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# THE EU:CROPIS ASSEMBLY, INTEGRATION AND VERIFICATION CAMPAIGNS: BUILDING THE FIRST DLR COMPACT SATELLITE

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## Abstract

Eu:CROPIS (Euglena Combined Regenerative Organic Food Production In Space) is the first mission of DLR's Compact Satellite program. The Compact Satellite is a small, highly customizable and high performance satellite bus, providing a platform for scientific research as well as for demonstration of innovative concepts in space technology. The launch of Eu:CROPIS onboard a Falcon 9 is scheduled in Q4 2018 within Spaceflight Industries SSO-A mission. The name-giving primary payload features a biological experiment in the context of coupled life support systems. The stability of such kind of a system shall be proven under different gravity levels with a focus on long term operations. In this context the rotation of the spacecraft will be used to utilize simulated gravity for the first time.
A further biological experiment dealing with synthetic biology comprising genetically modified organisms (GMOs) was provided by NASA Ames Research Center as secondary payload.

The integration and acceptance of a satellite flight model containing biological experiments faces constraints regarding schedule, facility certification and process definition. The driving parameters for the Eu:CROPIS AIV campaign are the degradation time of chemicals stored inside the primary payload, the GMOs used in the secondary payload, which cause handling and transport restrictions due to biosafety regulations, as well as schedule constraints due to the chosen dedicated rideshare mission. Furthermore the development of a spin stabilized system for gravity simulation had impact on the overall verification approach, especially towards the attitude control subsystem.

This paper describes the model and verification strategies to design and build the spacecraft under said constraints. The applied verification processes comprises the hardware, software as well as all third party payloads and focuses on the utilization of a flexible tabletop engineering model approach. To achieve a smooth transition to project phase E, this concept enables co-alignment of the ground segment development and verification with spacecraft AIV as of early phase C. Furthermore scientific projects like Eu:CROPIS, with small project teams and financial budgets, encounter few personnel redundancy. The existing structural organization gets confronted with challenges where dependability, testability and safety of the processes and the product are expected to be achieved with minimal effort. The paper presents how the technical management adapts work flows, cooperation and tools in project phases C and D to achieve a reliable system realization.

**Keywords**: Small Satellite; AIV; Integration; Verification; Processes, BRLSS

**Acronyms and Abbreviations**

| | |
|---|---|
| AFSPC-MAN | Air Force Space Command Manual |
| AIV | Assembly, Integration and Verification |
| AOCS | Attitude and Orbit Control System |
| AoS | Acquisition of Signal |
| APR | Array Power Regulator |
| AR | Acceptance Review |
| ATC | Acceptance Test Campaign |
| BRLSS | Biological Regenerative Life Support System |
| BSL1 | Biosafety Level 1 |
| C.R.O.P. | Combined Regenerative Organic-food production |
| CAD | Computer Aided Design |
| CCS | Central Check-Out System |
| CDH | Command and Data Handling System |
| CDR | Critical Design Review |
| CFRP | Carbon Fibre Reinforced Polymer |
| CLA | Coupled Loads Analysis |
| CPM | CPU Module |
| CPU | Central Processing Unit |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center |
| ECSS | European Cooperation for Space Standardization |
| EGSE | Electrical Ground Support Equipment |
| EOL | End of Life |
| EPS | Electrical Power System |
| ESD | Electrostatic Discharge |
| Eu:CROPIS | Euglena Combined Regenerative Organic Food Production In Space |
| FCS | Facility and Communications System |
| FDS | Flight Dynamics System |
| FEM | Finite Element Method |
| FOS | Flight Operations System |
| GEVS | General Environmental Verification Specification |
| GMO | Genetically Modified Organisms |
| GNC | Guidance, Navigation, Control |
| GRFP | Glass Fibre Reinforced Polymer |
| GRM | Ground Reference Model |
| GSE | Ground Support Equipment |
| GSN | Ground Station Network |
| IFM | Interface Modules |
| KIP | Key Inspection Point |
| LC | Launch Campaign |
| LEOP | Launch and Early Operations Phase |
| LoS | Loss of Signal |
| MCS | Mission Control System |
| MDPS | Micrometeoroid and Debris Protection Shield |
| MDS | Mission Data System |
| MGSE | Mechanical Ground Support Equipment |
| MoI | Moments of Inertia |
| MOS | Mission Operations System |
| MPM | Mass Properties Measurement |
| MTECU | Magnetic Torquer Electronic Control Unit |
| MUSC | Microgravity User Support Center |
| NCR | Non-Conformance Report |
| NRB | Non-Conformance Review Board |
| OBC | Onboard Computer |
| OM | Office Mode |
| ORR | Operational Readiness Review |
| OST | Orbit Simulation Test |
| PA | Product Assurance |
| PCDU | Power Control and Distribution Unit |
| PCLSS | Physico-chemical life support systems |
| PCM | Power Conversion Module |
| PDR | Preliminary Design Review |
| PEEK | Polyether ether ketone |
| QA | Quality Assurance |
| QR | Qualification Review |
| RAMIS | RAdiation Measurement In Space |
| RoD | Review of Design |
| SCORE | SCalable On-boaRd computer |
| SDM | Software Development Model |
| SE | System Engineering |
| SM | Structural Model |
| SMD | Spacecraft Mass Dummy |
| SMS | Structure and Mechanisms Subsystem |
| SoE | Sequence of Events |
| SSO-A | Sun Synchronous Orbit – Mission A |
| STM | Structural Thermal Model |
| SVT | Software Verification Test |
| TBT | Thermal Balance Test |
| TMM | Thermal-Mathematical Model |
| TMTC | Telemetry and Telecommand |
| TPS | Toyota Production System |
| TVC | Thermal Vacuum Chamber |

# 1 Introduction

Eu:CROPIS is the first satellite of the German Aerospace Center (DLR) compact satellite program and is developed by the DLR Institute of Space Systems in Bremen. The DLR compact satellite program is a set of satellites each designed for a specific purpose and mission objective. Eu:CROPIS is a spin stabilized small-satellite and will be operated for two years in a sun-synchronous low earth orbit after its launch in 2018.

## *1.1 Mission Overview*

The primary objective is the verification of the Compact Satellite concept, including operations with various scientific payloads. The primary payload must provide scientific findings of growth of plants under reduced gravity levels including germination, growth, flowering and seed production of plants as well as demonstrate the usage of algae as long term life support system. The technology here includes On-Board Computer and Power-Distribution elements, avionics S/W and radiation measurement technologies, with the objective of demonstrating functionality and for improvement of technology readiness levels.

## *1.2 Scientific Overview*

Long term space exploration requires reliable life support systems that can provide a human exploration crew with water, oxygen and food since it is nearly impossible to have sufficient cargo onboard a space craft or outpost. Eu:CROPIS is a testbed for a combination of a physico-chemical (PCLSS) and a biological system [1] [2] [3] [4].

The core element of Eu:CROPIS is a biological trickle filter (C.R.O.P. - Combined Regenerative Organic-food production, [5] [6]) which will convert urine into a fertilizer, and Euglena Gracilis, a single cell flagellate [7] [8] [9] that provides oxygen and protects the BRLSS against high ammonia levels. Germination, growth and the nitrification rate of the tomatoes will serve as a bio indicator and thus show the stability and performance of the overall system.

Two identically designed compartments host greenhouses, filter, water and Euglena as well as devices for ion chromatography, expression analysis, valves, pumps and general electronics. One compartment will be operated at Moon and the other one at Martian gravity level. The role of the name giving *Euglena gracilis* is to provide oxygen to the filter which will then convert urine to nitrate. Once the tomatoes have grown sufficient they will take over the oxygen production by means of photosynthesis. While the tomatoes need nitrate as fertilizer, Euglena prefers ammonia and will thus guarantee a low ammonia level and at the same time avoids food competition with the tomatoes. Finally, artificial urine and carbonate will serve as nitrogen and carbon source and will thus compensate the lack of a human crew. The experiment duration of each compartment is six months [10].

The primary payload is developed by the DLR Institute of Aerospace Medicine in Cologne and the Friedrich-Alexander University of Erlangen-Nürnberg.

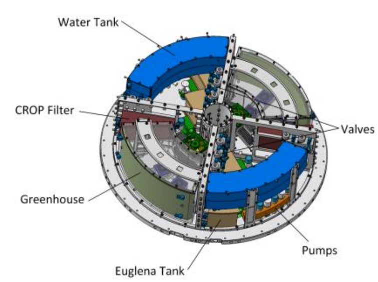


Figure 1: Eu:CROPIS Primary Payload Module

The secondary payload is a contribution of the NASA Ames research center: PowerCell. Two enclosures each containing two modules of genetically modified organisms (GMO) are part of Eu:CROPIS. The scientific objectives of PowerCell are to investigate the performance of microbial mini-ecologies containing photosynthetic microbes and consumer organisms, to conduct synthetic biology remotely in space and to test protein production at 0.014g, 0.22g and 0.52g [11].

