

## **Dealing with the ageing Fluid Science Laboratory facility: the successful integrated approach for payload development and operations preparations for FSL mission extension on the ISS**

**Denis Van Hoof<sup>a\*</sup>, Carla Jacobs<sup>b</sup>, Yenn Arijs<sup>c</sup>**

<sup>a</sup> *Space Applications Services SA/NV, Belgium, denis.van.hoof@spaceapplications.com*

<sup>b</sup> *Space Applications Services SA/NV, Belgium, carla.jacobs@spaceapplications.com*

<sup>c</sup> *BIRA-IASB, Belgium, yenn.arijs@busoc.be*

\* Corresponding Author

### **Abstract**

A fast development and operations readiness process for the European Space Agency (ESA) experiments on-board the International Space Station (ISS) allows for an increase in utilisation and a more efficient mission planning. The Fluid Science Laboratory (FSL) installed in the European Columbus Module of the ISS is a multi-user facility to study the physics of phenomena in fluids (such as heat transfer, boiling, foaming and foam coarsening, emulsification and behaviour of granular material) in the absence of gravity. In order to implement several new scientific experiments and also to re-establish and enhance failed science data storage and transmission functionality of the aging facility, ESA initiated the refurbishment of the FSL infrastructure on ground and in orbit in 2016, with a specific project activity called 'FSL-ON'. The main objective of the FSL-ON project setup is to maximize the scientific and operational success of the on-orbit activities of FSL, which are led by the Belgian User Support and Operations Center (B.USOC). This ESA project, with industrial partners Airbus, Thales-Alenia and Space Application Services, manages all related hardware and software development, integration and test activities, and coordinates the scientific and operational preparation and implementation activities in close coordination with the B.USOC.

One of the main features of FSL-ON is to put a strong focus on an extensive testing programme in support of development and operations preparation, allowing a highly integrated and overlapping implementation of three mutually different scientific campaigns.

By conducting all critical stages at the operationally representative setup with the FSL Engineering Model located at B.USOC premises, this allowed a highly integrated development, operations preparation and scientific operations approach to almost occur in parallel. At the same time, the resulting cross-functional understanding of the complex interactions of ground segment operations, facility capabilities and experiment scientific demands fostered a high mission maturity and effective handling of anomalies.

In contrast to the typical Engineering Model / Flight Model approach where most testing is done with Ground Support Equipment (GSE) at the developer's premises and a formal delivery of the models to ESA initiates the operations preparation activities, the final phases of the development were organized hand in hand with real-time flight and ground operations preparations following a very tight time schedule.

This integrated strategy allowed the early introduction of the Operations Engineering team to be actively included in the tests and to initiate the preparation of ground segment and operations quasi in parallel. By doing so, operational feedback and inputs could be introduced into the ongoing development and vice versa. In turn, this introduced strong challenges related to the sharing of responsibilities, coping with different approaches in development and operations, as well as very tight and dynamic schedules on all levels. Building on the success of the initial part of the FSL-ON project, additional experiments and additional flights for the initial experiments could be proposed resulting in the successful execution of four distinct experiments and 11 science campaigns over 6 years and counting.

Now, with the end of the FSL-ON project in sight, this paper presents the project achievements after a brief introduction of the FSL Facility, including a description of the experiments and hardware developments as well as the approach that was envisaged for the project. It will outline the operations preparations and describe the coordination between the many interfaces. As a conclusion, the paper will provide the lessons learned of this unique approach including recommendations for future similar projects.

**Keywords:** Fluid Science Laboratory, mission extension, European Space Agency, payload development and operations preparation, integrated approach

## 1. Introduction

### 1.1. The origin

FSL is a multi-user modular facility designed for conducting fluid science experiments in the microgravity environment of space. It consists of different modules and equipment functionally and operationally integrated into one International Standard Payload Rack (ISPR) location on the European Columbus Orbital Facility (COF) attached to the ISS [1,2]. It was part of the final Columbus programme as it was approved for funding by ESA in 1995 and would be launched together with the Columbus laboratory as one of its core microgravity facilities [3]. Studies and requirements definition by potential users from the science community started already in the 80s in a context of prospects of affordable and frequent access to Low Earth Orbit (LEO), with resupply flights every few weeks or so. This led to the design and development of a highly complex and capable space facility at the edge of technological sophistication of the 90s, allowing various very different fluid science experiments to be performed in interchangeable dedicated Experiment Containers (EC) and continuous upgrades of the system capabilities throughout its operational life-time that was estimated at 10 years.

A microgravity science research announcement of opportunity of ESA in the year 2000 mentioned 4 different ECs that were considered from the start [4]:

- FSL Experiment Container for investigations on Aqueous Foams
- FSL Experiment Container for investigations on Emulsions
- FSL Experiment Container for investigations on Convection and Interfacial Mass Exchange
- FSL Experiment Container for investigations on Fluid Motions in Spherical Gaps

### 1.2. The FSL facility

The EC is at the core of the FSL facility, containing the fluid cell and all dedicated equipment for the experiment [1]. It features windows to allow an optical path for the diagnostic equipment of FSL and it fits in a drawer positioning it amidst the optical elements to allow for scientific imagery. The optical elements comprised highly versatile sets of light and laser sources, actuated mirrors, cameras, filter wheels, allowing for many optical diagnostics including velocimetry with light/laser sheets and several types of interferometry. All in all, 88 independent optical modes could be automatically configured depending on the requirements of the experiment. The EC and optical elements are structurally mounted on the Facility Core Element (FCE) which can be isolated passively from the rest of the facility and Columbus through rubber brackets or even free floating, with active microgravity isolation provided by the Microgravity Vibration Isolation System (MVIS) through sets of actuators and accelerometers for force feedback. MVIS was a late addition from the Canadian Space Agency (CSA) to the FSL facility and was an experimental active microgravity control system. Further on, FSL provides power at several voltage levels and water cooling to the EC. The Rack Interface Controller (RIC) provides 1 Hz telemetry and telecommand capabilities, powerful thermo-electrical controllers (TEC) and stepper motor boards in addition to what can already be accommodated inside the EC with the limited power provided to it. Housekeeping and low-rate science data of the experiment is handled by the RIC and forwarded for downlink to the ground. High-rate science data (HRD) and images are acquired by the Video Management Unit (VMU) which also controls the cameras. The VMU is able to stream the acquired data in realtime to Ground and as well record science data streams onto a recorder which can then be played back to the Ground at the appropriate time. It is connected by fibre optics in a one-way manner to the Columbus High-Rate Multiplexer (HRM) and can reach data transfer rates of up to 32 Mbps. The VMU recorder can also be used as a staging point for large MVIS data files produced by the MVIS controllers and microgravity sensors for downlink at an appropriate time. Finally, the VMU also acquires measurements from the Microgravity Measurement Assembly, a set of accelerometers (independent from the MVIS ones) mounted onto the FCE structure for microgravity assessment in the vicinity of the EC.

