Recollections of XMM David Lumb

some personal memories of a selection of key points of XMM history

PhD

In 1979 I started a PhD in the the Leicester University X-ray Astronomy Group on the topic of developing silicon CCD (charge coupled device) imagers for X-ray applications in astrophysics. At the time the very first attempts to apply this technology to ground based astronomy were getting under way in the USA. This instrumentation was eventually to revolutionise visible waveband astronomy and lead indirectly to the need for the leap forward in large aperture telescopes.

It was a fortuitous time and place to embark on this topic: Leicester had a strong track record in instrument research and development. An industry co-sponsorship was arranged with a nascent CCD manufacturer, GEC Hirst Research Centre. This was eventually to morph variously into EEV, Marconi and E2V and (arguably as a result of these early investments in UK astronomy projects) go on to provide many of the future state of the art astronomy imagers for ground and space-based applications.

At the same time the Einstein Observatory had just been launched by NASA. The instrument complement included high resolution imagers and a solid state spectrometer. The CCD promised not only to provide natural spatial high resolution through small pixel size, but also if used in a photon counting mode the measured signal would indicate the X-ray energy, with spectral resolution comparable with the Einstein spectrometer. Several groups concentrated on developing the CCD for the future AXAF (aka Chandra) mission. I had demonstrated improved CCD performance by increasing the detection depths of the CCD pixel, so I was invited to Harvard Smithsonian CfA for a year to work on AXAF proposals.

XMM first appearance

In 1985, I had finished the year as Visiting Fellow at the Harvard Center for Astrophysics, but this proposal was ultimately beaten by the eventual providers of the ACIS instrument. I returned to Leicester, continuing developments to optimise CCDs for X-ray applications. A number of colleagues were invited to a scientific workshop in Lyngby, organised by ESA to discuss a future mission design, and I compiled a poster paper highlighting our recent performance improvements.

The mission design coalesced around concepts of multiple thin foil telescopes, but with diverse ideas about the instrumentation for imaging and dispersive spectrometers.

ESA Technology Development Activities

On the back of our promising results, the ESA study scientist (Tone Peacock) pushed for targeted Technology Development Activities in CCDs. These were designed to facilitate key instrument features such as high detection efficiency at low and high energies, using respectively back illuminated architectures, and high resistivity silicon wafers. Leicester University teamed with the manufacturer, EEV, to design, develop and measure prototype CCDs aimed to match the needs of X-ray astronomy in general, and XMM in particular.

XMM Instrument Working Group

A study phase for XMM was initiated, with a Science Study team to define the performance requirements for a high throughput spectroscopy mission. Feasibility studies for telescope systems to meet these requirements were addressed by a Telescope Working Group. Previous concepts assumed a large number of separate High- and Low- energy telescopes, so that it was also assumed that a range of different imagers and spectrometers would be selected. As a consequence an Instrument Working Group was formed to advise on the optimum instrument payload complement. I was appointed to this group to provide expertise on potential CCD implementations.

Over a period of several months, the telescope system was consolidated to seven identical modules. The focal length was selected to allow the required effective area at 8keV. The instruments were also reduced to a simple mix of a dedicated instrument to each telescope: 5 with imaging systems, where CCDs won out over microchannel plates and proportional counters. Two telescopes were to be equipped with high throughput Reflection Grating Spectrometers, rather than a mix of crystal spectrometers and transmission gratings. As an adjunct it was recommended to study a modest coaligned optical telescope to provide a simultaneous visible wavelength monitoring of variable sources.

Choosing the orbit
The detailed technical studies suggested that maintaining the thermal stability of telescopes, and achieving cryogenic temperatures for CCDs would be very difficult in low Earth orbit. A highly eccentric orbit similar to the one pioneered by EXOSAT would alleviate these concerns. A higher observing efficiency than a LEO location was expected to provide a favourable trade-off for the reduced mass launchable with an Ariane IV rocket even though that would limit the number of telescopes from 7 to either 3 or 4.

Experience from operating the EXOSAT MEDA instrument suggested that this orbit could be used above altitudes of 40,000km. Similarly the EXOSAT experience suggested that there should be no enhanced radiation problem, except for the increased dose encountered from transiting the proton belts every orbit. See the later sections for how optimistic this choice turned out to be.

