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DOCUMENT

L1 Mission Reformulation

ATHENA - Advanced Telescope for High Energy Astrophysics

Technical & programmatic review report

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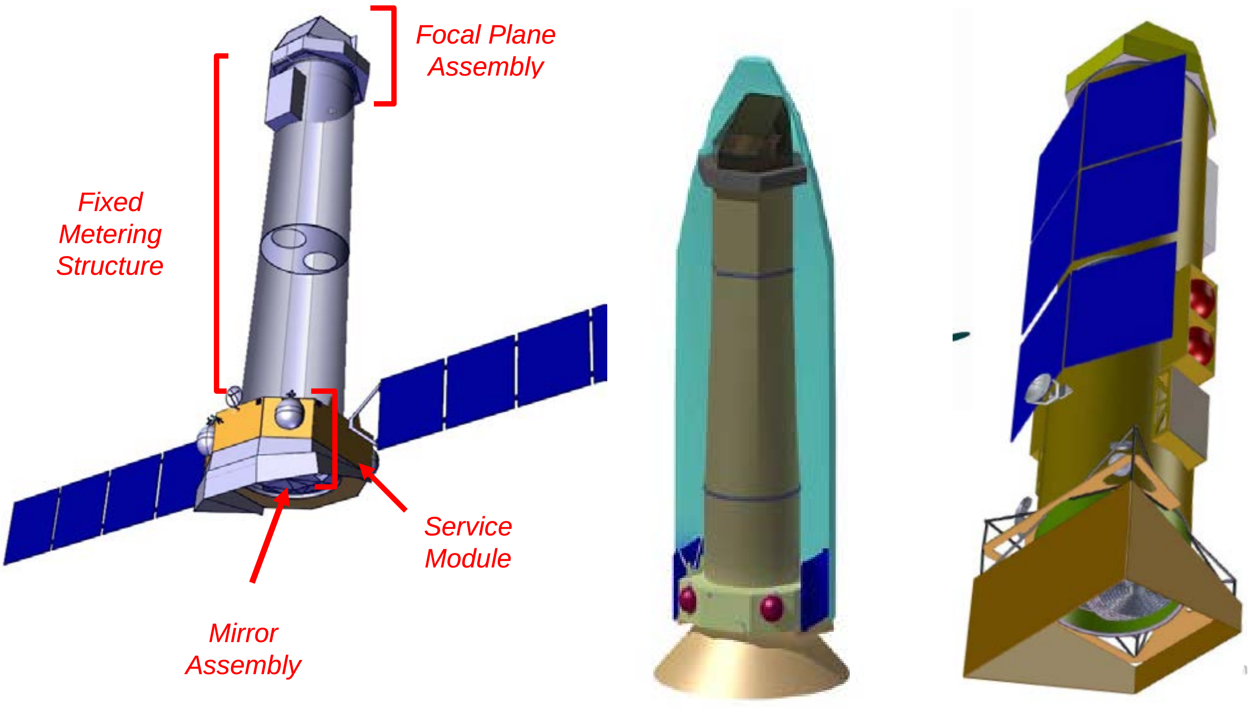
1 INTRODUCTION

This report summarises the findings of the ESA review on the reformulation of IXO – International X-ray Observatory (L class candidate of the Cosmic Vision 2015-2025 programme) into the new mission concept named ATHENA (Advanced Telescope for High Energy Astrophysics). The reformulation activities have included the following steps:

- Identification of reformulated mission concept in close cooperation with the science team (April 2011).
- ESA internal phase 0 study (May 2011).
- Parallel industrial support activities with EADS-Astrium and Thales Alenia Space (June – September 2011).
- Instrument assessment studies conducted by consortia of scientific instruments (April – September 2011).

The system level studies have converged to a conventional spacecraft architecture, including the following main elements: a) the Focal Plane Assembly (FPA, hosting the focal plane instruments); b) the Fixed Metering Structure (FMS, rigidly connecting the X-ray mirrors with the focal plane instruments); c) the Service Module (SVM); d) the Mirror Assembly (MA, including two identical X-ray mirrors), see figure 1.1 below.

Fig 1.1 – Spacecraft architecture (left: ESA design; centre: EADS. Right: TAS design).



The independent ESA review covered all mission areas (thus including all aspects of the spacecraft design, instrument design and optics technology developments).
The review objective is to establish the overall feasibility and credibility of the L1 mission candidate reformulated concepts – for both platform and payload - for a launch in 2022, and an ESA CaC of 850 M€ (e.c. 2010). The basic assumption underlying the reformulation exercise is that the work done in the previous years should enable a fast identification of technical possibilities, a preliminary technical reformulation and a clear identification of the related impacts on the science case.

2 TECHNICAL REVIEW

2.1 Mission profile, system level and service module

The reformulation from IXO to ATHENA provided a significant reduction of complexity and development risk. The current spacecraft system concept is modular and robust. The comparison to IXO (main design parameters and performance requirements) is presented in the following table.

