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TRANSFERRING PAYLOAD OPERATIONS FROM ONE CENTRE TO ANOTHER: THE FSL CASE

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The Fluid Science Laboratory (FSL) is a research facility installed in the European Columbus module of the International Space Station. It provides 70+ different optical diagnostics to insertable Experiment Containers (EC). In the first 6 years of its operational life, FSL operations were managed by the Italian Microgravity Advanced Research and Support Center (MARS) following the European User Support and Operations Centre (USOC) concept. In 2013 however it was decided that the Belgian USOC (B.USOC) would take over the operations, with the actual hand-over process starting in spring 2014. This article reports on how this hand-over was executed. It lists the events in a chronological way, and discusses the main challenges encountered by B.USOC. It was found that operational knowledge is difficult to transfer due to the different forums where the information is tracked. A changing ground segment concept complicated the hand-over, which would also have benefited from a consolidated overview of the upcoming activities. Still, B.USOC managed to overcome the difficulties and perform its first on-board FSL operations in April 2015.

I. INTRODUCTION

The Fluid Science Laboratory (FSL) is an International Standard Payload Rack mounted in the European Columbus module on board the International Space Station. As the name suggests, it is a facility dedicated to fluid science, but in itself it is not an experiment. Rather, Experiment Containers (ECs) can be installed in FSL. FSL provides to the experiments services such as thermal control, power distribution, data processing, and most specifically, a broad range of optical diagnostics suited to the needs of fluid physics. The Experiment Container and the optics are contained in the so-called Facility Core Element (FCE), see Fig. 1, acting as an optical bench that can be free-floating within the FSL envelope, reducing the effects of residual microgravity disturbances on board the station. Additionally, the FCE contains a microgravity sensor to map the remaining disturbances.

Experiments in FSL can generate up to 32 Mbps as data rate, which falls under the class of "High Rate Data" (HRD). Those data are processed by the Video Management Unit (VMU) that also routes the data to Columbus, from where they go to ground. The computing unit of FSL is called the Rack Interface Controller (RIC). It processes incoming commands from ground, monitors essential values of sensors inside FSL and initiates an automatic reaction if needed.

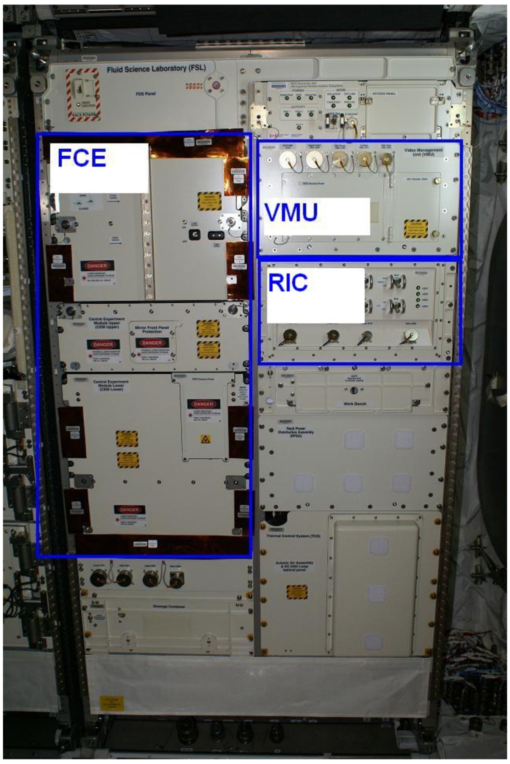

Figure 1: The FSL rack in the Columbus module. Indicated are the Facility Core Element (FCE) , which contains the optics and the Experiment Container, the Video Management Unit (VMU) that processes the high rate science data, and the Rack Interface Controller (RIC).

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FSL has been launched together with Columbus in 2008, and since then experiments such as Simulation of Geophysical Fluid Flow under Microgravity (Geoflow) and Fundamental and Applied Studies of Emulsion Stability (FASES) have been executed. Geoflow consists of two concentric spheres (see Fig. 2) with a viscous fluid in between, and as such simulates the upper mantle of the Earth [1]. Microgravity conditions on ISS ensure that the unidirectional gravity vector on the Earth surface can be ruled out and that instead a central force field can be simulated by applying voltage differences between the two spheres. Moreover, different rotation speeds and temperature differences between the two spheres can be applied to study different conditions. Geoflow uses Wollaston interferometry as diagnostics.