There was now a problem of optimising the mix of imaging spectroscopy and grating spectroscopy telescopes, and I put forward the idea that as telescopes with gratings would not intercept all the radiation focussed by the mirrors, so those (2 out of 4 at the time) telescopes could have CCD imagers at the focal point to receive the straight through beam.

Radiation damage
An important milestone before pressing ahead with releasing the XMM Announcement of Opportunity was to verify that CCDs were capable of withstanding the radiation environment. It was already known that EEV CCDs had withstood a dose of 100krads in experiments at CERN. At Leicester Andrew Holland and I carried out a quick check for performance after a range of modest gamma radiation doses. Immediately an apparent problem was identified that the signal charge transfer properties were sufficiently degraded to destroy the energy resolution. Intense investigation, started at the same time for similar issues for the CCD instruments of HST and other space missions.

Study of this problem spawned whole PhD theses on related topics: establishing the mechanism of bulk displacement damage, design of shielding, changing CCD architectures, optimising operating parameters and methods of annealing. The scale of the issue can be judged by considering that after the mission expected radiation dose, a charge packet of less than 100 electrons might have to pass through a volume containing ~1e15 silicon atoms, where about half a million high energy protons may have created displacement damage and associated charge trapping sites.

EPIC
Following the announcement of Opportunity for the XMM payload teams, a consortium was formed comprising potential CCD suppliers from 3 countries (France, Germany and UK) and a large number of other research groups with expertise in digital electronics, coolers, test facilities etc.. The team was led by Nanni Bignami from Milan. Initially there was intense competition between the different detector advocates, and to greater or lesser extent this complicaed various phases of the instrument development in terms of delaying design decisions or hampering the information flow

between different sub-system developers. There was furthermore intense discussions about which sort of imagng device should be allocated to which of the telescopes (open or grating obscured).

In 1990 I became disappointed with the local (Leicester & UK) concentration on the JET-X payload that had been selected for launch on the Soviet Spectrum X-Gamma mission. The impending collapse of the Soviet Union was taking its toll on the development of that mission, and consequent lack of progress for the UK supplied items to the programme. This all seemd to dilute the attention we could give to the XMM EPIC developments.

Optical Monitor

Therefore I took advantage of the chance to move to Penn State University as Program Manager for Space Missions, which entailed overseeing the US activities on the XMM Optical Monitor, and for the local efforts in the PI team of the AXAF CCD Imaging Spectrometer instrument.

The simple optical monitoring instrument first proposed to the Instrument Working Group had now mushroomed to a very capable 30cm telescope with separate Red and Blue channels defined by a dichroic filter. The detector fields had also grown substantially so that the science driver of monitoring time variability in the prime target source would now be supplemented with the ability to cross-ID all serendipitous X-ray sources seen in EPIC. However the instrument was limited to the spacecraft resources originally allocated for the smaller telescope. The US activity therefore concentrated on a processing unit to manage memory and complex observation modes, all the while compensating in real time for a spacecraft motion expected to be several times worse than the intrinsic instrument angular resolution.

Again the detector choices entailed detailed trade-offs for different CCD options, with attendant concerns about radiation damage. The Red channel CCD was a traditional CCD imager, but eventually removed from the payload due to lack of funding for the Italian sub-system group. The Blue channel was implemented with an image intensifier readout with phosphor coupled CCD.

Instrument Team Leader

As the XMM progressed through phase B activities, ESA set up a Science Operations Team. In 1994 I was appointed Instrument and Calibration Team Lead. Now I was working closely with the EPIC team again, if from the "the other side" of the fence.

A significant portion of the work was to define the science and instrument requirements of the Ground Segment of operations. In 1995 ESA had launched the ISO mission, and due to the short-lived cryogenic nature of that payload, had invested heavily in an operations system to support and maximise the science operations. This led to a large cost over-run, and ESA management were keen not to replicate the experience with XMM. Following the current paradigm, the development contract for software systems was put to an outside contract at firm fixed price. The instrument team were tasked with specifying the science requirememts of the instruments that needed to be enabled by these systems. The waterfall flow of increasingly detailed design and implementation following requirements specifications, was supposed to lead to an implementation without further input from our team. However the industry needed more and more clarifications to understand implementation details, and to solve the number of Review Item Discrepancies that we identified at each milestone in the development. The SOC Team were forced to provide pseudo-code, test harnesses and specimen data to help industry progress. Subsequent deliveries of operations subsystems did not meet expectations, and the experience certainly hampered the early years of in-orbit operations.

