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DOCUMENT

L Class internal review report

IXO - International X-ray Observatory

Technical & programmatic report

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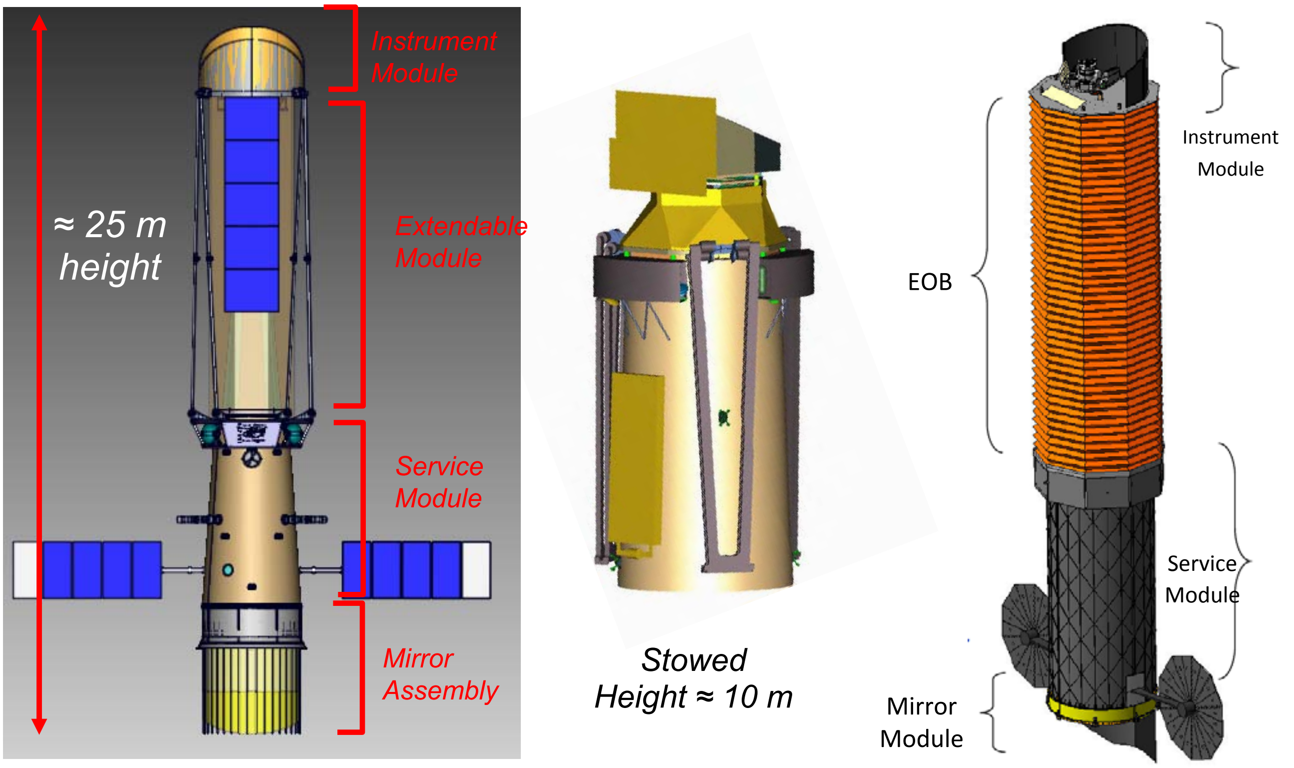
1 INTRODUCTION

This report summarises the findings of the ESA review on the assessment phase activities of IXO – International X-ray Observatory (L class candidate of the Cosmic Vision 2015-2025 programme). IXO is the result of the merge between the XEUS (ESA) and Constellation X (NASA) mission concepts and is based on an ESA-JAXA-NASA international cooperation scenario. The assessment study activities have included the following key steps (Q2/08 to Q3/10):

- NASA phase 0 system level study carried in Q3-Q4/08 and used as input to the US Astro 2010 process
- ESA internal phase 0 system level study performed via the ESTEC Concurrent Design Facility (Q4/08-Q1/09)
- two parallel industrial phase 0/A system studies with EADS-Astrium and Thales Alenia Space (Q3/09 – Q3/10)
- instrument assessment studies conducted by consortia of scientific instruments (Q3/09 – Q3/10)

The four system level studies have converged to the same spacecraft architecture, including the following main elements: a) the Instrument Module (IM, hosting the focal plane instruments); b) the Extendable Optical Bench (EOB); c) the Service Module (SVM); d) the Mirror Assembly (MA, including the X-ray optics), see figure below.

Fig 1.1 – Spacecraft architecture (left: European design, deployed; centre: stowed. Right: NASA design, deployed).



The independent ESA review covered all mission areas (thus including all aspects of the spacecraft design, instrument design and optics technology developments) disregarding any preliminary international cooperation scenario agreements, but put additional emphasis on the reference scenario put forward by the joint study team. Such a reference scenario is summarised by the table below: ESA would have responsibility for the provision of the Instrument Module (including the integration and testing of the European and other Agency provided instruments) and of the Mirror Assembly (including the procurement of the optics), JAXA would contribute with the Extendable Optical Bench (EOB) and the cryogenic chain of the Micro-calorimeter Spectrometer (XMS), while NASA would have overall system level responsibility of the observatory, including Launch Vehicle and operations.

Table 1.1 - reference IXO cooperation scenario (model payload in light blue. MS = ESA Member States)

	ESA	Europe MS	NASA	JAXA
System Integration & Testing			X	
Service Module			X	
Extendable Bench + Shroud				X
Mirror Assembly (with optics)	X			
Instrument Module	X			
Launcher Vehicle & Adaptor			X	
Mission Operation Centre			X	
Science Operations Centre	(X)	(X)	X	(X)
Micro-calorimeter Spectrometer (XMS)		(~ 1/4)	X (~1/2)	(~ 1/4)
XMS cryogenic chain				X
X-ray Grating Spectrometer (XGS)		TBD	X	
Wide Field Imager (WFI)		X		
Hard X-ray Imager (HXI)				X
High Time Resolut. Spectrometer (HTRS)		X		
X-ray Polarimeter (XPOL)		X		

2 TECHNICAL REVIEW

The review work has been organised in two main parts: a) review of the mission profile and system design (including all mission elements); b) in-depth review of the intended ESA contributions. This report is organised accordingly.

