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REPORT (TECHNICAL, BUDGET, COST, MANPOWER, TRAVEL, AUDIT, ETC.)

LISA Pathfinder Lessons Learned

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1 INTRODUCTION

1.1 Purpose

This document describes the conclusions of the Lessons Learned for LISA Pathfinder. Section 2 describes the organisation and purpose of the LLL, Section 3 contain a summary of the most important findings of the LLL and one input on the LPF Science Archive that arrived too late for discussion at the LLL sessions but is important enough to warrant a place in this report.

1.2 Scope

This document discusses only a subset of the around 400 inputs that were submitted for discussion to the LLL coordination board. Due to the large number of inputs, it is not practical to include them all in the document. The inputs discussed in this report were selected by the coordinators as the most representative from the full list.

The Annexes to this report contain the MOM circulated to all the participants after each session, the slides used in the presentations, and a spreadsheet containing the totality of the inputs submitted by the originators for discussion during the LLL with a summary of the discussion around each of them and the associated dispositions.

1.3 Applicable and Reference Documents

1.3.1 Applicable

AD-01: SCI-O Policy and Procedure for Lessons Learned, SCI-O-PR-00208
AD-02 : LPF Lessons Learned Procedure, S2-ESAC-RP-5036
AD-03: SCI-O Policy for Document Management, SCI-O-PR-00144

1.3.2 Reference

RD-01: DFACS User Manual, Issue 1.5, S2-ASD-MA-2004
RD-02: TM Release Experiments, J. Mendes, ESOC, 28/09/2017, Presentation slides

1.4 Glossary of term

NOM1 and **ACC3** are two of the DFACS operation modes. The details can be found in the DFACS UM [RD-01]

URLA and **UURLA** are two of the LTP low force authority modes that were introduced during operations in order to reduce actuation noise. These are the two modes with the lowest force authority in a sequence of modes with decreasing authority that were gradually introduced during the mission. The reason for the stepwise approach is that it was not clear from the beginning whether the system would cope well with such low force authorities. The equivalent authority mode for the **DRS** is **DURLA.**

An **Analysis Object** (**AO**) is an xml based format used by the LTP data analysis software.

1.5 Acronyms

AO	Analysis Object
ATLO	Assembly, Test and Launch Operations
CCD	Charge-Coupled Device
CCU	CM Control Unit
CGAS	Cold Gas Sub-system
CM	Caging Mechanism
CMPS	Colloid Micro-Propulsion System
CMS	Charge Management Sub-system
CRF	Command Request File
DA	Data Analysis
DC	Direct Current
DFACS	Drag-Free Attitude Control Sub-system
DMU	Data Management Unit
DOF	Degree of Freedom
DOY	Day Of the Year
DURLA	DRS Ultra Ridiculously Low Authority
DRS	Disturbance Reduction System
EDAC	Error Detection And Correction
EDDS	EGOS Data Dissemination System
EEPROM	Electrically Erasable Programmable Read-Only Memory
EGOS	ESA Ground Operations System
EM	Engineering Model
ESDC	ESAC Science Data Centre
FDIR	Fault Detection, Isolation and Recovery
FEC	Forward Error Correction
FEE	Front-End Electronics
FPGA	Field-programmable gate array
FSW	Flight Software
FTP	File Transfer Protocol
FTS	File Transfer System
GPRM	Grabbing and Positioning Release Mechanism
G/S	Ground Segment
HGA	High Gain Antenna
GUI	Graphical User Interface
HR	High Resolution (DFACS MODE)
HW	Hardware
ICL	Imperial College London
IS	Inertial Sensor
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Lab
LEO	Low Earth Orbit
LGA	Low Gain Antenna
LISA	Laser Interferometer Space Antenna
LLL	LPF Lessons Learned

LPF	LISA Pathfinder
LPFMCA/B	LPF MCS A/B
LPFSA	LPF Science Archive
LTP	LPF Technology package
MCS	Mission Control System
MEO	Medium Earth Orbit
MGA	Medium Gain Antenna
MOC	Mission Operations Centre
MOM	Minutes of Meeting
OBC	On-Board Computer
OBCP	On-Board Control Procedure
OE	Operations Engineer
OMS	Optical Metrology System
OS	Operations Scientist
OSTT	On-Station Thermal Test
OWLT	One Way Light Time
PCU	Power Conditioning Unit
POC	Person of Contact
RAM	Random Access Memory
RLU	Reference Laser Unit
RTB	Real-time Test Bench
S/C	Spacecraft
SDP	Software Data Pool
SEO	System Engineering Office
SEU	Single Event Upset
SK	Station Keeping
SOC	Science Operations Centre
SOVT	System Operations Validation Test
STM	Structural and Thermal Model
STOC	Science and Technology Operations Centre
TC	Tele command
TM	Test Mass or Telemetry
TOQM	Thermal Optical Qualification Model
TTC	Telemetry, Tracking and Control Subsystem
ULU	UV Lamps Unit
UM	User Manual
URLA	Ultra Ridiculously Low Authority
UURLA	Ultra Ultra Ridiculously Low Authority
VM	Virtual Machine
WG	Working Group
WR	Wide Range (DFACS Mode)

2 THE LPF LESSONS LEARNED EXERCISE

2.1 Objectives

The objectives of the LLL were:

- To capture the experience gained during operations of LPF which could be relevant and useful to future missions with particular emphasis on the development of LISA;
- Formulate recommendations based on these experiences with emphasis on the applicability to the development of LISA;

Unlike most other ESA missions, LPF was planned, developed and operated with a future mission, LISA, in mind. Given the commonalities at the hardware level between the two missions it made sense to take this into account when running the LLL. Also, because of this fact it made sense to dedicate part of the LLL to hardware development specific issues.

2.2 Audience

The target audience for this exercise consisted of:

- ESA, in particular the LISA study team;
- Engineering and scientific teams preparing LISA;
- Industry with emphasis on the teams involved in the development of LISA.

The LLL was led by the LPF STOC. Input was solicited from members of:

- ESA (ESAC, ESOC, ESTEC)
- Industry involved in operations of LPF;
- The instrument operation teams;
- Satellite operations teams;
- Data analysis teams;
- Representatives of the target audience;

As far as it was practical we asked for inputs to the LLL to a range of originators as wide as possible. In particular, we decided from early on to include industry in the list of the originators. As it was noted in the previous section we believe this will greatly benefit the development of LISA.

The list of attendees can be found in the documents linked to in Appendix I.

2.3 Process

Late in May 2017 a procedure was circulated containing the organizational details for the entire exercise and all the potential originators where asked for contributions. As described in the procedure [AD-02], the lessons learned exercise was split in three sessions. Dates, topics covered and coordinators are summarised in Table 1 below. Note that for the 1st session, because of the large number of contributions received, four coordinators were appointed in order to review the inputs submitted before the 1st LLL session.