### 1.3. The FSL operational setup

FSL is designed to minimise the needed crew time, as such, nominally the crew is not needed to operate the rack and the role of the crew limits itself to hardware installation (e.g. EC or sample swaps), routine maintenance or exceptional last resort troubleshooting activities. The telescience approach is the baseline for remote monitoring and commanding of the FSL facility and the EC functions. The FSL RIC allows to store and interpret/run dedicated software sequences called Experiment Procedures (EP). Atomic commands are grouped and timed to perform higher

level functions for the experiment or FSL subsystem. The EP can also monitor experiment or FSL housekeeping low-rate data parameters through the definition of monitoring variables and use it as conditional statements in functions. During commissioning phases or experiment parameter fine tuning, the ground operator can take direct control in a step-by-step approach based on real time monitoring of the telemetry and near-real time analysis or processing of HRD science data. For the routine phases of a science campaign, the EP can make use of a Parameter Table containing lines of instructions that can be executed by the EP in an automated way e.g. to perform sequences of science runs with each time slightly updated conditions and scan through the intended experiment parameter space, or to play back a set of VMU science records from previous runs until an input is required from the operator.

ESA opted to set up a decentralised concept for the support of ground operations of the European ISS segment [5], with the Columbus Control Centre (Col-CC) in charge of the laboratory support systems and operations and interface to the International Partners on one side and distributed European national User Support and Operations Centres (USOC) for the operations of the ESA scientific facilities and resource coordination with Col-CC on the other side.

A USOC can be assigned as Facility Support Centre (FSC) for science operations at experiment level or both and acts as an interface for the scientific user. The USOC is responsible for defining an experiment operational concept, prepare and validate operational products, plan science activities and coordinate resources needed from Col-CC. A USOC hosts the Engineering Model of the facility, in support of science campaign preparation, operational product validation, baseline science runs in 1G when applicable and for system or sub-system troubleshooting purposes when needed during on-board operations. During a science campaign, members from the science team of an experiment can follow operations remotely from their premises through a so-called User Home Base (UHB) for real time coordination and steer scientific decisions remotely or they can be accommodated to follow operations as a visitor at the USOC.

#### 1.4. The first 6.5 years of FSL operations

A first batch of two FSL ECs was being developed initially, and a third EC was later also being assessed:

- Geophysical Fluid Flow under Microgravity (Geoflow) to study thermal convection in the gap between two concentric rotating spheres to model Earth's liquid core
- Fundamental and Applied Studies on Emulsion Stability (FASES) to investigate the stability of emulsions
- Convection and Interfacial Mass Exchange (CIMEX) to focus mainly on flows and instabilities with evaporation

Only the Geoflow EC Flight Model was completed in time for launch with Columbus and FSL in February 2008.

At the start of FSL operations in Columbus, the FRC for FSL was MARS USOC in Naples, Italy and the FSC for the Geoflow EC was E-USOC in Madrid, Spain. After launch, the FSL facility was relocated to its final O1 (first overhead position from the hatch) location in the Columbus laboratory, a few months were needed to commission the rack, troubleshoot some initial issues, make some repairs and perform some preparation tests for the Geoflow experiment.

The first Geoflow science campaign (Geoflow-1) took place from August 2008 till January 2009. After that, the FSL was used from February 2009 till June 2009 for the acquisition of microgravity measurement assembly (MMA) data in support of the Protein Crystallisation Diagnostics Facility (PCDF) in the European Drawer Rack (EDR), located in the F1 (first forward position from the hatch) of Columbus.

Then MVIS has been commissioned [6], with a first phase in July 2009 and phase 2 in January 2010 and January 2011. A third phase was still foreseen but could not be planned in yet. Several optical checkout tests and troubleshooting were also performed in between.

In the meantime, the Geoflow EC had been returned to ground, refurbished with a different liquid and launched again to the ISS. The Geoflow-2A campaign took place from March 2011 till May 2012 [2], with a break in operations from Jul 2011 till the end of September 2011, due to issues with the VMU and with the post-processing of MMA data on ground. Troubleshooting was needed to understand the issues and it resulted in the definition of VMU Hybrid Configuration where the tape recorder would be descoped and instead of recording on tapes for download, all recorded data would be downlinked instead. For this, the storage capacity on VMU hard drives was increased ten-fold (to about 300 GB). After testing and validation of the VMU Hybrid Configuration and assessing options for the MMA issue, it was decided to acquire microgravity measurements with MVIS instead and the Geoflow-2A campaign could be started again.

After the Geoflow-2A campaign was concluded, the months between July and December 2012 were dedicated to more troubleshooting of the MMA issue and the testing and validation of a solution implemented in an application

software update of the Central Experiment Module (CEM) dealing with the forwarding of the MMA data to the RIC. Also the VMU needed more fixing.

The period from December 2012 till April 2013 was dedicated to one more science campaign with the Geoflow EC: Geoflow-2B. From March 2013, the VMU finally lost the capability to record on its disks, having an important impact on the operational concept of the science runs (with the science data needing to be fully downlinked in realtime).