2.1 Mission profile & system level aspects

This section summarises the board findings on the feasibility and level of definition of the overall mission concept. The section is organised according to the main questions raised in the review procedure.

- *Completeness and consistency of the requirements definition.*

The high level mission requirements are clearly defined in the IXO Mission Requirements Document, which captures all key science requirements formulated in the Science Requirements Document (e.g. effective area, angular resolution, spectral resolution, observation efficiency, access to sky, etc.) and the main functional and design requirements (e.g. payload operations, LV constraints, mission analysis), to a level in line with phase 0/A.
The instrument requirements for absolute focus location within a sphere of 1 mm radius are over-specified. The Field of View (FoV) of the most constraining instrument, XMS, allows a larger lateral off-set up to 3 mm and the actual depth of focus of the telescope allows an axial off-set of up to +/- 2-3 mm, both without degrading significantly the telescope Point Spread Function (PSF) and without degrading significantly the telescope Effective Area (EA). For the lateral off-set there is in any case the possibility to re-point the telescope and operate it slightly off-axis. Lateral off-set up to 10 mm has no significant effect on PSF and EA. The EOB is believed to perform well within such lateral off-sets, thus enabling to considerably simplify the spacecraft design by eliminating the lateral adjustment mechanisms for the instruments.

- *Definition of mission profile and overall feasibility.*

The mission profile (direct injection to SEL-2, large halo orbit) is well defined and known to ESA (e.g. Herschel, Planck, GAIA, JWST) and does not present any significant challenges (mission analysis and operations). Operations at L2 provide a constant thermal environment, good sky visibility, with a favourable radiation environment (far more benign than XMM-Newton). Given the existing heritage, the partnership agreements with NASA and JAXA and the proposed spacecraft design (classic observatory, with SVM based on existing technology), the mission is considered as feasible.

- *Completeness and consistency of the resource budgets.*

A detailed mass budget, broken down to unit level, was produced by EADS-Astrium and Thales Alenia Space. Both budgets present margins exceeding the minimum required level, with a total mass growth potential (design maturity margins combined with system level margins) of about 42%. Standard equipment nominal values correlate well with Herschel-Planck units. Similar margins were obtained by NASA. A system study reflecting the agreed detailed contributions of the international partners has not been done, but is not likely to significantly impact the overall mass situation. The mass of in particular the IM structure and the need for several levels of Hold Down Release Mechanisms (HDRM) is under-estimated and needs revision (see section 2.2). The mass of the XMS instrument is also associated with a high risk for mass growth (see section 2.2.3). It is, however, believed, that the proposed elimination of the IM adjustment mechanisms and the simplification of the XMS instrument detector lay-out will neutralise the risk for mass growth. The evolution of the mass budget especially for the IM needs close monitoring in the future project phases.
The power budget converges on a total of 5.5-6.5 kW and is not considered as critical. The main difference is related to the power required for the thermal control of the Mirror assembly. The delta-V (and propellant) budget is in line with recent SEL-2 missions (~ 100 m/s) and is not critical (compatible with mono-propellant design).
The data rate and down-link budget are compatible with X-band capabilities from L2 and are not critical (a K-band option is foreseen by NASA, providing a higher performance solution). Sizing of the mass memory is not critical. The contamination budgets are in line with the XMM-Newton experience but need further investigation and monitoring.

- *Overall maturity and robustness of the mission design.*

Four different system level studies resulted in: a) very similar system architecture; b) similar level of mass contingency/margins (~40% level); c) similar system resources and capabilities; d) a significant heritage from recent X-ray missions (XMM, ROSAT, Chandra, SAX) reflected in the design. The model payload has been studied since several years (both XEUS and Con-X heritage), which is well reflected in a mature Payload Definition Document. On this basis, the system architecture is considered as robust and mature. The European design focused on the adoption of the baseline optics technology (Silicon Pore Optics), while NASA investigated the Segmented Glass Optics accommodation. The system design is classical for an observatory and includes only a few technology driven elements. The system design is characterised by a residual off-set between Centre of Mass (CoM) and Centre of solar radiation Pressure (CoP) leading to a permanent disturbance torque: this effect needs to be further mitigated by design, reducing the impact on the attitude control system. The design solutions proposed for the extendable structure offer adequate bending stiffness (f> 1 Hz), and will thus not significantly impact the settling time after attitude manoeuvres. But such a parameter needs monitoring not to become a design driver and affect observation efficiency.

- *Definition of the interfaces between contributing parties.*

The IXO system design provides a modular design, with clear physical and functional interfaces. The split of work between the Agencies is well aligned to such interfaces. The payload definition is well advanced for this stage of the projects, providing a robust starting point for the definition studies of the IM. Future negotiations between the Agencies should aim to consolidate further the detailed interfaces based on the “Clean & clear” approach, thus simplifying management, development, handling and testing. The interfaces between Instrument Module and XMS (largest instrument onboard) is in principle “Clean & clear”, but needs to be carefully monitored as it is so resource demanding.

- *Compliance of system design and performance with science requirements.*

The baseline system design is compliant with all key science performance requirements. The most critical areas are the telescope angular resolution (better than 5” at 1.25 keV) and the XMS energy resolution (better than 2.5 eV at E<7 keV) (see discussion in section 2.3). However, there are no “hard walls” and a degraded angular and energy resolution will have a graceful impact on the science performance. The requirement applicable to the reconstruction of the line of sight (AME < 1.5”), although achievable, is also considered as challenging.

- *Risk to ESA (design evolution and technology development).*

The system architecture is considered as mature and it is not expected to evolve significantly in absence of drastic changes in science requirements. The mission modules are well defined and characterised by clear interfaces.

