X-ray imaging performance of the flight model JET-X telescope

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ABSTRACT

Abstract

Construction of the Flight Model Joint European X-ray Telescope (JET-X) for the Russian Spectrum-X mission has been completed and performance tests and calibration of the instrument have been carried out. Separate measurements of the responses of the X-ray mirrors, the CCD detectors and the optical filters already indicate that JET-X will achieve spatial resolutions of around 20 arcsec, an on-axis collecting area of 310cm ^{2} at 1.5 keV and an energy resolution of 130 eV at 6 keV. As a final step in the calibration of the telescope assembly, end-to-end X-ray tests on the complete instrument have been performed in the X-ray beam line facility at MPE Garching. Results from this calibration programme are reported and the overall response of the two X-ray telescopes are compared with the previously measured responses of the mirror, the CCD detectors and the optical filters. In-orbit sensitivity responses are derived from these calibration data sets, for the normal operating modes of JET-X.

1. INTRODUCTION

Funding limitations in the Russian space science programme have delayed launch of the Spectrum-RG mission(1), and deliveries to Moscow of the flight model instruments for the scientific payload have therefore also been delayed. In the case of the Joint European X-ray Telescope (JET-X) construction of the Flight Model has been completed and performance tests and calibration of the instrument have been carried out, but JET-X is now awaiting delivery to Moscow for integration on to the spacecraft as soon as the spacecraft programme reaches an appropriate stage of readiness.

As previously reported, the major scientific goal of JET-X is the study of faint X-ray sources, by spectroscopy, imaging and timing.(2) The high resolution optics, low noise detectors and the 4-day orbit of Spectrum-RG combine to emphasise the value of long exposures for JET-X. Throughout the 5-year mission lifetime, JET-X will be the prime instrument (i.e. determining the pointing axis) for at least 180 spacecraft orbits, each with an effective observing time of 2.7×10^5 seconds.

The key scientific objectives of JET-X are:

i) *Deep Fields:* Deep surveys to identify the major constituents of the X-ray background in the 2-10 keV band.

ii) *Medium Surveys:* Broad-band spectroscopy sources detected in the ROSAT survey to examine the evolution of the X-ray emission and absorption in AGN.

iii) *Extended source Spectra:* Imaging and spectroscopy of rich clusters and elliptical galaxies.

iv) SNR : Measurement of temperature, density and chemical abundance distributions and hence mass and evolution of SNR's.

v) Bright Source Observations: Study of variability in flux and spectrum and hence the geometry of individual emission and absorption features.

In addition, between 20 and 100 serendipitous sources can be expected in each 10^5 sec exposure.

The scientific capabilities of JET-X are:

i) Imaging with 20 arcsec resolution (HEW) with a limiting sensitivity of ~3 x 10^{-15} ergs/cm^2/sec for a 10^5sec observation.

ii) Medium resolution spectroscopy in the 1-10keV band with emphasis on high sensitivity and spectral resolution ($E/\delta E \geq 50$) around the 7keV Fe-line complex.

iii) Time variability of X-ray spectra on timescales ranging from milliseconds to months.

JET-X is being developed by a consortium of groups from the UK, Italy, Russia and Germany. JET-X is one of the core payload instruments of Spectrum-RG.

Any instrument which seeks to extend observational capabilities beyond current state-of-the-art requires calibration which leads to full understanding and exploitation of its capabilities. For JET-X, an accuracy target of 3% has been defined for the performance-defining parameters of collecting area, detection efficiency, spatial resolution, and spectral resolution.

The calibration programme has been carried out in two stages. The responses of individual components of the optical train, -X-ray mirrors, filters, and detectors -have been calibrated separately, to about 1% accuracy. The overall response has then been constructed by folding together the individual response values into an overall instrument response matrix. For the second stage of calibration, the assembled JET-X telescope was installed in the long beam X-ray facility at MPE Garching and end-to-end calibration were performed on the whole instrument. The convolved response has then been compared with the results from the end-to-end tests in order to verify the overall instrument performance.