Figure 2: Breadboard of Geoflow. Clearly visible are the 2 concentric spheres [2].

FASES, on the other hand, was designed to study emulsion stability and kinetics in microgravity. It consisted of 44 samples on a conveyor belt, such that every sample could be moved to the observation position. Some of the samples had to be heated, others had to be cooled, and some had to be stirred [3].

II. SETTING THE BACKGROUND

Although astronauts sometimes need to work on FSL, for example to exchange Experiment Containers, or to troubleshoot anomalies, most of the operations can be performed from ground by telecommand. For ISS, the preparation and execution of the payload operations are delegated by ESA to one of the User Support and Operations Centers (USOC) (see Fig. 3). USOCs prepare and execute payload operations for ESA on the ISS. They are the link between scientists and the ISS. The FSL responsibility was initially assigned to the Microgravity Advanced Research and Support (MARS) Center in Italy.

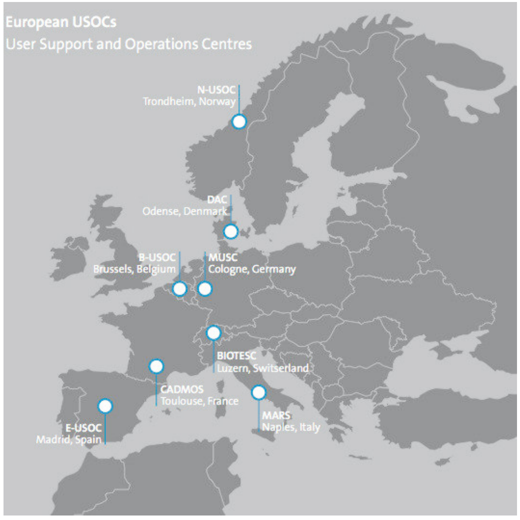

Figure 3: Overview of the USOC network as it was in 2013. Since then, the MARS USOC has been closed. Image courtesy ESA

During the summer of 2013, B.USOC was informed that the MARS center would be closed and that the responsibility for FSL would be moved to B.USOC, the Belgian USOC. No official start date of the hand-over process had yet been declared, hence B.USOC could not yet contact MARS to start elaborating the hand-over process. Still, there were several aspects that could already be tackled by the B.USOC team.

One of them was training. Engineering documentation for ESA payloads on ISS was stored on the Document Management System (DMS), and was as such readily available for the B.USOC operators. The Operations Manual was an evident starting point. In parallel, it was investigated what kind of training ESA could provide, even before hand-over discussions with MARS started. ESA provides a payload training to new flight controllers, focusing on the racks in Columbus. Since B.USOC was never responsible for a rack in the past, this payload training has not been part of the nominal B.USOC operator training plan. It was decided that a special version for the B.USOC Operators would be organised, covering only the part on FSL. With the training taking place at the European Astronaut Centre, the FSL Training Model was available for a first hands-on experience. Unfortunately, this agreement was put on hold, as there seemed to be still questions on the details of the hand-over.

In parallel, ESA had the plan to change the way the USOCs interface with the Columbus Control Centre in

Munich, and as such with the ISS. The new ground segment set up introduced the Payload Data Center (PDC) and was a far more centralized concept than what was used in the past. At the start of the hand-over, the PDC was planned to roll out in November 2013, with completion in July 2014. Either B.USOC would take over the legacy system from MARS, mirroring the set-up at B.USOC and then later moving to the PDC, or it would be a straight transfer to the PDC.

III. THE HAND-OVER

In the fall of 2013, a discussion between ESA, MARS and B.USOC was organized. ESA put on the table that the hand-over should start at the end of the FASES operations, which at that time were planned to end in May 2014. The work on a formal hand-over plan would start one month earlier, in April. It was also agreed that B.USOC would go to MARS to follow the FASES operations and get on the job training. Regarding the ground segment, ESA pointed out that B.USOC should use the PDC for operations, and that the legacy ground equipment was not going to be transferred. Finally, MARS indicated that over the course of the years, they had developed software to operate FSL that was not part of the contract with ESA and hence would not be transferred.

