ESA assessment study activities on the International X-ray Observatory

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ABSTRACT

The International X-ray Observatory (IXO) is an L class mission candidate within the science programme Cosmic Vision 2015-2025 of the European Space Agency, with a planned launch by 2020. IXO is an international cooperative project, pursued by ESA, JAXA and NASA. By allowing astrophysical observations between 100 eV and 40 keV, IXO would represent the new generation X-ray observatory, following the XMM-Newton, Astro-H and Chandra heritage. The IXO mission concept is based on a single aperture telescope with an external diameter of about 3.5 m, a focal length of 20 m and a number of focal plane instruments, positioned at the focal point via a movable platform. A grating spectrometer, enabling parallel measurements, is also included in the model payload. Two parallel competitive industrial assessment studies are being carried out by ESA on the overall IXO mission, while the instruments are being studied by dedicated instrument consortia. The main results achieved during this study are summarised.

Keywords: X-ray, space mission, observatory, IXO, X-ray optics, X-ray instruments

1. INTRODUCTION

The International X-ray Observatory (IXO) is an international cooperative project pursued by ESA, JAXA and NASA and resulting from the merge of the previous XEUS [1] and Constellation-X [2] studies. Following this merger, IXO has become an *L-class mission candidate* in the ESA Cosmic Vision 2015-2025 programme [3], with a target launch by 2020. Similarly IXO is also a candidate mission submitted to the US Decadal Survey (Astro2010) [4], while it is considered as the Astro-H follow up in the JAXA science programme.

The International X-ray Observatory is meant to become the next-generation X-ray observatory capable of addressing some of the most important themes posed by ESA's Cosmic Vision 2015-2025 science objectives, such as: a) Evolving violent universe (finding massive black holes growing in the centers of galaxies, and understanding how they influence the formation and growth of the host galaxy); b) Universe taking shape (studying how the baryonic component of the Universe formed large-scale structures and understanding how and when the Universe was chemically enriched by supernovae); c) Matter under extreme conditions (studying how matter behaves in very strong gravity at a very high densities, such as occurs around black holes and compact objects). IXO will also help to understand the cosmological evolution of the Universe, by enabling independent measurements of dark matter and dark energy using galaxy clusters. Being an observatory class mission, IXO will also be able to address a large number of additional problems in contemporary astrophysics, such as the origin of cosmic rays in Supernovae, studies of the interstellar medium, stellar mass loss and star and planet formation.

The ESA assessment activities have started in 2008, with an internal phase 0 study, performed via the ESTEC Concurrent Design Facility. In Q3/2009 two parallel competitive industrial studies have started with EADS Astrium and Thales Alenia Space, to be completed in July 2010. Instrument studies are also being conducted at scientific institute's consortia. A number of technology development activities are ongoing in parallel. All study activities are geared to the L class down-selection process of Cosmic Vision 2015-2025, planned to take place in Q1-Q2/2011. The main IXO requirements applicable to the ESA study are summarised in table 1.

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Table 1. Summary of IXO requirements applicable to the ESA study

Mirror Effective Area	> 2.5 m^2 @1.25 keV, with a goal of 3 m^2 > 0.65 m^2 @ 6 keV, with a goal of 1 m^2 > 150 cm^2 @ 30 keV, with a goal of 350 cm^2
Spectral Resolution	ΔE = 2.5 eV within 2 x 2 arc min (0.3–7 keV). ΔE = 10 eV within 5 x 5 arc min (0.3-7 keV) ΔE < 150 eV @ 6 keV within 18 arc min diameter (0.1-15 keV) $E/\Delta E$ = 3000 from 0.3–1 keV, with an area of 1,000 cm^2 for point sources ΔE = 1 keV within 8 x 8 arc min (10 – 40 keV)
Mirror Angular Resolution	5 arc sec HEW (0.1 – 10 keV) 30 arc sec HEW (10 - 40 keV) with a goal of 5 arc sec
Count Rate	1 Crab with > 90% throughput. ΔE < 200 eV (0.1 – 15 keV)
Polarimetry	1% MDP on 1 mCrab in 100 ksec (2 - 6 keV)
Astrometry	1 arcsec at 3σ confidence
Absolute Timing	100 μsec

2. MISSION PROFILE

The IXO mission concept is based on a single, large aperture, x-ray telescope, with a focal length baseline of 20 m. The telescope would illuminate different focal plane instruments, located at the optical focus via a moving platform. The required focal length, not compatible with the existing launching vehicles, is reached via a deployable optical bench, locked to its final position after launch. The overall spacecraft design is divided into separate modules to optimize the development activities and is compatible with both the Ariane 5 and the Atlas V/551 launcher vehicles, for a total launch mass of about 6500 kg.

