

EDR2 Rack: A drawer rack in the Columbus module of the ISS – Systematic adaptation of the operational teams to the on-orbit and on-ground constraints to respond to a multi-mission stake
Matthieu Desveaux^{a,*}, Bryan Sepiere^a, Audrey Duthil^a, Arielle Depriester^a

^a *TELESPAZIO France – 26 avenue Champollion, BP 52309, 31023 Toulouse Cedex 1, France*

* Corresponding Author

Abstract

The European Drawer Rack Mark II (EDR2) is the second version of an existing European drawer rack, developed by Thales Alenia Space Italy. The concept of the drawer rack is to provide all necessary support for scientific experiments and technology demonstrators (i.e. power, data communication, cooling, nitrogen and venting waste gasses) that will be integrated into the rack as exchangeable drawers. The aim is to optimize the exploitation of the ISS resources with improved flexibility as the configuration of the experiments within EDR2 is adapted based on the scientific needs at a given time. EDR2 was initially launched to the Columbus European module in the ISS in May 2020 and has been operated by CADMOS at CNES, Toulouse since September 2023.

The first experiment installed in EDR2 rack in February 2024 was the METAL-3D printer, developed by Airbus Defense and Space in Toulouse. This technology demonstrator aims to produce metal parts through additive manufacturing in microgravity, a crucial step in building structures and parts in space.

Another example of experiment that will be hosted in the EDR2 rack on board is the Heat Transfer Host 2 (HTH2), developed by RedWire Space. It is planned to be launched in June 2025. HTH2 is an experiment of applied physics, consisting of a Facility interfacing with EDR2 (mechanically and for the resources) and an exchangeable Experiment Insert installed in the Facility. Three different types of Experiment Inserts are planned to be used, each type with its specific characteristics and objectives.

Keywords: ISS, Columbus, Experiment Rack, Microgravity research, Payload operations, Multi-user facilities

Acronyms/Abbreviations

ADS	Airbus Defence and Space
CADMOS	Centre d'Aide au Développement des activités en Micropesanteur et des Opérations Spatiales
CNES	Centre National d'Etudes Spatiales
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EDR(2)	European Drawer Rack (Mark II)
ESA	European Space Agency
FCT	Flight Control Team
FSL	Fluid Science Laboratory
HTH(2)	Heat Transfer Host (Mark II)
HTV	H-II Transfer Vehicle
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
MPCC	Multi-Purpose Communications Computer
MUSC	Microgravity User Support Centre
OS	Operating System
PODF	Payload Operations Data File
TASI	Thales Alenia Space Italy
USOC	User Support and Operations Centre

1. The EDR2 Rack: Installation on board the ISS and preparation for the first activities

1.1 EDR2 installation and commissioning

The EDR Mk2 rack was uploaded to the ISS with the HTV-9 cargo spacecraft, launched by JAXA in May 2020. Once delivered on-board, the rack was stored in a temporary location of the Columbus European module. It remained stored until it could be moved to its final location in September 2023.

The EDR2 rack was initially supposed to take the place of another rack, FSL. As the FSL mission was extended while EDR2 was still in its temporary location, the rack had to be installed in another location in Columbus, for which it was not configured, meaning that, once installed, it was not possible to communicate with the rack from ground facilities.

To update the rack’s configuration so it could be operated from ground, the payload developers and the CADMOS operators had to plan for a software reconfiguration of the rack that could only be manually performed on-board by an astronaut. In October 2023, Andreas Mogensen who was in the ISS at that time for its “Huggin” mission, was the one that executed the procedure that had been prepared on ground. The reconfiguration was successfully executed via direct commanding using a dedicated laptop connected to the rack via a Serial line, with real-time support from the ground teams.

