The Status of the XEUS X-ray Observatory Mission

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ABSTRACT

The X-ray Evolving Universe Spectroscopy (XEUS) mission [1,2] is under study by ESA and JAXA in preparation for inclusion in the ESA long term Science Programme (the Cosmic Vision 2015-2025 long-term plan). With very demanding science requirements, missions such as XEUS can only be implemented for acceptable costs, if new technologies and concepts are applied. The identification of the key technologies to be developed is one of the drivers for the early mission design studies, and in the case of XEUS this has led to the development of a novel approach to building X-ray optics for ambitious future high-energy astrophysics missions [3,4].

XEUS is based on a single focal plane formation flying configuration, building on a novel lightweight X-ray mirror technology. With a 50 m focal length and an effective area of 10 m^2 at 1 keV this observatory is optimized for studies of the evolution of the X-ray universe at moderate to high redshifts.

This paper describes the current status of the XEUS mission design, the accommodation of the large optics, the corresponding deployment sequence and the associated drivers, in particular regarding the thermal design of the system. The main results were obtained in two Concurrent Design Facility (CDF) studies and other internal activities at ESTEC [5].

Keywords: X-ray astronomy, X-ray optics, Micro-pore optics, Mission concepts, XEUS

1. INTRODUCTION

A novel X-ray optics technology has been developed over the last few years which effectively reduces the specific mass of the X-ray optics by more than one order of magnitude compared to the XMM-Newton optics technology. At the same time the angular resolution is improved by a factor of three, and the industrial production of large optical systems is simplified. The maturity of this new optics technology has progressed to a level where it provides a suitable baseline for an optimized mission scenario based on a lightweight high performance X-ray telescope.

Based on this new optics technology, it has become possible to conceive of a large area, high angular resolution, X-ray telescope, which could be deployed into a halo orbit around the Earth-Sun Lagrangian point L2. A single focal plane instrument assembly is assumed, populated by cryogenic spectrometers, a semiconductor wide field imager and other instruments. To achieve the required long focal length of 50 m (baseline), the optics and detector instruments are mounted onto two spacecraft, flying in formation. The more massive Mirror Spacecraft (MSC) flies an inertial orbit, followed by the Detector Spacecraft (DSC), which is tracking the telescope focal position. The change of active instrument is performed by shifting the DSC location relative to the focal point of the MSC optics (see Fig. 1).

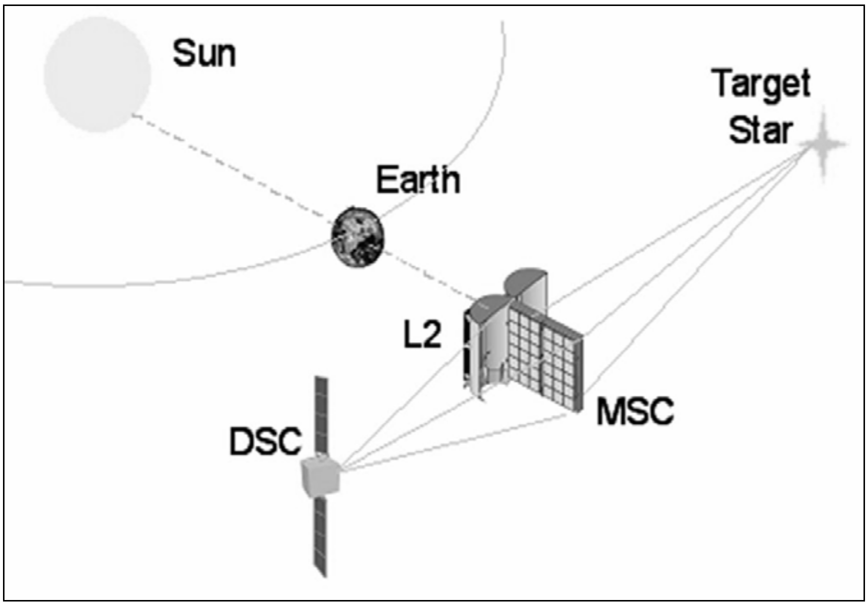

Figure 1: XEUS is deployed at the 2nd Earth-Sun Lagrangian point, L2. The Mirror Spacecraft MSC is flying in an inertial halo orbit, and the Detector Spacecraft follows the MSC at a distance of 50 m. The DSC is the active spacecraft in the formation flying. The XEUS telescope is nominally pointing normal to the sun-vector (±15° TBC), i.e. the instantaneously accessible sky area is a great circle of 30° width.

