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WFXT Technology Overview

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Abstract. The Wide Field X-ray Telescope (WFXT) is a medium class mission for X–ray surveys of the sky with an unprecedented area and sensitivity. In order to meet the effective area requirement, the design of the optical system is based on very thin mirror shells, with thicknesses in the 1–2 mm range. In order to get the desired angular resolution (10 arcsec requirement, 5 arcsec goal) across the entire 1×1 degree FOV (Field Of View), the design of the optical system is based on nested modified grazing incidence Wolter-I mirrors realized with polynomial profiles, focal plane curvature and plate scale corrections. This design guarantees an increased angular resolution at large off-axis angle with respect to the normally used Wolter I configuration, making WFXT ideal for survey purposes. The WFXT X-ray Telescope Assembly is composed by three identical mirror modules of 78 nested shells each, with diameter up to 1.1 m. The epoxy replication process with SiC shells has already been proved to be a valuable technology to meet the angular resolution requirement of 10 arcsec. To further mature the telescope manufacturing technology and to achieve the goal of 5 arcsec, we are considering different materials for the mirror shells with particular care to quartz glass (fused silica), a well-known material with good thermo-mechanical and polishability characteristics that could meet our goal in terms of mass and stiffness, with significant cost and time saving with respect to SiC. To bring the mirror shells to the needed accuracy a deterministic direct polishing method for the mirror shells is under investigation. A direct polishing method has already been used for past missions (as Einstein, Rosat, Chandra): the technological challenge now is to apply it for almost ten times thinner shells. Our approach is based on two main steps: first quartz glass tubes available on the market are grinded to conical profiles, and second the obtained shells are polished to the required polynomial profiles by Computer Numerical Control (CNC) polishing machine.

Key words. Telescopes — X–rays: general — instrumentation: high angular resolution

1. Introduction

The Wide Field X-ray Telescope (WFXT) is a proposed medium-class mission dedicated to survey the sky in the soft X–ray band (0.2–7 keV) [Murray et al. (2008); Rosati et al. this volume]. In five years of operations, WFXT will carry out three extragalactic surveys, allowing direct physical characterization of a very large amount of sources (in particular AGN and clusters of galaxies) via X–ray spectroscopy with no need of follow-up observations. All the acquired data will constitute a scientific legacy to address key questions about cosmic origins and physics of the cosmos. To those ends, WFXT foresees an X–ray Telescope Assembly whose main requirement

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Table 1. WFXT Mission Performance Requirements and Goals.

Parameter	WAXS/WFXT* (ASI call, 1998)	Panoram-X+ (ESA call, 2000)	Requirement (Current design)	Goal
Effective Area at 1 keV (cm^2)	310	600	6,000	10,000
Effective Area at 4 keV (cm^2)	80	250	2,000	3,000
Field of View 50% vignetting (deg)	1	1	1	1.25
$< \mathrm{HEW} >_{\mathrm{FOV}}$ at 1 keV (arcsec)	< 15	< 15	< 10	< 5
Energy Band (keV)	0.2–7	0.2–7	0.2–7	0.1–7
Energy Res. ($\Delta E/E$)	> 10	> 10	> 10	> 20
Time Resolution (s)	< 4	< 3	< 3	< 1

* WAXS/WFXT was a mission concept developed in reply to an ASI call for small missions in 1998. It is described in Chincarini et al. (1998).
* Panoram-X was a mission concept developed in reply to an ESA call for Flexi-missions in 2000.

is to be orders of magnitude more effective than previous and planned X–ray missions in carrying out surveys. This is obtained through a telescope design that makes use of polynomial profiles for the mirror shells together with focal plane curvature and plate scale corrections [Burrows et al. (1992); Conconi & Campana (2001); Conconi et al. (2010)]. This design guarantees an increased angular resolution at large off-axis angles with respect to the usually adopted Wolter I configuration; in this way, it is possible to get the desired almost-constant angular resolution on the entire Field of View (FOV). WFXT main scientific requirements and goals are reported in Table 1. In the following we will describe the design of the mirror module for the WFXT and the first tests carried out to reach the mission goals.

