Recollections on X-ray Optics and satellite developments for XMM-Newton
Robert Lainé, with support from Daniel de Chambure
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Background

My engineering education is in Radio Electronics and Electric-mechanical. After developing equipment in industry for TD1A and ESRO-4 satellites, I joined then ESRO-ESTEC and eventually ended up in EXOSAT Payload team led by Brian Taylor and Reinhold Zobl, along side Hans Eggel, Dave Andrews and others. The issue at the time was for the payload team to develop two lightweight X-ray telescopes beside some of its detectors. Having some mechanical industrial experience, albeit a bit far from optics, I ended with that task together with EXOSAT Telescope Scientist Piet de Korte from Leiden University.

Then, once the X-ray development saw under control, ESA management moved me to Giotto in Dave Dale team. Later on I went back in Industry, this time in Telecommunications Satellites, a bit closer to my background. Life went on and in 1992, while I was posted in California, I met again with Prof. Roger Maurice Bonnet and Dave Dale, and they explained that they had a problem with XMM X-ray optics which development was not progressing. Clearly, they wanted to tease my memory on what I did for EXOSAT telescope. I thought about it and when we met again next morning, after some discussion on the current development status and what I remembered from Exosat, they asked me if I was willing to come back to ESA as project manager to lead XMM. Another change of direction in my career ? After some discussion with the family, I said yes why not, went for an interview, was selected and then moved back from California to Toulouse, pack our household and hit the road again for The Netherlands.

That is how I ended up at the deep end of XMM-Newton[1] !

My early days on XMM

When I arrived to ESTEC, I found new buildings everywhere ! Obviously the place was thriving !

When I met some people who I had known in EXOSAT and GIOTTO days, I was a bit surprised to observe that the way business was conducted had not changed much apart from being more bureaucratic than I remembered.

The first meetings with XMM team was another shock. People were defensive and full of certainties but not really facing the reality that progress had been very limited. The way the team operated with each individual looking only at his field was for me a bit awkward compared to what we had developed in industry in terms of human relations and project management style.

Bottom line, I had the feeling of having gone back to the past and I started questioning myself on the wisdom of my move back to ESTEC ! Some face to face discussions with Prof. R. M. Bonnet and D. Dale, convinced me that I would have a relatively free hand for reshaping the team and the project.

My list of priorities for the project success was then established in the following order:

1 In orbit, XMM was renamed XMM-Newton.

1. Develop an X-ray optics, which worked and find a launcher with sufficient capacity to put XMM-Newton in a 48h orbit with apogee in the northern hemisphere to minimise operations cost.
2. Once 1 was under control, and the team looking forward, write the call for tender for satellite procurement with a flat industrial organisation instead of the usual ESA project mille-feuille. The ultimate objective being to save some management overhead in industry which amount to about 20% per layer and launch XMM-Newton corner stone mission in 1999.

On the human side, I am grateful to Franck Danesy from ESTEC Human resources for providing us with a very good coach namely Terry Ostroviak. Terry was instrumental to turning the individuals from being defensive to thinking positively about the challenges facing us, namely success of a mirror technology or abandoning the project. He ruffled many feathers and habits and took us all out of our comfort zone to good effect and always in a nice way. After that, the team functioned well.

X-ray optics development

Despite all the work done so far, we did not have a working solution. Piles of paper on theoretical considerations and a priori, but no measure of performances at each step. To break that runaway situation, I first cut off all work not directly related to the X-ray optics as without mirrors, it was meaningless to work on the spacecraft, and dived in the details of the current process being promoted for the mirrors: a Carbon Fiber Reinforced Plastic shell replicated over a super polished master mandrel. The principle was similar to what we had done for EXOSAT, but with an important difference: the EXOSAT shells were made of Beryllium with a polished internal face while CFRP was used for XMM. The other main difference was that for EXOSAT, we had put in place a step by step verification of the polishing of both the shell interior and the master mandrel before laying the reflecting the gold layer on the mandrel and replicating it in the Beryllium shell.

Another surprise came when questioned, both the in-house expert and Zeiss team producing the master mandrel stated that there was no way to "see" the quality of an X-ray mirror surface being polished! I had to dig the 1975 Applied Optics paper of Piet de Korte and myself showing how we did it then… which caused a bit of uneasiness in the audience… I then imposed that the polisher be equipped with a Zeiss Nomarski phase contrast microscope such that he could visualise progress during polishing, and explained the meaning of what we saw of the surface being polished. Very quickly indeed the quality of polishing improved, leading to reproducible very high quality of mandrel surface. This was achieved in less than a year.