The third payload is a radiation detector called RAMIS (RAdiation Measurements In Space) built by the

DLR Institute of Aerospace Medicine. There are two RAMIS modules on Eu:CROPIS: One module is facing space environment and is mounted on the top plate of the space craft, the second module is located inside the pressure vessel of the primary payload. The objective is a further development of radiation field models [12].

The fourth payload is an On-board Computer called SCORE (SCalable On-boaRd computEr) developed by the DLR Institute of Space Systems. Three cameras on-board the space craft are controlled by the technology demonstrator SCORE. The baseline design is described in [13].

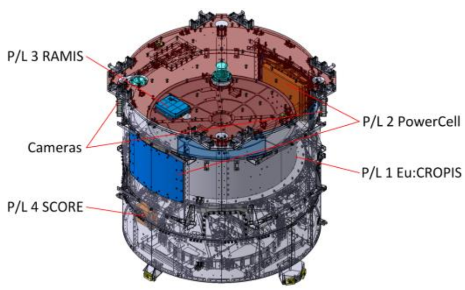


Figure 2: Eu:CROPIS Payload Distribution

### *1.3* System Overview

The outline dimensions of Eu:CROPIS in launch configuration are approximately 1.1m x 1.1m x 1.1m. After panel deployment on orbit the dimensions increase to 2.9m x 2.9m x 1.1m (Figure 3). The launch mass of the whole satellite is 234kg.

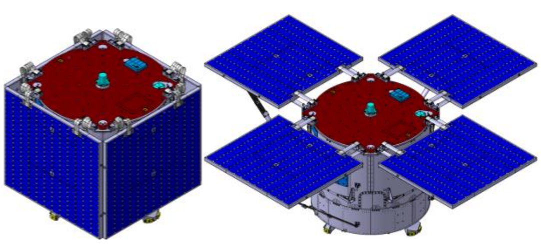

Figure 3: Eu:CROPIS in stowed and deployed configuration

Eu:CROPIS is divided into two main structural assemblies to enable simultaneous integration activities: the Bus section and the Micrometeoroid and Debris Protection Shield (MDPS) section . The two sections are merged after integration of the primary payload. The Bus section consists of a bottom plate, interface ring to launcher separation mechanism, cylindrical walls, stiffening structure and conical adapters to the primary payload. Most of the S/C electronics are directly attached to the Bus bottom plate. This leads to short and direct load paths. The heavy primary payload is attached to the bus bottom plate via conical adapters and cylindrical walls (Figure 4) which thicknesses are driven by mechanical and also thermal requirements.

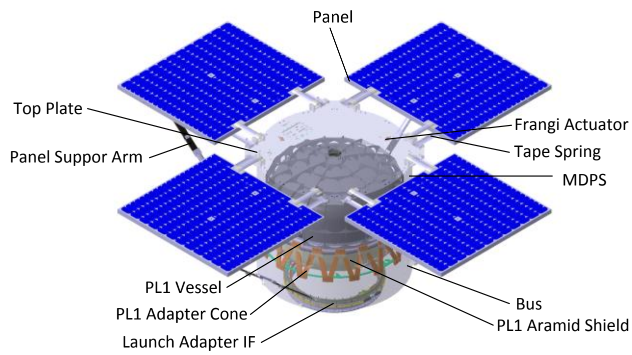


Figure 4: Main structural components and mechanisms

The primary payload is encapsulated into a pressure vessel made of a linerless carbon fibre reinforced polymer [14]. The MDPS section consists of cylindrical walls, local stiffening structure and the top plate. It also contains PowerCell and RAMIS as well as magnetic torquers and some sensors; additionally it covers the primary payload. The micrometeoroids protection system of the primary payload pressure vessel consists of an aramid shielding, the top plate and the 1mm thick MDPS cylindrical wall. For launch, the solar panels are in stowed configuration attached to the MDPS section by two Frangibolt mechanisms each. Panel deployment is performed via tape spring hinges; additional struts increase the solar panels natural frequency. The cylindrical shape of the satellite gives an excellent stiffness in all axes and a good buckling stability. The mechanical testing of the structural test model is described in [15].

The passive thermal control system consists of a sun shield attached via PEEK stand-offs to the top plate, tapespring covers, radiator, internal insulation and washer. Heaters are applied on temperature sensitive units like battery and the biological payloads. The sun shield and the tapespring covers are made of a 5mil second surface mirror single insulation foil made of a polyimide aluminium mix. A thin coating and bonding is applied to avoid electrical charging of the foil. Second surface mirror tape acts as radiator and is directly laminated on the bus cylinder wall which enables also late trimming possibilities. This tape is also used on one RAMIS module located on the top plate facing space. The only internal insulation applied is on the battery: it is insulated via PEEK washers to prevent conductive and via a single layer insulation to prevent radiative heat losses.

The communication system is based on a pair of hot redundant receivers and cold redundant transmitters, two diplexers and one 3dB coupler in assembled into one electronic box. Two omnidirectional S-Band antennas with opposite polarization are installed on the Top Plate and on the Bus and provide a nearly omnidirectional coverage. The key performance characterizes a simultaneous and full-duplex link which is used to send telemetry and receive commands from the ground station. The overall daily data amount is 130Mbyte/day. One challenge for the communication subsystem is the spinning rate of the satellite with up to 31rpm as this leads to dynamical characteristics in the link budget (e.g. amplitude variations, phase rotations) [16].

The Attitude and Orbit Control System (AOCS) of Eu:CROPIS is based on a spin stabilized concept. The satellite is rotated around its z-axis which is also the major moment of inertia axis so the motion is asymptotically stable. The rotation generates a defined centrifugal force at the reference radius of the Payload. The AOCS stabilize the satellite with the angular momentum vector pointing to the sun. A minimum level of rotation speed is required by such a concept to achieve stability. A permanent precession manoeuver of about 1°/day is performed to retain sun pointing. Attitude and orbit determination is performed via GPS units, two magnetometers, ten sun sensors providing full spherical coverage and 4 gyroscopes installed in a tetrahedron. Three magnetic torquers orthogonally installed to each other as well as corresponding magnetic torquer electrical control unit (MTECU) perform the attitude control [17].

### *1.3.1 Command and Data Handling*

All the Command and Data Handling (CDH) functionality of Eu:CROPIS has been integrated into a single unit. This CDH unit consists of a central, redundant on-board computer, which provides interfaces to sensors, actuators, communication equipment, the power control and distribution unit, and the payloads. It is composed of several subunits with dedicated functionality, representing an on-board computer (OBC). At its core are the CPU modules (CPM) which also contain different memories, the Interface Modules (IFM) which extend the CPM's functionality with regard to external interfaces. The management logic controls the cold redundancy of the CPM and ensures the hot-redundant operation of the IFM. Hot redundancy and cross coupling of the IFM enables operation of nominal and redundant external units at the same time. Thus the CDH unit is referred to as being warm-redundant.

The power conversion modules (PCM) supply the voltages required to operate the subsystem from an unregulated battery voltage.

### *1.3.2 Electrical Power Subsystem (EPS)*

The EPS consists of the Power-Distribution and Control Unit (PCDU), the Battery, and the Solar Panels. All of these components have been procured and built to specification by different suppliers, as the underlying procurement process had to involve a bidding process.

The PCDU is composed of a redundant control module which connects it to the CDH unit, a redundant Array Power Regulator (APR) providing maximum power point tracking, a battery management module, and latching current-limiting switches, which are accommodated to provide redundancy..

The solar arrays are mounted on top of four CFRP-sandwich panels at the top of the cylindrical body of the satellite, facing the sun once deployed, and being able to generate up to 250 W of electrical power per panel. The power generation capacity exceeds the required generation capacity during the nominal mission, but is required for the LEOP, when the panels are stowed and the satellite is spinning at a random attitude, providing the power to operate the system until it is stabilized. After deployment of the solar panels the excess capacity of power generation provides for redundancy until EOL.

The battery provides power storage with a bus voltage of up to 32.4V. The cells of the battery are protected against propagation of failures, and an eventual failure will result in the loss of only a single string. The capacity of the battery is such that a single string failure can be tolerated, and will not influence the mission [18].

### *1.4 Ground Segment Overview:*

The Eu:CROPIS ground segment consists of the German Space Operations Center (GSOC), a globally distributed ground station network (GSN), and a Central Checkout System (CCS) located at the DLR's Institute of Space Systems (DLR-RY) in Bremen.
The Eu:CROPIS satellite will be operated by GSOC with support of DLR-RY. For LEOP, commissioning phase, and emergency recoveries, the core GSN is strategically composed of ground stations in Germany, Spitzbergen, Antarctica and Canada to ensure increased command capability and short reaction times. During routine operations Weilheim, Germany is the primary ground station with up to four passes per day.