2. Mirror design

Focusing telescopes for X–ray astronomy are usually built in the Wolter I configuration, constituted by two mirror segments (the first parabolic and the second hyperbolic) joining at the intersection plane. This design guarantees a perfect image along the telescope optical axis but the image quality rapidly degrades for large off-axis angles. Being WFXT a mission for survey purposes, it is necessary to act on the mirror design in order to increase the off-axis response and optimize the performances over the entire field of view. The present design is based on shells with polynomial profiles [Burrows et al. (1992)]. Polynomial mirror profiles are described usually by forth or third order polynomial and optimization techniques can be implemented to optimize the angular response over a desired field of view [Conconi et al. (2010); Conconi & Campana (2001)]. The first step is to optimize a single mirror shell over a 30 arcmin field of view. This can be done by optimizing a merit function based on the linear combination of HEW and 80% energy encircled fraction in order to have a small spot and not too extended wings in the source Point Spread Function (PSF). This has been done parametrizing the mirror shells (diameter, focal length, etc.) and reducing the optimization to a single parameter. The following step is to optimize a mirror assembly. In this case we have to modify the merit function in order to include also as a weighting factor the effective area (at 1 and 4 keV) and we have to provide a scaling law for the mirror thicknesses and mirror shell lengths. In the best design each nested mirror shell presents a different length dependent on the radius, decreasing from the outermost to the innermost shell in such a way to keep the same curvature of the focal plane. A displacement of few mm between the intersection planes of the mirror shells is introduced to compensate for the different focal plate scale of the shells that causes focusing of X–ray in slightly different positions at any off-axis angle. The proposed design consists of three telescopes with focal length of 5500 mm and diameter ranging from 330 mm for the innermost to 1100 mm for the outermost mirror shell. Shells thickness ranges from 1.2 to 2.2 mm. The total

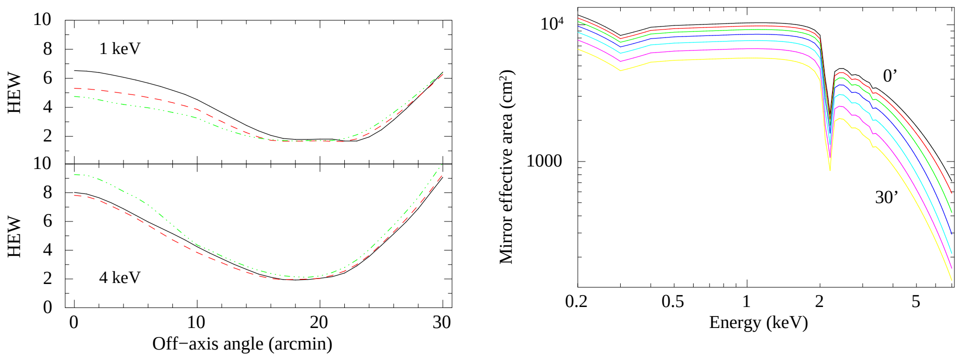

Fig. 1. Left: angular resolution for the WFXT telescope for three slightly different mirror design at 1 keV and 4 keV (the adopted one is marked with a dashed line). Right: Effective area of the three mirror modules (without the inclusion of the detector quantum efficiency and filter transmission).

length of each shell is different because of the butterfly-like adopted design. The main characteristics of the optical module are summarized in Table 2.

Table 2. Characteristics of the proposed WFXT surveying telescope.

Focal Length	5500 mm
Number of Optics Modules	3
Material	Quartz
Numbers of Shells	78
Radius [min max]	165 – 550 mm
Total length [min max]	200 – 440 mm
Thickness [min max]	1.2 – 2.2 mm
On-axis Effective Area* (1 keV)	9,236 cm^2
On-axis Effective Area* (4 keV)	2,565 cm^2
Total Weight (incl. mech. struct.)	930 kg

* this area refers to the total mirror area for the three modules and accounts for a 10% obstruction from the support structure.