2. INSTRUMENT DESCRIPTION

2.1 System Design

JET-X consists of two identical, co-aligned X-ray imaging telescopes, each with an angular resolution of 20 arcsecond over the energy band 0.3-10keV. Focal plane imaging is provided by cooled CCD detectors, which provide spatial resolution of the telescope images combined with high spectral resolution, particularly around the 7 keV Fe-line complex. The x-ray mirrors are 0.3m in diameter with a focal length of 3.5m and consist of a nested array of 12 mirrors shells with combined on-axis effective area for two telescopes of 360 cm^2 at 1.5 keV and 140 cm^2 at 8.0 keV. The field of view is 20 arcmin radius and an angular resolution of 20 arcsec corresponds to a spatial resolution in the focal plane of 0.340mm

The CCD pixel size, is 27μm square, which comfortably oversamples the focussed image of a point source. Spectroscopic capability is provided by using the CCD to detect single photons, whose energy is determined from the deposited charge - in silicon, the conversion energy per hole-electron pair is approximately 3.68eV. The CCD developed for JET-X is a large area three-phase MOS frame transfer CCD fabricated on high resistivity silicon and operated in deep depletion [(3)]. The combined response of the CCD and the x-ray mirror covers a bandpass from 0.3 to 10 keV.

Spacecraft drift and thermal distortion over 10^5 sec observations would lead to image blurring and loss of sensitivity. However, JET-X has an attitude monitor to measure the instrument pointing direction to 5 arcsec, and thereby allow drift in pointing between successive CCD frame images (integration time 2.5sec) to be corrected in the data analysis. The attitude monitor detects and monitors positions of up to four stars in its 4° x 5.4° field of view, and a post facto attitude solution for JET-X, probably to about 10 arcsec precision, can be established through data processing on the ground.(4) Two attitude monitors, operated in cold redundancy, are installed on JET-X.

A silicon radiation monitor detector measures the ambient cosmic radiation levels, so that the X-ray telescopes can be switched off during solar flares and passages through the Earth's radiation belts.

2.2 Sub-systems

JET-X operates as a stand-alone instrument with simple interfaces to the spacecraft. The JET-X structure is constructed from three carbon fibre tubular sections. The structure acts as an optical bench, which maintains the focus of the x-ray mirrors relative to the focal plane detectors and establishes the mutual co-alignment between the two x-ray telescopes and the two attitude monitors. A telescope alignment monitor (TAM) measures thermal mis-alignments and angular distortion between the mirror and focal plane bulkheads to 5 arcsec accuracy. The structure is under active thermal control by means of a distributed array of heaters and thermostats. Heat flows to and from space are controlled by multilayer insulation, and by thermal baffles in front of the x-ray mirrors, and stray light baffles in front of the attitude monitors. The forward section of the structure has a deployable door, which remains closed until the satellite has reached orbit. A pyrotechnic cutter releases the door latch on command and the door is opened by spring-loaded hinges with dampers. The function of the door is to protect sensitive optical surfaces from contamination and moisture during ground operations and launch procedures.

The x-ray mirrors are mounted on a bulkhead in the forward section of the structure. The CCD detectors, together with a shutter and a filter wheel mechanism, are mounted on separate focal plane transoms, themselves located inside the rear structure tube. Each CCD is cooled by a passive radiator which is mounted on the outside of the structure and connected to the CCD cryostat by a thermal link. The thermal link is rigidly clamped for ground handling and launch activities and released in orbit to isolate the CCD/thermal link assembly from the cryostat structure. Signal processing electronics for the CCDs are also mounted on the focal plane bulkhead.

The instrument incorporates an on-board command and data management electronics with a 60 Mbyte mass memory sufficient to store 24 hours-worth of scientific data. The command and data management system (CDMS) electronics, the 60 Mbyte mass memory and the power converters and power distribution unit are housed in the electronics compartment, which is mounted on the side of the aft section. The CDMS is designed around four identical microprocessors, one for control and data formatting, two for processing events - one for each x-ray telescope, and the fourth in redundancy. All spacecraft and internal interfaces are redundant. On-board software is held in PROM's. All electrical interfaces to the spacecraft, including spacecraft power, timing and commands are in the electronics compartment. Power and commands are routed through the power distribution unit and CDMS, respectively, to the other sub-systems. Heat from electronics units is radiated directly to space via a high emissivity surface on the electronics compartment.

The main attitude monitor is mounted on the outside of the forward section, together with a stray light baffle, whose aperture is kept closed prior to launch, by an extension on the JET-X door. The drive electronics for the attitude monitor CCD are integral with the attitude monitor; signals are transferred to the CDMS unit for processing and transfer to the Spectrum-X telemetry. The back-up attitude monitor is mounted on the mirror bulkhead.

2.3 Spacecraft Interfaces

The Spectrum-RG data handling system consists of a spacecraft on-board computer (BIUS), which communicates with the individual instruments over multiple MIL-STD-1553 busses, both for sending commands, and for transferring science data to the telemetry. Telemetry is provided via a low speed link for command verification and housekeeping and a high speed link for science data. Telemetry and telecommand links are for up to 1.5 hours daily during normal mission operations.