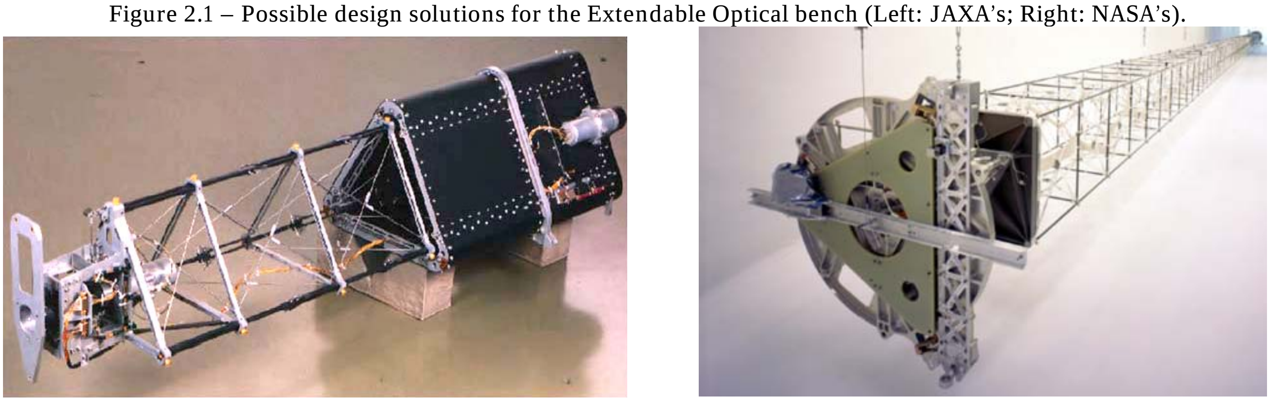
The model payload has been under study for several years and shows stable mass, power and data rate requirements. However the XMS instrument, with largest resource demands among the instruments, the lowest TRL and not under ESA control, is a high risk to ESA (Instrument Module development), requiring a risk mitigation strategy to be agreed with JAXA and NASA.

Concerning the Mirror Assembly, the main risk factors are late design changes induced by the x-ray optics development and the procurement time for the flight x-ray optics. Such risks can be mitigated by progressing vigorously on the planned development activities, confirming the optics technology baseline by the end of 2012 and addressing as early as possible the series production aspects.

- *System level trades*

Based on the work of the review board the following trades should be closed by ESA during the definition phase: a) consolidation of the EOB requirements and performance (ADAM/coil-able masts/hinged fixed length beam) with the aim to eliminate the need for the instrument lateral and axial adjustment mechanisms; b) design finalisation of instrument exchange mechanism (translation Vs. rotation); c) IM level Vs. individual instrument focusing capability; d) centralised Vs. de-centralised Data Handling System (possible inclusion of Payload Data Handling Unit and mass memory on the IM) ; e) mirror heating approach; f) contamination covers (internal/external). The closure of these trades (considered as normal work for the definition phase) requires active contributions from the NASA and JAXA teams. Other trades (e.g. balancing of Solar Radiation Pressure torque) fall under the responsibility of partner Agencies.

Figure 2.1 – Possible design solutions for the Extendable Optical bench (Left: JAXA's; Right: NASA's).



2.2 In-depth review of Spacecraft design

This section summarises the detailed board findings on the feasibility and level of definition of the intended ESA contributions to the IXO mission, namely the Mirror Assembly (including SPO optics) and the Instrument Module.

2.2.1 X-ray optics (Silicon Pore Optics (SPO) technology)

- *Completeness of the requirements & interface definition*

The key requirements of effective area and angular resolution are clearly defined. Preliminary image quality budgets at mirror module and observatory level exist. The stray-light and off-axis performance requirements need to be established. The environmental requirements applicable to the SPO pre-qualification (e.g. shock, vibration loads, and quasi-static load test) are being progressively defined and this effort should be quickly completed. Internal and external interfaces of the MM are properly defined (e.g. stack mounting, isostatic mounts, integration of MM in a petal, petals mounting on MAM).

- *Status and maturity of the design*

The design proposed is very robust. One of the main advantages of the Silicon Pore Optics technology compared with backup solutions is the intrinsic stiffness of the mirror modules. The alignment tolerances studies demonstrate that also the positioning of the mirror modules and petals is not critical. The modularity is also considered a strong advantage of the proposed design.

- *Performance and compliance status*

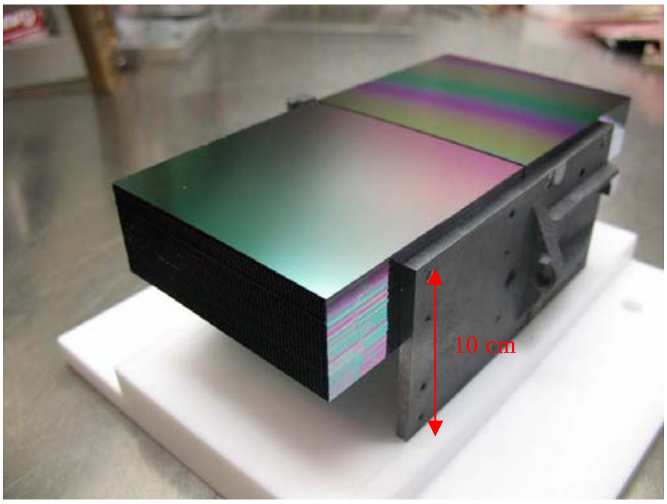
The SPO performance has been verified with representative X-ray tests. Present resolution performance is in the 16 arcsec region (3 keV). The latest samples indicate that simple process control can allow reaching better than 10 arcsec. This will be demonstrated in the ongoing Technology Development Activity (TDA). To reach the required 5 arcsec it is necessary to improve the conical approximation to true Wolter-1 geometry. The technological feasibility of this step has not been proven yet. It is recommended to push the technological developments to prove this step after the 10 arcsec has been demonstrated. No problems are expected for meeting the effective area.

- *Development plan & model philosophy*

A detailed SPO development plan exists, targeting TRL=5 by the end of 2012 (see section 2.4). Pre-qualification (TRL=5) will be obtained at bread-board level for a single Mirror Module (MM). This will be followed by full qualification at Mirror Module and petal level.

The innermost MM is significantly longer and more curved than has been demonstrated up to now and is likely to pose new development difficulties. It should be noted that the innermost MM contribute mainly to the hard end of the energy spectrum, where the required angular resolution is 30 arcsec HEW compared to the 5 arcsec HEW for the low end of the energy spectrum. MM representing all radii is scheduled to be developed by the end of 2012, which is considered feasible.

Figure 2.2.1 – Mirror Module based on the Silicon Pore Optics (SPO) technology.