Calibration

The Instrument Team were charged with capturing the instruments' expertise in calibration. However initially there was not a system-wide plan for the calibration.

The AXAF project ***had*** established a system wide Calibration activity with a flow from science requirements, apportionment to instruments and mirrors, with overall end-to-end calibration to be carried out under the Project Office at the XRCF in MSFC Huntsville. The aim was to achieve a '1%' calibration.

The XMM team took benefit of their overall approach, and with participants from the Science Working Team and Instrument Teams attempted to define driving science requirements, in-orbit calibration standards and possible distribution of calibration accuracies between the mirror systems and the focal plane detectors. Unfortunately this effort was considered to be rather late to have any influence on the ability of instrument teams to secure specific funding for new ground-based calibration activities. Furthermore, unlike the NASA AXAF case, there was no formal agreement or MOU between agency and PI teams on calibration deliverables.

The mirror system WAS however considered to be under ESA control, and through the use of a Project-procured vertical test facility at CSL Liege, and the co-operation of the Telescope Scientist (PI role of B Aschenbach at MPE) to measure the mirrors at the Panter facility in Garching, there was a comprehensive programme of testing the mirrors. Rather than calibration, this work was concentrated on supporting the development of mirrors for meeting the angular resolution requirements. There was a huge effort understanding discrepancies in measured focal length (necessary for locating the gratings and focal planes correctly) and apparent loss in effective area compared with geometric models. The difficulty for Panter in particular came from a finite source distance, where ~30% of the mirror surfaces could not be illuminated. The tension between needs of the Project Team and the scientific calibration requirements led inevitably to prioritisation of engineering and schedule at the expense of the detailed calibration.

The SOC team invested heavily in a model-based description of the payload system to support this work, and to aid translation of the ground calibrations into in-orbit conditions. This Science Simulator - SCISIM - was also invaluable in providing test data to exercise operational software. However the large number of instrument data anomalies could not be translated into the physical model, so that its comprehensive use for in-orbit alibration was never realised.

Lifetime

The issue of mission lifetime became a hot topic. There were no real worries about consumables that could limit the life of XMM, other than the expected degradation in performance with accumulating damage. The nominal lifetime had been declared as two years, where the industry teams would be reluctant to guarantee a longer life without significant (expensive) work qualifying and verifying designs and electronic parts or mechanisms. Scoping the observing programme to include commissioning, calibration and verification phases showed that the amount of time left for general open observing programmes would be unacceptably short. We suggested the constraint could be circumvented by formally declaring the lifetime as 2 years AFTER end of calibrations, (formally 2.25 years total) thus not having to revisit any significant technical and programmatic decisions.

In the end, following some initial infant mortality failures, the mission has kept on performing. However some challenges resulting from this include the difficulty in sustaining long term commitments from skilled staff and resources (e.g. in the SSC) and the need to modify outdated infrastructure. Nevertheless the long life is no doubt due to excellent robust design decisions and commitment from hardware teams, Project and Industry.

Mirrors Technology Choice
The requirement for angular resolution better than 30 arcsecond Half Energy Width and effective area specified at 1 and 8 keV had driven the choice of mirror fabrication technology towards replicated shells. At the time of mission adoption the concept chosen was a carbon fibre wound shell with smooth epoxy surfaces. Development models were approaching the required performance, but after environmental tests under vacuum and thermal cycling this performance degraded unacceptably. The project was forced to consider changing to a nickel replicated shell technology, that had been successfully demonstrated on the JET-Xproject.

Confirming that decision was challenging as the mass of such shells was significantly greater than for the carbon fibre versions, and the available spacecraft mass limited with an Ariane IV launcher. In the end skillful negotiations by the Project Manager allowed a change to Ariane V and with that the mass limitation solved to allow this change in mirror technology. It is interesting that the current paradigm of Technology Readiness Levels (TRL) would not have allowed such a brave decision. We should perhaps learn that rigid TRL definitions are no substitute for informed judgements of risk/benefit analysis!