In total, around 400 inputs were received. Although the bulk of the inputs was received before the 1st session, the last inputs came around the time of the 3rd (and last) session and there was an input which did not arrive on time for the discussion but was deemed important enough to include in this list (See LPF Science Archive). Even though each session was dedicated to a specific topic, we still accepted inputs on a given topic after the formal session on the topic was closed. Another problem we had to deal with was that not all the participants could attend all the sessions and therefore some inputs had to be discussed in a different session from that which was originally targeted in order to allow the originators to be present when their contributions were discussed.

Given the importance of LPF and its Lessons Learned to the development of LISA we tried to be as flexible as possible in order to provide some time for discussion for all the contributions received. This meant that both in the 2nd and 3rd sessions we dedicated some time to discuss topics that were formally allocated to past sessions but either for lack of time or the unavailability of key persons could not be discussed there.

Table 1

Session	Topics covered	Coordinators
1. 17-19 July 2017, ESOC	LTP and STOC Operations	MOC Operations: Ian Harrison Science Operations: Luis Mendes Data processing: Paul McNamara Payload Operations: Steve Foley
2. 12-14 Sept. 2017, ESAC	DRS and MOC Operations[1]	Luis Mendes
3. 27-29 Dec. 2017, ESOC	Hardware[2]	Luis Mendes

[1)]We also discussed some DRS hardware issues as our DRS colleagues were not be available for the last session.

[2)]Operations related items that could not be discussed before because of the absence of key people were also discussed in this session

In order to enforce some uniformity in the inputs format, the potential originators were asked to provide the inputs in a template spreadsheet. The information required for each input is detailed in Table 2

Table 2

Field Name	Description
Raised	Institution or person raising the input
ID	Unique ID for each input
Domain	One of • Ground Segment Ops • Space Segment Ops • Science Ops • Data Processing • Hardware • Other/Unknown
Title	Short description of input
Severity	One of

	• Low • Moderate • Significant
Lesson Learned Details	A detailed description of the issue reported and how it affected Operations/Development
Lesson Learned Recommendation	A recommendation from the originator

The full list of inputs can be found in Appendix II. The inputs were reviewed by the coordinators with the goal of ensuring all contributions were assigned to the correct categories and of merging similar inputs - in some cases several input Lessons were of a common theme and these were brought together in an overarching Common Lesson for disposition. Apart from this, all inputs were accepted and no other cuts were performed.

From the list of inputs provided by the contributors, slides were prepared for the presentation during the sessions (Appendix III).

3 SELECTED INPUTS

For the summary presented here we selected those inputs we considered the most significant. In some cases we merged several inputs that were close enough and could logically be grouped together. Note that the merging done at this level was different from the merging mentioned in the previous section. The former was done because there were originally a few inputs from different sources that just repeated each other whereas the latter was done to inputs that complemented each other and were logically related, in order to keep the number of inputs summarized in this report at a manageable number. Examples of this last case were inputs FM-10 and FM-11 (See the spreadsheet with the original inputs in Appendix II).

The next few sections contain the inputs selected for this report. In some cases at the end we added some notes summarizing the discussion during the LLL sessions, especially in the cases when some important points were raised that were not captured in the original input.

In order to make it easier to find a particular point we split the inputs according to their class according to the classification in the Domain field in Table 2. At the end of this section we also add a science archive related item that was not discussed during the LLL sessions but which was deemed to be important enough to include here.

3.1.1 Ground Segment Ops

3.1.1.1 LLL-GSO-01

Title: Industry simulator
Severity: Significant

Details: The OSE delivered (and used) by industry was a useful tool at the start of the data analysis and science planning activities. However, there were many bugs in the simulator, which were found by the scientists. If this had not been used as extensively, many of these bugs would have appeared in the ESOC sim and RTB models.

Recommendation: It's not enough for industry to work in isolation. The DFACS team was very competent, and we would not have a mission without the work they put into the design and testing. However, they are not end users and do not know the subtleties of the system when used for science. For LISA, the design and development of the simulation platform (and hence DFACS) should be more open to the end users.

3.1.1.2 LLL-GSO-02

Title: Documentation storage
Severity: Significant

Details: There was some difficulty in finding relevant documentation as there was no organised central archive/repository of relevant documentation (e.g. hardware requirements and measurements) and also datasets that were produced during testing.

Although *git* was used extensively this is an appropriate system to use for version control not for stable documentation storage. For documents that have reached a stable version and it is known they will not evolve, *git* is not the best choice of system.

Recommendation: Instead of a source control system, like git, a dedicated documentation management system should be used. A cloud storage system could be used as a repository of documents that have reached a stable state and are not foreseen to undergo any significant changes. Something like Mendeley could be used for storing references and descriptions of the documents.

Notes: Taking into account SCI-O Policy for Documentation Management [AD-03] recommends the use of Content Server/Livelink, that should be the tool of choice unless there is a good reason not to use it.

There are some common aspects between this input and the discussion on the LPF Science Archive below.

3.1.1.3 LLL-GSO-03

Title: Need for simulations
Domain: Ground Segment Ops

Details: Pre SOVTs, and formal simulation exercise were key to identifying issues, and to force all the component of the team (industry, scientists and ESA) to gather, communicate and work together. For LPF simulations ensured procedures (for planning, data delivery and data analysis) could be tested in realistic conditions. With the use of simulations, data analysis scientists not involved in the design and construction of the HW could learn how to work with the satellite data and commands.

Recommendation: For LISA, in the same way it was done for LPF, we should plan for the use simulations in order to make the operations teams familiar with planning, data delivery and data analysis in a realistic environment.

3.1.1.4 LLL-GSO-04

Title: Robustness of the Ground TM Processing Chain
Severity: Moderate

Details: The lack of robustness in the Ground TM Processing Chain at the MOC has caused several small loss of data events. Huge amounts of human effort were put in by the STOC and MOC to identify, investigate and fill the data gaps.

The reason for the gaps were mostly (in order of occurrence):
1. Individual Packets lost in the RAPID file transfer between LPFMCA and LPFMCB
2. EDDS stopped servicing TM retrieval requests with FTP delivery (FTS stopped)

Perhaps the most important lesson here is that we made, early on, an assumption that data could only be lost in the space to ground link, and not within the ground itself. Therefore, we implemented gap checking at the Frame level, and not at the packet level. We could not have been any more wrong!

Recommendation: Two main recommendations can be derived:
1. The reliability of the MOC MCS and should be improved;
2. The MOC systems need to invest in proper gap checking tools, at the level of the product that the external partners retrieve (in the case of LPF, this was at the packet level).