3. Manufacturing the mirror shells

3.1. The SiC way

Starting from the late ’90 we worked on the building of WFXT mirrors [Citterio et al. (1999); Ghigo et al. (1999)] (see Table 1). We explored different materials with respect to Nickel that were used to build the mirrors for missions such as BeppoSAX or XMM-Newton with the characteristic of being lighter but stiffer. These first attempts concentrated on SiC. The technique used to make a replica with SiC requires first to produce a SiC carrier which is the element that gives the mechanical structure to the mirror shell. The scheme for the manufacture of the SiC carrier is based on the Chemical Vapor Deposition (CVD) process. The SiC carrier is deposited on a mandrel manufactured with a material (for example graphite) capable to survive the high temperature of the process (1300 degrees). After removing the mandrel by burning it in the case of graphite, the carrier is grinded to achieve the precise shape required for the replication process. The carrier is then positioned on the gold coated superpolished mandrel leaving a gap of about 150 micron. The gap is filled with epoxy resin; after the curing of the resin, the mandrel is removed by cooling it. With this technique we were able to obtain a large single mirror shell (60 cm diameter) satisfying the mission requirement, i.e. with an HEW $<$ 10 arcsec over a 60 arcmin diameter FOV (see Fig. 2).

3.2. The glass way

The WFXT design as described above has been further refined. In order to reach the the stringent angular resolution requirement (5 arcsec

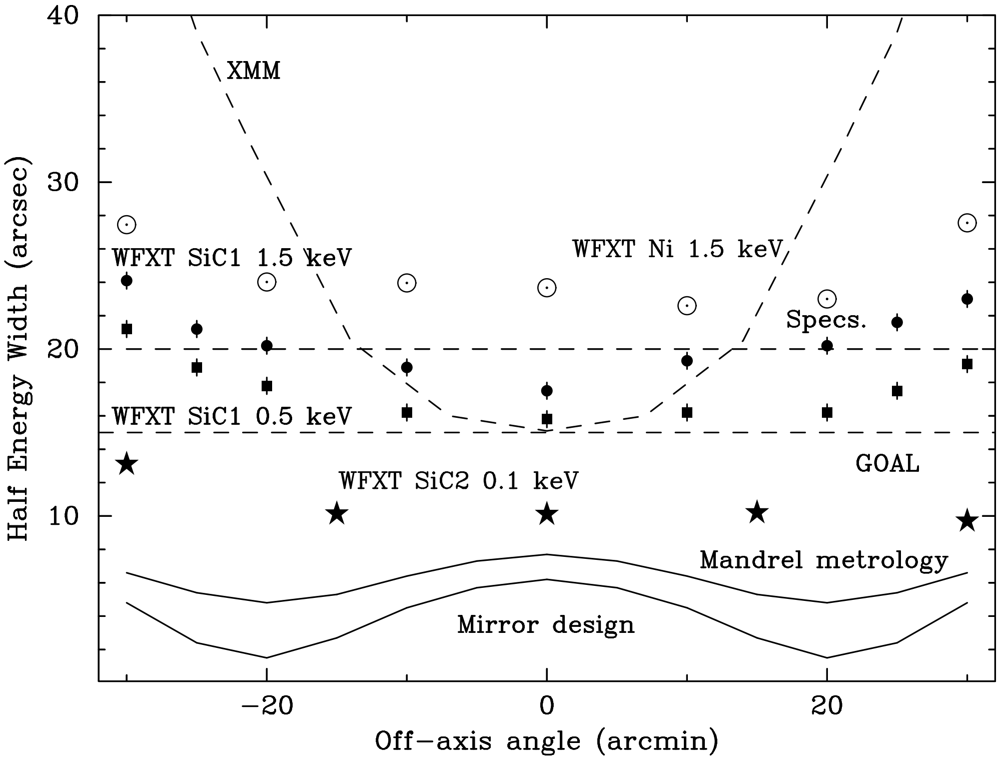

Fig. 2. Off-axis response of a WFXT mirror. Continuous lines indicate an early mirror design and mandrel metrology. Different mirror realizations were obtained with this mandrel either in Nickel (large dots) or in SiC: SiC1 (measured at 0.5 keV, filled squares, and at 1.5 keV, filled circles) and SiC2 (measured at 0.1 keV, filled stars). The SiC2 mirror shells satisfy the mission requirement of an HEW over a 60 arcmin diameter FOV.

