Ground Calibration GSE for the XMM-EPIC instrument at the Orsay Synchrotron facility

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ABSTRACT

The European Photon Imaging Camera (EPIC) is one of the major instruments on board the European Space Agency's X-ray Multi-Mirror (XMM) *cornerstone* mission planned for launch at the end of the century. Ground calibrations have been performed in 1997 and 1998 on the electrical and flight models of the MOS-CCD and on the flight model of the p-n-CCD focal plane cameras at the Synchrotron facility at IAS Orsay in France. The complexity of the imaging system required a correspondingly sophisticated calibration equipment, capable of automatically setting and calibrating the synchrotron beam at a particular energy, controlling the camera head movement in synchronism with the CCD frame readout, initializing the instrument and acquiring both the instrument data and the facility monitor data in real time. Furthermore, always in real-time, the data stream was unpacked and stored as photon lists in FITS format and made available via NFS to the off-line analysis software. Contemporaneously, a quick look program allowed the operator to continuously monitor the calibration procedure from a scientific point of view, ensuring the correct operation of the system. The calibration system from the point of view of the instrument and the current status of the project is described.

Keywords: X-rays, Instrumentation, Satellites, Calibration

1. INTRODUCTION

The X-ray Multi-Mirror (XMM) telescope is one of the European Space Agency's `cornerstone' missions as defined in its Horizon 2000 plan for the development of space science until the end of this century. XMM is designed specifically to investigate in detail the intensity distribution, spectra and the temporal variability of the X-ray emission from cosmic sources down to a limiting flux of the order 10-16 erg/(s cm^2). The basic characteristics of XMM's X-ray telescopes are a 6" (FWHM) point-spread function, a 30' field of view, spectroscopic resolution ($E/\Delta E$) in the range from a few tens to several hundreds and a large effective area of 4650 cm^2. The basic arrangement of the telescope consists of 3 sets of nested grazing incidence mirror systems. The European Photon Imaging Camera (EPIC), sensitive to X-rays of energies between 0.1 and 10 keV, is one of the major focal plane instruments on XMM, comprising three Charge Couple Device (CCD) X-ray cameras, one at the focal plane of each mirror module. Two of these camera heads (built by the Leicester University X-Ray Group) are based on MOS technology with 7 CCDs of 600x600 pixels and one (constructed by the Max Planck Institute fur Extraterrestrische Physik, Munchen) is of p-n type with 4 Quadrants, each containing 3 CCDs of 200x64 pixels. Each camera is equipped with four filters and one calibration source. During calibration, the EPIC On-board Data Handling unit is replaced by a Fast Data Handling Simulator in order to acquire the Science Data produced by the CCD's with a rate of about a factor of 10 higher than the nominal flight rate. A more detailed description of XMM can be found elsewhere in these proceedings.

In order to calibrate the camera heads before launch of the instrument, several calibration campaigns have been performed during the period April 1997-July 1998 at the synchrotron facility in Orsay, France. The following equipments have been calibrated: the Electrical (EM), Flight (FM1 & FM2) and Flight Spare models of the MOS chain and the FM1 model of the

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p-n . In the following sections we describe the calibration test equipment which was developed in order to allow as full as possible a calibration to be performed over a reasonable time-scale and in as automatic a manner as possible.

2. INSTRUMENT CALIBRATION APPARATUS

2.1 Beam Lines

The Synchrotron IAS facility at the PARIS XI University Campus is unique in that a clean vacuum chamber (2m in diameter, 6m in length) is located at the crossing of two beam lines from two different storage rings (the Super-ACO and DCI). On each line a dedicated monochromator has been built in order to calibrate the EPIC experiment on board XMM. The main goal is to measure the Quantum Efficiency of the cameras, while auxiliary results are (among others) : gross estimation of the flat-field, transfer function of the CCDs at all wavelengths of interest and energy linearity. Together, the 2 monochromators cover the soft X-Ray range from 0.1 to 17 keV with a small gap of less than 200 eV around 1.4keV. The beam lines have been designed and built in order to meet the requirements of the Ground Calibration Plan which translates into spectral, spatial and temporal performances[1].