2. THE SPACECRAFT DESIGN

The X-ray telescope is hierarchically structured, as depicted in Fig. 2. The core of the optics is formed by the optics modules. These are made of silicon and form a monolithic unit, very stiff but lightweight (the actual mirrors are only 175 micron thick!), and contain integral mounting strong-points. Two such modules form a tandem, producing the two reflections required for a conical approximation to the Wolter-1 design. About 50-100 of these tandems are assembled into a petal, which also contains the required X-ray and optical baffling systems. The petals are integral, independent, units which are individually assembled, tested and characterized/calibrated. They are small enough to be efficiently handled on the ground, yet large enough to ensure a practical integration onto the spacecraft. These petals interface to the MSC via the optical bench of the telescope, a deployable structure forming part of the MSC.

One of the most prominent drivers in the design of the MSC is thermal considerations. The size of the X-ray telescope, formed by up to 64 petals and covering an area of >40 m^2, and the severe mass constraint limit the available options for the thermal control system. The extremely large surfaces on both sides of the optics (entrance and exit planes) are open to (cold) space, and correspondingly a large amount of thermal energy is radiated into space. At the same time the distances are large (many meters) and the optics mass density is low (~60 kg m^{-3}), thus the thermal conductivity is very small. The most efficient way of controlling the temperature of the telescope optics is the use of radiators. Fig. 3 shows the concept for the MSC thermal design. The main structure of the MSC, a split cylinder, functions as a sunshield, and deployed radiators define the optics temperature.

The resulting absolute temperature of the optics is well below room temperature, at -161 to -124 ºC, despite large area radiators deployed on both sides of the MSC main body. Figures 4 and 5 summarize the temperature distribution over the complete telescope optics showing that both the dependence of the telescope pointing direction and the longitudinal temperature gradients stay within a few degrees. Due to the small size of the sensitive elements the temperature gradients over the monolithic silicon optics modules remain at ~1 ºC or below laterally and even much less longitudinally (along the optical axis). The baffle system, which is located within the optics modules (on the entrance and exit planes) provides efficient thermal control for the critical longitudinal direction.

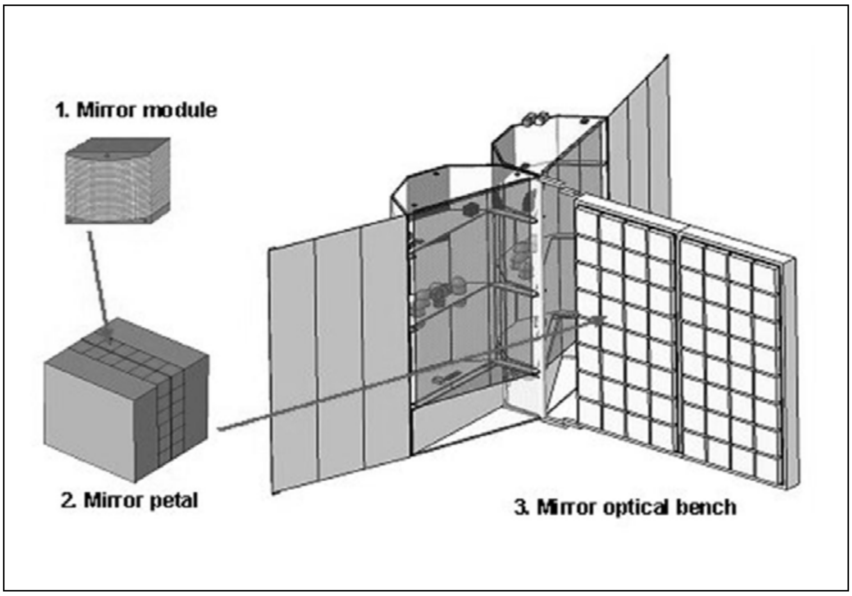

Figure 2: XEUS telescope optics hierarchy. The core of the optics is formed by small modules made of pure silicon, allowing mass production with automated equipment. Many such modules are combined into a ‘petal’, the size of which is defined by ground handling and spacecraft integration considerations. The petals also incorporate the required baffling systems (X-ray and IR/visible/UV). The petals are finally mounted onto the deployable optical bench, which in itself is stowed and supported by the main MSC structure during launch.

