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DOCUMENT

LOFT Preliminary Requirements Review (PRR)
Technical and Programmatic Report

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APPROVAL

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CHANGE LOG

Reason for change	Issue	Revision	Date
Fixed broken reference	1	1	22/11/2013
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CHANGE RECORD

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Broken reference	22/11/2013	4	§1.2
Incorporation of SRE Dept. head comments and feedback.	06/12/2013	throughout	throughout
Incorporation of 2nd round comments.	10/12/2013	throughout	throughout

Contents

1 INTRODUCTION

1.1 M3 mission in ESA Cosmic Vision plan

Following the Call for M3 mission proposals that was issued in July 2010, five mission candidates are today competing for M3 nominal launch slot in 2024:

- EChO, an Exoplanet Characterisation Observatory,
- LOFT, a Large Observatory For X-ray Timing,
- MarcoPolo-R, a Near-Earth Asteroid (NEA) sample return mission,
- PLATO, an Exoplanet mission devoted to PLAnetary Transit and Oscillations of stars,
- STE-QUEST, a Space-Time Explorer and Quantum Equivalence Principle Space Test.

M3 timeline is recalled in Table 1. With the exception of PLATO, for which an assessment study was completed in 2011, the other missions have recently completed their Assessment Phase (phase A). A Preliminary Requirements Review (PRR) of all candidate missions has been performed to review their status in support of the M3 selection. This document reports the results of the technical and programmatic review for the LOFT mission candidate.

Event	Date
Selection of M3 mission candidates	*Feb 2011*
Industrial studies kick-off	*Feb 2012*
Industrial studies mid-term reviews with model payload	*Jul 2012*
Instrumentation AO	*Sept 2012*
Selection of instrument teams	*Feb 2013*
Industrial Phase A studies data package delivery for PRR	*Sept 2013*
ESA technical and programmatic reviews completed	Dec 2013
Public presentations, Science Advisory Structure assessment and SSAC recommendation for M3 selection	Jan 2014
M3 mission selection by the SPC	Feb 2014
Phase B1 completion for the selected mission	Nov 2015
M3 mission adoption by the SPC	Q1 2016
Industrial Phase B2/C/D kick-off	Sept-Oct 2016
M3 nominal launch	by 2024 (*)

Table 1- Timeline for M3 selection and implementation

(*) Compatibility of M3 implementation with a launch by 2022 was requested

1.2 M3 Reviews: Process and Objectives

The independent reviews followed a common procedure and have several objectives:

1) Assess the design maturity of the mission at the end of Phase A
2) Evaluate ESA Estimate at Completion (EaC)
3) Provide recommendations for the next phases

While objectives 1) and 2) serve the M3 selection process, the third objective is actually applicable only to the mission that would be selected.

For each mission candidate, the reviews were chaired by an experienced project manager and supported by a number of senior engineers and technical experts across the Agency, involving typically about 20 people per mission, with a natural dispersion depending on the mission needs and the review Chairman requests. The reviewers are independent of the study team, and the latter was supporting the review process on the request of the Chairman e.g. by providing the historical background and answering questions raised by the reviewers. For practical reasons, the reviews were conducted in parallel for the five missions and the reviewers were distributed in two panels:

- A technical and programmatic panel (also called Review Panel), assessing all technical aspects for the mission implementation, including: mission requirements and flow down to engineering level; spacecraft definition and technology readiness; science payload definition and technology readiness; launch aspects and launcher compatibility; ground segment and operations; spacecraft development plan (model philosophy, schedule for the spacecraft and payload elements) and the associated development risks.
- A cost panel, in charge of assessing ESA costs (EaC), taking into account the technical and programmatic findings

The input documentation is constituted of:

- ESA requirement documents (e.g. Science Requirements Document, Mission Requirements Document, Experiment Interface Documents, etc)
- The data packages provided by the two industrial contractors
- The data package provided by the instrument consortia

The Review Panel was specifically tasked with the following activities:

a- Confirmation of the Mission and System requirements:
  - Adequacy and completeness of ESA Mission Requirements
  - Adequacy, completeness and traceability of spacecraft, payload, ground segment and launcher requirements
  - Adequacy and completeness of interfaces definition

b- Confirmation of the mission technical feasibility:
  - Mission design justification and compliance with applicable requirements

- Concept of operations, observing strategy and modes (where applicable), calibration aspects, driving requirements on mission, spacecraft and payload design
- Validity and maturity of the spacecraft and payload design concept
- Margin philosophy
- Adequacy, completeness and credibility of system, spacecraft and payload budgets and margins
- Availability of appropriate models and analyses in support to design definition
- Identification of critical technologies for the spacecraft and payload, identification of current technological maturity and availability of credible roadmap to achieve TRL 5 before adoption, critical review of ongoing technology development activities

c- Confirmation of the mission programmatic feasibility:
- Critical review of the spacecraft and payload development plans
- Adequacy and completeness of the proposed development and verification approach
- Model philosophy
- Realism and completeness of spacecraft and payload development schedule (incl. margins)
- Compatibility of payload need and delivery dates
- Critical path analysis
- Risk assessment and related mitigation plan
- Credibility and compatibility of technology maturation roadmap schedule with system schedule

The reviews were implemented through a series of meetings held throughout October and November. Towards the end of the review process, the major findings were presented to a common management board in the science directorate, who further challenged some findings and, in some cases, requested additional clarifications. A substantial effort was devoted to the harmonisation and cross-verification of the cost estimates.

This report provides a summary of the Review Panel findings. It is made public for the sake of transparency and for providing feedback to all teams who actively contributed to the mission assessment phase, namely: the study science team and the science community supporting the mission, the science instrument consortia, the industrial study teams, and ESA study team.

2 LOFT MISSION DESCRIPTION

2.1 Science Goals

High-time-resolution X-ray observations of compact objects provide direct access to strong-field gravity, black hole masses and spins, and the equation of state of ultra-dense matter. A 10 m^2 class instrument in combination with good spectral resolution is required to exploit the relevant diagnostics and answer two fundamental questions of ESA's Cosmic Vision Theme "Matter under extreme conditions", namely:

- Does matter orbiting close to the event horizon follow the predictions of general relativity?
- What is the equation of state of matter in neutron stars?

Due to an innovative design and the development of large monolithic silicon drift detectors, the Large Area Detector (LAD) on board LOFT will achieve an effective area of ~10 m^2 (more than an order of magnitude larger than current space-borne X-ray detectors) in the 2-30 keV range (up to 80 keV in extended mode). With this large area and a nominal spectral resolution of <240 eV over the entire band, LOFT will facilitate the study of collapsed objects in our galaxy and of the brightest supermassive black holes in active galactic nuclei, yielding unprecedented information on strongly curved space-times and matter under extreme conditions of pressure and magnetic field strength.

The Wide Field Monitor (WFM) will provide a ~1.5π steradian coverage of the sky, acting as a context provider to the LAD instrument.

In addition to these core science goals, LOFT will provide a 50% allocation of observing time to observatory science, and also provide a burst-alert function (LBAS) to the astronomy community.

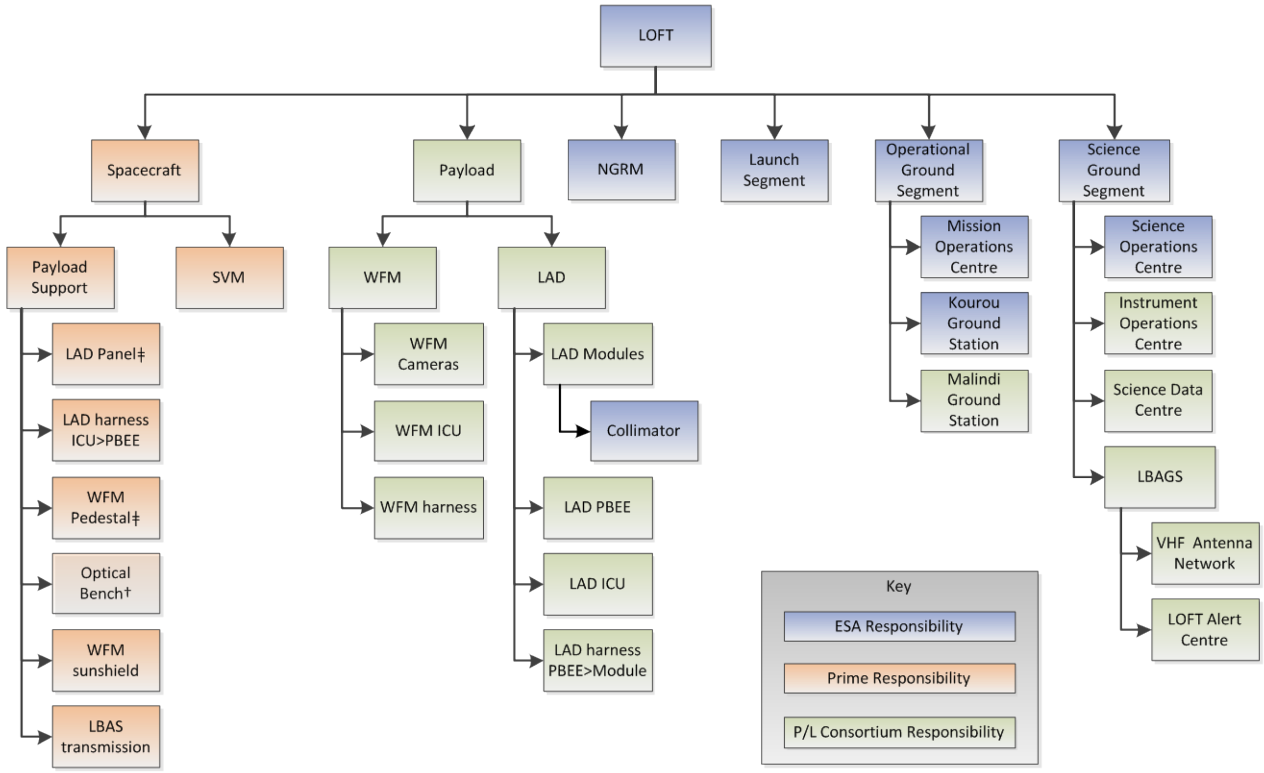
2.2 Mission & System Description

The LOFT mission consists of the complete end-to-end system (Payload, Spacecraft, Operational and Science Ground Segments, Launcher), which fulfils the mission requirements according to the Product Tree shown below.

The LOFT space segment consists of a Spacecraft (hereafter SC), composed of a Payload Module (PLM) hosting the payload (PL), and the Service Module (SVM). The PLM mainly consists of the two[1] scientific instruments of the mission, Large Area Detector (LAD) and Wide Field Monitor (WFM), as well as the structure and mechanisms that support them (additional SC equipment can be accommodated on the PLM as well, e.g. star trackers).

The space segment will be launched in to an equatorial LEO by the Soyuz-Fregat launch vehicle from Kourou – this orbit is chosen in order to limit the radiation damage to the detectors of

[1] The Next Generation Radiation Monitor (NGRM) is accommodated on the PLM, but is not part of the LOFT payload.



‡ Includes thermal control and deployment/hold-down mechanisms
†if applicable, can include other supporting structure within a clearly defined PLM (alternatively can be considered part of SVM structure)

Figure 1: LOFT system product tree

the LAD and WFM instruments throughout the mission lifetime (balanced primarily against the propellant requirements to maintain the low altitude orbit against atmospheric drag.)

The ESA ground segment comprises a Mission Operation Centre (MOC), a Science Operation Centre (SOC) and uses the Kourou and Malindi Ground Stations (GS) to control the SC. The ground segment receives and processes the telemetry, and disseminates and archives the generated data products. This is complemented by the Payload Consortium provided Loft Burst Alert System (LBAS), a distributed network of VHF ground stations, which provides near real-time alerts of transient x-ray events.

The MOC is responsible for the operations of the spacecraft and instruments, for ensuring the spacecraft safety and health, for provision of flight dynamics support including determination and control of the satellite’s orbit and attitude and for provision of auxiliary data to the SOC. The MOC performs all communications with the satellite through the ground stations.

Note that this does not include the WFM burst-alert transmissions, which are communicated to the Payload Consortium provided VHF ground network and then distributed to the scientific community and SOC.

The SOC is further supported by a Science Data Centre (SDC) and two Instrument Operation Centres (IOC).

3 APPLICABLE AND REFERENCE DOCUMENTS

3.1 Applicable Documents

[AD 1] Preliminary Requirement Review (PRR) of candidate M3 missions in the ESA Cosmic Vision programme – Review procedure. SRE-F/2013.042, Issue 2.3, 15/10/2013.

3.2 Reference Documents

[RD 1] M3 Missions Reference Schedule (in preparation for M3 missions PRRs). SRE-F/2013.039, Issue 1.0, 23/04/2013.
[RD 2] LOFT – PRR Document List. ESA-LOFT-LI-0001, Issue 1.0, 01/10/2013.
[RD 3] LOFT – PRR Cost Report, ESA-LOFT-RP-0007, Issue 1.0, 29/11/2013.

