IXO Silicon Pore Mirror Technology Development Plan

(TDP)

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Preface

The IXO Silicon Pore Mirror Technology Development Plan describes developments that are required to reduce technical and programmatic risk associated with implementation of the mirror subsystem of the IXO mission. The plan identifies key technology development areas, mission and system drivers, leading to a number of activities that are planned to be pursued during the early stages of the programme, in the Assessment Phase and prior to the start of the Definition Phase.

The activities described include only the x-ray telescope payload, including the x-ray optics, their mounts and optical bench. Issues related to spacecraft sub-systems and the detector payloads are not covered in this document.

List of Acronyms

CDF	Concurrent Design Facility
Con-X	Constellation-X
HPO	High-performance Pore Optic
IXO	International X-ray Observatory
XEUS	X-ray Evolving Universe Spectrometer

1 Introduction

The technology development status and development requirements listed in this document are based on ESA's definition of Technology Readiness Level, as described in Figure 1-1. The development plan considers ongoing developments that are being carried out to develop x-ray optic technologies, mirror accommodation studies and continuing developments towards IXO.

Science Directorates plan for Cosmic Visions [RD1] has defined that specific TRLs are achieved, on all key units and elements, within a given timeframe to allow down selection of the missions competing for large mission slots. IXO, formed by merging Europe's XEUS and the USA's Con-X, is one of three large mission candidates that will be down-selected to two missions 2010, with confirmation of final selection expected in late 2011. Demonstration of TRL 4-5 is expected at the first down-selection and TRL 5-6 for the final selection. This level corresponds to a technology level readiness allowing detailed studies to commence whilst minimising risks for mission implementation.

For the purposes of the optics technology development for IXO mission various breadboards are being built under development activities. However, the breadboards being built in preparation for the final down selection will meet the specifications for the IXO mission and as such can be considered a prototype, built using industrial (albeit small scale) manufacturing equipment. [In parallel an activity will ensure that large scale, mass production is considered.] At the end of the planned development the optics manufacturing will be at a mature state ready to hand over to an industrial entity for build. As such, the European development for the IXO optics can be considered to reach TRL 6 in time for the mission implementation phase.

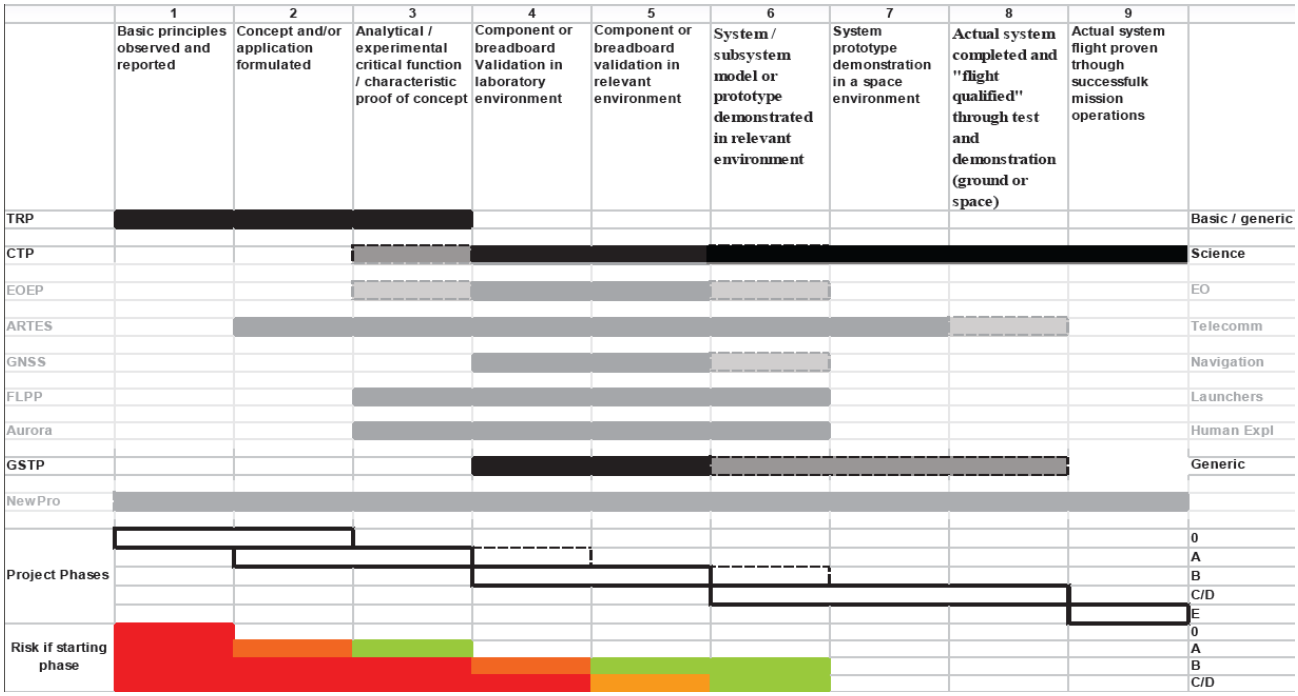

Figure 1-1: ESA's definition of Technology Readiness Levels

1.1 General approach strategy description

The development plan considers the criticality of technology developments related to their influence on ability to carry out the mission and meet the performance requirements. The plan stages developments according to the selection process with priority assigned to mission critical elements. To increase cost effectiveness, where possible developments are delayed until after first down selection to ensure that budget is not expended until a higher level of certainty is obtained regarding mission selection.

The relative importance of different technology developments is thus affected by:

1) Current TRL
2) Criticality within framework to perform mission
3) Priority with regard to affect on meeting performance requirements

Ideally the TDP would assess documented Mission Requirements, Payload Definition, Mission Analysis and Design. However the technology development needs have been assessed from the limited documents currently available (section 1.2). Technology development activities have been extracted and prioritised.

In the timeframe set by the Cosmic Visions process, IXO system level assessment studies will be carried out until 2010, in preparation for the first down selection from three to two large missions. During these studies trade-offs will be carried out to establish a baseline system. At that point this TDP should be reviewed to assess the impact of further technology developments and the results of system level studies. The TDP will be regularly updated to include additional technology development efforts identified by the studies, remove obsolete activities and adjust activities where necessary.