Arrangements were made for a B.USOC visit to MARS in January 2014. Unfortunately, in the same period the operational concept of ESA changed, which made that B.USOC had to be available on console 24/7 instead of an interchanging 8/7 – 16/7 schedule to operate the current payloads under B.USOC responsibility. Due to the late notice it was not possible to hire and train new operators in due time, such that the operators planning to go to Italy could not be missed for the on-going operations. In the end, it turned out impossible to find suitable dates for both MARS and B.USOC, as well as having FSL operations scheduled on those days. The fact that difficulties had risen with the on-going FASES operations and the subsequent work load of MARS did not help to the issue.

In the mean time B.USOC operators continued studying, and also got involved in future experiments to be accommodated in FSL by reviewing the science requirements and the preliminary designs. As agreed, a hand-over plan with MARS was drafted in April and finalized in May. Also the training at EAC took place in that month. 2 sessions had to be organized to train all B.USOC operators, again to allow having enough personnel available to continue 24/7 payload operations in the mean time.

In the beginning of June, finally B.USOC travelled to Naples to visit MARS. Besides the on the job training, a follow-up meeting between MARS, ESA and B.USOC was scheduled as well. This time, more details could be filled in. The target time for the move of the FSL Engineering Model (EM), symbolic to the hand-over process, was now the second half of July. It would first go to the Payload Developer, Thales Alenia Italy (TAS-I) in Turin for anomaly investigation and functional testing, and then go to B.USOC. B.USOC was requested to be ready to perform Geoflow operations by January 1, 2015.

For this to succeed, several items still had to be tackled. For Geoflow, the "cascading" principle had to be implemented: Although FSL, as a Class 1 payload, used to be the responsibility of MARS and would now be under B.USOC control, the experiment container, a Class 2 payload, can belong to another USOC. For Geoflow, the Spanish USOC, E-USOC, is responsible for the Geoflow operations. In the past Geoflow operations had already been performed, but were not completed yet. MARS used to set up FSL, and then allowed E-USOC to send commands through the MARS ground segment to the Columbus module: E-USOC was in "cascading" configuration with MARS. This principle had to be implemented at B.USOC as well, but the same set-up could not be mirrored as B.USOC was supposed to implement the PDC, at that time not yet available and also not really meant to allow the cascading concept. This had to be clarified.

Another item to be taken into account was the certification of the B.USOC Operators. Before being allowed to perform operations on the ISS, an operator has to go through training and simulations during which he/she is evaluated by the ESA training team. All operators had been certified for the instruments already under B.USOC responsibility, but for FSL a delta certification was required. To have the possibility to be ready for FSL operations in January 2015, it was mandatory that one simulation per person would be sufficient for this delta certification, and that B.USOC would get priority in the simulations, of which about 24 per year are organised. It was the aim of B.USOC to certify all 10 operators, but for the few days of 24/7 operations each Geoflow run required, five people was declared the absolute minimum. Unfortunately, the ESA training board decided that two simulations per person were needed. To help B.USOC out however, it was proposed to have three stand-alone FSL simulations. For a normal simulation, payload operations are just part of a more diverse timeline, during which several USOCs and the Flight Control Team in Munich are participating on console. For the stand-alone simulations however, it would all be about FSL, with the required Flight

Controllers to practice interactions, travelling to B.USOC.

The on the job training was limited to a period of two days, but it was enough to show that FSL operations are challenging, and for B.USOC to be ready in time, it was mandatory to heavily rely on the way operations were done at MARS. Any structural modifications if needed could be made later, when B.USOC would have more experience and the workload would have been reduced. To do this, B.USOC would need the software, called "ground HCI" that MARS had developed outside the ESA contract, as all operations products such as procedures were referring to this tool. Moreover the tool provides features that are essential for FSL operations, that are not available in the agency provided tools. Hence discussions were started with MARS to find an agreement for the use of this tool, as well as for their support both for the training of the operators, and training and support to the B.USOC ground controllers, who are taking care of the ground segment. Additionally, the payload developer was contacted to explore the possibility of having a familiarization session on the technical details of FSL. This familiarization had to take place before the operations training by MARS.

During the summer of 2014, the FSL EM was transported from the MARS premises to TAS-I, where B.USOC could observe part of the testing. Moreover an agreement with the Payload Developer was found for a technical familiarisation, and also the MARS-B.USOC support agreements were concretized. B.USOC would have a one year license for the ground HCI, and support for training would be provided, focused on the different aspects such as basic operations, Geoflow operation, and the ground segment.

