SRON's TES Microcalorimeter:

A brief summary of its technological history.

1 Introduction

The 15-year development of the European interpretation of the Transition Edge Sensor (TES) microcalorimeter is described within this document. In essence, a TES microcalorimeter is a high-resolution cryogenic photon detector that converts temperature changes induced by incoming photons into changes in electrical resistance. Conceptually, the device consists of an absorber, a detector, heat sink, amplifier, and a current loop. When a photon strikes the absorber-detector pair, its energy is converted into heat and the temperature of the detector increases. The detector, which resides at the transition point between the superconducting and non-superconducting state, undergoes a significant and measurable change in its Ohmic resistance profile. As a result, the photon's energy can be measured very accurately by the change in electrical resistance of the detector. [D1] After the photon is absorbed, the resulting heat is removed from the system by a momentary reduction of the electrical power that is fed into the detector, thus returning the system to its pre-measurement state. Since the TES microcalorimeters can be produced using lithographic techniques, they can be made into imaging spectroscopic arrays, thus enabling efficient and high quality astronomical observations.

Netherlands Institute for Space Research (SRON, formerly *Stichting Ruimteonderzoek Nederland*), a research institute under the Netherlands Organization for Scientific Research (*Nederlandse Organisatie voor Wetenschappelijk Onderzoek*, NWO), has been the prime mover with respect to TES development in Europe. While the intended application of the TES devices has always been X-ray astronomy, the specifics of the target mission has evolved quite substantially in terms of its context within the ESA program, the scope of international contributions, mission architecture, and relative priority. In order to understand some of these interactions, it is helpful to quickly review SRON's history and its institutional position within the Dutch space context.

Dutch space activities stem from a long and rich history in astronomy. A firm understanding of the celestial movements and world-renowned expertise in cartography contributed greatly to the strength of the Dutch naval fleets in the 1600s. Modern Dutch astronomers include Gerard Kuiper and Jan H. Oort, whose names are recognized both by those in the field of astrophysics, as well as by the general public.

Around 1960, COSPAR president Henk van de Hulst, a colleague of Oort, formed the Netherlands Geophysics and Space Research Committee (*Geofysica en Ruimteonderzoek Commissie*, GROC). [D2; D37] Institutionally, this fell under the Royal Netherlands Academy of Sciences (*Koninklijke Nederlandse Akademie van Wetenschappen*, KNAW), which also housed other permanent advisory councils being formed as part of this organization. [D38] GROC's aim was to coordinate the space research activities in the Netherlands, as well as provide a focal point for government funding. [D2] In this context, Kees de Jager proposed X-ray observations of the sun, and in 1961 he received eighty thousand Dutch guilders to establish the Sun and Stars Research Working Group (*Werkgroep Ruimteonderzoek van Zon en Sterren*) within the GROC framework. [D39] As de Jager explains:

> *"I'd never seen that much money in one place before. I brought an engineer, a physicist, and a technician onboard [and] that's how we got our start in a room here in the Sonnenborgh observatory [in Utrecht]." [D39]*

As the team expanded their original X-ray research over the years, other groups emerged, such as the Cosmic Ray Working Group (*Werkgroep Kosmische Straling*) in Leiden and the Kapteyn Institute at the *Rijksuniversiteit* in Groningen. In 1983, the Dutch government decided that a more consolidated structure was needed. As such, the loose coalition of these groups under GROC was amalgamated into SRON, reporting to NWO. Since then, SRON has counted on a relatively stable source of funding for its salary and day-to-day operations. SRON only requires external funding for new projects or capabilities [I4]; funds that originate from research projects tendered to ESA grant programs like the Technology Research Program (TRP) and the General Support Technology

Program (GSTP). These tenders are coordinated by the Netherlands Space Office (NSO), which also channels funds from the Ministry of Economic Affairs to Dutch space sector actors as a way to consolidate Dutch space activities, provide a focused mandate, and promote increased cooperation and cross-pollination amongst its base and ESA. [D41] Interestingly, NSO has left SRON to tackle the Dutch space science portfolio as a whole. [I12]

Partly because of the stable funding environment, the SRON staff directly involved with cryogenic detector technology has remained relatively constant, fluctuating only on the periphery. This has kept the core subject matter experts together and thereby allowed SRON to maintain a strong corporate knowledge on this subject. Scientists can pursue topics where an immediate, tangible payoff is not immediately apparent. As such, the employee's effort becomes the main variable that team leaders can actively manage without investing further project funding: through paperwork, lobbying, and fund raising. In this environment, acquiring the required laboratory equipment can become the major sticking point. As a result, the team often finds ways to substitute labor costs for equipment by “MacGuyvering” a solution with the resources at hand, before considering a purchase.