Finally, from June 2013, operations could be started with the FASES EC. Soon it was realised that a temperature control system was not working properly, having a big impact on which types of samples could be processed and limiting the science objectives that could be achieved. After a lot of troubleshooting and tests, some science runs could be performed, but along the way the transmission of HRD with the VMU became more and more erratic resulting in many corrupted science data products on the ground. Further attempts to operate FSL with FASES were abandoned in June 2014 and the FASES EC was removed from FSL for return to Earth.

#### 1.5. Main issues impacting FSL operations at the time of handover of operations to B.USOC

From the start of FSL operations, several issues were experienced with the FSL facility:

- The EC would suffer occasionally from spurious reboots, losing the on-going setpoint from a science run and interrupting on-going operations
- The communication on the serial line between the EC and the FSL RIC would sometimes be lost, losing the telecommanding capability of the EC and also freezing the EC telemetry within the broader FSL telemetry as it was received on ground. Since the TEC system of FSL would use values of temperature sensors from the EC for its temperature control, an outdated and frozen value could in some cases lead to a temperature run away effect.
- A safing mechanism of the TEC driver boards would trip sometimes for no apparent reason, turning off the components providing power to the temperature control devices in the EC.
- Due to the way that the MMA data would be transferred from the CEM to the VMU over the milbus with the mil 1553 protocol, it seemed that the processing of the data on ground was negatively impacted and the data could not be interpreted with the needed temporal accuracy. This issue has been solved already in the second half of 2012 through a CEM software update.
- The VMU Digital Line Tape (DLT) recorder could not be made to work, making operators have to rely on the limited disk space of the VMU recorder (about 30 GB). The upgrade of the VMU disk space to about 300 GB in 2011 improved the situation.

In the course of the years, some issues appeared and would worsen over time:

- At the start of any operational session with FSL, after powering the facility, the operator has to cycle through operational modes to activate the various subsystems. After activation of the CEM and the Optical Diagnostics Module (ODM), an automatic test would be performed to check out and properly initialise all the optical components and diagnostic systems. This automatic test would take around 45 minutes and once complete allowed to set the required optical mode used in the science campaign. After a while, errors started to appear in the telemetry for some components and if the faulty component was needed for the intended optical mode, the automatic test would have to be repeated, sometimes multiple times.
- Several problems occurred with the hard drives of the VMU recorder, needing crew to replace disks and to install additional filters on the data connectors. When issues occurred, the operator could initially regain functionality after performing a number of VMU reboots, but ultimately the recording functionality of the VMU was definitely lost in March 2013.
- Over time, more and more corruption seemed to impact science data transmitted to ground over the HRD channel. This corruption originated in a degrading chip inside the VMU converting the electrical signal in an optical one to transmit over the fibre optics connection to the Columbus lab data systems. For a while stable data transfer could be regained successfully by rebooting the VMU, but operations were halted in 2014 when the periods of stable communications decreased and made effective operations unpractical.

It was in this context that the news came that the MARS USOC would close down and that FRC duties for FSL would be taken over by the B.USOC.

## 1.6. FSL operations under B.USOC responsibility before the FSL-ON phase

Following the transfer of the Fluid Science Laboratory (FSL) [7] from the MARS USOC to the Belgian User Support and Operations Centre (B.USOC) and once a working ground segment was set up, the first activities could start in 2015 to troubleshoot and to assess the HRD transmission issues. An application software update of the CEM was installed in order to address the errors encountered during the Automatic Test. Through a VMU software update, functionality was also added to reset the TAXI chip by telecommand, hoping that this would recover the quality of transmission when the HRD transmission issues would occur. It was then assessed that two activities that were in the pipeline could actually go ahead:

- The MVIS commissioning phase 3 (featuring the characterisation and activation of the microgravity isolation system with an actual EC installed in the CEM drawer).
- The next Geoflow science campaign (2C) using a new development to work around the HRD issues (using an analogue S-video output connector on the VMU and routing the signal to an analogue to digital video convertor attached to a laptop controlled from the ground through KU-IP services that were in a demonstration phase at that time (Multi-Purpose Computer and Communication (MPCC) demo 2)

While those two activities were being prepared by the B.USOC Team, significant efforts also had to be dedicated to the development of the FSL ground segment at B.USOC to support the FSL flight operations, moving from the legacy and partially proprietary systems from the MARS USOC to customised systems for the B.USOC environment and for the evolution of the generic ground segment used by the USOCs (from local systems to virtualised environment in servers in Col-CC: the Payload Data Centre (PDC)).

Also in parallel, ESA ordered the development of a new Video Management Unit (VMU MkII) for FSL, not only to solve the VMU issues encountered so far, but also to support newer and faster cameras, other sensors and enhance the VMU capabilities (increase the number of channels, recording data rates and recording capacity and providing on-board data processing capabilities). For this development several tests and fit checks were performed at B.USOC on the FSL EM with the support of B.USOC operators.

Finally, an assessment was on-going about the feasibility of the completion of the development of the last batch#1 EC still being worked on: CIMEX. A couple of tests were performed, one in December 2014 to verify the special needs for a combination of optical modes to be used concurrently and a complete interface test with the proto-flight model of CIMEX (including the EC and an additional Experiment Extension Box) on the FSL EM in January 2016.

Due to last minute safety related discussions, the MVIS commissioning phase 3 had to be delayed and so the Geoflow 2C science campaign was conducted first, lasting from November 2016 till February 2017. For this campaign, the Spanish E-USOC acted as FSC, in charge of the EC operations and B.USOC as FSL FRC would operate at FSL system level and also manage the VMU work-around with remote control of the MPCC laptop to acquire the videos coming from the VMU S-video output. The setup actually allowed the Geoflow science team to focus more on runs with higher camera frame rate that were only rarely performed in previous campaigns due to the limited VMU recorder space [8].