HEW over a 60 arcmin diameter FOV) a different technology has to be explored. To meet the effective area and mass requirements, the shells need to be very thin, with wall thickness of few mm or less. SiC and quartz glass are two materials whose thermo-mechanical (T/M) properties (in particular low density and high rigidity) are very attractive and suitable to reach the necessary stiffness of the peculiar WFXT mirror shell configuration. The WFXT mirror shells are not only thin, but characterized by a very small Length-to-Diameter ratio (L/D 3 times smaller than for XMM-Newton mirrors) making more difficult their building. SiC and quartz can be adopted for the production of thin shells both by epoxy replication approach and by direct polishing approach. Quartz is adopted because of costs and production time reasons. Tubes of quartz glass to be used as raw material for shells production are available on the market. Learning from past experiences such as Chandra, and ROSAT, our approach is to follow a deterministic direct polishing method. In the last few years, new machines and polishing techniques have been developed with performances very promising in the perspective of directly optical machining thin mirror shells.

3.3. Thermo-mechanical aspects

The technological challenge is therefore to produce thin and short mirror shells. Several aspects have to be considered, in particular:

- Deformation during the machining and the metrology phase
- Propagation of deformations in thin and short shells
- Resistance to launch conditions

More details can be found in Proserpio et al. (2010).

The WFXT mirror shells are not only thin, but also characterized by a very small Length-to-Diameter ratio making their building more difficult because short mirror shells are more sensitive to perturbing effects related to edge loads since the they have a belt like rather than a tube like behavior. Under the same perturbing edge loads, short mirror shells show degradation 6–16 times larger with respect to long mirror shells and this ratio becomes even bigger in case of perturbing loads producing local deformed shapes. That happens because the angular resolution is strongly affected by the slope errors caused by azimuthal errors, which for a determined Out-Of-Roundness (OOR) error is inversely proportional to the mirror shell length. It is worth noting that the consideration of concentrated loads at the free edges of the shells is representative of the real conditions since normally the mirror shells are fixed to the mirror module structure by spot connections at the one or both end sections and, during metrology and integration, they rest on concentrated astatic supports at one-end section. Two astatic supports are available at INAF-OAB, one with 12 and the other with 16 sustaining points. It was verified by Finite Element Method (FEM) and ray-tracing analyses that with the available astatic supports, the deformations introduced on the shells are negligible, in the order of 0.5 arcsec HEW.

Preliminary FEM analyses have also been carried out in order to estimate a value for stress peaks in the quartz glass mirrors during launch, even if at this stage of the project, exact load levels, and operative and survival temperatures are not yet available and need to be evaluated in near future. A complete check of quartz components will require some more information, relevant to the characterization of the specific material, which are not known at the moment. Nevertheless, simple preliminary consideration can be performed based on engineering evaluations and past experiences. Considering a traditional X–ray telescope, the single mirror shells are connected to the telescope structure just at the end sections (one or both) through spokes wheel elements. Point connections between each mirror shell and the spokes wheel are realized by adhesive contacts. If such a configuration is adopted during FEM analyses, the maximum stresses in the glass might exceed the tensile stress limit in points of stress concentration. Local refinement of the analyses and the design are needed considering the use of a brittle material like quartz. Revised design criteria with respect to the traditional approach will allow obtaining surviving loads conditions. In addition to that, the use of chemical etching treatment of the shell surfaces in order to reduce the micro-cracks cause by the grinding is under investigation to improve the intrinsic stiffness of the quartz.