JET-X has 14 relay commands from the spacecraft, which are used mainly for power switching. The MIL-STD-1553 bus with the BIUS spacecraft computer includes provision for block commands containing up to 16 data words and for transfer of housekeeping data from JET-X to BIUS. Science data is transferred to the BIUS at 740 kbit/sec, requiring around 10 min for dumping the 60 Mbyte JET-X memory during ground contacts. The slow telemetry JET-X interface with the spacecraft operates at 16 kbit/sec and can be used to transfer blocks of 120 bytes of housekeeping data at intervals between 5 and 60 sec as an alternative to BIUS. In addition there are a number of direct monitors of voltages, thermistors and relay contacts within JET-X.

The mass of JET-X is 545Kg and the power consumption is 260W, approximately half of which is used for thermal control.

3. INSTRUMENT OPERATING MODES

JET-X has several engineering modes and commands but most of these are for selection of redundant systems to deal with failure situations or to adjust engineering parameters. However, the operating modes required for science observations have been optimised and there are only three modes required for each of the two telescopes;

(i) Framestore Mode; (ii) Bright Object Mode and (iii) Timing Mode.

Table 1:JET-X Primary Instrument Science Operating Modes

Science Mode	Source Strength	XRT A mode	Int Time	Filter Wheel	XRT B Mode	Int Time	Filter Wheel
Prime F1	<1 mCrab	Framestore	5 posns	Open, etc.	Framestore	2.5 s	5 posns
Prime M1	1-20 mCrab	Bright Obj	5 posns	Thin/Thick	Framestore	2.5 s	5 posns
Prime B1	>20 mCrab	Framestore	5 posns	Thin/Thick	Framestore	2.5 s	5 posns
Prime B2	>20 mCrab	Bright Obj	5 posns	Thin/thick	Framestore	2.5 s	5 posns
Prime B3	>20 mCrab	Timing	5 posns	Thin/Thick	Framestore	2.5 s	5 posns

Five filter positions: open, opaque, three redundant filters. Thin filters, included in an earlier design, have been removed.

All laboratory and system testing now exercises these modes at each stage of the AIT and calibration programme, so that a history log of performance data is being compiled, that enables current results to be compared with previous benchmark data.

4. MIRROR, DETECTOR AND FILTER RESONSES

4.1. X-ray Mirrors

Mirror performance were measured on the two flight units and the flight spare in tests at Panter during 1996[5,6]. The mirror point spread function (PSF) and effective collecting area (Aeff)) were determined.

Both a CCD and a PSPC, detector were used for different aspects of the calibration. Because of the high angular resolution of the mirrors, the PSPC could not resolve the response with sufficient accuracy and the CCD was the preferred detector. Wide angle scattering in the wings of the PSF fell outside the small field of view of the CCD and the lower resolution PSPC was used for measurements of the Half Energy Width and encircled energy fractions and the measurements of collecting area.

Table 2: Mirror HEW and 90% Encircled Energy Fraction Measurements with CCD and PSPC

	Energy	FM1	FM2
CCD HEW	0.9 keV	-	12".9
PSPC 90% EEF	0.9 keV	-	37".4
CCD HEW	1.5 keV	15".1	14".6
PSPC 90% EEF	1.5 keV	61".5	46".6
CCD HEW	8.1 keV	18".7	18".8
PSPC 90% EEF	8.1 keV	203".5	202".9

Results of the PSF measurements are given in Table 2. Effective area measurements are in Table 3 and Figure 1 shows the theoretically derived collecting area curve together with two measured points at 1.5 keV and 8.1 keV taken with FM2.