4 ACRONYM LIST

AIT	Assembly Integration & Test
AKE	Absolute Knowledge Error
AOCS	Attitude & Orbit Control System
APE	Absolute Performance Error
ASD	Astrium Deutschland
ASIC	Application Specific Integrated Circuit
CFRP	Carbon Fibre Reinforced Plastic
CoNOPs	Concept of Operations
CP	Cost Panel
CTE	Coefficient of Thermal Expansion
EaC	Estimate at Completion
EFM	Electrical Functional Model
EFoR	Extended Field of Regard
EID-A	Experiment Interface Document (Part A)
EID-B	Experiment Interface Document (Part B)
EM	Engineering Model
EMC	Electro-Magnetic Compatibility
EO	Earth Observation
EoL	End of Life
EOP	Extended Operations Phase
EQM	Engineering Qualification Model
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESD	Electro-Static Discharge
ESOC	European Space Operations Centre
FEE	Front End Electronics
FEM	Finite Element Model
FM	Flight Model

FoR	Field of Regard
GMM	Geometric Mathematical Model
HDRM	Hold-Down & Release Mechanism
I/F	Interface
ICU	Instrument Control Unit
ITT	Invitation To Tender
JAXA	Japanese Aerospace Exploration Agency
LAD	Large Area Detector
LEOP	Launch & Early Operations Phase
LISA	Laser Interferometry Satellite Antenna
LOFT	Large Observatory For x-ray Timing
LST	LOFT Science Team
MAD	Mission Assumptions Document
MAIT	Manufacturing Assembly Integration & Test
MBEE	Module Back End Electronics
MIRD	Mission Implementation Requirements Document
MOC	Mission Operations Centre
MPC	Micro Pore Collimator
MRD	Mission Requirements Document
NFoR	Nominal Field of Regard
NIEL	Non-Ionising Energy Loss
NOP	Nominal Operations Phase
OAR	Open Area Ratio
OBC	On-Board Computer
OoF	Out of Field
PBEE	Payload Back End Electronics
PCB	Printed Circuit Board
PCDU	Power Control & Distribution Unit
PDR	Preliminary Design Review
PFM	Proto-Flight Model
PI	Principal Investigator
PL	Payload
PLM	Payload Module
PPS	Pulse Per Second
PRD	Payload Requirements Document
PRR	Preliminary Requirements Review
QM	Qualification Model
QR	Qualification Review
RPE	Relative Performance Error
RTM	Reduced Thermal Model
RW	Reaction Wheel
s/s	Subsystem
SAA	Sun Aspect Angle
SC	Spacecraft
SciRD	Science Requirements Document
SDD	Silicon Drift Detector
SDM	Structural Dummy Model
SEU	Single Event Upset
SIRD	Science Implementation Requirements Document

SM	Structural Model
SMOS	Soil Moisture & Ocean Salinity mission
SOAD	Science Operations Assumptions Document
SOC	Science Operations Centre
SPBD	System Performance Budgets Document
SPC	Science Programme Committee
SRD	System Requirements Document
SRR	System Requirements Review
STS	System Technical Specification
SVM	Service Module
TAS	Thales-Alenia Space
TB	Thermal Balance
TDA	Technology Development Activity
TID	Total Integrated Dose
TM	Thermal Model
TMM	Thermal Mathematical Model
TRL	Technology Readiness Level
TV	Thermal Vacuum
WFM	Wide Field Monitor
XMM	X-ray Multi Mirror mission

5 TECHNICAL REVIEW OUTCOME

5.1 Mission and System requirements

5.1.1 ESA mission requirements

The specification tree has been properly structured (see Figure 2) and is adequate for Phase A. It is based on the following key documents:

- Science Requirements Document (SciRD)
- Concept of Operations (CoNOPs)
- System Performance Budget Document (SPBD)
- Mission Requirements Document (MRD)

with a clear traceability and sound first iteration of the requirement breakdown, and unambiguous allocation of requirements to the different mission elements.

For the next project phase it is recommended to produce a System Requirement Document (SRD) & Payload Requirements Document (PRD) to elaborate requirements on the Spacecraft and payload (these are currently held as MRD chapters.)

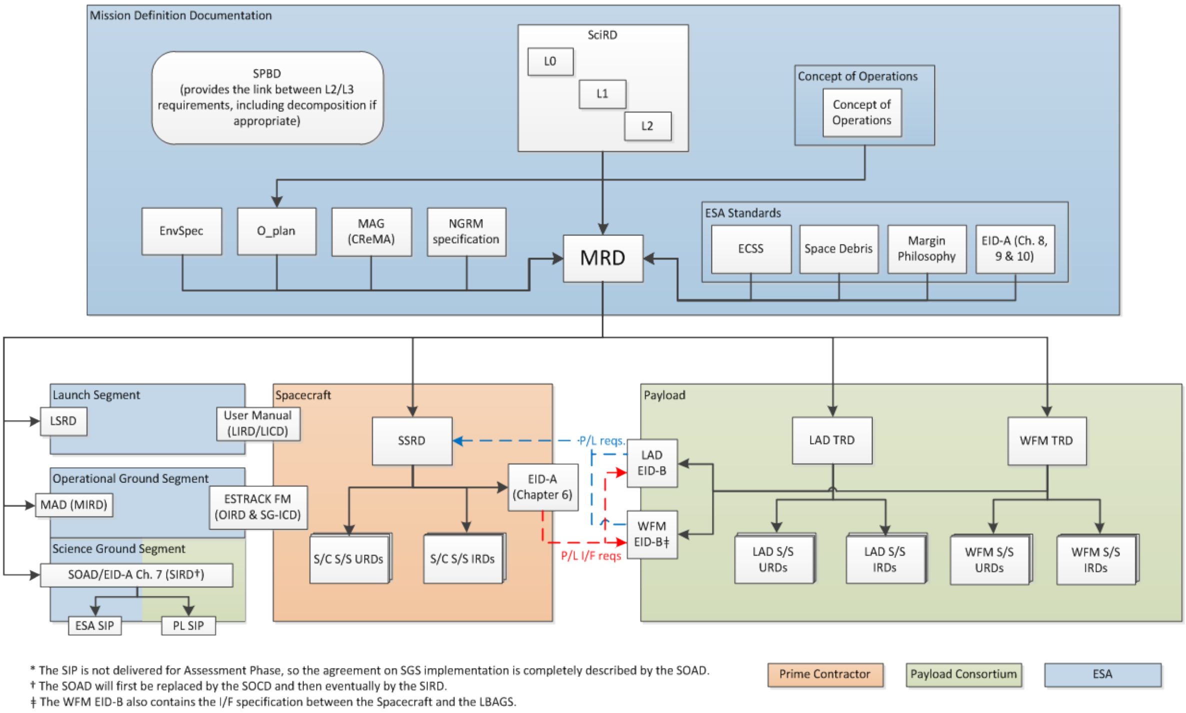


Figure 2: LOFT ESA requirement tree

5.1.1.1 SciRD

The SciRD has a clear flow-down from top-level science objectives to instrument performance requirements, classifies requirements according to their criticality for the mission and provides good information on the dependencies between the critical science requirements of:

- LAD effective area [SCI-LAD-R-01]
- LAD spectral resolution [SCI-LAD-R-08]
- LAD sky visibility & Field of Regard (FoR) [SCI-SYS-R-19, SCI-SYS-R-05]
- Mission lifetime [SCI-SYS-R-09].

The relationships between key parameters have been quantified and understood, allowing them to be traded. ***Particularly important is the robustness of the science case to moderate non-compliances in effective area and spectral resolution, which can be compensated by increased observation times (mission lifetime.)***

However, certain SciRD requirements, which were flown down directly to the MRD and which drive the SC design, were not sufficiently justified. These have been removed or loosened after consultation with the Loft Science Team (LST) and Payload Consortium, within the framework of the PRR:

- **Pointing knowledge (AKE) [SCI-SYS-R-10] –** the requirement was not properly justified, and in any case is covered by requirements on APE. It is recommended that this requirement be removed, and covered by a requirement on the availability of data for post-facto attitude reconstruction.
- **Minimum observing time for Out of Field (OoF) targets [SCI-SYS-R-04]** – this requirement compromises on-board safety and imposes operational complexity. It is also not explicitly related to parent requirements in the SciRD (i.e. justification is weak) and is therefore recommended to be removed as a requirement (can be kept as a goal during phase B1.)
- **LAD response stability requirements above 1200Hz [SCI-LAD-R-25]** – Are not meaningful as a requirement because they are not quantified. It is recommended to remove the requirement [SCI-LAD-R-26] and leave only the goal [SCI-LAD-G-26] for Phase B1.
- **Nominal Operations Phase (NOP) Duration* –** the SciRD currently specifies mission lifetime on the basis of assumed LAD instrument availability and Field of Regard. It is recommended to change the specification to just specify net observing times and rare event detection probabilities, related to the Field of Regard (hereafter FoR).

**Note: current SC performance allows the science requirements to be met with a 3 year NOP – see §6.1.2.3.*

These relaxations (along with the LAD temperature stability relaxation described in §6.1.3.1) have the cumulative effect of increasing the robustness of the mission.

5.1.1.2 CoNOPs

The CoNOPs provides an initial justification of those MRD requirements which do not have a basis in the SciRD (programmatic, launcher, applicable standards etc.), completing the derivation of all MRD requirements – for example compliance with Space Debris regulations. ***However it is recommended to develop the CoNOPs further in cooperation with the PI to ensure that operational requirements and use-cases (particularly on the ground segment) are properly captured and justified in time for B1 KO.***

5.1.1.3 MRD

The MRD captures all science and operational requirements, leaves design freedom and trade-space to industry, and allocates requirements unambiguously to the mission elements (SC, PL, MOC, SOC, launcher). ***The decomposition is considered to be sound for the project phase.***

However there are still a few areas in which the MRD should be improved prior to B1 ITT:

- Several requirements from the SciRD were relaxed or removed (see §6.1.1.1), and the MRD should be updated[2] accordingly
- There should be a removal of the excessive number of goals which can cause a confusion in priorities; it is recommended to maintain goals for only a few critical requirements (i.e. the most critical ones such as effective area, FoR, lifetime…) during phase B1.
- A correction is needed for a slight mismatch between PI-reported requirements on WFM camera boresight APE (48'' – WFM EID-B) and the requirement of 55'' stated in the MRD [MRD: R-POIN-020]
- Replace WFM thermal shielding requirement [MRD: R-SYS-080] with WFM temperature stability requirements in [WFM EID-B: Table 6-6]
- Inclusion of effective area loss due to APE in the effective area budget (this requires one additional LAD Module to be accommodated on the SC)
- More quantification in the operational and science ground segment requirements (forming the basis of MIRD/SIRD to be issued by the Project Office during B1)
- Additional requirements to enforce the controlled re-entry scenario.

5.1.2 Tradable MRD Requirements

5.1.2.1 Reference Orbit

Currently the MRD specifies an orbit range to the SC [MRD: R-MIS-030] and launcher [MRD: R-LS-010], defined as:

- 500 – 600 km altitude

[2] These revisions have been made in consultation with the LST and Payload Consortium during the PRR.

- 0 – 5 degrees inclination
- eccentricity ≤ 0.002.

However both Primes have converged on the same reference orbit (550km/2.5°i) where the radiation damage is minimized and thus avoid further need to cool the detectors. The engineering challenge of providing the required cold thermal environment is clearly more difficult than the impact of a lower orbit on propellant requirements.

As a result it is recommended to update the MRD for B1 ITT to enforce a restricted baseline orbit with the following parameters:

- ***550 km altitude***
- ***<2.5 degrees inclination***
- ***eccentricity ≤ 0.002.***

This will avoid any re-opening of the trade during B1, while maintaining the significant launcher performance buffer between 2.5°i down to 0°i (~800kg for a 550x550km orbit.). By this the system and instrument design can progress faster.

5.1.2.2 Effective Area

Currently both industry SC design concepts, which accommodate 124 and 125 modules, have several modules of margin with respect to the requirement of 121, and that this margin can be converted into a relaxed alignment specification if needed. (e.g. ~4 additional modules would allow a more than factor 2 relaxation in the mechanical alignment requirement).

It is recommended to keep the trade-space open in Phase B1 in order to optimize the implementation.

5.1.2.3 LAD Availability, Extended Field of Regard (EFoR) and Nominal Operations Phase Duration

Given the demonstrated Extended Field of Regard (EFoR – see Figure 8***) and LAD availability performance of the two industry SC designs (both >55%, compared to a requirement of 40%), a 3 year NOP duration would be sufficient to meet all science goals.*** A reduction in NOP duration would have minimal impact on the rest of the mission architecture - the total LOFT delta V requirement is dominated by the ΔV required for End-of-Life de-orbit manoeuvre (required to satisfy casualty risk requirements), and is only weakly driven by the orbit maintenance ΔV which is proportional to the number of years in orbit - one year of orbit maintenance is only ~7% of total ΔV.