3.1.1.5 LLL-GSO-05

Title: Diversity of operating systems at the STOC
Severity: Moderate

Details: The STOC used almost every operating system known to mankind. This lead to the dispersion of resources. On top of that, the bulk of the planning was done on windows machines that did not allow multiple logins. This presented a significant hazard for planning.

Recommendation: Stick to one operating system, preferably not MS windows.

3.1.1.6 LLL-GSO-06

Title: Use of virtual machines
Severity: Moderate

Details: The LPF STOC used physical machines at ESOC and several VMs at ESAC. The low performance of the VMs at ESAC had a negative impact on operations in the last part of operations at ESAC. Because of memory constraints on the VMs at ESAC, the performance was never good enough and regular reboots were required.

Recommendation: Due to performance constraints, VMs are not a suitable solution for everything. Database servers, GUI software, and so many other things work much better in physical machines. The use of VMs should therefore be avoided for operational tasks. If that is not possible in every case, at least avoid the use of VMs for critical tasks.

3.1.1.7 LLL-GSO-07

Title: Challenges with IT access
Severity: Significant

Details: This was a problem both for DRS members and the STOC configured machines and databases.

DRS: Obtaining accounts for non-JPL affiliated users in the JPL system is a long and arduous process which requires time and a lot of personal info. We need to identify the off-lab people earlier in order to have their credentials in place prior to ops start. JPL access also requires regular renewal, so the JPL POC needs to be on his toes and pay attention to expiration notifications.

Workstations running within the JPL firewall also need to be continuously certified for external access, so we needed to constantly monitor emails from JPL security to comply with guidelines otherwise external access will be disconnected, potentially in the middle of Ops (GDS). Same issue applies for JPL users access to building 264's network.

Five levels of access: our access to foreign serves, foreign national access to our data, external NASA (GSFC), external US (non-NASA, i.e. Busek), and internal JPL all had different requirements (i.e. VPN, fixed IPs, etc.), which made obtaining and maintaining access to operations data and telemetry challenging.

STOC: Connection among machines (both external and internal to ESA networks) was very difficult and often impossible to negotiate due to overburdening security restrictions. This is particularly problematic in a mission like LPF where the STOC was split between ESAC and ESOC

Recommendation: *DRS:* Work with NASA and ESA early on to establish access to necessary IT. Continual maintenance of IT resources likely requires a dedicated part-time member of the team for future projects.

STOC: Relax the rules for connection of critical machines in terms of data ingestion and data distribution. If it turns out this is completely impossible when outside access is required at least make the rules more flexible for machines located at different ESA sites.

3.1.1.8 LLL-GSO-08

Title: DRS interface with LPF Operations Tools
Severity: Significant

Details: Training and support of the LPF provided tools (CRF and EDDS) proved to be difficult. While we understand the tools were not developed specifically for us, we did end up using them as no other tools were available (or would have required us to develop our own tools, which would have been challenging in terms of interfaces, updates, validation, and budget) requiring *Microsoft Access*, which is a complex tool requiring its own training, licensing, and in some cases using a virtual machine for functionality. Obtaining immediate support from ESOC/ESAC was also challenging due to time difference.

Recommendation: JPL could have had more support in the planning stages for developing usable ops tools.

Notes: Taking into account the NASA contribution to LISA, attention should be paid to the support out NASA colleagues receive regarding planning tools. This issue should be dealt with early enough during development.

3.1.1.9 LLL-GSO-09

Title: DRS *bathtub* period between delivery and launch was challenging
Severity: Significant

Details: The DRS team was operating under constrained resources up to delivery and throughout the remainder of ATLO and operations. The time between delivery in 2008 and the year prior to launch in 2015 required the DRS team to reduce to about 4-5 people, all working part-time. While this was certainly not ideal and may have prevented the DRS from participating more in LPF activities, the working nature of this period came down to this small team being members of DRS team continuously from 2003 - 2017, including in operations, working with a consistent set of ESA and Airbus counterparts (Rozemeijer, Wealthy, Mendes, Harrison, Martin, etc.). Keeping key personnel engaged while the DRS project conserved resources was critical for success.

Once again, the DRS team appreciates ESA's efforts, especially during anomalies, to help the DRS be ultimately successful. ESA's familiarity with the DRS and willingness to work together seamlessly clearly helped in resolving issues on orbit. However, limited resources did not allow for experiment planning or extended operations simulations and sequence development during this *bathtub* period, and was left to the 1-yr to 6-month period of ramping up labour and team efforts prior to launch. While ultimately successful, additional resources should be considered for ESA/NASA team interactions post-delivery.

Recommendation: Keeping key staff engaged on the project over long periods, even at low levels, was successful. In the future, more resources, especially for the science team, should be planned for post-delivery activities prior to launch.

3.1.1.10 LLL-GSO-11

Title: DRS Sequence Validation Process
Severity: Significant

Details: The DRS developed operational *sequences* that contained multiple DRS specific commands instead of developing detailed flight procedures with ESOC. These sequences were integrated into the timeline by relatively simple execution commands that did not allow significant validation on the ESOC simulators, which were relied on heavily during operations. Instead, the DRS Testbed (at JPL) and the RTB at Airbus were used to validate the sequences prior to upload to the S/C. While the DRS testbed was available as needed for the DRS team, the RTB was very limited in terms of access, and only critical events (software uploads, commissioning activities, first walk-up through our control modes, and a limited number of signal injections), FSW functions (regression tests), and *flight sequences* (sequences that turned the thrusters on and off, handover and handback, and used FDIR) were tested well before execution, not allowing all DRS activities to be verified in a high-fidelity simulator prior to operations.

This approach was chosen due to the high availability of the DRS testbed compared to the expected lower availability of any other ESA test environment, the complexities of modelling the interfaces, and the initial project ITAR constraints on sharing software and pre-compiled code. In fact, the original approach agreed to early on in the project with ESA was to have only a dozen *opWrite* commands for the DRS that provided very limited functionality (executing sequences, resetting the DRS, etc.). Later, this approach was abandoned because of the limits in the DRS flight software, and mainly the need to have more accessible commands for normal and unexpected operations (e.g. a write command for each of our symbols). If providing ESOC access to all symbols in the DRS FSW was the baseline early on, perhaps higher fidelity simulators could have been created by ESOC and less confusion would have been created. However, this change in approach was only contemplated after delivery, during the *bathtub* period when the DRS team was at a low level, which did not make it easy to implement.

The strength of this sequence architecture and validation approach included the DRS team's ability to quickly validate new operational sequences *in house* and provide a simple operational interface with the STOC and MOC. The weakness of this approach was the lack of visibility into the sequence operations for the STOC and MOC and the reduction in fidelity of the DRS simulations, which relied on older and incomplete performance models of the LTP. The insight into and test fidelity validation of critical handover, handback, and FDIR sequences was improved by use of the RTB; however, this resource had limited access and operational time constraints allowing for less than 90 days of DRS simulation time over the seven year period post-delivery and during operations.