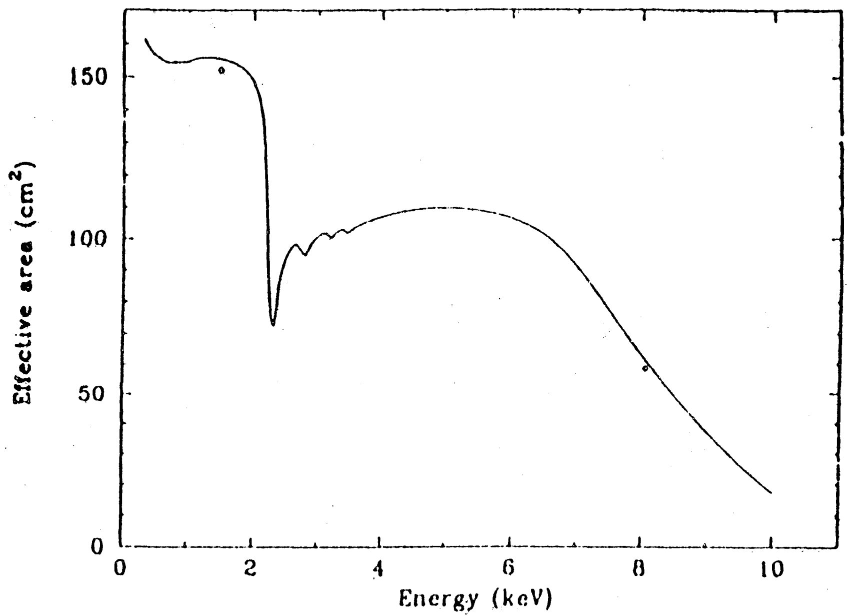


Figure 1: Theoretical JET-X effective area (one telescope). The two points represent the measurements on JET-X FM2 at 1.5 and 8.1 keV.

As Table 2 also shows, the FWHM PSF is considerably better than the 20 arcsec HPW target specification. The focal lengths of FM1 and FM2 were determined in these tests at 3501.4mm and it has been decided to defocus the detector positions by 2.5mm to obtain a flat field response over a field of view of 15 arcmin radius.

Table 3: Effective Area Measurements for FM1 and FM2, measured with PSPC

Energy (keV)	FM1 cm^2		FM2 cm^2		Theory cm^2	
	130 m	∞	130 m	∞	130 m	∞
1.49	150.0±1.0	158.9±1.1	152.0±0.8	161.0±0.8	155.4	164.6
8.05	58.3±0.5	69.2±0.6	58.5±0.5	69.5±0.6	61.4	72.9

The quoted error derives from the counting statistics.

4.2. CCD Detector Response

The flight CCDs have been calibrated in two ways. In the laboratory, spot energy measurements have been made over the working range of the CCDs to determine energy resolution and quantum efficiency. Separate radiation tolerance measurements were also carried out as part of the qualification programme as has been reported previously(3). The laboratory measurements have been backed up by measurement in the beam of the Daresbury SRS (Synchrotron Radiation Source), operated in a novel low current mode to enable detectors to be operated in the SRS beam in single photon counting mode. The SRS calibrations provide a high resolution energy calibration, including, crucially, the EXAFS fine structure which materially affects the spectral response of the instrument. JET-X is the first X-ray astronomy instrument ever to realise the importance of EXAFS and to take the effects into account in the calibration.(7)

Figure 2 shows the quantum efficiency calibration of the JET-X flight CCD, including the fine structure effects revealed by the SRS calibration. The spot energy data points are also shown.

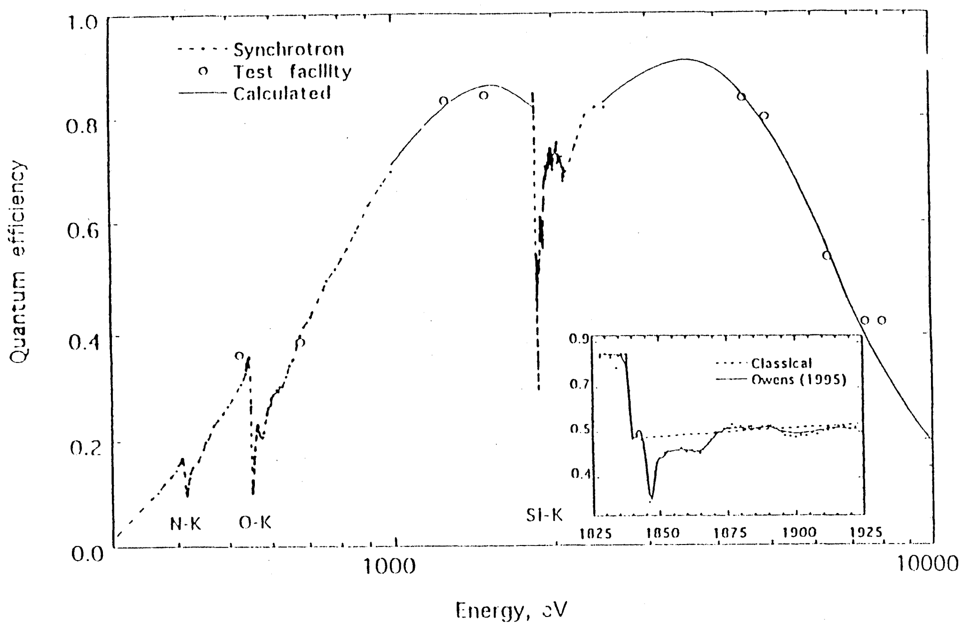


Figure 2: High resolution CCD quantum efficiency measurements.