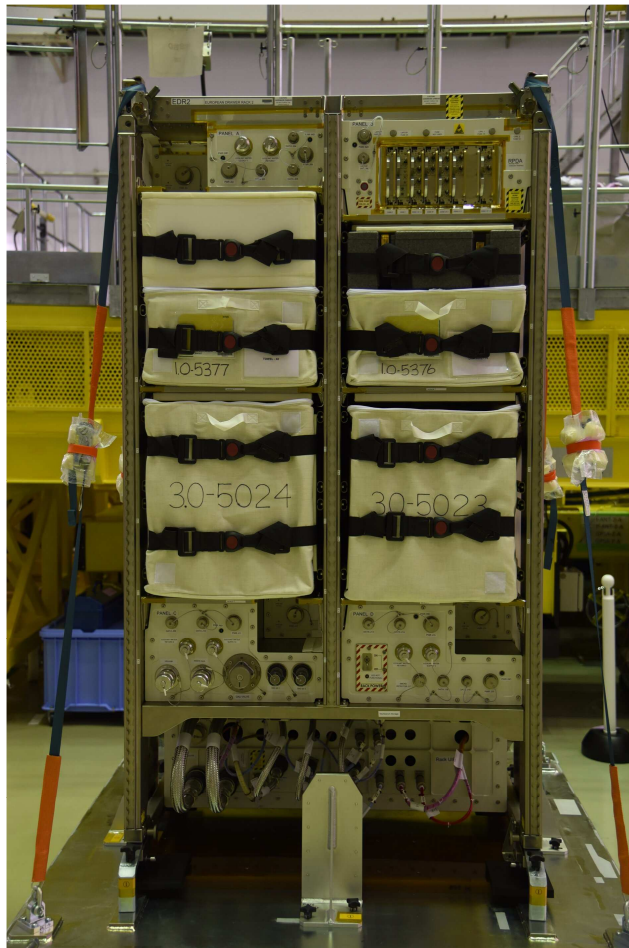


Fig. 1. EDR2 Rack before its integration in HTV-9 launcher in Tanegashima
Credit: ©ESA/JAXA - R.Postema

Once the EDR2 rack was successfully configured for its operational location, two additional steps were required before declaring it qualified for nominal operations. First, due to a significant risk highlighted by the space agencies security boards, linked to the version of the embedded Operating System (VxWorks), a major OS software update had to be carried out in order to mitigate the risk of Security breach. This was applicable to all the equipment entailing hardware compatible with such update, which was the case for the EDR2 rack as a second step, the EDR2 rack had to undergo a commissioning of all its basic functionalities, in the perspective of being used for Class 2 Payloads operations.

In January 2024, the first attempt to update the OS on-board was unsuccessful. After performing the update on one of the rack’s backup partitions, the communication with the rack from ground was lost. Fortunately, it was still possible to communicate with the rack by booting from its main partition, still configured with the old OS version.

As an on-board activity involving crew was already planned a couple of days later, it was decided to use it as a troubleshooting session. Before starting the session, the payload developers wanted to lift some securities on the new OS to see if it would allow communication with ground. Similarly to what had already been done for the Software reconfiguration in September 2023, the crew connected a laptop to the rack, configured it to command the rack from a remote terminal but, during the boot sequence it was observed that some error messages were triggered and that the boot sequence could not be properly completed. This time, the visibility on the boot sequence allowed to collect some logs and error messages through the live video stream that the crew had set up for this activity.

After deeper investigations and some additional tests on ground, the payload developer found some misconfigurations in the OS installer. In early February, the second attempt to update the rack OS was successfully conducted from ground.

Once the OS upgrade was completed, the last step remaining before the rack could be operated was the commissioning, whose scope was to confirm that all of the rack’s resources and functionalities were operational (thoroughly checking all parameters, switching ON all the power outlets, testing file transfer capability, testing commanding capabilities from the on-board laptop, etc.). The first commissioning attempt could not be completed due to unexpected loss of telemetry, after which the rack started streaming telemetry again but was in an unexpected state as readings showed it had booted on a backup partition. As the laptop was connected to the rack around the same time, it was first suspected that the connection itself could have triggered the loss of communication. First, it was decided to run a long-duration test to verify the on-board stability of both the old and newly installed Operating Systems, which proved to be successful.

Since the first experiment to be run in EDR2, the Metal-3D Printer, had arrived on-board early February 2024 with the Cygnus NG-20 cargo spacecraft, it was decided to shortly perform a light version of the commissioning, aiming to validate only the features that would be used by the printer, and to complete all other tasks when a time slot would be available. In addition to the execution of a light commissioning, some crew time was granted for a troubleshooting session to test if the laptop connection to the rack could once again induce interferences in communication, as previously assumed. Several configurations and scenarios had been prepared in coordination with the Payload Developer. As the loss of EDR2’s internal computer (PCCU) could not be reproduced during this session, it was concluded that the anomaly was a single event, and that the EDR2 rack was ready to start operations with the Metal-3D printer.