4. Building the first mirror shells

To fulfill the WFXT requirements a direct polishing approach on the thin mirror shells is under study. The proposed method foresees the direct figuring and polishing of mirror shells after grinding. The monolithic mirrors are made of materials with good mechanical properties (but easy to polish) like quartz. Quartz is indeed a well known material and its thermo-mechanical and polishability properties make it ideal for the realization of high precision optics, also for space application. It offers a number of advantages such as low density (2.203 g/cm^3), low thermal expansion coefficient (0.5×10^{-6} /K), high modulus of elasticity (70 GPa). The main drawback related to quartz is that the material is quite brittle. However, this does not represent an unsolvable problem since it can be overcome with suitable surface treatments (as chemical etching) in order to eliminate, or at least reduce, the surface damages coming from the machining

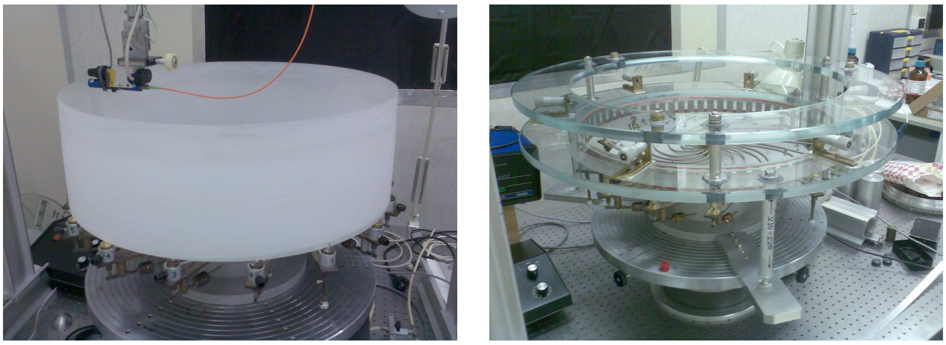

Fig. 3. Left: Raw quartz glass tube. Right: First shell integrated in its support structure.

steps, that tend to originate the cracks. On the other hand the direct polishing of X–ray telescope mirror shells made by quartz or glass material is a technology that has been proved since many years for the manufacturing of very high angular resolution X–ray telescopes (like Einstein, with 4 arcsec HEW, ROSAT, with 3 arcsec HEW, or Chandra with 0.5 arcsec HEW). The challenge now is to obtain a good angular resolution on the entire FOV but for considerably thinner (a factor 5–10 less) mirror shells.

In the last years, computer numerical control (CNC) polishing machines, able to perform a precise figuring also on thin substrates have been developed. The production flow here envisaged foresees to start from a quartz glass tube already available on the market. The tube is firstly ground with a double cone profile at the required thickness of a few millimeters. Then, it is figured and polished to the final polynomial profile making use of a "deterministic" figuring method and then superpolished. This implies that after the measurements of the actual profile of the mirror shell to be polished, a corrective matrix is determined and supplied to a CNC polishing machine which provides the corrective action according to the given error matrix. In a few iterations it is possible to reach the required specifications once we start from an acceptable profile after grinding with P-V roundness errors of a few tens of microns. Between the grinding and the polishing step it is necessary to integrate the shell in a suitable jig structure able to allow the metrology, machining and all the necessary steps before the assembling of the shell into the final structure (i.e. reflective coating deposition and X–ray characterization at an X–ray facility, at least until the telescope structure with spiders is not developed). This jig structure is also necessary for handling and will be used for the shell integration into the final mirror module structure. After that, it can be removed and used for another shell.

For the purpose of this study, 8 quartz glass shells have been realized to set the best parameters of the grinding phase and get useful hint on surface treatment to reduce surface imperfections that degrade the mechanical characteristics of the material. Two of these shells have been integrated in the suitable structure appositely designed to allow polishing, metrology, and all the necessary steps before the integration in the final structure. One of the integrated shells has been used for polishing tests. More details on the production of these demonstrative parts are presented in the following paragraphs, together with the present obtained results.