Following the first large mission down selection there will be a definition phase, during which technology developments will continue. Particularly for IXO, importance is placed upon the industrialisation of processes, since the demand to build a very large number of mirror modules means that an automated production process must be demonstrated to be viable.

1.2 Documents

1.2.1 Applicable Documents

AD1 IXO Science Requirements Document

1.2.2 Reference Documents

RD1 "*Cosmic Visions*" plan, ESA Document

RD2 "IXO Mirror Modules Performance Specification and Interface Requirements", SCI/AM/IXO-MM-SPEC/08, v0.1, P.Gondoin, ESA, 08 Dec 2008

RD3 "*Large effective area high angular resolution x-ray optics*", M.Bavdaz et al, Proc. of SPIE Astronomical Telescopes and Instrumentation, Vol.7011-08, June 2008

RD4 "*Performance of silicon pore optics*", M.Collon et al, Proc of SPIE Astronomical Telescopes and Instrumentation, Vol.7011-52, June 2008

2 Mission Description and Requirements

In May 2008 ESA and NASA established a coordination group involving ESA, NASA and JAXA, with the intent of exploring a joint mission merging the ongoing XEUS and Constellation-X efforts. The coordination group met twice, first in May 2008 at ESTEC, then in June 2008 at the Center for Astrophysics. As a result of these meetings a joint understanding was reached by the coordination group on a proposal to proceed towards the goal of developing an International X-ray Observatory (IXO).

The coordination group proposed the start of a joint study of IXO. A single merged set of top level science goals and derived key science measurement requirements were established. The starting configuration for the IXO study will be a mission featuring a single large X-ray mirror and an extensible optical bench with a 20-25m focal length, with an interchangeable focal plane. The instruments to be studied for the IXO concept will include an X-ray wide field imaging spectrometer, a high spectral resolution non-dispersive X-ray spectrometer, an X-ray grating spectrometer, plus allocation for further payload elements with modest resource demands. The study will explore how to enhance the response to high-energy X-rays. This plan establishes an IXO study, which will be the input to the US decadal process and to the ESA selection for the Cosmic Vision Plan. The IXO study supersedes the ongoing XEUS and Constellation-X activities.

As part of the plan for IXO the Agencies established an IXO coordination group (IXO-CG) charged with the definition of the science requirements for the IXO study, scientific supervision on the IXO study activities and providing inputs to the agencies.

The IXO mission terms of reference include input elements to the IXO configuration:

1. A single large X-ray mirror assembly compatible with both pore optics and slumped glass technology
2. An extensible optical bench to reach F=20 to 25m + ways to maximise A_{eff} above 6 keV
3. Instruments include a wide field imager, a high resolution non-dispersive spectrometer, an X-ray grating spectrometer + instruments with modest resources.
4. The IXO concept must be compatible with both Ariane V and Atlas V 551 launchers.

2.1 Main requirements of the IXO mirror

The following tables contain very preliminary figures for some of the main performance and interface requirements of IXO and the mirror modules; the mirror module specification and interface requirements are documented in RD2 and the IXO science requirements in AD1. These figures also lack the key feed back expected from a system study, for example no coupled analysis has yet been carried out, therefore it can be expected that considerable changes may occur in load requirements.

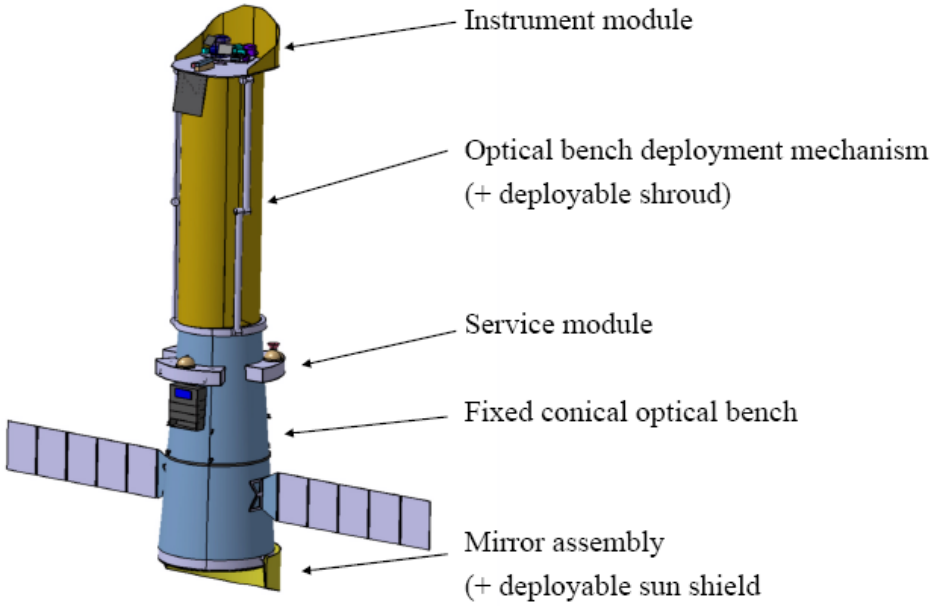

Figure 2-1: Telescope configuration

Angular resolution HPD (0.1 – 10 keV) (10-40 keV)	 ≤5 arcsec 30 arcsec (goal 5 arcsec)	Large scale structure, cosmic feedback, black hole evolution, missing baryons Black hole evolution
Spectral resolution HEW 0.3 – 7 keV 0.3 – 7 keV 0.1 - 15 keV 0.3–1 keV 10 – 40 keV	 ΔE = 2.5 eV within 2 x 2 arcmin ΔE = 10 eV within 5 x 5 arcmin ΔE < 150 eV @ 6 keV within 18 arcmin diameter E/ΔE = 3000 with an area of 1,000 cm2 for point sources ΔE = 1 keV within 8 x 8 arc min	 Black Hole evolution, Large scale structure Missing baryons using tens of background AGN
Mirror effective collecting area @ 1.25 keV 6 keV 30 keV	 3 m^2 0.65 m^2 (goal 1 m^2) 150 cm^2 (goal 350 cm^2)	 Black hole evolution, large scale structure, cosmic feedback, EOS Strong gravity, EOS Cosmic acceleration, strong gravity
Count rate 0.1 – 15 keV	 1 Crab with >90% throughput. Δ E < 200 eV	Strong gravity, EOS
Polarimetry 2 – 6 keV	 1% MDP on 1 mCrab in 100 ksec	AGN geometry, strong gravity
Astrometry	1 arcsec at 3σ confidence	Black hole evolution
Absolute timing	50 μsec	Neutron star studies