For the ground segment, B.USOC was notified in September that the legacy system of MARS was ready to be transferred to B.USOC, quite unexpectedly. B.USOC chose to accept it since there was a delay on the implementation of the PDC. Although it would mean double work – setting up two ground segments, B.USOC wanted to get hands-on with High Rate Data as produced by FSL, an aspect which was new for the B.USOC ground controllers. Also it was considered beneficial to have the ground segment ready when receiving the EM, such that the operators could start training as soon as possible, given that readiness was expected by January 1, 2015. Later on, B.USOC learned that the infrastructure needed to be upgraded to receive high rate data, i.e. the MPLS bandwidth, would not be ready in time for operations in January, and the target date was moved to March 2015.

On October 14, the FSL EM was received at B.USOC, leading to a quite spectacular installation. The complete installation and check-out by TASI took about a week, after which the EM was officially handed over to B.USOC. Also the PD familiarisation for all operators was included. Over the course of November the sequence of on-board activities was becoming clearer. It was considered beneficial to have a first activation of FSL by B.USOC, testing the basic functionalities to have a view on the state of FSL, which had not been activated since June. It would also be the final ground segment validation of the High Rate Data link. At this point there would not be an involvement of the Spanish USOC yet. The next step would then be to do a more complex check-out, and update software governing the optical elements of FSL in the FCE, and the software of the Video Management Unit (VMU). After that, Geoflow runs could be started. At this point, with some experience on the EM and the operational scenarios clear, B.USOC operators successfully completed a first simulation, ending the year on a positive note.

2015 started with the stand-alone simulations. Extensive FSL scenarios were simulated at the B.USOC premises, in the presence of an ESA Columbus Flight Director, a STRATOS engineer (responsible for Columbus systems), and a representative of the ESA training team. A crew activity was simulated on the EM, as well as several anomalies. It was up to the B.USOC operator to solve the problems and execute the correct interactions with the Flight Control Team. During these simulations several issues were flagged which needed to be addressed before performing operations. It turned out that several ops products had been created in the beginning of the mission, but had not been updated for changing circumstances. There were issues with the way of commanding with the ground HCI tool that did not follow the B.USOC best practices. Also it showed that B.USOC lacked ops products needed for proper execution of crew activities with potential impacts on safety.

Subsequently a telecon with ESA was arranged to explain the shortcomings and challenges, and how they could be solved. Instead of going for a general readiness statement, B.USOC would adopt a stepwise approach. Preparation would continue for the planned initial end-to-end test, but if unexpected anomalies showed up (contrary to common anomalies for which B.USOC was already prepared), those would not be handled by B.USOC, instead the activity would be aborted. In the next phase, B.USOC would update the necessary ops products for everything related to the required software upgrades, also including more anomaly resolution actions. Then there would be the Geoflow activities, followed by the remaining specific knowledge on FSL.

IV. FIRST OPERATIONS

In the end, the first operations with the FSL Flight Model took place in April 2015. During the end-to-end test, FSL was activated and configured in so-called "nominal mode". During this transition, a 40 minute automatic test is executed on the optics of the FCE, to bring them all in home position. In the past, FSL had been notorious for failing this test, after which it would have to be repeated, up to 5 times. If still not successful, the whole facility needed to be power cycled, in order to repeat the process. It is clear that the time needed for successful FSL activation was highly variable. Surprisingly however, during the end-to-end test, the automatic test was successful at the first attempt. During this first B.USOC FSL activity, no science data were generated yet, but to finally validate the path followed from FSL to ground for science data, the data stream of the accelerometer in the FCE was downlinked.

Hence the end-to-end test was successful, except for one small item. B.USOC performed its nominal commanding using standard ESA provided tools, so not relying on the ground HCI, but the ground HCI provided some features that would be needed for future activities that the ESA tools did not provide. During the end-to-end test a test command was sent via the ground HCI, that for a then unknown reason was blocked on board the station. Being crucial for the future, B.USOC concentrated on solving this issue. The culprit turned out to be a wrong timestamp in the command generated by the ground HCI. In another session, FSL was activated again to successfully test ground HCI commanding.

By the end of June, B.USOC was ready to perform an extensive functional test of FSL, upgrade the software of the FCE and the VMU, and to do another functional test to commission the new software. In this case the activation of Geoflow was required, as it provides the triggers to the FSL cameras that generate the images that make up the science data. A data stream of up to 24 Mbps was generated, compared to the few kbps during the end-to-end test. The Spanish E-USOC was responsible for commanding Geoflow. Although they were connected directly to the PDC just like B.USOC, B.USOC still needed to enable them for commanding.