Parameter	IXO	ATHENA	Change rationale
Focal length	20m	12m	Avoid complexity of extendable bench, simplify AIV, reduce risk, stiffer S/C.
No. Apertures	1	2	Maximise EA at 6 keV. Avoid instrument exchange mechanisms.
Mirror Modules	1800	500	Reduce cost and schedule. Maximize focal length.
Eff. Area (m^2, 1 keV)	2.5	1.0	Reduce cost and schedule. Maximize focal length.
HEW (arcsec, 1 keV)	5	10	Goal of 5" is maintained. Development risk mitigation.
Model payload	XMS WFI HXI HTRS XPOL XGS	XMS(*) WFI(*)	Reduce complexity of the Focal Plane Assembly. Match to number of apertures & science drivers. Reduce total cost of instruments (member states). More compact FPA enables longer focal length. Match instrumentation to telescope energy response. (*):= *simplified focal plane detector*.
Launcher	A5-ECA	A5-ECA	Maintained (driven by fairing size).
Mass (kg)	6500	4500	Resulting from mission simplifications.

- *Completeness and consistency of the requirements definition.*

The high level mission requirements are clearly defined in the Athena Mission Requirements Document, which captures all key performance requirements formulated in the Science Requirements Document (e.g. effective area, angular resolution, spectral resolution, observation efficiency, access to sky, etc.), the main functional and design requirements (e.g. payload operations, LV constraints, mission analysis) to a level in line with phase 0/A.

- *Definition of mission profile and overall feasibility.*

The mission profile (direct injection to L2, 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.

- *Completeness and consistency of the resource budgets.*

The total spacecraft launch mass (including margin) is close to 4500kg and there is plenty of growth possibility towards the Ariane-5 limit of 6.5 ton.
The power budget demands a total of 5 kW and is not considered as critical due to the large margin for accommodation of Solar Arrays. The budget is driven by the power required for the thermal control of the Mirror Assembly and the power for the XMS cryo cooler chain.
The delta-V (and propellant) budget is in line with recent SEL-2 missions (~ 100 m/s) and is not critical, due to the large mass margin (compatible with mono-propellant design).
The data rate and down-link budget are compatible with X-band capabilities from L2 and are not critical (being presently sized for an unrealistic continuous peak science data rate). Sizing of the mass memory is not critical for the same reason.
The contamination budgets are in line with the XMM-Newton experience.
Detailed resource (e.g. mass, power, data rate, delta-V) budgets are available and realistic.

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

The internal ESA study and the industrial activities (TAS-F/I, ASUK) resulted in very similar system configurations, similar resource budgets and a very significant heritage from recent missions. The model payload has been studied since several years (both XEUS and IXO heritage), which is well reflected in the FPA definition. On this basis, the system architecture is considered as robust and mature. The system design is classical for a three axes controlled observatory. The SVM has significant commonalities to recent missions, (e.g. XMM and Herschel units) and on this basis its design maturity can be considered as high. The design solutions proposed for the Fixed Metering Structure are based on XMM heritage and lead to a segmented design, in order to cope with the limitation of the existing European test facilities. In order to ease the optics alignment specification derived from science requirements, it is proposed to operate the optics at 20 deg C, simplifying AIV, but raising the complexity of the MA thermal control.

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

The science requirements are driving the system design in a few areas: the overall spacecraft dimension is driven by the desired telescope focal length, which is limited by the fairing length; the outer diameter of the Mirror Assembly is driven by the outer diameter of the Payload Adaptor Separation system, which limits the telescope effective area. All the required service functions can be fulfilled with existing technologies and off the shelf sub-systems.

- *Definition of interfaces.*

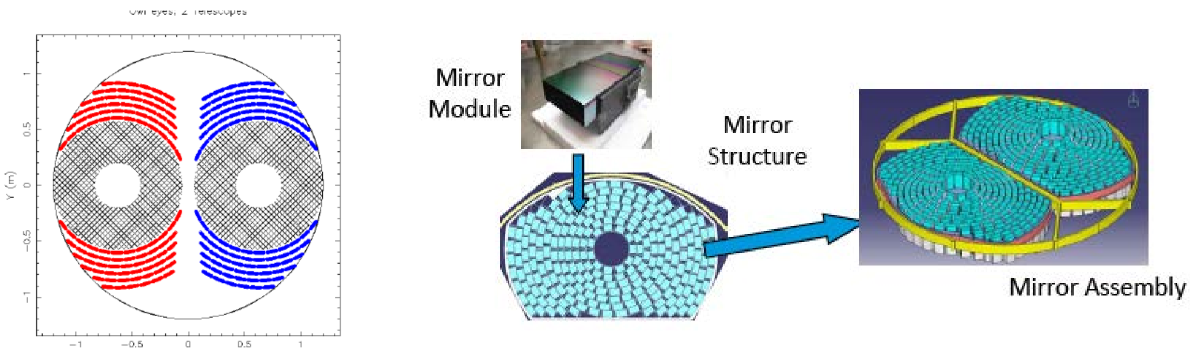
The spacecraft system architecture is modular with self-contained modules with clean and clear interfaces: Mirror Assembly (MA); Service Module (SVM); Focal Plane Assembly (FPA) and Fixed Metering Structure (FMS). This simplifies design, test and procurement.