Table 2-1: Key IXO science performance requirements

Wolter I or Double-conical approximation to Wolter I	
Focal length	20 m
Field of view	18 arcmin diameter
Coating Mirror shells at r>0.375 m Mirror shells at r<0.375 m	 Iridium + C overcoating Multilayer (TBC)
Radius of clear aperture	0.25 – 1.90 m

Table 2-2: IXO optics characteristic requirements

Item	**Mass (kg incl. 20% margin)**	**Power (kW incl. 20% margin)**
Mirror assembly mass	1800	
Mass of silicon pore optics mirrors	<1300	
Heater power		2

Table 2-3: IXO telescope and optics mass and power budgets (TBC)

Requirement	**Operational**	**Non-operational**
Mean temperature of mirror modules	$268 < T \leq 293$ K	238- 323 K
Mirror module temperature gradient along optical axis	< 11 K m^{-1}	TBD
Mirror module temperature gradient across exit plane	< 20 K m^{-1}	TBD
Mirror module temperature gradient across entrance plane	<20 K m^{-1}	TBD
Mirror plates to petal interface area delta temperature	TBD	TBD

Table 2-4: Telescope and optics thermal requirements (TBC)

Maximum static acceleration to be combined vectorially	Parallel to X-Y plane	80 g
	Normal to z-axis	100 g
Dynamic behaviour (bolted to rigid interface)	X	> 200 Hz
	Y	> 200 Hz
	Z	> 200 Hz

Table 2-5: Environment requirements (TBC)

3 Technology Development Process

IXO depends upon successful implementation of x-ray optics to form the x-ray mirror. The European concept to form the IXO aperture is summarised in Figure 3-1. Following proof of concept, the industrialisation of the assembly process, alignment, metrology, and demonstration of a fully representative mirror petal is required. The mounting method for the petals to the optical bench must be considered and contamination covers with a failsafe protection cover and mechanism are required at petal level.

3.1 Technology Development Status

3.1.1 Silicon pore optics

To meet the challenging requirements necessitates development of a new technology. State of the art technologies are exemplified by:

- Chandra Observatory (NASA) with modest a collecting area of ~400 cm^2 at 1 keV, angular resolution of 0.5 arcsec and an area-to-mass ratio of ~0.8 cm^2/kg;

- XMM-Newton Observatory (ESA) comprising 3 identical mirror systems each with a collecting area of ~1400 cm^2, a modest angular resolution of ~15 arcsec at 1 keV and an area-to-mass ratio of ~6 cm^2/kg.

The huge step to reach IXO requirements can be seen by comparison. IXO optics must deliver an area-to-mass ratio of about 35 cm^2/kg, significantly better than provided by current technology, while at the same time retaining a high angular resolution. The mirror substrates or shells must be very thin and hence low mass, but also be held in a rigid, stiff structure so that the angular resolution is maintained. To meet the requirement a novel technology using commercially available silicon wafers from the semiconductor industry forms the European baseline for the IXO optics. Technology development has already been pursued by ESA for some years and a proof of concept demonstrated [RD3, RD4]:

- Silicon mirror surfaces have been shown to be of adequate smoothness (~3 Å rms roughness), flatness (< 0.2 µm over 25x25 mm^2) and uniform thickness (< 3 µm PTV on 750 µm);
- Stacking and bonding of Si mirror plates to form pores has been demonstrated. Mirror plates of required size are cut from Si wafers and structured with rectangular grooves, the ribs of which will form the pore walls. Ribbed plates are bent to shape and bonded into a stack;
- Wedging of bondable plates has been demonstrated; a small thickness taper is introduced into the plate shape (~4 µm change in thickness from edge to edge);
- Coatings of suitable heavy metal have been applied, including patterned coatings to leave bonding surfaces bare;
- Stacking has been of the mirror plates to form bonded stacks of tens of plates has been demonstrated using a robotised process;
- Wolter units have been assembled (currently with a conical approximation), each using two of the above units. These units can be mounted via three interfaces on their brackets, forming an isostatic mount;

- X-ray testing of the Wolter units has been performed and 17" performance demonstrated over full area to the height of 4 wedged plates by 2007;
- The assembly of Wolter units into a petal has been demonstrated and the ability to replace Wolter units verified. X-ray tests of the complete petal were performed and confirmed stability.

Environmental tests are some way off, but stacks are already shown to be robust and capable of retaining their integrity.

The programmatic requirements for large scale production of Si pore optics and petals of a large x-ray aperture have been considered during development. Because of the requirements to assemble a very large number of x-ray optic modules - around 2000 for the flight program, meaning assembling 4000 plate stacks - all of which must be carried out in high class cleanroom conditions, a robotised process for plate, stack and mirror module production must be realised. Additionally the process of aligning and mounting mirror modules into a petal must be automated and allow individual modules to be removed and replaced.

Fundamental to achieving the requirement on collecting area is the design of the mirror modules. The effective collecting area of each mirror module depends on the size of each pore, the thickness of the pore walls, the grazing angles of reflection, the surface coating, and the X-ray energy. In addition, the design of the mirror module mount and the petal structure to support it determines how much of the telescope collecting aperture is blocked by structure. The mirror module size is therefore determined by its radial position within the x-ray aperture (plate length) and the limits on circumferential radius imposed by both the Si wafer size and the ability to form a structurally sound, ruggedised construction.

The TRL status of silicon pore optic technology developments is described in Table 3-1.