Still, while the *sequence interface* with the STOC and MOC could have been improved, the DRS testbed focused validation of the sequences worked well, at least by post-mission review. None of the DRS sequences created an unsafe condition on the S/C and almost all of them performed as expected/simulated. Periodic validation on the RTB was key to the ultimate success of this approach, as well as the detailed certification procedure the DRS used to validate the sequences. While some minor mistakes were made during operations, mainly related to the lack of immediate insight or personal memory of sequence contents, none of them were unrecoverable and generally just required minor sequence updates for better functionality. Also note that for a technology demonstration mission, this approach may be more acceptable than for a future *Class A* mission where a higher level of project visibility and validation would be required. For the future LISA mission, all simulators should be provided to ESA.

Recommendation: The DRS-focused sequence use and validation approach worked well enough, and could be used as a model for future ESA/NASA technology demonstration projects. However, extra effort should be made early on to provide full visibility into all command functions (not a limited set) to allow for better nominal operations validation work and contingency planning. If possible, high-fidelity NASA payload simulators should be provided to ESA early on in future missions.

Notes: Needs follow up during the development of LISA. The details depend on NASA's contribution to LISA.

3.1.2 Space Segment Ops

3.1.2.1 LLL-SSO-01

Title: Flexibility in telemetry and telemetry rate.
Severity: Significant

Details: As we found during LTP operations, more flexibility in the telemetry would be beneficial. We always found a way, but usually this required new packets and/or SDMs. For LISA, we should have a more flexible approach (something easily configurable and flexible like the the (128,4) packet), which can be used when needed. SOC tools must be capable of decoding the packets using the relevant TC history.

Recommendation: More flexibility, particularly during instrument/constellation commissioning, should be built into the LISA ground segment. In particular high data rate telemetry is a must.

For this we need to consider mass memory availability and bandwidth. This will result in requirements on hardware and telemetry data rates.

Notes: Before setting a requirement, a list of telemetry to be extracted at high frequency should be compiled.

3.1.2.2 LLL-SSO-02

Title: FDIR function for thruster usage was too complicated for operations
Severity: Moderate

Details: The CMPS and CGAS thruster usage monitoring functions were too complicated and in some cases did not work properly which led to them not being used during flight operations, resulting in a waste of resources.

Recommendation: FDIR functions should be kept simple and easy to be validated, otherwise they should not be implemented.

3.1.2.3 LLL-SSO-03

Title: RTB availability for tests should be improved
Severity: Moderate

Details: The avionics bench (RTB) at Airbus DS Stevenage was very useful for tests by both ESOC and Airbus DS. However it takes time to start the RTB and on several occasions it had to be restarted as it would normally crash after 1 day.

Recommendation: For LISA make the avionics bench more robust and easy to use. Add the possibility to save context and restart directly at a *saved point* in a sequence.

3.1.2.4 LLL-SSO-04

Title: Limit time spent in LEO radiation belts
Severity: Significant

Details: The radiation belts around the Earth have a known deleterious effect on spacecraft electronic components and significantly the Star Tracker CCDs. In order to mitigate the damage to the star trackers a direct injection to the operational orbit is of benefit.

Recommendation: Due consideration of the detrimental effect of spending significant time in the LEO/MEO environment should be made. The star tracker performance is key to spacecraft stability and damaging effects during transfer should be limited (for example by choosing direct injection to the operational orbit).

3.1.3 Science Ops

3.1.3.1 LLL-SCO-01

Title: Missing tool to check agenda.
Severity: Significant

Details: In an experiment like LISA Pathfinder, some experiments are affected by earlier operations, so it would have been interesting to have a tool to quickly check the activity of the spacecraft at specific DOY without having to examine every day the packet TC Reports in order to check experiments, conditions, etc.

Recommendation: An easy to use tool (e.g. database/agenda) summarizing past and planned operations is necessary. Apart from standard investigations, it should also contain all variables impacting the environment of the S/C: temperature, thruster feed branch, Star Tracker software, etc). Along with the times and dates it would also be nice to have the ability to:

1. Perform simple and complex searches through the investigations for the full mission using keywords;
2. Add notes and analysis documents to add more detail to the investigations;
3. The names of those who are responsible for the analysis of that investigation;
4. Details on the current state of analysis.

All this information exists but it is not accessible in an easy to use way. There is a nice calendar tool in the LPF legacy archive. Having something similar and updated (and maybe more complete) during the mission would have been useful.

Notes: Requirements for such a toll should be drafted early in the development process. The tool would also be of great value when archiving and documenting simulations.

3.1.3.2 LLL-SCO-02

Title: STOC at ESOC during in-flight Calibration Phase
Severity: Significant

Details: LPF has shown that spacecraft operation is inseparable from instrument operations. The spacecraft is an active element of the science instrument and its dynamics enters directly into the science signal. It has been instrumental for the success of LPF that STOC and PI teams could operate in close contact with MOC at ESOC. LISA will not be any different and will require the same kind of organisation during the in-flight Calibration Phase.

Recommendation: For LISA the SOC should be co-located with the MOC and the Instrument Teams at the start of the mission (i.e. in-flight Calibration Phase). The SOC should then be able to move back to ESAC (around the end of the Calibration Phase), as demonstrated during the DRS ops phase.

Notes: Although there were some suggestions that the SOC should stay at ESOC for the duration of the LISA mission (of the order of 10 years) this is not possible from a human resources point of view due to the duration of the mission. However, it was widely agreed, that the close contact between MOC, SOC and the PI teams is most important during the early phases of the mission. In case of need the SOC can always be at MOC when deemed appropriate.

On the other hand, the LISA operations and analysis team should be prepared to the fact that for most of the mission they will not be co-located and therefore must learn to work remotely during the routine science phase.

3.1.3.3 LLL-SCO-03

Title: Respect planning cycles
Severity: Significant

Details: Due to the nature of the mission, it was clear since the beginning the STOC was going to be frequently put under pressure during operations. However because the scientific inputs were not received on time (not following the planning cycle schedule agreed by all the parties involved) on a regular basis, the pressure levels on the STOC were in general very high. That produced a couple of planning mistakes during operations that could otherwise have been avoided.

Recommendation: Due to the nature of LPF (a technology demonstration mission with a relatively short operations period) it was almost obvious from the beginning that ensuring the timing for the planning cycles agreed among all the teams involved in operations was going to be close to impossible. For LISA, however, after the calibration phase once operations enter the science phase, the agreed schedules for the planning cycles should be respected. No doubt there will be occasions where it will be basically impossible to follow the agreed timing for the planning cycles (e.g. contingencies), but all efforts should be made to keep these to a minimum.