The polishing process is performed by the Zeeko firm by means of a IRP600 machine. The Zeeko Company not only makes use of an innovative figuring and polishing approach, but also it developed the capability of machining shells with diameter up to 1100 m and height up to 440 mm. The equipments of the Zeeko IRP-Series are CNC polishing systems, controlled on 7-axis, that use a patented tool to provide a distributed pressure and variable area head for the polishing of aspheric and complex forms. By acting on the process parameters, such as tool pressure, precession angle, compression offset and head speed, it is possible to select the desired influence function, i.e. the 3D depression left by the spinning precessing tool as it is pressed onto a piece of the material to be polished. The influence function is generated to determine the best volumetric removal rate in dependence of the specific materials and requirements.

A number of tests have been performed during the study, in order to evaluate the applicability of this process for the manufacturing of the WFXT quartz glass shell. The effort was in particular focused on the problems caused by the deformations of the thin walls by effect of the tool pressure. The shell used for these preliminary tests was the first ground dummy shell used to test integration into Shell Supporting Structure that presents high out of roundness values (800 micron). The possibility of performing an intermediate coarser step “grolishing”) before the polishing was investigated. Grolishing is needed to correct possible residual errors coming from the grinding step and to remove the external layer of surface damaged at a microscopic level. Different process parameters were investigated in order to define the best influence (or removal) function. Faster influence functions are used for bulk material removal. While slow removal functions provide better results in manipulating smaller scale errors. Those tests will be important to evaluate the possibility of obtain a proper polynomial profiles starting from the double-cone shape. More details can be found in Proserpio et al. (2010).

5. Conclusions

The ability of X–ray images to peer deep into the early Universe is a key in providing a way to study the evolution o f classes of objects over cosmological time-scales. For a broad perspective see the WFXT white papers submitted to the 2010 Decadal Survey [Murray et al. (2009); Giacconi et al. (2009); Vikhlinin et al. (2009); Ptak et al. (2009)]. In a large survey, these issues can all be addressed in a statistically significant way, in order to precisely constrain theories. At the same time, extremely powerful and rare phenomena within our own Galaxy, become evident only when large volumes are explored in the high-energy domain of X–rays. A deep (nearly) all-sky X–ray survey with high spatial resolution is therefore a natural, necessary step to complement and significantly extend the optical sky surveys as the classic Palomar or SDSS sky atlas as well as radio and near-infrared already available or available in the next decade.

Here we described the optimization of the optical design in relation to the scientific drivers of the WFXT mission. In particular, we describe step by step the design of a wide field X–ray telescope tailored for surveying the X–ray sky. A general indication of the manufacturing process of the mirrors have been presented. We presented the first results of the tests performed to evaluate the deterministic direct polishing technique for the realization of thin quartz glass mirror shells, to be implemented aboard the WFXT mission. The development aims at achieving the angular resolution goal level of the mission of 5 arcsec HEW across the FOV of 1 deg in diameter. Several quartz glass shells with double cone shape and diameters of 490 and 620 mm, lengths of 200 mm and thicknesses of 1.5–2 mm have been produced for the scope. Three grinding runs have been performed to improve the process and, at the end, the tolerances expected after grinding (OOR error $<$ 10 micron Peak-Valley) have been achieved. Two of the produced carriers have been integrated in a suitable jig, specifically designed for all the steps in the shell manufacturing up to the integration in the final telescope structure. It has been verified that the integration process in the jig is able to maintain or improve the original shape. One of the integrated shells has been used for the preliminary polishing tests performed by Zeeko using an innovative optical machining based on the Bonnet tool. Preliminary “grolishing” results suggest that the process can meet the angular resolution requirements if the mirror shells after grinding is characterized by an OOR error $<$ 60 micron. The evaluation of chemical etching to remove the sub-surface damages on the surface of ground shells has started and analyses are in progress. Upcoming activities include polishing tests to evaluate the feasibility of obtaining mirror shells with a correct polynomial profiles. The mirror prototypes realized in this way will be X–ray tested in full illumination mode.

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