2.2 Mirror Assembly (MA)

- *Status and maturity of the design*

The reference design is based on a focal length of 12m and a two-aperture, non-circular telescope design, exploiting the modular nature of the Silicon Pore Optics and allowing an optimal use of the available space. The two telescopes are identical, each feeding a fixed focal plane instrument. Each telescope consists of a mirror structure populated with mirror modules (see section 2.3). This configuration is considered as logic and well defined. During the Definition Phase, the following areas need to be further addressed: a) selection of the mirror structure material (aiming at a cost effective design and avoiding complex manufacturing processes or materials with poor flight heritage, also in view of the available mass margins); b) consolidation of the mirror thermal control; c) further definition of the MM to mirror structure interfaces; d) definition of the stray-light requirements (aiming to avoiding the use of any external baffling device, as both integrated baffles or sieve plates would considerably increase complexity); e) definition of the telescope covers and sun-shield (giving preference to flight proven solutions, such as XMM-Newton based and a single, hinged cover).

Figure 2.2 – Athena optics: from Mirror Modules to the Owl-Eye design of the Mirror Assembly.



- *Definition of interfaces*

The MA interfaces are well defined. The interfaces between mirror assembly and mirrors structure and between web structure and mirror assembly (isostatic mounts) are clearly defined. In order to make the MA testable in one piece it is important to have a common support structure as interface to the SVM. This would also add additional shock attenuation capability, and provide the decoupling of deformations between the two modules.

- *Resource budgets*

The Mirror Assembly resource budgets (mass and power) are complete, including adequate margins. The thermal control resources and technical solutions are consistent across the different studies and appear as adequate. The required heating power is directly dependant on the temperature requirements of the mirror (20 +/-2 deg C), which need to be consolidated performing a trade-off at system level (accommodation/power & mass budget versus optical testability / AIV complexity).

- *Development plan & model philosophy*

The Mirror Assembly primary structure will be qualified using the STM. 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 MA structure and thermal control. The contamination cover and the telescope sunshield shall be qualified at equipment level. Due to the modularity of the system design and the clean interfaces, it is possible to deliver to the observatory integrator a fully tested and self-standing Mirror Assembly.

2.3 X-ray optics – Mirror Module (MM)

- *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 and appear as realistic. The working assumption for shock appears too optimistic considering the proximity to the Launcher Vehicle Adapter (LVA) and need to be properly justified. 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 Mirror Assembly Module).

- *Status and maturity of the design*

The X-ray mirrors are based on the Silicon Pore Optics (SPO), which is made by stacking several ribbed silicon plates. The design proposed is very robust. One of the main advantages of the Silicon Pore Optics technology is the intrinsic stiffness of the mirror modules. The alignment tolerances studies demonstrate that also the positioning of the mirror modules and the petals is not critical. The modularity is also considered a strong advantage of the proposed design.
The size of the MM stacks has been reduced from 45 to 33 plates and each MM contains now four instead of two stacks. This is an elegant way to improve the angular resolution, minimise production risk and increase the yield. The added complication of installing four instead of two mirror stacks in each MM is considered not critical. The mirror stacks are mounted in a symmetric way in the MM structure with easy access during the integration.
The mirror stacks are bonded to the MM structure and static proof tests of these bonds have been performed on one sample. It is recommended to perform statistical testing on a higher number of samples for the implementation phase.

- *Performance and compliance status*

The SPO performance has been verified with representative X-ray tests. Present angular resolution performance is 16 arcsec (at 3 keV) for a stack of 45 plates. The innermost 10 plates of this stack have HEW just below 10”. The results from latest sample mirror stacks manufactured with improved cleanliness control and using flatter silicon wafers have shown significant improvements and indicate that 10 arcsec HEW (<7 keV) is feasible. No problems are expected for meeting the effective area.

- *Development plan & model philosophy*

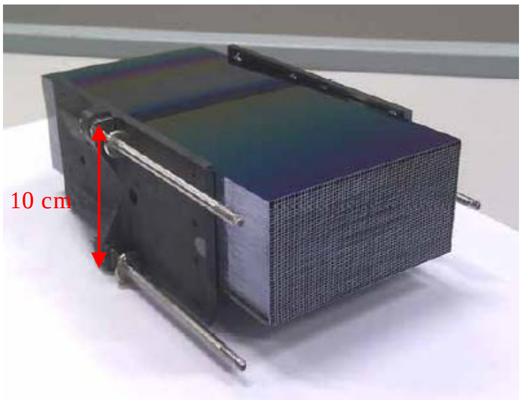
A detailed SPO development plan exists and includes the following key steps and expected completion dates:

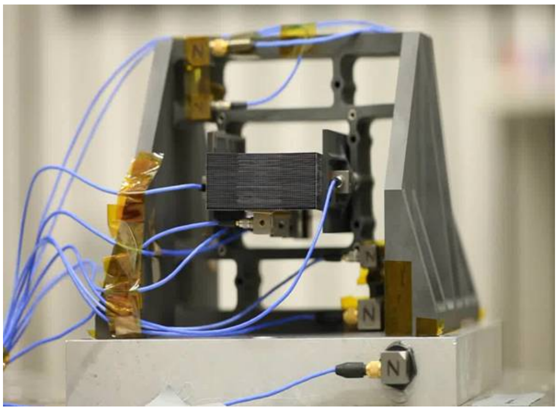
- 0.7 m radius MM, IXO geometry: process optimisation and pre-requalification (TRL-5), end 2013.

