The Fluid Science Laboratory on the ISS Columbus Module Performances and Operations

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Abstract

The Fluid Science Laboratory (FSL) is an element of the ESA Microgravity Facilities for Columbus program, designed to operate on-orbit within the Columbus module of the International Space Station (ISS).The FSL supports scientific microgravity experiments in th0e field of fluid physics; it distributes standard utilities and specific services and retransmits images, science and housekeeping data. Each experiment is hosted into an Experiment Container, designed under the Science Coordinator direction.The FSL is one of the most complex microgravity laboratory never built. Based on multi-user capabilities, integrating very sensitive optical diagnostics, hosting the exchangeable largest experiment containers ever designed, the FSL represents the leading edge of the European technology. The possibility to ground control it totally ensures the independence of the experiment conduction from the on-board crew.In the last years, the FSL Operations Team, composed by Payload Developers and User Support & Operation Centers experts, worked jointly to prepare the flight operations and the related products to operate the facility.This paper intends to illustrate the peculiarity of the FSL, aimed at the exploitation of its scientific performances for future generations of experiments, and the operations activities that are making the laboratory ready to work.

1. The International Space Station

The ISS enables utilization activities in the fields of physical and life sciences, space science, Earth observation and technology innovation. In addition, commercial research and development, novel services (such as education and outreach) and innovative commercial use (such as advertising and broadcasting) are also activities which benefit significantly from use of the capabilities of the Station.

The utilization of the Station by users started with experiments carried out on the Zvezda service module and will continue with facilities and resources becoming increasingly available throughout the rest of the assembly phase. Routine utilization will then be available for at least ten years following completion of assembly.

The ISS offers:

- the capability to perform an experiment or observation program over an extended period of time in weightless conditions
- the capability to perform iterative research on a short timescale through the provision of regular access to and return from the Station
- the provision of access to a significant level of resources
- the permanent presence of crew
- an extensive range of facilities to enable activities in a large number of utilization fields.

2. FSL: a scientific European ISS payload

The FSL facility is a multi-purpose modular facility designed for conducting fluid science experiments in space. Its project is one of the primary efforts of ESA participation to the ISS.

A huge number of European industries and scientists participate to the FSL realization phases, from feasibility to design and utilization.

The FSL is designed to be integrated in the Columbus module for launch and for 10 years on-orbit operation onto the ISS. The FSL consists of different modules and equipment functionally and operationally integrated into one International Standard Payload Rack (ISPR).

Adequate conditioning and routing of the Columbus resources is needed in order to support the following main FSL system functions:

- power conversion and distribution
- thermal control and fire detection
- commanding and monitoring
- communication and data processing, including data & video recording and playback
- services for experiments: stimuli & diagnostics, resources and interfaces

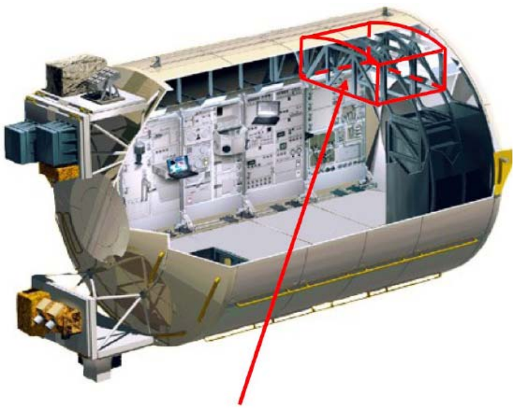

Fig.1 FSL position inside the Columbus module

The FSL can be operated in a fully automatic or semi-automatic mode by the flight crew or remotely controlled from ground in Telescience mode. This essentially resulted in a highly modular concept allowing for continual upgrades of the system capabilities.
On May 2007 the Fluid Science Laboratory, after 9 years of development carried out at Thales Alenia Space Italia, was finally integrated into the Columbus module and is now ready for the launch, currently planned in December 2007.
The FSL Facility Responsible Center (MARS, Napoli, Italy) has the possibility to control totally the laboratory and its experiments from ground.