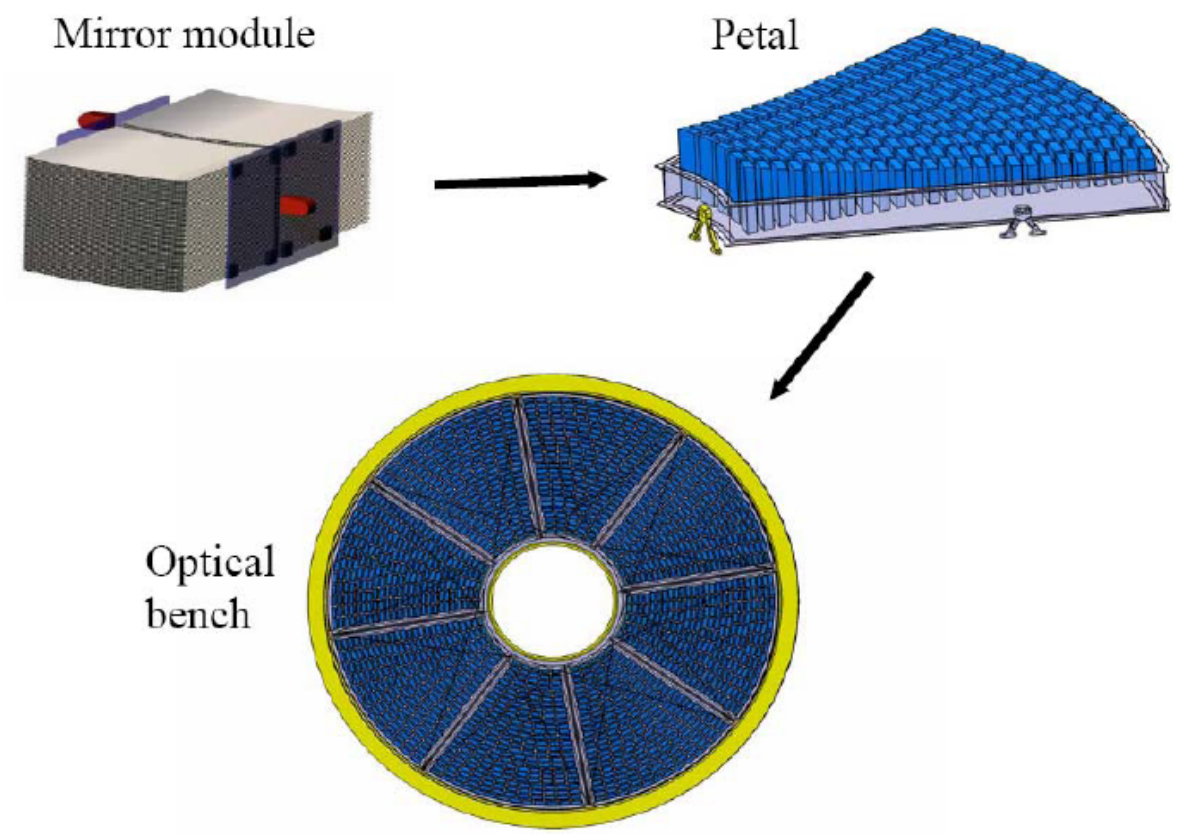

Figure 3-1: Mirror module and petal in context of IXO aperture; the main technology demonstrations address the mirror modules, whereas the petal and optical bench can be implemented base-lining state of the art technology

[The European concept for the IXO aperture envisages individual, silicon pore optic modules, each formed from a pair of mirror plate stacks, which forms a focusing optic at a particular radius of the IXO aperture. Modules are individually replaceable and are delivered to the telescope prime to be mounted into petals. Petals can be individually integrated and characterised (for instance under x-ray). Petals are mounted onto the telescope optic bench to form the aperture.]

Technology area	**Current TRL**
Silicon pore optics:	
Silicon pore optic mirror plates	4 (6 by mid-2010)
Mounted silicon mirror plates (HPO)	4 (6 by 2011)
Focussing silicon pore optic mirror module	3-4 (6 by 2011)
Silicon pore optic mirror module coating	4 (6 by 2011)
Silicon pore optic mirror module mounting	4 (6 by 2011)
Silicon pore optic mirror module mass production	NA

Table 3-1: TRLs of silicon pore x-ray optic technologies currently in development

4 Mission and System Drivers

4.1 Mission Drivers

Mission drivers are considered to be critical to the success of the entire mission. The critical mission drivers for IXO are mass, angular resolution and effective area. To address these issues the following technology developments need to be addressed for the baseline silicon pore optic technology. In consideration of implementation of the back-up optic technology all these issues still apply, however additional developments will also need to be considered.

4.1.1 X-ray optic modules

Demonstration of 17 arcsec angular performance over a stack height of 4 plates was achieved in 2007, for a 50 m focal length optic. [In 2008 attention shifted to upgrading the stacking system.] Development is required to demonstrate that the silicon pore optics can meet IXO 5 arcsec requirement over 45 plates with a 20 m focal length, addressing also the inner radius of the IXO aperture, which is considered more challenging. Sufficient mirror module effective area also needs to be demonstrated. No deformation of mounted mirror modules was measured during x-ray testing, neither before/after module mounting into petal, or due to gravity, however compatibility with IXO environment requirements (temperature and vibration) needs to be demonstrated. The mirror module mount, with interface defined at the three points to be mounted to a petal, will need development in line with the development of the IXO petal. Module developments will focus on particle detection and removal during stacking, metrology improvement, coating, annealing, fabrication of inner radius mirror modules, environmental testing of a mounted mirror module and baffling.

4.1.2 Industrialised mass production processes

The cost of several hundred thousand processed silicon plates, and their alignment and bonding to form thousands of mirror modules, must be drastically reduced in order to enable the IXO mission. This can only be accomplished via automation in a mass production process. The silicon plate manufacturing processes currently used are inherently suitable to a production line and the stacking process is also automated with robotic equipment, albeit currently on a small laboratory scale. However the development of mass production lines, metrology and robots requires development and feasibility demonstration to show that the required number of mirror modules can be produced to meet science, schedule and cost requirements.