- 0.7 m radius MM, Athena geometry: TRL-5, process optimisation, preparation of industrialisation, early 2015.
- 0.25 m radius MM (innermost), Athena: TRL 5, process optimisation, preparation of industrialisation, end 2014.
- Production of a MM with true Wolter I geometry, to reach the goal of 5 arcsec (HEW at E <7 keV), end 2014.

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 15 arcsec HEW (7-10 KeV) compared to the 10 arcsec HEW (< 7 keV).
Manufacturing of a MM representing the outermost radii of 0.9 m is not scheduled before the mission adoption, which is considered too risky. It is proposed to re-define one of the development activities above in order to envelope all the extreme radii and with geometries relevant for Athena.
Moreover, in case of resource limitation or need to prioritise, the focus on basic process consolidation must take precedence over the performance tuning (Wolter-1 geometry).

Figure 2.2.2 – Left: Athena Mirror Module including interface brackets and mounting pins. Right: MM on vibration table.





2.4 Focal Plane Assembly (FPA)

- *Status and maturity of the design*

The FPA design is driven by the need to accommodate two instruments with a large total mass (in particular XMS) and to maximise the telescope focal length. Each instrument is located at the focus position of a mirror, thus not requiring any exchange mechanism, which is a significant simplification compared to IXO. In addition, due to the shorter focal length and the fixed metering structure between FPA and MA, on-board metrology for reconstitution of the actual alignment status is not required. The thermal control architecture proposed for the FPA is solid and possesses a lot of room for growth. Due to the long distance between the FPA and the Launcher Vehicle Adapter, the mechanical loads might be critical for the heavy XMS and need proper assessment in the early part of the Definition Phase.

- *Definition of responsibilities and interfaces*

The proposed FPA design offer clear and clean mechanical interfaces with the rest of the S/C (Fixed Metering Structure). Clean electrical interfaces can also be easily defined. The sharing of responsibility between platform and instruments is standard and does not present criticalities.

- *Resource budgets*

Detailed mass and power budgets with the required design maturity margins are available and realistic.

- *Development plan & model philosophy*

The primary structure of the FPA will be qualified using the Structural Thermal Model (STM). This approach is deemed as realistic given that no critical technologies are identified for its structure and thermal control.

2.5 Focal plane instruments

The level of design maturity and definition of the Athena model payload is considered as rather high, beyond what is 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 option for dual readout speed in WFI is not required by the science requirements and, in view of the considerable increase in instrument complexity and interface requirements it implies, should be discarded. The requirements of the XMS cryogenic chain are well defined. Electrical, mechanical and thermal interfaces are also properly defined. However, a margin philosophy for the cooler chain (in nominal and failure mode) needs to be established.

- *Identification of design drivers and critical areas*

The small sub-window of the WFI detector used in the high time resolution mode drives the pointing requirements. The requirement on co-alignment of the small sub-window of the WFI detector and the XMS detector drives the alignment accuracies of the two telescopes. XMS is the largest, heaviest and most complex instrument onboard and it drives a large part of the FPA design and resources. The large field of view of WFI is driving the design of the baffle and of the particle diverters.

- *Status and maturity of the design definition*

Both instruments have good heritage and a rather high level of design definition. The design of WFI has become even more robust in the absence of the complex thermal and mechanical interface with the HXI instrument. WFI has taken over some of the high count-rate/high time resolution functionality of the HTRS instrument from IXO, but this has been possible without impact on the instrument design.

The robustness of the XMS focal plane assembly to evolution has been significantly improved compared to IXO by simplifying the detector array and relaxing the accommodation constraints. However, XMS is by nature a complex instrument, and must therefore be seen as a critical. The design of the entire detector assembly, consisting of detector array, SQUID's, connections, anti-coincidence detector, magnetic shielding, has been further developed and has become less critical for the accommodation in the cryostat, again due to the reduced detector size.

The definition level of the XMS cryo-chain can be considered as high as it is based on the Astro-H design.

- *Completeness and consistency of resource budgets*

The mass, power and data rate budgets of the instruments are found correct, complete and with the required design margins. XMS requires the same large resources in terms of mass and power as for IXO, but the risk of exceeding the budgets has been reduced by a simpler focal plane design.