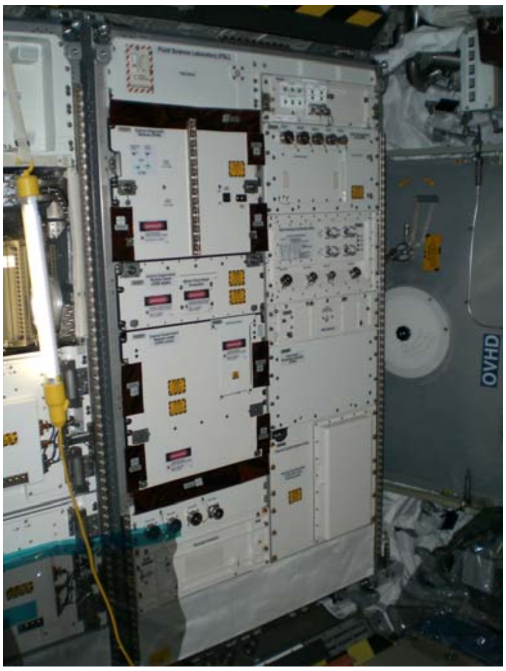

Fig.2 FSL integrated into the Columbus module

3. FSL facility overview

In order to allow the execution of a wide range of experiments, proper stimuli and optical diagnostics are provided by means of a set of interfaces and resources in a well-defined area inside the FSL volume for the accommodation of individual Experiment Container.
The Experiment Container (EC) is the real core of the facility, containing the fluid cell and all the equipment dedicated to the experiment itself. This part is completely experiment dependent; it is conceived by the scientist to include all the hardware and software to support the specific experimental features. The EC is hosted inside, and supported by, in the lower left part of the FSL module, the Central Experiment Module (CEML), providing all the needed interfaces to the EC, and supporting part of the FSL optical equipment and microgravity measurement. The CEML is part of the Facility Core Equipment (FCE).
Other components of the FCE are:

- the Central Experiment module Upper (CEMU), containing other optical equipment, and
- the Optical Diagnostic Module (ODM), supporting optical diagnostics on the fluid cell.

The Master Control Unit (MCU) drives the general management of all the FSL resources.
Experiment images are recorded by various cameras inside the FCE or mounted on the front side of the FCE (Front Mounted Cameras – FMC's). The Video Management Unit (VMU) supports all the experiment video images collection and management.
The Lap Top Unit (LTU) represents the interface with the astronaut crew.
Other support equipment is represented by the Power Control Unit (PCU), Fire Detection and Suppression (FDS) Panel, Stowage Container, Work Bench, Avionic Air Assembly (AAA), Secondary Water loop Assembly (SWLA).

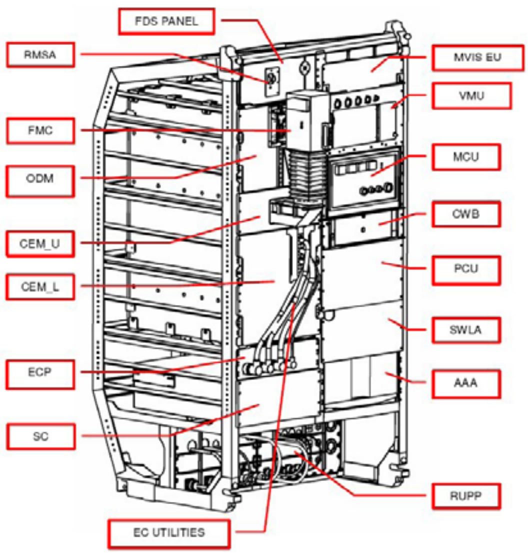

Fig.3 FSL subsystems

4. FSL utilities

The FSL is designed to support the EC with the following utilities and services:

- Electrical power up to 300 Watt
- Low Rate Data (RS-422 and Mil-Bus-1553)

- Video Interfaces and High Rate Data on electrical media
- Water cooling up to 420 Watt of heat rejection
- Discrete Commands
- Discrete Monitors
- Thermo-electrical device driver interfaces
- Stepper Motor driver interfaces

The science data and images generated inside the EC and the cameras (as well as the FSL housekeeping telemetry data) are routed to the Columbus for downlink to the ground. Two downlink channels are available:

- low rate, handled by the MCU, mainly intended for housekeeping and low rate scientific data,
  and high rate, handled by the VMU at olumbus

video interface, mainly intended for video images, and for high rate scientific data.