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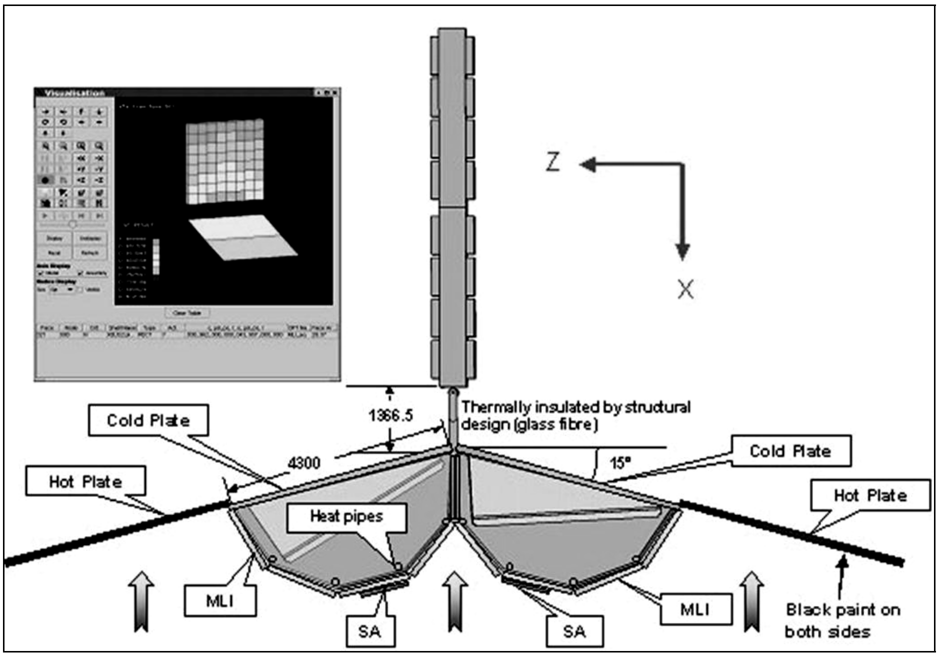


Figure 3: The concept for the thermal design of the MSC utilizes sun-shields and radiators to maintain the optics at a stable and uniform as possible temperature. The Sun is located to the bottom of the image, ‘z’ indicates the telescope pointing vector. The body of the MSC structure functions in the operational phase as a sunshield. A number of radiators at different temperatures are required to reduce the thermal gradients.