2.2.2 Mirror Assembly Module

- *Completeness and consistency of the requirements definition*

The performance and functional requirements of the MAM are properly defined. Thermal and structural requirements are adequately flown down from system to module level (more clearly defined for EADS than for TAS). The lowest allowable resonance frequency for the MAM needs to be confirmed (associated to LV choice), so as to optimise the design of the module structure (now performed for the most stringent axial stiffness requirement).

- *Status and maturity of the design*

The Mirror Assembly is based on a spoke-wheel design and 8 petals. Thermal control is ensured by a combination of heaters, heat-pipes and thermal baffles. Inner and outer contamination covers are proposed. The all CFRP design appears as a working solution, justified by extensive analysis and optimisation, and providing confidence that the requirements can be met within the allocated resource budgets. The design solutions are robust to potential evolution of the telescope effective area requirement.

- *Definition of responsibilities and interfaces*

Both industrial designs offer clear and clean interfaces with the rest of the S/C (fixed metering structure of the SVM) at 8 discrete interface points, with decoupling of deformations between the two modules. Also the interfaces between mirror module and petals and between petals and mirror assembly (isostatic mounts) are clearly defined. The launcher adaptor should be part of the SVM and not of the MAM.

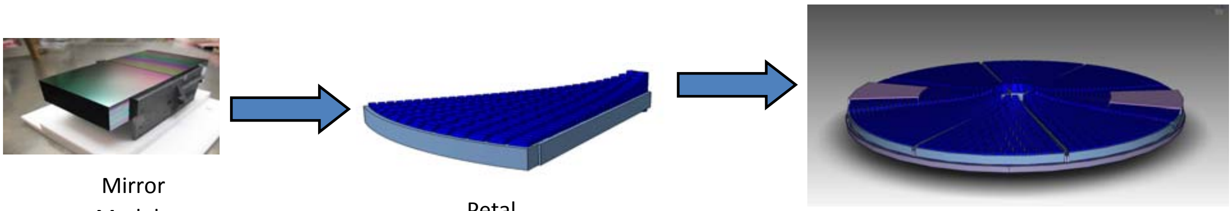
- *Resource budgets*

The Mirror Assembly resource budgets (mass and power) are complete and adequate mass and power margins are properly included. The thermal design combined with the operating temperature drives the heater power for the telescope. Significant room for optimisation exists in this area.

- *Development plan & model philosophy*

The Mirror Assembly primary structure will be qualified using the STM, and the MM and the petal will be qualified with the QM. This approach is deemed as realistic given that no critical technologies are identified for MAM structure and thermal control. The contamination covers shall be qualified at equipment level and be included in the STM. The objective is to deliver to the observatory integrator a fully tested and self-standing unit.

Figure 2.2.2 – IXO optics: from Mirror Modules to Mirror Assembly.



2.2.3 Instrument Module (IM)

- *Completeness and consistency of the requirements definition*

A preliminary set of performance, functional and design requirements applicable to the IM exists, but additional work is required to clarify: a) requirements applicable to the mechanisms (instrument exchange); b) mechanical requirements applicable to the IM design and qualification; c) mechanical requirements applicable to the instrument design and qualification; d) confirmation of the level of Data Handling System and Electrical Power System functionality at IM level (e.g. Payload Data Handling Unit and mass memory).

- *Status and maturity of the design*

The IM architecture is driven by the requirement to accommodate numerous instruments with a large total mass, to implement several mechanisms to achieve the necessary focussing and to allow the movement of the different payload units into the focal point, and to provide the required thermal environment. The IM is very densely populated and simplification measures should be taken. The adoption of complex instrument lateral adjustment mechanisms is not justified at system level and should be eliminated, thus simplifying significantly the module design without impacting on science performance. The need for the axial adjustment mechanism shall be carefully addressed in the definition phase, as no system level recovery option exists for this alignment error. The design complexity and technology readiness level of XMS constitute the lowest maturity among the instruments. Due to its high resource demands, it represents a high risk for the IM. The following issues need to be investigated in the next phase (including specific trades): a) detailed implementation of the instrument exchange mechanism; b) accommodation of instrument units and harness; c) refined thermal and mechanical analysis.

- *Definition of responsibilities and interfaces*

The proposed designs offer clear and clean mechanical interfaces with the rest of the S/C (Extendable Optical Bench). Clean electrical interfaces can also be easily defined, following a decision on whether to include in the IM a dedicated payload data handling unit with associated mass memory, which is recommended to simplify the deployable harness.

- *Resource budgets*

Detailed mass and power budgets with the required design maturity margins are available. Based on the present IM design and on a total supported mass ~ 700 kg, the nominal mass values of the HDRMs and associated structure are underestimated. Similarly, the IM structure (e.g. crown in the TAS design) and mechanisms mass are underestimated. The total mass increase depends on the specific design and could be as much as ~ 250 kg. However, by eliminating the lateral adjustment mechanisms this will be reduced to ~ 100 kg and will not severely impact the global mass status.

- *Development plan & model philosophy*

The Instrument Module primary structure will be qualified using the Structural Thermal Model (STM). This approach is deemed as realistic given that no critical technologies are identified for IM structure and thermal control. The IM mechanisms shall be qualified at equipment level and be included in the STM, as it will affect significantly the overall structure load path. The objective is to deliver to the observatory integrator a fully tested and self-standing unit.

2.3 In-depth review of Instruments design

The board has reviewed the documentation package provided by the instrument consortia. The level of design maturity and definition of the IXO model payload is considered as rather high, beyond what usually achieved during the assessment phase.

- *Completeness and consistency of the requirements applicable at model payload level*

In general the instruments requirements are found complete and well advanced for this study phase. The model payload is fully compliant with the science requirements. The requirements of the XMS cryogenic chain are well defined. Electrical, mechanical and thermal interfaces are also properly defined. The following issues need further considerations: a) the WFI pixel size is significantly over-sampling the PSF and needs to be reconsidered; b) the required radiator temperature of the instruments should be harmonised as much as possible; c) the XMS detector array size (inner array) needs to be reconsidered in view of simplifying the instrument and de-risk the overall mission; d) the XGS effective area requirements needs to be reformulated in order not to penalise the other instruments, and its pointing requirements on the system need careful review not to become a system driver.