2.2 SACO beam line (0.1 - 1.3 keV)

The low energy SACO monochromator is based on plane VLS focusing gratings. It consists of different optical elements (toroidal entrance mirror, entrance slits, selectable gratings, spherical mirror, exit slit, bendable focussing mirror). Filters can be inserted before and after the dispersive element. A grid of period 10 microns can be put in the light path to homogenize the beam. The synchrotron current is recorded as well as the signal from a photo-cathode located in the zero order of the monochromator. The width of the monochromatic beam arriving to the camera is larger than 70 mm, its peak-to-peak lateral homogeneity exhibits typically a factor of 2 due to tilted striations generated by the imperfect focussing mirror (made of float glass) sampled by the ultimate slit in front of the focal plane. The spectral quality is better than 1% of undesired photons (higher orders or scattered) above 200 eV. The intrinsic flux stability is better than 5%, but is still limited by the mechanical coupling of the optics with the ground and the 40 meters distance between the monochromator and the experiment chamber, hence the need for monitoring. The flux level is chosen to avoid pile-up at the camera (typically 300 events per frame) or reference detectors (typically a few hundred counts per second per square millimeter). An IRD diode is available for the setting up of the beam-line without requiring the main chamber.

2.3 DCI beam line (1.5 - 20 keV)

The higher energy DCI beam-line consists of a 2-crystal monochromator having selectable pairs (quartz, InSb, Si 111) equipped with a filter wheel and various slit mechanisms. A so-called "clarinet" assembly allows the insertion of 7 metallic foils independently for flux adjustment. Here again the spectral purity can be made very high . The beam width on the camera is larger than 70mm at all energies and the peak-to-peak homogeneity along this dimension is usually better than 50%. It is now limited by the crystals themselves (quality and polishing). Flux variations as high as 20% with a period of about 40 minutes were observed earlier this year, but they were monitored during the first campaigns of calibration, and were then attributed to the periodic cooling of a slit. The temporal stability is now better than 1%. The synchrotron current is recorded for long duration measurement purposes.

2.4 Focal plane set-up

The two previously described beam-lines cross in the "JUPITER" vacuum chamber. All the instruments involved in the photometric measurements are attached to a Mechanical Optical Ground Support Equipment (MOGSE) able to rotate toward either of the 2 synchrotron beam lines or an additional X-Ray Tube. The three functional tables are successively :

- An adjustable (~1mm x 70mm) slit can be made non-parallel to compensate for dis-symmetries of the beam. A channeltron next to one edge of the slit is available for monitoring purposes.
- A second translational table supports two reference detectors : a Si(Li) detector calibrated at BESSY and a Proportional Counter inherently calibrated for the lowest energies (O.15 micron Silicon Nitride window). A channeltron behind a gold photocathode and a thin Hamamatsu Silicon diode are also available for tests.
- The third table supports the camera and provides the robust translation motion needed for scanning the camera millions of times through the beam.

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A chopper wheel is also mounted onto the adjustable slit assembly, and can be inserted in and out of the beam. It works as a neutral attenuator with a transmission of ~4%. It adapts the fluxes in a known neutral (spectroscopically and spatially) manner from the higher acceptable counting rate of the Si(Li) (1000 cps) to the pile-up limit of the camera.

3. CALIBRATION PROCEDURES

3.1 Basics

The main objective of the campaigns at the Orsay synchrotron was to calibrate the energy response of the three flight EPIC cameras and of the four filters through three main classes of tests:

1. the *contamination* tests to measure the QE of the camera just below the Carbon threshold at the beginning and at the end of each campaign;
2. the *edge and continuum scan* (CCDs and filter) tests to measure the global QE around six energy thresholds : C-K (277 eV), N-K (41 0 eV), O-K (525 eV), AI-K (1.486 keV), Si-K (1.740 keV) and Sn-L (from 3.9 up to 4.5 keV) and to scan the whole energy spectrum of interest for EPIC (from 0.1 up to 15 keV);
3. the *flat fields* tests to measure the local QE at some energy of interest.

Most of the tests have been devoted to point 2 measurements.