2.6 Technology readiness

The system requirements are fully enveloped by preceding space missions. Thus the service module uses conventional technologies and the envisaged units should be off the shelf.
The fixed metering structure, connecting the Focal Plane Assembly (FPA) with the Mirror Assembly (MA), and the FPA itself are specific to the mission, but only conventional technologies are envisaged to be utilised. A standard development process is adequate.
The Mirror Assembly (MA) units are not off the shelf and need a specific development program. However, significant relevant design heritage exists from XMM for the mirror door/cover and the sun baffles and a standard development process is considered adequate. The petals supporting the mirror modules and the thermal baffle are very unique but not technology critical. A standard development process is adequate, also considering the very robust mission mass margin.
The mission elements requiring attention in terms of technology readiness are: a) X-ray optics (presently at TRL 4-5, full TRL 5 expected by end 2013); b) XMS focal plane detector and front-end electronics (presently at TRL 4).

- *X-ray optics (SPO development)*

The Mirror Modules are technology critical in relation to the required angular resolution. This requirement has been relaxed from 5 to 10 arcsec, thus reducing considerably the technical and programmatic risks. A very robust technology program has been defined and is being executed with planned conclusion in early 2015. The feasibility of the basic mirror technology is proven, the on-going technology activities are focussed on the manufacturing process consolidation. The presently achieved performance gives high confidence that the required angular resolution will be achieved.

- *XMS focal plane assembly*

The XMS detector and readout consists of Transition Edge Sensor based micro-calorimeters, with Time Division Multiplexed (TDM) SQUID readout, both without heritage in space applications. However, with respect to IXO, the baseline design for Athena has become considerably less complicated and risky. The detector has been simplified to a single array of 32x32 pixels of 250 micron size, with a reduction of the number of pixels by a factor of two, without the outer array of Hydra-type pixels (with lower TRL). The array size has already been demonstrated as well as the required energy resolution for this pixel size.
The criticality of the readout has been reduced by adopting 16 instead of 32 pixels per readout chain, much closer to the demonstrated 8x multiplexing. In addition the requirement on energy resolution, was which considered a critical issue in IXO, has been relaxed from 2.5 to 3.0 eV (c.f. 2.8 eV already demonstrated). The baseline detector and multiplexed TDM SQUID readout will be US supplied and the required funding (NASA) for further development is secured for 2012.
Because of the much reduced detector size (from 30x30 to 8x8 mm), also the anticoincidence detector has become easier.
European detector and readout technology is less advanced than the baselined US technology. Currently, 4 eV resolution is demonstrated, but without multiplexing. 32x32 pixels array have been made, but not fully wired. TDM multiplexing technology exists but has not been demonstrated at the required number of pixels and resolution level. Compliance with the science requirements is likely, but further development for these technologies is required.

- *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 (to be launched by 2014), but any deviations from this assumption will need close scrutinising. The full cryo-chain of Astro-H is planned to be tested by mid 2012.
For the European cryo-chain back up solution, multiple architectures exist and will be traded-off by a dedicated consortium in mid 2012. The first studies show that they will require more resources or be more complicated than the baseline solution, thus their impact on the system design needs to be better assessed in the definition phase.

- *WFI*

Whilst the development of the WFI detector is a significant task, mainly due to its large size, it was not considered a critical issue for IXO. Moreover WFI has been further reduced in complexity, largely because the complex thermo-mechanical interface with HXI no longer exists, but also through a smaller detector size and the choice of an existing readout ASIC. Concerning the instrument Field of View, an increase from 24 arcmin to 29 arcmin (FL=12m) would be possible with a modest increase of the instrument resources, and without surpassing the level of complexity of WFI on IXO. A further increase in FoV beyond 29 arcmin would require a mosaic approach for the detector, which is considered too complex and risky and should not be pursued.

Table 2.6 – Athena Technology Readiness summary

Mission element	**Present TRL**	**TRL 5 expected by**	**Remarks / justification(*)**
Spacecraft units	> 5	NA	No technology development required
X-ray optics (SPO)	4	Q1/2013	BB already passed first vibration tests
XMS focal plane baseline:	4	Q1/2014	DM activities funded & ongoing, includes complete focal plane assembly
XMS focal plane EU back-up:	3-4	Q2/2014	Based on running/planned TDA's
XMS coolers baseline: US last stage	5	NA	First vibration tests performed in 2011
JAXA pre-cooling chain	4	Q1/2012	EQM activities ongoing for Astro-H
XMS coolers EU back-up: ADR	4-5	Q2/2012	Ongoing developments (e.g. SAFARI)
pre-cooling chain	3-4	Q2/13	Based on running/approved TDA's
WFI	4	Q4/13	Based on BepiColombo MIXS instrument, passed environmental tests

(*): Justification based on applicable technology development plans or instrument development plans.

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 acceptable and in line with the risk areas. A classical Structural Thermal Model (STM), Avionic Test Bench (ATB), Proto-Flight Model (PFM) approach is proposed at system and module/assembly 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.
XMS, being the most technology critical instrument, has in addition proposed a full instrument Development Model (DM), with the end-to-end detector performance demonstrated before the down select in early 2014. The XMS development is on the mission critical path and late cooler delivery will impact directly the mission schedule. The presented JAXA development schedule is not compliant with the overall XMS development plan and needs consolidation. However, based on the Astro-H heritage, a timely development plan should be feasible.