4.1.3 X-ray test facilities

X-ray test facilities need development and modification to bring them in line with the requirements for testing IXO optics. The long focal length of the optics needs to be accommodated at the available large area illumination facility, MPE Panter (D). Additional equipment, such as thermal shrouds, suitable rigs etc., need to be installed to facilitate thermal testing. These modifications need to be carried out in a coherent manner with modifications already envisaged for the facility to accommodate other missions such as Simbol-X, e-Rosita, in order to minimise the facility downtime and ensure its availability as necessary. At the PTB lab of the Bessy synchrotron (D) a beamline is available and already extensively used for silicon pore optic development activities. However certain equipment upgrades are also necessary here, such as tube extensions to 20 m and installation of a

monochromator to enable a range of x-ray energies to be used. This modification is necessary to accommodate the grazing angles for 20 m focal length and inner radii.

4.2 System Drivers

System drivers are defined not to be crucial for the mission feasibility but for the overall system design. The complexity and cost of the mission can significantly be reduced if the risk in these items can be demonstrated to be non-critical. These drivers also apply to implementation of the back-up optics technology.

4.2.1 Petals

The petal design must provide a suitable optical bench to maintain the mirror modules within environmental limits during launch, cruise and on-orbit operations. A suitable material must be identified to meet mass and manufacturing requirements. Issues such as moisture absorption and outgassing must be considered, especially in light of the need to mount mirror modules at room temperature and humidity and operate following several months cruise where susceptible materials have opportunity to release water. The petal and interfaces to the mirror modules need to be designed to minimise structural blockage of the aperture, but must allow individual mirror modules to be removed and replaced. The petal interface to the optical bench also needs to be developed.

4.2.2 X-ray baffling

The detectors need to be baffled from both straylight and x-rays impinging from out of field sources. Although the pore optics inherently block most straylight, a detailed straylight analysis needs to be performed. A baffling system at mirror module level needs to be developed. Baffling of rays that could enter between structural components needs to be identified.

4.2.3 Contamination covers

The IXO aperture needs to be protected during ground operations, launch and cruise stages. Contamination covers, attached to the petal or to the optical bench structure, need to be designed to be extremely low mass but operate with a fail-safe mechanism and no or negligible impact on the telescope throughput. The design must protect the pore optics from molecular and particulate contamination that will reduce the x-ray throughput of the telescope. Consideration will need to be given to outgassing and water release from the spacecraft structure.

4.2.4 Thermal requirements

The design of the x-ray optic mirror modules benefits from a stable thermal environment with low temperature gradients, which prevents distortion of the modules. In order for the modules to accommodate large differentials a greater percentage of the telescope aperture would need to be allocated to structure, thereby reducing the effective area. However the potential system impacts of stringent thermal requirements must not be forgotten.

5 Technology Development Activities

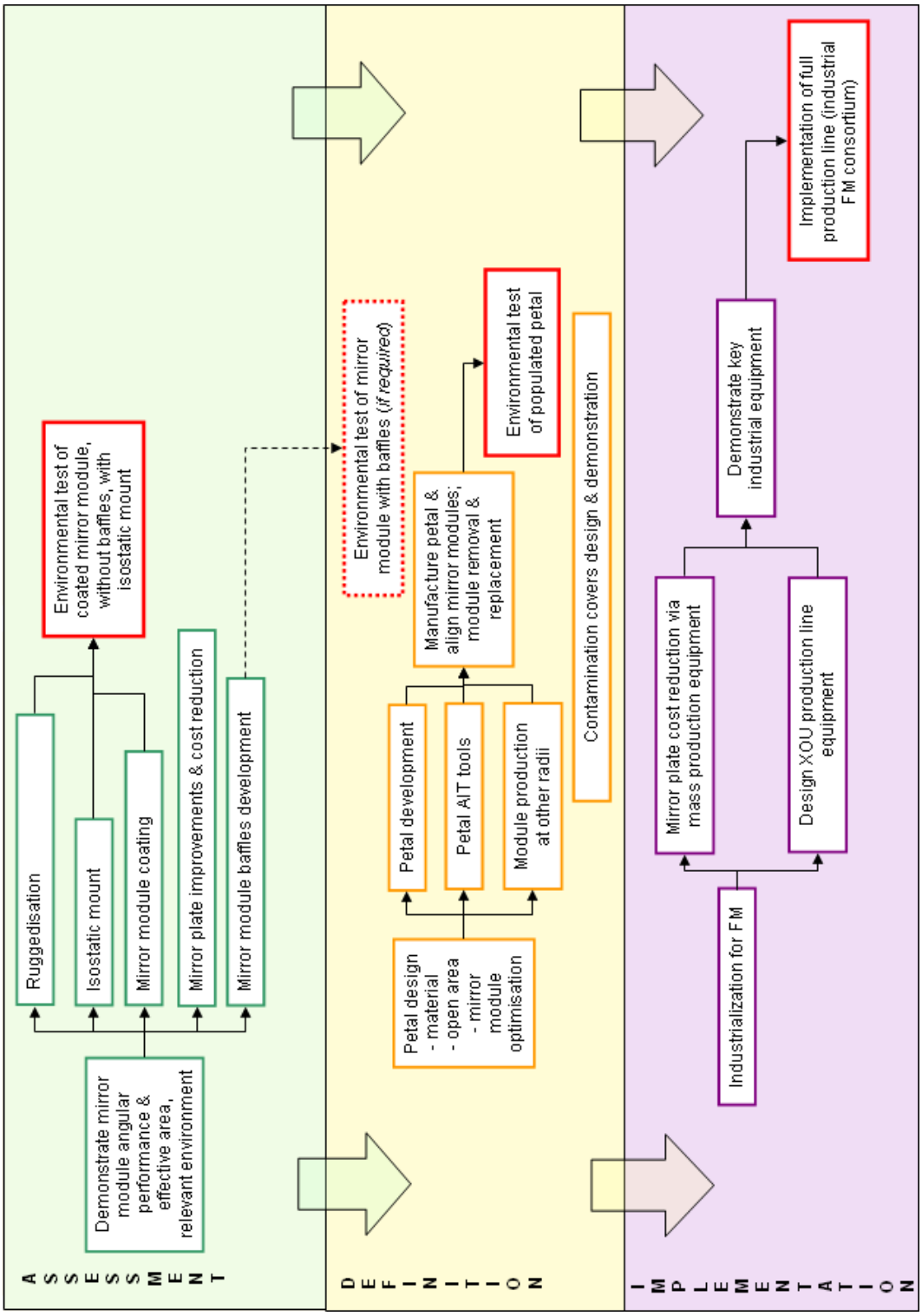

Figure 5-1: Flow diagram of pre-FM technology development process

The Technology Development Plan is built from a core of Technology Development Activities. It arises from the mission requirements, accounts for past and currently running activities, and is designed to be coherent with system level activities and the Cosmic Visions schedule.

