Invited Paper

Status of the qualification model of the X-ray optics for the Jet-X Telescope aboard the Spectrum X-Gamma satellite

O. Citterio, P. Conconi, M. Ghigo, F. Mazzoleni, E.Poretti

Osservatorio Astronomico di Brera-Milano
Via E. Bianchi, 46 - 22055 Merate, Italy

G. Conti

CNR, Istituto di Fisica Cosmica
Via E. Bassini, 15 - 20133 Milano, Italy

G. Cusumano, B. Sacco

CNR, Istituto di Fisica Cosmica
Via M. Stabile, 172 - 90139 Palermo, Italy

H. Brauninger, W. Burkert

Max Planck Institut fur Extraterrestrische Physik
Giessenbachstrasse, 85748 Garching - Germany

ABSTRACT

The Joint European X-ray Telescope, JET-X, is one of the core instruments of the scientific payload of the Russian SPECTRUM-X astrophysics mission.
JET-X is designed to study the emission from X-ray sources in the band of 0.3-10 KeV; particularly to meet primary scientific goals in cosmology and extragalactic astronomy.
JET-X consists of two identical, coaligned X-ray telescopes, each with a spatial resolution of 30 arcsecond Half Energy Width (HEW) or better. Focal plane imaging is provided by cooled X-ray sensitive CCD detectors which will combine high spatial resolution with good spectral resolution, with particular emphasis on high sensitivity and spectral resolution around the 7 KeV Fe-line complex.
Each telescope is composed of a nested array of 12 mirrors with an aperture of 0.3 m and focal length of 3.5 m; the total effective area is 360 cm^2 at 1.5 KeV and 140 cm^2 at 8 KeV.
The mirror shells have a Wolter I geometry and are manufactured by a nickel electroforming replica process. The paper presents a status report of the qualification Model of the X-ray optics.
Keywords: X-ray optics, grazing incidence optics, X-ray telescope, JET-X.

1. INTRODUCTION

JET-X [1] is a joint European X-ray telescope developed by a consortium of scientific institutes in UK (University of Leicester and Birmingham, the Rutherford Appleton Laboratory and the Mullard Space Science Laboratory), in Italy (Brera Astronomical Observatory, CNR Institutes in Milano and Palermo,

0-8194-1874-9/95/$6.00

University groups in Milano and Rome), in Germany (Max Planck Institute in Garching) and ESA-ESTEC. The JET-X telescope is one of the key instruments aboard the SPECTRUM-X satellite, a scientific mission aimed to the study of astrophysical sources in the X and gamma spectrum range.

The primary objectives of JET-X are the study of X-ray sources in the energy range 0.3 - 10 KeV with a spatial resolution of ≤ 30 arcsec HEW and a spectral resolution $E/\Delta E > 10$ over the whole energy range and with a better spectral resolution ($E/\Delta E > 50$) around the 7 KeV Fe-line complex. The requested limiting sensitivity at 1 KeV is of 0.5 nJy. To obtain these goals two identical and coaligned X-ray telescopes each made of 12 nested confocal and coaxial mirrors will be build with a total effective area of 360 cm^2 at 1.5 KeV and 140 cm^2 at 8 KeV. The 12 mirrors are 600 mm long and have diameters that range from 300 mm to 191 mm with a focal length of 3500 mm. Due to the requested resolution, the Wolter I optical configuration has been choosed. The image in the focal plane is acquired with cooled X-ray sensitive CCD able to match the spatial and spectral resolutions requested.

The mirrors are produced by the electroforming process which has been also successfully used for the manufacture of the X-ray telescopes of SAX [2]. In this technique, an aluminium mandrel is coated with a thin layer of electroless nickel and then superpolished to a surface finish of ≤ 0.5 nm RMS. A layer of gold, about 1000 Å thick, is then evaporated on the mandrel. Subsequently the mandrel is transferred in an electrolytic bath where a layer of nickel is deposited with a thickness dependent on the mirror diameter. The separation between the mirror and the mandrel is obtained by cooling the latter because the thermal coefficient of the aluminium is about twice that of the nickel. Since the adhesion of the evaporated gold onto the mandrel is poor and instead is strong on the electroformed nickel, the gold itself separate with the shell. Gold has been choosed because of its good X-ray reflectivity in the range 0.3-10 KeV .