The operations to be performed in order to accomplish the above objectives lead to the identification of a set of calibration procedures consisting of elementary tasks to be executed in a given sequence for each required energy. The principle of the calibration measurement is rather simple: The idea is to scan vertically the focal plane into an elongated calibrated beam a number of times so that the Poisson noise level goes below 1%. In reality, it necessitates numerous steps and precautions. The main phases for the evaluation of the QE at one energy are:

- The monochromator is tuned to the selected energy (it has been calibrated in energy beforehand)
- The neutral attenuator (chopper) is removed from the beam path.
- The calibrated reference detector is positioned in the middle of the beam (laterally).
- The flux level is verified and adjusted if necessary.
- The flux is sampled for ~150s by the reference detector at the median point.
- The reference detector is removed and the neutral attenuator inserted into the beam.
- A camera acquisition is started with synchronization of the integration time and the vertical motion in the MOS camera case. In the p-n case, the integration time is derived from the data analysis due to the higher readout speed.
- The neutral attenuator is removed.
- The reference detector is scanned horizontally to calibrate the beam profile with a statistical level consistent with the camera acquisition and a step given by Shannon.
- The foreground detectors are put aside.
- The neutral attenuator is inserted again.
- A second camera acquisition is started, possibly followed by other acquisitions with the filters of the EPIC instrument in order to calibrate them.

The above steps can be divided into two classes: those pertaining to a *Beam Calibration Phase*, where the beam is set and calibrated/re-calibrated and those pertaining to the *EPIC Instrument Calibration Phase*, where the beam is measured with the camera in different configurations. Each Calibration Phase is preceeded by a Preset Phase, where either the variable values related to the beam operations are defined (e.g. energy) or the required configuration for the EPIC camera is set.

4. FACILITY CONTROL

To implement the beam procedures as well as the many test sequences a special software tool has been developed. Although dedicated to this application it has still a general purpose use which could integrate many evolutions of the procedures and

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the hardware. As the measurement involves geographically distributed instruments spread over an extended facility, the control of the sequences had to take this into account. Another input was the expected evolution of the procedures, simple at first and then complicated by the quest for more accuracy and efficiency. The so-called EICC (Extended Instrumentation Computer Control) comprises four programs which run on each of the seven operational PC's.

The first program is the *Script Server*. It is able to interpret command lines usually gathered in a script ASCII file. The second program is the *Instrument Server*. It serves local instrumental requests from local or remote Script Servers. In the case that a special action requires an intricate algorithm, or if a piece of hardware does not have a standard interface, a "Network Instrument" server is written. It is then operated as any other instrument with dedicated commands.
The last server is the *Variable Server* whose role is to record and provide numerical values to the two other type of servers. Finally a Graphical User Interface (GUI) enables the operator to launch script executions, and to plot variable values.

The main functionalities of the EICC script language are the command flow control (loops, tests, calls), the instrument control (IEEE 488, RS232, TCP/IP), the variable computations and the data-file management. Thus the EICC has the ability to perform networked multithreaded operations which can be selected upon the results of computations or previuos acquisitions. The measurements can be recorded in data files as well as communicated over TCP/IP to other machines (e.g. the EPIC EGSE Science Console). In the same way, the EICC can trigger further scripts executions or receive external request (e.g. from the EPIC CCOE).

As detailed hereafter, during the calibration campaigns the script executions are triggered by the EPIC EGSE CCOE instead of the EICC GUI, and the useful measurements or settings are dumped into the EPIC EGSE Science Console as well as into the IAS disks. The modular architecture of the scripts greatly facilitates their management and optimization.