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

There is no strong link between successful technology development and the system design from a technical point of view. The ongoing development activities impact on performance parameters as opposed to system interfaces and resources. This is assuming that the XMS instrument is constrained by the ASTRO-H cooler chain performance. The overall development program related to the technology critical elements is well synchronised with the planned mission adoption mid 2014 and envisaged start of the implementation end of 2015:

- XMS detector: detector/read out and last cooler stage, end to end test planned completion early 2014
- XMS cooling chain: ASTRO-H cooling chain CDR is on-going and the ASTRO-H cooling chain Qualification Model testing is planned in 2012.
- Mirror Module: conclusion of technology development is planned early 2015 with the test of the high performance Mirror Module. This plan does also include industrialisation aspects.

The start of the implementation phase is four years from now. Considering the present development status of the critical technologies and the defined development plan, it is considered highly likely to reach the desired performance targets by end of 2015.

3.2 Development schedule (spacecraft and instruments):

- *Instruments schedule*

The XMS schedule is used as reference, since it is by far the most demanding instrument. Due to the instrument technical and programmatic complexity, the margin was increased to a total of one year. The overall duration from SRR to delivery is then six and a half years, which is considered as challenging but realistic. The completion of the detector Development Model before the mission is considered a main asset from a schedule point of view. Note, six and a half year is slightly faster compared to bench-marks such as HIFI/Herschel and other complex and large instruments.
The proposed model philosophy includes an early Development Model of the full XMS instrument. This is a robust approach in view of the complex design and international collaboration. The instrument PDR is currently before the KO of the prime contractor (implementation phase). This imposes some risk on the level of definition of the interfaces between the FPA and instruments. This risk should be mitigated if the interfaces are properly defined in the definition phase.

- *X-ray optics (SPO)*

The SPO schedule is based on a technology development period concluding early 2015. The logic of the proposed schedule is good and durations are found realistic. This schedule is also supported by and independent industrial assessment of the required production facilities and schedule. 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 proposed schedule.