The last part of the commissioning could eventually be performed in July 2024, to validate some remaining functions that could not be tested before, e.g. commanding capability from the laptop available on-board, and a file transfer between EDR2’s internal computer and the laptop.

1.2 CADMOS operators' role in this sequence

CADMOS is one of the European USOCs (User Support and Operations Centre) that are responsible for the preparation and execution of ESA payload operations on-board the ISS. USOCs main partners in accomplishing their tasks are Payload Developers, the COLUMBUS Flight Control Team (FCT) and the ESA management teams.

CADMOS is divided into different teams, each taking care of specific payloads or experiments. The TA (Technology Applications) team is responsible for the preparation and support to operations related to the EDR2 rack and its payloads (i.e. Metal-3D Printer, Heat Transfer Host Mk2 and Vibrated Grains). At the time of the preparation and commissioning operations previously described, the team had four certified operators and will ramp up to six operators before HTH2 experiment starts.

To prepare for real-time operations, CADMOS receives the technical details of the procedure to be executed from the Payload developers and rewrites it, splitting the steps to be executed between ground and on-board steps. Steps to be performed on-board will have to be transformed into a defined standard ISS procedure (aka PODF), using a format that all astronauts are familiar with. Once ground and on-board procedures are ready, CADMOS operators can test and validate them using the Engineering Model, a replica of the on-board equipment hosted at CADMOS laboratory. The PODF procedures are also reviewed by the FCT and PASO team (Product Assurance and Safety Officers).

For the execution of real time ops, live support from the payload developers is most of the time required because: first on board operations and complexity of software reconfiguration/update. For geographical reasons at first it was decided to have support from the PD via a phone patched directly to the voice loops used by all ISS partners so CADMOS operators could easily discuss any RT issue with them while maintaining situational awareness of any other RT discussions. For the EDR2 OS update it was even decided to have support from the PDs on-site, directly from the CADMOS control room.

2. Metal-3D Printer, demonstrating capabilities of on-orbit metallic additive manufacturing, EDR2, and operations from ground

2.1 Presentation of the payload

The first payload hosted in EDR2 is the Metal-3D Printer, a technology demonstrator developed by Airbus Defence and Space (ADS) for the European Space Agency (ESA), which aims at testing the manufacturing of metal parts in microgravity via 3D metal deposition melted with high-power laser. The mission planned to print four “specimens”, each printed on a dedicated substrate (a small disk of metal on which specimen are printed). After completion, each of them will return to Earth for in-depth analysis and comparison with their respective 1g reference.