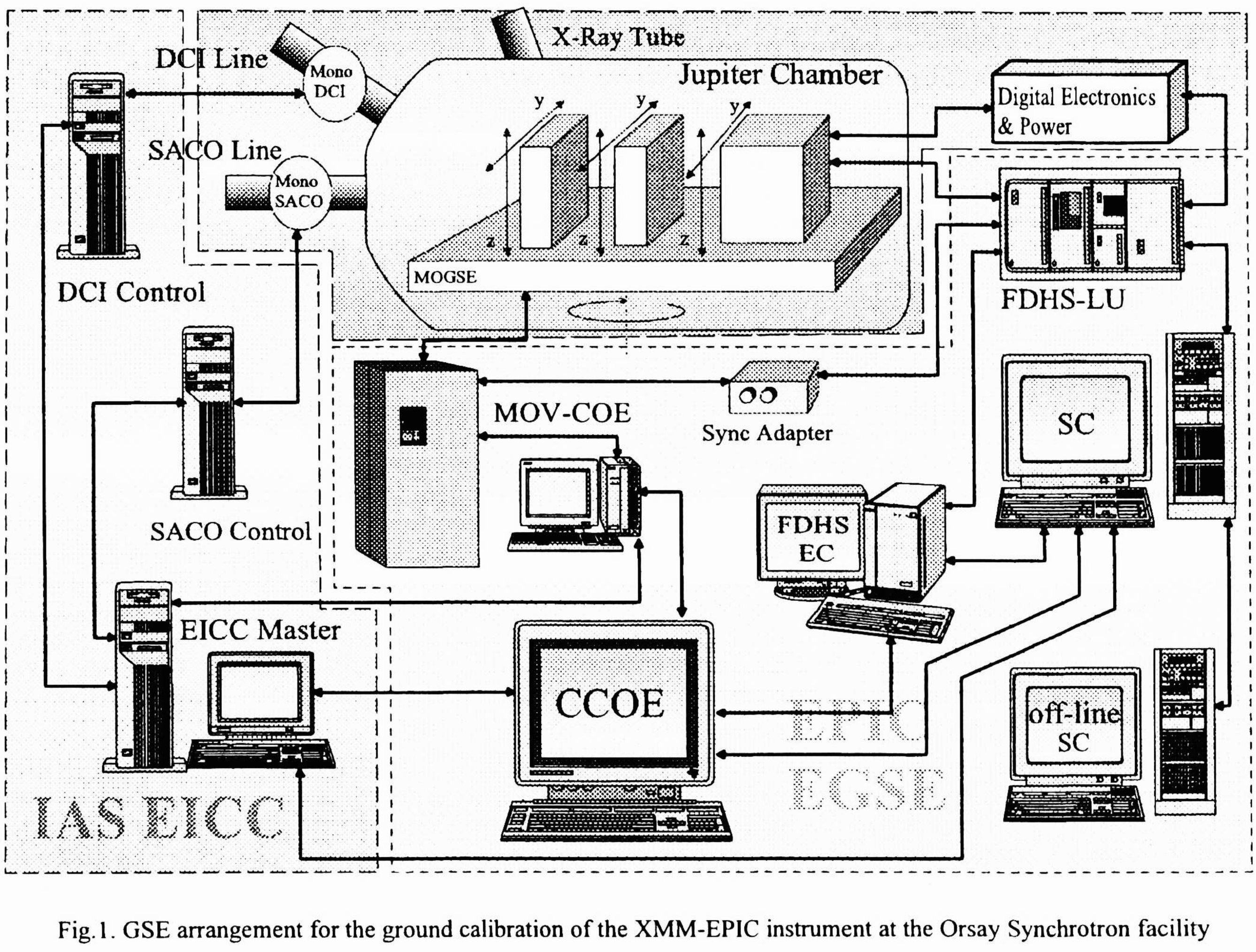

Fig.1. GSE arrangement for the ground calibration of the XMM-EPIC instrument at the Orsay Synchrotron facility

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5. EPIC ELECTRICAL GROUND SUPPORT EQUIPMENT (EGSE)

A number of networked computer-based apparatuses have been provided to specifically support the operations to be performed on the EPIC camera during calibration at Orsay and to provide overall control of the whole calibration procedure: the EPIC Electrical Ground Support Equipment (EGSE).

Fig. 1 above shows how the EPIC EGSE is integrated in the calibration apparatus: the *Central Checkout Equipment (CCOE)* provides the Test Conductor Console, the *Movement Checkout Equipment (MOV-COE)* interfaces to the MOGSE and allows local and remote control of any positioning inside the Jupiter tank, the *Fast Data Handling Simulator (FDHS)* controls the EPIC camera and forwards to the *Science Console (SC)* all the HK and Science data in order to be archived and inspected for quick look purposes.

The solution adopted on the CCOE in order to coordinate the execution of different Calibration Phases constituting a given Calibration Procedure is based on a Master Test Sequence (MTS) running under the TESLA environment. The MTS contains *sub-routines* devoted to each elementary task foreseen in the procedure. They are executed in the sequence defined in the configuration file prepared for the given Calibration Procedure to be performed, using an interpreted meta language. The MTS executes all the operations defined in the configuration file for each energy value specified by the operator in the energy file. This approach allows the user to change the order of execution of the operations and the related parameters by simply editing ASCII files.

Specific synoptics give the Test Conductor the current status of the execution of the Calibration Procedure. His intervention is requested whenever the MTS detects an error condition or a breakpoint is encountered. Conditional breakpoints included in the configuration file can be enabled and disabled at any time by the operator, while the MTS execution can be restarted from any point of the configuration file. In order to carry out the operations related to each elementary task, the CCOE sends a request, through a TCP/IP socket connection, to the relevant equipment and waits until the task completes or terminates in error conditions.