The observatory would operate at L2, orbiting around the second Lagrangian point of the Sun-Earth system on a large halo orbit. This orbit has been selected as it provides a benign and stable thermal environment as well as a good instantaneous sky visibility. The operational orbit would be reached with a direct transfer trajectory towards L2, with limited delta-V demands. Only two correction manoeuvres would be performed after launch, respectively on day 2 (main launcher dispersion correction manoeuvre) and on day 10 (final corrective manoeuvre). The present baseline is to perform the telescope deployment after the second correction manoeuvre, thus enabling the beginning of the commissioning activities. The operational orbit at L2 will be reached after about 100 days from launch. Monthly station keeping manoeuvres will allow remaining on the nominal halo orbit, for a total delta-V of only 2 m/s/year. The total delta-V budget over a 10 year lifetime mission is about 120 m/s.

The nominal lifetime is 5 yr, with a possible extension of another 5 year. By an accurate choice of the launch date and time, it is possible to avoid any eclipses, during both the cruise to L2 and the operational phases.

The design of the spacecraft will be compatible with large pointing excursion around the average S/C-Earth-Sun direction (X axis, yaw, +/- 180 deg) and more modest rotations in pitch (around the transversal Y axis, +/- 20 deg) and roll (around the longitudinal Z axis, +/- 10 deg).

In the present ESA study, IXO would have a daily ground contact period of about 4 hr with a 35m diameter ground station. The link budget has been calculated assuming down-link in X-band and the DSN New Norcia station, with a nominal data rate of about 9 Mbps. Alternative configurations may be enabled depending on future agreements within the international cooperation program. IXO will have a single Mission Operations Centre, distributing the science data to the Science Operations Centres. An ESA Science Operations Centre (SOC) is baselined, in order to support the activities of the European scientists making use of the IXO observatory.

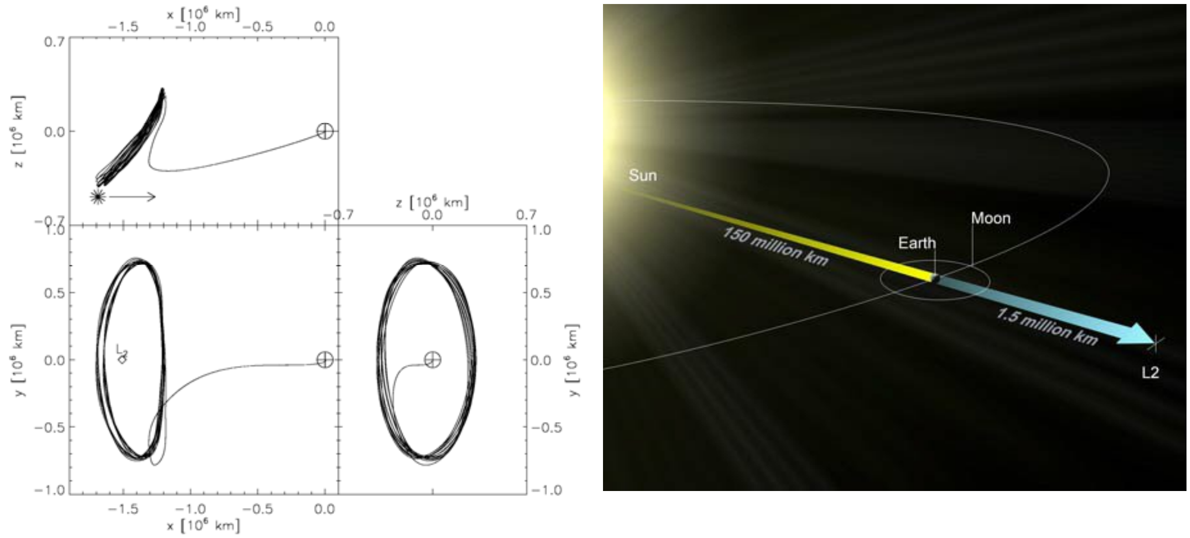

Fig. 1. On the left: Large-amplitude libration orbit around L2, including transfer from low-Erath perigee (Z axis is pointing to the ecliptic north pole, X-Y is ecliptic plane). On the right: artist view of SEL-2.

3. INSTRUMENTS

The IXO focal plane instruments are a cryogenic imaging spectrometer (XMS), a wide field imager (WFI), a hard x-ray imager (HXI), a high time resolution spectrometer (HTRS) and an X-ray polarimeter (XPOL) [5]. These units would be accommodated on an adjustable platform, allowing to accurately positioning one instrument at a time at the telescope focus. The platform, an integral part of the instrument module, will host all main instruments units (such as front and back-end electronics), thus minimizing the demands on the harness between moving platform and the rest of the spacecraft. In addition to the above listed focal plane instruments, a grating spectrometer (XGS) would be continuously illuminated by the X-ray optics. The actual XGS gratings will be located between the X-ray mirror optics and the mirror module, while the focal plane camera will be accommodated in the instrument module, but on a fixed platform, separate from the moving platform. The cryogenic chain required to operate XMS (a micro-calorimeter based instrument, with the focal plane detector operating at about 50 mK) would be based on a closed cycle system, with a set of mechanical coolers and would also be accommodated on the moving platform.