All Eu:CROPIS housekeeping and scientific data will be transferred to GSOC, where it is processed, filtered and distributed to all external partners. Namely, the Microgravity and User Support Center (MUSC) in Cologne, which serves as the User Segment for the principal investigators of Eu:CROPIS and RAMIS experiments, NASA Ames for PowerCell data, and DLR RY for SCORE and the Satellite BUS data.
The provision of a CCS for early preparation phases has many advantages. It supports the manufacturer to ease spacecraft AIV activities and supplies a TMTC frontend to the space segment. Since the design and software components of the CCS are identical to the later operational system used at GSOC, a continuous pre-validation of the ground segment concept can be performed. As a result, mission specific configurations of GSOC multi-mission components are already tested at the integration site and potential errors or problems thus detected early in the ground segment development phase.
Furthermore, a close and constructive cooperation between space- and ground-segment during early AIV phase is beneficial for the success of the overall mission.

## 2 Eu:CROPIS Assembly, Integration and Verification Campaign

### *2.1 Challenges and constraints*

The Eu:CROPIS project encountered several challenges and constraints caused by the overall system- and payload design.

All logistics of the spacecraft have been impacted by three factors: First, the GMOs used by the PowerCell Payload lead to the inability to transport the system to facilities without biosafety classification due to German and European regulations, ruling out the contracting of external test facilities for FM testing. Second, the FM lithium-ion battery made it necessary to classify the spacecraft as dangerous good with all resulting implications regarding transport to test facilities and launch site. Third, the nature of both primary payloads with its living organisms inside the different compartments prevents any standard practice when handling spacecraft such as a system bake out for cleanliness with respect to molecular contamination and storage under very narrow temperature limits. The most important constraint however, when handling living organisms, is certainly the life span of the organisms, which requires a regular exchange in case of launch delays and thus contradicting any standard AIV and PA approach with respect to the acceptance status of the overall system. The impact on the test strategy is summarized in 2.4.2.

The all-magnetic ACS of the spacecraft turned out to be a major design driver for the FM development and verification, since a defined magnetic cleanliness of the spacecraft structure regarding residual and induced magnetic fields had to be achieved to guarantee the necessary gravitational levels for the payloads. The difficulties to simulate magnetic interactions in complex systems made it necessary to define a detailed test approach on system and subsystem level to comply with the associated requirements. The magnetics verification is described in section 2.6.5

*2.2 AIV Schedule*

The Eu:CROPIS AIV schedule is primarily driven by the launch date of the chosen dedicated rideshare mission as well as by the degradation rate of the biological agents and chemistry integrated in the primary and secondary payloads. The initial launch window envisaged for the SSO-A rideshare mission was Q3/2017. An overview over the project milestones is given in Figure 5.

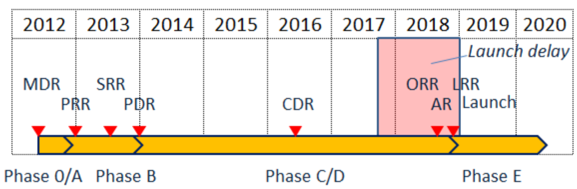


Figure 5: Project milestones

After completion of the SM qualification tests and the final integration of the avionics testbed in Q1/2016 the FM campaign was started at Q3/2016 and reached acceptance test readiness after the flight biology integration in Q1/2017. Due to the degradation of the biology, the Acceptance Test Campaign had to be kept floating to synchronize a biology exchange with the potential launch delay. The time for exchange and acceptance has been estimated to be three month in total.

Due to a series of launch delay announcements starting in Q2/2017, only the acceptance tests booked at external facilities have been conducted to allow biology exchange operations later on. With publication of this paper, the launch has been delayed about 1.5 years to the initial date, causing two additional biology exchange operations. The next envisaged exchange date is due in 12/2018. In total, the project schedule has been on biology exchange standby for almost two years due to the unclear launch manifest, stressing both project budget and personnel availability. Positively, a lot of additional software and functional testing could be implemented in the spare time to optimize the spacecraft functional performance. Figure 6 shows the latest status of the AIV schedule. The additional bio exchanges are not shown in the graph.

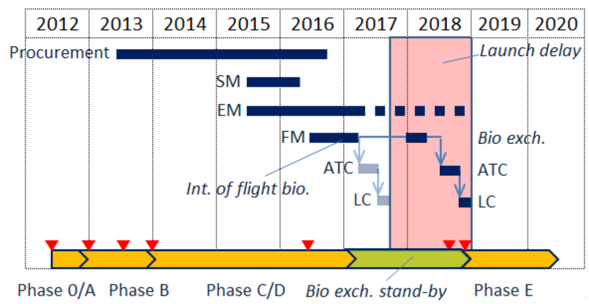


Figure 6: AIV schedule for Eu:CROPIS

*2.3 Model Philosophy*

The drivers to choose a suitable approach for the AIV of the satellite are the maturity level of the subsystems and the complexity of the whole system. For the Eu:CROPIS satellite most of the subsystems will be delivered qualified by other suppliers. The payloads will also have their own AIV approach and thus will be treated as qualified delivery items like all other subsystems.

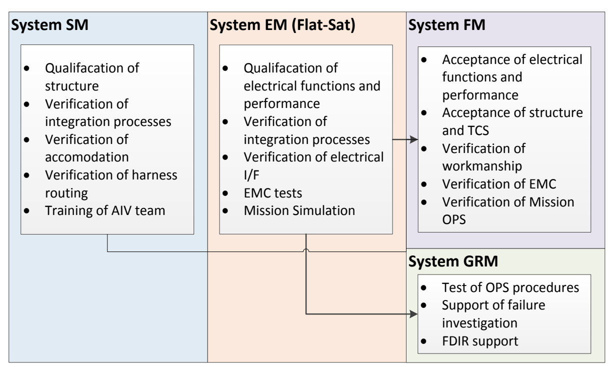


Figure 7: Model Philosophy for Eu:CROPIS

As the structure of the satellite is a new development, it is suitable to choose a hybrid model philosophy in which the qualification of the satellite is assigned to two models in order to reduce the complexity of tests on one model and to simplify the finding and assigning of failures.

The mechanical qualification and the functional verification of the mechanisms subsystem will be done on the Spacecraft Structural Model (SM). The SM is not only used to verify the structural integrity, but also to…

- *Verify the system handling capability (Fit checks, GSE, transport equipment)*
- *Verify the integration flow and dedicated integration processes (Fasteners, gluing, drilling, riveting etc.)*
- *Verify the bolt and fastener positions and lengths, optimization of the harness routing*
- *Design necessary jigs and tools for FM integration*
- *Operator training: Handling, processes, hazardous operations, ESD*
- *Test facility and methodology evaluation*
- *FM Integration and Test Procedure optimization*

With the SM integration campaign results it is possible to use the procurement time of the FM components to optimize the FM integration flow, adapt processes and procure new tools while all operators and subsystem engineers have received a defined level of hands-on training, thus drastically speeding up the FM operations.

The functional performance qualification is done on a System Engineering Model, operated as avionics testbed ("Flat-Sat"). After the EM functional test campaign it will be used for functional unit tests during the FM campaign. After that the avionics testbed will become the Ground Reference Model (GRM).

The Flight Model (FM) will only undergo tests at acceptance level to find workmanship failures during the integration of the spacecraft and confirm that the launcher requirements are met. The structural model will be used as Spacecraft Mass Dummy (SMD) after passed FM acceptance review.

### *2.4 Assembly, Integration and Verification Strategy*

The AIV approach of an institutional scientific compact satellite mission comprises several restrictions and chances regarding the production processes. The limiting boundary conditions of these kinds of projects generally are:

***Project***

- *Tight schedule for implementation after phase B is closed out successfully*
- *Mission EOL is max. two years in orbit*
- *Tight budgets (<15M€ for the space segment)*
- *Small, highly integrated teams*
- *Rideshare launch*

***Technology***

- *Payload driven projects: Few off-the-shelf solutions can be implemented*
- *The system is (at least in parts) a prototype, demanding a high level of flexibility in verification*
- *The model philosophy is limited by the budget*

The DLR compact satellite program offers the opportunity to implement and test new approaches in the AIV process, which are tailored towards the realization of compact class science missions with the above mentioned restrictions. Building and verification of a spacecraft consists of two fields: The assembly / integration methodology and the verification program. Both fields are subject to examination during the Eu:CROPIS project and are described in the following sections.