The successful MVIS commissioning phase 3 campaign was finally conducted from October 2017 till November 2017 with the on-site support of the Canadian Space Agency (CSA) representative and the MVIS payload developer.

## 2. Context

Following the transfer of the Fluid Science Laboratory (FSL) [7] from the MARS USOC to the Belgian User Support and Operations Centre (B.USOC), the first mission operated by B.USOC was GeoFlow-2C. Due to anomalies in FSL's high-rate data link, the mission had to be conducted through an alternative approach (see section 1.6), which significantly reduced the downlink speed and consequently prolonged the mission duration.

These limitations would be addressed by the new Video Management Unit (VMU MkII), which was under development since 2014. The integration of this hardware necessitated an update to the FSL RIC Application Software (ASW). This updated software aimed not only to resolve existing anomalies but also to introduce enhancements in preparation for upcoming Experiment Containers. At that time, two development efforts were already underway for the next generation of science experiments: the Soft Matter Dynamics (SMD) Experiment Container with FOAM-C (Foam Coarsening) sample cells [9] and the MultiScale Boiling Experiment Container [10]. Each of these four initiatives—the VMU MkII, updated FSL software, and the two new Experiment Containers—implied substantial changes to FSL's operational concept. However, they were being developed independently, each with its own hardware and software verification and validation campaign, and without an integrated system-level approach.

In response, a joint analysis was carried out in 2016 by ESA, Airbus Defence and Space (DS), and Thales Alenia Space Italy to assess the ongoing projects and identify potential risks, especially given their alignment with the overall projects critical paths. This assessment revealed gaps in hardware and software needed to fully meet the mission objectives of future FSL operations involving VMU MkII and the new Experiment Containers.

As a result, the FSL-ON project was initiated to serve as an overarching master project that would unify these parallel developments [11]. Its primary goal was to ensure compatibility and interface integration across FSL, the VMU MkII, and the payloads. Led by Airbus DS, with ESA acting as overall Project Manager, the project included Thales Alenia Space Italy and Space Applications Services NV/SA as subcontractors. FSL-ON was tasked with identifying all additional interface requirements and necessary developments as well as updates in supporting documentation. Beyond overseeing individual project-level verification efforts, it also established a consolidated testing schedule, including integrated verification and validation of the final system configuration within the FSL facility using the FSL Engineering Model.

From its kick-off in 2017, FSL-ON emphasized close coordination among all stakeholders, including B.USOC, which was responsible for hosting the FSL Engineering Model and preparing and executing operations for all FSL-related on-orbit activities.

### 3. Method and implementation

Faced with important strategic choices in terms of European microgravity research on the ISS (including whether or not to cancel all future FSL operations in the view of the technical issues), a team at ESA and Airbus pieced together the FSL-ON project aiming at ensuring a successful future of science campaigns on the FSL facility [11].

To address the technical issues that had impacted the facility in the first 6.5 years of operations, aging parts of FSL were descope or replaced:

- All optical elements and optical modes provided by the ODM and CEM were descope and passivated, only keeping the CEM active to provide the microgravity measurements of the MMA sensors.
- The old VMU was to be replaced by the newly developed VMU MkII based mostly on Commercial Off The Shelf (COTS) components and a modular design that allowed for elements to be easily replaceable on-board by crew in case of failure or upgrade needs.

This approach would greatly reduce the risk of long delays due to troublesome or failed components of the facility. It also meant that the ASW of FSL had to be updated to accommodate all these changes.

An important consequence of this new setup was that the future ECs could only rely on sensors installed inside the container and internal cameras controlled by the VMU MkII, without any of the previously available optical modes. Hence the batch#1 EC CIMEX had to be descope from the FSL-ON project as well as another experiment called Thermal Platform. The full focus was set on the batch#2 ECs already in development: SMD and Multiscale Boiling.

To maximise the use of the remaining time FSL would still have on the ISS, an aggressive schedule was set up to finish the development and verification of the FSL ASW, VMU MkII, SMD EC and Multiscale Boiling EC, all in parallel by the respective teams and industrial contractors. Thales Alenia Space Italy (TAS-I) was in charge of the update of the ASW, Space Applications Services was in charge of the VMU MkII and Airbus Friedrichshafen was in charge of the two ECs. Airbus would also be in charge as a prime contractor of the coordination of the FSL-ON project at industrial level. In this way, it was insured that responsibilities would be clearly established, that there would be a common overall schedule and that the environment was created to work with an enhanced integrated approach in terms of teams and schedule. Furthermore, the project would follow the paradigm shift at ESA of keeping the industrial developer accountable through milestones covering not only the flight acceptance before the start of a mission (as was the case early on during the Columbus module utilisation), but also throughout the mission with an acceptance review milestone after on-board commissioning and a final mission closeout review.

A big enabler for the success of the scientific missions during the FSL-ON phase, is the VMU MkII. Other than its modular design and easy serviceability with CompactPCI boards accessible to the crew, it features 2TB of recorder space and 6 parallel channels. Those channels can be connected to scientific diagnostic sources and can be recorded on one side and multiplexed into a HRD data stream forwarded to the Columbus systems over fibre optics on the other side for downlink to ground. They can also be connected to the recorder to downlink recorded data. It supports scientific diagnostic sources such as cameras with a gigE Vision interface and Genicam control standard, cameras using Low-Voltage Differential Signaling (LVDS) digital video data transmission standard, sensors using the Universal Serial Bus (USB) 2.0 standard, serial line communication protocols for science data transfer and a milbus interface for when MMA or MVIS data has to be acquired. Field-Programmable Gate Array (FPGA) based synchronisation units can provide very precise triggers to the scientific sensors and provide image timestamping in the order of nanoseconds

precision. Furthermore, the VMU MkII facility control logic also provides multiple instances of a Tool Command Language (TCL) interpreter allowing to use scripting for task automation and even off-loading of processing power demanding tasks from the TCL interpreter running the science EP on the aging FSL RIC processor by synchronising and taking over complex VMU MkII tasks from the EP. Finally, the VMU MkII also features the possibility to provide on-board science data processing in order to reduce the data volume before downlink. Several models of the VMU MkII were delivered, including the Flight Model and Engineering model, a Training Model for crew training, a Development Model and a functional Video Ground Segment Equipment (VGSE) to connect stand alone with the ECs at Airbus during development phase.

