto-flight model delivered. The results for both clock distribution (jitter, skew) and data transmission (bit error ratio) showed sufficient margin to fulfil the mission requirements. In terms of mass and power consumption, most results are well below the requirement - only the MOHA/LICEF mass came close. Finally, sufficient timing margin has been demonstrated at all digital interfaces.

Environmental acceptance and qualification testing of all modules passed without any major non-conformance.

Parameter	Requirement	Result	Compliant?	Remark
Bit error ratio of I/Q data links	$< 10^{-10}$	0 errors	Yes	Each link tested for a duration that gives 99% confidence
Reference clock skew	< ±1 ns	< ±0.8 ns typ. ±0.2 ns	Yes	Worst case shows fastest channel under fastest operating condition vs. slowest channel under slowest operating condition
Reference clock jitter (RMS)	< 50 ps	< 48 ps typ. 11 ps	Yes	Worst case tested for zero link margin. Typically, the link margin is 7 dB.
MOHA/LICEF: mass and power consumption	< 130 g < 0.75 W	< 130 g < 0.61 W	Yes	
MOHA/CCU: mass and power consumption	< 8 kg < 20 W	6.6 kg < 17 W	Yes	
LICEF interface: clock to valid I/Q data	> 2.7-4.0 ns	2.3-5.5 ns	Yes	Acceptable variation of clock-to-data delay for error-free data recovery within MOHA/CCU
CCU interface: set-up time	> 0.5 ns	> 2.5 ns	Yes	
CCU interface: hold time	> 9 ns	> 13.3 ns	Yes	

Table 1. Summary of MOHA test results

VI. FROM SUBSYSTEM DELIVERY TO PRESENT

After delivery, the fibre-optic harness was integrated into the MIRAS payload by EADS Astrium, Spain. Fig. 6 shows the CCU integrated on the instrument's hub, with its MOHA part and the 74 fibre connectors on the right-hand side. Fig. 7 shows one of the nine deployable MIRAS arm segments. Fibre-optic cables are recognized by their blue colour.

In 2007, the integrated MIRAS payload underwent a series of functional and environmental tests, including image validation. Fig. 8 shows the deployed MIRAS at ESTEC's Maxwell EMC chamber.

Following successful qualification, MIRAS was finally integrated with the Proteus Service Module, to make the SMOS satellite. A further seven-month test campaign was performed to qualify the whole satellite for the mission.

SMOS was launched from Plesetsk Cosmodrome in northern Russia on November 2nd, 2009, by an Eurockot launch vehicle. On May 21st, 2010, commissioning was completed, and all the elements of the mission were found to be in excellent shape. At that day, SMOS formally began operational life. So far, all 168 fibre-optic clock and data links are working fine, without any failure.