It is therefore recommended to change the specification:

- ***Increase the required Extended FoR requirement from the current 50% to 64%***
- ***Increase the LAD availability requirement from 40% to >53%***
- ***Reduce the Nominal Operations Phase from the current 4 years to 3 years, and increase the Extended Operations Phase from the current 1 year to 2 years.***

5.1.3 Spacecraft Requirements

SC requirements are expressed via the relevant chapter of the MRD to the industry Primes, who respond with their System Technical Specification (STS). Currently:

- For the TAS industry design only a preliminary STS exists.
- For the ASTRIUM industry design a full set of preliminary specifications exist down to s/s level, ***and is considered mature for the project phase.***

There is a need for requirements to be consolidated at STS-level, for example the mechanical specification.

5.1.3.1 Critical Spacecraft Requirements from EID-B

LAD Temperature Stability: The LAD temperature stability requirements (driven by ASIC gain and offset stability requirements) in the latest EID-B include a temporal and spatial constraint, in comparison to the industrial assessment study formulation which was temporal only. Both industrial designs are not compliant with the EID-B requirement, particularly between different observing attitudes, and this non-compliance will introduce additional dead-time in LAD observations during the period immediately after slew manoeuvres, estimated to degrade the LAD availability by ~10%.

However, as it was known since January 2013 that ASIC test results were available demonstrating very stable ASIC gain/offset stability as a function of temperature, backed up by an on-board linear gain-correction. ***Consequently the requirement has been dropped completely on the basis of these test results and discussion with the PI. Removal of this requirement is very good for the robustness of the mission and SC configuration.***

LAD Absolute Temperature: The LAD detector absolute temperature requirements within the NFoR (currently -10°C at end of nominal operations for a 500km/2.5°i orbit), derived from the nominal energy resolution requirement [SciRD: SCI-LAD-R-08], are absolutely key to the feasibility of the mission. There is evidence of a considerable amount of work having been performed to improve the understanding of this issue:

i. Analysis of radiation damage of the SDDs performed by PL
ii. Measurements of the radiation damage to the SDDs, including measurement of soft proton damage
iii. x20 safety factor on proton environment taken when calculating the detector temperatures applicable to the SC, resulting in an additional margin on temperature of ~few degrees C.
iv. PL consortium analysis of impact of degraded energy resolution on the science return - it has been illustrated that even in the event of an energy resolution not meeting the requirement, consequences for the science objectives can be mitigated by longer observations, with the exception of the Fe-line profile fitting where a 10% spectral resolution degradation is still within the science requirements but a 20% degradation will not meet the requirements (see Table A-3 in the SciRD.)
v. Evaluation of the large discrepancy between radiation models - concluding ***that there is considerable margin on the environment considered in deriving the detector temperatures.***

vi. ***Based on iv, the radiation environment is benign, and the resulting induced leakage current is negligible compared to the intrinsic leakage current.***

This requirement is considered well-consolidated, which is good for the robustness of the mission and SC configuration.

5.1.4 Payload Requirements

The Payload Consortium have provided a set of Payload requirements specifications, including LAD and WFM specifications (clearly linked to the assigned requirements from the MRD), main unit specifications and critical component specifications for the SDD and ASIC, covering both LAD/WFM designs.

The payload specification tree is considered mature for Phase A.

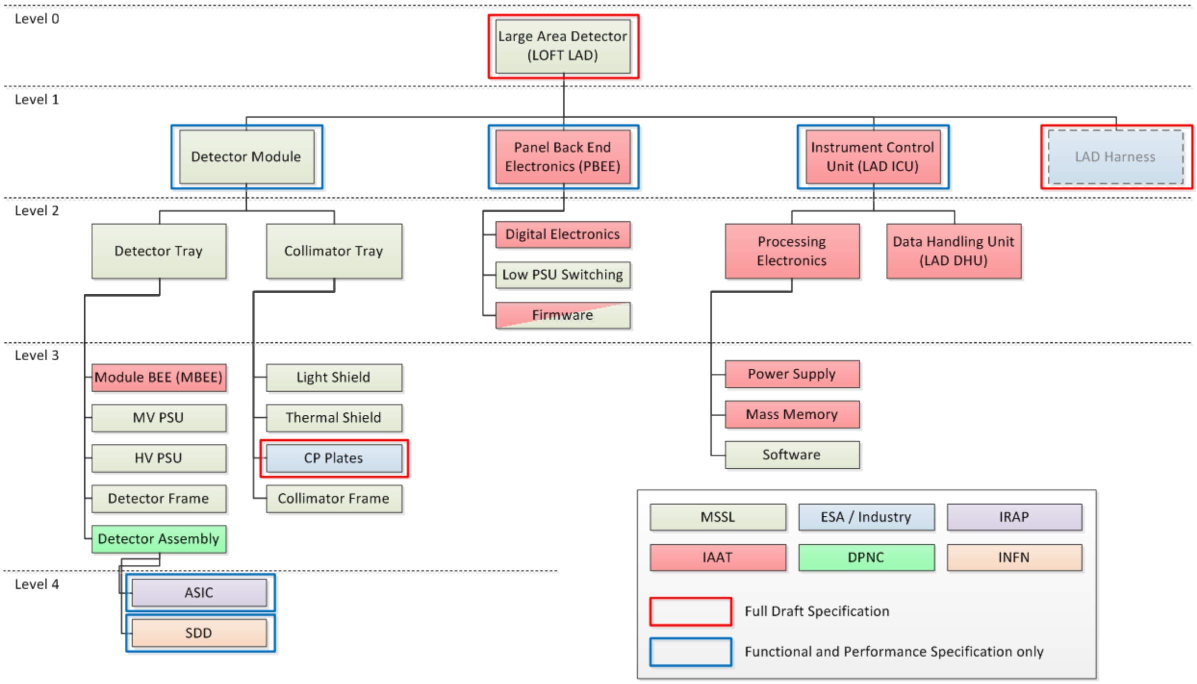


Figure 3: LAD specification tree, indicating those specifications provided at I-PRR (blue/red outlines)

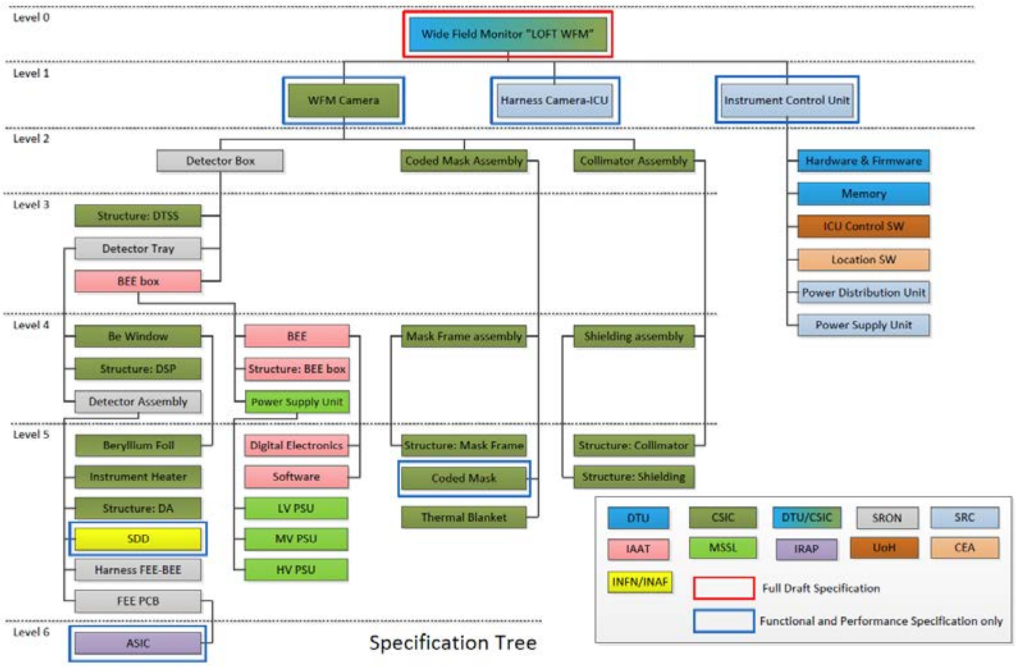


Figure 4: WFM specification tree, indicating those specifications provided at I-PRR (blue/red outlines)

5.1.5 Ground Segment Requirements

Ground Segment requirements are expressed discursively via the Mission Assumptions Document (MAD) and Science Operations Assumptions Document (SOAD), which in due course will be replaced by the Mission/Science Implementation Requirements Document (MIRD)/(SIRD). The level of detail of these documents is adequate for Phase A.

There is a recommendation from ESOC to include a 3rd ground station during LEOP to support operations during deployment (in-line with normal practice for EO missions.) This ground station could be a re-use of the LEOP support station to be procured for the LISA Pathfinder mission.

5.1.6 Launcher Requirements

The only requirement on the launch segment currently expressed in the [MRD: R-LS-010] is to insert the SC into the candidate orbit range with the performance, based on initial calculations provided in the Mission Analysis Guideline Document (MAG) – performance to the LOFT orbit is not covered by the Soyuz-Fregat (from Kourou) User Manual.

However no consideration was given to de-orbiting the Fregat upper-stage after the payload has been delivered (to comply with Space Debris Regulations). Consequently it is expected that there may be a performance reduction (<100kg) with respect to the predicted capability. However this is small compared to the significant mass margin and ***does not affect the feasibility of the mission.***

Nevertheless it is recommended to request performance estimations from Arianespace prior to Phase B1 ITT to properly bound this critical parameter.

5.1.7 Interfaces Definition

The mechanical (iso-static mounting for WFM Cameras and LAD Modules) and electrical (power line, SpaceWire, PPS for synchronization) payload interfaces are rather simple. Alignment requirements are not very stringent and should allow a simple I/F design and alignment procedure. ***I/F definition is at a reasonable level of detail for the phase of the project***.

EID-A: The overall content covers the essential subjects at the stage of a PRR.

EID-B: EID-A requirements have been analysed and appear to be well understood and well reflected in the EID-Bs. Detailed information on the main budgets (mass, power, telemetry, volume) is provided and are in line with the EID-A requirements. In contrary to the LAD EID-B the WFM EID-B does not provide clear requirement identifiers for requirements against the SC and needs to be improved in this respect.

SC/PL Interfaces and Responsibilities: The allocation of responsibilities between the various actors is clearly defined. ***The PRR agrees with the logic of the allocations, except for the Panel Back End Electronic (PBEE) to Module harness***, currently under Payload Consortium responsibility. Considering the simplicity of the harness (power, data, Pulse Per Second (PPS) only; no sensitive analogue signals) it is recommended to bring the harness under Prime responsibility. The main argument against PL responsibility is that the instrument will anyhow not be tested in full configuration but delivered in batches, therefore an end-to-end test in full instrument configuration requiring the entire payload harness cannot be done by the payload consortium. I/F specifications to industry will be simple as the I/F is reduced to the connectors and electrical parameters, routing aspects can be handled by the prime contractor. Regarding the cost aspect, the instrument harness has also already been costed by industry and appears in the LOFT EaC.

Thermal interface: Currently the thermal I/F between the Payload and SC is managed through the provision of a reduced TMM/GMM from the payload to the Primes, and the end-to-end modelling of the entire SC & payload by the Prime to verify that thermal requirements are met. This arrangement is appropriate during assessment phase, because it allow the Prime to maintain design freedom in meeting the payload thermal requirements.

Electrical interface: The LAD electrical architecture has been updated by the Payload Consortium at a very late stage and has therefore not been taken into account by the industrial studies. Nevertheless, the latest concept for the LAD harness is much simpler than what has been previously assumed by industry and should lead to easier routing and lower mass estimates. ***Consolidating and defining a clear LAD harness concept should be done in early Phase B1.***

The LAD instrument requires a large amount of power (1.3kW) – this number is considered to be well consolidated, taking into account adequate margins throughout as well as conservative numbers on voltage-conversion efficiencies.

Mechanical interface: ***The mechanical mounting I/F for WFM cameras and LAD Modules is not yet clearly defined and should be improved in early Phase B1.***

5.2 Spacecraft Technical Feasibility

5.2.1 Summary of Proposed Spacecraft Designs

The SC designs proposed by the two industrial prime contractors are shown in Figure 5 and Figure 6, and summarized in Table 2.

The ASTRIUM design features two large deployable LAD panels into which the LAD modules are sunk. The panel structure is used as a sunshade when tilting the LAD instrument towards the Sun. The SC design is integrated with no separation between PLM and SVM, and a fixed solar array which also serves as sunshield for the LAD modules.