One of the batch#2 FSL ECs in development was the Multiscale Boiling experiment [10], addressing two-phase heat transfer during boiling processes. The EC contained a boiling cell with a heated substrate where bubbles were selectively ignited using a short laser pulse. The experiment investigated the undisturbed growth of the bubbles, the influence of a shear flow, and the influence of an electric field within the same test facility. The scientific diagnostics were performed by a gigE high-speed black and white camera, an LVDS high-speed infrared camera and in-situ high-speed science measurements (pressure, thermocouples, thermistors) transferred over a serial line. Both an Engineering Model and a Flight Model of the Multiscale Boiling EC were delivered.

The other EC in development was the SMD [9], which could also be considered as a facility dedicated to different forms of soft matter, since the EC can host several types of sample cells contained in standard format Sample Cell Units (SCU). These SCUs are installed on a moving tray with 5 SCU positions. Each sample cell on the moving tray can be positioned in a diagnostics position, where optical paths are converging for:

- a gigE black and white overview camera looking top down at the observation volume of the sample cell through a scanning microscope,
- a laser to illuminate the material in the observation volume,
- a gigE high-speed line camera to record multi-speckle backscattered laser light
- 2 Avalanche Photo Diode detectors (so-called correctors) using the USB standard, one for laser light transmitted through the observed volume and one for backscattered laser light from the observed volume.

These last 2 sensors recording transmission and backscattered signals are allowing to use Diffusing Wave Spectroscopy (DWS), Diffuse Transmission Spectroscopy (DTS) and Time-Resolved Correlation spectroscopy (TRC). One type of sample cells would consist of a tube of transparent material containing a piston connected to a magnetic element. This piston could be actuated up and down in the sample cell at a settable frequency by varying electric fields produced by electromagnetic coils in the diagnostic position externally to the sample cell. Four such sample cells would fit into one SCU. These sample cells are used for the FOAM-C (Foam Coarsening) experiments studying the evolution in time of wet foams and for the PASTA (particle stabilized emulsions) experiments studying evolution in time of emulsions. This type of sample is also foreseen to be used for future experiments. The other type of sample cells consists of a transparent volume containing granular material which could be varied in size by a piston connected to a stepper motor. The piston was also used to compress the material. Inside the volume, piezoelectric elements are positioned that can be used to inject vibrational energy in the material contained in the volume. The electronics needed for the actuation and commanding of the piston motor and the piezoelectric elements had to be contained in the SCU such that only one sample can be housed in such an SCU. These samples are using the electrical interface with the moving tray of SMD to provide power and communications to its electronics. The experiments using these sample cells were CompGran (Compacted Granular), a collaboration with the German Aerospace Center (DLR) to study compaction phenomena in dense granular media. Both an Engineering Model and a Flight Model of the SMD EC and of the various sample cells were delivered.

In parallel with this, the operations and ground controller teams at B.USOC had to prepare all operational products related to the upgrades to FSL and to the science mission campaigns as well as develop the ground segment to support all operations with the upgraded system and subsequent science missions. A considerable part of the effort here was dedicated to the management of the science data coming in as HRD through a different path as the housekeeping telemetry of the FSL facility and the EC, and the challenge presented by the integration of realtime images from the experiment into the display environment used for the operations and control of the experiments. The tool that was developed for this was the HRD broker for FSL operations [12]. Also the support to the science teams through User Home Base connection to B.USOC was further developed for realtime monitoring of their science experiments when needed and further dissemination of the consolidated science products.

All these developments needed to be carefully planned and coordinated also due to interdependencies between the projects. The VMU MkII project would e.g. need mature interface information about the science sensors of the ECs and from the EC side there was the need for a mature enough VMU MkII to be able to acquire science data during integrated tests. During the entire duration of the FSL-ON project, bi-weekly teleconferences between the industrial

partners, ESA (comprising project management, payload integration management, technical officer and science officer) and B.USOC. For the preparation and execution of the science missions, regular teleconferences were also held with the science teams. The resource that proved to be a natural bottleneck was the FSL EM at B.USOC. Indeed at some point or another, every development, be it ASW, engineering model or flight model of the VMU MkII and the ECs would have to be integrated and tested with the closest replication of the operational environment they would work with on-orbit: the FSL EM. The FSL EM is also the only facility on ground running the same unique and little documented TCL interpreter as the one running on the FSL FM RIC, so all the EP development for new facilities and science experiments had to be extensively validated on the FSL EM. To manage the presence and activities of the external teams at B.USOC with the FSL EM, a specific service level agreement was established between B.USOC and Airbus. Whenever needed and possible, the opportunity was seized to work with integrated teams during development and validation tests in order to maximise knowledge transfer from developer teams and science teams to the operator team which will ultimately have to operate the systems and monitor the science runs routinely. This also ensured to allow the science team to give feedback about how the intended science runs were implemented based on science data produced in a representative way and also the operators to give feedback as a user in the loop, making it possible to still implement features that would increase the efficiency of operations. Also the fact that teams at the different entities would remain fixed or at least key personnel would remain available has greatly contributed to a pleasant and productive atmosphere throughout the project. Finally, the project made sure that the overall schedule would capitalise on opportunities to test as much as possible flight hardware from the different entities together on the FSL EM before flight. This made sure that the VMU MkII FM was verified to work together successfully with the SMD EC FM and the multiscale boiling EC FM, including power and video harnesses.

#### 4. Results

The table below gives an overview of the main preparation campaigns on the FSL EM and the on-board science campaigns on the FSL FM for the different facilities and science payloads developed and utilised during the FSL-ON project period.