Now, having a good master mandrel is one thing, obtaining a good X-ray mirror from it is another thing. Here we were caught by the need to have very thin and very light shells to achieve a telescope mass compatible with the payload capacity of Ariane-4 launcher selected years before.

From past experience of EXOSAT, I had doubt that the epoxy replication inside the CFRP shell would work, in particular for High Energy X-ray. That is what I had said to Prof. Bonnet in California. My main problem was that in-house experts, the Telescope Scientist and other experts were convinced that there was no alternative technology available… Such a conviction statement is always for me a flashing red light as it is often just a cover for not really wanting to look for an alternative to what they are working on. By then, I had recruited Daniel de Chambure who had some experience of technology development in industry, and we went on a tour of various labs working on X-ray optics to see what was done elsewhere. Eventually we went with Prof. Citterio to a small workshop near Lecco (Italy) where Roberto Villa was developing small X-ray mirrors in nickel electrolytically deposited on a mandrel for Jet-X telescope[2]. It was very interesting to see that the nickel surface micro-roughness was identical to that of the mandrel. However, the process was not very well controlled and sometime the result was a failure with destruction of the mandrel. Humm, still some work to do!

Another disturbance was that the workshop were these nickel mirrors were developed, soon appeared to be going bankrupt and with it, all the nickel replication development would be lost. A quick analysis of the situation with ESA management and ESA contract department (in particular Pierre Reynaud) showed that for very little money we could help Roberto Villa to extract immediately the nickel replication tools from the workshop going under, of course with the explicit agreement of the workshop owner and lawyers. The outcome was the creation of Media-Lario company whose sole customer was initially ESA, to develop XMM full size nickel replicated mirrors such that we could do some comparative tests with the CFRP mirrors which development continued as per initial plan.

Daniel de Chambure spent a lot of time in Media-Lario to organize the removal, to guide the new plant setup, to restart the manufacturing and then help put under control each step of the nickel mirrors production process.

By beginning 1994, we had two potential solutions to make X-ray mirrors replicated from Ni coated Aluminium master mandrels. Meanwhile, Henrich Brauninger of MPE did set up the Panter facility in Neuried (close to Munich) to be ready to measure the scattering function of the mirrors with real X-rays, not just by comparison of roughness measurements.

When the CFRP mirror went in the vacuum facility it showed a good focal image, but next day that focal image was much wider and the following days it had almost disappeared! What happen is what I feared, the Carbon fibers weaves were printing through the epoxy layer supporting the X-ray reflecting gold film. Basically, the epoxy was drying and shrinking with time. It was the same print through problem which had led us to polish the Beryllium shells used for epoxy replication of EXOSAT mirrors, unfortunately physics had not changed in 20 years and CFRP could not be polished!

As a side anecdote, for FIRST[3] telescope primary mirror, NASA wanted to sell ESA a similar CFRP technology as their contribution to the project. We told them that our experience was that it would not work and therefore we would keep active the polished Silicon Carbide technology available in Europe as backup. Physics worked again and ESA developed and flew the SiC mirrors.

We waited anxiously for the first full size nickel mirror to arrive. That mirror was immediately put in Panter facility and the focal image was good and stable over time! Everybody was relieved that one of the technologies was working.

Now the challenge was to develop not one mirror but three time 58 mirrors, a serious industrialisation undertaking for Media-Lario which did require some change in management and the take-over of Media-Lario by Kayser-Threde in 1995 which had experience and capability in

2 Joint European Telescope for X-ray astronmy (Jet-X) xas to be constructed as part of Spectrum-X-Gamma project and completed in 1994, but never launched. It is now on display in the Science Museum, London.

3 FIRST became Herschel

space engineering needed to ensure success of the project. Axel Schmalz initially and later Arnoldo Valenzuela made sure that the necessary Quality Assurance and management was in place and maintained in Media-Lario. Beside the mirrors we had to find a contractor to machine the extremly accurate mirror support structure. André Pugin, CEO of APCO (Switzerland) and his Technical Director Claude Jabaudon with their network of high accuracy machining companies were the only one prepared to take the challenge and they succeeded.