- *Identification of design drivers and critical areas*

The large field of view of WFI is driving the design of the IM baffle and of the particle diverters. XMS is the largest, heaviest and most complex instrument onboard and it drives a large part of the IM design and resources. XGS has a large impact on accommodation, given the separate optical path from the gratings to the focal plane. Pointing requirements associated to XGS need careful monitoring. XGS is also driving the stray-light sensitivity requirements. The different demands on detector temperature (e.g. 173K for WFI vs. 213K for HXI) constrain the design of the thermal control system of the IM.

- *Status and maturity of the design definition*

All instruments have good heritage and a rather high level of design definition. In particular, the design appears as rather robust in the case of WFI, HTRS, XPOL and HXI. The definition level of the XMS cryo-chain can be considered as high as it is based on the Astro-H design. However, an increase of the detector volume has been identified in comparison to Astro-H, which could propagate with impact on the overall cryo-chain. The robustness to evolution of the XMS focal plane assembly is less mature due to the low technology readiness of this unit. In addition an insufficient heat lift margin has been identified for the first cooler stage necessitating additional cooling of the first shroud. In summary, the XMS has the lowest maturity of all the instruments, is the most resource demanding instrument and has the most complex consortium set-up. The XMS must therefore be seen as a high risk for the IM development and any simplifications of the instruments should be stimulated. The baseline CAT-XGS design is simple and robust (focal plane assembly), while some design evolution could be expected in the gratings area due to ongoing development.

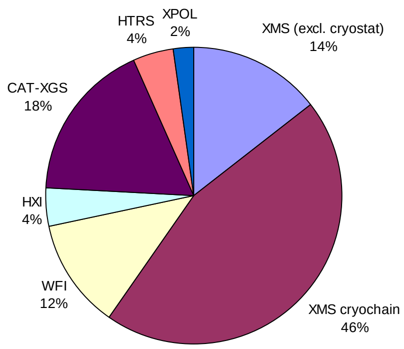
- *Completeness and consistency of resource budgets*

The mass, power and data rate budgets of the instruments, with the exception of XMS, are found correct and complete, with the required design margins. XMS requires a large fraction of the resources (see figure 2.3and its mass budget is less solid due to the status of the ongoing detector developments.

- *Identification of simplifications*

Before finalizing the instruments AO, the following issues need to be addressed; a) simplification of XMS (descope of focal plane size and streamlining of consortium); b) reduction of number of pixels for WFI; c) reformulation of the effective area requirement of XGS; d) prescription of a given S/C location for the XGS gratings; e) simplification of the IM thermal control design by revisiting the requirements applicable to the instruments focal planes.

Fig. 2.3 – Instruments mass budget (fraction per instrument).



2.4 Technology readiness

The S/C (excluding instruments and optics) does not require specific technology developments, based on the assumptions of the re-use of ADAM based solutions for the deployable bench (JAXA contribution). The deployable bench will require adequate bread-boarding to address mission specific aspects (e.g. synchronised deployment of three masts). The instrument exchange mechanism will as well require careful engineering (ROSAT and Chandra heritage, but larger supported mass), including adequate bread-boarding.

The mission elements with the lowest technology readiness are: a) X-ray optics (SPO presently at TRL=4, see section 2.2); b) XMS detectors and read-out electronics (presently at TRL=4); c) CAT-XGS gratings (TRL=4), see section 2.2); d) mirror contamination covers (TRL=3). In the first three cases, the development challenge could be drastically reduced by modest relaxations of performance requirements (i.e. ~ 10" HEW, 3.5 - 4 eV FWHM, modest EA reduction for XGS). The development of the contamination cover is considered as standard engineering work. The technology developments associated to the ESA contributions are covered in the IXO technology development plan. The link between planned development activities and system level definition needs further strengthening, under the supervision of the study team.

- *SPO development and technology back-up*

The mirror modules are at TRL 4 (for 2 meter radius). TRL5 can be achieved in the short term. The MM will benefit from further improvements of wafer surface quality and dimensions expected from current trends of the semiconductor industry. Dicing, ribbing and wedging of plates are consolidated processes. Manufacturability of inner radius modules is considered potentially more critical (larger plates, smaller curvature radius). Mechanical analyses and experimental activities have been performed, but an inner radius module has not been manufactured yet. The plan to reach TRL 5 by end 2012 is deemed credible. The main risks at present are: a) Impossible to reach 5arcsec resolution. Risk is assessed as high. However, the risk of not reaching better than 10 arcsec is considered as low. b) Sensitivity to shock. Risk is considered low. c) Impossibility to produce inner central element. The central modules are more important for hard x rays (with relaxed HEW < 30"). Also alignment tolerances are more relaxed for the central elements. Risk is moderate.

In conclusion while there are still some significant issues to resolve, none is likely to lead to a no-go and TRL-5 should be reached by 2012. This is assuming the planned activities takes place without delays. Given the need to produce a large number of modules, it is not likely to build a full mirror assembly ready for qualification and acceptance test in less than 5 to 6 years from stat of activities. To mitigate a possible risk in the industrialisation of the processes and associated procurement schedule, it is strongly recommended to address this aspect in parallel with the technological development.

The status of the Segmented Glass Optics back up has been reviewed and was found to be behind the SPO as far as technology readiness is concerned, associated with significantly higher risks as much as for performance as for manufacturability and impact at system level (larger demands on mass and power for a given effective area). At this point in time, the Segmented Glass Optics cannot be considered as a risk mitigating option.

- *XMS cooling chain*

The XMS cooling chain (JAXA provided) involves a significant development effort. Considerable risk mitigation was achieved by base-lining the reuse of the cryo-chain being developed by JAXA for Astro-H (L=2014), but any deviations from this assumption will need close scrutinising. In the frame of Astro-H, a triple Adiabatic Demagnetization Refrigerator is in development, derived from previous flown ADR on Astro-E. Although this is not exactly the same as the one foreseen for IXO, TRL=5 status is expected in 2011. The full cryo-chain of Astro-H is planned to be tested by mid 2011.