Figure 3 shows the energy response. The energy resolution at 7 keV is 130 eV, which is exactly consistent with the theoretical value expected from Fano statistics and the residual noise of the CCD read-out. The JET-X CCDs actually do operate at the theoretical Fano limit.

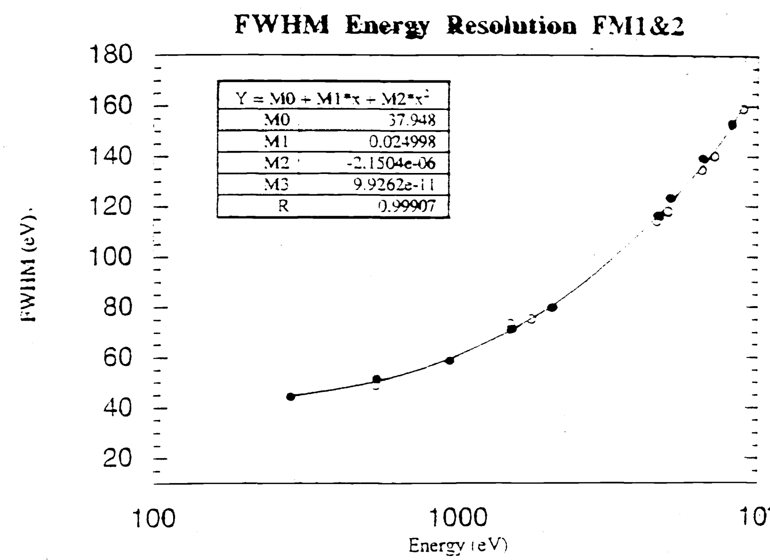


Figure 3: CCD Spectral Resolution

4.3. Filters

Changes to the filter design have been incorporated to eliminated unwanted optical and UV light leakage, without significant change to the X-ray transmission. EXAFS effects are also apparent in the filter response. Oxidation effects at the Al edge have also been mapped and further work is planned covering C and O edges. Further results on the JET-X filters are reported in an accompanying paper.(8)

4.4. Convolved Instrument Response Matrix

The individual responses of the optical elements have been convolved to produce an overall instrument response curve. The effects of the EXAFS fine structure on this response can be seen in Figure 4 which also shows the response when CCD and filter responses are computed using simple absorption coefficients in the modelling used, erroneously, to interpolate between measured data points.