3.1.4 Data Processing

3.1.4.1 LLL-DA-01

Title: LTPDA and other analysis tools were useful for DRS, but also provided challenges
Severity: Significant

Details: LTPDA was extendable to DRS telemetry to help build similar data structures and analysis used on LTP. While it was used by only a couple of people on the DRS team, it was very useful for having both the DRS and LTP data in the same environment. While more DRS team members could have been trained to use LTPDA, it was not part of our original plan or budget, and would have required significant additional resources. Still, for the two DRS team members heavily involved in LTP data analysis, they could readily modify their LTPDA tools for use in DRS DA, which helped significantly with the DRS DA staffing problem.

IGOR macros for processing data and posting initial looks at the data were useful, but required specialized knowledge and training for use. LTPDA Quick Look analyses of DRS data lagged the data acquisition by a few days, but were also still very useful for sanity checks. MATLAB scripts were also available and used by various team members. ESA also had their own data visualization software that looked very useful and provided more immediate access, but was not accessible to DRS team members.

Recommendation: Creating telemetry parsers for multiple platforms was useful, but also led to configuration management issues and different timing for data availability. A single, simple to use, basic data processing and visualization tool that is accessible to all parties would be extremely useful.

Technology demonstration missions need significant resources for data analysis, focused on near-term products that can influence later experiment designs.

3.1.4.2 LLL-DA-02

Title: AO conversion and data ingestion into the LTPDA
Severity: Moderate

Details: The ingestion of data into the LTPDA did not always work as expected. The system was too complicated and not always documented at an appropriate level. Some of the problems were probably due to issues of compatibility between MATLAB and Java but no well-defined culprit could be found. This forced many restarts of AO conversion/data ingestion/replication system which in a few cases lead to otherwise avoidable delays in making the data available to the PI team. This could have impacted much more negatively in the data availability if it was not for the prompt intervention of the STOC OS and OEs. The fact that the AO conversion/data ingestion system was written in a mix pf languages (MATLAB, java, shell scripts, ruby,...) did not help.

Recommendation: AO converter/data ingestion software should be more robust and fully documented. Also a mix of such a large number of languages and systems as was used here should be avoided.

3.1.5 Hardware

3.1.5.1 LLL-HW-01

Title: Missing On-Board clock synchronization
Domain: Hardware

Details: Time synchronisation between the service module Data handling system, the Payload Data Handling System and the ISFEE commanding is very important for actuation commanding and telemetry time stamping. In LTP the ISFEE and the OMS receive the main clock signal from the DMU, which is a different clock than the one used in the OBC, with which ISFEE exchanges data. This causes mutual clock drift and from time to time, when two clocks *cross* each other, a transient and change in the sensing noise when ISFEE is in WR mode. The reason for this is that the 10 Hz pace of the ISFEE and the DFACS are drifting w.r.t. each other, leading to a non-deterministic scheme of applying actuation versus the sampling of the mass position. Some of the consequences of this are:

i. In order to get 10Hz data from the OMS (via the DMU) the synchronisation is done by dropping one of the 100Hz DMU samples, or by using one twice - depending on the clock drift and jitter;
ii. Combining data sampled with drifting clocks requires resampling of the data onto a common grid. This produces beat note like artefacts, especially at high signal frequencies;
iii. FEE clock drifts are very messy;

A large extra effort was required to mitigate the timing issues both for HW and DA, e.g. for drift mode and OMS:

i. Pre-processing and resampling was required to correct timing issues;
ii. Required workarounds in the MOC;

For LISA it is still not clear if time synchronization of all 3 spacecraft is required. Performing the time correlation of the 3 spacecraft with only one spacecraft contact per day could be a problem. In this case inter-satellite correlation would be needed.

There must be a fixed scheme of when samples of the mass position are read from the ISFEE and actuation is applied. That requires the DFACS to run synchronous with the ISFEE. If drifting between the two is prevented by providing a common clock, it is to be considered that the ISFEE is sensitive to clock quality (jitter, stability etc.). Interface requirements must be established early in the project, as changes in the clock interface have a huge impact on the ISFEE design.

Recommendation: Either a common clock for OBC and ISFEE shall be used or the ISFEE shall implement its own free-running clock that can synchronize to the OBC clock. When a redundant clock is available, it is required that any swap over of clocks should not lead to time discontinuities.

Interface requirements must be established early in the project, as changes in the clock interface will have a huge impact on the ISFEE design.

3.1.5.2 LLL-HW-02

Title: TM release should be reliable and automated.
Severity: Significant

Details: All TM Releases after commissioning and before the end-of-mission campaign, were performed in a manual fashion driven by the operator, along the following lines:

- Prepare the CCU/DFACS/ISFEE for TM release
- Release with small (few 100s um) TM Plunger displacement and observe TM velocities and position/attitude
- Allow bouncing somewhere/everywhere to dampen the velocity
- Wait for TM to cross the centre of the housing, and then enable DFACS control (and ISFEE actuation)
- Wait and Pray…
- If TM sticks somewhere/everywhere, stop DFACS control, kick TM with plunger/pin and repeat

The key in this process was waiting for the TM state vector combination to be ***good enough*** before enabling actuation, otherwise control was impossible and TM would always end up in a corner.

This approach was possible for LPF, only because twice the OWLT was around 10s, which allowed ground intervention in a timely manner. For LISA, the OWLT is closer to 6 mins and this approach would simply not be possible.

As part of the end-of-mission automatic TM release campaign, it was demonstrated that a timeline driven and dependable TM Release procedure is possible with the flight hardware flown for LPF, albeit with significant changes to the control and actuation software.

Recommendation: For LISA:

1. Taking into account the release campaign performed at the end of the mission:
    a. Work to understand what are the driving factors behind the large and inconsistent TM release velocities observed on most releases. There are more than 100 releases to look at for each TM, but unfortunately there was no way to inspect the TM-Pin-Plunger geometry prior to release and what happens during the release process.

b. Take particular attention to the fact that TM1 was consistently better than TM2 during the Automatic Release case where all the tricks were put in place as part of the procedure. There is certainly knowledge hidden here and perhaps hard evidence in the as-built documentation. If all LISA TMs can be built as LPF TM1, TM Release would be a breeze!

2. Carefully judge any change proposals to the GPRM & Housing based on its merit vs risk of making things worse;
3. For the reasons explained in the details the TM Release procedure for LISA needs to be driven without expecting quick ground response.
4. We were very lucky that we found the *right* combination of tricks just before the end. The Automatic TM Release procedure and changes implemented in the control and actuation software were passed to the key actors in this area in LPF. Draw the necessary lessons from this knowledge and implement a reliable system in LISA.