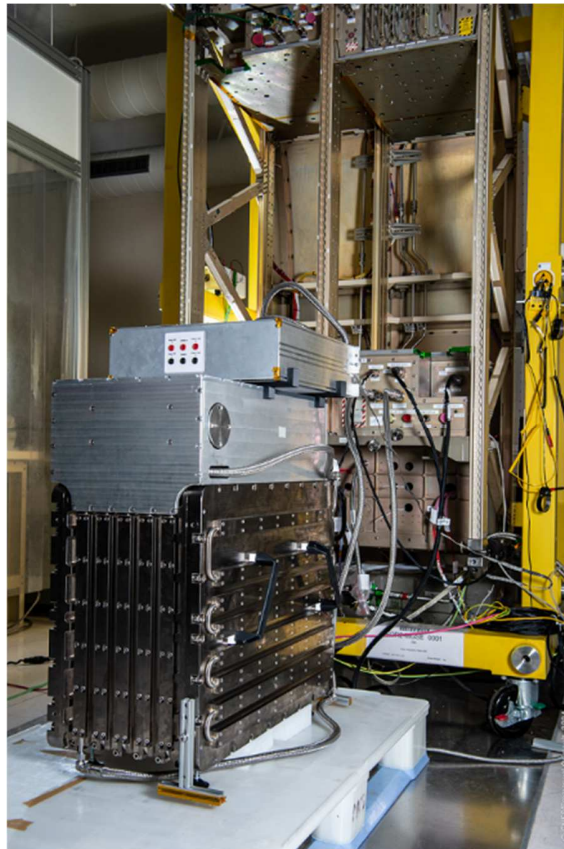


Fig. 2. M3DP EM & EDR2 EM at CADMOS
Credit: © CNES/Emmanuel Grimault, 2024

2.2 Operations preparation at CADMOS

After the printer was built by ADS and before operations could start on board, an Engineering Model (EM) of the printer was delivered to CADMOS so the operators could refine all procedures and test the ground systems. This replica of the flight model had also been used at the ADS premises to print on ground the 1g reference specimens that would later be printed on orbit. The M3DP EM was installed in the CADMOS laboratory, connected almost entirely to the EDR2 EM, as it would be on-board, for power supply, data transmission and water cooling. On ground, due to structural constraints on the fastening mechanism chosen for the payload, the M3DP EM could not be physically installed in EDR2 EM due to its mass (see Fig. 2). In addition, due to the limitations of the EDR2 EM version, the nitrogen supply as well as the waste gasses venting capabilities were provided directly to the M3DP EM by the laboratory.

With this setup available at hand it was then possible to completely test and validate all procedures that astronauts would have to execute later for setting up and installing the printer into EDR2 : indeed for safety reasons, some parts like the air filter or wire cassette were packed separately from the printer and had to be reinstalled on board, other procedure included specimen retrieval, substrate replacement or SD card replacement for the on-board computer driving the whole printer, in case of a software issue.

This setup also allowed for preparing and testing all ground procedures and applications in flight-like conditions: ground segment hardware and software that ensure the data transmission (for commanding, monitoring and data acquisition) could have been validated for the on-board operations. The procedures to prepare the commanding from ground could also be validated in the laboratory: for example, the procedures for the initialization sequence of the payload could have been rehearsed on ground. This allows also to assess all the deltas or anomalies that have not been previously anticipated.

One of the key challenges that the CADMOS team had to face before being completely ready for operations was the leak check sequence to be performed once M3DP would be connected, through EDR2, to the COLUMBUS module venting system (a gas line to dump waste gases to the space vacuum) and nitrogen supply. To ensure the safety of the astronauts was not put at risk the jumpers connections and telemetry readings had to be sequentially planned in such a way that was approved and could be implemented by all teams involved. For example, one of the initial checks that was required was to ensure leak tightness at nitrogen supply level. During the procedure preparation and coordination with FCT counterparts, it was figured out implementing this feature was actually a service already provided by NASA. As NASA supplies nitrogen to the Columbus module, they regularly perform leak checks on this section. Therefore, the Safety documentation had to be updated accordingly to reflect this change of concept.

All teams finally agreed to perform a leak check in 3 parts. Each segment would be tested separately to be able to quickly identify the culprit in case a leak would be observed. To describe how it was split:

- #1. One check of the venting line between the EDR2 rack’s panel and the Columbus module (performed by COL FCT)
- #2. A second leak check on the segment between EDR2 rack and M3DP, on both Nitrogen and Venting lines, up to M3DP’s sensor (performed by CADMOS)
- #3. Third leak check to ensure the payload was airtight (performed by CADMOS)

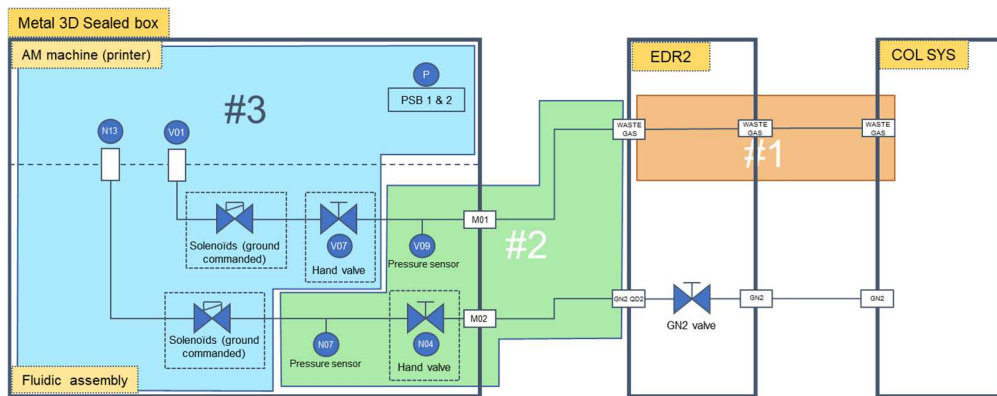


Fig. 3. Schematic of the three leak checks

2.3 Execution of operations on-board

Once everything was ready on ground and M3DP had been delivered on-board the ISS and installed in the EDR2 rack, preparation for operations could be started. Power and vent lines were not connected yet at this stage for safety reasons.