Of paramount importance to the development of the x-ray optics is the definition of the interface between the mirror module (already under technical development) and the petal. The technical development of the mirror module includes the isostatic mount interface to the petal.

The goals of the TDP are to schedule readiness of the novel x-ray optics to form the IXO X-ray mirror, with significant risk reduction in their implementation via investments in infrastructure and demonstration that an industrialised process can produce the mirror within an acceptable timeframe. The needs are:

- Demonstration of required performance of the novel technology;
- Demonstration of technical feasibility of IXO mirror production;
- Industrialisation plan and design of related equipment, with implementation and demonstration of the critical components.

The development logic prioritises developments in a staged approach, considering both the Cosmic Visions schedule (minimising expenditure write-off according to risk of de-selection) and the limitations imposed by available funding. It is not possible to include every development that may be desired by industry and start all developments as soon as possible, however activities have been prioritised according to assessment, definition and pre-implementation stages:

1) ASSESSMENT: Mirror module including fully isostatic mount;
2) DEFINITION: Mainly petal developments;
3) IMPLEMENTATION: Industrialisation and programmatics for a flight model production.

A fast track is implemented to address the critical issues, coherent with Cosmic Visions schedule.

5.1 Assessment

The assessment phase is characterised by fast-track developments of the mirror modules necessary to demonstrate that the novel technology can provide the necessary performance:

1) Demonstrate angular performance (currently 17 arcsec, requirement specification of 5 arcsec) and effective area;
2) Isostatic mount;
3) Ruggedisation (towards demonstration in environmental test, annealing);

In parallel:

4) Coating;
5) Module level baffling (with IXO TWG support);
6) Improved and lower cost mirror plates;

Followed by:

7) Production and testing of complete mirror module (coated, without baffles, with isostatic mount).

5.2 Definition

The definition phase is characterised by system level developments, which centre on the petal. Petal developments are scheduled to start only when necessary inputs are received from mirror module developments and from system studies, which are needed to provide requirements such as operational temperature, ensure that straylight is understood and that the method of baffle implementation is available. When such data is available the following activities can run in parallel:

1) Structural petal design and build with minimal footprint and demonstration of suitable material characteristics;
2) Contamination covers with failsafe roll-back mechanism (system input required regarding implementation onto petal or optical bench);
3) Environmental test of baffled mirror module, if required;
4) Production of mirror modules at different radii, coherent with petal design (necessitates additional mirror module tooling, demonstration of tightest bending radii, strain energy);
5) Development of AIT tools to align and mount a mirror module into a petal and allow replacement of individual mirror modules;
6) Reduction of mirror module cost (phase 1)

Followed by:

7) Integration and alignment of mirror modules into a petal and demonstration of replacement of individual mirror modules;
8) Performance tests of a petal, populated with real and dummy mirror modules, at relevant temperatures, with mission-like cooling and gradients plus vibration testing.

5.3 Implementation

The final development stage is pre-industrialisation and it is here that serious investments will be important. However, large investments in infrastructure cannot reasonably be expected before final mission selection. Therefore a staged approach has been considered:

1) Reduction of mirror module cost (phase 2);
2) Design of mirror module production line equipment;
3) Build and demonstration of key industrial equipment;

Following final down-selection of missions the final industrialisation stage can be expected:

4) Implementation of full FM production line (carried out and by an industrial consortium involving the prime).

5.4 X-ray facility upgrades

In parallel with all of the above and coherent with schedules for X-ray characterisation:

1) Upgrade of facilities of the PTB laboratory at Bessy synchrotron to accommodate alternative energies via a four crystal monochromator plus the IXO focal length;

2) Upgrade of facilities at the Panter laboratory to accommodate the IXO focal length and equipment for cryogenic testing. Modifications in this case need to be coherent with the needs and upgrade schedule of the Simbol-X mission.

5.5 List of TDAs

The activities identified for implementation by ESA are listed in Table 5-1

Activity	
High Resolution Pore Optics	(activity currently running)
Mirror module level baffle	(activity currently running)
Upgrade of the facilities at Bessy PTB lab	(activity currently running)
Upgrade of the facilities at Panter lab	
IXO mirror module breadboard ruggedising and environmental testing I	(activity currently running)
IXO mirror module prototype ruggedising and environmental testing II	
Development of IXO silicon pore optics and mass production processes	
Demonstration of IXO petal breadboard with mirror modules at specific radii	
Demonstration of a baffled IXO mirror module	
IXO contamination covers demonstrator	
IXO industrialised mass production process for mirror modules	

Table 5-1: List of Technology Development Activities

5.5.1 High Resolution Pore Optics (activity currently running)

Start	**Duration**	**Current / Target TRL**	**Need date**
Q3 2007	20 mo	3 / 4	End 2009

Objective: Demonstrate capability to achieve 5 arcsec optical performance using Si pore technology.

Description:

- Transfer of know-how (from Qimonda, who declined to follow further the activity, following company re-organisation) for plate production processes and characterisation of plates (wedged and un-wedged) to demonstrate that the new supplier can meet requirements;
- Procurement of Si mirror plates for test purposes and for stacking 6 mirror module HPO stacks;
- Improvements to the laboratory robot set-up to improve cleanliness (within the available budget);
- Stacking and integration of Si mirror plates, using upgraded equipment, to form a stack to hyperbolic and a stack to parabolic approximations and characterisation of stacks in x-ray;
- Stacking and integration of Si mirror plates to form 2 mirror modules and characterisation in x-ray – resolution, effective area;
- masked coating of plates with high Z material and characterisation in x-ray;
- stacking of coated plates and characterisation in x-ray.