In the present paper we describe the status of the Engineering Qualification Model (EQM) of the JET-X optics.

2. X-RAY OPTICS OF JET-X

The design of the X-ray optics of JET-X was published in a previous paper [3]. Briefly each X-ray optics of the two JET-X telescopes is constituted of 12 nested, confocal and coaxial mirror shells (MS). The characteristics of the optics are summarized in table 1.

Outer mirror shell	300 mm
Inner mirror shell	191 mm
Mirror length	2 x 300 mm
Focal length (parabola + hyperbola)	3500 mm
Shells thickness	0.65 - 1.1 mm
Number of shells	12
Reflecting surface	Gold
Surface finish (microroughness)	≤ 0.5 nm
Configuration	Wolter I
Angular resolution	≤ 30 arcsec HEW
Field of view	20 arcmin (50% vignetting)
Weight of one mirror module (M.S.'s + structure)	67 kg

Table 1 - Characteristics of the optics

Dimensions, thickness, geometric collecting area and weight of each mirror shell are reported in table 2.

Mirror number	Maximum ∅ mm	Medium ∅ mm	Minimum ∅ mm	Thickness mm	Collec. area cm^2	Weight kg
1	299.985	293.760	274.808	1.10	29.0	5.3
2	287.935	281.960	263.769	1.05	26.7	4.9
3	276.375	270.640	253.179	1.00	24.6	4.5
4	265.285	259.780	243.019	0.95	22.7	4.1
5	254.624	249.340	233.252	0.90	20.9	3.7
6	244.392	239.320	223.879	0.85	19.3	3.4
7	234.568	229.700	214.879	0.80	17.8	3.0
8	225.153	220.480	206.254	0.75	16.4	2.7
9	216.105	211.620	197.965	0.70	15.1	2.4
10	207.425	203.120	190.014	0.65	13.9	2.2
11	199.092	194.960	182.380	0.65	12.8	2.1
12	191.086	187.120	175.046	0.65	11.8	2.0

Table 2 - Characteristics of JET-X mirror shells. The values of the diameters are the nominal ones derived from the optical design

The MS's are integrated into a mechanical supporting structure which is composed of two spiders with 12 spokes each, that are supported by a tube on which the spacer for the interface to the JET-X bulkhead is fixed. The support and the alignment of the nested mirrors are provided by precise grooves machined on the spider's spokes. The MS's are glued to the spiders's spokes on both sides. Fig. 1 shows the assembly drawing of the JET-X optics.

3. EQM MIRROR UNIT

The JET-X EQM is the first complete Mirror Unit (MU) produced by MEDIALARIO of Bosisio Parini under a contract from ASI (Agenzia Spaziale Italiana) for the manufacture of the X-ray optics for the JET-X project. It will be followed by two flight units and one flight spare model. The EQM is a fully representative model of the JET-X optics that will undergo vibration and termovacuum test and an integrated X-ray test with the JET-X CCD detectors at the PANTER X-ray facility of the Max Planck Institute in Munich. The MS for the EQM unit were replicated from the set of 12 mandrels manufactured by the Company C. Zeiss of Oberkochen - Germany.
The characteristics of the mandrels are given in table 3. The replicated set of MS were tested in quasi free standing condition on the UV optical bench [4] at the Brera Observatory.
This facility consists of an UV source generating a collimated beam at 372.5 nm and can test mirrors up to a diameter of 0.5 m by fully illuminating the entrance aperture of the MS. In the focal plane of the MS is located a CCD sensor producing images analyzed by a suitable software. The use of UV light allow to reduce the contribution of the diffraction effect to the blurring of the image. It must be pointed out that from the measurements on the UV optical bench, after removing the contribution of the diffraction effect, we obtain a prediction of the HEW expected at X-ray wavelength due only to the geometry of the MS's. No information are derived concerning the microroughness effect.
Table 4 gives the results of the UV measurements.