First part was to connect EDR2 rack to the Columbus vent line then perform leak check #1 (see Fig.3), to ensure that the ISS crew’s safety was not compromised. Second part was to configure the EDR2 rack’s software for M3DP operations. As the rack has a modular design and can host multiple payloads in various dispositions, each physical setup has a corresponding software configuration. This update was performed in April 2024, after this commanding and monitoring capability of the printer was activated. Finally, once an astronaut was available to connect the power and vent lines between EDR2 and M3DP in early May 2024, it was then possible to perform the last part of the preparation for operations which included a complete check of the printer’s telemetries, leak check #2 (see Fig. 3) to confirm that the vent and nitrogen lines were leak tight, calibrating the printer’s internal hardware with a pointer laser and targets, and finally flushing the oxygen out of the sealed box to reach the necessary conditions that allowed to print some commissioning lines.

These preparation activities had to be spread over several days due to a flight rule that allowed to activate the printer only 3.5 hours a day. That flight rule is here to ensure that astronauts are not exposed to high levels of noise and the measurements made on ground showed that, with its fans and water pump, the printer emitted noises louder than 52dB which induces a limit of 3,5 hours of activation per 24H period. This limit was strictly respected during the first days of operations but soon it appeared that the printing process was then much slower than expected. After a discussion between the Columbus FCT, CADMOS and ESA management on the possibilities to extend the activation time for each day, it was decided that the rule would be waived on a case-by-case basis, depending on how long astronauts were present in the module. This would be assessed each day of operations, in real-time, by the Columbus Flight Director. It was then agreed to plan for 4,5 hours of activation each day and keep it when conditions allowed, or to shrink it to 3,5 hours in real-time. It was actually not possible to extend much more than 4,5 hours because of several factors:

- Only one operator can be present each day due to limited staff.
- Activation and deactivation of EDR2 rack, along with all resources (N₂, Vent, high rate TM) have to be performed each day.
- Operators have to come on-console approximately one hour before activation of the rack and remain after rack deactivation for processing and sharing data generated each day with the payload developers and scientists (e.g. images and scans of the prints).

This one additional hour helped increase the printing speed closer to the payload developer’s expectations.



Fig. 4. M3DP Specimen A when received on earth
Credit: ©ESA – M. O’Reilly

The first specimen “A” was printed from June to August 2024. It included three “bending” samples made of 111 layers and three “tensile” samples of 224 layers. As each sample of each layer is printed and scanned with two telecommands, the total amount of commands to send was significant and could have led to operator errors. During operations there always was one operator from CADMOS and one payload developer from ADS, so each command would be double checked. To increase robustness, it was decided to use Spell, a TM/TC scripting software initially developed by SES which was forked by Space Application Services (SAS) to integrate it with Yamcs, the monitoring and control system used at CADMOS. Each telecommand would then be instantiated by the script, then checked and sent by the user.

Once the first specimen was completed, the printer had to be de installed from EDR2 rack so it could be opened in order to retrieve the specimen. Astronauts performing these operations would then pack the specimen in multiple layers of bubble wrap, inspect key elements of the printing mechanism and take pictures for further analysis on ground. For each specimen retrieval, CADMOS operators are turning all requests from payload developers, management and scientists into different procedures so that astronauts can take the best possible pictures of the printer and the finished specimen. A blank substrate is the installed in the printer for the next specimen to be printed and the printer can be reinstalled in EDR2. Specimen A was retrieved in August 2024 and the printer was ready for printing the upcoming specimen “D” which was completed and retrieved in November 2024. Both specimen would be delivered on earth a few months later in February 2025 at European Space Research and Technology Centre (ESTEC) in the Netherlands.