The total mass of the IXO instruments is about 410 kg (including maturity margins and excluding the XMS cryogenic chain). The mass of the cryo-chain is presently estimated to be of order 290 kg (including maturity margins), depending on the specific design solutions adopted. The instruments operation scheme is based on continuous operations for XGS, an additional instrument operating at the main telescope focus, while another instrument is on stand-by. In this scheme, the maximum power consumption is estimated to be of order 1.7 kW (including XMS cryo-chain).

The IXO model payload is presently undergoing assessment studies conducted by a number of instrument consortia and to be completed by July 2010. The results of these study activities have been taken into account in the ESA system level studies conducted by industry.

Table 2. Summary of IXO instruments (mass and power including design maturity margins).

Instrument Characteristic	WFI&HXI Combined		XMS	HTRS	XPOL	XGS[1]
	WFI	HXI				
Detector type	Si APS (DEPFET)	CdTe + Si strip detectors	Micro-calor. (TES)	Silicon Drift Diodes	Gas Pixel Detector	CCD
Mass (kg)	101 129	28	392[2]	30	15	122
Peak Power (W)	283 339	56	1017[3]	145	55	115
Detector Tops	210 K	233 K	50 mK	233 K	283 K	183K
Cooling	Radiator	Radiator	Closed cycle, ADR	Radiator	Peltier	Radiator
Detector Size (mm)	102.4 × 102.4	50 × 50	31.2 × 31.2	24 (circular)	15 × 15	786 × 24
Energy Range (keV)	0.1 – 15	10 – 40	0.3 – 12	0.3 – 15	2 – 10	0.3-1
En. resol. (FWHM)	50 eV @ 0.2 keV 125 eV @ 6 keV	1 keV @ 40 keV	2.5 eV @ <6 keV	200 eV @ 6 keV	1200 eV @ 6 keV	E/ΔE > 3000
Pixel size (μm)	100	250	300 (& 600)[4]	3400	50	24
Pixels in one dimension	1024	192 strips	40 (+ 32)[4]	7	300	32768
Field of View (arcmin square)	17.6 × 17.6	8 × 8	2 × 2 (& 5.4 × 5.4)[4]	N/A	2.6 × 2.6	N/A
Typ/max data rate (kbps)	45/450	11/256	64/840	840/840	840/840	750/750 (1280)[5]

1 Assuming the CAT grating option design for the Silicon Pore Optics Mirror
2 Total of 113 kg for XMS instrument and 279 kg for the cryostat + cryo-cooler chain (ESA CDF baseline cooler)
3 Total of 520 W for XMS instrument and 497 W for the cryo-cooler chain (ESA CDF baseline cooler)
4 For inner and outer array respectively
5 Peak rate for < 6 hr/month

4. SPACECRAFT CONFIGURATION

4.1 Design drivers and spacecraft architecture

The main IXO design drivers are the need for a single, large aperture x-ray telescope and the need to illuminate a number of different focal plane instruments. The size (diameter) of the single aperture, in conjunction with the photon energy range and the optics technology, implies a long focal length (set to 20 m), exceeding the height of the existing launcher fairings. As a result, the spacecraft architecture is driven by the need to deploy after launch in order to achieve the nominal focal length by means of a dedicated extensible optical bench. In order to be able to illuminate a set of different focal plane instruments, the spacecraft is equipped with a movable instrument platform, allowing to switch units (respectively, WFI/HXI, XMS, HTRS and XPOL), while the grating spectrometer (XGS) is permanently illuminated.

The spacecraft is divided in different functional modules, as it follows:

- **Mirror Assembly (MA):** the MA is located inside the fixed telescope metering structure (part of the Service Module) and contains the X-ray optics, the associated supporting structure and thermal control hardware.
- **Service Module (SVM):** the SVM includes the fixed telescope metering structure, the deployment mechanism, the deployable shroud and the actual S/C service platform.

- **Instrument Module (IM):** the IM accommodates the focal plane instruments and includes the moving platform, the focusing mechanism and the XMS cryogenic chain, with dedicated thermal radiators.

An overview of the deployed spacecraft is provided in the artist view of figure 2, with the IM towards the reader and the MA pointing to the object under investigation. The basic characteristics of the mission are summarised in table 3 below.