#### *2.4.1 System Assembly and Integration methodology*

For the Eu:CROPIS mission, the overall goal of the AIV campaign was to reduce the cost and time allocated for the spacecraft integration and test phase, leading to longer development time for the bus- and payload subsystems. To achieve the above mentioned goals, it is necessary to analyze the assets provided by the organization, in this case DLR-RY and the associated institutes, to make best use of the available resources. For the given project and institution, the major benefits identified are:

- *Diversified in-house department structure backing the system engineering (SE, Avionics, GNC, Testing)*
- *Flat hierarchies, small Teams with high dedication and expertise*
- *In-house production capacities (Clean room, Electronics Lab)*
- *In-house testing capacities (Vibration, shock, thermal and vacuum)*
- *Integrated Ground Segment (GSOC)*

To realize a project in the defined time- and cost frame with a small team and (at the beginning) limited infrastructure it is necessary to implement a defined and agreed production methodology within the team and facilities. To keep to schedule and PA requirements it is vital to avoid the drift towards "institutional chaos", that is often seen within research oriented organizations, and "industrial overkill", coming with the implementation of large-scale project methodologies in small-scale projects, as seen in the industrial environment.

To make best use of the listed assets and to cope with the described restrictions, two fields of work have been identified to be subject to optimization: Production philosophy and the application of standards. The first covers the overall implementation of the work environment and PA coverage, the second describes how existing standards are adapted and modified to fit the project specifics. The realization within the Eu:CROPIS project is described hereafter.

***Production philosophy***

For the Eu:CROPIS project, it was decided to take a lean production philosophy, in this case the Toyota Production System (TPS), and tailor its approaches for prototype development. This breaks down to three major branches: Production Logistics, Product Assurance Driven Processes and Workplace Management. The goals are maximum quality, productivity and adherence to schedule.

1. *Production Logistics*

To optimize production logistics during integration, a just-in-sequence method is used in combination with a structured cell production. For this instance, the chain of integration of the spacecraft is fragmented in as many autonomous compartments as possible, which are integrated in identically equipped production cells. This methodology has several assets: The interchangeability of tools between cells, flexibility in the order of compartment integration to compensate for delays caused by suppliers and non-conformances and parallelization of work on several compartments to speed up the integration process. This is backed by the fundamental idea of the TPS, which is to eliminate waste wherever possible.

2. *PA driven processes*

The PA driven process includes the standardization of tools per cell and usage of defined, reviewed and optimized processes for the operations and work preparation. The processes have to be balanced between reproducibility (PA approach required) and flexibility (Prototype approach required), to allow quick adaption to unexpected problems during integration and test of a system. This is implemented by a flexible, standardized system of integration procedures, using a checklist-type design rather than a sequential work instruction.

Checklist items and process steps are (to a certain amount) flexible in their order of operation, allowing free modifications during the integration and test process by the AIV team. This methodology is a feasible compromise between the requirements mentioned above, allowing higher speeds during integration and tests by giving the AIV teams more freedoms with the operations, while enabling comprehensive process documentation. Furthermore it is vital to implement a positive culture of error and to back this culture with quick and responsive non-conformance handling (NRBs, corrective actions, strict avoidance of finger-pointing). This also includes the constant review of the given operational processes and quick adaption of improvements (Continuous Improvement Process).

*3. Workplace Management*

Since communication problems between subsystems and system engineering, especially in teams scattered over different sites, can be identified as a major cost driver during the phases C and D of a project, a special focus has been laid on the work structuring during integration. To avoid the disconnection between subsystems, system engineering and AIV during the integration and test phase and to foster direct communication on an agreed and understood basis, it was decided to implement mixed teams of AIV- and subsystem engineers during integration (Philosophy: "you designed it, you integrate it"). This is backed by short regular pre-shift kick-off meetings with the core project team. This structure shortens the feedback time for the subsystems in the development phase and makes it possible to directly implement changes in the design of the following models. Furthermore, the AIV teams are empowered to take over a lot more PA responsibility, which improves the overall quality of work, reduces the PA workload and enhances the work dedication of the team members through trust. This, in combination with the quick feedback towards subsystems and process design, directly enhances the productivity and employee satisfaction.

***Standards and processes***

The ECSS and all related space standards are designed for the management of large projects, in the frame of several tens of M€ and above, looking for long space segment lifespans and harsh environments, such as deep space, while scattering development from an institutional customer over an industrial primary contractor to several subcontractors.

For institutional compact satellite projects with mission times of less than two years in an earth-bound orbit, it is not feasible and necessary to implement a full ECSS process on all levels, since the resulting implications are not manageable by a small team. Furthermore, an institutional mission is able to accept higher risks than a mission with an industrial primary contractor, allowing more flexibility in the standardization and process control.

Given the fact, that the direct communication between subsystems is fostered through the project structure, a huge documentation overhead is not necessary. To reduce the effort, the ECSS has been tailored to match the project size without giving up the benefits from the vast experience provided. This is achieved by both reviewing and picking out the promising production methods, such as crimping or soldering, defining acceptable parameters for off-the-shelf components and drastically reducing the amount of ECSS required documentation by merging.

*2.4.2 System verification program*

The overall verification strategy of the Eu:CROPIS project applies a classical ECSS approach, tailored to the mission specifics. The verification methods used are Review of Design, Analysis, Inspection and Test, distributed on the domains Structure, EMC, Thermal, Cleanliness and Contamination Control, Model Build Standard and Ground Operations. This includes the usage of three spacecraft models (see 2.3) and the verification stages qualification and acceptance.

The requirements covered by RoD are considered to be validated during the respective reviews (PDR, CDR and AR). Analyses are carried out in the field of the respective subsystem or on system level. Inspections are system level activities. Tests are applied on both subsystem and system level.

For the Project, one focus for the verification was the application of end-to-end test scenarios as early as possible to both gain experience with the spacecraft behaviour and to identify possible design flaws caused by system interaction as early as possible, to reduce cost impact in later project phases. End-to-End testing was started after the qualification test campaign of the SM by combining EM and SM components for different test setups (e.g. panel deployment).

To keep cost control during testing, the Pareto principle was applied to the tests setups, stating that most critical malfunctions can be found even with a less representative test setup. The FM acceptance is closed by a full orbit simulation under vacuum in the solar simulation chamber at DLR-RY to validate the system autonomy as well as the whole command- and telemetry chain from spacecraft to ground segment.

Due to the Biosafety Level of the mission, all hardware related acceptance testing of the flight model was subject to severe restrictions regarding access, handling and transportation, what denied contracting external test facilities. To cope with these boundary conditions, the test facilities at DLR-RY had to be upgraded to allow testing of compact class spacecraft, while the cleanrooms had to be classified as Biosafety Laboratory. Due to the BSL a new 89kn shaker had to be procured and installed in the institute's vibration test laboratory. For all mass property related tests, a mobile measurement jig from an external contractor was used inside the BSL-facility. A side effect of the effort made to make testing of a GMO payload possible, the project experienced a significant speed up during the acceptance test campaign, reducing the total time for the structural verification from 3.5 (SM) to two weeks (FM) in total. The increase in speed also comes with a greater flexibility in the scheduling, since no dependency on external contractors is impacting the project planning.

### *2.5 Product Assurance Strategy*

Within the Eu:CROPIS project one product assurance (PA) manager is responsible for product assurance during the complete project lifecycle. The PA program already starts in the development phase and is in effect in all following project phases. The PA responsibility ends after spacecraft acceptance to the launch provider (e.g. when integrated to the launcher payload stack); but chairing non-conformance review boards (NRBs) from non-conformances reports (NCRs) generated within LEOP, commissioning or operational routine phase is still under project PA responsibility.

The Eu:CROPIS PA program ensures especially that

- *Any potential risk conditions are identified and appropriately addressed within risk control oversight continuously throughout the project in close cooperation with the project team*
- *Quality assurance activities take place (e.g.. inspection planning, verification & traceability management, documentation review)*
- *Dependability design and operation principles are involved so that the maximum project success expectance is achieved*
- *Processes, materials and parts are suitable for the space mission based on suitable databases and experience gained from previous missions. In-house facilities are utilized to characterize materials with unknown properties e.g. outgassing and thermal behavior.*
- *Configuration control is implemented within documentation and hardware activities. Anomalies, defects, damages or unforeseen discrepancies between documentation and the actual hard- or software are documented and tracked by NCRs.*
- *PA reviews (i.e. manufacturing readiness review, test reviews) serve as advantageous milestones*
- *No failure within the Eu:CROPIS provided equipment can propagate into higher level systems*
- *No safety risk is created or that safety hazards are controlled.*

The safety design of the spacecraft within the Eu:CROPIS mission has to be validated against requirements within the AIR FORCE SPACE COMMAND MANUAL (AFSPCMAN 91-710) insofar as the launch is provided by SpaceX from the military air force base in Vandenberg. The compliance to that air force standard has to be documented in a compliance matrix to be supplied to the launch provider plus a design description which is a dedicated document called Missile System Pre-launch Safety Package.