5.5.2 Mirror module level baffle (activity currently running)

Start	Duration	Current / Target TRL	Need date
Q3 2008	18 mo	2 / 4	2010

Objective: Demonstrate a technology to baffle out-of-field x-rays at mirror module level.

Description:

- Analytical investigation of manufacture and integration of tapered baffle plates, at all IXO mirror module radii;
- Manufacture of 20 wedged, tapered baffle plates and stacking to demonstrate manufacturability of tapered baffles stack, including characterisation in x-ray;
- Coating of test baffled plates and of 10 tapered baffled plates which will be stacked to demonstrate baffle compatibility with coating.

5.5.3 Upgrade of the facilities at Bessy PTB lab

Start	Duration	Current / Target TRL	Need date
Q4 2008	24 mo	N/A	Ready end 2010

Objective: Upgrade of the PTB lab at Bessy x-ray test facility to facilitate characterisation of IXO mirror modules.

Description:

- Installation of a four-crystal monochromator on the (currently fixed energy) Bessy PTB beamline;
- Accommodation of 20-25 m focal length.

5.5.4 Upgrade of the facilities at Panter lab

Start	Duration	Current / Target TRL	Need date
Q1 2009	24	N/A	Ready end 2010

Objective: Upgrade of the Panter x-ray test facility to be prepared for IXO focal length.

Description:

- The Panter test facility will undergo upgrades. Modifications with a new collimator and detector configuration are required to enable mirror modules and populated petals to be tested at the correct focal length. Thermal shrouds also need to be installed within the vacuum chamber;
- Analysis of the testing requirements and modifications and design & installation of appropriate equipment to meet IXO testing requirements for mirror modules and populated petals;
- Procurement, installation, calibration and test of the necessary equipment.

5.5.5 IXO mirror module breadboard ruggedising and environmental testing I

Mirror module ruggedising is planned in two parts. This first activity will address ruggedisation of the module, including its mount interface to the aperture structure, build and characterise a module using the manufacturing equipment already developed. This existing equipment is built to manufacture modules to XEUS specifications of focal length and radius. A phase II ruggedisation will build a mirror module to IXO performance specifications (following installation of a new manufacturing robot to build modules at the new specifications in parallel to Phase I of ruggedising).

Start	Duration	Current / Target TRL	Need date
Q4 2008	18 mo	3-4 / 5	TRL 5 end 2010

Objective: To demonstrate the flight worthiness of Si x-ray pore optic modules for IXO.

Description:

- Modelling & analysis of stack adhesion forces.
- Improvements to state of the art manufacturing of mirror modules to ensure compatibility with environmental requirements, for instance annealing, contamination control, bracket/dowel pin modification including:
  * trade-off new materials compatible with integration at room temperature and operational temperature, e.g. HB-Cesic, Si3N4, Si;
  * light-weighting;
  * compatibility with integration into a petal and possible baffle mounts;
  * build compatibility is with the optical requirements of XEUS (50m FL, 2m radius);
- Component level tests, such as pull tests;
- Equipment upgrades and any necessary modification of the stacking robot, including Si plates sufficient for test purposes;
- Build of test stacks to test new equipment;
- Planning for industrialisation of processes and preliminary cost reduction analysis.

5.5.6 IXO mirror module prototype ruggedising and environmental testing II

Mirror module prototype built to IXO performance specifications.

Start	Duration	Current / Target TRL	Need date
Q1 2010	18	3-4 / 6	TRL 6 end 2011

Objective: To demonstrate the flight worthiness of Si x-ray pore optic modules for IXO.

Description:

- Procurement of sufficient silicon mirror plates and brackets to perform tests and stack prototype IXO mirror modules with pristine mirror plates;
- Environmental testing at relevant facilities (mechanical, thermal) with x-ray testing of the prototype modules pre and post each environmental test;
- Planning for industrialisation of processes.

5.5.7 Development of IXO silicon pore optics and mass production processes

Start	Duration	Current / Target TRL	Need date
Q4 2008	15 mo	3-4 / 6	TRL6 end 2011

Objective: Development and improvement of automated manufacturing processes to demonstrate that required number of mirror modules can be manufactured in timescale and cost of IXO telescope.

Description:

- Elaboration of 2nd generation plate developments including further consideration of industrialisation for mass production, for instance to reduce plate costs;
- Analysis of modifications necessary to the automated stacking process to address cleanliness levels. Procurement and installation of new equipment;
- Procurement of Si mirror plates and proof of new processes on samples to demonstrate improved processes (time, cost), which are compatible with producing bondable plates;
- Installation of a stacking robot for production of mirror modules at IXO specification (20 m FL, 0.7 m radius);
- Sample characterisation (e.g. SEM, x-ray characterisation, bonding tests);
- Analysis to show that necessary number of mirror modules for IXO telescope can be built in relevant timescale, with appropriate yield (for instance 70-80%) and description of the manufacturing process that will achieve this.

5.5.8 Demonstration of IXO petal breadboard with mirror modules at specific radii

Start	Duration	Current / Target TRL	Need date
Q2 2010	24 mo	4 / 5-6	TRL6 end 2011

Objective: To demonstrate by bread-boarding the achievement of TRL 5-6 for a petal that meets the requirements for IXO.

Description:

- Detailed design, analysis and modelling of a petal to meet the requirements for IXO;
- Specification of the alignment and mounting process to mount x-ray Si pore optic mirror modules into the petal using a method that allows their individual removal and replacement;
- Procurement, installation and modification of any new equipment necessary for manufacturing mirror modules at outermost, mid and innermost radii (TBC number of mirror modules and radii);
- Procurement of all parts necessary, including suitable manufacturing margin, for petal, mirror modules and mirror module dummies manufacture;
- Manufacture of a petal, 6 (TBD) mirror modules and dummies (to fill other slots), alignment and mounting of the tandems (& dummies) into a petal that meets the requirements, including environmental, for IXO. Mirror modules will be manufactured and integrated to fill the cells in petal rows where modelling shows that the highest mechanical and thermal loads are experienced;
- X-ray testing, pre and post environmental testing, at suitable facilities, of Si stack, mirror module and petal;
- Elaboration of a route to industrialised IXO petal production.