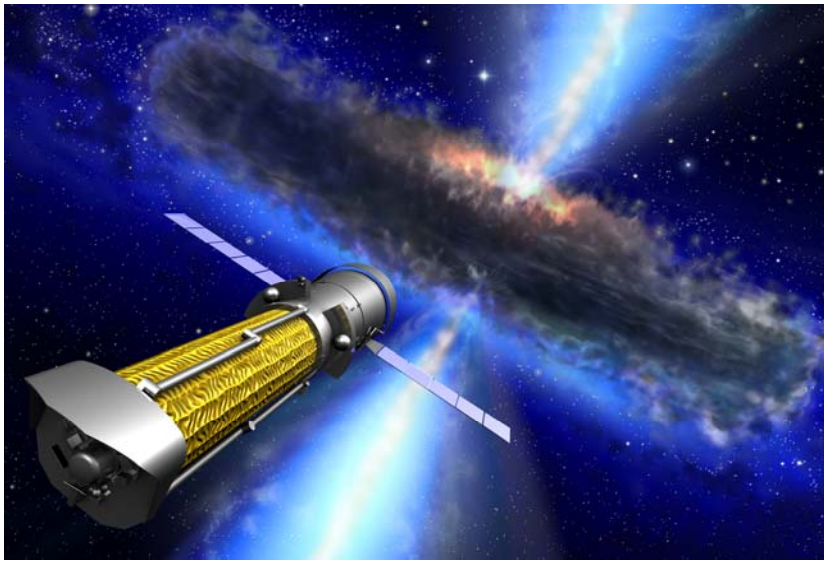

Fig. 2. Artist view of the *International X-ray Observatory* spacecraft.

Table 3. IXO mission summary

International X-ray Observatory - Mission summary	
Orbit:	Large amplitude libration orbit around Sun Earth L_2 (halo orbit)
Launcher:	Ariane-5 or Atlas-V/551 (TBC)
Total S/C mass / power	6500 kg / ~5.5 kW
Launch date:	End 2020 (reference launch date for L1 – Cosmic Vision plan)
LEOP and Transfer	3 days - 3 month (TBC)
Operational Mission:	5 year (possible extension of another 5 year)
Attitude control:	3-axis stabilised spacecraft (RW's and thrusters actuators)
Payload:	- Large X-ray telescope (effective area > 2.5 m^2 at 1.25 keV) - Grating spectrometer (always illuminated) - Wide Field Imager & Hard X-ray Imager - Micro-calorimeter Spectrometer (with cryogenic chain) - High Time Resolution Spectrometer - X-ray Polarimeter
On Board Science Data:	~ 90 Gbit/day (average, downloaded in 4 hr)
Communications:	X-Band: 1x steerable HGA and 2 Omni-directional LGA
Ground Station:	New Norcia (additional stations depend on international cooperation)

4.2 The Mirror Assembly

The architecture of the IXO mirror assembly is conceived as an independent unit, to be integrated into the fixed metering structure of the Service Module, and it is based on a hierarchical and modular approach, designed around the individual x-ray optical units.

The circular MA primary structure has a ‘spoke-wheel’ geometry, with 8 radial struts connected to a central hub and to an external circular frame. The primary structure supports 8 separate petals, each populated with individual mirror modules based on the Silicon Pore Optics technology [6], transferring the launch loads to the metering structure. Kinematic mounts allow minimising the impact of mechanical and thermo-elastic loads onto the optics alignment.

Light weight, thermal baffles are located in front of the X-ray optics (sky side) and heated via electrical heaters, thus allowing to keep the mirror elements at a temperature close to ambient. The gratings required by the XGS spectrometer (CAT scenario) are also located in close proximity of the optics and supported by the petal structure (focal plane side). Dedicated covers are also baselined to protect the X-ray optics from contamination during AIV, launch and early phase operations (including the deployment of the observatory). A sun-shield is protecting the MA from stray-light. Figure 3 below illustrates the design of the Mirror Assembly, as from the ESA study performed in early 2009.

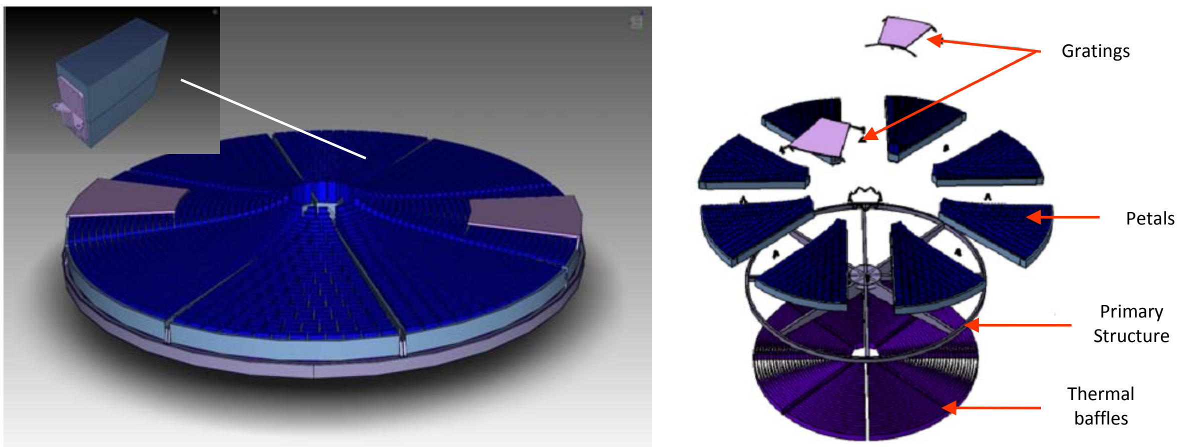

Figure 3 – Left: Overview of the Mirror Assembly, including the XGS gratings (as from the ESA CDF design). Right: main elements of the MA (exploded view).