No.	HEW final (arcsec)	HEW axial slopes (arcsec)	HEW roundness (arcsec)	$F_{mandrel}$ (mm)	Microroughness (WYCO 20x) (nm RMS)
1	4.9	4.9	0.47	-0.3	0.38
2	5.4	5.3	0.90	1.1	0.63
3	4.4	4.4	0.55	12.9 (°)	0.33
4	5.0	5.0	0.51	-1.2	0.44
5	4.7	4.7	0.18	-3.4	0.46
6	5.0	4.8	1.50	-0.6	0.47
7	5.0	4.9	1.19	-0.5	0.43
8	4.3	4.1	1.45	1.3	0.48
9	3.3	3.2	0.57	-0.1	0.38
10	5.2	5.2	0.52	-1.0	0.44
11	4.5	4.5	0.29	2.4	0.42
12	3.8	3.6	1.27	2.2	0.42
average	4.62	4.55	0.78	0.0±1.7(1s)	0.44

Table 3 - HEW, focus position and microroughness for the full set of Jet-X mandrels. The $HEW_{axial\ slope}$ and the $HEW_{roundness}$ are root squared summed to get the final HEW. The focus position is measured with respect to the nominal value. (°)The focal length of the mandrel No. 3 is not considered for the average because it was the first mandrel built and has a length of 640 mm instead of 600 mm. The replicated MS will be cut to 600 mm adjusting the cutting length of the front and rear end in such a way that the focus of the MS will coincide with the best focus of the system of MS's.

During the initial tuning phase of the replication process for the manufacture of the set of MS for the EQM unit, slight damages were produced to the surface of few mandrels. After the correct definition of the various parameters of the process, the replication of the remaining MS went wery smootly. Of the damaged mandrels, the N.2 and 6 are still to be repolished by MEDIALARIO. For this reason table 4 does not include the MS N.2 and 6.

Mirror No.	HEW (UV Test) arcsec
1	11.0
3	10.4
4	11.5
5	10.7
7	12.2
8	12.8
9	11.8
10	9.9
11	12.2
12	11.2

Table 4 - HEW of MS to be integrated into JET-X EQM model. Measurements made with Vertical Bench at 372.5 nm.

Nevertheless, due to the stringent requirement of the JET-X time schedule, the originally produced MS N. 2 and 6, also if they present a non acceptable quality for the reflecting surface, will be integrated into the EQM in order to proceed with the scheduled qualification tests. This two MS will be shielded off during X-ray test. The EQM unit is now (March 95) in the integration phase.