Spacecraft Mass
As with any space mission, the issue of payload mass was always critical. The initial payload resources had been defined in the era when 7 telescopes were the baseline, and redundancy within instruments thought not to be required. After the Announcement of Opportunity, and only 3 telescopes were considered the instruments had to provide for cold redundant systems as much as possible, increasing their unit mass requirements. At every Science Working Team meeting the Project Manager would show the gradually increasing declared payload mass and the limited spacecraft mass budget, showing the critical nature of the problem.

Towards Launch
The spacecraft development phases B & C proceeded well with relatively minor delays to the schedule. It was apparent that launch would be towards the end of 1999. In common with all large organisations at the time, this raised the interesting problem about what to do to counter possible effects of the 'Millenium Bug'. Were the ground systems robust against this? Would there be on-board software problems? After some debate it was decided it would be best to launch early, and if necessary fix ground software problems while the spacecraft would be idle in orbit. Although this was counter the instrument teams' argument that the payload could irreversibly be damaged by a solar flare before being able to make key observations. The Project team arguments won out, and launch was set for December 1999.

In the summer of 1999 came disturbing rumours from the Chandra project, that the CCDs of the ACIS instrument had suffered rapid radiation damage. With the full co-operation of the project teams of both missions, a workshop was convened in Penn State University in the autumn. The Front-illuminated versions of the ACIS CCDs had been damaged at each perigee passage, significantly degrading their charge transfer properties. It was confirmed that in order to limit the number of operating cycles of the CHANDRA instrument exchange mechanism, the ACIS had been left at the mirror focal plane, and soft protons scattered and focussed through the mirror system during proton belt passage onto the detectors.

XMM instrument teams fully cooperated with modelling and measurement campaigns to verify this explanation. This analysis showed that the RGS and EPIC PN detectors would be largely immune due to being of back-illuminated technology. For the EPIC MOS it was decided to close their filterwheels at each perigee, noting that the wheels were qualified for ten's thousand of cycles.

Up Close and Personal
Towards the end of assembly and test operations at ESTEC, the EPIC PN team requested a visual inspection of the camera location. Their CCD quadrant architecture required the telescope aim point to be deliberately set a few mm away from the dead space cross in the middle of the array. They requested to inspect the camera head location on the spacecraft platform, to ensure the instrument was located with its prime quadrant in the correct location. Ulrich Briel traveled to ESTEC to do carry this out and as EPIC instrument responsible person in ESTEC, I was delegated to accompany him. The whole satellite was assembled vertically in one of ESTEC's clean rooms. Passing close by the satellite and seeing up close the thermal blankets swathing the telescope tube and the instrument bays was an almost poignant goodbye to friend about to be sent out into hostile deep space. We ascended the scaffold to the top of the satellite (actually upside down with mirrors facing the floor). It was a truly tremendous view of the enormous beast - the largest scientific satellite ever assembled in Europe. We carried out the required inspections, then had a near disaster as a loose power cord connected to a vacuum cleaner on the scaffold platform caught my foot and nearly caused a trip. Visions of a falling scientist careering into the side of the precious cargo briefly flashed through my mind, but safety precautions held up.

Launch and Early Orbit experiences
The number of attendees at the Kourou launch site was sufficiently regulated that none of the Science Operations team could attend the festivities of early December 1999. According to language or specialism, several of us were deployed to different ESA offices to provide local expertise or commentary for the launch day. The indescribable tension, knowing that 15 years of commitment to one project might be vapourised in one malfunction was almost unbearable. However this first commercial flight of Ariane V proved faultless, and XMM was on its way.

Over the next few days there were frequent updates and reports covering the essential sub-system deployments, RF contacts, orbit raising manouvers etc.. Particular interest came with the activation of door opening mechanisms for each camera: one by one each of the 5 doors were successfully opened.

On 4 January the activation of the instruments began. First Light for the Optical Monitor came almost immediately. Extensive checks of internal calibration sources and monitoring of the in-orbit background and radiation were carried out to be sure the instruments could be opened to the sky. EPIC MOS started on 16 January, the EPIC PN a week later and RGS at the beginning of February. Procedures to check the onset of high proton background were developed to ensure no repeat of the CHANDRA experience.