Notes: For LISA, TM release procedure must be iterated with the LISA MOC team before implementation. For details of the TM release campaign at the end of the mission see the presentation in [RD-02].

3.1.5.3 LLL-HW-03

Title: Improve robustness to micro meteorite impact
Severity: Significant

Details: There were at least 3 cases were we dropped out of Science (via LTP Safe), due to micro-meteorite events. In all these cases, control was lost due to excessive CGAS actuation causing overflow to the virtual thruster and loss of TM control in Z.

There is at least one additional event which had sufficient energy to drop us out of science, but it happened during DRS Science operations, so we didn't.

The current System design was not robust to these events, and this caused loss of science time, around 1 day per event.

Recommendation: For LISA, we should try to survive through these impacts without dropping out of science, just like it happened when the DRS was in control. It is suggested the following should be taken into consideration at the design stage:

1. Analyse the micro-meteorite impacts in LPF and extract the momentum transfer;
2. Formulate a requirement to define a threshold/criteria that the system should be able to cope with without dropping out of science.

Technically, the only way to make this happen, is to implement the micro-thruster system such that the produced forces and torques have the same spatial direction as requested by the controller, even though the magnitude may be clipped. In practice this means:

1. Implement a symmetric micro-thruster system such that there is no need for a virtual thruster in the thruster allocation algorithm;
2. If the micro thruster system is asymmetric (like with the CGAS in LPF), implement appropriate means, e.g. force/torque scaling/clipping or a different Thruster

Allocation Algorithm, such that the produced force and torques have the correct direction.
3. LISA must implement full 6-DOF control for the S/C control

The situation in LISA will be worse due to the size of the satellite (solar array) and the fact that we have three S/C in the constellation and must not lose constellation lock (not just TM control). The situation is helped (slightly) due to the mass of the s/c, but it is worse due to higher torque for an impact at the edge of the array.

Notes: A similar issue was raised by the DRS.

3.1.5.4 LLL-HW-04

Title: Missing temperature stabilization in the RLU
Severity: Significant

Details: There was a design error in the RLU temperature stabilisation. This was highlighted by scientists but industry did not want to change the design, even when a suitable design solution was proposed. The result of this was:
1. During operations it was difficult and labour intensive to stabilise the laser temperature;
2. The method for finding a laser working point was non-reproducible;
3. Could not develop a laser stability vs. temperature map;
4. The newer units show some improvement in the temperature stability.

Recommendation: For LISA:
1. Perform end-to-end testing (for LPF there was no end-to-end testing that could spot the control strategy used);
2. Management should ensure that technical advice is used when the impact is large and the changes minor;
3. Use proper laser temperature control.

Notes: This may not be relevant for LISA because OMS will very likely be different from the one used for LPF.

3.1.5.5 LLL-HW-05

Title: EDAC protection of all the RAM systems
Severity: Significant

Details: The shared RAM of the MIL-BUS-1553 chipset used in DMU was not EDAC protected. During operation several errors were raised and they have been traced to the lack of protection. This problem should have been flagged during development.

For LISA, with 3 satellites we should expect three times the frequency of errors and possible interruptions.

Recommendation: For LISA use integrated memory or in the case external memory is required ensure it is EDAC protected.

Notes: The robustness of each LISA S/C is crucial for the reliability of the constellation.

3.1.5.6 LLL-HW-06

Title: SEU related interruptions
Severity: Significant

Details: Payload and Spacecraft should be resilient to SEUs, in working memory, ram, CCD, controllers and communications. Many occurred on LPF leading to the affected unit (some with hot swap-over, some without) becoming unavailable.

For LISA we should keep in mind that with three S/C we should expect three times the frequency of interruptions, with each interruption stopping 2 of the 3 laser arms.

Recommendation: Use radiation tolerant components in all units, payload and service module. FDIR should do swap-over of SEU affected unit without interrupting science.

3.1.5.7 LLL-HW-07

Title: ISFEE actuation channels can saturate and lock
Severity: Significant

Details: The ISFEE actuation sigma-delta loop in LTP can under certain limiting conditions saturate and not respond (lock) to new commands, which leads to a larger power consumption and possibly uncontrolled TM movement. In addition, the actuation commanding in both HR and WR mode necessitates restrictions, i.e. full level AC amplitudes or DC voltages cannot be applied in one step. These restrictions complicate operations and could also lead to saturations if not followed, e.g. in FDIR mode. A lack of knowledge of real operation in WR mode contributed to the missing verification of transitory operational cases.

Recommendation: Requirements must be updated in order to cover all flight scenarios including all possible transitions that can occur.

The unit must be tested as it is flown. Verification of the ISFEE shall be defined accordingly.

Notes: The requirements on the ISFEE should be more complete in order to cover all possible flight scenarios so that ground testing can be as complete as possible.

3.1.5.8 LLL-HW-08

Title: DFACS and CMS configurability was overall a very powerful tool
Severity: Significant

Details: The DFACS and CMS implementation topology, based on well-defined blocks, parametrized by matrixes/vectors, and then loaded at mode entry, proved to be very powerful. This provided the flexibility to modify/add new control/configuration modes in flight with reduced effort.

Recommendation: For LISA, the configurability of the controllers should be maintained.

3.1.5.9 LLL-HW-09

Title: LTP Safe to protect the S/C and experiment from itself was the single most useful on-board FDIR.
Severity: Significant

Details: The LTP Safe FDIR was used extensively in flight. There were at least nine anomalies whose consequences were mitigated by its existence. This FDIR has saved us from several Test Mass Grabs and even System Safe Mode, saving us several days to perform science activities. What not everyone knows is that this FDIR was a late addition to the on-board design, and was not there during the SOVT! Finally, even the last recovery activities were only implemented in flight at the end of commissioning (passivate the CMS, Lamps, DFACS signals, etc) via OBCP.

In an integrated spacecraft like LPF, where the experiment controls the S/C, the S/C and the experiment needs to be protected from itself and therefore a first level FDIR which looks at the flight envelope (in this case, TM and S/C) should always exist, with a thorough and robust recovery to all defaults.

Recommendation: For LISA, a mode independent FDIR like LTP Safe that monitors the science envelope should be foreseen in the design from the start.

Notes: Instrument Safe mode is a must for LISA. This mode should be based on the LTP Safe mode. Instrument Safe mode should be implemented at the beginning, not the end as in LPF.

Before SOVT, if the ISFEE was in WR mode, then any anomaly resulted in direct grab of the test masses. After SOVT, the ability to go from NOM1 (or DRS) back to ACC3 was implemented. Thanks go to DRS for this as it was only noticed when they lost control during SOVTs!