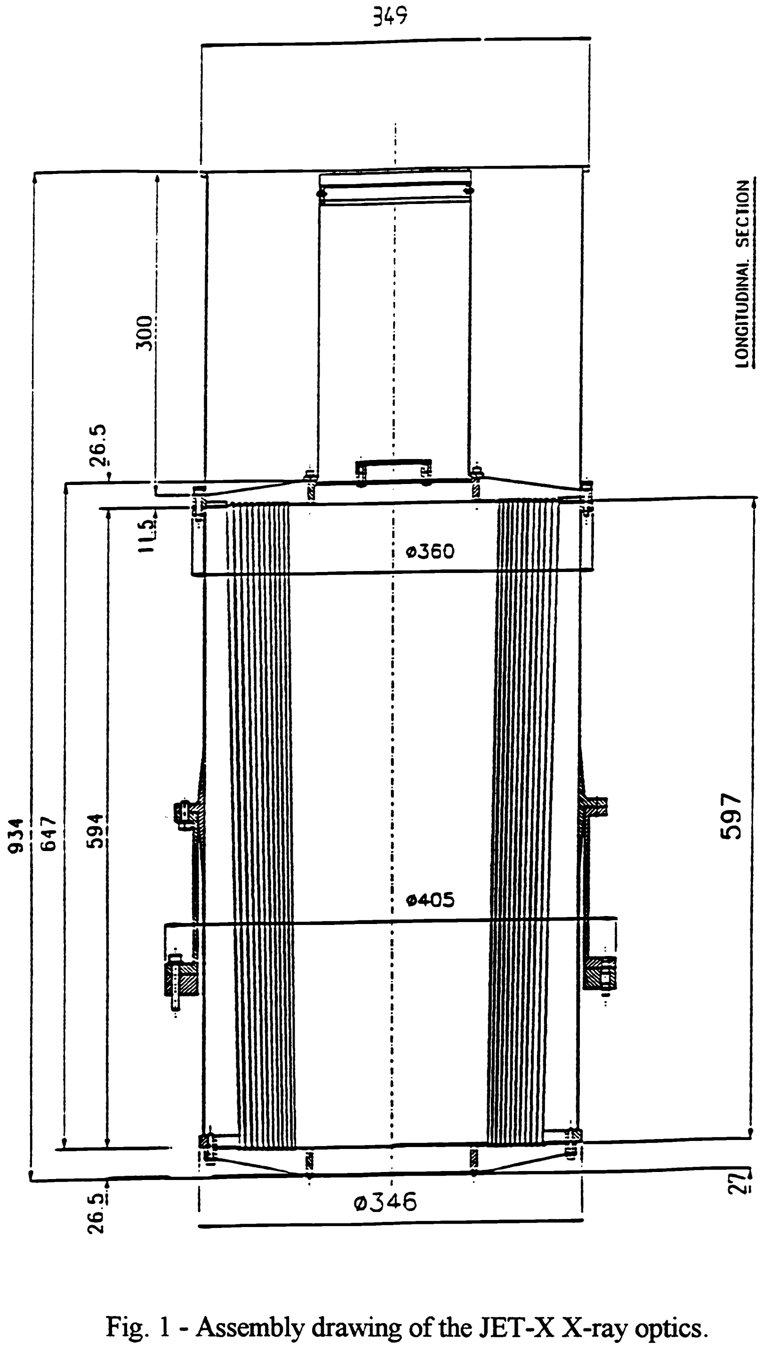

Fig. 1 - Assembly drawing of the JET-X X-ray optics.

Fig. 2 shows the 12 MS and the mechanical structure. The first X-ray test of the complete unit at the PANTER[5] facility are foreseen for next May. To have an assessment of the MEDIALARIO production process, two MS replicated from two different mandrels were integrated into a supporting structure similar to the EQM unit and were X-ray tested at the PANTER facility on March 95.

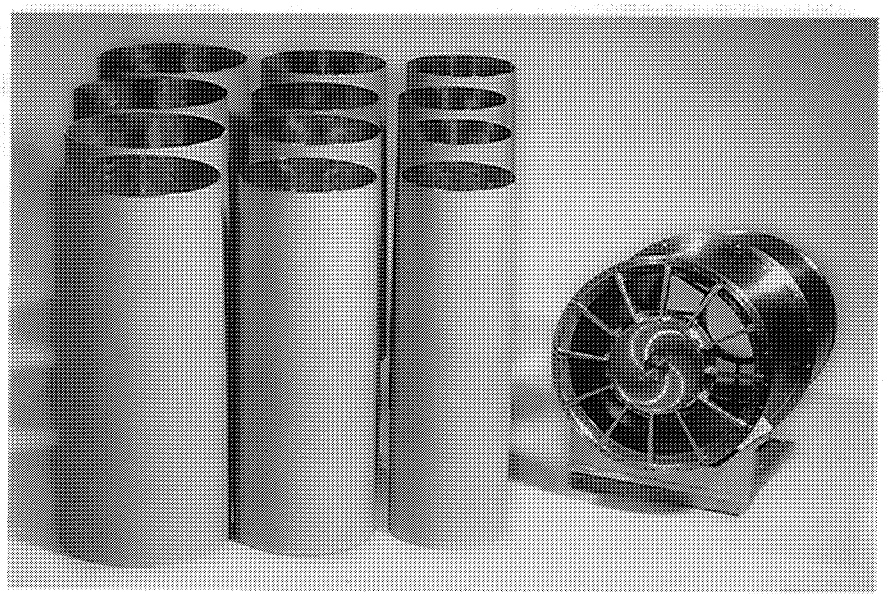

Fig. 2- Set of 12 mirror shells and mechanical structure for the EQM model.

4. X-RAY TEST

Inside the PANTER test chamber, the mechanical structure which support the MS's is mounted on a bench that can be horizontally and vertically tilted in order to align the optical axis of the MS's with respect to the axis of the X-ray beam.

Three detectors provided by Max Planck Institut für extraterrstrische Physik (MPE) are mounted on the focal plane optical bench: the engineering model of the ROSAT Position Sensitive Proportional Counter (PSPC) [6] for imaging and two polypropylene window proportional slit counters for making horizontal and vertical slit scans. The slit width is respectively 100 and 50 μ. Each detector can be centered and focused on the image of the MS by means of a remote controlled three axis manipulator. Another proportional counter is mounted at the entrancy of the test chamber to monitor the stability of the intensity of the X-ray beam (Monitor counter).