As far as the beam operations are concerned, the CCOE interacts with the Master computer of the IAS EICC system.
Each Beam Calibration Phase is carried out as follows. The CCOE connects to the EICC *Variable Server* in order to set the value of all the required variables: the *energy*, the *protocol* defining the specific calibration procedure, the *run number* associated to the measurement. Thereafter it closes this connection and connects with the EICC *Script Server* to ask for the execution of the beam calibration operations. Once the beam is ready, an EPIC Instrument Calibration Phase is started by the CCOE which sequences all the tasks required in order to set the camera and start the data taking. The CCOE connects to the MOV-COE in order to prepare for the vertical scan to be performed during the data taking:

- the spatial limits and the time to be spent for each vertical scan to be performed at constant speed are defined;
- the trigger mode is enabled and the start scan command is sent in order to start a scan movement when the synchronization pulse is received by the MOV-COE.

In order to command and control the EPIC camera, the CCOE establishes at startup three TCP/IP links with the Engineering Console (EC) part of the FDHS. Every CCOE command directed to the rest of the EPIC chain is forwarded by the EC to the other part of the FDHS, the Local Unit (LU), located close to the instrument. These TCP/IP links are kept open as long as the system is up and running. If necessary they can be re-established at any moment from the EC. Once the MOV-COE has been set up, the CCOE sends to the EC the commands which perform the required changes in the camera configuration (e.g. filter wheel positioning) and, eventually, the commands which start the observation mode. After the required observation time is elapsed, the CCOE sends to the MOV-COE the commands that disables the trigger mode (i.e. completes the current scan movement and waits until the trigger mode is enabled again) and that switches the camera to idle mode. In case further data taking with different EPIC filters is required, the CCOE commands the filter wheel positioning, enables the trigger mode on the MOV-COE and starts a new observation. At completion of the last data taking to be performed with the camera within the current phase, the CCOE terminates the scan procedure and closes the connection with the MOV-COE.

Further beam re-calibration and EPIC instrument calibration phases foreseen in the configuration file are sequenced and controlled by the CCOE as described above. At completion, the MTS restarts the operations from the beginning of the configuration file using the next energy. During the observation, the data taking from the EPIC instrument is performed by the FDHS. The FDHS forwards all the HK and the scientific EPIC data to the On-line Science Console (SC), which archives them in raw format and perform on the scientific data the near-real time Quick-Look and the reformatting into FITS formats. The HBR data are sent by the FDHS LU to the SC on a dedicated LAN, using the UDP protocol in order to minimize its workload.

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Additional TCP-IP connections are established by the SC with the EICC Master computer in order to gather and archive in near real time the HK data related to the beam calibration and monitoring. A set of files is created for each EPIC observation and for the related idle period without requiring any operator intervention. The SC archive is made available through NFS to the off-line analysis workstations and, at the end of the campaign, it is distributed on DAT tapes.

6. EPIC SCIENCE CONSOLE

6.1 Overall Architecture

The SC software for the EPIC calibration at Orsay is based on that developed for the EPIC calibration at Panter[2]. Additional effort was expended to cope with more stringent performance and operative requirements. The EPIC instrument data rate during most of the Orsay measurements is at least 20 kbytes/s, a factor 5 more with respect to Panter. All the operations required to acquire and archive the data in a different set of files for each observation must be performed without any operator intervention as the calibration procedures are sequenced automatically by the CCOE. In addition, HK data from the facility have to be acquired from the EICC with specific modalities not only during the measurement with the camera, but also during the calibration of the beam.