The PA group within the quality management department of the institute brings an additional view to the project. The intention of PA is different than from development and manufacturing engineers. Making decisions is not based in the first place on cost, time or feasibility aspects but focuses to be reliable, available, maintainable and safe. The different existing PA disciplines are not separated within the department. All PA tasks for one project are coordinated and implemented by one dedicated person being the main product assurance manager for that project reflecting as well all technical PA aspects (Parts, materials, process, reliability) from a system point of view as well as on subsystems, instruments and their interfaces and interaction. PA is strongly integrated into the project team activities. The PA department follows a matrix approach by appointment of one dedicated PA responsible manager for the entire run-time of the project while still being part of the PA department to assure exchange of experience gained and for discussion of actual problems. Within the Eu:CROPIS project the PA manager is informed on daily activities, design states or occurred problems. He will not accompany every activity (e.g. all integration steps) but can contribute with key inspection point (KIP) definition and reviews at decision points. That means that no complete PA/QA coverage is predefined. But the PA manager stays informed and is involved in key decisions and activities. Status and problems are communicated also to other existing PA managers in the specific department of DLR to always have a representative and to exchange views.

The PA responsibility within Eu:CROPIS ends at interfaces of lower level units (especially payloads) assuming that no propagating effects exist. In subsystems and payloads where no specific and full PA coverage is assured DLR PA supports in terms of performing KIPs that include inspection of processes, workmanship and documentation. In general the PA functionality is a work package on system level same as AIV. The complete v-model being a representation of a systems engineering process is supported by PA. The Eu:CROPIS PA Manager on satellite system level is directly responsible and reports to the Eu:CROPIS Project Manager. Especially, he reports about the progress of the PA program and about potential problems also including issues of lower levels that could impact satellite activities. One special organizational characteristic of the Eu:CROPIS project is that subsystem engineers (being the development engineers of the satellite bus units) accompany the integration & test processes from phase C & D. It means that the unit experts assist the handling and testing also within system level activities. The benefit is that only little information gets lost when the subsystem engineers get involved to the critical AIV processes. Inherent knowledge is thereby available directly within the process. Involving the development engineers into those processes keeps review/approve authorities close into the processes.

Within all tasks, decisions, trade-offs and evaluations the premise of Eu:CROPIS PA is to find a pragmatic way. However, the assurance of safety has the highest priority. Collocation avoids unnecessary formalism and improves largely the communication baseline within the team especially, the awareness of problem resolution and engineering changes. All methods and tools engaged in the PA field have been critically analyzed if they are valuable to pro-actively promote mission success. This includes especially the early consideration of possible reaction to failures in terms of safe states and reaction on on-board hardware, software and on-ground control team reaction. A way has to be found to balance the implementation of applicable and tailored space standards with practical engineering judgement. At many points it must be sufficient to apply normal engineering expertise instead of complex software based tools. Although the here described and usual implementation of PA workflows into projects might decelerate in the end the main aim is not to impede but to support and improve. The self-defined objective of Eu:CROPIS PA is trying to be advantageous by implementing PA into the project lifecycle.

### *2.6 Space Segment Activities*

This section describes the activities performed to build and verify the Eu:CROPIS spacecraft.

#### *2.6.1 Assembly and Integration Approach*

Since all subsystems and payloads are delivered as boxed and qualified units, no mechanical assembly on subsystem level, except structural parts, has been performed by the system AIV team during the project phases. For the integration activities on system level, a flexible integration flow has been set up in order to speed up the integration process (cp. 2.4.1).

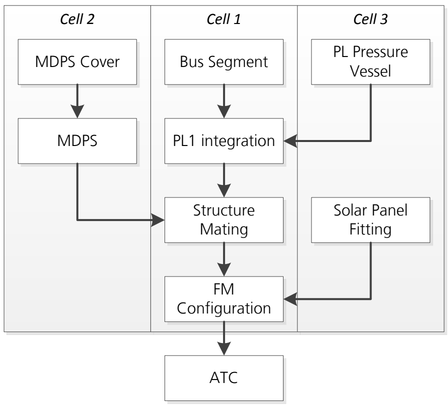


Figure 8: Integration flow of the Eu:CROPIS Spacecraft

Therefore the system has been broken down to three compartments, each integrated in a standalone production cell inside the cleanroom facilities:

- *Cell 1: Bus segment*
    - *Avionics, ACS, Radiator, TCS*
    - *PL4*
- *Cell 2: MDPS segment*
    - *ACS, TCS*
    - *PL2, PL3*
- *Cell 3: Payload 1 and Solar Panels*

Cell 4 contains the EM testbed and serves for FM unit functional check-outs prior transfer to the integration cells one, two and four. Furthermore the cell holds all necessary Electrical Ground Support Equipment (EGSE) and TMTC lines.

After successful integration of the system compartments, the structure mating and solar array integration takes place in Cell 1, which contains the primary spacecraft system Mechanical Ground Support Equipment (MGSE).

All utilized MGSEs, used for the spacecraft, battery handling, solar panel integration etc., are unique designs fitted to the intended purpose using a large stock of off-the-shelf construction profile systems. This allows a quick flexible adaption to the changing design specifics during SM and FM campaigns, but also slows down the integration process, since there are no dedicated MGSE constraints applicable in the project design phases. This leads to an increased workload during the AIV campaigns in order to optimize the MGSEs while, in parallel, working on spacecraft integration. The MGSE concept design has been identified to be a major cost and schedule driver during the project phases C and D and will be subject to optimization in follow-on projects.

### *2.6.2 Thermal Verification Approach*

The thermal verification approach of the Eu:CROPIS spacecraft utilizes a bottom up approach with a broad end-to-end test spectrum rather than development testing.

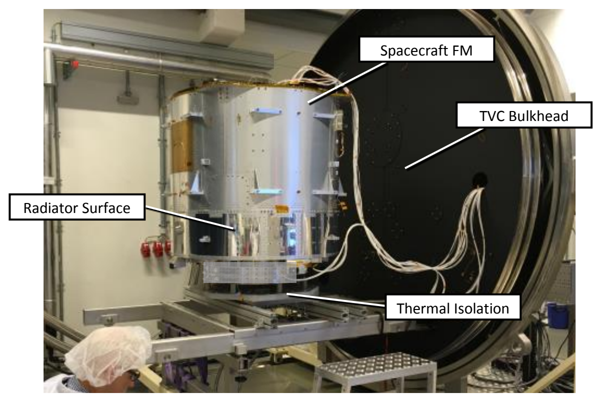


Figure 9: Radiator sizing during Thermal Balance Test

The applied thermal control system is a passive, heater-backed radiator setup making use of the spacecraft orientation towards the sun. The main heat sources, the bus compartment units and the primary payload, are directly connected to the radiator surface on the rear side of the spacecraft central cylinder via conductive paths. The radiator itself consists of the spacecraft bus compartment cylinder wall, which is covered by a tape-based second surface mirror.

In order to save time, personnel occupation and costs in early phase C, only a minimalistic structural thermal model was used to determine the thermal behaviour of the main conduction path, using one payload flange delta structure and a cut-out of the main radiator with its second surface mirror. A Thermal Balance Test (TBT) was performed on this setup to validate the Thermal-Mathematical Model (TMM) and to size the radiator. All units have been acceptance- tested with the standard ECSS cycling approach prior delivery.

All thermal tests following the reduced TBT have been designed to serve as FM end-to-end test for subsystems, software and operations, allowing integrated system verification during all large-scale tests (test what you fly – fly what you test). The thermal verification includes three major test campaigns:

- ***System Thermal Balance Test:*** *Equilibrium test for hot- and cold case determination, radiator trimming, long term standalone operation in acquisition and science mode. The test was done during the FM integration campaign since the radiator is no longer accessible once the solar panels are integrated.*
- ***System Thermal Vacuum Test:*** *Hot- and cold case switch-on, system characterization and heater performance, command operations verifications and operator training*
- ***Orbit Simulation Test:*** *Autonomous operations both in acquisition- and nominal mode (á 48hr) under orbit conditions (cold wall, solar simulator, 62 min. illumination, 35 min. eclipse), payload operations training (see 2.6.7)*

Due to the GMO restrictions, all tests had to be designed such that they could be performed in the test facilities of DLR-RY under BSL1-conditions. The tests delivered a gradually increasing understanding and characterization of the system thermal behaviour and delivered vital inputs for the software development both on system and payload level. With the end-to-end-approach, several severe potential malfunctions have been ruled out under controlled conditions, minimizing the threat of in-orbit loss of functionality.