The TAS-I design features a well-defined separation between the Payload Module (PLM) and the Service Module (SVM). In the PLM, the LAD is comprising 5 deployable panels that are connected to an optical bench located on top of a cylindrical tower. The SVM is based on an existing product line, with SADM-driven solar arrays.

Both designs are compliant with all the mission requirements. In some cases, compliance is also achieved with the goal requirements (nominal and extended FoR, observing availability, effective area, lifetime, etc.). ***There are no major spacecraft or mission technical feasibility issues identified by the panel.***

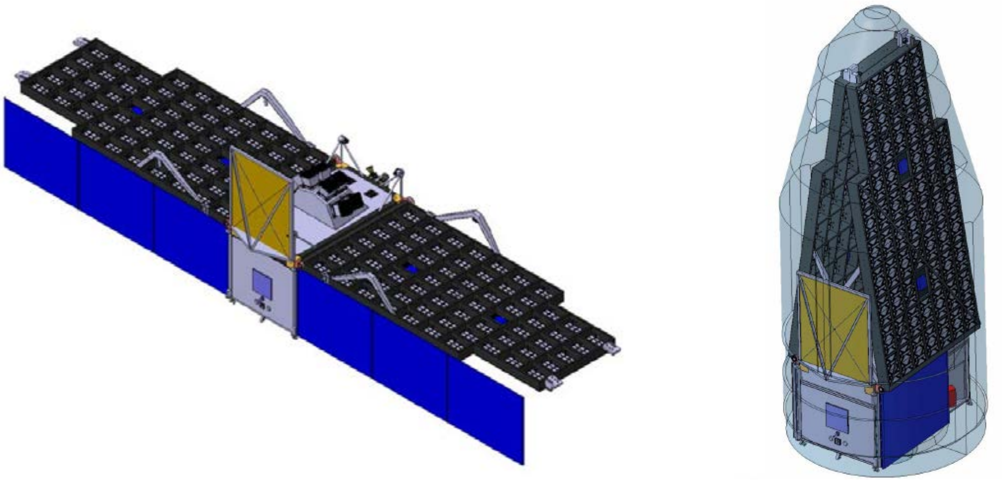


Figure 5: ASTRIUM SC design (also shown stowed in fairing)

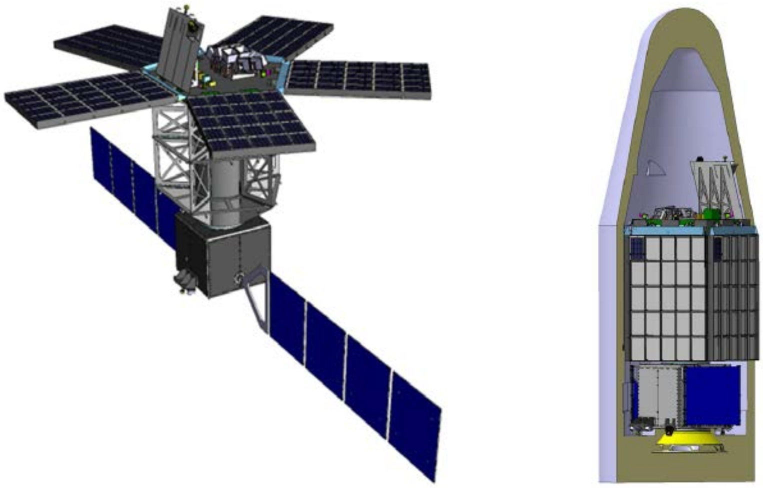


Figure 6: TAS-I SC design (also shown stowed in fairing)

Table 1: Summary of the SC design as proposed by TAS-I and ASTRIUM

		TAS-I	ASTRIUM
Reference Orbit	Altitude, inclination	550 km, 0 deg	550 km, 0 deg
LAD	Number of panels	5	2
	LAD panel dimensions [mm]	1924 x 3242 x 147	3000 x 5900 x 240
	Total number of modules	125	124
SC dimensions	In orbit configuration (deployed) [mm]	16169 x 7036 x 9246	14120 x 3644 x 3610
Mass	Dry mass w/o system margin [kg]	2973.9	3848.7
	Dry mass with 20% system margin [kg]	3568.6	4618.5
	Wet mass [kg]	4121.6	5205.9
	Launch mass [kg]	4236.6	5347.7
	Launcher performance to reference orbit (after subtracting 5% margin)[3][kg]	5624	5624
	Margin w.r.t. launcher performance [%]*	24.7	4.9
Delta-V	[m/s]	260.1	250

[3] It can further be noted that the SC designs are compatible with the LAD detector temperature requirements derived from the radiation environment at 2.5° inclination. The mass margins are reported with respect to 0°inclination launcher performance. There is therefore very considerable margin here (~800kg Δ between 0° - 2.5° inclination.)

		TAS-I	ASTRIUM
Power	Maximum SC power demand [W]	2767.3	2517.2
	Solar array [m2]	Rotating, 18.4 m²	Fixed, 18.8 m²
Communication	Frequency Band	X-Band (TM/TC) UHF (LBAS TM)	X-Band (TM/TC) VHF (LBAS TM)
	Data Rate	6.7Gb/Orbit	
Pointing	Absolute Performance Error (APE)	1arcmin @ 3σ	

5.2.1.1 Margin Philosophy

The ESA assessment study margin philosophy has been made applicable, and appears to have been correctly enforced during the industrial and payload assessment studies. As a result, ***the margin policy used by both the industrial contractors is adequate and complete for a Phase A***.

Because LAD absolute temperature is a critical system driver, a sensitivity analysis on module temperatures as a function of thermo-optical properties (of primary importance are the properties of the collimator plates) should be run early in Phase B1 in order to consolidate the temperature margin requirements.

5.2.1.2 Budgets

Both industrial contractors have provided complete and credible spacecraft budgets.

Concerning the mass budget, the mass estimations provided are considered credible and, in general, conservative. Both SC designs show positive margins with respect to the mass capability of Soyuz-Fregat from Kourou to the baseline orbit. The margin of the TAS-I design (1390 kg) is particularly remarkable.

The power and link budgets are also credible and show positive margins. ***There is a possible issue regarding antenna-switching which may reduce TM-performance slightly, and which needs to be investigated during B1 prior to ITT.***

Additional budgets (pointing, alignment, LAD availability) are addressed in the following sections.

5.2.1.3 Availability of Appropriate Models and Analyses

The analysis that has been performed in the industrial assessment study is commensurate with a Phase A study, consisting of the usual analyses: FEM, TMM/GMM, etc. AOCS analysis (particularly for the ASTRIUM study) has been very thorough and beyond a normal Phase A.

5.2.1.4 Technological Maturity

Each design relies in technologies with heritage and high TRL. No technology development activities are required to raise the TRL for any spacecraft component.

5.2.2 Thermal Aspects

The thermal requirements for the LAD have been a design driver for both industrial contractors to ensure sufficiently low absolute temperatures for the LAD modules for a wide range of SAA. The two contractors have reached the required performance by different design solutions (i.e. additional module radiator fins per module and panel back radiator plate for TAS-I, solar array and panel structure used as sun shield by ASTRIUM). Both designs show compliance with the LAD absolute temperature requirements for the required nominal and extended FoR, as shown in Figure 8 and Figure 8 (TAS SC is marginally compliant to NFoR, though this is not considered to be a feasibility issue as can be compensated by mission duration). However note that the FoR is also determined by other constraints (mainly WFM and spacecraft temperatures, and SC power constraints for the ASTRIUM SC with a fixed solar array), which are not indicated in this figure.

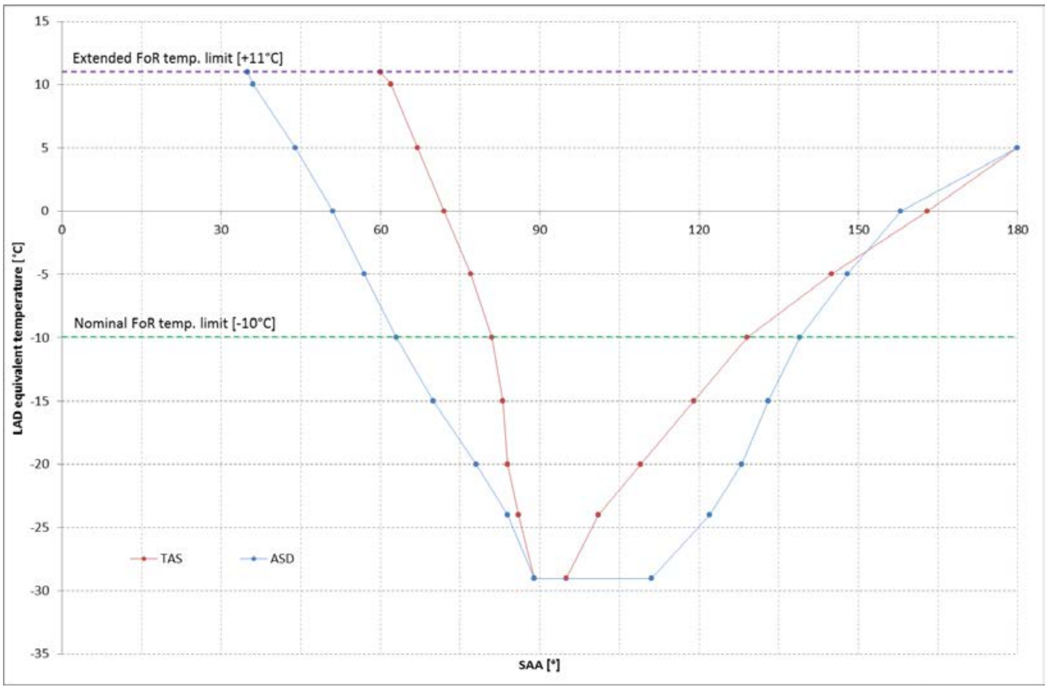


Figure 7: TAS and ASTRIUM SC orbital average (not taking into account ~+/-5deg C variation along the orbit) predicted LAD equivalent temperature as a function of Sun aspect Angle

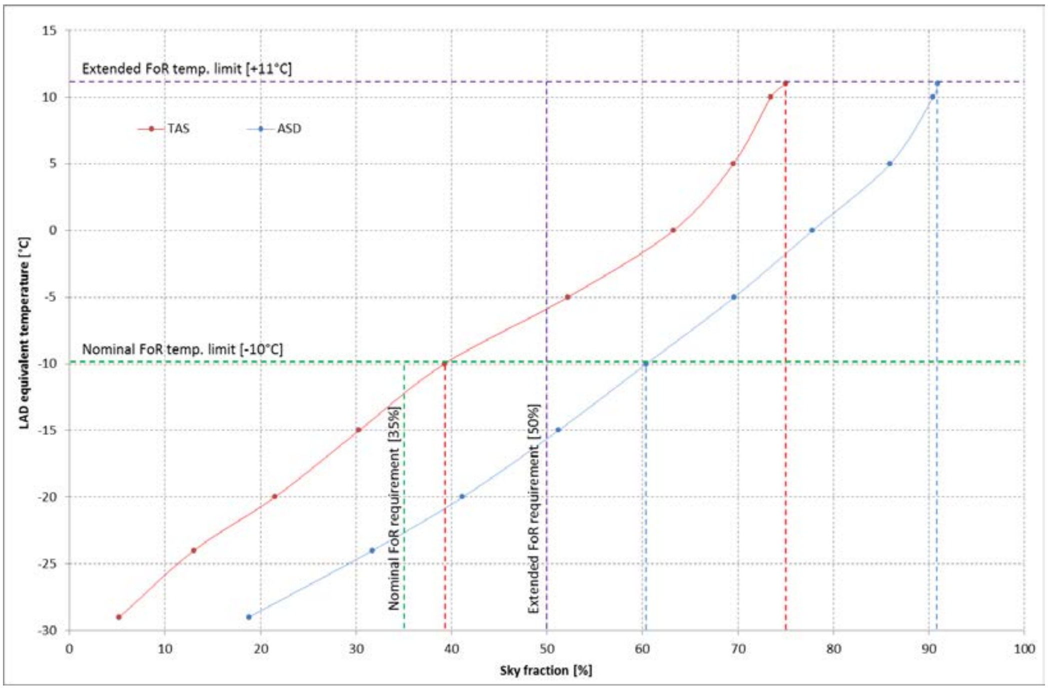


Figure 8: TAS and ASTRIUM SC *orbital average (not taking into account ~+/-5deg C variation along the orbit)* predicted LAD equivalent temperature as a function of Sky Visibility

In the cold cases, the LAD absolute temperatures are close to the minimum allowed temperatures in some operational (SAA of 90°) and non-operational (panels stowed, safe mode) scenarios. ***Therefore the recommendation of the panel is to baseline LAD Module heaters in order to limit the impact of this uncertainty for future phases*** (this solution has already been adopted by TAS-I.)