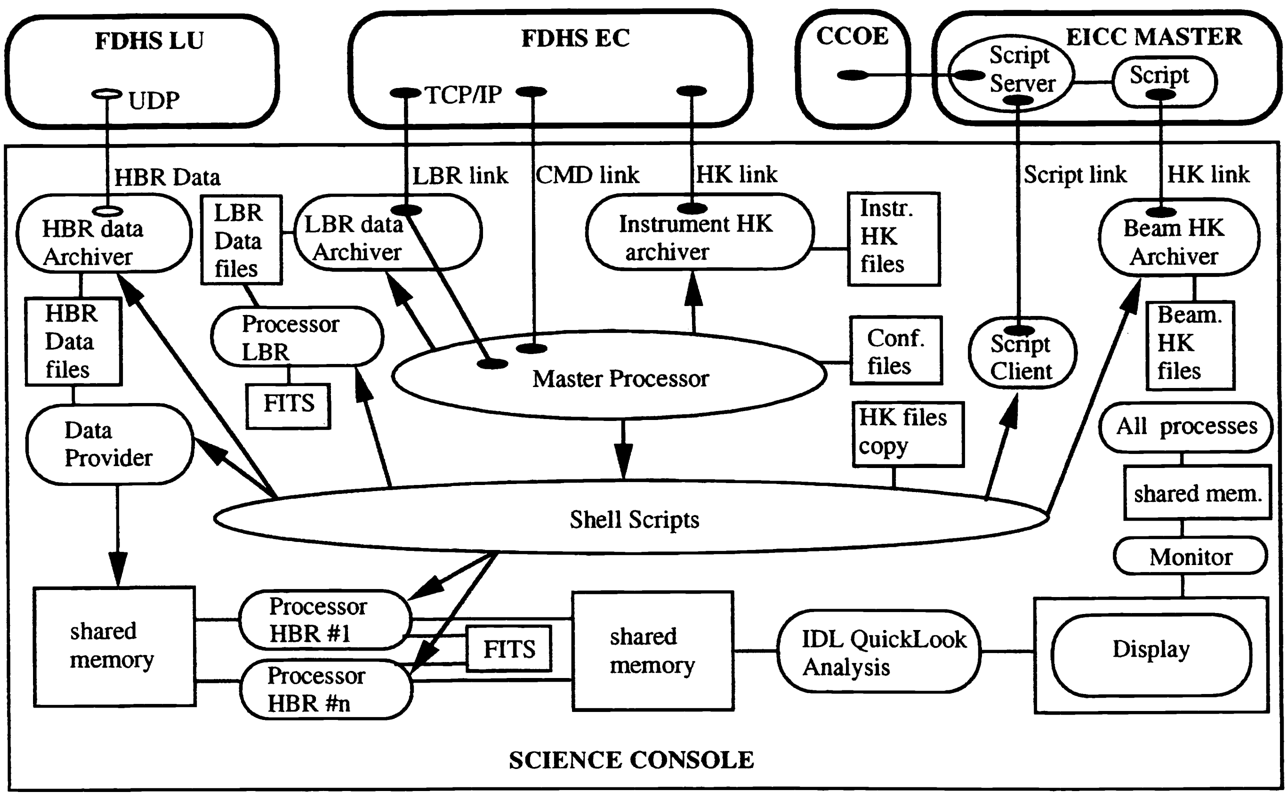

Fig.2. Science Console Software Architecture

As sketched in fig. 2, the SC s/w consists of several programs written in ANSI C and Fortran 77 languages, sequenced by a *Master Processor* (MP) and *Shell Scripts*. At startup, the MP establishes with the FDHS EC three permanent TCP/IP links and starts the two programs which are devoted to the archiving of the EPIC HK:

- the *Instrument HK Archiver*, which acquires from the *HK link* the HK produced since the camera is switched on;
- the *Beam HK Archiver* server, which waits for a TCP/IP connection request from the EICC in order to acquire the Beam HK produced during the beam calibration phase;

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On the *CMD link* the MP receives the echo of the commands directed to the camera in order to start and stop each observation together with the information which defines the operating mode running on each CCD. Consequently the MP prepares the configuration file for the current observation and runs/stops the related programs:

- the *HBR Data Archiver*, which acquires and archive in a single file all the Science data sent by the camera on the HBR lines (one for each CCD in the MOS case, one for each quadrant in the p-n case). This program is composed of two sub-processes: one acquires from the network the buffers sent by the FDHS and puts them in a shared memory which is read by the second that copies each buffer on the disc file. In order to optimize the I/O performances, the former has been divided again into two sub-processes communicating through a message queue.
- the *HBR Data Provider*, which reads from the file and writes to a shared memory the data, separated by HBR;
- the *HBR Processors* which access the raw data with the purpose of reconstructing the CCD photon list and auxiliary information on a Frame and Oservation basis. These data are written both on disc file, using the FITS format, and to a third shared memory which can be accessed and processed by the Quick Look program, as described hereafter. When the end of exposure is detected, the FITS files are closed and the Quick Look program is notified that no more data are available.

The *LBR link* is used in the p-n case in order to send the Offset, the Status and the Noise maps, which are processed by:

- the *LBR Data Archiver*, which acquires and archives all the data in a single file;
- the *LBR Processor*, which is started at completion of the run in order to transform the raw data into FITS format, from where they are read by the Quick Look program.