In addition to the cautious start, the heavy workload of spacecraft engineers coping with the commissioning of new software systems dictated the slow start to the mission. An example came with the first light image of EPIC PN, which was a frustrating experience. Coming out of perigee, all instrument set-up procedures were carried out and we awaited the appearance of an accumulating image in real-time on the Quick Look Analysis system. A small t appeared, hen apparently everything stopped. It eventually was diagnosed that the majority of X-ray events in the downlinked data stream were very low energy "partial events" ascribed next to their main pixel. The engineering restrictions of the industry-provided QLA had restricted the memory size for accumulating events, and therefore was not adequate for this simple imaging task.

Eventually the first light press-conference was held on 9 Feb 2000, and the new name of the mission - XMM-Newton revealed. Then the Calibration and Performance Verification phase began. In parallel instrument anomalies were investigated and ironed out, and the science analysis system modified to include algorithms and experience of the instrument teams.

In setting up proceedures to avoid high proton fluxes, it was realised that rather than the 40000km altitude expected from EXOSAT, high rates were being experienced out to 70000km, forcing a shorter observation window than originally proposed. It further became apparent that episodes of high background rates could be experienced anywhere along the orbit, and for a wide range of durations. Although adoption of safe filter wheel opening strategies seemed to alleviate concerns about damage, the latter "soft proton flare" phenomenon unexpectedly ate into the usable exposure durations, especially for low surface brightness imaging observations. This could persist for up to 30% of exposure durations. The soft proton flares have been attributed to magnetic reconnection events around the Earth's magnetopause, but also to charge exchange mechanisms between the solar wind and residual neutral atoms in the heliosphere. Location along the orbit, viewing direction, season and energy range all seemed to be important and complex variables that took a long time to decipher

An additional radiation issue was a higher than anticipated background. Outside the radiation belts, the Earth's magnetic shielding is not affective against Galactic Cosmic Rays. Therefore the intrinsic background is higher than for traditional low Earth orbits used in most earlier X-ray astronomy payloads. Despite the very high rejection efficiency of primary particle events, it now transpires that secondary electrons are likely to be the cause of elevated background in both XMM-Newton and Chandra, and sophisticated graded density shielding would be needed to ameliorate this.

An immediate request from the Project Team was to measure the mirror Point Spread function - not for calibration, but to confirm that the performance requirement was met, allowing a milestone payment to be awarded to the spacecraft contractor for achieving the key performance goal. Next it was necessary to properly calibrate this parameter in order to have a complete description of the encircled energy function as part of the effective area calculation.

An isolated point source with simple spectrum turns out not to be easy to select: To accommodate a reasonable S:N ratio at the higher energies implies a very bright flux at lower energies and, for photon counting CCDs, an excessive pile up and flux loss in the core. For fainter sources, the high background and excessively long exposures mitigated against completing the PSF calibration in a timely manner.

It is perhaps not surprising that the on-going calibration efforts are still refining the PSF, and its consequent application to effective area measurements also complicate the overall spectral response. It was originally thought that having 5 co-aligned X-ray imagers and spectrometers would be a strong lever via cross-calibration to achieve an acceptable calibration accuracy. In fact this feature just highlights that their different systematic unknowns must interact with the complex astrophysics of the 'standard candle' sources and render this task never-ending.

The long lifetime has allowed XMM-Newton to investigate far more science topics than originally envisaged. Furthermore these often place more stringent requirements on performance and calibration than were ever considered necessary and the 1980's and 90's. However I believe it is a testament to the vision of XMM-Newton's first advocates, its detailed designers, engineering teams and community payload teams that it continues to be productive beyond the original expectations.

Future Missions

It is also important to capture the experience of the mission cycle for the next family (Athena and Lynx) of X-ray astronomy. As Athena Study Scientist I could already testify that the whole Assembly Integration and Test methodology for XMM-Newton has been adopted to scope the Athena system studies. The careful lessons learned from XMM-Newton contamination control are being adopted into the telescope and instrument designs. The calibration of the Athena telescope is being engineered directly into build and assembly phase so that it is not an afterthought. Thus the XMM-Newton heritage will persist even beyond its potential late 2020's operations and into the 2030's when these future missions will inherit lessons learned.