4.3 The Service Module

The IXO Service Module includes three main elements: a) the fixed telescope metering structure; b) the actual observatory platform subsystems; c) the Extendable Optical Bench required to achieve the nominal focal length. The three elements are physically connected, with the fixed structure (about 7 m long, fabricated in two sections using an Al honeycomb core and CFRP skins) representing the interconnecting element (also to the MA). The platform subsystems are hosted in dedicated equipment bays, located close to the upper end of the fixed structure and supported by interconnecting struts. Thrusters and solar panels are also connected to the fixed structure.

The Extendable Optical bench has been subject of specific trades in the ESA studies (both the internal CDF activities and the industrial studies); the preferred solution is based on three articulated booms, hinged at one end on the fixed structure and on the other end on the Instrument Module (see figure 6 and 7). Slightly different detailed designs have been suggested by EADS Astrium and Thales Alenia Space. The articulated booms have showed significant advantages when compared to alternative solutions (e.g. deployable truss or telescopic booms) in terms of deployment control, reliability and structural stiffness. A deployable shroud, consisting of a sandwich of multilayer insulation materials, would ensure that no stray-light enters the telescope; the shroud would be deployed by the EOB, when moving to its final configuration.

All three SVM elements will be covered by MLI in order to minimize the temperature gradients. Dedicated analysis has showed that it is indeed possible to maintain the inner surfaces at a temperature close to ambient, with modest gradients between the Sun (+X) and the anti-Sun (-X) sides.

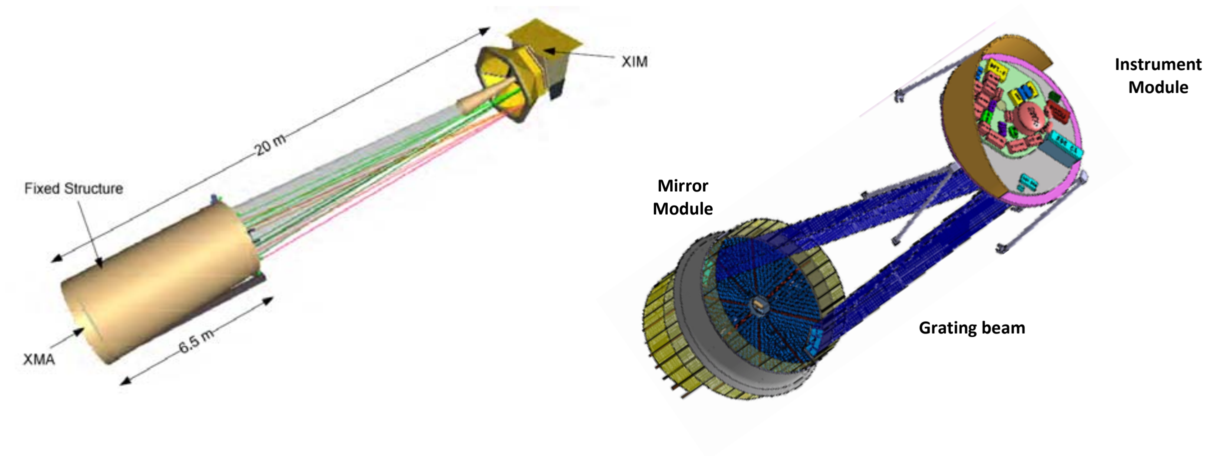

Figure 4 – Exploded view of the telescope in deployed configuration. Left side: EADS Astrium design. Right side: Thales Alenia Space design (deployable shroud is not shown for clarity).

4.4 The Instrument Module

The Instrument Module hosts all focal plane instruments and enables changing the instrument being located at the nominal telescope focus position via a dedicated moving platform. The XGS focal plane camera is also supported by the IM, but it is located on a fixed platform, at a radial distance of about 700 mm from the nominal focus position. All instruments are protected by a fixed sun-shield on the +X side.

The fixed platform is directly interfaced to the upper end of the EOB (articulated booms) and is supporting the moving instrument platform. Dedicated mechanism solutions have been identified for allowing the lateral movement of the platform (in the X-Y plane) as well as correcting any defocusing effects induced by deployment inaccuracies or thermo-elastic effects (along the Z axis). The amount of harness passing from the moving to the fixed platform has been minimized by installing on the moving platform most of the back-end units of the instruments.

The IM also provides a controlled thermal environment to the instruments, via a combination of MLI, radiators and substitution heaters. Dedicated thermal analyses demonstrated the possibility to satisfy the different thermal requirements in the different S/C attitudes, coping with the relatively large power dissipations (~ 1.0 -1.5 kW).