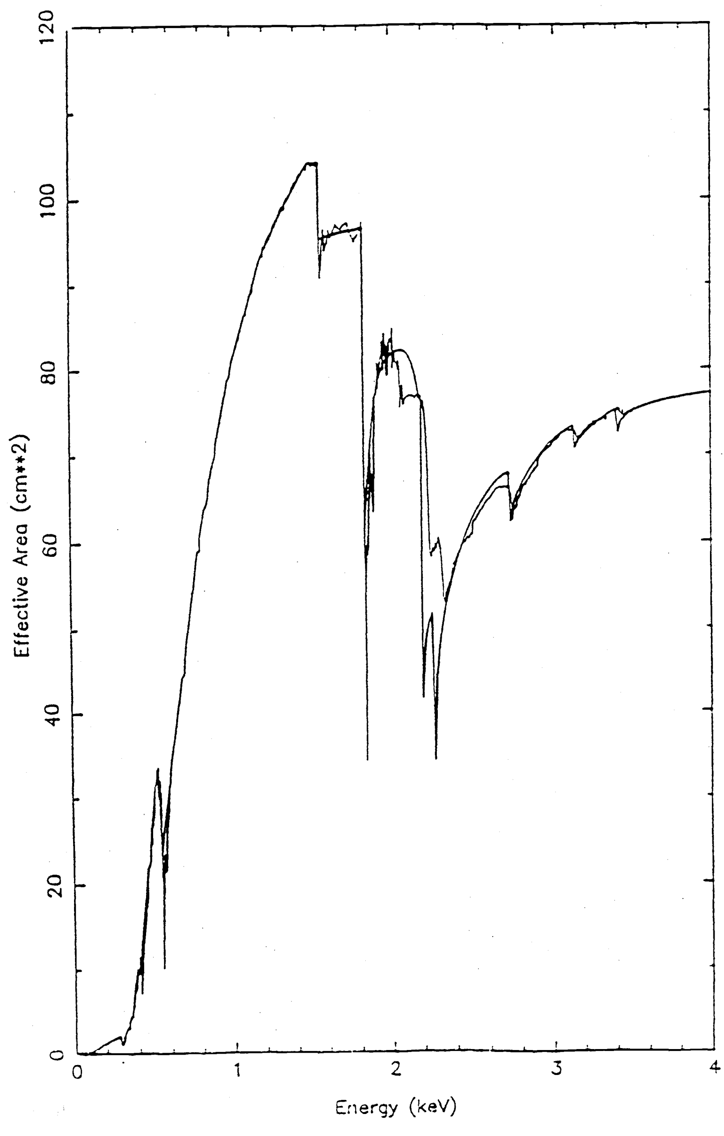


Figure 4: The all-up effective area for the JET-X telescope. Two curves are given - one for which the detailed edge structure was input from direct measurement (thin line) and the other in which the edge shapes were calculated using classical cross-sections (thick line).

5. JET-X END-TO-END X-RAY CALIBRATION

5.1 Test configuration

The complete JET-X telescope was mounted in the MPE Panter facility on the $\theta-\Phi$ table with the join plane of the mirrors 756 mm behind the table pivot and 124.56 m from the X-ray source. A space ring, 100.8mm thick was inserted between the JET-X mirrors and focal planes to compensate for the finite source distance. The two X-ray telescopes are mounted in a common vertical plane, with XRT1 on top and XRT2 below. The mirror centres are separated by 430mm, corresponding to a subtended angle at the X-ray source of 11.9 arcmin.

X-ray beam flux was monitored with a proportional counter detector.

JET-X was tested in the Panter vacuum over the period from March 20 to April 6 1997 during which time a total of 290 observations/exposures were completed. Test objectives were:

Functional tests and checks of all operating modes of JET-X with CCD's cooled to operating temperatures;

Checks of telescope focus;

Checks of co-alignment of XRT1, XRT2, attitude monitors and telescope alignment monitors;

Calibration of the PSF, collecting area and vignettting of the XRT's;

Calibration of pulse pile-up in the CCDs;

Calibration of off-axis X-ray light leak;

Check of filter performance;

Attitude monitor source detection and tracking.

The test matrix in Table 4 summarises the X-ray energies used for the calibration programme, and the measurements obtained.

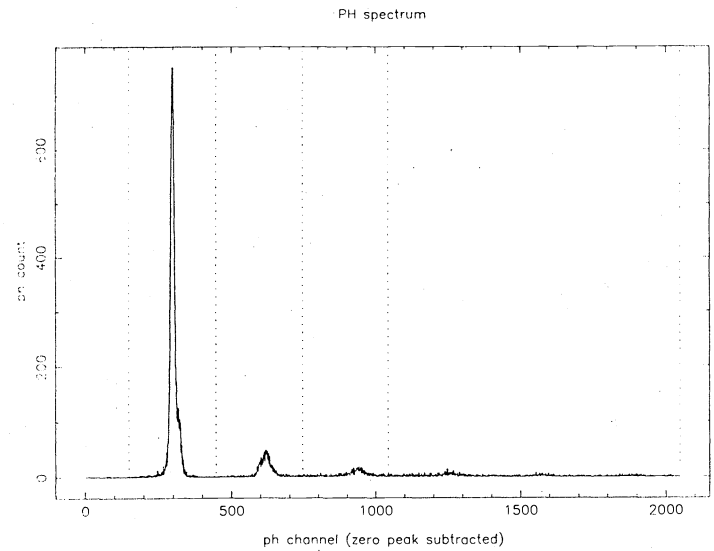
Table 4. JET-X Calibration Test Matrix.

emission lines	Cu-L	Al-K	Ti-K	Fe-K	Cu-K
energy keV	0.93	1.49	4.51	6.40	8.05
PSF	*	*	*	*	*
Area	*	*		*	*
Vignetting	*	*	*	*	*
Pile-up	*	*		*	*
Focal length		*			*
Alignment	*	*	*	*	*
Timing mode			*	*	
Off-axis leak		*			
X-rays + AM					*

5.2. Pulse Pile-Up

Pulse pile-up effects impose tight limitations on the achievable accuracy of PSF and Collecting Area calibrations. Typical count-rates available from the Panter X-ray sources are inherently too high to avoid pile-up in the CCDs but when source brightness was turned down to levels below 1ct/sec, 1% statistical accuracy (the calibration design aim) could only be achieved with excessively long integration times. This problem was partly overcome by operating the CCDs in low gain mode and which permitted multiple events, that inevitably occur at the higher flux rates, to be detected within the dynamic range of the CCD ADC. Figure 5 shows a typical pulse pile-up spectrum. Whilst this technique worked well for low energy beam fluxes, it could not be used for the high energy calibrations (e.g. at 8.05 keV) because multiple events fall outside the dynamic range of the ADC even in the low gain mode. Consequently the accuracy of our high energy calibrations remain somewhat compromised, except for the few measurements that were possible at low flux and in high gain mode.