The FCE software was upgraded to avoid the need of multiple repetitions of the automatic test at the transition to nominal mode. The upgrade of the VMU software was rather to troubleshoot and have a more convenient work-around for a long known VMU issue All science data go through the VMU that multiplexes them and encapsulates them in packets, after which they are passed on to the Columbus equipment. However at random moments, the data rate that the Columbus equipment would measure coming from FSL (FSL does not have telemetry for that) would go down and then stop completely. When this happened, in the past, power cycles of the VMU were executed, and if that would not work, power cycles of the whole FSL. Given that every time this happened, FSL had to be brought back to nominal mode and hence the 40 minute automatic test had to be executed, this created quite some delay. Moreover during this recovery, no science data could be gathered, which could mean a multi-day science run had to be stopped and partly or completely repeated. By the end of the MARS FSL operations, the question was when this issue would occur, rather than if. The new software would enable new telemetry that would hopefully allow pinpointing where the problem was. Since the development of a new VMU was ongoing, this would be essential to exclude without a doubt that the new VMU would suffer from the same problem. Moreover a new telecommand was implemented that resets one of the VMU chips, reenabling the data stream. Hence if the High Rate Data (HRD) issue would occur again, it could hopefully be solved by sending one simple command.

During the functional test at the start of the sequence of activities the HRD problem already occurred more than once, even at very low data rates. After the VMU software upgrade, of course, the same anomaly occurred, providing a good occasion to study the new telemetry and test the new reset-command. For all this, B.USOC was in continuous contact with the Payload Developer, who was following the FSL activities in real time. Surprisingly, the new telemetry was indicating that the VMU was doing exactly what it should be doing. And the chip reset command, correctly reset the data stream, but this had no effect on restoring the data transmission. Revoking to the old countermeasures, the VMU power cycle and the FSL power cycle, showed that these actions work or do not work on a random basis. Hence the new software has lead to the idea that the problem might not be in the VMU itself, but rather in the interfaces between FSL and Columbus. Since then, the Payload Developer came up with a troubleshooting plan, going over all FSL connections and interfaces, for which crew interaction will be needed. At the moment, Geoflow activities have been put on hold.

V. CHALLENGES ENCOUNTERED

During the hand-over, B.USOC encountered several challenges and learned valuable lessons:

Spread information. When a payload is developed, all required information is available in the operations manual and associated engineering documentation. At the start of operations however, this changes: anomalies arise that are documented in specific forums, work-arounds are created, a way of coordinating with the Columbus Flight Control Team evolves over time, and many tips and tricks become part of the experience of an operator but are not necessarily documented. If then a hand-over such as the one for FSL takes place, it is difficult to get an optimal knowledge transfer. B.USOC tried to counter this issue by requesting familiarisation sessions from both payload developer and MARS, to get information that goes further than the documents, that also encompasses the best practices. Still, B.USOC had to undergo, and still will at least partially follow the same process of learning by doing as MARS did. The problem could have been diminished by having had a longer period of on the job training at MARS.

Time pressure. B.USOC was given strict deadlines from the beginning. Due to this fact, it was not possible to take the time to get to know the whole FSL, and assess the situation regarding operational products, tools and concept. Decisions were taken based on knowledge of only a part of the set-up, and turned out to be not always the best ones in hindsight. Because of this, some decisions had to be reverted, leading to time loss, which is not ideal when deadlines are already tight. On the other hand, goals have to be set with some time constraints. If not, it is easy to get lost in the available documentation and forums, and to just keep studying the available information. A goal and time limit will help setting priorities. The difficulty is of course finding the equilibrium between too little and too much time.

USOC way of working. Although all USOCs use operational products following the same standards defined by ESA, it showed that MARS and B.USOC have different ways of working, and habits are hard to change. At first, B.USOC decided to take over all MARS operational products, and then, if needed, update them in due time. However, by the time the first on-board activity took place, B.USOC had already created its own operational products. For example, MARS used lots of different displays, each showing telemetry of one subsystem. B.USOC was used to monitor overview displays, shown the essential telemetry of the whole facility. After working with the MARS displays for a considerable amount of time, the constant changing of display proved to be too cumbersome for the B.USOC operators, and an overview display was created. At the same time, B.USOC reworked all procedures necessary for the upcoming activity (via the step-by-step approach), to have them following a new ground commanding set-up that allows commanding with easier coordination with the Columbus Flight Control Team, and easier updates.