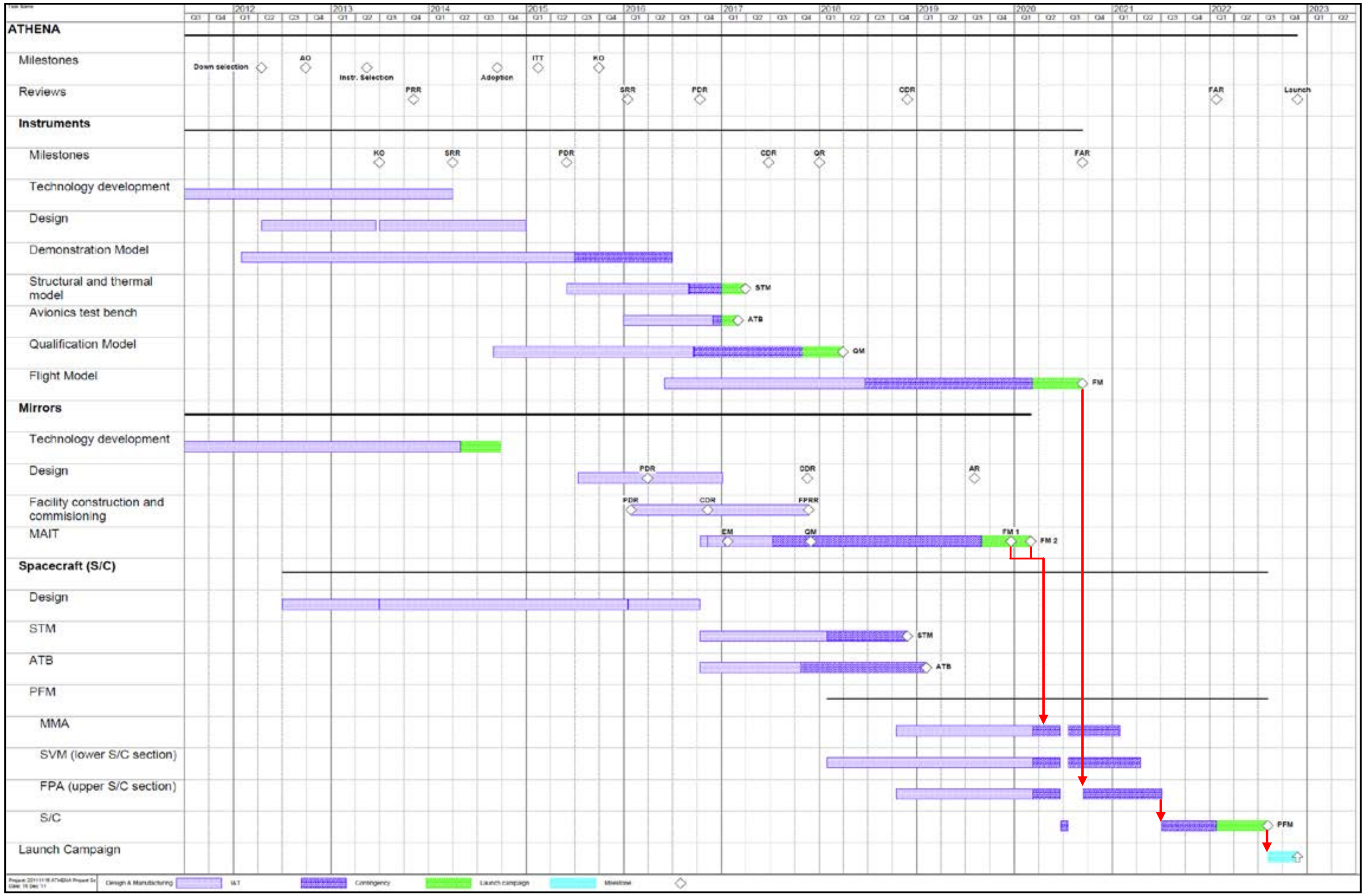
- *Spacecraft schedule*

The new procurement approach with S/S contractors selected during the Phase B2 and unit contractors selected just after system PDR is assumed. The clean modularity of Athena should be fully explored in this procurement approach concluding in parallel development and full environmental testing of the separate modules.

- *Critical path & Conclusions*

Based on the provided schedules, an overall schedule has been constructed bottom-up for the Athena project and leading to a feasible launch date before the end of 2022 (see figure 3.2). The Athena schedule critical path is the XMS instrument followed by the module and system level testing. The successful pre-development activities of the XMS detector, which is mainly done by NASA, is therefore most critical for the overall mission schedule.

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



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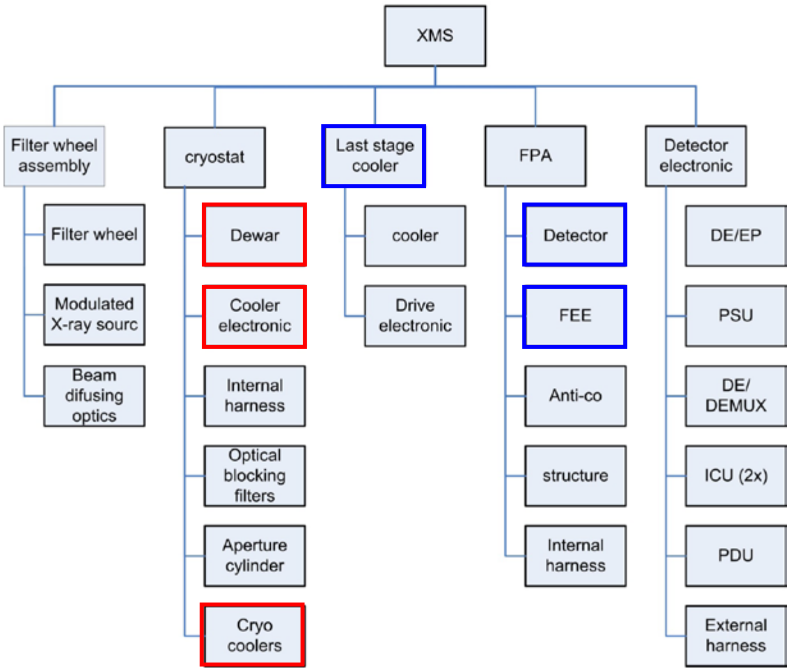
3.3 International contributions to XMS

- *Credibility of the international cooperation scenario*

The proposed reference scenario, as depicted in the XMS product tree and preliminary work breakdown structure provided below, reflects the technical expertise of the different parties. In particular, state-of the art TES-based micro-calorimeter arrays are under advanced development at NASA/GFSC (a FWHM performance of 2.8 eV at 6 keV has been achieved on 2x8 arrays), while time division SQUID multiplexing technology is led by the National Institute for Standards and Technology (US). The cryogenic chain of XMS developed by JAXA is derived from the cryogenic chain for ASTRO-H (expected to fly in 2014), where it cools a similar X-ray calorimeter instrument.

Figure 3.3 – XMS work-breakdown structure (contribution from JAXA in red frame, from NASA in blue frame).



- *Definition of the interfaces within the international contributions*

The proposed interfaces within the consortium are well defined.

- *European back-up solutions*

The proposed contributions from non-ESA member states to XMS are currently representing the most mature technical solutions, therefore significantly reducing the schedule risk to XMS and, hence, to ATHENA. The potential programmatic risk posed by the lack of control on the funding of these contributions shall be mitigated by establishing firm agreements with the international partners with the release of the instruments AO. In addition, credible European alternatives are available for the sensors, TDM SQUID readout, the cryostat and the coolers, including the last stage cooler, but they will need to be further advanced by funded development programs. It is therefore recommended that these development programs are started as soon as possible.