- *XMS focal plane assembly*

The XMS detector and readout are complex technologies with development risk: A) no flight heritage for TES based micro-calorimeters and multiplexed SQUID readout; B) very tight budget for energy resolution of the core array. C) 40x40 pixel arrays are required, 32x32 are starting to be addressed. D) Multiplexing of 8 pixels per channel has been demonstrated with 2.9 eV resolution, but not on fully representative pixels. E) The baseline concept for the outer array has relatively low TRL=3. F) Compact and complex design of the FPA module in which the above techno's are combined: risk of growing in diameter and hence cryostat mass. G) No back-up scenarios are described. The development plan for the detector and readout technology is clear and detailed. All necessary steps to achieve the required TRL level by end of 2012 are understood and described, but the plan will need to be followed closely and activities will need to be vigorously pursued in order to maintain the schedule. Descope options (e.g. core array of 32x32 pixels instead of 40x40) need to be identified.

- *Contamination cover development*

The deployable covers (membrane concept) are presently at TRL=3. In order to reach TRL=5 before Q4/2012 a development activity needs to be started as soon as possible, with adequate funding. Actual need for inner cover needs to be scrutinised and confirmed.

3 PROGRAMMATIC REVIEW

3.1 Development plan

- *Critical review of model philosophy and verification approach*

The model philosophy proposed for the different mission elements is generally acceptable and in line with the risk areas. A standard Structural Thermal Model (STM) + Proto-Flight Model (PFM) approach is proposed at module level (no technology risk areas), while a Structural Thermal Model (STM), Qualification Model (QM), Flight Model (FM) approach is adopted on higher risk units such as mechanisms, optics and instruments (in the case of XMS also including a Development Model (DM). It is recommended to upgrade the build standard of module level STM's including the mechanisms Qualification Models (QM's).

- *Identification of critical elements (for both S/C and instruments)*

For the S/C the critical elements requiring specific attention are: a) Extendable Optical Bench; b) Instrument Module mechanisms; c) instruments accommodation on IM; d) system level AIV (observatory level).
For the instruments the critical elements are: a) XMS focal plane assembly; b) XMS cryo-chain (if deviating from Astro-H). For the optics: a) achieving the required angular resolution; b) series production of flight units.
All these elements are addressed in the S/C and instruments development plans (see section 2.4). The corresponding recommendations from the board should be taken into account.

- *Link between start of Phase B2 (implementation phase) and success of the technology developments*

The link between successful technology development and start of B2 is from a technical point of view considered as weak, since the ongoing development activities impact on performance parameters as opposed to system interfaces and resources. From a programmatic point of view the board identified the following two targets to enable the start of implementation phase (B2/C/D): a) a clear demonstration of the optics performance, reaching 10" HEW; b) a realistic assessment of the manufacturing time and cost of the mirror assembly flight units. This assessment must equivalent to a definition study thus enabling industry to submit a committing proposal in the beginning of the implementation phase. It is proposed that two parallel assessments are being carried out in order to maintain a competitive situation.

3.2 Development schedule (spacecraft and instruments):

The study team presented two scenarios: a) launch by end 2020 (nominal CV15-25); b) launch by end 2022 (lower risk). The board constructed an independent schedule based on the review findings and on the CV15-25 boundary conditions. It is assumed that the final down selection for the Large Mission would take place at the June 2013 SPC.

- *Instruments schedule*

Assumptions - It is currently base-lined that IXO will fly five instruments WFI/HXI, XMS, HTRS, XPOL and XGS. All schedules have been assessed, however, for the overall project schedule XMS is used as reference, since it is by far the most demanding instrument. The start point of the XMS schedule received from the consortium has been delayed half a year to take into account a realistic AO plan and down selection process. The kick-off of the Development Model is now coincident with the final down selection at the SPC of June 2013 (assuming NASA, JAXA and European funding Agencies release the funds for XMS at that same time). An earlier start will obvious minimise the XMS schedule risk. Due to the instrument complexity, the margin was increased to a total of one year margin. The overall duration from SRR to delivery is then six and a half years, considered as realistic when compared to bench-marks such as HIFI/Herschel and other complex and large instruments.
Potential risks - The proposed model philosophy includes an early development model for XMS. This is a robust approach in view of the complex design and collaboration. The instrument PDR is currently scheduled in the same time frame as the KO of the European prime (implementation phase). This imposes some risk on the level of definition of the interfaces

between the Instrument Module and instruments. This risk could be mitigated if the interfaces are properly defined in the definition phase. Given the XMS complexity, the schedule margin currently allocated might not be sufficient (medium risk).

- *X-ray optics (SPO)*

Assumptions - The optics baseline is the Silicon Pore Optics technology developed by ESA. The backup is the Slumped Glass technology developed by NASA. The final selection will take place by end 2012. The SPO schedule is based on a technology development period concluding before the end of 2012. This phase is followed by an industrialisation phase lasting two years (resulting in a qualification of the full manufacturing process) and by the flight production phase lasting four years. The logic of the proposed schedule is good and durations are found realistic. However, in order to cover the current concerns and risks, a margin of one year has been added to the original schedule.
Potential risks – SPO is a new development and, although the technology is feasible (several Mirror Module have been manufactured & x-ray tested) the production speed (4 Mirror Module/day) and the angular resolution are still not demonstrated. The existing schedule margin is based on additional facilities or additional shift work. However there are common mode problems which could shut down the full manufacturing plant for longer periods (e.g. quality, cleanliness, supplier shortage, etc.), and potential industrialisation risks. Therefore a margin of one year has been added to the original schedule (low risk). The industrialisation of the Mirror Modules production process and corresponding production rate has been difficult to assess. This aspect shall be addressed during the industrial assessment proposed to be part of the Definition Phase, see sec. 3.1. The Background Intellectual Property Rights are also to be agreed at an early stage with the consortium producing the Mirror Modules.

- *Mirror Assembly & Instruments Modules*

Assumptions - The Mirror Assembly Module (MAM) and the Instrument Module (IM) would be ESA contributions. The MAM schedule is driven by the availability of the Mirror Modules and the IM schedule is driven by the instruments, mainly by XMS. All other instruments have been assumed to be integrated and checked-out before the arrival of XMS. To avoid the instrument exchange mechanism becomes a schedule driver, early BB activities and the inclusion of the exchange mechanism in the STM program should be base-lined. It is anticipated that the MAM and IM will go through a full acceptance campaign before delivery for system integration at NASA. The Assembly Integration and Test (AIT) of the MAM and of the IM are estimated to take about 6 month (plus 1 month of margin).
Potential risks - The late availability of both the last mirror petals and XMS instrument are likely to create gaps in the schedule (critical path) which means that further delays on them will have a one on one impact on the MAM and IM deliveries. Overall, the risk on the actual MAM and IM integration activities is considered as low.