USOC-developed software. MARS developed the HCI software on their own initiative upon the needs of FSL. As this was not funded by ESA, it was also not part of the hand-over to B.USOC. The ground HCI provides some features (such as the reception of on-event telemetry) that are up to now not covered by the ESA tools. Given that neither time nor funding was available for B.USOC to develop their own software, MARS and B.USOC agreed on a lease period of 1 year for a ground HCI license. However, no support for the software is available, and no development will be done for future experiments. After this 1 year license, already ending in November, the way forward still has to be decided. For its other long-term payloads B.USOC also created software for easier and more efficient operations, leading to the suggestion that this is a general need for payloads, and it might be worth discussing if a generic tool could be a solution.

Commanding. MARS used to send commands from their telemetry monitoring displays. The displays contained fields were parameters could be filled in, with an associated command-button, that upon clicking would construct and send the telecommand. Initially, again to have an efficient hand-over, B.USOC used the same commands on the engineering model, but issues were encountered. The command would not be sent, or it would not be received, or it looked like it arrived at the engineering model but was not executed. For the B.USOC operator, as there was no insight in the commands, there was no indication what went wrong. It could be the ground segment, something could be wrong with the command itself, or it could have been a problem with the engineering model itself. B.USOC was able to retrieve the scripts that were constructing the commands, and together with software manuals available for FSL and its subcomponents, all commands were recreated in their raw form, giving visibility on the content of the command. This was a time consuming task, but gave the operators a lot of insight in the FSL facility. Moreover, operators now have complete insight in the command and how it passes through the ground segment.

Ground segment changes. From the beginning B.USOC was told to implement the new PDC that soon would become available, and that the old equipment would not be used anymore. Eventually the old equipment was actually transferred to B.USOC, and this was a good choice. It allowed B.USOC to, with some adaptations for the B.USOC set-up, reproduce the MARS ground segment, making the best use of the MARS support. MARS personnel assisted B.USOC to set up the system and transferred a significant amount of knowledge on how to deal with high rate date, which would have been far more cumbersome if there had been a direct transfer to the PDC. Moreover there was a delay on the PDC roll-out, which, without the legacy system, would have prohibited B.USOC from working with the EM for the period of the delay. Practicing operations on the EM have proven to be very valuable and a delay on EM availability would have impacted the schedule.

The schedule. When FSL was assigned to B.USOC, the only activities planned were the Geoflow runs. Over the course of the preparation time, however, more and more activities were inserted. There were several investigations on the engineering model for the resolution of flight model anomalies. Although primarily a task of the payload developer, support of B.USOC personnel was required. There were documentation review cycles for the development of future experiments and the new VMU. For future experiments, some tests on the EM were performed as well. At one point, a new 5 day on-board activity was introduced, i.e. the full functional test and software upgrades, which, at B.USOC side, was not foreseen. This lead to several major revisions of the schedule, and to a feeling of not being in the loop. Ideally, at the beginning of the hand-over there would have been an overview of all activities coming up. This could haven been ensured by having a kick-off meeting with all FSL stakeholders, where all contributing factors would be put on the table, with a common plan as a result.

VI. CONCLUSION

In the summer of 2013 B.USOC was informed by ESA that it would to take over the responsibility of the FSL rack accommodated in the Columbus module of the ISS, from the Italian MARS USOC. In October 2014, the engineering model was transferred to B.USOC, which was asked to be ready for Geoflow operations in January 2015. The project was very challenging: FSL is a very complicated facility, and in a very short period B.USOC agreed on a handover plan with MARS, provided all logistics to install the EM, trained all operators on FSL operations, for which 5 are already certified, embedded the FSL operations console and systems in the B.USOC ground segment and generated and validated the needed ops products. Due to complications during the hand-over, the Geoflow runs were not started in January 2015, instead it was chosen to follow a stepwise readiness approach. However the challenges occurred during this handover contain valuable lessons. Finally, FSL on-board activities were resumed in April 2015, starting with an end-to-end test, followed by software upgrades. The Geoflow activities have been put on hold due to problems with the high-rate data stream from FSL to ground. A troubleshooting plan is currently being developed.

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