The measurements were made at 0.27 KeV (C-Kα), 1,5 KeV (Al-Kα) and 8 KeV (Cu - Kα).

The imaging properties of the measured MS's were determined by taking on axis images with the ROSAT PSPC and horizontal and vertical scans with the slit counter. After the measurements with the slit counter, it was found that the slit width of 100 μ was too large for making a correct sampling of the image slit function.

Consequently, considering the good circular symmetry of the images as seen from the PSPC, the results here reported were derived analyzing only the vertical scans (slit width of 50 μ).

With the slit counters, scans across the on axis images at the focal plane were performed between ± 20 mm from the peak at each energy.

The scan step was 25μ for ± 1 mm around the peak and 100 μ for the other parts; in each position the detector accumulates counts for a fixed time interval.

The Encircled Energy Function EEF is derived from the deconvolution of the slit scans [7] assuming a circular symmetry of the image.

The results of the PSPC measurements are corrected for the intrinsic resolution of the PSPC counter.

The determination of the HEW with the PSPC is rather critical because its intrinsic resolution is similar to the resolution of the JET-X MS's. Due to its large sensitive area, the PSPC is very useful for determining the scattering characteristics of the MS's. The results of the X-ray measurements are reported in table 5.

The HEW and W90 are the diameters of the image which encircle respectively 50% and 90% of the photons.

MIRROR	ENERGY	SLIT (50 μ)		PSPC	
	KeV	HEW arcsec	W90 arcsec	HEW arcsec	W90 arcsec
8	0.27	10.8	53.5	--	66.5
8	1.5	11.4	58.7	10.6	77.6
8	8.1	17.2	137.8	14.2	182.6
9	0.27	10.9	55.8	--	76.9
9	1.5	11.3	61.4	7.6	212.7
9	8.1	13.7	198.8	11.3	273.4

Table 5 - HEW and W90 diameter at different energies for MS 8 and 9

Fig. 3 shows an example of slit scans at different energies for the MS 8 while fig. 4 shows the EEF for the same MS derived from the deconvolution of the slit scans.

Fig. 5 shows an in focus and an out of focus image of MS 8 taken on the UV vertical bench. It is clearly noticeable the effect of the diffraction.

Fig. 6 shows an in focus and an out of focus image of the same MS 8 taken with the PSPC detector at 1,5 KeV.