2 Early Days

2.1 The Pilot Study

Though SRON's practical involvement in TES devices started in 1996, some of the groundwork was laid through a series of related projects. Early research into X-ray Charge Coupled Device (CCD) detectors and production of transmission gratings for X-ray spectroscopy were the precursors to SRON's first foray into cryogenic technology: Superconducting Tunnel Junctions (STJ). CCD's not only demonstrated that SRON was technically apt to involve itself with flight devices, but this work also added a clean room to the SRON infrastructure used to fabricate the detectors. [I4] The clean room would later prove to be a major asset to future projects. A partnership with the Paul Scherrer Institute (PSI) was formed in order to provide the appropriately level of cooling for the CCD instrument. At the time, PSI employed a PhD student researching Sn STJs. Despite poor results, a key member of SRON's management staff, hereafter referred to as SM2, recognized the value of launching a cryogenics research line at SRON while performing CCD work at PSI.

The STJ campaign, similar to other campaigns within this group at SRON, was started in a very chancy fashion. As recounted by SM2:

> *“Shouldn't we embark on something like [STJs] as well? Not realizing, at that time, how complicated and how much brains and money [it required]. I was brave in a way, [...] maybe too brave.” [I4]*

A pilot study into STJ detectors for the X-ray spectrum was completed in 1989 by SM2 in collaboration with a member of the technical staff, ST1. [I1; I4; D3] Despite a history of superconductivity, low temperature work, and single-photon detection in the Netherlands, research activities concerning the application of these as cryogenic detectors for X-rays was minimal. This fact proved to be beneficial with respect to grants awarded to the project. Furthermore, it was conceivable that research at other SRON offices[1] could lead to cross-pollination with the research into X-ray detectors. [D3; D4] In fact, as SRON expanded into several new initiatives over the years, the staff continuously searched for avenues where their previous work will bolster efforts in the new project. Thus, in line with this focus on expansion, the team set out to find collaborators.

Weighing their strengths and finding partners to provide needed support, a proposal was written the Dutch Foundation for Applied Research (*Stichting Technische Wetenschappen*, STW). [D4; D5] In general, funding from STW concentrates on technology that matures to industrial applications in four to six years, thus partners in industry are required by design. [I4] The report also proposed a three-year follow up project, in collaboration with other institutes working on this technology. [D3]

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[1] SRON-Groningen was involved in heterodyne mixing junctions.

The main partner and major recipient of the proposal's funding was the Low Temperature Group at the University of Twente (UTwente) [D5], which had previous experience with STJs for medical applications. [I4; D3] The STW grant funded a PhD student, equipment, and production work at UTwente from 1990 to 1994. SRON's program was funded through NWO's Physical Sciences Council between 1993 and 1997. [D5; D6]

In the end, STJ detectors were being produced by both SRON and UTwente [I4; D7], due in large part to a knowledge transfer between the two organizations[2]. During this time, SRON built up key technology and expertise for future endeavors, such as deposition of superconducting layers, low temperature measurement, basic calculations of noise, and measurement of the sensitivity of detectors [I1; I4]; all of which contributed to the overall expertise of the lab and the staff.

2.2 Early Bolometer Work

In line with pursuing novel detector ideas, the SRON R&D group began an effort[3] to develop high-T_C (77 K) superconducting bolometers[4] in 1994 [D8]. This was done in collaboration with the SRON office in Groningen, MESA+ (a different group within UTwente), ESA, and others. Through this partnership, SRON acquired experience with Si_XN_Y-technology, the deposition technique for Au absorbers, and bolometers in general. [D9] This project was funded by ESA's Earth Observation Preparatory Program and resulted in a high-T_C bolometer with a record setting noise equivalent power. [I1; D9; D10]

2.3 A Disappointing Discovery

SRON's research on STJs had been ongoing for several years at this point, with an eye towards NASA Goddard's Next Generation X-ray Observatory. [D8; D22] By 1997, SRON had made progress on theoretical understanding of STJs with support from UTwente. [D8; D9] However, the best energy resolution measured was approximately 11-12 eV at 6 keV, and typically in the range of 20 to 30 eV [I4; D7]; quite a ways off from SRON's theoretical goal of 1 eV. [D5] Because of this discrepancy, SRON decided to discontinue this research line[5].

SRON personnel contend that the flaw was the surfaces of the superconductors. [I4] Injection of X-rays into a superconductor breaks up Cooper-pairs creating quasi-particles. These tunnel through the tunnel junctions producing the signal required. The quasi-particles die off by loss processes such as phonon creation and recombination into Cooper-pairs. Also, trapping of Cooper-pairs occurs in defects in the material, especially along the surfaces. This made the response of material (and signal), position dependent, limiting the resolution due to the difference in response (as a function of position) in the sensor. [I4] It is likely that this is a fundamental limitation of STJ technology; SRON certainly saw it as such and chose a different path.