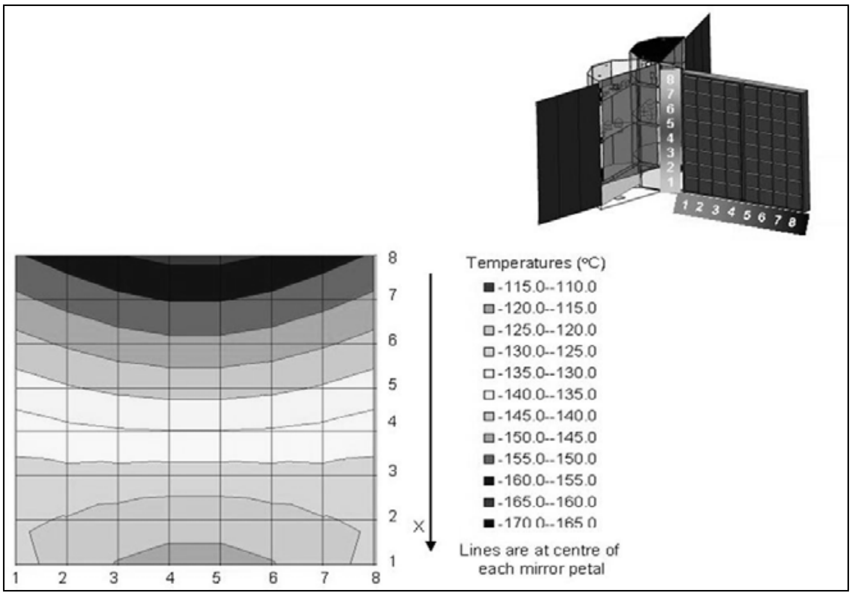
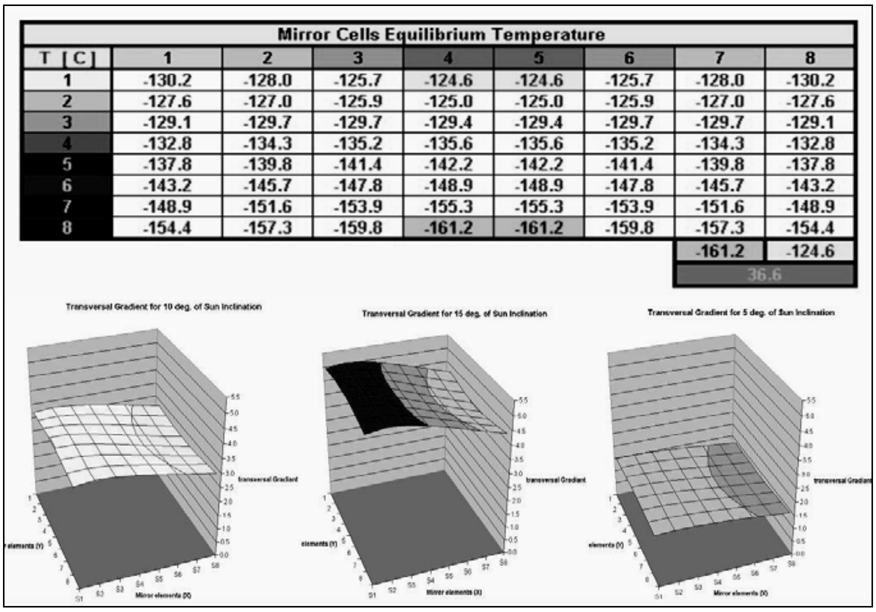


Figure 4: A temperature map of the XEUS optics, based on the preliminary thermal design, and before detailed optimization. The temperature ranges from -161 to -124 ºC, with the main gradient along the sun-vector axis (i.e. the temperature mainly depends on the distance from the main MSC structure = sunshield and radiators). This gradient is large, ~40-50 ºC, but is spread over 8 petals, and within each petal over typically 8 optics modules. The resulting gradient within any single optics module is ~1 ºC or less.



Mirror Cells Equilibrium Temperature

T [C]	1	2	3	4	5	6	7	8
1	-130.2	-128.0	-125.7	-124.6	-124.6	-125.7	-128.0	-130.2
2	-127.6	-127.0	-125.9	-125.0	-125.0	-125.9	-127.0	-127.6
3	-129.1	-129.7	-129.7	-129.4	-129.4	-129.7	-129.7	-129.1
4	-132.8	-134.3	-135.2	-135.6	-135.6	-135.2	-134.3	-132.8
5	-137.8	-139.8	-141.4	-142.2	-142.2	-141.4	-139.8	-137.8
6	-143.2	-145.7	-147.8	-148.9	-148.9	-147.8	-145.7	-143.2
7	-148.9	-151.6	-153.9	-155.3	-155.3	-153.9	-151.6	-148.9
8	-154.4	-157.3	-159.8	-161.2	-161.2	-159.8	-157.3	-154.4
							-161.2	-124.6
							36.6	

Figure 5: Sensitivity analysis of the telescope temperature as function of the XEUS pointing direction. If the telescope is pointed away from the normal to the Sun vector, a temperature difference develops between the entrance and the exit planes of the optics. However, this difference remains below 4º C over the petal ‘thickness’ of 0.8 m. The largest part of this gradient occurs within the

entry and exit baffle systems of the petals, and the sensitive optics modules experience only minor longitudinal temperature gradients.