#### *2.6.3 Mechanical Verification Approach*

The mechanical verification approach consists of two branches. The first branch deals with the development and verification of the MDPS, the second with the design and verification of the structure and mechanisms subsystem (SMS) and the spacecraft.

Due to the usage of a pressurized tank to hold the missions primary payload, a dedicated protection against particle impact had to be provided. The utilized system consists of three layers of material with dedicated free space in between as part of the spacecraft structure (From outside: 1mm Aluminum shell, aramid fabric, CFRP tank). The validation of the debris shielding has been achieved for an impactor diameter of 1mm fired by a light gas cannon on a reduced structural model of the MDPS at the Fraunhofer Ernst Mach Institute. The MDPS was designed and tested during project phase B.

For system validation towards the expected mechanical loads during launch and operations, a classic two-model verification approach has been used for qualification and acceptance with accompanying analytical model validation. Like the verification of the thermal control system, an end-to-end-centered methodology is used. The approach comprises:

- *SM Qualification Tests (Vibration, Shock, Mass Properties (MPM), Mechanisms End-to-End)*
- *Development Tests (Mechanisms)*
- *FM Acceptance Tests (Vibration, MPM, Mechanisms End-to-end)*

As can be seen, a dedicated acoustics test has not been performed; the acoustic loads have been covered in the random vibration spectrum of the SM and FM vibration test campaigns.

Since the spacecraft has to provide a defined spin axis for the primary and secondary payloads, a highly reliable MoI determination had to be achieved using a staged MPM test campaign to validate the spacecraft CAD model and trimming strategy.

***Launch Loads Verification (Vibration, Shock)***

Since no dedicated launch loads or coupled loads analyses (CLA) have been available during phase B of the project, a generic GEVS launch environment has been used for development of the structural design and the associated finite element model (FE model) [15] . For the shock- and vibration qualification, accelerometers have been placed on the mounting bases of all Bus units and on defined reference points of every payload and the MDPS. The performed load- and shock runs with the given GEVS spectra allowed measuring the local spectra for each of the units, the payloads and MDPS. This information was used to validate the system FE model as well as to provide dedicated acceptance loads and spectra to all subsystems. Especially the shock responses of the system were used to verify, that all unit qualification and acceptance tests meet the specifications. In spite of the excessive loads seen by the SM, the structure performed well without any major malfunction, rupture or deformation. For qualification, the following tests have been performed:

- *Pyroshock excitation (on the separation adapter, 42g / 100Hz, 1414g / 1kHz, 1414g / 10kHz, GEVS spectrum)*
- *Static acceleration / Sine Burst (Acceptance loads +3db, 13.25g, eight cycles, all axes)*
- *Random vibration (Acceptance loads +3db, GEVS spectrum, 11.73 $g_{rms}$, all axes)*
- *Resonance search (low level sine sweep, between all runs)*

Since the need exists for a biology exchange capability of the primary payload, the FM acceptance vibration tests had to be shifted to the very end of the acceptance campaign, so an eventual refurbishment of the payload biology will not compromise the system structural integrity, urging a mechanical re-acceptance. The acceptance has been performed with the launch system CLA analysis results, thus changing the input spectra in comparison to the qualification test. This change in dynamics has been covered by the excessive loads applied due to the GEVS environment.

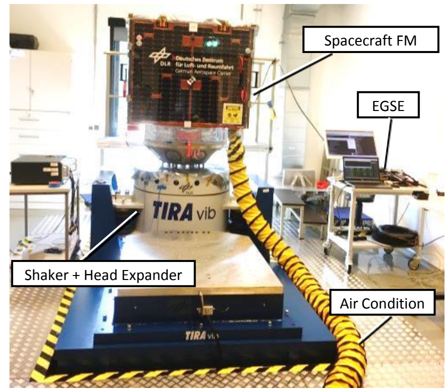


Figure 10: Spacecraft FM during Vibration Acceptance functional check out

Nevertheless, a dedicated notching strategy had to be developed together with the launch provider. The test runs were started by a leading natural frequency examination on all three axes, utilizing a standard sine sweep as well as a low level random vibration approach. The natural frequency distribution serves as input for the notching strategy development and pre- and post-test mechanical property comparison. The following tests have been run:

- *Sine Sweep 20-100 Hz (Acceptance load, 2g, all axes)*
- *Static acceleration / Sine Burst (Acceptance loads, 4g in plane, 7.5g out of plane, eight cycles at 15hz, all axes)*
- *Random vibration (Acceptance loads, CLA spectrum, 4.47 $g_{rms}$ in plane, 4.41$g_{rms}$ out of plane , all axes)*
- *Resonance search (low level sine sweep, between all runs)*
- *System Functional Check Out (between all axes)*

Due to the GMO restrictions, all tests had to be designed such, that they could be performed in the test facilities of DLR-RY under BSL1-conditions. Due to the excessive loads used as baseline for the system design and the conscientious testing, the acceptance has been performed without any mechanical or electrical issues.

*2.6.4 Mass Properties Verification Approach*

The mass properties verification approach utilized MPM tests on the SM, on the FM and an accompanying mathematical model.

Due to the experiments demand for low artificial gravity gradients, the system mass properties have to be known with high certainty. Deviations between Centroid axis and Structural Coordinate Frame shall be as low as possible (<5°) during payload operation, Launcher (mass, CoG offset, inertia tensor) and AOCS (ratio of moments of inertia, major moment of inertia) requirements had to be respected as well. The mass properties verification activities started with a measurement of the SM. The results of this test indicated the need for trimming measures on the FM. In addition, discrepancies between CAD analysis data and test data showed up. As FM structure was already manufactured, it was not possible to make any changes in the FM design, e.g. dedicated positions for trim mass. Therefore a mass properties mathematical model was established to investigate possible trim mass locations. To support validation of chosen trimming measures, a three phase MPM campaign was planned at different integration states:

1. *FM bus fully integrated S/C bus with PL1 non-flight bio (Figure 11 left)*
2. *FM fully integrated with P/L non-flight bio and solar panel mass dummies (Figure 11 right)*
3. *FM in acceptance configuration (Figure 12)*

GMO restrictions applied for test #3; therefore, all FM tests were performed in-house at DLR-RY facilities under BSL-1 conditions for comparability reasons. The third measurement also included the mass properties measurement of two of four solar panels stand-alone. After each test, the mathematical model was updated accordingly and the model was used to post-process test data. This became necessary as all tested configurations differ to relevant launch or flight configurations, e.g. for test #2 a Launcher Separation Dummy System and other MGSE components were installed. The post-processed data was then used to check if the chosen trimming measures were still sufficient.

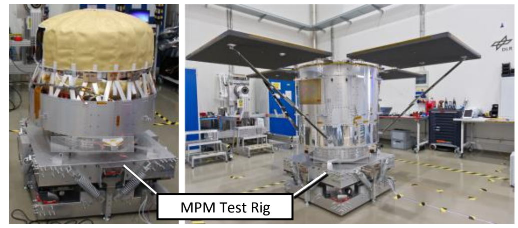

Figure 11: FM MPM test #1 and #2

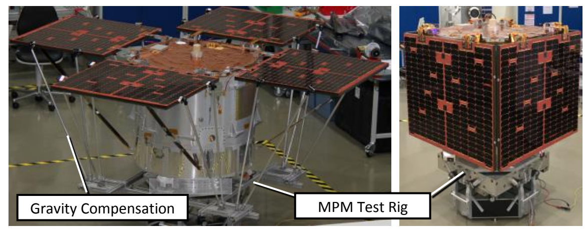

Figure 12: FM MPM acceptance

The outcomes of the ongoing analyses showed the need for a rotation of the heavy primary payload and in total nine distributed trim masses to fulfill payload, Launcher and AOCS requirements. The final analysis of the FM acceptance MPM test confirmed the preceding analyses.

*2.6.5 Magnetics and EMC Verification Approach*

The Eu:CROPIS EMC verification is implemented as a three-stage process to cover effects induced by electromagnetics and remanent magnetic moments.

1. *Subsystem level EMC verification*

Due to the personnel, schedule and environmental restrictions, the primary EMC verification in terms of conducted and radiated emissions as well as conducted and radiated susceptibility is shifted to subsystem level, meaning that all subsystems and their respective harness are certified to be electromagnetically clean upon delivery for integration.

2. *Subsystem level magnetics verification*

Since a detailed analysis of the magnetic behavior of the spacecraft is not feasible, it has been decided to perform measurements of the remanent magnetic field of all units after delivery during the incoming inspection. The resulting dipole values can then be added to gain a worst case estimation of the spacecraft remanent magnetic field and to implement design changes, such as trimming magnets, if necessary.