Ultimate calibration accuracy of Aeff is limited by pulse pile-up in JET-X.



peak 1 13.604 events/sec 13.604 photons/sec

peak 2 1.827 events/sec 3.655 photons/sec

peak 3 1.090 events/sec 3.271 photons/sec

peak 4 1.320 events/sec 5.281 photons/sec

total 17.842 +- 0.130 evts/sec 25.811 +- 0.222 phts/sec

Figure 5: Analysis of Pulse Pile-Up

5.3. Focal Length Setting

As previously stated, the detectors were positioned 2.5mm forward of the optimum on-axis focus in order to obtain a more uniform off-axis resolution. Analysis of the stand-alone mirror focus and off-axis response indicated that a focus off-set of 2.5mm would give a resolution of 18 arcsec HEW, flat out to 15 arcmin off-axis.

Figure 6 shows the off-axis resolution at two energies (1.5keV and 8.05keV) for XRT 1, obtained by rotating JET-X relative to the X-ray beam using the Panter θ–Φ table. These data show significant differences relative to the stand-alone mirror tests. The 1.5 keV data show that the defocussing effects have been over-corrected, leading to degradation of the HEW width resolution on-axis of around 2 arcsec. Analysis of this data indicates an apparent decrease of the on-axis focal length of 1.14mm at 1.5 keV and 1.91mm at 8.05 keV. In XRT2, a defocus error of 1.22mm at 1.5keV and 2.0mm at 8.05 keV has been measured.

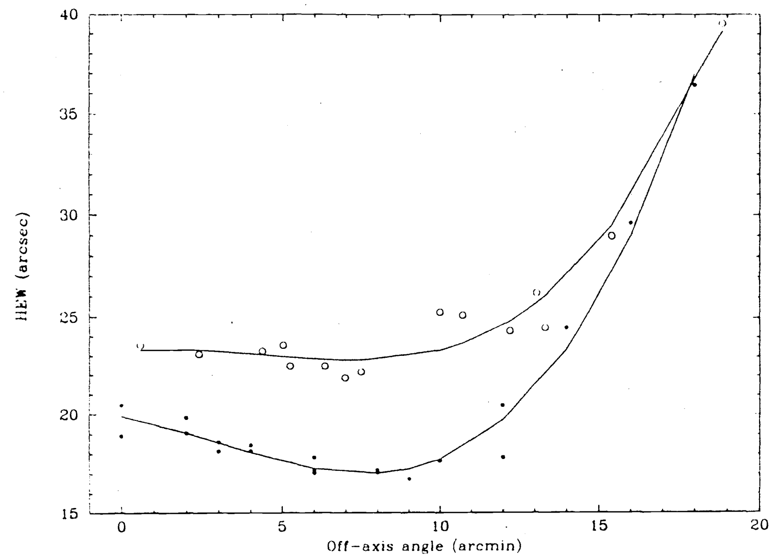


Figure 6: Off-Axis Response

Post-test investigation of this anomaly is still going on, but early indications suggest that the seating of the mirrors in their mounting flanges are slightly out-of-flat. When the mirrors are clamped down on to the bulkhead it is possible that slight taper errors are being introduced into the mirrors which affect the focal length. These errors remain small and the achieved resolution is within the JET-X design specification so the project decision is to fly the telescope as it is presently assembled and not to correct this small error.

5.4. Point Spread Function

PSF has been calibrated at five energies and the response is remarkably uniform over the whole energy range of JET-X. The response is also axially symmetrical to very high precision. Figures 7 shows typical data.