> *"That never really got solved." [I4]*

2.4 The Spark

Having recognized the limits of the STJ approach, SM2 and his team began searching for technical alternatives. They came across one such alternative at one of the biennial Low Temperature Devices (LTD) conferences, namely the LTD-6 conference in Beatenberg, Switzerland. [I1; I2; I4] The LTD conference is an international

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[2] The intent to transfer the expertise is stated in [D4].

[3] Though superconducting as well, these high-T_C bolometers operated at temperatures higher than the TES bolometers describe later in this report.

[4] "Bolometer" is an IR detector where signals are integrated. In the X-ray regime, each photon results in a pulse, which is analyzed.

[5] [D8] mentions a planned stop to STJ operations in 1997.

meeting that brings together scientists working on high precision particle and radiation detectors operated at cryogenic temperatures. [D23] The particular talk that sparked SM2's interest was delivered by NIST's Kent Irwin: specifically, Electrothermal Feedback TES. Among the SRON delegates, the choice was clear:

> *"We were far off... application, sensitivities, energy resolution [were] quite bad at that moment, but the TES seemed to be much easier to make a big step forward." [I1]*

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3.1 The Switch

> *"And then around that time I decided to swap; to stop working on STJ and start work on TES". [I4]*

Due to the limited progress in the worldwide development of STJ spectrometers for medium to high energy X-rays, SRON technical staff wagered that STJs would not provide the resolution that would be required for participation in future missions. [I1; I2; I4] They then redirected their research program towards microcalorimeters by the end of 1995. [D6; D7; D12] This would be the first time that their annual reports specifically mention the technology in question, referred to at the time as a "hot electron bolometer"[6]. [D8]

The capabilities that the STJ project added to SRON's organization were important in the overall path towards TES devices (see 2.1 The Pilot Study). The change from STJ to TES was, however, not without its own issues. The STJ collaboration with UTwente had to be stopped after parts of their expertise were assimilated into SRON. After the decision had been made, UTwente remained partially involved with SRON; contributing to a tradeoff study that recommended Superconducting Quantum Interference Devices (SQUIDs), which is briefly explained in 3.5 Two Potential Partners, as the readout amplifier for both X-ray and IR TES. [D8]

3.2 First Steps

From the start, SRON saw the potential crossover and synergies between the IR and X-ray regimes, and began initial research and experimentation for both applications. This strategy increased their initial chances for a breakthrough in either field. Lessons learned and the technology transferred from the cooperation with UTwente allowed SRON to create a solid basis for further experimentation.

After the redirection, the nascent microcalorimeter program was supported by NWO's GB-E (/GB-EW) and by European Community's Training and Mobility of Researchers program during 1998 and 1999. [D6; D10; D11]

The SRON office in Groningen, aware that ESA was defining the COBRAS/SAMBA mission, suggested SRON's participation through the High Frequency Instrument operating in the IR spectrum. Unfortunately for the SRON team, despite making some progress towards this mission [I1], it seemed that CEA Grenoble in France [I5; D43] was already tapped to deliver this instrument, with bolometers made by NASA's Jet Propulsion Laboratory. [I9] To hope for a different outcome was perhaps a bit too optimistic; SRON was not yet at a stage where they could deliver a complete instrument to a developing mission. The SRON team realized that further research needed to be done in order to build their expertise.

The follow up to the ESA X-ray mission XMM Newton was the X-ray mission for Evolving Universe Spectroscopy (XEUS). The first meeting concerning this new mission was organized by Martin Turner in 1998 in Leicester, UK [I4] about a year before XMM Newton was launched. The ideas for XEUS had already been discussed prior to this conference and the mission became one of the design points for SRON's X-ray TES devices in 1997 - the other was NASA's Constellation-X. [D9] At this point, XEUS was comprised of a rather large focal plane

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[6] Here, SRON is referring to TES-bolometers, not the previously mentioned high-T_C bolometers.

containing three X-ray instruments on its “first detector spacecraft (DSC1)” iteration: a Wide-Field Imager (WFI), Narrow Field Instrument (NFI) 1 and NFI2. [I7; I14; D6; D7; D24] NFI1 (the STJ detector), being developed at ESA’s European Space Research and Technology Centre (ESTEC), was to be optimized for the energy band of 0.05-3 keV, whereas NFI2 (the TES microcalorimeter) would cover the 1-7 keV range. [D24] The decision whether the NFI2 instrument was to be delivered by SRON or Goddard rested with ESA, who presumably delayed the selection until a clear front-runner surfaced. It is likely that favoring one over the other would have resulted in negative political fallout for the groups involved. Some of the personnel who were interviewed feel that ESA’s delay in releasing a call for proposals for the TES microcalorimeters (see 3.11 Funding Delays Hamper Progress) was also partly to avoid a weakening, perceived or actual, of the in-house research into STJs: interested parties wanting explicit confirmation whether STJs would be a better option than TES for the XEUS mission. A mission re-scope, where fewer instruments would be flown, was not outside the realm of possibility, especially since the TES microcalorimeters from Goddard were still further along than the European counterpart.