3.1.5.10 LLL-HW-10

Title: Proprietary information restricts knowledge of industry built units
Severity: Low

Details: In general, proprietary information restricted knowledge of industry built units. An example illustrates the problem: the internal layout of the RLU was not known in detail prior to operations. As far as we know, no thought went into this before operations began. Only after consulting industry mostly on a *good will* basis did we learn about the layout of the RLU. Still, the knowledge we have is still slightly unofficial. Similar experiences were reported with the ISFEE FPGA and the power supply of the PCU (ISFEE).

Some negative consequences arise from this lack of official information:

- Commissioning was more difficult and labour intensive than it could have been: e.g. the unknown location of heaters in RLU made controlling the internal temperature more difficult;
- Publishing information about systems with proprietary industry components may be problematic;
- When the team working on the units is no longer available due to the long time between delivery and operations (even longer for LISA than for LPF) obtaining the relevant information on industry provided units may become almost impossible.

Recommendation: For LISA:

1. Make sure we have official access to important information about industry provided units;
2. Think in advance about what information we might need during operations and commissioning for each industry provided unit;
3. Reach agreements prior to launch regarding publications.

Notes: Project should be informed about this lesson learned to avoid its repetition in LISA. Extensive testing to characterize these subsystems is required.

3.1.5.11 LLL-HW-11

Title: Charge Management Software Support for both TMs simultaneously
Severity: Significant

Details: The Charge Management Software implemented in LPF only supported discharge operations on one TM at a time. There is/was no technical constraint for this, as the charge estimation was independent, and a single Lamp could have been used for discharge of each TM, to be chosen depending on the discharge direction.

This lead to an unnecessary waste of time to discharge both TMs sequentially, when they could have been discharged in parallel.

Recommendation: For LISA, the discharge of both TMs should also be supported in parallel in order to save time.

Notes: In LISA we will use UVLED as the UV light source. The bigger issue in LISA is the coordination of test mass discharge around the constellation. This is something for the Calibration WG to ponder on.

3.1.5.12 LLL-HW-12

Title: DFACS Electrostatic Actuation Algorithm improvements
Severity: Significant

Details: There were several improvements to the Electrostatic Actuation Algorithm implemented during LPF flight:

1. In Science mode, there was a need to reduce the actuation noise, which is proportional to the AC carrier amplitude. For this, we invented the URLA and the UURLA configurations, which consisted essentially in a reduction of the stiffness in the HR Constant Stiffness actuation scheme. However, this also reduced the maximum force authority in HR. To restore the maximum force authority, in case of unplanned need, we changed the HR actuation algorithm to implement a Variable Stiffness fall-back. In reality we only needed HR Variable Stiffness once for fall-back reasons, but we were also never very aggressive in reducing the stiffness further, as the electrostatic noise was no longer the limiting factor. Nevertheless we used the HR Variable Stiffness routinely in some other experiments (e.g. DRS and Newton's constant);
2. The original actuation algorithm is a zero order algorithm derived for a centred TM, for each individual DOF. Due to the non-linear nature of the electrostatics, there are large actuation errors implemented the further away from the centre the TM is. To improve the situation a new electrostatic algorithm with TM state vector feed in, coupled Force/Torque calculation and Asymmetric clipping was implemented and demonstrated in flight. This algorithm was fundamental in the success of some of the most daring tests we did in the end-of-life phase:
    a. Maximum displacement test to approximately 2mm on all DOFs (3mm along x with OMS control);
    b. SK on steroids at 2mm displacement and 500uN S/C acceleration;
    c. Automatic TM Release (See LLL-HW-02)

Recommendation: For LISA, it is suggested:

1. The electrostatic actuation algorithm selection should NOT be ISFEE mode dependent, but instead a DFACS mode dependent configuration parameter. This will allow the selection of the algorithm to be used for each case/DOF, regardless of the ISFEE WR/HR mode, albeit different constants may be needed for each case;
2. The Constant Stiffness algorithm should implement as a fall-back in case the maximum force is exceeded, e.g. Variable Stiffness;
3. Implement a higher order algorithm with TM state vector fed in, to improve TM handling off-centre

3.1.5.13 LLL-HW-13

Title: TTC Downlink data rate lacked configurability
Severity: Significant

Details: LPF has a medium gain antenna, orientation fixed to the S/C. To allow a wide range of final orbits, the antenna needed a relatively wide coverage, and therefore we needed to size the TTC to a relatively low gain, but maintain a large dynamic gain range. For LPF the design gain range of the antenna was about 7dB (over 17deg).

As it often happens, the S/C was launched on the target date, into a good final orbit, meaning we used the antenna always close to the boresight, and therefore had much more margin than was foreseen by the worst case driven design. Unfortunately, we could not easily use this margin because the Transponder available data rates were hardcoded in the unit. Eventually we managed to slightly more than double the data rate by removing FEC (Convolutional Coding and Reed Solomon coding), but at the expense of also losing the coding gain efficiency, and ultimately having no FEC left. If we had additional data rates options available on board, we would easily have been able to at least quadruple the original "high data rate" in flight, from 50kbps to 200+ kbps.

Recommendation: Spacecraft TTC design should foresee various coded data rates to cover the link margin dynamic range the S/C will see in its operational orbit, such as to best fit the data rate to the conditions seen in orbit and optimize the S/C science return or reduce the mission cost by reducing G/S coverage and MOC manning.

Notes: Due to the alignment of the MGA to Earth (we were aligned within 4-5 degrees of the boresight), we had excessive margin on the link. Therefore on Day 1 we switched on convolutional encoding, doubling the data rate!

For LISA we should size the system and design the telemetry such that we optimise the link as we scan across the HGA antenna pattern.

3.1.5.14 LLL-HW-14

Title: On board Software updates (Service module SW, Payload Module SW, Star Tracker Software) should be possible without mission interruption.
Severity: Significant

Details: Software updates should be possible to all on-board systems without reboot of payload or service module computer, re-grabbing the test masses or losing laser sync; RAM patches should be possible for isolated function updates prior to any EEPROM reboot.

During flight there will be many issues experienced and optimisations discovered which can significantly improve the in-flight science return. OBCPs, and SDP updates can be used for some of them but software updates are required for some to really improve the situation, and are often far easier to write and validate that other work-around alternatives.

Recommendation: Either hot swap over of units or hot RAM patching of software should be possible. Building RAM patches is something that is typically possible with standard on board software compilers with the correct configuration and processes with minimal human intervention.

3.1.5.15 LLL-HW-15

Title: System testing
Severity: Significant

Details: During the OSTT, with the TOQM, the interferometer could have been tested in the flight configuration. However, due to the laser power, additional fibres were added to reduce the laser power stabilisation diodes. This led to the test being non-flight representative. In this case, most unexplained noise observations were blamed on the fibres!

Recommendation: All system tests of flight hardware performed on ground, should be done in the flight configuration. ***Test as you fly, fly as you test***.