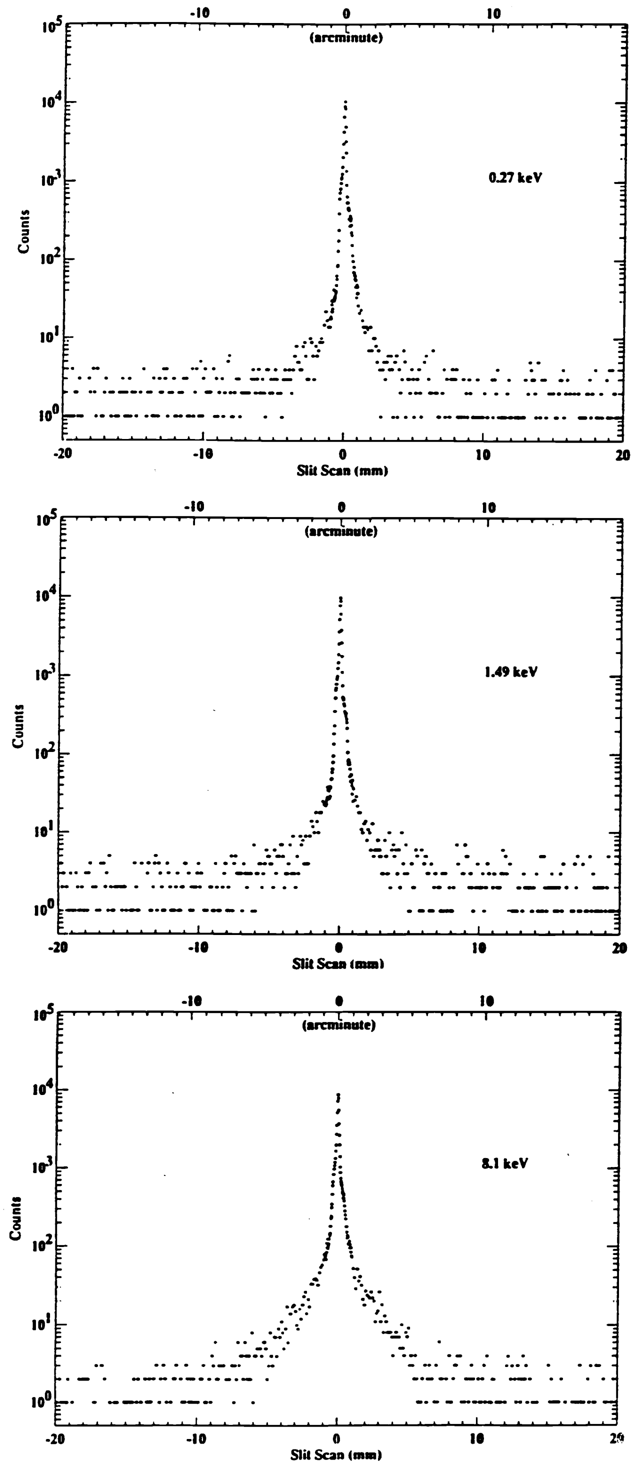

Fig. 3 - Slit scans at different energies for MS8.