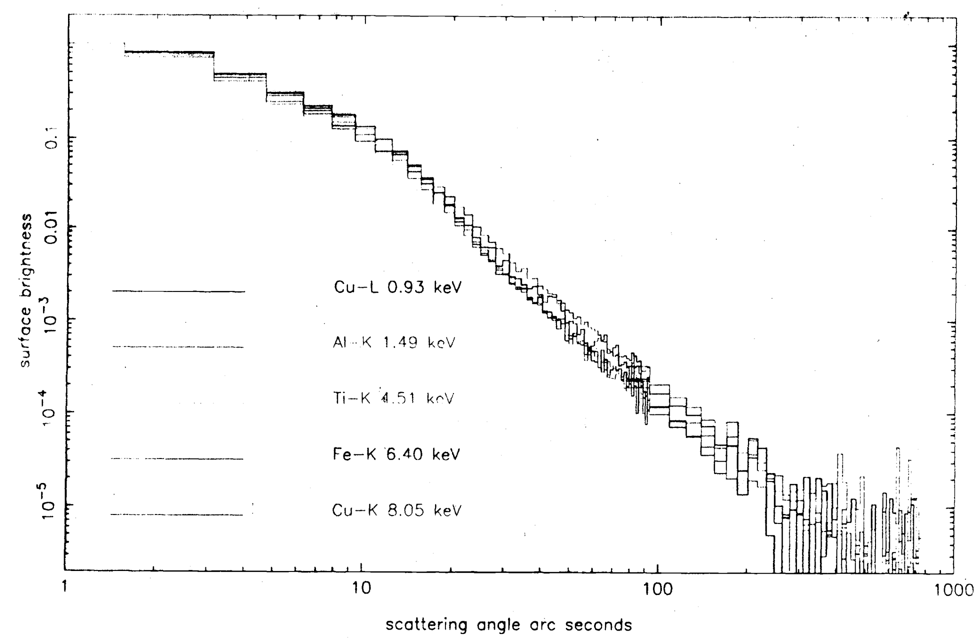


Figure 7: JET-X Mirror Off-Axis Scattering at 4 energies

The uniformity and axial symmetry of the PSF allows its form to be represented by simple functional forms which only vary slowly with energy. The response matrix for JET-X has been be released on WWW.

5.5. Off-axis Response

Vignetting functions for both XRTs have been derived from the calibration data. The data are shown as a ratio of JET-X counts to Monitor counts, awaiting a final calibration of the monitor counter in order to turn these calibrations into absolute Aeff values. Within the present uncertainties in the monitor counter calibration it has been confirmed that the JET-X effective area is nominal to within about +/-10%. The effective area curve is shown in Figure 4.

5.6. Other Calibration Results.

Timing mode has been successfully operated, using a beam chopper to simulate a time-varying X-ray source. Co-alignment between the XRT 1 and XRT 2 mirrors has been measured; a setting-up error of 6 arcmin has been detected and is being corrected. The attitude monitor has been exercised, both to determine co-alignment with the XRTs and to demonstrate tracking mode. Energy resolution of the CCDs has again been measured in the End-to-End tests and found to agree with the CCD stand-alone calibrations.

6. CONCLUSIONS

JET-X End-to-End calibrations have been completed. The response matrix of JET-X has been determined and a preliminary version is accessible on the JET-X Web page http://www.jetx.xra.le.ac.uk. The point source sensitivity of JET-X mets the original design specification. Figure 8 shows the limiting sensitivity and indicates that, because of the high spatial resolution achieved with the JET-X mirrors, JET-X remains scientifically competitive, for faint source studies, not only with ASCA but also with the AXAF ACIS instrument. Further analysis is continuing. The focus error, found during these tests, is the only significant item still under investigation, but the present project baseline is to accept the small error and fly in the present configuration.

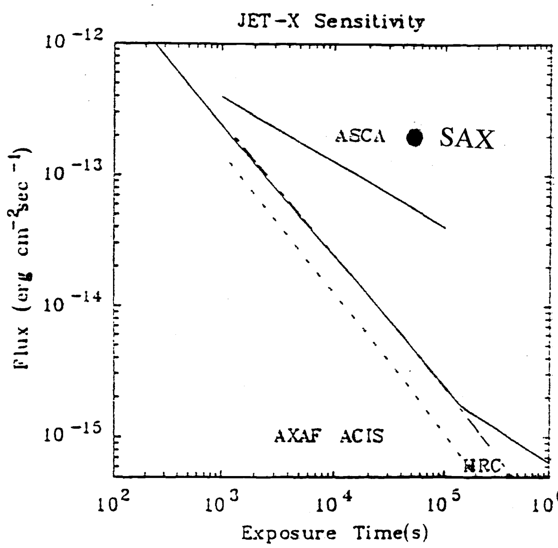


Figure 8: JET-X On-Axis Point Source Sensitivity

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