3.1.5.16 LLL-HW-16

Title: Integration procedures
Severity: Significant

Details: Two flight fibres were inadvertently swapped during final integration. Fibres damage also occurred during STM integration resulting in suggestion that final integration should include subsystem support, which was never implemented.

Recommendation: Some subsystem integration operations should include presence of subsystem reps.

3.1.5.17 LLL-HW-17

Title: System level requirement specifications (CMS)
Severity: Significant

Details: The full system level requirement recommendations from the CMS Engineering Model studies were not fully assimilated by the Project at an early enough stage resulting in late stage recovery actions.

Recommendation: Make sure all parties are properly engaged in early system requirement specification evaluations, especially where the overall performance relies on several sub-systems (hardware and flight software) working together.

Notes: The EM of the ULU was delivered without a system spec being in place and therefore the EM was not compatible with the RTB! As a consequence, there was no ULU in the RTB.

Also, originally the ICL contribution was the ULU but later they were asked to also provide the UV harness within the same mass budget. This lead to the mass increase and subsequent descope of one of the lamps. Had the harness been included from day one, the mass of the harness would have been included in the overall ULU mass budget and the descope would not have happened.

For LISA we will establish a System Engineering Office which will have visibility all the way down to subsystem level. Consortium members will also participate in the SEO, so will also have the visibility. This has been established to try to avoid this type of problem.

3.1.5.18 LLL-HW-19

Title: Thruster configuration on the spacecraft
Severity: Significant

Details: Having only two clusters of four thrusters did not provide much contingency, in terms of redundancy in control, for DRS and the spacecraft. The third DRS thruster cluster was descoped early on in the mission, but having it could have avoided the need for *crutch mode* when thruster 4 shorted.

After the thruster 4 short, DRS was able to continue and execute its extended mission by using *Crutch Mode* in which four cold gas thrusters were used to provide a static bias so that the remaining 7 colloid thrusters could operate in drag-free modes. While this operating mode was functional, the cold gas thrusters measurably increased the propulsion noise as compared to the pure colloid modes.

Recommendation: Thruster configurations on the spacecraft should be robust to one or more thruster failures in terms of full spacecraft attitude control.

3.1.5.19 LLL-HW-20

Title: STOC access to DRS documentation
Severity: Low

Details: The STOC had very limited visibility the DRS documentation and in particular to the scientific planning. Given that all this information was available from the DRS wiki it would have been very useful if the STOC could access the wiki from early on during mission development. The limited visibility the STOC had of the DRS documentation and scientific planning made it also very difficult to track the versions of the sequences uploaded to the S/C.

Recommendation: For LISA, the documentation of the NASA provided systems that is relevant for planning and operations should be made available to the SOC with as little restrictions as possible. A wiki at ESAC allowing access to all the operations team could be a viable solution. This could be also be integrated in the LISA Operations Archive (see LPF Science Archive for a discussion of the LISA archive).

3.1.6 Other

3.1.6.1 LLL-OTH-01

Title: Organisation of Lessons Learned
Severity: Moderate

Details: The Lessons Learned review is always done at the end of operations, and often focussed solely on the operations. Some of the issues found out during the Lessons Learned, if spotted early on during the mission could be corrected before the end of the mission. A Lessons Learned review at the end of the Development phase would make it possible to try to fix some of the issues found out during the development phase, or in the worst case, at least make the science teams aware of limitations that could otherwise go unnoticed until they are rediscovered during operations. A Lessons Learned review at the end of the development phase would require a Lessons Learned register to be in place since the beginning of development in order to keep track of all the issues reported.

Recommendation: Start a Lessons Learned register at the beginning of the mission development and have a Lesson Learned exercise at the end of the Development phase to keep track of the issues registered since the beginning of the development phase.

Notes: The possibility of having a LL repository open from the beginning of the study phase is contemplated in [AD-01].

3.1.7 LPF Science Archive

3.1.7.1 LLL-SCA-01

Title: LPF Science archive development
Severity: Significant
Details: The development of the LPFSA started late, just a few months before launch and the first public release only happened in October 2016. The late development start for the LPFSA, led the PI teams (with support from the STOC) to develop their own archiving infrastructure. As this was written mainly in MATLAB, a tool that is not compatible with the archives developed by the ESDC, the PI teams will not be able to use the LPFSA as the development effort involved in making their pipelines compatible with the LPFSA is not feasible at this point. Availability of the LPFSA during the mission would also have allowed the development of an operations archive which, once again, was developed completely outside the LPFSA environment.

The late development of the LPFSA had as a consequence the duplication of effort in the development of the archiving infrastructure with all the risks associated. In particular, in the case of LPF, a problem was found after the ingestion of the raw AOs that could have been avoided with a more integrated approach to archive development.

Recommendation: The archive development schedule for future missions (and of special concern here is LISA) should contemplate the development of an Operational Archive taking the following into consideration:

1. Development of the archives should take into consideration the commonalities between the Operations and the Science Archives.
2. Access to the archives should be granted taking into account that different user profiles will need to access different types of data, i.e.
   a. Operations teams should have access to all the relevant Operational data;
   b. Science teams should have access to all the data required to their normal work. This may include simulations;
   c. Normal users with no affiliations to any of the teams involved in Operations should only be granted access to data after the proprietary period has expired;
3. Operational data should be distributed between the different agents (SOC, MOC, Operations teams, PI teams) through the operations archive;
4. Early on during the development stage and foreseeably much before launch, the Operational archive should store and provide access to simulated data to all relevant users involved in mission development activities. This may actually be the requirement that sets the schedule for the initial step in the development of the archives;

5. The transition from the Operations Archive to the Scientific Archive should be seamless. For the users it should be completely transparent. The only changes users should notice is that their access privileges will change according to the different phases of the mission;
6. The development plans should be drafted in order to avoid as much as possible the duplications of tools and infrastructure between the Operations and the Science Archive;

4 CONCLUSIONS

Although by the time the last session of the LLL was held, the LPF teams were already dismembering, the interest and effort put by all the participants in this exercise had not in any way dwindled. This undiminished effort can easily be traced to the fact that each and every one of the issues discussed during the LLL, is of relevance to LISA. The more that 400 separate inputs received are a clear evidence the of interest of the LPF community in the development of LISA.

APPENDIX I: MINUTES OF LLL SESSIONS

Minutes of LLL Session I
Minutes of LLL Session II

APPENDIX II: FULL LL INPUTS FROM LLL SESSIONS

Inputs for LLL Session I
Inputs for LLL Session II
Inputs for LLL Session III

APPENDIX III : PRESENTATIONS FROM LLL SESSIONS

Slides for LLL Session I
Slides for LLL Session II
Slides for LLL Session III