The deployment sequence of the MSC is illustrated in Fig. 6. The sensitive optical bench is supported during launch by the shell of the MSC main structure. This enables the design of a very lightweight optical bench, dimensioned for the operational phase in zero-g. In the stowed configuration dedicated antennae and solar panels are used. The deployment has three main phases: (1) opening of the main MSC cylinder, (2) the deployment of the optical bench (which is folded during launch), and (3) the deployment of the thermal radiators controlling the optics temperature.

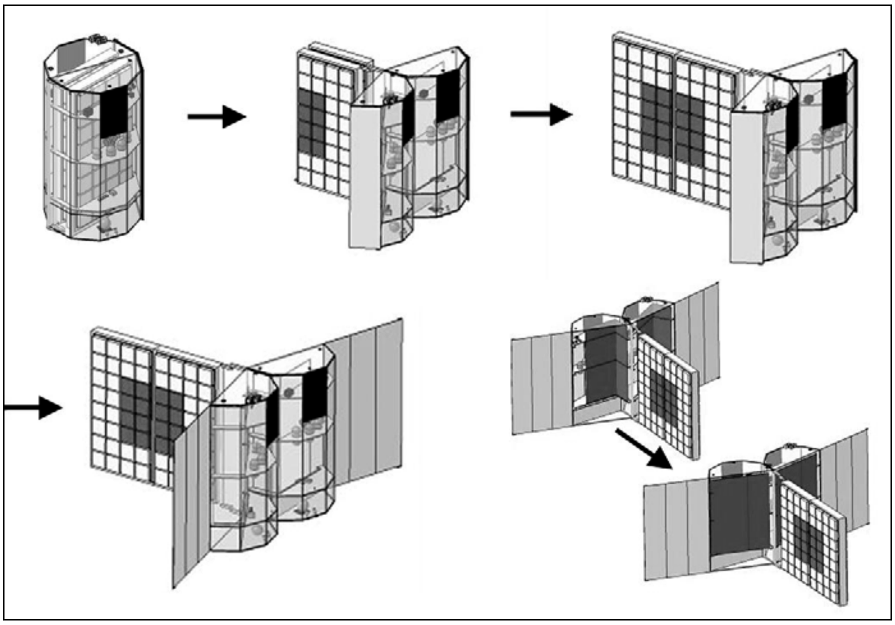


Figure 6: MSC deployment sequence. During launch the optical bench is supported and protected by the main MSC structure. The main MSC cylinder then opens, and the optical bench unfolds to reveal the X-ray optics system. In the final step, the thermal control radiators deploy, forming a >100 m^2 structure.

The DSC is a comparatively traditional spacecraft, with the addition of cryogenic instruments and the formation flying (FF) package. The DSC is the active spacecraft in the FF, and it also handles the data and command traffic to the MSC.

3. THE LAUNCH SCENARIO AND FORMATION FLIGHT

The DSC and the MSC are launched as a single stack. A direct injection into the escape orbit to L2 is possible, but other alternatives exist, increasing the available payload mass, but complicating the scenario. In the CDF studies the trade-offs favored direct injection, which, on the Ariane 5 ECA launcher, provides a total mass of 6800 kg at L2.

If the insertion into a halo orbit is performed along an escape direction, there is no insertion maneuver into the desired L2 halo orbit as such. For any launch date, there is a transfer orbit from Earth allowing insertion into a halo orbit without additional ΔV. The departure leg of the transfer orbit may be in eclipse during a maximum duration of 75 minutes.

For each Earth departure day the transfer orbit is different, with a transfer duration of between 3 and 5 months. The launch energy needed at Earth departure is near parabolic The inclination of the departure orbit can be as high as 63°. Typically, for a launcher equipped with a modern liquid upper stage, correction of the launcher dispersion is less than 25 m s^{-1}, to be performed not later than 2 days after launch. Apart from this, a trimming maneuver of less than 2 m s^{-1} is to be performed about 8 days later, and finally a mid-course maneuver of less than 1 m s^{-1} is required about 50 days after launch. From that time on no more major maneuvers need to be scheduled and scientific operations can commence. The coasting period is also used to allow the MSC and DSC to outgas before the deployment and associated exposure of optics and detector systems, minimizing contamination. During the transfer phase the stack is slowly spinning (~1RPM, ‘BBQ-mode’).