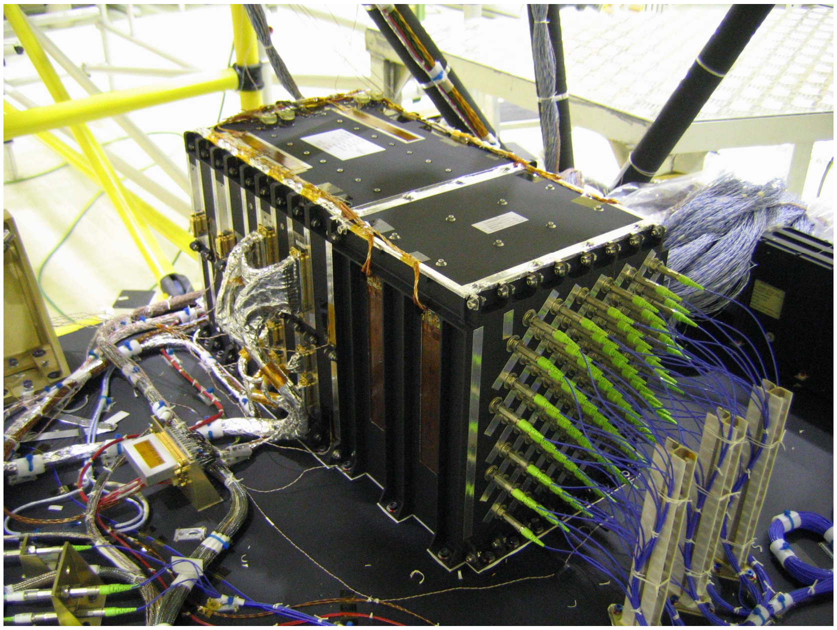

Fig. 6. The CCU and its MOHA part mounted on the MIRAS hub

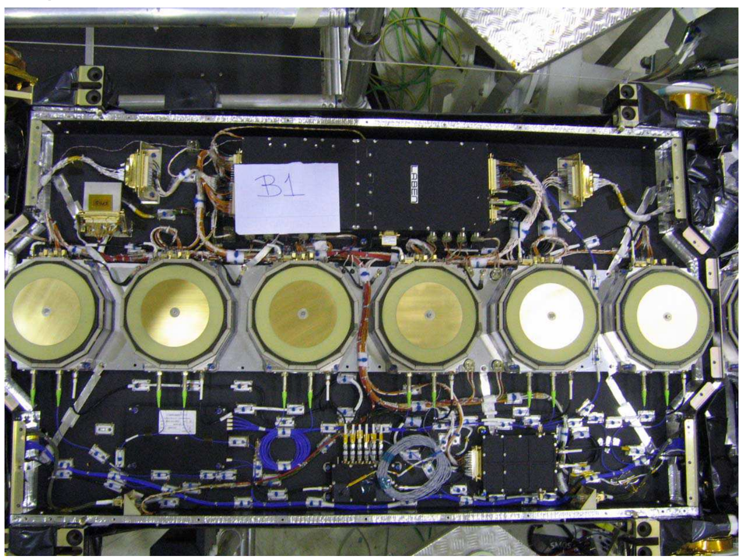

Fig. 7. A MIRAS arm segment with 6 LICEF, 1 CMN, and a fibre-optic 1x8 splitter

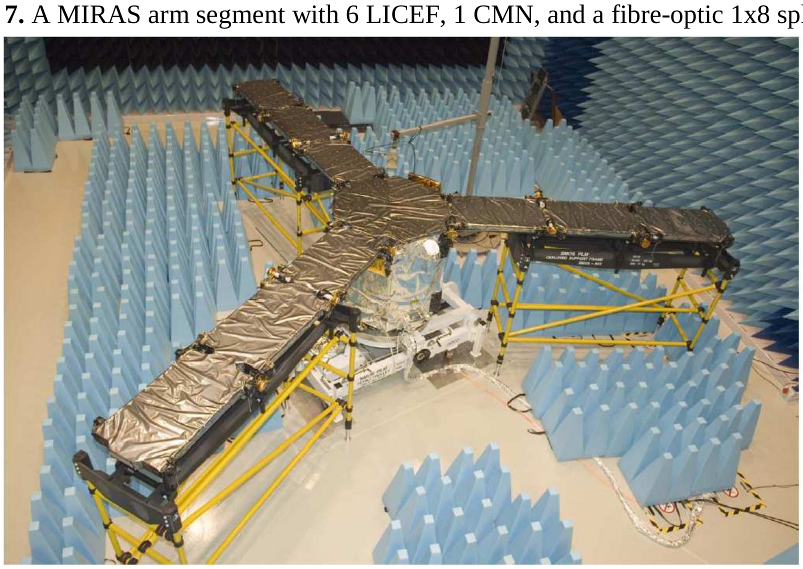

Fig. 8. The deployed MIRAS payload at ESTEC's Maxwell EMC chamber

VII. CONCLUSION

Apart from advancing the knowledge of the Earth's water cycle and demonstrating the feasibility of a large, deployable synthetic aperture L-band radiometer, SMOS is also the first European space mission to extensively use on-board fibre-optic communications. Several commercial-off-the-shelf fibre-optic components have been qualified for this mission, to achieve on-board clock distribution and data transmission with unmatched EMC performance, as well as phase stability and mechanical flexibility.

ACKNOWLEDGMENT

The MOHA Subsystem in SMOS would not be in the present shape without the continued strong support of ESA/ESTEC during all phases of the project. In particular, the authors would like to thank François Deborgies, François Garat, Achim Hahne, Karin Lundmark, Kevin McMullan, Carole Villette, and Igor Zayer.

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