A fourth shared memory receives from all the processes the information which is continuously displayed by the *Monitor* program to the user for monitoring the EPIC data acquisition. In particular, this alphanumeric display includes for each HBR channel: a buffer counter, the number of events in the last CCD frame; the total number of CCD frames and events, the total number of events or buffer words discarded as pertaining to a non complete frame.

The above arrangement allows the SC to organize the data archiving with a new set of files for each "exposure" or "measurement run", as identified by a progressive number (run ID) included in the file names. The archive is split in two parts: the Raw archive, including all the science and the HK data as received by the SC the EGSE Reduced Data Files (ERDF) archive, containing a copy of all the HK data and of all the FITS files. The latter is accessed on site (via NFS) and distributed on DAT for off-line analysis purposes.

All of the SC operations use the Interactive Data Language (IDL) for the man-machine interface. They are carried out by shell scripts which are activated using two main widgets:

- The CONSOLE widget which launches the Master Processor, the Monitor program and the Quick-Look program, resets all connections and memory areas at startup or reboot, allows the user to perform the playback of any measurement by just specifying the run ID.
- The ARCHIVER widget which allows the operator to move both the Raw and the ERDF from the hard disc to a magnetic optical disc (MO), to inspect each file in the ERDF MO disc in order to produce summary files which are added in the disc itself; to produce a DAT tape from the ERDF MO, to perform the backup operations.

6.2 Quick Look Analysis

The Quick-look analysis (QLA) software is also written using the IDL widget library interface to the X-window system, to perform the graphical presentation and the man-machine interface (MMI). As described above, the Science Console unpacking routine reconstructs entire frames and writes them in a cyclic fashion to an area of memory to which the QLA also has access. Thus, when the QLA reads a new frame, it will always retrieve the latest frame written, skipping a number which depends on the work load on the program.

For the case of EPIC, there are separate interfaces for the two types of camera head - MOS and p-n, and also for the various modes, but herein only the MOS imaging mode is described as they differ mainly in layout and array dimensions rather than in functionality. For the CCD's working in both imaging and timing modes, there are windows which allow a user-defined display of the scientific data, and an area which gives the user information such as the number of frames sampled, the

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number of counts in the images and if any frame overflow is encountered. Each window also has a set of functions in common. These include:

- interactively setting the colour look-up-table for draw items,
- producing a hard-copy of the screen display,
- saving the currently displayed image/spectrum to file,
- pausing the display update,
- interrupting the QLA to go to either the IDL prompt or the UNIX prompt.
- attaching and releasing the shared memory

Furthermore, from these basic modes of operation it is also possible to look at the 'test' mode output such as diagnostic images or offset and variance data or noise data reading from the FITS archive.

In particular in imaging mode (the most common mode of operation), it is possible to have a rough timing display which is used to check the synchronism between the MOGSE movement and the CCD read-out, by checking the total number of events recorded per frame.

The user may pre-select certain items to a desired value before the QLA commences, in particular the upper and lower thresholds for display, the active CCD's to display, and whether to display the energy deposited in a pixel or accumulate the number of counts in a particular pixel. Some of these parameters are set using the appropriate buttons, while others, such as the thresholds and the area of interest to display are set by using the mouse on the spectral and image display areas respectively. Upon commencing, the display is updated automatically with the chosen information. In memory all the information is stored cyclically in a large structure allowing all the parameters of over 360,000 events to be stored. At any time in the procedure the image may be frozen and displayed with a different choice of display parameters, or reset and a new accumulation started with either the same or changed accumulation selections.

7. CONCLUSIONS

The IAS calibration facility hosts a unique set of synchrotron beam lines and associated instrumentation and control software. It has been developed over the last years thanks to the French space agency (CNES) to permit the calibration of the EPIC experiment of XMM. The MOGSE and EGSE, furnished by the Italian part of the EPIC collaboration and financed by the Italian Space Agency (ASI) allowed the calibration team to satisfy the stringent requirements of calibrating a very complicated instrument in a reasonable time-scale at a high data rate and great degree of automatism and so to make full use of the IAS facility. This is an ongoing effort as the third MOS camera is currently (July 98) being calibrated and the second PN camera will be calibrated during the fall of 1998. Other scientific X-Ray instruments could benefit from this work in the future.

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