5.5.9 Demonstration of a baffled IXO mirror module

Start	Duration	Current / Target TRL	Need date
Q2 2010	12 mo	2 / 6	TRL6 by 2011

Objective: To demonstrate flight worthiness of a mirror module level baffle for IXO Si x-ray pore optic modules.

Description:

- Procurement of all parts, including suitable margin on Si plates, manufacture and alignment of a baffled Si pore optic module to meet the requirements of IXO;
- X-ray testing at plate, stack and mirror module level;
- Environmental (mechanical and thermal) testing of the baffled x-ray pore optic with x-ray testing performed pre and post each environmental test.

5.5.10 IXO contamination covers demonstrator

This activity is a pre-development in the system context and not an optics technology development proper. It is intended to cover the complementary aspects of accommodation on the IXO spacecraft.

Start	Duration	Current / Target TRL	Need date
Q2 2010	18 mo	2 / 4	TRL 4 by end 2011

Objective: To demonstrate contamination covers for the protection of the optics of the IXO telescope.

Description:

- Design, modelling and analysis of large covers to meet the requirements of the IXO optics during ground operations, launch, cruise and operation mission stages; roll-back covers using failsafe mechanisms could be considered;
- Design of attachment to petal or optical bench;
- Manufacture of a contamination cover and demonstration of design;
- Characterisation of the cover's performance both while installed (particle tightness, humidity), and during opening to expose full aperture.

5.5.11 IXO industrialised mass production process for mirror modules

Start	Duration	Current / Target TRL	Need date
Q1 2010	12 mo	NA	2011

Objective: Development of an industrialised mass production process for mirror modules for IXO.

Description:

- Assessment of facility, manpower, equipment requirements for scaling up to large scale, industrial, mirror module mass production;
- Development, procurement and demonstration of an industrial, robotised system (or parts there-of) for an automated process to produce mirror modules, on a mass scale, in suitable cleanroom facilities;
- Assessment of risks and mitigation routes for the industrialised process in a flight production programme.

6 Development schedule

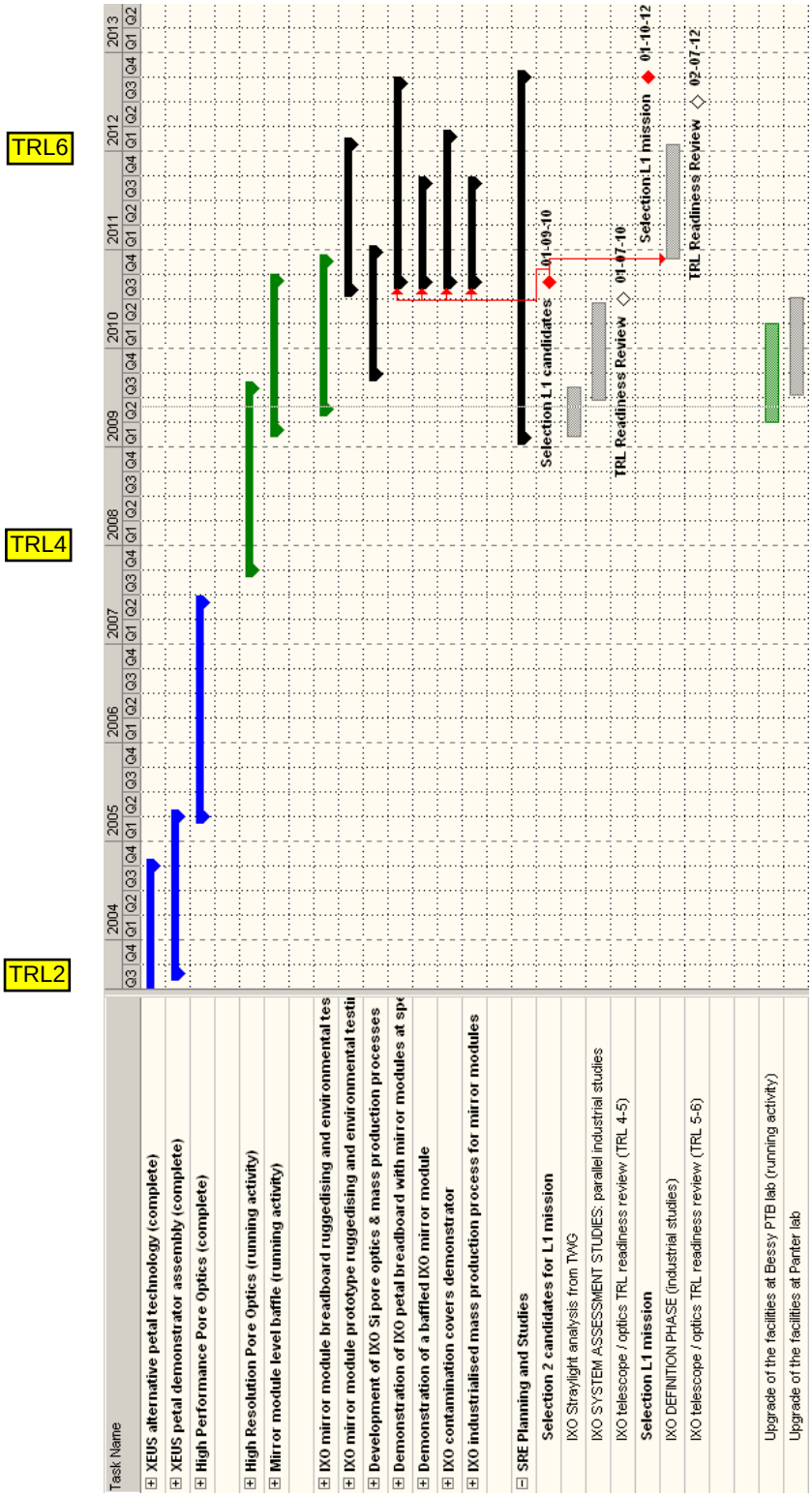

Figure 6-1: Top level development schedule for IXO silicon pore mirror development