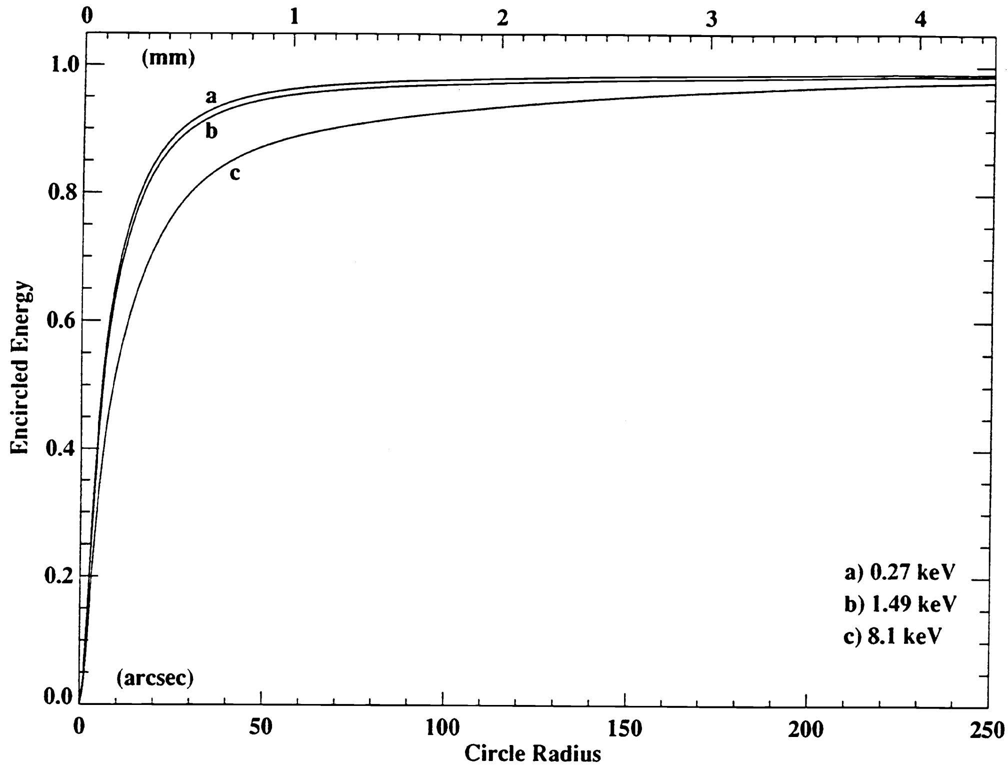

Fig. 4 - Encircled Energy Function derived from valuation of slit scan for MS 8

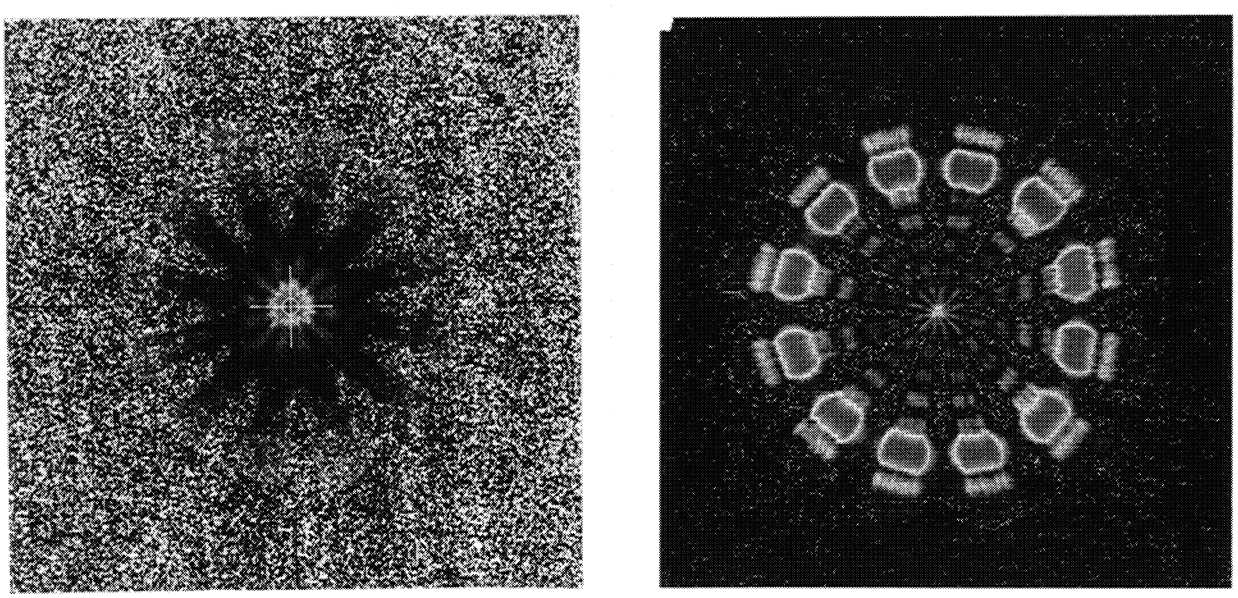

Fig. 5 - In focus and out of focus images of MS 8 taken on the UV vertical bench.

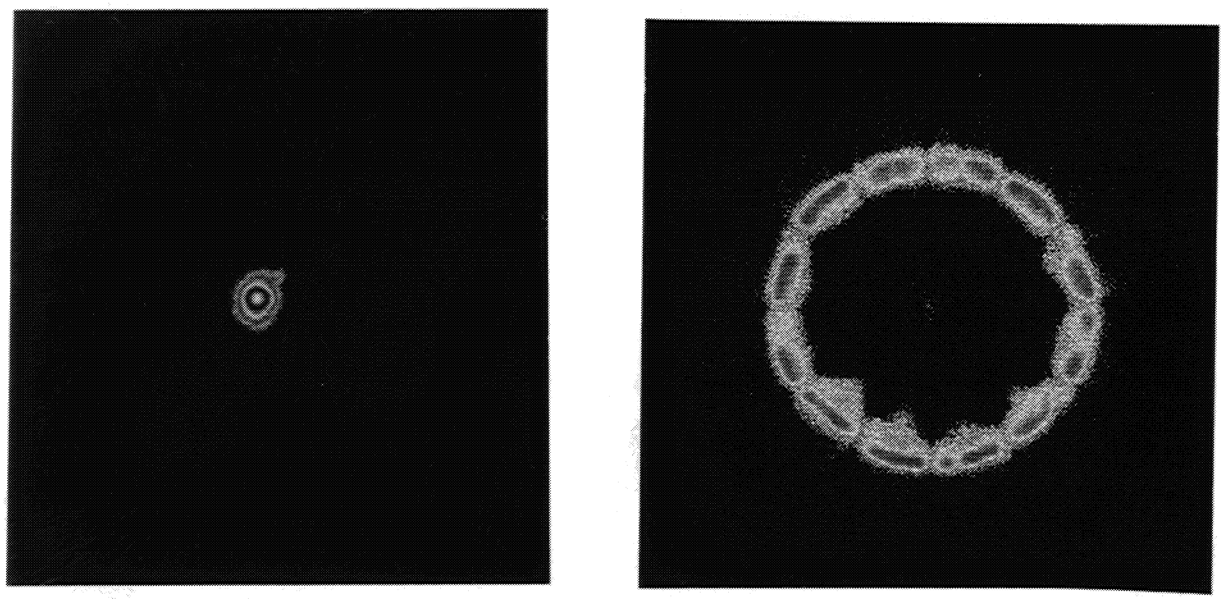

Fig. 6 - In focus and out of focus images of MS 8 taken with the PSPC detector at 1,5 KeV