Unfortunately, due to an uneven surface, as some irregularities started to build up from the first layers, the third specimen “C” had to be aborted in March 2025, to avoid damaging the printer. It might be completed at a later stage, but this is still under discussion. Specimen “D” was started shortly after and was completed in one week. It was retrieved and packed in April 2025.

3. Heat Transfer Host 2, adding more complexity in the data downlink management

The experiment Heat Transfer Host 2 (HTH2) will be installed inside EDR2 rack in Columbus in June 2025. The objectives of this experiment is to study the change of phase and heat transfer of different liquids in microgravity. In the long term, the results of this experiment will allow a better optimization of thermal control technologies in space. The payload has been developed and produced by Redwire Space in Belgium and will be operated for at least 2 years in the ISS by CADMOS at Toulouse.

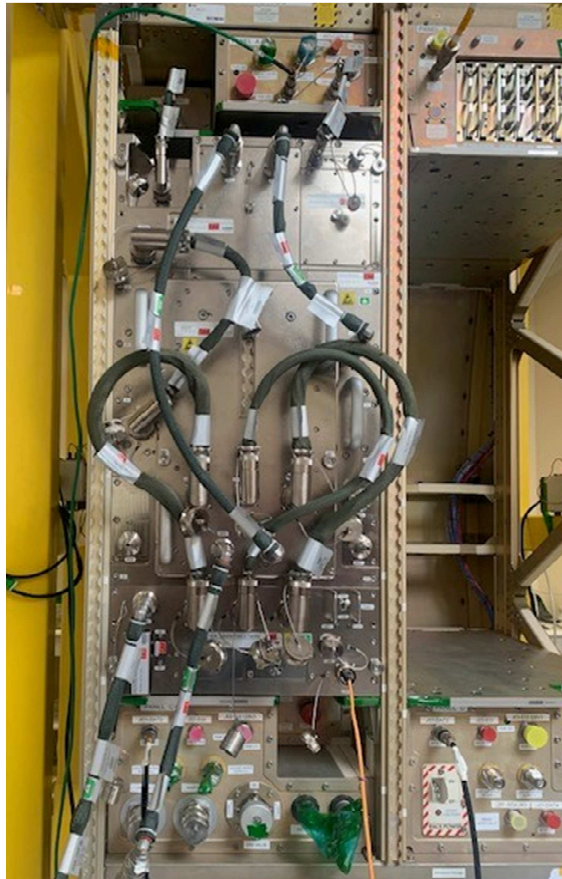


Fig. 5. HTH2 GM installed in EDR2 EM at CADMOS

The HTH2 payload is made of one main Facility, installed inside the left side of the rack, and three different kind of Experiment Inserts which are installed inside the Facility. Each insert will study a specific physic phenomenon.

- Condensation on Fins (CoF): It aims to evaluate the heat transfer coefficient along a curved surface on which condensation occurs. This coefficient is estimated by the measurement of the condensation film thickness on the surface. This fundamental study can be applied to heat pipe capacitor, coolers and air conditioners technologies. The aim of Condensation on Fins is to demonstrate that the heat transfer rate is higher on curved surfaces and particularly on complex geometry. It is foreseen to upload three different models of Condensation on Fins, with various curved surface shape. Each model will be operated for 7 weeks.
- Marangoni in Films (MiF): It will allow to study instabilities occurring in liquid films heated by a rough solid substrate. It mainly investigates the Marangoni convection, evaporation and pattern creation in the liquid films over different substrate's shape. The results of this experiment will be used to identify efficient strategy for hydrodynamics film control. 5 models of Marangoni in Films insert have been developed and each of them will be operated for 8 weeks.

- Drop Evaporation (DrE): This experiment aims to study the evaporation of pure fluid and binary mixture drop with and without electric field constraint. The results will be used to improve heat transfer using electric field in space cooling devices using droplet evaporation technology. It is planned to operate 4 different models of Drop Evaporation inserts.



Fig. 6. 3D modelling of MiF insert

The scientific results of each experiment consists in high definition images captured by three types of camera: infrared, black and white and interferometer. An additional camera called LITHI can be installed on the top of Marangoni in Films Experiment Insert to capture and measure the liquid thickness. This removable camera module is used only for this specific experiment. This important amount of images is recorded on high capacity storage disks, which will be replaced at each Experiment Insert exchange. Each insert will generate different amount of data, from 8 TB to 23 TB. This represents a challenge to downlink this amount of data from the ISS to the ground, that is why the strategy will be adapted depending on the data size to optimize the process.