The baseline for all the FSL experiment operations is the Telescience operation. The scientist interacts with the on-orbit facility from his/her User Home Basis (UHB) by sending telecommands and monitoring telemetry data and images downlinked to the ground. Crew time is one of the most valuable resources on-board of the ISS: the FSL is designed to minimize the required crew intervention, while providing the scientist with a highly flexible facility.

The science support to the EC is provided by the FCE. The FCE is located at the left-hand side of the FSL rack and is composed by the ODM (Optical Diagnostic Module), the CEMU (Central Experiment Module Upper) and the CEML (Central Experiment Module Lower).

These three modules are extractable and constitute a complex optical bench supporting optical diagnostics for the fluid cell including:

- Velocimetry in xy plane
- Velocimetry in xz plane
- Front side viewing (-y axis) with white light background illumination
- Bottom side viewing (-z axis) with white light background illumination
- Electronic Speckle Pattern interferometry (ESPI)
- Wollaston interferometry in 2 perpendicular directions
- Schlieren interferometry in 2 perpendicular directions
- Holography interferometry in 2 perpendicular directions
- Light-sheet illumination and imaging.

The above diagnostics is supported by the following light sources:

- 2 white light sources for fluid cell illumination above and behind (WLSA and WLSB)
- 2 white light sources for 1-to-30 mm white light sheet generation (LSXYW and LSXZW)
- 2 laser diodes for 0.1-to-5 mm monochromatic light sheet generation (LSXYM and LSXZM)
- 1 690-nm laser diode for light scattering (LDLS)
- 1 532-nm laser source for interferometry (LSODM).

The main function of the FCE is to support the optical modules and to keep them stably aligned.

The exchangeable Experiment Container is accessible by extracting the CEML.

The main design requirement of the FCE is the minimization of possible deformations induced by 1-g to 0-g transition, thermal gradients, launch and on-orbit loads / vibrations.

The ODM drawer contains all the main optical diagnostics which are distributed on the two faces of the ODM plate (Upper and Lower).

The ODM contains:

- equipment for visual and interferometric observation and diagnostics
- illumination (laser)
- interferometers: ESPI, differential, holographic, Schlieren, Wollaston.

The CEML drawer contains:

- the Experiment Container with EC functional interfaces (power, data, cooling) and a feed through panel for the EC interface connections
- baseplate for Optical Reference Target (ORT), used for calibration
- laser and white light sources for background and sheet illumination (with suitable optical systems and moving prisms to create two perpendicular movable light sheets in the EC)
- light openings to the ODM
- CCD cameras
- tiltable mirror assemblies
- microgravity measurement assembly.

The CEMU drawer contains:

- supporting diagnostic equipment
- laser source for light scattering applications
- equipment for light sheet thickness variation
- mirror assemblies
- Mirror Front Panel (MFP), interface to Front Mounted Camera.

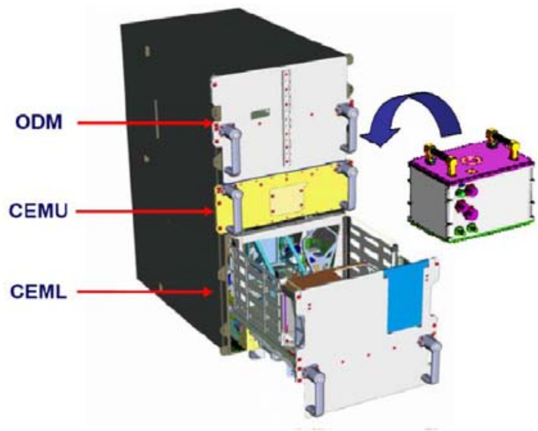

Fig.4 The FSL FCE main components

The Video Management Unit (VMU) is in charge of the FSL video images handling; it is capable of multiplexing and processing all analog and digital, monochrome and colour video data generated in the FCE cameras, in the Front Mounted Cameras of FSL and in the EC internal cameras.