5.2.3 Mechanisms

The LAD deployment mechanism is critical for the LOFT mission. The ASTRIUM SC design includes only 2 extremely large panels. A low number of panels makes the deployment accuracy more critical. The ASTRIUM estimated deployment accuracy is considered as optimistic. In contrast the TAS-I design including 5 panels is much more resilient to one panel misalignment. Table 3 compares the two industry designs with relevant industrial heritage.

Table 2: Proposed LAD deployment mechanisms. SMOS and Sentinel-1 deployment mechanisms are shown for comparison

		SMOS	TAS-I	Sentinel-1	ASTRIUM
		3 segments	1 segment	2 segments	1 segment
Panel Size (per segment)	m x m	0.7 x 4.0	3.2 x 1.92	unknown	5.0 x 2.5
MoI	Kg m²	150	800	820	3600
Initial Torque	Nm	54	31	60	100
Deployed Torque	Nm	7.5	6	60	100

		SMOS	TAS-I	Sentinel-1	ASTRIUM
		3 segments	1 segment	2 segments	1 segment
Deployed Eigenfrequecy	Hz	1.98	1.2	unknown	1
Deployment Accuracy (3σ)	arcsec	18	30	144	6.9
Temperature Range	°C	-52/54	-25/55	-52/85	-25/55

The selected technologies for the deployment mechanisms are adequate:

- Motorized (in combination with an active latch) for ASTRIUM, similar to Sentinel-1
- Spring-damper actuated (in combination with a passive latch) for TAS, similar to SMOS.

However, the unusually large size of the panels in the ASTRIUM configuration will require a re-design of the active latch, the motorization chain, and also likely the Hold Down and Release Mechanism (HDRM) function. Several components, like the bearings and the latches, have limited space heritage for the required loads and performances, and will therefore require dedicated development and qualification. The deployment mechanism is required to be stiff and equipped with alignment capability at the same time. Their development depends on the availability of proper off-gravity jigs, which would be a new development. Previous examples of deployment with similar size and similar deployed accuracy do not exist, and it is felt that the accuracy stated by ASTRIUM is optimistic for LOFT (only one 1 rotation in the hinge is considered). The major driver influencing the ASTRIUM mechanism design is the lateral forces that the motorization chain can accept, which in turn is linked to the quality of the off-gravity jig.

The major driver influencing the TAS mechanism design is the harness resistive torque. However the LAD harness has been significantly simplified and reduced as a result of the agreed update to the electrical architecture.

5.2.4 LAD Effective Area, Alignment, and Pointing

Accommodating the large LAD effective area has been a clear driver for the spacecraft design for both industrial contractors. Both SC design concepts are currently able to accommodate more LAD modules than the required number of 121 (TAS-I: 125 modules, ASTRIUM: 124 modules). This provides an option to relax the LAD alignment requirements, which are driven by effective area (§6.1.2.2).

Both industrial prime contractors have provided LAD alignment budgets which are based on preliminary, simplified calculations. LAD alignment is mainly driven by the mechanical alignment of the modules on ground. ***The required alignment is not seen as critical by the primes.*** Additional important contributors to the alignment budget are the deployment mechanism alignment (see previous point on mechanisms) and the panels thermo-elastic deformations. In the latter case, the preliminary calculations indicate that the expected thermo-elastic deformation of the panel will stay within the requirement. Note that the panel structure is manufactured in CFRP (low CTE) in both proposed designs.

LAD pointing requirements (APE and RPE) are also met by both contractors, although with low margins for the APE. The APE is driven by LAD thermo-elastic deformations (the AOCS contribution to the pointing budgets is not considered to be challenging). ***For that reason, the panel recommends that the thermo-elastic deformations are investigated in further detail during Phase B1 and that the logic (summation rule) for alignment budget is consolidated.***

5.2.5 AOCS

The mission requires 3-axis inertial pointing to a wide range of target directions, but with not particularly stringent pointing requirements. Both designs are able to meet the required AOCS performances with a design based on the use of reaction wheels, together with magneto-torquers for wheel de-saturation (avoiding the use of thrusters). 4 optical heads appropriately mounted ensure that potential Earth blinding of the star trackers will not impact the mission.

5.2.6 Controlled Re-Entry

Both spacecraft designs are compatible with the need to perform a controlled re-entry at end of life. The system impact and the operational aspects of such a manoeuvre have been adequately assessed at this stage by both industrial primes (e.g. the sequence of burns and associated gravity losses have been computed also in the case of the failure of one of the branch of thrusters, and the low-perigee passes have been addressed). ***The panel notes, however, that additional work will be needed in Phase B1 to consolidate the spacecraft modes for the controlled re-entry phase and to estimate the reliability of the system with respect to the success of the controlled re-entry.***

5.2.7 Operational Concept

Orbit control manoeuvres are only performed every few months, so they do not disturb significantly the observations. The fact that there are no stringent orbit control requirements, combined with the detailed mission analysis and the margins assumed in terms of solar activity, give confidence on the robustness of the designs in this respect.

A detailed reference observing plan has been used by industry in their analysis and sizing of SC subsystems (most importantly for the AOCS) and also to show compliance with the LAD availability requirement.

Both contractors currently estimate that a significant over-performance with respect to the 40% LAD availability requirement is possible; this forms the basis of the PRR recommendation to reduce the NOP duration to 3 years (see §6.1.2.3.)

For both spacecraft designs there are no significant constraints introduced by the spacecraft on the planning of the observations. This is also favoured by the removal of the LAD thermal stability requirements (see §6.1.3.1). It is however noted that an optimization of the observing plan may result in an increase of the observation availability (e.g. shorter slew times) and/or increased science (e.g. nominal resolution temporarily possible for EFoR targets due to thermal inertia.)

5.2.8 Spacecraft Configuration

The two parallel industrial assessment studies have resulted in significantly different external SC configurations. The two industrial primes diverged in their designs at a moment during the assessment study (summer 2012) when there was significant uncertainty in the LAD detector absolute temperature requirements (due to uncertainties in radiation environment modelling.)

The ASTRIUM spacecraft configuration is more strongly driven by thermal considerations and is based on the concept of using the solar array and the LAD panel structure as sunshields for the LAD modules. Shading the LAD modules allows indeed to keep the absolute temperature of the LAD SDDs low for almost all the desired range of SAA (90 ± 30°), ensuring nominal energy resolution. The LAD spatial temperature gradient is also low (with a maximum difference of 10 K between modules at any time). ***This configuration can be considered as the thermally-optimal solution to keeping the LAD modules cool and stable during operation.***

However, the benefits at mission-level of such a configuration (wide FoR) are offset by the fact that the extended FoR may be effectively power-limited by the fixed solar array to a lower SAA range. Although the spacecraft can temporarily be pointed outside that nominal SAA range, the battery discharges in few orbits and will require the spacecraft pointing again in the SAA 90° position for several orbits to recover its charge. ***This operational strategy is considered risky by the panel and is therefore not recommended.***

A number of aspects of the ASTRIUM design are considered as challenging by the panel. Although compliance with the requirements is shown and no major feasibility issues exist at present, the design may lead to technical issues in future phases:

Structure: The spacecraft requires a large and complex CFRP structure. The structural mass is unusually high, representing 46% of the total dry mass of the spacecraft. Although appropriate margins were considered for Phase A, a more detailed structural analysis will be required in the next phases to consolidate the design. The impact on the spacecraft of any potential underestimation of the structural mass will be high. *e.g. secondary structure.*

Mechanisms: refer to §6.2.3.

Modularity: The ASTRIUM design does not feature PLM/SVM modularity which complicates the AIT campaign and limits the flexibility of procurement (note that it was not required to maintain PLM/SVM modularity in the design, so there is no issue of non-compliance in this regard.)

Launcher compatibility: although the proposed design is currently compatible with a Soyuz launch, margins in terms of volume inside the fairing, adapter, and performance are limited. The proposed design fills almost completely the volume envelope inside the Soyuz fairing (see Figure 5); any future growth in payload or platform dimensions may result in the need to remove some rows or columns of LAD modules to fit within the fairing (estimated ~11% loss of effective area.) Furthermore, due to the large spacecraft mass and the relatively high position of the CoG, the margin in terms of static moment for the PAS 1666 launch adapter is minimal (~0.6%). Should the static moment further increase in the future, then a reinforcement of the clamp-band and a delta-qualification of the launcher adapter might become necessary. In terms of launcher performance, the mass of the current design (including all margins) is 276 kg lower than the expected launcher performance (also considering a 5% launcher performance margin) to the reference orbit.

Internal accommodation of equipment: it is constrained by the volume of the platform (that cannot grow further, as described above) and by the internal structure (central cone and shear panels). The accommodation of the units in the current design is considered to be somewhat tight and offering limited margins and flexibility for units growth (the batteries, for instance, were already placed outside of the platform for this reason); the accessibility and the harnessing are considered to be complex.

LAD deployment: In the current design the LAD deployment must take place a few hours after launcher separation due to thermal considerations in a survival attitude. This type of time constraint within a critical phase like LEOP is judged to be unacceptable. Due to the high inertia of the LAD panels the deployment duration will be around one hour; which raises some concern from ESOC because it will not be possible to completely monitor the deployment (typical pass duration is 10 minutes).

AOCS: The configuration has very large differences in moments of inertia, resulting in a very large gravity gradient disturbance torque and very large actuators (e.g. 9 of the largest European magneto-torquers are required to off-load the RWs). This narrows down the competition for the procurement.

The motivation[4] for the ASTRIUM design is clearly understood and appreciated, and the proposed design is feasible and compliant with the mission requirements. However, the design penalty of providing an optimal cold environment for the LAD detectors is quite high, as summarized in the points above. The proposed design has low margins to accommodate potential future growths in payload and/or spacecraft resources, and is overall judged by the panel to be a more constraining and less robust solution than alternative designs. ***Therefore, the PRR-panel recommends that ASTRIUM re-consider the spacecraft design in Phase B1 (on the basis of an updated set of applicable requirements.)***

[4] At the time of configuration selection, there were large uncertainties surrounding the required LAD detector temperatures needed to satisfy the nominal energy resolution requirement; the ASTRIUM configuration was a response to this uncertainty.

5.3 Payload Technical Feasibility

5.3.1 Design Maturity and Resource Margins

The overall instrument as well as the Science Ground Segment concept is considered to be mature and well documented. The level of detail with which the instrument design is described significantly exceeds general expectations at the end of a Phase A study.

In particular the LAD Modules and WFM Cameras are already very detailed as illustrated in Figure 10 and Figure 11.

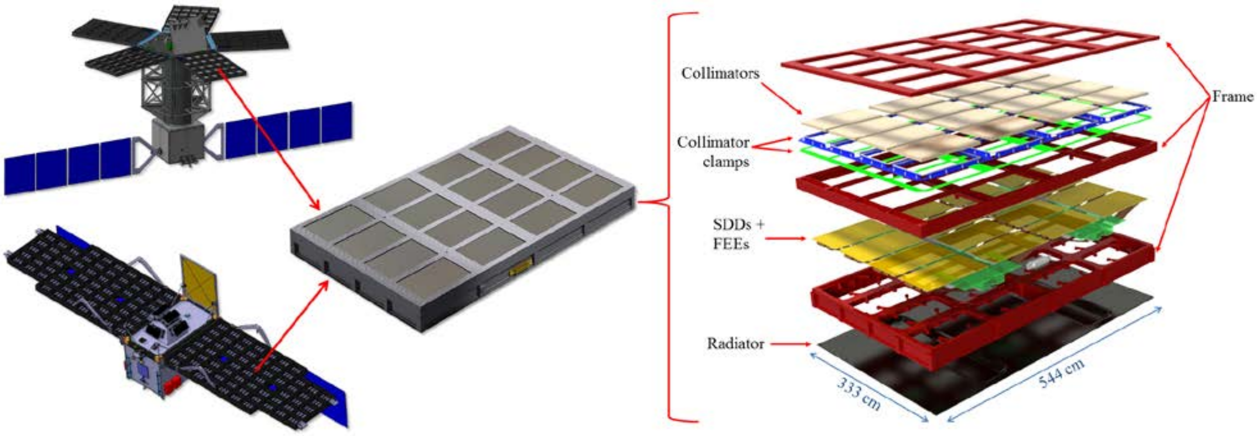


Figure 9: LAD Module Design

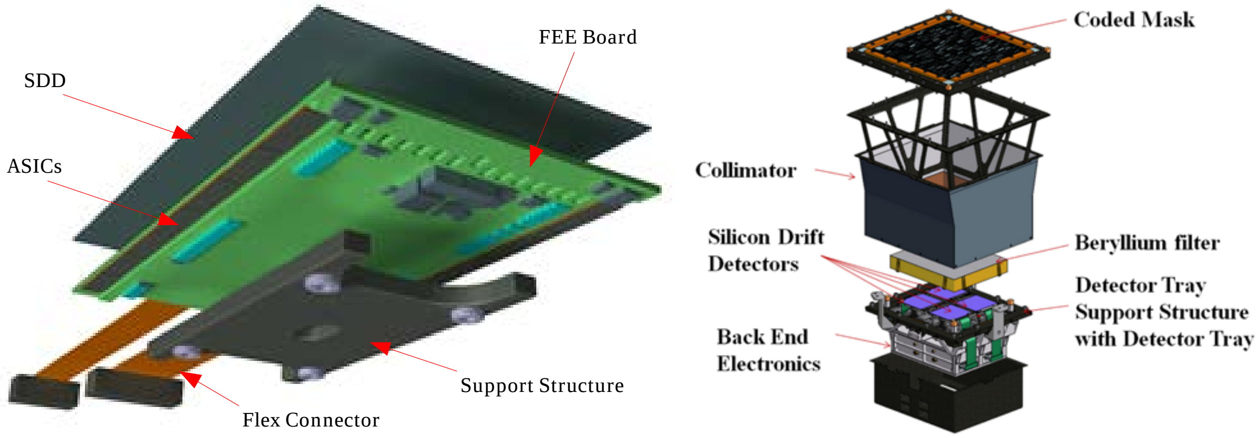


Figure 10: LAD Detector Assembly (left) comprising Silicon Drift Detector (SDD), and Front End Electronics (FEE) Board with readout ASICs; WFM Design (right)

Remaining electrical units are defined with sufficient detail (functional requirements and mass/power/volume allocations). The high level of detail of the LAD Module design gives some confidence that future small changes of the design lead to only minor mass and power changes within the currently maintained 20% maturity margin. Due to the large number of LAD Modules, ***a***

small Module mass increase can have a significant impact on the overall PL mass but remains only low risk due to the available SC mass margins.