4 RISK ASSESSMENT

The system architecture is considered as mature and it is not expected to evolve significantly. The spacecraft 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 large resource demands and some units at lower TRL, is a risk, requiring a mitigation strategy.
Concerning the Mirror Assembly, the main risk factors relate to the optics performance and its manufacturing time. Such risks can be mitigated by progressing vigorously on the planned development activities, and addressing as early as possible the series production aspects.
Summary of identified main risks, their ratings and proposed mitigation actions:

- XMS energy resolution not achieved:
  - Rating: Low.
  - Mitigation: complete Development Models activities before mission adoption. Consider alternative array/pixel sizes.
- Late XMS and overall schedule slip:
  - Rating: Medium/high.
  - Mitigation: Maintain full early funding to complete the XMS detector end to end signal chain Development Model before mission adoption. Ensure an immediate start of the implementation phase after the mission adoption. Consolidate the system design during the definition phase in order to freeze the XMS interfaces as early as possible, i.e. before the selection of the spacecraft prime.
- Non-participation of NASA:
  - Rating: Medium/high.
  - Mitigation: Ensure and maintain full funding and development of a “European only” detector and pre-cooler stage design option.
- Non-participation of JAXA:
  - Rating: Low.
  - Mitigation: continue funding of European cooler system and maintain planned development activities. Ensure that a reliable and competent cooler chain system lead is appointed. Note: activities are already foreseen and funded, including building and testing of full cooling system.
- System level impact of XMS evolution:
  - Rating: Medium.
  - Mitigation: clear definition and agreement on margin philosophy for both nominal and failure mode. Take into account possible design changes in the FPA architecture. Ensure the availability of adequate margins (e.g. coolers heat lift and related radiator area).
- Telescope angular resolution not met:
  - Rating: Low/medium.
  - Mitigation: complete on-going development work as scheduled. Prioritise MM with smallest and largest radii.
- Late delivery of flight optics:
  - Rating: Medium/low.
  - Mitigation: complete on-going/ planned development work addressing fabrication aspects. Ensure an efficient hand-over from development to production.

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

The Athena mission concept represents a major simplification and risk reduction compared to IXO. All key recommendations from the IXO review were taken onboard by the study team. The main conclusions of the Athena internal review are the following

- System level requirements are properly defined.
- The mission profile (SE-L2) does not pose difficulties.
- The spacecraft system design is classical and the spacecraft (i.e. observatory minus science payload) can be constructed with existing technology.
- The resource budgets are complete, with very robust margins (additional margin of ~ 2 ton in addition to all required design maturity and system level margins).
- The key technology developments are: a) x-ray optics to achieve an angular resolution better than 10" (goal of 5"); b) XMS focal plane assembly to achieve an energy resolution better than 3 eV over large arrays; c) XMS cryo-chain (already on-going for Astro-H needs). Solid technology development programs are defined and being executed. Required performances are considered feasible.
- The main risks are: a) late delivery of XMS and b) non-participation of NASA.
- The mission is considered as compatible with a launch by the end of 2022.

5.2 Technical recommendations

At system level:

- Confirm the optics operating temperature, in order to simplify the thermal control of the Mirror Assembly.
- Minimise the Centre of Pressure – Centre of Mass lever arm to reduce the load on the AOCS (e.g. optimisation of the Solar Arrays configuration).
- Make intelligent use of the high mass margin to limit risk, complexity and reduce cost.

Concerning the Mirror Assembly (MA):

- A common support structure for the 2 optical modules is recommended to allow unit testing and provide a simpler interface to the SVM.
- A random vibration spectrum for the MA and MM should be derived from a vibro-acoustic analysis taking into account the ATHENA specificities (the large hollow tube and the proximity to launcher interface might significantly impact the levels). Similarly, the shock spectrum derived for MA and MM is deemed critical and should be revisited, while the MM's should be tested accordingly, including representative mounting.
- The optical baffles should be avoided if possible as tapered edges of the mirrors are not possible and sieves are considered to increase complexity and risk.
- The ejection of the contamination cover should be avoided to limit debris in space

Concerning the Fixed Metering Structure (FMS) and the Focal Plane Assembly (FPA):

- CFRP sandwich (with Alu core) is preferred to skins only in order to reduce the CME impact. Cyanate ester resins are preferred to epoxy resins for better CME characteristics.
- The radial thermal gradient across the FMS tube should be minimised to provide better alignment stability.
- The loads acting on the FPA shall be revisited using representative boundary conditions and models.

Concerning XMS:

- The effect of the XMS cryo-cooler micro-vibration with respect to both instrument alignment stability and possible micro-phonics effects shall be revisited (e.g. need of isolation/damping measures).

- The cooling power margins for nominal and failure mode should be specified and confirmed for all different stages.

5.3 Programmatic recommendations

Concerning programmatic aspects the board recommends to:

- Maintain clear and clean interfaces between the different spacecraft elements during the definition phase. This will simplify the design, procurement and test effort.
- Make use of the available robust resource margin to simplify the design, analyses and test approach.
- 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.
- Revisit the XMS cooler chain schedule in order to safeguard the instrument schedule and minimise design evolution compared to the ASTRO-H design.
- Maintain full funding and development of a "European only" detector and pre-cooler stage design option to mitigate a possible NASA non-participation.
- Focus the mirror development activities on process consolidation for the innermost and outermost radii.
- Obtain early agreements with each company developing the MM regarding the Background Intellectual Property Rights.