It additionally handles science data received from the Experiment by the MCU.
The VMU supports real time onboard and ground monitoring (compressed downlink), short term data storage (2 hard disks) and long term data storage (digital recorder) for later data retrieval & replay and downlink/evaluation. Up to three video channels can be recorded simultaneously.
The high rate downlink channel is used for data transmission to ground; S-video transmission to the FSL laptop for real-time onboard monitoring is available as well.
Temporal resolution (frame rate) and spatial resolution (number of pixel and lines) can be adapted to the user needs either by the camera or by the VMU. Any further compression/encoding can be performed in real-time.
A JPEG data compressor with selectable compression rate is available.
The VMU delivers appropriate trigger signal to all cameras in parallel when external timing is required.
Camera commanding is performed via a serial interface to every camera by the VMU based on commands from the MCU.

The Microgravity Vibration Isolation Subsystem (MVIS): actively isolates the FSL FCE from the environment vibrations over the frequency range 0.01 Hz to 10 Hz.
The system is based on six degree of freedom magnetic levitation using wide gap actuators, whose magnets are located on the FCE and coils are mounted on the FSL Rack structure.
The system includes position sensors, which allow position and orientation tracking of the FCE relative to the FSL fixed rack, and accelerometer sub-assemblies, for monitoring the FCE and rack accelerations. Both the accelerometers and the position sensors are used in the active control system.
The stiffness and damping characteristics and the control parameters can be programmed over a wide range to accommodate experiments with widely ranging mass properties. The forces required at the eight actuators depend on the mass distribution of the complete system including the experiment. The control system automatically controls the coil currents to get isolation performance; the control gains depend upon the overall FCE mass properties, and are defined in data files that are uplinked and used by the MVIS control software.

The FSL is equipped with a Front Mounted Camera (FMC), which covers requirements not fulfilled by the standard cameras of the FCE. The FMC is accommodated on the FCE front panel (ODM) during the operational phases of the FSL.
The FMC concept allows the accommodation of different (present and future) types of camera, e.g.:
- High speed camera
- Photographic cameras (analog, digital) with different formats (multipurpose cameras)
- Infrared camera

The camera functions are started and conducted by ground, through the VMU. The recorded images of the FMC's are transferred to the VMU - if a digital video camera is used - or they are stored for transportation to ground if photographic film is the storage medium.

5. Typical experiments that can be performed on FSL

The Fluid Science Laboratory is a class-1 facility that has purposely been devised to perform Fluid Physics experiments in weightlessness conditions. The FSL experiment concept is based upon a modular concept that foresees a dedicated EC for each experiment. Only one EC at a time can be operated in the facility, but more than one (typically 2 or 3) EC can be stowed in Columbus each mission increment.
The scientist has to conceive its experiment considering that it shall be entirely confined within a dedicated EC, which shall be provided with all those tools that are experiment-specific, i.e., not supplied by FSL. In this respect it must be noted that, while FSL is equipped with very sophisticated optical diagnostics, most of the read-out capabilities, which are strictly experiment-related, must be supplied by the EC itself.
Thus, besides of a specific Fluid Cell, with its dedicated sensors and mechanisms, the EC shall also contain some experiment-specific subsystems and electronics (namely, the Experiment Container Control Unit, ECCU), which is typically used for signal read-out/conditioning purposes.
Most of classical fluid dynamics experiments can be performed with FSL, including:
- Rayleigh-Benard convection
- Marangoni-Benard convection
- Buoyancy and Marangoni convection along free surfaces
- Marangoni migration of inclusions (drops and bubbles)
- Drop dissolution
- Melting and solidification fronts dynamics and interaction with inclusions
- Crystallization
- Boiling/bubble nucleation
- Heat and Mass Transfer
- Critical Point phenomena
- Liquid bridges in fluid or gas matrix
- Electro-hydrodynamics
- Coalescence/non-coalescence
- Wetting/non-wetting
- Interface ageing due to surfactants
- Mixing
- Fingering (ferromagnetic fluids)
- Fluid film dynamics
- Emulsion dynamics
- Multilayer system
- Colloids, emulsions and aerosols
- Particle agglomeration
- Plasma physics

Of course the possible experiments that can be performed with FSL are not limited to the list above;

the ability and creativity of scientists can surely find a lot of original situations involving fluids, which can be tested in microgravity.