The volume of the LAD Module is also considered consolidated, as it is mainly defined by the size of the Silicon Drift Detector which has been well defined and fixed (***some lateral growth risk remains in the implementation of the collimator-plate mounting.***) Some growth in LAD Module thickness could be still expected but is considered not critical as in this dimension some more volume can be accommodated by both SC designs.

The maturity of the iso-static mounting concept for mounting of the LAD Modules to the Panel structure is questionable (TAS potentially too stiff to compensate CTE mismatch, ASD potentially too soft to limit Eigenfrequency). The volume allocated by the SC primes for the iso-static mounting might therefore be underestimated - see §6.1.7.

5.3.2 Payload Performance

The designs of the LAD and WFM instruments are in general compliant with the performance requirements in the SciRD/MRD, and respective performance analyses and models are provided in the PRR data package. The following exceptions/positive remarks are made by the PRR:

LAD Effective Area: The required LAD Effective Area requirement of 9.5m² is met with some margin (3-4 LAD Modules more than required) which could be used to relax the pore-to-pore alignment requirements for the Collimators and/or alignment of the LAD Modules on the SC if needed.

LAD Energy Resolution: Although major concerns regarding the radiation environment could be answered with the I-PRR documentation, some concerns regarding the ASIC development maturity remain. At the PRR it could not be demonstrated that the ASIC development provides sufficiently good performance needed to meet the energy resolution requirement. The provided test results have not been achieved under relevant conditions (SDD not connected to ASIC) and interpretation of the available test results can lead to the conclusion that the ASIC is currently underperforming. ***However, from previous ASIC developments (StarX-32 ESA development, VEGA ASIC) it is known that the targeted performance is in principle achievable.*** Test results with the next iteration of the ASIC connected to an SDD prototype are expected for early 2014.

The SDD intrinsic leakage current still needs to be demonstrated on a representative detector. Compliant performance has already been demonstrated on test diodes and test structures, therefore the risk associated to the SDD performance is considered low, but performance still needs to be confirmed on a real detector prototype. In addition, since also a new manufacturing process is used for SDD production ***it is also highly recommended to re-perform the NIEL radiation test campaign to confirm that the currently expected end of life radiation effects are predicted correctly.***

WFM Low Energy Threshold: Due to the same reasons as for the LAD Energy Resolution concern regarding the ASIC performance, there is a concern that the WFM noise performance will not allow proper detection of low energy X-rays (2keV). Events generated by one photon are spread over several anodes leading to very low signals per chain (e.g. 200eV for a 2keV photon when spread over 10 anodes). Since the energy threshold is very close to the noise level, this could lead to false trigger events.

EMC: The PRR documentation does not specifically address electrical shielding of the detector units. It is essential to protect the charge sensitive amplifier (CSA) inputs from radiated EMC disturbances. ***The PRR recommends early performed radiated susceptibility EMC tests on a module demonstrator to prove robustness of the design.***

5.3.3 Payload Technology Readiness and Development Plan

Only three payload items have been identified that require some development effort before SRR (end 2015) to achieve TRL5 or higher:

- LAD/WFM Readout ASIC
- LAD/WFM Silicon Drift Detector (SDD)
- LAD Micro Pore Collimator (MPC).

On all three items significant development effort has been spent already before the PRR and development plans to reach TRL5 before the SRR are provided. The actual status and the required next steps are summarized in Table 4.

While the ASIC and SDD are developed by the Payload Consortium, the MPC development is covered by an ESA Technology Development Activity since the MPC is an ESA contribution to the Payload.

The PRR baseline for the LAD Collimator has been a square pore collimator. Standard technology for Micro Channel Plates (for e.g. night vision applications) are round pores that are easier and significantly cheaper to manufacture than square pores, with the drawback that a slightly worse pore alignment performance is expected for round pores. However a round pore demonstrator with 1.8acrmin pore alignment (requirement is 1arcmin) has already been manufactured by Hamamatsu (Japan, see Figure 12), but with 60% Open Area Ratio (OAR) only. The underperformance in pore alignment corresponds to a small reduction of Effective Area that can be compensated with the surplus LAD Modules that can be accommodated on the SC (124/125 instead of required 121). Increasing the OAR to 70% is not considered technically challenging but still remains to be demonstrated. ***The PRR therefore recommends to further investigate the option of using round pore MPCs for the LAD instrument. Based the expected cost, manufacturing duration and risk reduction, the PRR recommends round pore collimators as the new baseline for the LAD instrument.*** Talks with the European MPC supplier have already been started and demonstrating round pore MPCs for the LAD instrument within 2014 appears feasible.

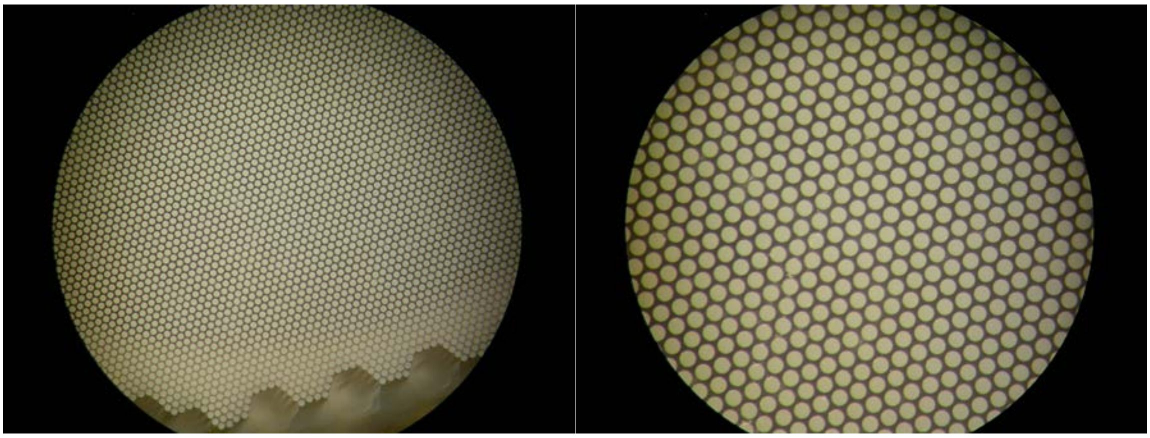


Figure 11: Magnified photographs of the small-size, 100 µm pore capillary plate produced by Hamamatsu (Japan) to test the feasibility of the LOFT specifications

The payload consortium is currently in talks with JAXA concerning the possibility that the collimator is provided as a Japanese contribution, manufactured by Hamamatsu Corporation. This dialogue has reached a high-level and already includes the provision of sample plates by Hamamatsu to the Payload Consortium. ***The PRR recommend that the Hamamatsu LAD collimator plates are considered in Phase B1 as an alternative to the European solution, potentially as an international contribution from Japan; such a work-share distribution will be easy to manage and Japan is well progressed with this technology.***

While developing the SDDs and MPCs is considered straight forward with low risk, there are some concerns regarding the ASIC noise performance which could not yet be demonstrated on the latest development model (SIRIUS-1, tests without detector attached show out of specification performance, while tests with an SDD are still pending). The technical feasibility in general is not questioned as relevant performance has already been demonstrated on the Italian VEGA ASIC, but the iterations needed to achieve the same performance with the French SIRIUS ASIC might be underestimated: SIRIUS-2 is currently being manufactured thus test results are still pending. After the SIRIUS-2 test the WFM and LAD Prototypes will be manufactured. In case full performance cannot be achieved on the Prototypes, the schedule would in principle allow one more iteration without delaying the LAD Module QM AIT, but such an additional step is not yet planned. As backup the Italian ASIC is also further developed, but switching from Italy to France was necessary due to national funding reasons which might also be a show stopper for going back to an Italian ASIC. ***The PRR panel recommends to organize a technology transfer/discussion between the French and Italian ASIC vendors for securing the ASIC development schedule and avoiding unnecessary and costly iterations.***

Although not considered to be technically critical, also some other technologies have been already bread-boarded and tested such as the WFM Coded Mask, LAD Panel and Module Back End Electronics, LAD Thin Film Thermal Filter and LAD Collimator Mounting Frame, providing additional confidence in the technical maturity of the LOFT payload.

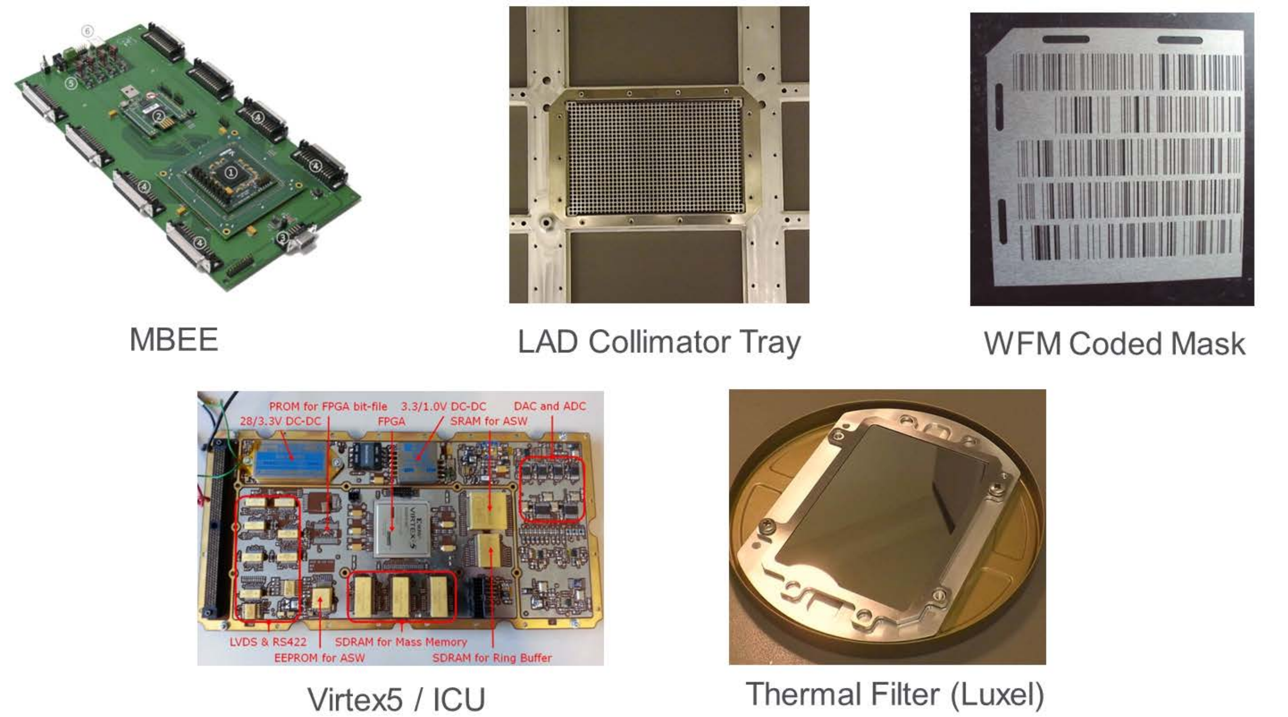


Figure 12: In addition to the key SDD, ASIC and MCP develop, several supporting LOFT technologies are undergoing development and testing

A flight representative LAD Module prototype will be setup and tested in the second half of 2015. Demonstrating TRL6 before SRR for the whole LAD Module seems to be very realistic. The same can be said for the WFM Detector Plane for which also a flight like prototype is planned in 2015.