5. CONCLUSIONS

A set of 12 MS's for the JET-X EQM model have been replicated and are now in the process of being integrated into the mechanical structure.
The measurements of the MS's on the UV vertical bench in quasi free standing condition show an average HEW of 11.4 ± 1.4 arcsec.
The relative low dispersion obtained for the HEW values, indicates that the replication process presents a good degree of reproducibility.
The X-ray measurements of MS 8 and 9 confirm the performances previously obtained for the Development Model of JET-X [8] of 10.0 and 14.4 arcsec respectively at 1.5 and 8.1 KeV.
The completed EQM unit will undergo an intensive X-ray test programme at the PANTER facility on May and June 1995 including an end to end test with the JET-X focal plane detector.

6. ACKNOWLEDGMENTS

We wish to thank G. Boella, G, Chincarini and L. Scarsi for supporting and encouraging our work.
U. Bergamini, G. Castelli, G. Crimi, D. Garegnani, A, Salini and R. Valtolina from OAB have given valuable technical assistance during the various phases of the project. The technical contribution of P. Cerutti, R. Graue, G. Valsecchi and R. Villa from MEDIALARIO has been very much appreciated.

P. Cecchini, B. Negri and G. Rossetti from ASI have given active support for contracts management with the Industries involved in this project. Many thanks go to C. Macchi for preparing the manuscript. This work was carried out under contract from ASI (Agenzia Spaziale Italiana)

9. REFERENCES

1. A. Wells, E. Antonello, H. Brauninger, O. Citterio, M.S. Cropper, W.J. Curtis, C.J. Eyles, C. Goodal, T. Mineo, S. Peskett, B. Sacco, G.C. Stewart, O. Terekhov, M.J.L. Turner, D. Watson, C. Withford, "The JET-X instrument for the USSR Spectrum-RG mission: its design and performance" Proc SPIE 1546, 205 (1991).

2. O. Citterio, G. Conti, E. Mattaini, B. Sacco, E. Santambrogio, "Optics for the X-ray concentrators on board of the Astronomy Satellite SAX" Proc SPIE 597, 102 (1985).

3. O. Citterio, P.Conconi, M. Ghigo, F. Mazzoleni, E. Poretti, G. Conti, G. Cusumano, B. Sacco, H. Brauninger, W. Burkert, "X-ray optics for the JET-X experiment aboard the SPECTRUM-X gamma Satellite" Proc. SPIE 2279, 480, (1994).

4. P. Conconi, U. Bergamini, O. Citterio, G. Crimi, M. Ghigo, F. Mazzoleni, "Evaluation by UV optical measurements of the imaging quality of grazing incidence X-ray optics." Proc. SPIE 2011, 89 (1993).

5. B. Aschenbach, H. Brauninger, K.H. Stephan, J. Trumper, "X-ray Test Facilities at Max Planck Institute, Garching" Proc. SPIE 184, 234 (1979).

6. U. Briel and E. Pfefferman, "The Position Sensitive Proportional Counter (PSPC) of the ROSAT Telescope", Nucl. Instr. and Meth. A242, 376 (1986).

7. G. Conti, E. Mattaini, E. Santambrogio, B. Sacco, G. Cusumano, O. Citterio, H. Brauninger, W. Burkert, "Engineering Qualification Model of the SAX X-ray Mirror Unit. Technical data and X-ray imaging characteristics" Proc. SPIE 2011, 118 (1993).

8. O. Citterio, P. Conconi, F. Mazzoleni, G. Conti, G. Cusumano, B. Sacco, H. Brauninger, W. Burkert, "Imaging characteristics of the Development Model of the JET-X X-ray telescope" Proc. SPIE 1546, 150 (1991).