Table 1. Overview of main activities both on FSL EM and FSL FM related to the FSL-ON project

Activity	project/model	FSL EM	FSL FM	Notes
VMU MkII mechanical fit check	VMU2 EM	24.02.2016		
VMU MkII fit check and electrical tests	VMU2 EM	01.08.2016-03.08.2016		
Geoflow 2C Science Campaign	Geoflow FM+VMU1 FM		21.11.2016-23.02.2017	
ASW Tests	ASW+VMU2 EM	14.12.2016-16.12.2016		
MultiScale Boiling DevT#1	MultiScale Boiling EM+VMU2 EM	10.01.2017-12.01-2017		
VMU MkII development test	VMU2 EM	20.02.2017-24.02.2017		
SMD DevT#1	SMD EM	13.03.2017-17.03.2017		
VMU MkII and ASW test	ASW+VMU2 EM	04.05.2017-12.05.2017		

Activity	project/model	FSL EM	FSL FM	Notes
SMD DevT#2	SMD EM+VMU2 EM	06.06.2017- 15.06.2017		
SMD DevT#3	SMD EM+VMU2 EM	07.07.2017- 20.07.2017		
ASW Test	ASW	27.07.2017		
SMD DevT#4	SMD FM+VMU2 EM	31.07.2017- 09.08.2017		testing with CompGran EM and FOAM-C EM samples
VMU MkII integration test	VMU2 FM	31.08.2017- 06.09.2017		
SMD DevT#5	SMD FM+VMU2 FM	28.09.2017- 05.10.2017		
ASW regression test	ASW+VMU2 FM	16.10.2017- 21.10.2017		testing with CompGran EM and FOAM-C EM samples
VMU MkII integration test	ASW+VMU2 FM	23.10.2017		
ASW development	ASW+VMU2 FM	24.10.2017- 26.10.2017		
MVIS Commissioning Phase 3	FSL FM+MVIS FM+VMU1 FM		30.10.2017- 10.11.2017	The large engineering data files recorded on the MVIS HDDs to be downlinked at later stage when HRD link re-established
SMD DevT#6	SMD EM+VMU2 EM	06.11.2017- 17.11.2017		
MultiScale Boiling DevT#2	MultiScale Boiling EM+VMU2 EM	20.11.2017- 23.11.2017		
VMU-MkII command tests	VMU2 EM	27.11.2017- 08.12.2017		
ASW regression test	ASW+VMU2 EM	12.12.2017- 15.12.2017		
SMD VerT	SMD FM+VMU2 EM	18.12.2017- 27.12.2017		
SMD MisT#1 (robustness)	SMD EM+VMU2 EM	25.01.2018- 29.01.2018		

Activity	project/model	FSL EM	FSL FM	Notes
SMD MisT#2 (experiment parameter)	SMD FM+VMU2 EM	30.01.2018-02.02.2018		use of CompGran FM samples
MultiScale Boiling DevT#3	MultiScale Boiling FM+VMU2 FM	12.02.2018-16.02-2018		
SMD MisT#3 (EST1)	SMD FM+VMU2 FM	02.03.2018-08.03.2018		use of CompGran EM sample
MultiScale Boiling DevT#4	MultiScale Boiling FM+VMU2 FM	12.03.2018-16.03-2018		
SMD MisT#3 (EST2)	SMD EM+VMU2 EM	12.06.2018-27.06.2018		
FSL ASW update	FSL FM+ASW		25.06.2018	
FOAM-C DevT	SMD EM+VMU2 EM	02.07.2018-10.07-2018		use of FOAM-C EM samples
VMU-MkII on-board commissioning	FSL FM+VMU2 FM		12.07.2018-13.07.2018	
SMD FM on-board commissioning	VMU2 FM+SMD FM		19.07.2018-23.07.2018	
SMD CompGran 1 commiss + science campaign	SMD FM+CompGran FMs		24.07.2018-26.04.2019	
MultiScale Boiling DevT#5	MultiScale Boiling FM+VMU2 EM	25.07.2018-03.08.2018		
FOAM-C Verification test	SMD EM+VMU2 EM+FOAM-C FM	20.08.2018-24.08.2018		
MultiScale Boiling VerT	MultiScale Boiling FM_VMU2 EM	18.09.2018-27.09.2018		including new FM power harness
FOAM-C EST	SMD EM+FOAM-C FMs	22.10.2018-26.10.2018		
MultiScale Boiling MisT#1 (robustness)	MultiScale Boiling FM+VMU2 EM	05.11.2018-23.11.2018		
MultiScale Boiling MisT#2 (exp parameter)	MultiScale Boiling FM+VMU2 EM	11.03.2019-20.03.2019		
MultiScale Boiling MisT#3 (EST)	MultiScale Boiling EM+VMU2 EM	13.05.2019-28.05.2019		
MultiScale Boiling mini science EST	MultiScale Boiling EM+VMU2 EM	08.07.2019-23.07.2019		