But, the selection of the nickel mirror technology had some non negligible side effects:

- The mass of the optics was significantly higher than what it would had been in CFRP. If we wanted to stay with Ariane-4 then would have to keep only one telescope instead of three and that was something the scientific community did not like. The alternative was switch to the new Ariane-5 launcher which had the capability of launching 4000 kg in the required 48h orbit, but was not yet fully qualified. ESA management had the guts to support that expansive choice for the benefit of the scientific community.
- The higher mass of the mirrors meant that their shape was sensitive to gravity. All the computation done in house were showing that the optical quality of the assembled 500kg module of 58 mirrors was affected when the mirrors module was in horizontal position (gravity perpendicular to the optical axis). The only case where the optical quality of the module was that of orbit zero-G situation was when the mirrors module was aligned with gravity, again physics was playing against us but at least we recognised that physics would win and we did not fight it. Additionally, the point source of Panter facility didn't allow us to fully illuminate all the mirror surface and especially the edges which are generally distorted. All that meant that in order to fully verify the quality of the optics prior to launch, thereby avoiding the trouble encountered with Hubble, we needed a vertical collimated beam able to illuminate the full aperture of the module. Unfortunately, the MPE Panter facility was horizontal and turning 90° its 100m long tube was not very practical! After some frictions with MPE, the solution agreed in 1994 was to develop a vertical EUV beam and split the final verification of the modules in 2 steps: measure its overall image quality at as far in EUV as possible then measure its scattering function at X-ray wavelengths in Panter facility. More work to be done to develop a vertical EUV beam (so called FOCAL X) in Liège University CSL facility and all the tooling, containers and logistic necessary to be able to safely transport the super clean modules and test them in Liège then in Neuried. Of course, all of that to be done fast such that XMM could still be launch in 1999. But that did not worry me as working faster is actually a good way to keep the team focused and save cost for the project. It simply meant longer days for everybody and by then, the team had changed to being very positive and prepared to take any challenge head on. A state of mind, which carried us to the end of the project.
- Last hurdle discovered on the way: The back side of the nickel shell was also reflecting and created an unintended path for straylight. To suppress that stray light, a baffle made of Invar had to be designed and produced in a short time. SENER (Spain) had a high accuracy electro-erosion technology which worked very well and saved the day.

At the end, the XMM flight model mirror modules were delivered on-time in December 1998 at ESTEC, for their integration on the S/C.

The payload development

While we were struggling with the X-ray optics, the payload instruments EPIC under the leadership of Giovani Bignami intially and Martin Turner later, RGS under the leadership of Bert Brinkman, OM under the leadership of Keith Masson were making good progress. It was good to have in the team Hans Eggel, which I knew from EXOSAT days, as he knew well the instruments, PIs and CoIs. It meant that I could concentrate on the X-ray optics and the rest of the spacecraft. The few times I had to look into some aspects of the payload were related to mainly to its interfaces with the rest of the spacecraft or planning issues. Apart from that, I enjoyed the regular meeting with the scientific community as it was a time were I would always learn something new about the purpose of XMM-Newton, a rare pleasure in the life of a project manager who is normally showered with recriminations from all sides !

Hans Eggel, Georgio Bagnasco, Stephan Thuerey and Fabio Gianini, would certainly be persons to be interviewed to know more about XMM payload development anecdotes seen from ESA side.

Associated with the payload development was the Science Operations Center a development essential to operate the instruments which did not progress well. The initial idea was that a group inside ESA Space Science department would develop it internally. However, that team did not have the resources and experience for developing what is essentially a very large software and, 2 years before launch, it became apparent that we would end up with either a satellite not operational scientifically or a long launch delay. After some hot debate, we decided to commission ESOC to take over the task of development of the Science Operations Center and work with them to define all the functions required. Howard Nye, which I knew from GIOTTO days, was instrumental in managing that task while maintaining reasonable relations with key players of the scientific community to simplify and formalised the Christmas list of wishes...

The spacecraft development

Having postponed all spacecraft contracts until after development of the mirrors technology, we had only 4 years left until end 1999, date promised for the launch XMM-Newton. Here again, with ESA management support, we deviated from ESA usual procurement policy. First we had found that industry prime contractor was not really prepared to take the risk associated with the development of all X-ray mirrors modules. They had their fingers burnt with the CFRP development and did not master any step of the nickel mirror technology. It was then obvious that ESA would have to provide these mirrors modules as customer furnished equipment just like the payload instruments built in scientific institutes. From there on, we wrote a simple and clear set of requirement for what industry could do best: provide a robust spacecraft platform which could carry the heart of XMM mission, its instruments and optics.