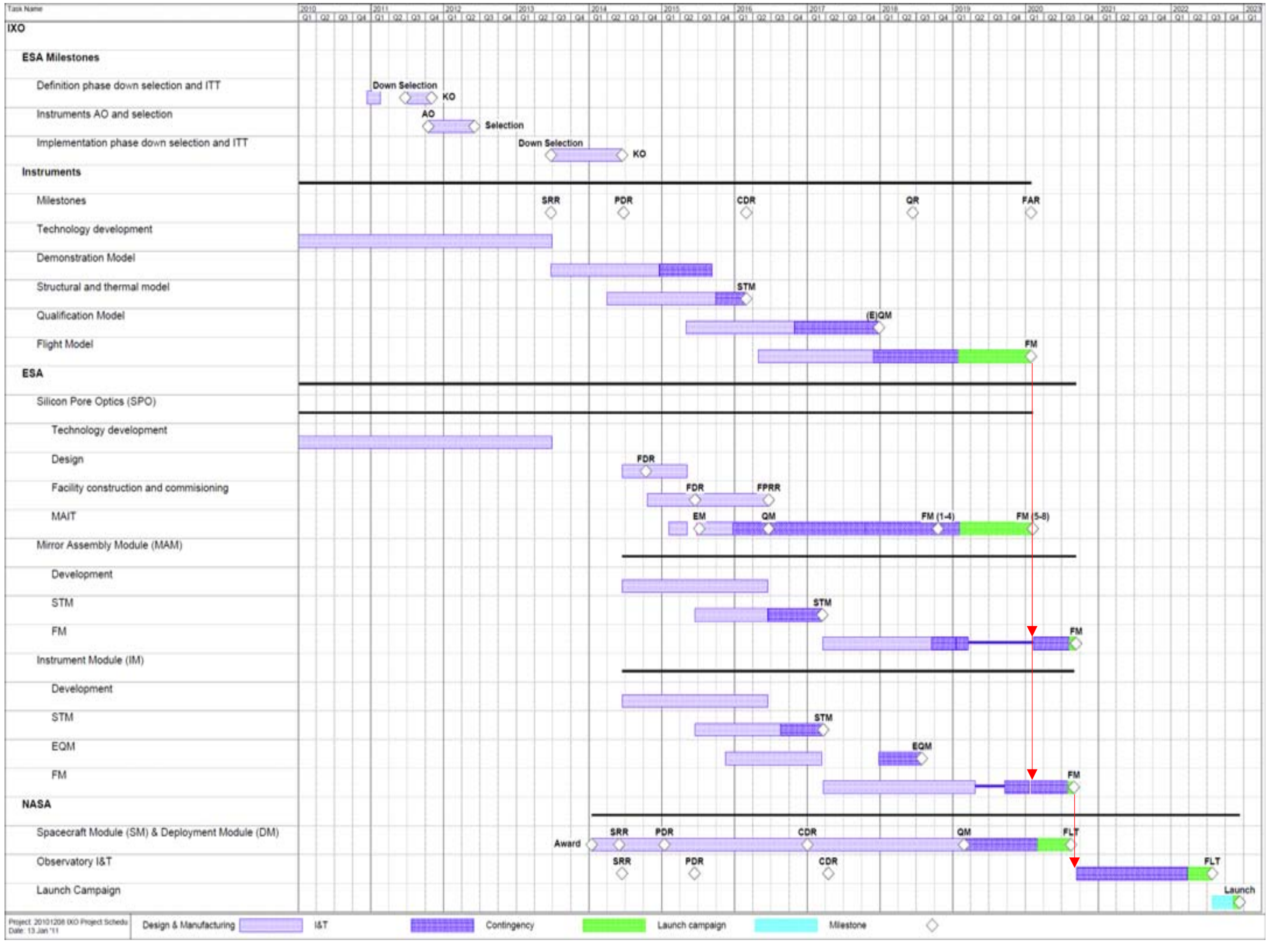
- *Service Module & Extendable Optical Bench*

Assumptions - The Spacecraft Module (SM) and Observatory AIT are provided by NASA. The EOB is provided by JAXA. The plan is based on the NASA 2022 schedule as presented on 6 November 2010 (kick-off). Total durations are realistic.
Potential risks – The SVM is not considered as a risk. However the EOB is a potential risk and the procurement of an early breadboard model and a full deployment test as part of the STM testing are considered as essential.

- *Critical path & Conclusions*

Based on the provided schedules an overall schedule has been constructed bottom-up for the IXO project and leading to a feasible launch date end of 2022, meaning a launch 8.5 years after industry KO, including 5.5 years for IM & MAM FM's delivery to NASA. The IXO schedule has two parallel critical paths. The first one starts with the implementation phase and goes via the XMS instrument, IM and Observatory I&T. The second one starts with the implementation phase KO and goes via the SPO, MAM and Observatory I&T. The proposed IXO schedule is comparable with the Herschel schedule.

Figure 3.2 – Overall programme schedule (as reworked by the board).



3.3 International cooperation

- *Credibility of the international cooperation scenario*

The proposed international cooperation scenario (see table 1.1) has been discussed and agreed by the IXO study coordination group, which includes representatives of the study teams from JAXA, NASA and ESA. The proposed reference scenario appears well balanced in terms of financial commitment, technical heritage, share of risk and visibility.

- *Is the reference ESA contribution well matched to the existing heritage and expertise in Europe?*

The proposed ESA contribution (X-ray optics, Instrument Module and Mirror Assembly Module) is very well matched to the heritage and technical expertise existing in Europe. More specifically, the contribution of the x-ray optics is leveraging on the recent progress obtained by the SPO technology and its intrinsic technical qualities; the provision of the Mirror Assembly Module can benefit from the XMM-Newton experience; the Instrument Module can leverage the existing heritage on instruments accommodation (including cryogenic units) from a number of recent ESA science missions (e.g. Herschel/Planck, XMM-Newton).