Activity	project/model	FSL EM	FSL FM	Notes
MultiScale Boiling comm and science campaign	MultiScale Boiling FM+VMU2 FM		05.09.2019-28.02.2020	Use of MVIS for a set of reference runs for comparison
FOAM-C confidence test	SMD EM+FOAM-C EM	14.10.2019-24.10.2019		
FOAM-C science campaign	SMD EM+FOAM-C FMs	12.11.2019-25.11.2019		
FOAM-C science commissioning test	SMD EM+FOAM-C EM	26.11.2019-20.12.2019		
MultiScale Boiling post-mission test	MultiScale Boiling EM+VMU2 EM	02.03.2020-2.03.2020		Characterise dissipation laser light pulse on substrate heater
FOAM-C commissioning and science campaign	SMD FM+FOAM-C FMs		09.03.2020-13.10.2020	
CompGran 2 integrated test	SMD EM+CompGran FM	06.07.2020-11.07.2020		
MultiScale Boiling -X Mission Readiness Test	MultiScale Boiling EM+VMU2 EM	06.10.2020-09.10.2020		
MultiScale Boiling -X science campaign	MultiScale Boiling FM+VMU2 FM		15.10.2020-13.01.2021	
CompGran 2 commiss and science campaign	SMD FM+CompGran FMs		26.01.2021-30.05.2021	
CompGran 2 science protocol validation	SMD EM+CompGran EM	04.02.2021-12.02.2021		
FOAM-C 2 Mission Readiness Test	SMD EM+FOAM-C FMs	24.03.2021-31.03.2021		
FOAM-C 2 commissioning and science campaign	SMD FM+FOAM-C FMs		11.06.2021-30.09.2021	Science campaign aborted due to broken laser on SMD FM
PASTA&FOAM-C 3 Mission Readiness Test	SMD EM+FOAM-C & PASTA FMs	20.10.2021-27.10.2021		
Ruggedised SMD EM Mission Readiness Test	SMD EM <sub>r</sub> +FOAM-C & PASTA FMs	16.12.2021-22.12.2021		
PASTA commissioning and science campaign	SMD EM <sub>r</sub> +PASTA FMs		28.02.2022-10.08.2022	Performed with the ruggedised SMD EM
FOAM-C 3 commissioning and science campaign	SMD EM <sub>r</sub> +FOAM-C FMs		17.08.2022-13.02.2023	Performed with the ruggedised SMD EM



impacted subsystem to an external power supply or another internal ESEM board outlet. There was also the failure of the CEM that was then replaced by a CEM milbus data emulator. All these workarounds increased manual intervention by the operator during activation and mode changes of FSL and necessitated a specific ASW for the EM as well as a selection flag in the EP and handling of it to specify whether it is working with the FSL EM or FM. The prompt reaction and implementation of the workarounds allowed to minimise delays in the very tight schedule.

Each development, be it hardware or software, must submit the extensive paperwork in order to be allowed to fly to the ISS and be installed in the Columbus laboratory. This paperwork will be reviewed and validated in the Flight Acceptance Review as part of the Certification of Flight Readiness. In the early years of utilisation of Columbus, the payload developer's responsibility would be released after FAR and usually another engineering support service contract would then be set up to follow-up in case of need, but in practice key personnel would be reassigned and more difficult to reach. The approach followed by the FSL-ON project was to have a dedicated set of milestones for the project in parallel to the FAR, particularly spanning the period of time after delivery and launch until the end of on-board experiment campaign. Next to the FAR, the project would foresee the Acceptance Review 1 (AR-1) after all ground testing and operational tests were completed successfully, AR-2 after completion of the on-board commissioning of the entity and then after mission completion still a mission closeout review. This has facilitated the support of the engineering team and has ensured the availability of the right experts along the way.

Finally, a summary of the performed science campaigns (for dates and duration, refer to the overview table):

- With the SMD EC:
  - o With CompGran sample cells:
    - CG-1 (first experiment under FSL-ON, received several extensions to explore more science protocols and making use of the available time after delays for FOAM-C due to sample tube material issues, it was followed by MultiScale Boiling).
    - CG-2 (after RUBI-X, additional protocols)
    - CG-3 (after PASTA-2&FC-4, new science team implementing new science protocols and an updated measurement approach after analysis of the first 2 mission, used the ruggedised SMD EM which then returned to ground after the campaign to be replaced again by the repaired SMD FM)
  - o With the FOAM-C sample cells:
    - FC-1 (third experiment under FSL-ON)
    - FC-2 (after CG-2. FC-2 was aborted early due to the failure along the way of the laser used for most SMD diagnostics, SMD FM needed to be returned to ground for repair)
    - FC-3 (after PASTA-1 and also with the ruggedised SMD EM, performed to complete the missing science runs from FC-2 and added a few new samples)
    - FC-4 (after FC-3. Shared setup with PASTA-2 samples in a mixed mission)
  - o PASTA using the same type of sample cells as FOAM-C:
    - PASTA-1 (first experiment performed with the ruggedised SMD EM launched to replace SMD FM with the laser that broke during FC-2)
    - PASTA-2 (after FC-3. Shared setup with FC-4 samples in a mixed mission)
    - *Planned PASTA-3* (after CG-3, using upgraded sample cells with volume compensator and using the refurbished SMD FM)
- MultiScale Boiling:
  - o Reference mUltiscale Boiling Investigation (RUBI)-1 (second experience under FSL-ON, science objectives impacted by a high-speed infrared camera that failed along the way and an actuator for a movable thermocouple rack not reaching intended positions in microgravity)
  - o RUBI-X (after FC-1, additional campaign proposed as compensation for the first mission's missed objectives to gather more datapoints and expand the range of some scientific parameters setting)