*3. System level EMC verification*

On system level compatibility is shown by a cold switch on and a long term functional performance test, since the bus structure is an isolated aluminium enclosure. Radiated emissions are ignored since the spacecraft is switched off until 120s after deployment.

The system EMC cold switch on verification is a staged process during the spacecraft integration campaign, beginning with the boot up at the first bus functional check out. A variety of functional and performance check outs are performed while the system is integrated to flight configuration to allow corrective action in case of EM driven incompatibilities. All harness items are tested alongside their units. For FM acceptance, the fully integrated flight unit is autonomously operated with a reference flight software under operational conditions for at least 48hrs.

*4. System level magnetics verification*

The System Magnetic Field Measurement serves as magnetic behaviour characterization test for the fully integrated satellite bus with stowed flight configuration solar panels. Aim of this test is to measure the residual magnetic dipole of the spacecraft and to verify the AOCS performance. For this purpose, the Eu:CROPIS flight model is set up inside a magnetic field simulation facility and will undergo at least three different test setups:

- *Remanent magnetic properties (S/C passive)*
- *Induced magnetic properties and effects on the on-board magnetometer (S/C active)*
- *Attitude control testing of magnetically stabilized spacecraft (S/C active)*

The test provides the following information for AOCS software development:

- *Vector of the residual magnetic dipole*
- *Magnitude of the residual magnetic dipole (A/m²)*
- *Vector/magnitude of induced magnetic moment*
- *Magnetometer calibration parameters*
- *Magnetic Torquer effectively generated dipole moment*

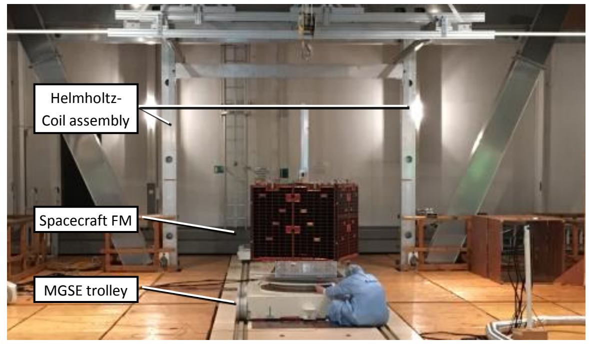


Figure 13: Spacecraft FM during remanent magnetic field measurement

*2.6.6 Software and Functional Verification*

The software development of the flight software has started early in the project and has been supported by the availability of a DLR-internal generic OBC hardware model (Office Model - OM), a functional-equivalent CDH Software Development Model (SDM) provided by the CDH unit manufacturer, and the ability to utilize the System EM-Flatsat before extending verification to the System Flight Model. The software verification approach includes unit testing, continuous integration testing, stand-alone testing with OMs and SDMs, and integrated testing on system models (EM, FM) [19] [20] [21]. In order to ensure operation not only of the software, but also of the hardware to be integrated into the system Engineering Model (Flatsat) and the system Flight Model a staged approach has been chosen, which enabled incremental verification and set-up of the Engineering Model as the units arrived at DLR premises, and pre-verification of flight units to be integrated into the system Flight Model. At the first stage the Engineering Model units went through incoming inspection and stand-alone testing to be then integrated to form the system EM. Once this model had been completed it provided the basis for early inclusion of operations teams from the GSOC, who will operate the mission later, for the development of flight operational procedures (FOP) and training on the system. It also enabled to move software testing and debugging to a more flight-representative setup. And finally the EM provided the ability to sequentially test incoming flight units for compatibility and functionality one-by-one before integration into the FM structure. These flight units went through magnetic characterization, followed by an integrated test at the system EM including interface signal characterization and functional verification. This process had been developed to cope with the initial tight schedule for integration and testing on the system FM, and helped to rule out problems with individual units prior to integration. Thus verification on the integrated spacecraft was focused on system-level functional verification.

*2.6.7 End-to-End Testing Approach*

During the Eu:CROPIS AIV campaigns end-to-end testing is implemented as method of choice for functional testing. This method aims to add a full system functionality chain to simple functional checks, such as actuation of motorized elements or deployment connectors, to evaluate the crosslink between all integrated system components. This methodology allows to detect functional glitches (e.g. EMC cross-talk etc.) in early project phases. Furthermore the use of a functional command chain supports the verification of the Space System User Manual and helps to train operations. In this section two significant end-to-end tests shall be shortly described.

1. *Orbit simulation end-to-end test*

The System Orbit Simulation Test is part of the Eu:CROPIS FM Campaign and serves as thermal functionality test for the fully integrated satellite bus with applied radiator surface and solar panels. Using the thermal-vacuum environment this test is also used to operate the system for 2 x 48 h in acquisition and nominal mode, respectively.

Aim of this test is to prove the operability of the system for dynamic orbital equilibrium in a solar simulation run. To simulate the environmental conditions, the Eu:CROPIS flight model is set up inside the DLR-RY thermal vacuum chamber and cycled to orbital average mean temperature. At least 2 x 48h of 96 minutes orbit simulations will be performed using the facilities solar simulator while operating the satellite in an endless LEOP state for the first 48 hours and in an autonomous state for the second 48 hours. Furthermore the test serves as a low temperature pre-flight bake-out for the flight hardware.

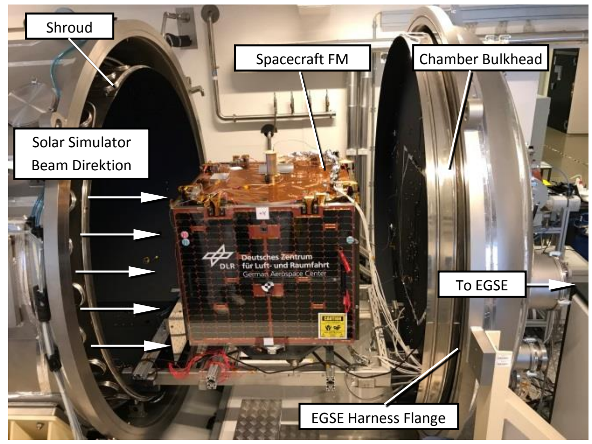


Figure 14: Spacecraft FM in Space Simulation Facility during OST

The test shall provide the following information:

- *TCS operability and temperature gradients for endless LEOP state*
- *TCS operability and temperature gradients for autonomous state*
- *Temperature gradient distribution over solar array for a minimum set of orbit cycles*
- *Positive power generation of solar array when using the chambers solar generator*
- *Flight S/W and Payload operability under realistic conditions*

As stated in section 2.4.2, the test is applying the Pareto principle in the way, that some of the orbital boundary conditions, such as the BBQ-mode, are not simulated during the test to reduce costs. The resulting inaccuracies, such as higher temperature gradients, are accepted for the test and seen as worst case scenario.

*2. Panel Deployment end-to-end test*

The Eu:CROPIS spacecraft uses a newly designed GFRP flexure hinge assembly for solar panel deployment [22]. In contrary to ordinary hinge concepts, the stored energy is originating only from the elastic deformation of the hinge geometry. This reduces the mechanical complexity of the deployment system and enhances reliability, but also allows a three dimensional trajectory during actuation, which has a major impact on the design of the test setup. To characterize the deployment process prior to launch, a dedicated End-to-End test was performed involving Spacecraft System as well as Ground Segment.

The Panel Deployment End-To-End-Test is part of the Eu:CROPIS FM Campaign and served as acceptance test for the FM solar array integration procedures, flight command- and actuation chain and actuation procedures. It had to prove the in-orbit cooperation between the deployment mechanics and ground operation procedures. The test shall verify the functionality of:

- *The FM electrical power system chain from Battery to FM panel release actuators*
- *The FM telecommand procedures and chain to C&DH*
- *The functionality of the FM panel release actuators*
- *The kinematics and dynamics of the FM panel deployment mechanisms*
- *Flight Calibration of the heating curve of all eight FM panel release actuators*

During the test, the panel deployment procedure is commanded to the FM OBC via TMTC link. The FM OBC will then activate the power interface to the actuators via FM PCDU and Battery. After activation, the panel is released by the stored energy of the tape spring hinges and the panel support arm. The gravity compensation will be achieved via a calibrated helium balloon attached to the solar panel. The principal test assembly an kinematics are shown in Figure 15.