The operational orbit of XEUS is planned to be a halo orbit around L2, with amplitude of 670 000 km and a period of 6 months. Such an orbit around L2 is shown in synodic space (a rotating coordinate system centered on the Earth) in Fig. 7 (*x*-*y* ecliptic projection), with the insert showing the projection on the *x*-*z* plane.

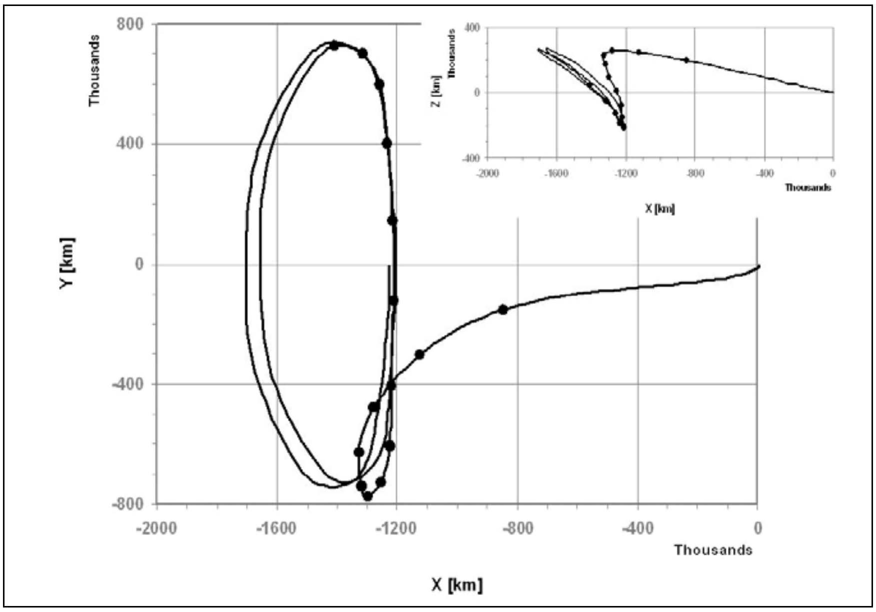


Figure 7: Halo orbit around L_2 in synodic space: ecliptic projection, The Earth is at coordinate (0, 0) and the Sun along the positive *x*-axis. Insert to right: x-z projection with the Earth again at coordinate (0, 0) and Sun along positive *x*-axis. The period of the orbit is 6 months, and the amplitude is 670 000 km.

After the cruise phase, the stack stops spinning and the DSC and MSC separate. It is the task of the DSC to cancel the relative translational rates with respect to the MSC before it reaches the 10 km range of the RF navigation subsystem. If the DSC moves beyond the operational radius of the RF navigation subsystem, it can be brought back within range with intervention from the ground system. In the following, the FF is acquired, with the DSC approaching the MSC in a sequence of stages, as indicated in Fig. 8.

The first two maneuvers of the formation initialization and acquisition (FIA) phase are grouped under the formation initialization sub-phase and utilize the radio navigation subsystem. The third part of the FIA phase is called the formation acquisition phase, where both the radio and the laser rangefinder are used to determine the relative position and velocity.