For each experiment a specific set of measurements is to be performed, according to the relevant case. Possible measurements provided by FSL include:

- Observation
- Velocimetry
- Temperature distribution field
- Composition distribution field
- Flow pattern
- Refraction index distribution field
- Surface/interface deformation
- Turbidity

The FSL optics can be automatically arranged in as much as 88 different optical modes, each characterized by a particular interferometry, holography or visualization set up.

6. FSL experiment operations

The operations scenario for the experiments foresees a distribution of tasks and responsibilities among the different ground facilities and the on-board crew, taking into account that the baseline of FSL operations is the Telescience approach, i.e. remote monitoring and commanding from ground, so local monitoring and control by astronaut is not expected to be a frequent event. In addition, full automatic experiment conduction is envisaged, as well.

Experiments are run by dedicated software sequences called Experiment Procedures (EP’s). On users’ request, during execution, the EP can be controlled modified, started and stopped again. Depending on the experiment features, the sequences may be designed to run in one of the following ways:

- Fully Automatic: no operator involvement, all experiment sequences and parameters are pre-mission defined; gathering of data that will be processed off-line
- Semi-Automatic: limited operator involvement, experiment sequences and parameters can be either pre-mission defined or modified in-flight
- Step-by-Step: under direct control of the PI or of the on board crew.

The Experiment Procedures driving the experiment execution are composed of “atomic” instructions, performing elementary functions on the single experiment, and of standard sequence control commands (like Go To, Call, Wait …). The same commands are available both to the PI on-ground and to the on-board crew.

Although the EP’s are stored and executed in the MCU, the EC itself may be provided with a dedicated internal processor running experiment specific software (ECSW), which interacts with the EP. Dedicated experiment interfaces can be also installed in the FSL Laptop (Experiment HCI, EHCI).

The EC processor is the recommended solution in case of very complex experiments, especially if strong time constraints or high processing or commanding rates are required. If the EC does not provide sufficient software capabilities to run its own dedicated software, the EP resident in the MCU can drive completely the experiment execution; in this case, the performance may be reduced, especially in term of command rates, having to cope with the limitation of 1 command per second intrinsic to the FSL data bus architecture.

Once the EC realization is successfully accomplished, the user’s next task is to use the FSL and its experiments. For the utilisation of the European ISS segment, a decentralised organisation is presently being set-up, based on the implementation and build-up of a harmonised network of European national User Support and Operation Centres (USOC’s) to be integrated within the decentralised ISS operational concept.

In practice, the USOC’s are placed into the context of the overall European ground infrastructure for the ISS, interfacing both to ESA and to other entities participating in ISS operations.

The USOC’s support or are responsible for the operations of the ESA scientific facilities and act as an interface for the ISS scientific user.

The USOC’s play an important role in linking the science user community to the ISS utilisation.

With decentralised USOC’s it is ensured that focal points for the preparation and the conduction of ESA payload operations are created.

The centres are outfitted with a set of ESA provided standard services. This includes the implementation of communications capabilities (video, data, voice) and the provision of Engineering Models and Science Reference Models.

Depending on the scope of the task assigned to a USOC, it is a Facility Responsible Center (FRC) or a Facility Support Center (FSC).

The FRC’s have a sufficient knowledge of the functionality of the facilities allocated to them to operate on them during flight. The FRC’s are primarily responsible for operating their payload rack at system level. The FSL FRC is the MARS Center, located in Napoli, Italy.

The FSC’s operate a facility at sub-rack level and they are evoked for the operations preparation and flight execution of individual experiments contained in the facility.

In case of a requirement for telescience from the user’s home laboratory (as per FSL), the FRC is responsible for the interface co-ordination of the set-up of an adequately equipped User Home Base (UHB) at the scientist’s location. The FRC also provides support for the specifications for hardware and software and the connectivity of the UHB to the ISS ground segment as well as for the UHB certification.