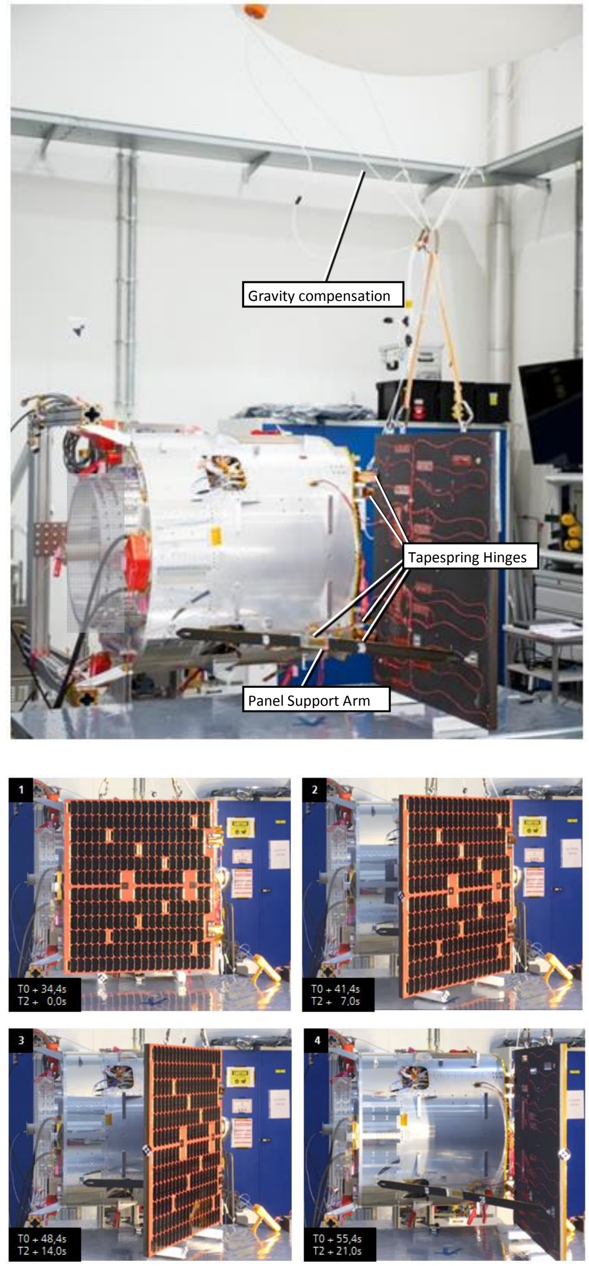


Figure 15: Panel deployment and kinematics

### *2.7 Ground Segment Activities*

#### *2.7.1 Ground Segment Assembly, Integration and Verification*

The ground segment AIV process at GSOC underlies a tailored ECSS standard and includes activities to be performed between the Critical Design Review (CDR) and the Ground Segment Qualification Review (QR). Certain technical system-level tests may be performed after the QR, in the context of combined operational validation tests or during ground segment integration.

Planning of the ground segment shall be performed using a top-down approach, by expanding the various systems into subsystems until a suitable level is reached. Integration and technical verification will be performed bottom-up, by requiring that all underlying elements have undergone the same AIV process before proceeding to a higher level system.

On a very abstract level ground segment functionalities can be grouped into three domains. The Mission Operations System (MOS) handles all aspects of mission operations, the Facility and Communications Systems (FCS) includes facility, network, and IT infrastructure, and the Flight Dynamics System (FDS) covers all tasks related to the spacecraft's orbital motion. Exemplary, the MOS domain can be broken down further into the subsystems flight operations system (FOS), mission data system (MDS), and mission planning system (MPS).

The AIV plan reflects this strategy, every subsystem is broken down into less complex subsystems and the underlying technical verification approach is presented. Each subsystem reduces the complexity further until individual test items can be identified. Due to the GSOC multi-mission approach thorough test procedures are readily available for most components which incorporate the lessons learnt from previous and ongoing missions. As a result most elements are repeatedly tested by following missions and particular focus can be attributed to Eu:CROPIS specific extensions. Once all subsystem tests are successfully performed, the ground segment AIV process concludes in a system validation test.

*1. Ground Segment Validation*

In the System Validation Test (SVT) the ground segment is validated as a whole to demonstrate the functionality required for operational usage, which entails verification of telemetry reception and telecommand capability, and testing of system and network redundancy. With hardware in the loop, this end-to-end test features a first realistic operational set-up for PIs. Provided input is fed into the Mission Control System (MCS) at GSOC, sent to the ground station (CCS), and forwarded to the FM at DLR-RY. The incoming telemetry stream from the satellite is routed back to GSOC for processing, and the resulting data products are distributed to the customers. This test also includes the validation of on-board firmware updates for all payloads and the on-board computer.

The SVT set-up allows for validation of Flight Operations Procedures (FOPs), which can only be tested on the Eu:CROPIS FM.

*2. Operational Validation*

The operational validation activities are carried out mainly between QR and Operational Readiness Review (ORR) to demonstrate the readiness of the ground segment as well as the full compatibility with the space segment. This is achieved by executing special test-campaigns and simulation-sessions which resemble a realistic operational context.

Additionally, the correctness and completeness of relevant mission operations data shall be validated. This process begins with the production and release of mission operations data (i.e. Mission Information Base (MIB), FOPs, LEOP Sequence of Events) in phases D1/2, and culminates with the System Validation Test (SVT) and simulations campaign in phase D3.

The MIB preparation and validation is coordinated between space- and ground-segment. Working on the same code base, pre-defined domains allow both parties to directly contribute to the MIB development with expert knowledge, which shortens the turnaround time for change requests. This close collaboration simplifies certain operational tasks and handlings, which will become advantageous during operations. As a result, many ideas and suggestions brought up by the operations team were implemented in the on-board software and the MIB.

In general mission operations are based on FOPs, which encapsulate a set of commands, checks, and decision branches, associated with the activities to be performed onboard a spacecraft. FOPs are typically designed far in advance of launch, and validated against the engineering model (EM) or FM. It is standard practice to manage FOPs with a tool linked to the MIB. For this mission, GSOC utilized a novel software development called ProToS to further aid the collaborative development of FOPs. Procedures for Eu:CROPIS were prepared by GSOC, DLR-RY, and MUSC to cover both standard and contingency scenarios. For FOP validation, timeslots for access to the EM or FM and the availability of subsystem experts of the space segment were granted to GSOC.

During LEOP and Commissioning Phase, procedures are executed according to a prepared Sequence of Events (SoE). This sequence includes information on planned ground station contacts, their Acquisition of Signal (AoS) and Loss of Signal (LoS) times, ground station elevation, scheduled activities during and in-between passes, as well as the personnel (e.g. in the form of shifts) allocated to these tasks. This SoE was validated during several Internal and Combined Training Sessions.

### *3. Training and Simulation*

The team training and simulation campaign starts off with classroom training with the purpose of familiarizing each team member with the operations work flow and the control room environment and the design and workflow of the other ground systems as well as the other subsystems of the spacecraft. Next, in total four internal (GSOC only) and four external (DLR-RY, Principal Investigators and GSOC) simulations took place. The activities, primarily the validation of both the whole ground system for Eu:CROPIS and the LEOP SoE, and execution of planned ground and satellite related contingencies during these simulations are logged and tracked in training and simulation reports. The objective of simulations is to demonstrate operational readiness. This means to demonstrate the ability of the ground segment to support operations as requested, the functionality of internal and external interfaces (e.g. between ground- and user-segment) and the proficiency of the team members to support the LEOP and early commissioning, which are usually the most critical operational phases, as well as the following routine phase.

The close cooperation between the operations team at GSOC and the satellite experts at DLR-RY during these training sessions allowed the detailed planning, testing and therefore risk reduction of LEOP and following commissioning and routine phase.

## 3 Conclusion

The programmatic goal of the DLR Compact Satellite is to provide a powerful and flexible research oriented satellite system. This is accompanied by the demand for an affordable access to space for small scale institutional payloads with high complexity as well as for a testbed for flight hardware verification. To achieve the necessary flexibility, schedule- and cost effectiveness, the SE-, PA-, AIV- and Operations processes involved in the project realization are a major part of the governing scientific program.

This paper gives an overview of the approaches and optimizations applied in the AIV- and Operations program of the Eu:CROPIS project, the first DLR Compact Satellite mission, and the achieved results. The project was characterized by several constraints, in particular the limited resources in terms of available qualified personnel due to a strict design-to-cost approach. As a result, the team had to derive strategies for development and AIV that would fit into the schedule even in the case of a potential shortfall in manpower. The spacecraft was assembled and tested in time, fulfilling project schedule and quality requirements. This could only be realized by an in-house multi-disciplinary team and in particular its continuity over all project phases as well as close interaction with GSOC starting in early project phases. Furthermore the project for the first time merges the development of ground- and space segment to optimize the knowledge transfer from project phase D to E, for example by the generation, test and validation of FOPs as early as phase C. A new test centre at the premises of DLR in Bremen and an integration lab both classified as bio safety level 1 were a major benefit in the integration and testing activities.

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