Table 3: LOFT payload TRL status

	ASIC	SDD	MPC
Current TRL	3-4	4-5	4-5
Already Available Prototypes	• VEGA-1 (Italy) • VEGA-2 (Italy) • VEGA-3 (Italy) • SIRIUS-1 (France)	• FBK-1 (2010) • FBK-2 (2011) • FBK-3 (2012) • FBK-4 (2013, not yet tested)	• LOFT Prototype (100µm square pores, PHOTONIS) • Round Pore Prototype (100µm diameter, HAMAMATSU)

	ASIC	SDD	MPC
Demonstration needed for TRL5	• Performance test of analogue section w/o ESD protection and demonstration of required noise performance • Test of ADCs and digital section and potential interference with analogue part • Channel Cross talk test for small pitch WFM channels • Radiation testing (TID, SEU, Latch-up)	• Intrinsic leakage current test on detector level (already demonstrated on test diodes and test structures on 6”wafer prototype) • Sensitivity test w.r.t radiation (NIEL induced increase of leakage current, not yet demonstrated for new ‘leakage current reducing process’) • Combined Thermal-Vacuum test	• Manufacturing of the combination of MPC size, pore geometry, Open Area Ratio and Al filming to be demonstrated (→ ESA TDA) • Mechanical test (shock/vibration) using a flight like mounting frame (could be considered as TRL6 test, Payload Consortium activity using MPCs out of the ESA TDA)
Planned date to achieve TRL5	End 2015 (tests with SIRIUS-2 in 2014 should allow demonstrating full functionality of the ASIC but performance is still expected to be out of spec., flight representative WFM and LAD prototypes will contain minor modifications and potential noise optimizations and will be tested in 2015)	October 2014	Beginning 2015 (mechanical tests will be done already earlier in 2014 using MPCs with flight like dimension but with a slightly lower OAR of 66% instead of 70% which will become available only at the end of 2014)
PRR Concerns and Recommendations	• Noise performance not yet demonstrated to be in specification, an additional iteration (ASIC run) might be needed • WFM trigger threshold is an area of concern w.r.t. ASIC noise performance and offset/gain/threshold stability	• New manufacturing process for leakage current reduction could lead to higher radiation sensitivity, NIEL radiation test has to be redone • The PRR recommends using high quality silicon also for upcoming development models but understands the problems in procuring such material as wafers. It is therefore considered acceptable to use selected high quality material for the QM/EM models for the first time.	• Manufacturing round pore MPCs is considered faster, cheaper and less risky with the drawback of degraded pore alignment performance. Investigating this alternative is highly recommended. • The α/ε thermal properties should be measured within 2014 to confirm the current assumptions for the LAD Module thermal model

5.3.4 Characterization and Calibration Concept

The LOFT on-ground calibration, especially for the LAD instrument, is a major effort which is an integral part of the overall MAIT. In view of the long duration of the MAIT, it is important that the on-ground calibration is well defined. The instrument calibration and characterization concept provided for the PRR (on-ground and in-flight) is well established and provides an overall credible approach to meet the technical performance requirements. LAD Modules and WFM Cameras can be individually calibrated and do not require a fully assembled instrument for any calibration step. The only parameter that cannot be measured end-to-end on ground is the LAD Effective Area knowledge. However, the absolute effective area knowledge requirement of 15% [SciRD: SCI-LAD-R-05] is not critical. Absolute effective area can be characterized on each individual Module and the overall LAD effective area could be predicted based on LAD Module alignment measurements. In addition the Absolute Effective Area can be characterized in flight using known sources (e.g. Crab nebula).

The most critical and time-consuming calibration is certainly the energy scale calibration w.r.t. detector/ASIC temperature. However, current estimates from the ASIC performance show that the accuracy of this calibration does not need to be very accurate w.r.t. temperature as the ASIC's gain and offset sensitivity to temperature is very low.

For all critical instrument parameters for the WFM and LAD instruments, in-flight characterization strategies have been identified and analysed. WFM and Line of Sight as well as the LAD angular response can be characterized by measuring a known X-ray sources, energy scale can be calibrated based on fluorescent lines from the WFM collimator walls and based on Pb lines for the LAD instrument.

5.4 Launch Segment Technical Feasibility

The only specific comment is that a very comfortable mass margin exists. However the volume margin with respect to the fairing envelope is critical for the ASTRIUM design.

5.5 Ground Segment Technical Feasibility

The functional roles and responsibilities of the ground segment parties: MOC and SOC supported by SDC and IOC are well defined and documented in the LOFT Science Operations Assumptions document.

The MOC, SOC, SDC and IOC design and implementation are all considered straightforward and no development or feasibility issues are anticipated.

The baseline use of Kourou and Malindi ground stations appears to be stable – there were some residual concerns about the availability of Kourou in the LOFT timeframe, as a consequence of a plan to decommission Kourou after serving XMM. However this plan has since been revised and the availability of Kourou now appears stable.

Malindi has been offered in-kind by ASI as a contribution to the LOFT mission. There is the risk that ASI might renege on their commitment, in which case ESA would have to fund Malindi.

The request to deploy a 3rd ground station during LEOP to enhance the monitoring of the deployment of the LAD detector panels can be facilitated by the LISA Pathfinder developed LEOP ground station or renting another commercial ground station.

5.6 Mission Programmatic Feasibility

5.6.1 Model Philosophy

Spacecraft: Different model philosophies were proposed by each of the industrial primes. These were considered by the Study Team and then a preferred ESA reference model philosophy was defined , which was used to drive the programmatic definition for the Payload Consortium.

The ESA reference SC philosophy comprises four spacecraft models:

1. Complete **Structural Model (SM)** of the SC with one flight representative LAD detector panel deployment mechanism. The SM structure will be refurbished for SC FM. The SM requires SC unit and instrument Structural Dummy Models (SDMs).
   - Structural Qualification of SC structure, incl. LAD Panels.
   - Mechanism deployment test

2. **Reduced LAD Panel Thermal Model (RTM)** for TB/TV including flight representative LAD detectors, panel structure and representation of other SC structures, which influence LAD detector temperatures. The critical design issue for early qualification is the LAD detector temperatures. The proposed model provides the required fidelity and is cost efficient. The RTM requires LAD module TMs along with LAD Module EMs.
   - Thermal balance test at different Sun illumination angles

3. SC **Electrical Functional Model (EFM)** including instrument electronics and reduced number of flight representative LAD Modules and WFM Camera
   - Functional verification
   - Conductive EMC test

4. SC **Proto-Flight Model (PFM)**
   - Functional verification
   - Thermal Vacuum and thermal balance test (one LAD panel deployed)
   - Structural Acceptance testing
   - Deployment tests
   - EMC testing
   - System validation tests with MOC/SOC

Note: No environmental test program is envisaged at PLM level.

All SC equipment and payload elements undergo complete qualification and acceptance prior to delivery to the Prime Contractor for SC integration and SC-level testing.

Payload: A sound model philosophy in line with the ESA Reference System Model Philosophy is presented by the Payload Consortium. In addition to the models identified above for delivery to the Prime, the Payload Consortium qualifies the instruments in-house using QMs. The critical payload activity is the early qualification of the LAD Module, which as a prerequisite for the commencement of mass production for the SDD/MPC/ASIC. This is considered a low risk thanks to the simple I/F to the SC of the LAD Module, combined with the already very mature LAD Module design status. For the WFM Cameras and electronic units a more traditional implementation schedule is used with Qualification Reviews in Phase D.

5.6.2 Spacecraft and Payload Development Schedule

SC schedules were proposed by each of the industrial primes. These were considered by the Study Team in order to establish a reference model philosophy and schedule which was used to define the programmatic constraints for the Payload Consortium (delivery dates).

The SC design and development is not considered critical (no technology-development needed, modest performance requirements and straightforward SC design), and the launch end of 2022 is considered possible subject to the following important provisos:

- The Payload MAIT plan is subject to the early qualification of the LAD module, required for the early start of the mass-production of the LAD Module internal LLIs (SDD, ASIC, collimators) for the LAD FM (immediately after successful module QR in Q3-2017.) ***This means that TRL5 by adoption (Q1-2016) is critically important and requires adequate funding.***
- ***All subsystem suppliers need to be kicked off very early.*** Subsystem suppliers need to be well advanced and fully involved at PDR such that unit procurements can be initiated early in phase C. This leaves 1.5 to 2.5 years for the design adaptation and MAIT of the units, which is considered critically short, especially for the PCDU and OBC, which are required early on for the EFM and FM integration. ***A proposed solution is to combine critical unit procurement with the relevant subsystem procurement - this will allow a gain of 6-9 months for these items by avoiding the unit ITT.***
- ***Any item requiring development (the LAD panel deployment mechanism, structural items…) must be procured together with the Prime as part of the core team***, in order to ensure sufficient time for the engineering/design activities.
- ***The PLM must procured as part of the core team because of the need of an early definition of critical interfaces*** (external interface to LAD modules and internal interface to deployment mechanism.)

Very detailed and sound payload MAIT and Calibration Plans are provided. Some main aspects underlining the robustness of the MAIT and calibration plan are summarized hereafter:

- The MAIT of several QM and EM LAD Modules including about 100 detector assemblies (for at least 6 complete Modules) provide a small scale mass production as a precursor for FM production.
- All time critical production and AIT steps, especially ASIC manufacturing and Front End Electronic (FEE) AIT, are done by industry that are used to professional mass production (see Figure 14). ASIC gluing and bonding operation was a schedule concern, but the identical design of all LAD Modules allows a highly automated fabrication which is

standard for industrial-scale applications: Gluing the ASICs to the FEE PCBs is done fully automatically by pick and place robots leading to glue times in the order of minutes per detector assembly and bonding is done in a semi-automated way by bonding machines.

- For most MAIT activity delays recovery options have been identified, e.g. by nominally not running production lines at full capacity or only with 1 or 2 shifts per day. Also for manufacturing machines (e.g. bonding machines) provision of back-up units is considered.
- Instrument Calibration and Characterization can be done on LAD Module and WFM Camera level, thus calibrating the instrument does not lead to any additional schedule dependencies.
- A credible implementation and mass production schedule has been provided with a goal of manufacturing one LAD Module every three days on average during the mass production phase, over a period of about two years. A detailed Monte Carlo and stock analysis has been performed to assess a realistic duration of the MAIT activities, also taking into account a variations in MAIT speed due to unforeseen events.
- The first LAD Modules are delivered already more than one year (including 6 months margin taken by ESA on the PL delivery) before the integration onto the LAD Panels starts, which provides an additional buffer that allows reacting to unforeseen MAIT delays.

However a few concerns remain:

- The documentation provided for the PRR did not include any information about the qualification status of the processes used for FEE manufacturing. ***The PRR therefore recommends to select the respective industrial partner already before SRR and to initiate the required qualification steps if needed.*** Failing to do so could delay the QM manufacturing and thus also the overall LAD MAIT.
- The SDD manufacturing facility is loaded to 80% of its overall capacity with two-shift operation. This provides little margin for recovery.
- The schedule does not include any time allocation after mission adoption to contractually set up the industrial consortium and ensure funding.

Considering the points mentioned above, the convincing schedule assessment by the Payload Consortium, and the 6 months schedule margin w.r.t. each PL delivery, a timely delivery of the PL appears credible. However, some schedule risks associated with (i) ASIC development and (ii) setting up a new mass production remain; these risks could lead to some schedule slippage beyond the allocated margin. The additional ESA contingency of 6 months provides some confidence that a launch date end 2022 can be met; a launch in 2023 is seen as realistic.