The commanding and monitoring of HTH2 will be performed through MPCC connection. This link allows the operator to access the payload via a VPN tunnel from the ground console to the HTH2 internal computer. This real time connection is reliable, efficient and flexible. The health and status telemetry and compressed images will be permanently downlinked via MPCC. The full scale images will be stored on the internal disk inside the payload, but not directly downlinked to the ground. It will be a post processing task performed by the operator and CLUSO (data management team) at the end of the science. To downlink this important amount of image data, crew will connect the HTH2 storage disk to a laptop on-board called EICL, to transfer the data in chunks to a dropbox. It is then connected to another dropbox on ground, from which CLUSO will gather the data and transfer it to CADMOS team. At the end of the process, CADMOS operators will be in charge of the last transfer to the science team for data analysis. This process is complex, but still faster than a physical download for around 8 TB of data. But for heavier ones, like for Marangoni in Films experiment, the physical download of the disk will be more efficient and will be preferred. The risk of each scenario must be considered, like physical damage during download, file corruption, unplanned loss of signal etc.

HTH2 science will be running non-stop and commanded via scripts. The operator at CADMOS will monitor the experiment with daily checks and on-call support. The science scripts have been written during operation preparation and have been tested on ground. The remote monitoring and alarm tool have been developed by CADMOS ground segment team, to raise alarms with adapted severity. The operator will be alerted via phone call or email and will check the telemetry remotely via an external monitoring computer. In case of anomaly, the operator will take action on console (at CADMOS) to solve the issue or switch off the payload if needed.

4. Future payloads for operations until the end of the ISS

4.1 VIPGRAN-ISS, taking advantage of the lessons learned from HTH2

One of the following payloads that will be installed in EDR2 will investigate the behaviour of particles in microgravity to better understand the physics of granular matters. In order to achieve that, the ESA payload VIPGRAN will be operated from CADMOS to observe via multiple high speed cameras how small beads interact with each other when they are vibrated by pistons inside of a cell. There are different types of cells that will be available, allowing to modify a variable in the experiment configuration and observe the impacts of the change.

Similarly to HTH2, VIPGRAN offers the possibility to be commanded and monitored via a MPCC link, a direct LAN connection from COLUMBUS to the payload that allow the operator to access the payload through a VPN tunnel from the ground.

At this stage the operational concept is being finalized by CADMOS and the involved teams to match the scientific needs and the operational constraints, but the payload will be running scripts continuously and be active 24h/24h during the science runs. That is why the same constraints as identified for HTH2 will apply to the VIPGRAN operations: while EDR2 is left continuously active, the operator will only be on console for the initialization phase and in the transition to another experiment, when changing the number of beads in a cell (via ground commanding).

In addition, the daily checks will still be performed by the operator that will be on-call. Indeed, a set of telemetry items defined in advance are automatically monitored by ground tools and in case of an anomaly - as out-of-limit parameter values, caution or warning events, or loss of telemetry - the on-call operator is automatically alerted by phone and/or email.

4.2 Life Cell Imaging, for joint operations outside CADMOS

The Live Cell imaging payload is a combination of FLUMIAS, a high-resolution fluorescence microscope and a centrifuge rotor to study biomedical samples. The payload can contain up to six experiment boxes with various samples. This payload will be operated by another USOC, MUSC (Microgravity User Support Centre) located in Köln, Germany at the DLR Aerospace centre. A new “cascading” monitoring and control concept will be tested for this mission, meaning all communications with the payload will transit through CADMOS facilities. At the moment this is still under testing and development.

5 Conclusion

As presented here, the EDR2 rack’s modular design allows it to accommodate a wide range of experiments and technology demonstrators, all of which present different challenges with different operational concepts for the ground teams to adapt to. The facility is still young but the first experiment, M3DP, has already achieved its main objectives and ESA is now looking at how it can be used to further improve knowledge of metal parts manufacturing in microgravity environments. Although the ISS’s lifetime is still uncertain, all the knowledge gained from this mission will be of great help in adapting to future space exploration missions.

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