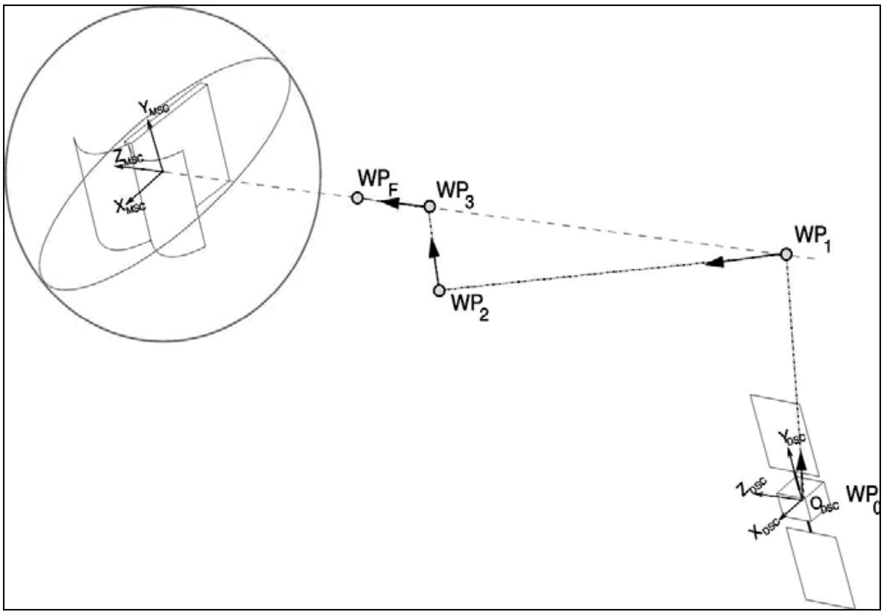


Figure 8: Maneuvers leading to the formation acquisition. A conservative approach is shown, with the first two maneuvers (WP0 to WP1, and WP1 to WP2) pointing outside the MSC safety sphere. The DSC stops the relative movement to the MSC, once the desired instrument is positioned at the focus of the telescope.

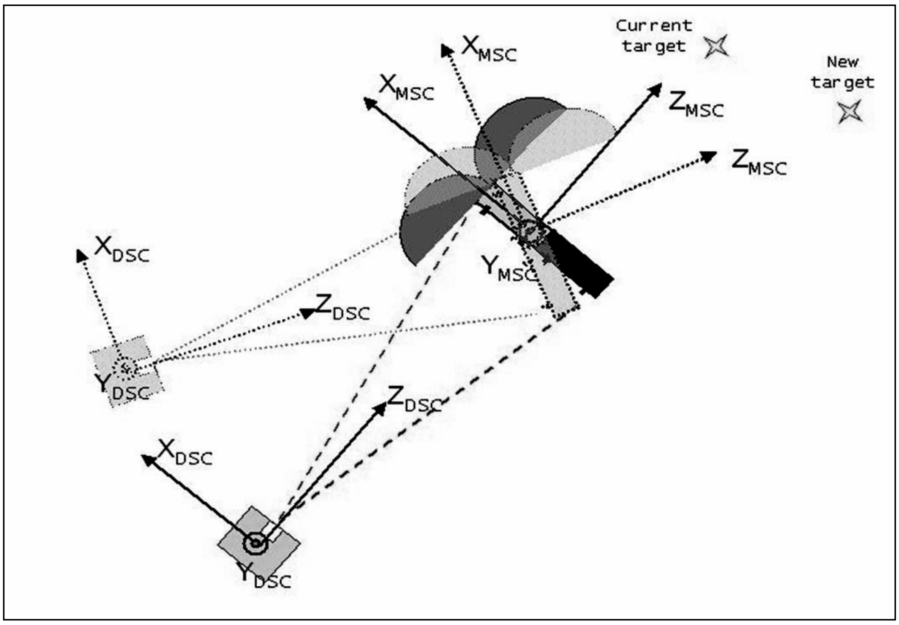


Figure 9: Re-pointing XEUS. With respect to operations, the observatory is operated like a single spacecraft. The MSC performs a standard slew, with the DSC following the focal position of the optics and simultaneously performing a synchronous slew around its CoM.

During the Target Acquisition Mode (TAM) the telescope is re-pointed at a new target. The MSC moves about its center of mass (CoM) only, i.e., it performs a “classical” slew maneuver. At the beginning of this mode the MSC receives an attitude profile from the ground segment. The MSC follows the attitude profile using the star trackers as sensors and the reaction wheels as actuators.