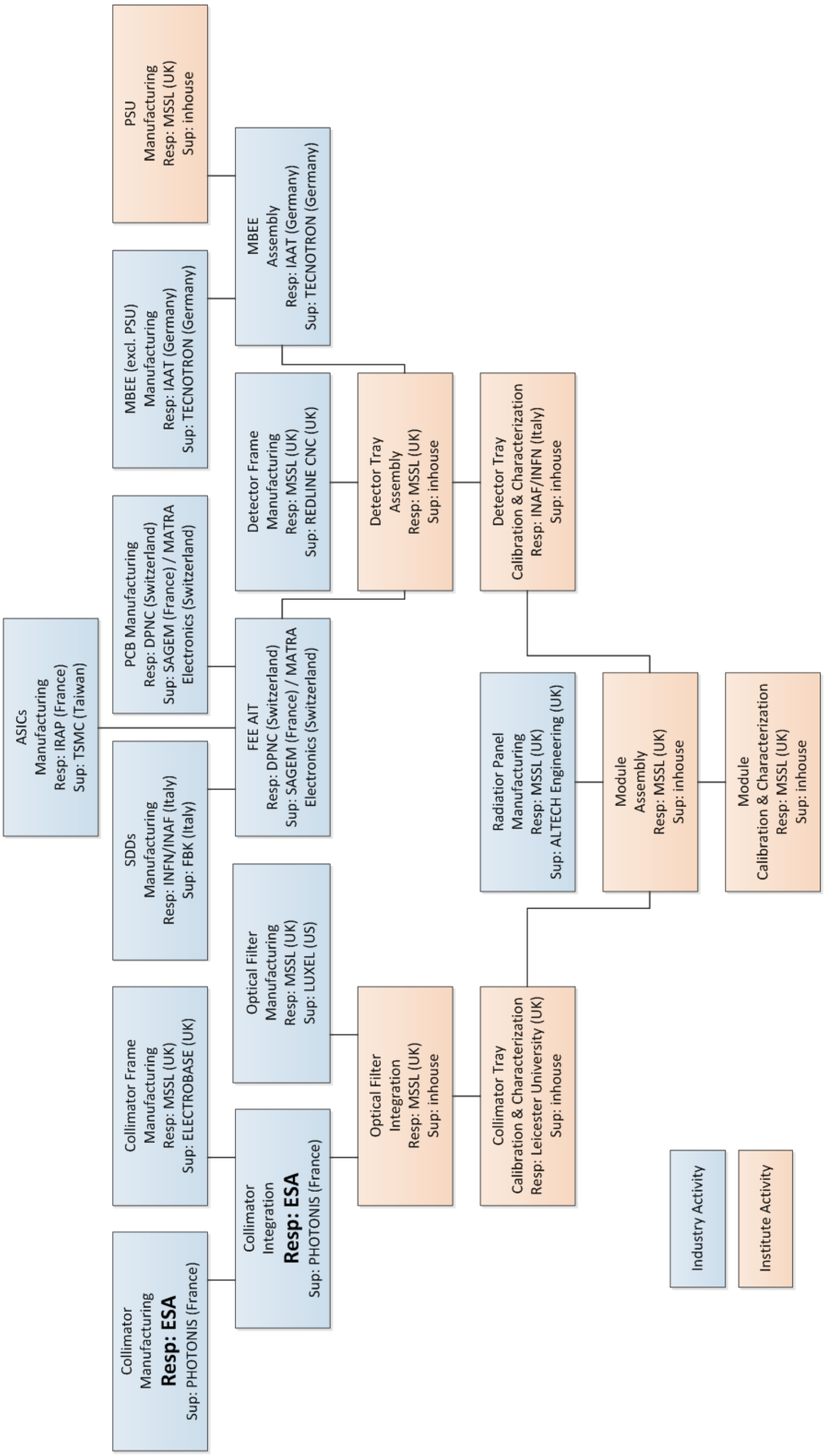


Figure 13: Industrial contributions to the LAD Module MAIT (note ESA is responsible for the LAD collimator)

5.6.3 Reference Schedule and Critical Path Analysis

Figure 15 illustrates the LOFT reference schedule generated by the PRR.

In total one year of schedule contingency has been taken for the instruments: 6 months on the LAD Module delivery and 6 months before the Launch campaign.

The reference schedule reflects the schedule provisos presented in chapter 6.6.2 for a launch by the end of 2022**.**

It presents two parallel critical paths, the LAD development and the SC development.

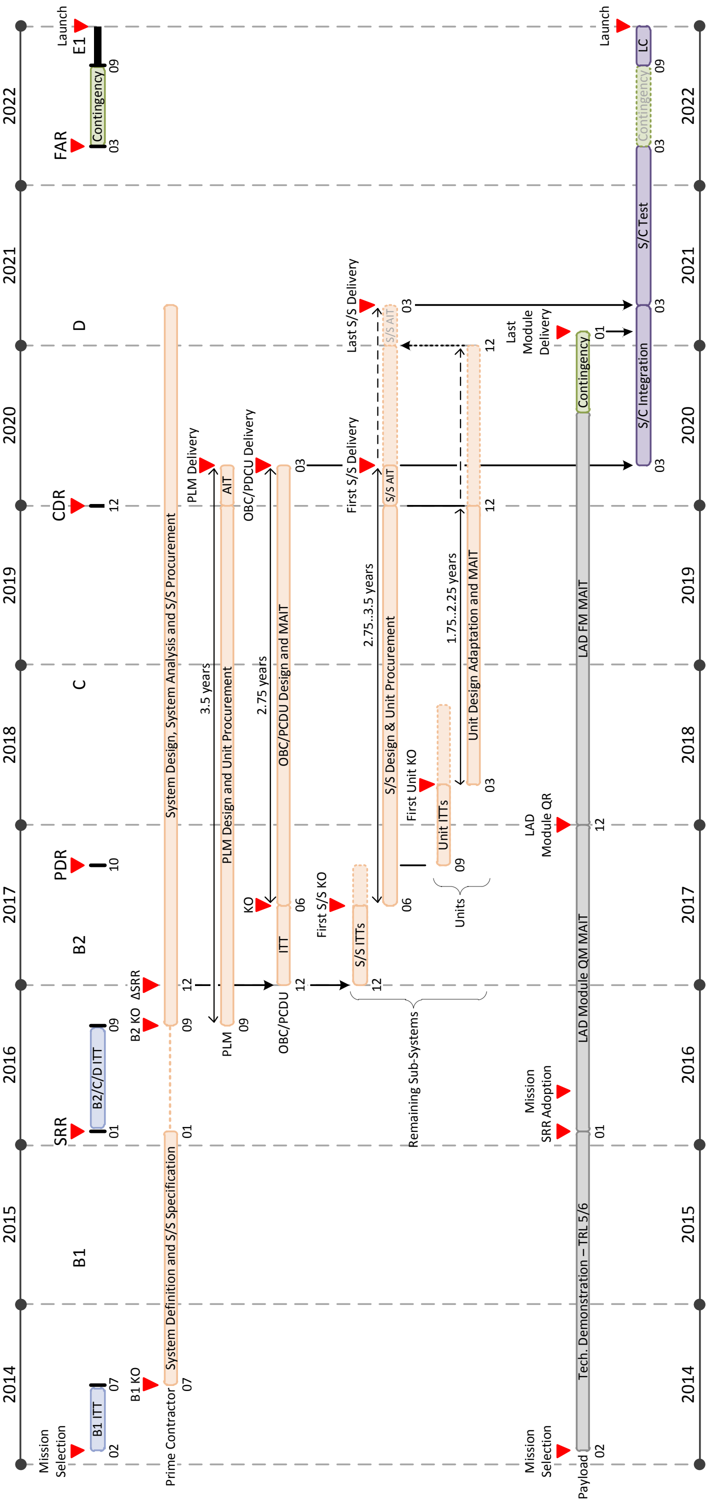


Figure 14: LOFT payload to spacecraft dependencies and critical path

5.6.4 Risk Assessment and Related Mitigation Plan

Each industrial contractor and the Payload Consortium have produced risk registers, and these have been synthesized into the ESA Risk Register. The PRR Panel has addressed these registers and based on the review of the Data Package in general has concluded as follows:

- ***Payload Risks are not considered to be associated to technical feasibility but rather only to schedule***. Failing to achieve TRL-5 (mainly for the ASICs) by the end of 2016 (SRR) is considered a low/medium risk, based on the detailed technology development plan provided by the Payload Consortium. The Payload Consortium plans achievement of TRL 6 by SRR, which is considered necessary to ensure the early availability of the LAD QM by end of 2017. A risk remains with the timely readiness of the FEE integration industrial partner (including process qualification) that will be taken on-board late after SRR. ***With this consideration the risk of not achieving LAD QM by end of 2017 is considered medium and is reasonably covered by the specific 6 months payload contingency***

Note: The above risk-ratings are assuming adequate funding for the LAD is available after mission selection.

- The MAIT for the LAD-FM is very well documented and analysed. A credible implementation and mass production schedule has been provided with a goal of manufacturing one LAD Module every three days on average during the mass production phase over a period of about two years. A detailed Monte Carlo and stock analysis has been performed to assess a realistic duration of the MAIT activities also taking into account variations in MAIT speed due to unforeseen events. Furthermore 6 months schedule margin for the delivery of the LAD-FM is included in the reference schedule. ***Based on this consideration the risk is considered low/medium and is reasonably covered by the 6 months payload contingency and the 6 months ESA contingency.***
- The contribution from the Member States to LOFT is concentrated within a few member states, with Italy as the biggest contributor. The consequence of any funding shortfalls after B2/C/D kick off, that affect PL production would be very significant as it will not be easy to redistribute the contribution between the participating member states due to the mass production required for the LAD payload. ***Accordingly it is paramount that the member states make firm commitments at selection. This risk is NOT covered by the ESA contingency.***
- ***Consideration for the timely availability of the WFM instrument is equally important to the schedule, but is considered less critical*** because the WFM follows a more regular development flow and also benefits from the early development of the LAD ASICS and SDD (the same technology is used in the WFM instrument.) ***Based on this the risk of a late WFM-FM delivery is considered low/medium and reasonably covered by the 6 months payload contingency and the 6 months ESA schedule contingency.***
- ***No significant technical risks have been identified for the SC.***

- ***The development duration from KO to launch is 6.3 years and any delay or slow-down in the establishment of the industrial consortium could be a source of delay. The implementation of the provisos proposed, enabling early procurement of the most schedule critical subsystems, will significantly reduce this risk. The remaining risk is considered medium and reasonably covered by the 6 months schedule contingency.***

6 CONCLUSIONS AND RECOMMENDATIONS

Overall the PRR panel considers the LOFT mission feasible and of low technical risk and medium schedule risk for a 2022 launch date; a launch in 2023 is seen as realistic, subject to adequate funding of payload activities in the next phases.

The requirement baseline is well established and a sound flown down and requirement partitioning has been done. The requirement baseline can be further simplified and needs some consolidation. However, in all the identified cases, this will increase the margin and robustness of the proposed system design.

The industrial studies have shown that a SC design which is simple, robust and with adequate margins is possible. They do not use any unproven technologies. A strong preference is given to the TAS proposed system design, which is more classical in nature, more flexible and has better margins.

The proposed instrument concept is simple and characterised by the high number of identical detectors. The Silicon Drift Detectors and the ASICS used for read-out are still under development (TRL 3-4) and a sound development plan is proposed leading to TRL-5 at SRR with a high confidence. The primary area of concern for the payload is the technology development of the ASIC, although this translates only into a schedule risk given that the required performance has been achieved by the ESA StarX32 development. The parallel ASIC development in Italy provides a mitigation action, but Italian production of flight ASICS is not considered realistic due to the anticipated high cost and already heavy financial involvement of Italy.

The schedule is driven by the development of the SC and the mass production of the LAD detectors The criticality of the SC development is driven by the early procurement of schedule critical subsystems. The in-depth analyses of the mass production set-up and the involvement of industries familiar with mass production provides confidence in the proposed schedule. But an important prerequisite for the timely start of this mass production is the early successful qualification campaign of the LAD detector already by the end of 2017. It must be emphasised that adequate funding of the instruments in phase B1 and B2 is required to achieve this.

The assumptions and task definitions for the ground segment are well defined and are rather classical and typical for an astronomical observatory mission.

- End of Document -

ANNEX A: ESA TECHNOLOGY DEVELOPMENTS

Spacecraft: There is no identified need for technology development for the SC.

Payload: Baseline at PRR is that ESA provides the Micro Pore Collimators (MPCs) for the LAD instrument. Accordingly the required pre-development is also done by ESA, which is the only on-going TDA.

Ongoing MPC Development:

In August 2013 a Technology Development Activity (TDA) was started with PHOTONIS (France, single European source for lead glass Micro Channel Plates). The goal of the TDA is to demonstrate the manufacturing capabilities of square pore MPCs with an Open Area Ratio (OAR) of 70%, a pore alignment of <1arcmin and the required size to cover a complete LOFT detector with one MPC (~7x11cm²). The TDA is organized in two steps/batches: Demonstration of 66% OAR MPCs until July 2014 and demonstration of 70% OAR MPCs until February 2015. Using these MPCs for mechanical tests in a representative LAD collimator frame allows reaching TRL 6 for this element in 2015 before SRR.

Future MPC Development:

There is a discussion currently underway concerning the possible replacement of square-pore with round-pore collimators. Round pores are the standard technology for commercial/night vision applications and provide similar performance, are easier and less risky to manufacture, and are less expensive than round pores. Consequently an additional TDA with PHOTONIS is envisaged to start in 2014 after mission selection to demonstrate technical feasibility and performance early 2015. The main concern that needs to be addressed by this TDA is that the round pore technology for an OAR of 70% does not provide the specified pore alignment performance, for a lower OAR of 60% pore alignment of 1.8arcmin instead of the specified 1arcmin have been demonstrated by HAMAMATSU.

Note: Instead of initiating a second TDA, the option of changing the second step/batch of the ongoing square pore TDA to round pores is under investigation at the time of the PRR.