The UHB is defined as the home laboratory of the user, which can be equipped to perform online experiment data monitoring or experiment control from that location. Different from the USOC’s, which can be considered as permanent institutions, a UHB is an operational centre for a limited duration.

The UHB’s represent a possibility for individual scientist to participate in the experiment planning and re-planning cycles and to follow and support the

experiment operations without necessarily being located at a USOC.
Direct real-time control of the FSL is implemented by using the infrastructure implemented at the FRC. Remote operations are possible within an operational window, within a resource framework defined in the time line on the basis of a set of previously validated commands. The user is able to monitor all payload data entitled to receive according to the scientific objectives of the research.
FSL commanding may be performed either with direct "ad hoc" commands from the USOC's and associated UHB's, from the Columbus Control Center (Col-CC) or from the crew
The Col-CC or crew can issue FSL commands in response to contingencies or anomalies according to pre-defined procedures. The FRC is responsible during the mission, for issuing authorized commands to FSL during predefined periods, or "operational windows".
The FRC monitors and verifies as well that the commands have been executed and have produced the desired results.
FSL operations are performed under the responsibility of the assigned FRC. They ensure that throughout the operations the payload stays within the agreed resource framework.
Whenever anomalies or faults are detected by this monitoring process, the FRC informs the Col-CC and appropriate contingency procedures are performed.

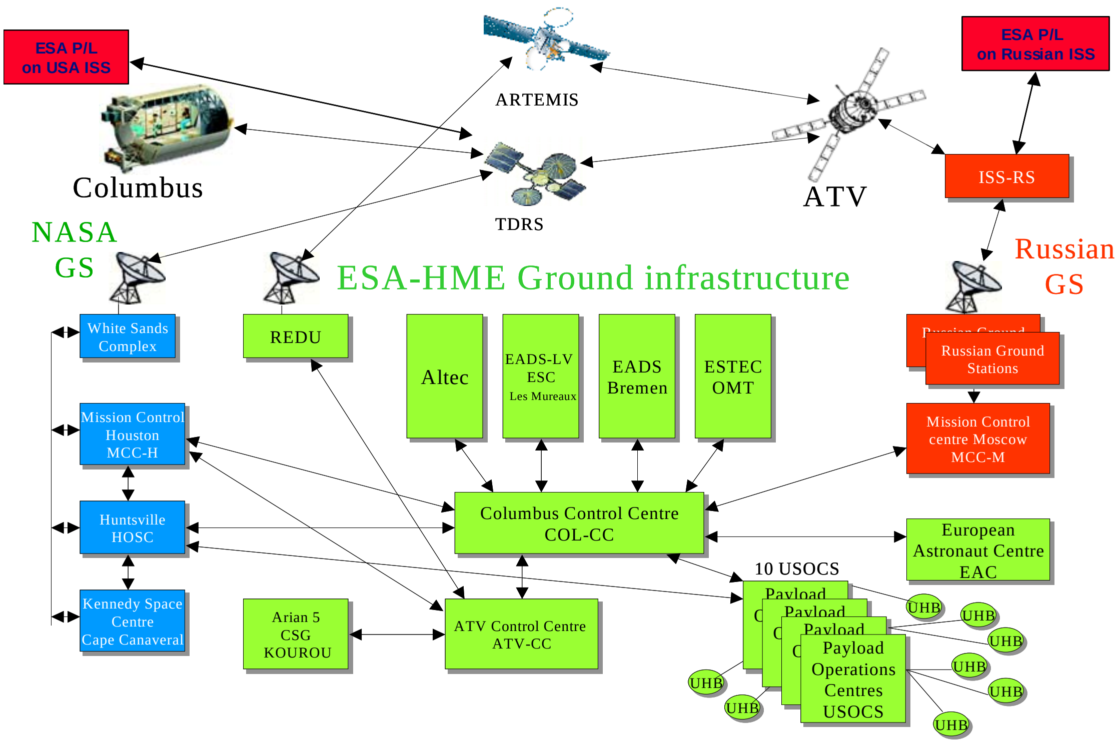

Fig.5 ESA Ground Segment overview fro the ISS