As the MSC slews, the DSC CoM translates on a circular arc (with a radius equal to the focal length) and it also rotates about its CoM so that the telescope made of the two spacecraft performs a rigid body-like rotation. The DSC control during slew is performed by its FF control loop. Note that from the point of view of ground operations XEUS appears like a single spacecraft. A telescope slew maneuver is shown in Fig. 9.

4. SCIENCE PAYLOAD AND LAUNCHER SELECTION

In the CDF studies a core payload was assumed, consisting of two cryogenic spectrometers and a wide field imager based on silicon detectors. The mass allocation for the Ariane 5 ECA accommodation was 1753 kg for the DSC, and 4882 kg for the MSC. The MSC mass breakdown results in an available mirror petal mass of 1435 kg, without system margin (assumed 20%). With an assumed average petal mass mirror area density of 61 kg m^{-2}, with petals of 0.7 m x 0.7 m, only the 48 petal positions (of the 8 x 8 petal positions available on the optical bench) could be populated, as shown in Fig. 10.

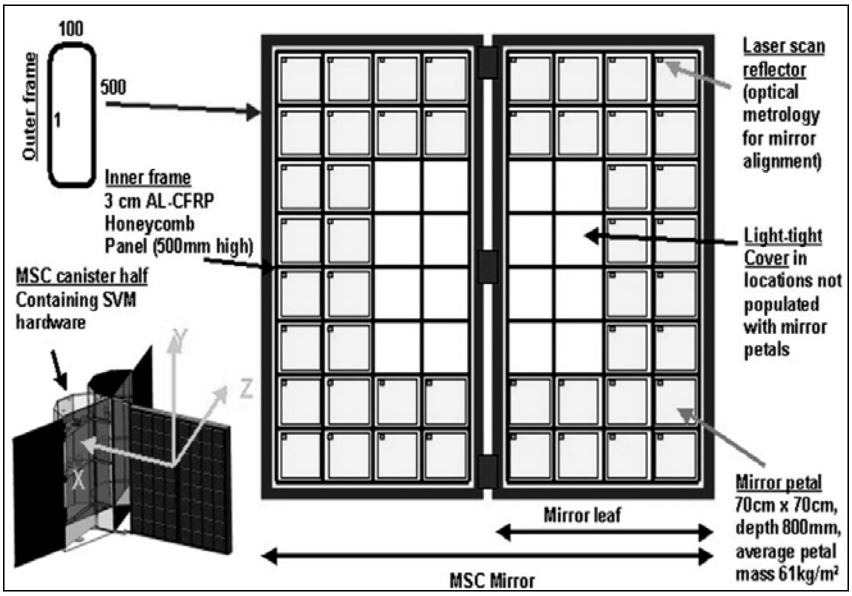


Figure 10: The population of the optical bench for an Ariane 5 ECA launch. Due to mass limitations the central 4 x 4 petal positions are not occupied and replaced by covers. In the case of a launch on the Delta IV Heavy, with its increased launch performance, all 8 x 8 positions can be populated with petals.

If all available 64 petal positions are to be populated, a more powerful launcher is required. Changing to the best performing launcher of the Boeing Delta IV family, the Delta IV Heavy, the mass delivered L2 increases to 9300 kg. The mass of the Payload Attach Fitting (PAF) is assumed to be 520 kg. Slightly larger mirror petals (0.75 m x 0.75 m), with a density of 72.5 kg m^{-2} and a dry mass of 2610 kg (again, without system margin) can be accommodated. The larger petal mass density is due to the heavier petals required closer to the optical axis.

With a DSC mass of 1753 kg, a mass margin of 550 kg is still available on the Delta IV Heavy, permitting the consideration of additional payload instruments.

5. CONCLUSION

Considering the recent developments of High-performance Pore Optics (HPO), and the associated reduction of the mass, very large effective areas can be achieved for the next generation high energy astrophysics missions.

The preliminary studies performed in the ESA CDF and other activities have produced a mission scenario, which fulfils the complete science requirements for XEUS, if accommodated on the Delta IV Heavy launcher. In the case of the Ariane 5 ECA accommodation, the main science objectives are met, but in particular the high X-ray energy response is limited due to the required omission of the central petals.

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