- *Definition of the interfaces within the international cooperation*

The IXO design is intrinsically modular. The proposed interfaces within the consortium appear as well defined. Further work is required to agree on a more detailed product tree for each contribution, investigating further all critical interfaces. The objective must be to define clear and clean border lines which reduce the programmatic and management overheads otherwise induced by large international cooperation's. This objective can be easily reached during the planned negotiations in Q1 2011, so as to enable a proper start of the Definition Phase activities.

- *Alternative cooperation scenarios*

The board recommends to confirm the reference cooperation scenario agreed at study team level, and to also take into consideration the following options: a) compatibly with the financial constraints, ESA to take the leading role in the area of Science Operations to better matched to the responsibility share, as ESA is providing the IM and Europe a relevant part of the instruments; b) to discuss within the consortium the possibility of a NASA led Extendable Optical Bench, based on the technology and flight heritage existing in the US.

4 CONCLUSIONS & RECOMMENDATIONS

4.1 Conclusions

The main conclusions of the internal review are the following:

- System level requirements are properly defined. Lower level requirements (module and S/S) need further work.
- The mission concept is well defined and was consolidated via four separate studies (ESA, NASA, EADS Astrium, Thales Alenia Space).
- The mission profile (SE-L2) does not pose difficulties. The system design is classic and the spacecraft (i.e. observatory minus science payload) can be constructed with existing technology. Given the technology pre-developments ongoing since years (on payload units), the partnership agreements with NASA and JAXA and the proposed solution for the space segment, the mission is considered as feasible.
- The resource budgets are complete, with adequate margins (total potential of ~ 40% mass growth available including maturity and system margin), with the possibility of realistic de-scoping to mitigate future risks.
- The key technology developments are: a) x-ray optics to achieve an angular resolution better than 10" (target of 5"); b) XMS focal plane assembly to achieve an energy resolution better than 2.5 eV over large arrays; c) XMS cryo-chain (already on-going for Astro-H needs). The board understands that the mission is compatible with a relaxation of angular resolution to 10 "HEW and an XMS energy resolution to 3 eV, as they result only in a graceful impact on the science objectives.
- Lower heritage areas requiring bread-boarding are: a) Extendable Optical Bench (not under ESA responsibility); b) Instrument Module mechanisms; c) mirror contamination covers.
- The complexity of the Instrument Module and instruments accommodation needs to be reduced, also to mitigate potential mass growth problems.
- The main risks to ESA (considered as acceptable for an L class mission) are: a) late delivery and complex interfaces of XMS (and in general excessive complexity of the IM); b) achieving the optics angular resolution; c) flight optics industrialisation process and late delivery of the optics.

4.2 Board recommendations

4.2.1 Technical recommendations

The board recommends enforcing in the next study phase a system engineering approach up front, challenging the critical science requirements and establishing priorities and an acceptable de-scope (e.g. optics HEW) and trade space. Potential sub-contractors should be involved in the Definition Phase activities on critical components. The launcher authorities should also be involved in the early phase on issues related to model philosophy, qualification and acceptance approach. Lessons learnt from recent X-ray missions should be fully considered. The board also recommends revisiting (early part of next study phase) a number of trades, including system level aspects:

- Requirements and design of the IM mechanisms (actual need for X, Y, Z stage; rotations Vs. translation).
- Choice of the final EOB design solution (e.g. JAXA's, NASA/ ADAM Vs. coilable/hinged fixed beams).
- S/C bus voltage (50 V vs. 100 V to minimise losses through the long deployable harness).
- X-band Vs. K-band telemetry link.
- Optics operating temperature (maintaining capability to accommodate back-up optics until end of 2012).
- Minimisation of the CoP- CoM lever arm to minimise the load on the AOCS.
- Approach to contamination control with emphasis on optics protection (external vs. internal cover/s).

Concerning the Mirror Assembly Module and optics, the board recommends to:

- To formalize with the science team a requirement of 10" for the optics angular resolution (with a goal of 5").

- Agree as early as possible on interfaces with the NASA provided elements (SVM) and on requirements flowing down from the system design, in particular on the design limit loads, shock loads and the minimum resonance frequency.
- To maintain compatibility with both optics technologies by agreeing on common interfaces.
- To maintain open the option of reducing the effective area in order to recover mass margins.
- To include the contamination covers in the STM of the Mirror Assembly Module.
- To exclude the launcher interface (which should remain part of the SVM).

Concerning the Instrument Module, the board recommends a considerable design simplification by:

- Removing unnecessary adjustment mechanisms & maintaining only the instrument exchange capability;
- Possibly removing the centralised focusing mechanism, in view of the optics depth of focus;
- Simplifying instruments accommodation constraints (e.g. number of radiators at different temperature and baffling).
- The STM of the Instruments Module should also include the required IM mechanisms.

Concerning instruments, the board recommends reducing the complexity of the model payload by:

- Revisit the XMS (60% of model payload in mass) design, requirements and consortium organisation in order to obtaining considerable simplification (e.g. smaller FoV of the inner array), resource savings, a streamlined management structure and lower programmatic risk.
- Removing unnecessary capability and/or requirements driving the Instrument Module and/or the system design (e.g. generous Point Spread Function oversampling of WFI, XGS pointing constraints and effective area demands).

4.2.2 Programmatic recommendations

Concerning programmatic aspects the board recommends to:

- Assume as earliest realistic launch date the end of 2022 (see assumptions and risks in section 3.2).
- To consolidate the technical requirements and definition of clear and clean interfaces before the start of the definition phase.
- To make provisions to reduce the programmatic risk by moving forward as much as possible the instrument AO and the start of the instruments development activities, in particular for XMS (schedule driver).
- To maintain full momentum on the critical technology development activities, in particular the ones related to the optics technology and to the XMS focal plane assembly, without interruptions.
- To consolidate during the Definition Phase the planning and cost of the SPO flight units' production via an appropriate industrial assessment, including HW demonstrations as required. Also early agreements have to be reached with each company of the consortium now producing the MM regarding the Background Intellectual Property Rights.
- To consider the possibility for ESA to take the lead role on Science Operations, in order to maintain full visibility of ESA's role in IXO during the operation phase.