The IM will also host the cryo-chain required to maintain the focal pane detector of XMS at the required cryogenic temperature. The recent IXO studies have identified a number of different feasible solutions for the XMS cryo-chain, all based on closed cycle coolers, compatible with a total lifetime of 10 years. A final decision on the XMS cooling chain will be made taking into consideration technical as well as programmatic requirements during the next study phase (phase A/B1).

An onboard metrology system based on a coarse lateral sensor and fiducial light sensors located in proximity of the focal plane instruments is baselined in order to allow a reconstruction of the telescope line-of-sight in line with the astrometry requirement of 1 arcsec.

A dedicated baffle is included in the IM design (extending into the deployable shroud volume) in order to reduce X-ray stray light from impinging on the detector at the focus position. The baffle is sized for the instrument with the largest field of view (WFI, 18 arcmin) and has a length exceeding 2.5 m, with an outer diameter of 60 cm. The baffle is also equipped with magnetic particle diverters, rejecting energetic charged particles (protons above 75 keV and electrons above 25 keV).

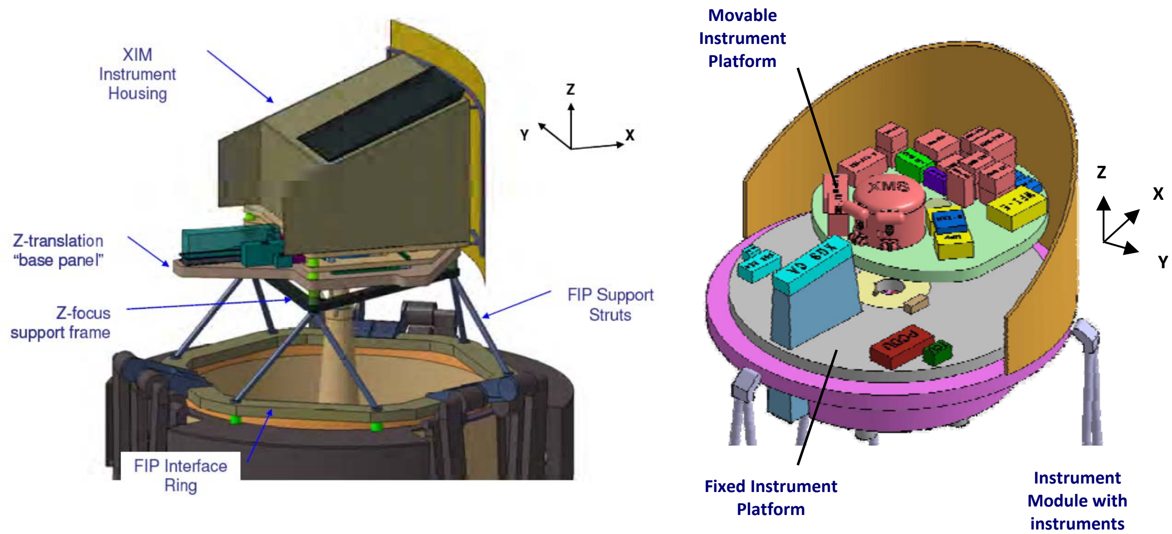

Figure 5 – IXO Instrument Module. Left side: EADS Astrium design. Right side: Thales Alenia Space design.