The next step was to convince many that to save money, we had to impose to industry a flat industrial structure as each management layer was typically adding 20% on cost through direct cost and delays. However in ESA there is the “juste retour” rule which means that each contributor expect to get its contribution in equivalent work, fair enough. However, over the years that “juste retour” had been interpreted by some contributors as getting a flagship return in the form of a sub-system management layer tailored to his country industry. Experience from industrial competitive bids on international business had teached me that the cost of artificial sub-systems layers on what is in the end a single piece of hardware was dear. Convincing everybody of that wisdom was not easy…

After a tendering process, ESA selected Dornier (based in Friedricshafen, Germany) as the prime contractor offering the best and cheaper platform. Under the leadership of Alan Hawkyard then Jan van Casteren on ESA side and of Uwe Minne and Gunter Hampel on Dornier side, the spacecraft development, assembly and mechanical-thermal-vacuum tests went smoothly at Dornier plant (Friedrichshafen-D) and at ESTEC with all reviews taking place according to schedule plans.

A challenge for the spacecraft development was the telescope tube connecting the instruments to the mirrors modules. Despite having a more powerful launcher, we still had to watch carefully at the mass of everything. Clearly, CFRP technology would be required but this time we were aware of the issues of humidity absorption and desorption with epoxy resins, and industry came up with a clean and simple solution to ensure that CFRP humidity and outgassing would not end up on the cold detectors.

Worth of note, we developed for the first time a S/C working gyro-less in nominal mode, following several lessons learnt the hard way on SOHO and other spacecrafts… Many experts doubted that strategy, but it worked, and in addition Hubert Barré managed the new generation gyros development contract to deliver gyros which still operate after 20 years of ON/OFF used for certain maneuvers around perigee or in case of on-board emergency.

However, alarm was raised one year before the launch during the spacecraft thermal vacuum test. Oh well, space development is never short of exciting surprises! This led to a complete rethinking of the thermal control of the deck supporting the mirror modules, including the implementation of additional heaters on the platform and the need to carry out additional thermal vacuum tests to validate the new concept.

Finally in summer 1999, XMM was completely assembled in ESTEC, after another scare which led me to put on a clean coverall mask and hat and climb in the telescope tube to inspect small bubbles indicating local delamination of the aluminium skin acting as a vapour barrier. To stop that delamination propagating during launch ascent after a short meeting with Uwe Minne we decided to drill small holes in the outer skin of the telescope tube to make sure that during lauunch the transient differential pressure on theses bubbles would be in the “right direction”. Our team Motto “finding a simple solution to a complex problem” worked again!

Launch campaign

The launch campaign started with XMM fully assembled, cocooned in its very large superclean container, with a road trip road behind the local Police from ESTEC to Katwijk. Then on by barge on the Dutch canals from Katwijk to Rotterdam to board on September 12th,1999 Ariane transport ship Toucan, destination Kourou. Boat trip for spacecraft are very unusual as “normal” spacecraft are small enough to fit in a cargo plane.

Launch campaign went quite smoothly under the leadership of Philippe Kletzkine despite the fact that various experts were extremely reluctant to fly our “black jewel” on the fourth Ariane-5 following initial failures. We even had to convince the launcher experts until last minute that our spacecraft will withstand the predicted acoustic noise and various shocks produced by the launcher during lift-off and at stages and fairing separation. These shocks were in reality much over stated, the usual margins on margins backside covering exercises.

Finally, thanks to Ariane-5 power, XMM fuel tanks could be loaded to the top, and everything went smoothly during launch on December 10th, 1999 at 14:32 UTC. The Arianespace party in Kourou was very nice and, tradition oblige, Uwe Minne and myself ended in the swimming pool of the Hotel des Roches: job done!

The spacecraft was then hibernated in orbit to outgas and remove all traces of humidity from the telescope tube before opening the instruments covers and checking out everything. I remember foundly the shinny eyes of everybody in ESAC control room while the first X-ray image was building up slowly on the monitoring screen of EPIC cameras, on the cold night of January 16th, 2000: it worked!

After that, it is the continuing history of a very successful Corner Stone mission of ESA Science Programme: a world wide class X-ray observatory operated by ESOC and ESAC.

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I am grateful to Professor Roger Maurice Bonnet for having given me the opportunuity to work on XMM-Newton, working for the Science community is a privilege.

I am also grateful to ESA-ESOC-Dornier-Industry teams for their hard work, putting together such spacecraft and operating it within budget and on time!

Some reading for details of XMM-Newton X-ray optics :

SPIEs 1998 Annual Meeting San Diego (paper 3444 25) : The X-Ray Telescopes for the ESA XMM Spacecraft.

International Symposium on the Optical Design and Production - EUROPTO Series 1999 – Berlin (Germany) – Plenary Session : LESSONS LEARNT FROM THE DEVELOPMENT OF THE XMM OPTICS .