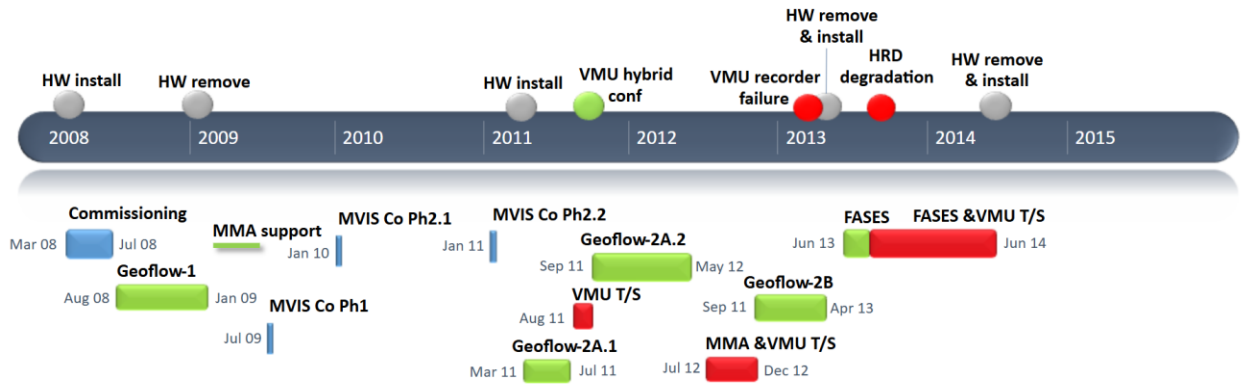


Fig. 1. Graphical overview of the first 6.5 years of FSL operations on ISS

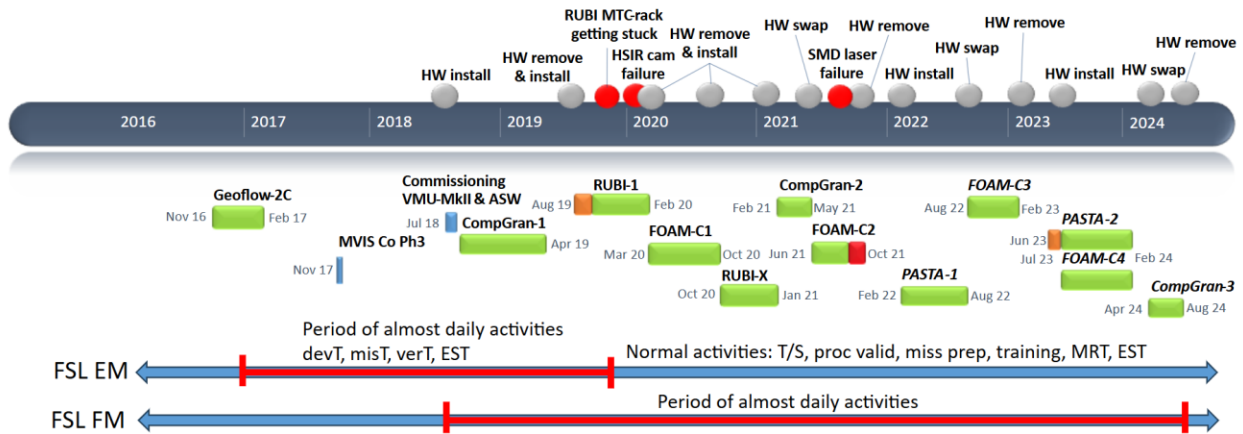


Fig. 2. Graphical overview of the FSL operations on ISS under B.USOC responsibility (on-board activities covered by the FSL-ON project starting mid-2018)

Two science campaigns had to be delayed by about 3 weeks due to anomalies:

- RUBI-1 was delayed due to a wrongly configured power harness
- PASTA-2&FC-4 mixed mission was delayed due to a false over-temperature flag caused by an electrical wiring issue in one of the SCUs.

Both of these anomalies could be analysed, troubleshooted in a reasonable amount of time and work arounds with minimal risk associated to them could be rapidly found and accepted, resulting in no impact on the science objectives, only causing a delay in the start of the campaigns.

During the FC-2 science campaign, the laser of the SMD failed and could not be made to work any more after some troubleshooting activities. Since the laser is indispensable for most of the SMD diagnostics (line camera and correctors), the science campaign had to be aborted. The payload developer and FSL-ON management swiftly came into action to qualify the SMD EM for flight, rebaptised ruggedised SMD EM. Science activities could finally be resumed with the PASTA-1 campaign after a forced break of five months.

Overall, more of the science campaigns could fully complete their objectives during the period under FSL-ON compared to the earlier FSL operations. Issues, failures and troubleshooting were processed faster and more effectively. The VMU MkII proved to be reliable and only 4 recorder hard disks were changed out per standard procedure with on-board spares. Other issues could be solved by simple software updates. The formal process to address on-board anomalies and system failures turned out to also go smoother with the various teams involved in FSL-ON, pre-coordinating inputs to resolution boards and speak as one voice. This integrated approach increased the confidence in the teams and allowed them to work with an increased level of autonomy for the different science campaigns.

## 5. Lessons learned

The FSL-ON project has demonstrated the advantages of working with integrated teams along the lifetime of the FSL experiments performed in the last 6.5 years. For the operator team it allowed to have a firsthand familiarisation with the systems, get hands-on experience from both engineering and scientific teams. It also allowed both the operations and scientific teams to provide users feedback in time to implement useful EP and sample design features that enabled more functionality and science protocols, this has also made operations more efficient.

The operator team has also learned from template and functional parameter tables provided during development and mission preparation and acquired experience for developing parameter tables and a parameter table creation tools in house. The appropriation of parameter table authoring allowed for a continuous upgrading and optimisation of science and data retrieval operations.

Close coordination with the science teams also allowed the operator team to better understand the significance of some optical diagnostics settings of the experiments and to come, in agreement with the scientists, to a fixed configuration that can be applied along the mission as opposed to continuously applying optimization loops.

An integrated team approach also allows authority entities, be it ESA or the Flight Control Team at Col-CC to build confidence towards the project and allow to work with more autonomy and making formal process more efficient. It facilitated the efficient anomaly and failure resolution and led to the attribution of experiment re-flights and even an announcement of opportunity for a last round of new experiments on FSL addressing new scientific aspect of fluid dynamics.

## 6. Conclusions

The FSL-ON approach ensured reliable and effective FSL operations supporting 11 science missions (and counting) with 2 different experiment containers. For the near future, there is one more PASTA campaign coming up and then a science campaign with 4 new types of experiments that came out of the latest announcement of opportunity for FSL SMD experiments. This will allow for FSL operations on ISS well into 2026.

The FSL-ON integrated approach is also applicable for future microgravity science in the post-ISS ecosystem and on future Commercial Low-Earth Orbit Destinations (CLD), maximising utilisation time and parallel development, representative for payloads and facilities that will run on future commercial platforms.

Enabling factors for the successful approach were:

- Early involvement of the operator team in preliminary and critical design review, assisting and supporting assembly, integration and testing as well as verification activities helped a lot to acquire the required expertise
- Flexibility built-in the experiment software allowing maximal experiment control from ground, this was the result of feedback on pre-mission tests
- Mission preparation with integrated team across payload developers, science teams, sponsoring agency and operations team is key to a successful completion of the flight mission.

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