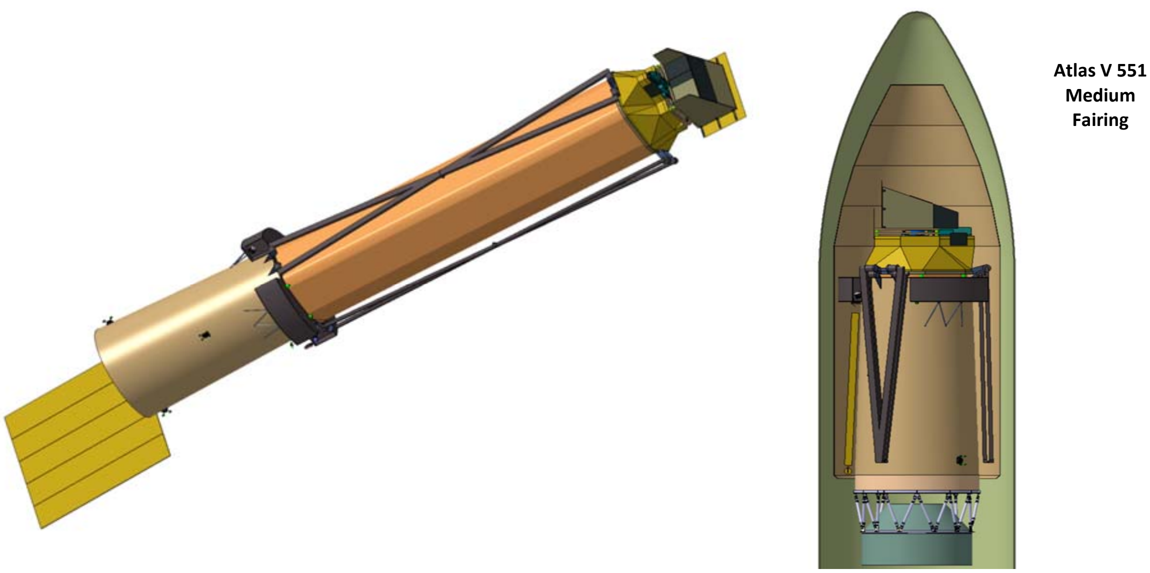

Figure 6 – Overview of IXO design (EADS Astrium) in deployed (left) and stowed configuration (right).

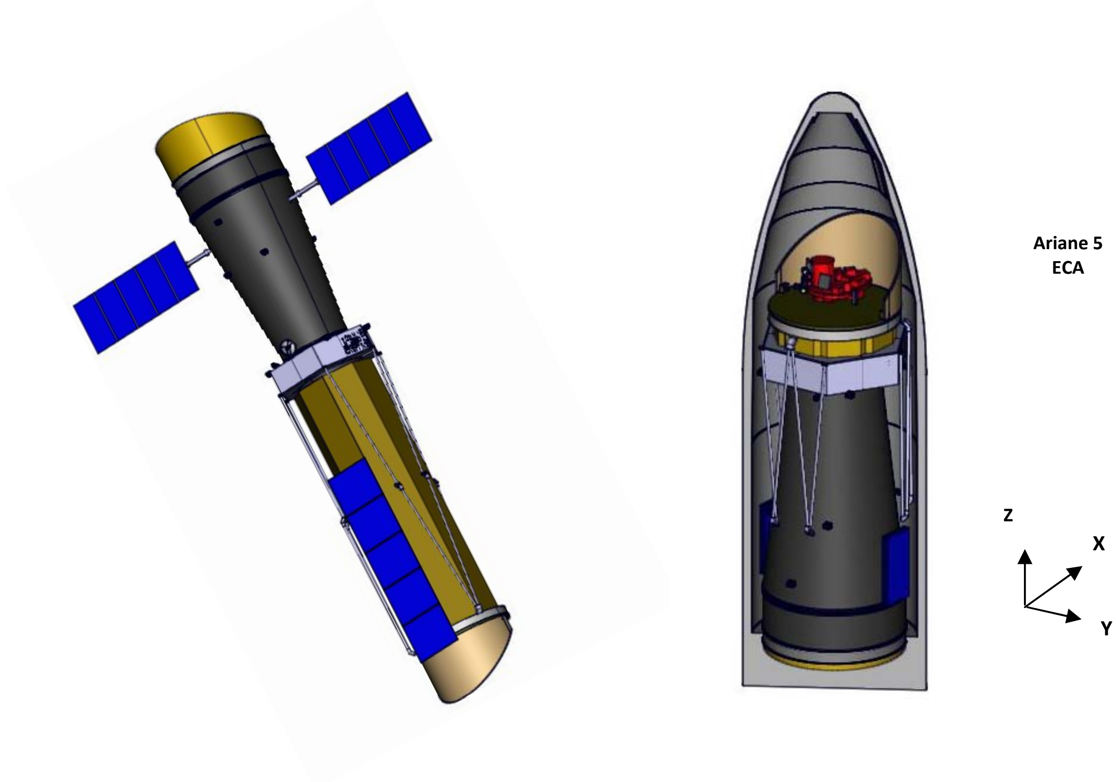

Figure 7 – Overview of IXO design (Thales Alenia Space) in deployed (left) and stowed configuration (right).

5. TECHNOLOGY READINESS AND WAY FORWARD

The technology readiness of the proposed IXO spacecraft design has been reviewed during the assessment study; the risk areas have been identified and corresponding risk mitigation actions have been planned. Moreover, following the consolidation of the international cooperation scenario, it will be possible to further mitigate the overall project risk, by taking advantage of the experience available at the partner agencies.

Given the XMM-Newton heritage and other scientific space projects, Europe is very well placed to contribute in an effective manner to the IXO project. The ongoing development of the X-ray optics (a mission enabling element) based on Silicon Pore technology, together with the experience acquired in the design, manufacturing and assembly of large X-ray telescope are distinctive advantages.

The SPO mirror modules have already demonstrated in representative X-ray tests (full illumination) an angular resolution of 10 arcsec (HEW) and further improvements are being implemented to achieve the nominal requirement of 5 arcsec (HEW). The Mirror Module will also undergo preliminary environmental testing by the end of 2010 and it is planned to achieve TRL>5 by the end of the definition phase activities (A/B1). Parallel development activities on segmented glass optics are being performed in the US, thus further reducing the risk on the IXO project.

Significant heritage is available in Europe also on the cryogenic chain of XMS (Herschel and Planck missions), in some cases with possible alternative design solutions for the pre-cooling and final stage of the micro-calorimeter.

Most of the platform equipment and subsystems have flight heritage or high TRL; only very few units would require qualification or modest development activities, not posing any difficulty given a launch by the end of 2020. The relatively benign space environment at SEL-2 does not require specific radiation hardening solutions or qualification activities. Manufacturing of large composite structure, such as the one requested for the IXO service module, has been

demonstrated on a number of different European space projects and does not require new development activities or new fabrication facilities.
The extendable optical bench, although presenting innovative aspects, is based on proven design solutions and has predicted performance fully compatible with the IXO requirements. The EOB will require dedicated test facilities which are well within the scope of a large class mission.
The IXO development plan takes into considerations the boundary conditions given by the project approval process (at ESA and at the partner agencies) as well as all relevant technical issues. Key events to be accounted for are: a) the outcome of the decadal survey in the US (Q3/2010); b) the L class down-selection at ESA (Q2/2011); c) earliest start date of the Definition Phase at ESA (Q4/2011); d) selection of the optics technology in Q4/2012; e) final selection and start of the Implementation Phase in 2013. A key schedule driver is represented by the time required to manufacture all the optics elements required to populate the X-ray mirror, presently estimated in no less than 3 year.

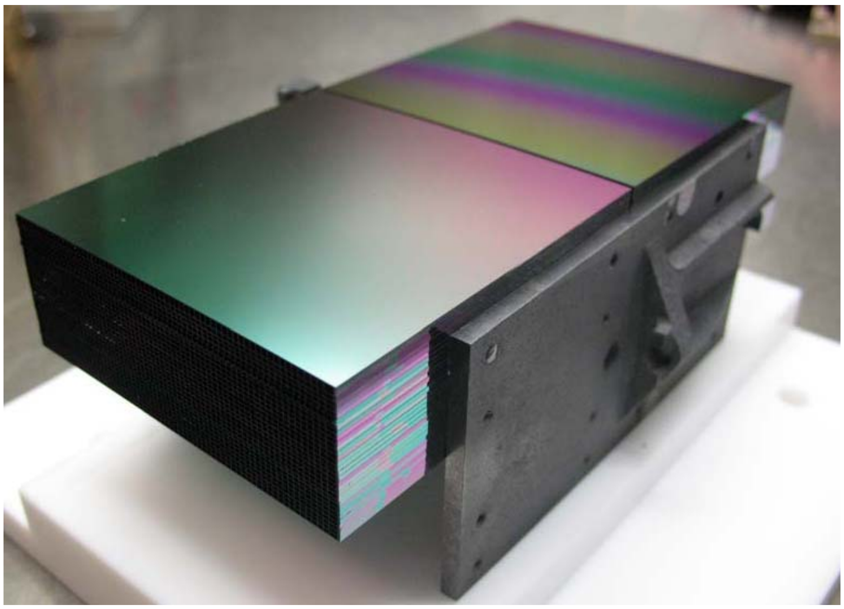

Figure 8 – Photograph of a recent Silicon Porte Optics mirror module. The two stacks (approximating the parabola and hyperbola mirror segments) are connected by the mounting bracket (courtesy of Cosine BV).

6. CONCLUSIONS

The industrial assessment study conducted on the International X-ray Observatory confirmed that the main requirements can be fulfilled with the proposed spacecraft design, fully compatible with the corresponding IXO NASA design [4]. The baseline design based on a single large aperture and a deployable optical bench reaching the required focal length of 20 m, has been analysed, and showed meeting the key performance requirements of the mission. On the basis of the existing heritage and technology capabilities, Europe can play a major role in the international cooperation scenario.

The Silicon Pore Optics development activities continue to progress, with representative X-ray tests which have already demonstrated and angular resolution of 10 arcsec at 1 keV (HEW) in full illumination mode, while the selection of the optics for IXO is planned by the end of 2012. The preliminary programmatic analysis showed a challenging schedule when assuming a launch date by 2020 and the need to address early on the large scale fabrication of the mirror units.

Following the completion of the assessment study activities in Q3/2010, the IXO mission will enter the planned L class selection process at ESA, competing with the mission to the Jupiter system (Laplace) and the large space gravitational wave interferometer (LISA). The selection of the two missions moving into Definition Phase is expected in Q2 2011.

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REFERENCES

[1] A. Parmar, G. Hasinger and M. Turner Proc 34th Cospar Assembly, p2368, (2004).
[2] J. Bookbinder et al, Proc. of SPIE 7011, (2008).
[3] G. Bignami et al, Cosmic Vision, ESA BR-247, (2005).
[4] Reference material available at http://ixo.gsfc.nasa.gov/resources/0209_Decadal_WhitePapers.html
[5] Instruments reference design document is available at the following link: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=44697#
[6] K Wallace, M Bavdaz, P Gondoin, et al Proc. SPIE **7437**, 74370T (2009)