3.3 Material Choices for the TES and Absorber

An important selection happened during the brief COBRAS/SAMBA period. SRON had carried out initial experiments with an Al-based TES, which was the same material that the NIST team employed. [D44] Unfortunately, SRON's experiments showed great instability in terms of the chemical structure [I1; I4], confirming earlier, unfavorable results from Goddard, which were brought to SRON's attention. [I2; I4] It is worth noting that members of the global cryogenics detector community openly share information, such as the choice of materials used for the TES devices, with laboratories which they have a good report. This allows them to compare their results with others facing similar problems.

SRON's 1998 annual report notes the production of Cu/Al and Ti/Au thermometers and states that work on Mo-based bilayers had started. [D10] The team eventually narrowed their initial selection down to Ti, which had the needed characteristics at the required temperatures, as well as suitability towards the deposition equipment. [I2] In the end, the major driver for continuing down the Ti/Au route was the lack of success processing Mo/Au with the available equipment, though some experimentation occurred within the X-ray context. [I1; D12] Mo required high heat to deposit [I1; I4] (on the order of 600 C) and the sample would then need to be cooled to deposit the Au. Funding for the procurement of specialized equipment to perform this deposition was not available, due to the constraints mentioned in 1 Introduction. Mo/Cu was also tested, but saw limited success as well. [I1; D11] Ti/Au, on the other hand, could be deposited on a substrate at room temperature through e-gun evaporation. [I4] Certain temperature boundary conditions needed to be considered for manufacturing and satellite testing/operations, but Ti/Au was otherwise stable [I4] and provided good results. [I1] In the end, SRON used Ti/Au for both IR and X-ray lines.

In the context of the early cryogenic detector work referenced in 2.2 Early Bolometer Work, the high-T_C bolometers “[had] a Cr/Au-coated spider web absorber”; Au to match the performance characteristics and Cr for adhesion to the Si_XN_Y. [D9] Conversely, X-ray microcalorimeter absorbers require different performance characteristics; satisfied by Bi combined with Cu to improve its heat transport. As one scientist recalls:

> *“We started just from looking to heat capacities and [Bi] seem[ed] like the only logical choice to combine thick x-ray absorbers with low heat capacity. [...] The Cu as just a result of calculation of how much heat capacity you need to tune the properties of the sensor.” [I1]*

This selection happened a few years after the high-T_C bolometer work, while the X-ray TES development proceeded in earnest. [D12] Due to the prioritization of detector optimization over absorber development, SRON did not implement “proper” absorbers in their 2007 testing. This despite further research on the thermalization of X-ray photon energy in Bi absorbers; a collaboration with Universität Heidelberg 2 years prior. [D25; D27]

3.4 Scaling Up

In parallel with the ongoing research on the single pixel microcalorimeter, SRON started the Imaging X-ray Microcalorimeter for Astrophysics (IXMA) project in 2000, which would meet the specifications required for the XEUS mission. [D6; D7; D12] The IXMA detector was regarded as a 5 x 5 detector prototype for a larger XEUS array. [I5] As the XEUS mission started to materialize, research funding opportunities started to open up. A proposal was written for a NWO-E at a level of 400-500 kEuro [I5], funding IXMA for three to four years [I5; D6], which began in 2000. [D6; D13] The project also had to look to new partners to replace the capacity lost with the departure of the Low Temperature Group. [D6] Luckily, SRON had previously cooperated with MESA+ on the high-T_C bolometers, and sought to further extend this cooperation to include Si machining for X-ray TES as well. [D12]

As mentioned before, SRON's priority lay with the detectors, but work had progressed to a stage where small arrays were within reach and the readout of the detectors needed to be seriously considered.

3.5 Two Potential Partners

Stated simply, each TES pixel is paired with a current amplifier in the cold stage called a SQUID. When dealing with a large number of pixels, it is possible to reduce the amount of amplifiers, and accompanying infrastructure, needed to operate the array. [D25] This reduces the overall complexity and mass of the device; of particular significance in space applications. In addition, multiplexing minimizes the heat load on the cold sections. The SQUID arrangement produces significantly several orders of magnitude more heat than an X-ray pixel, so it is advantageous to connect multiple pixels to a single SQUID. [I10] One of three main multiplexing schemes, briefly described in 3.6 A Bold Choice, can be selected, each with their own pros and cons.

With regards to SRON's selection of a multiplexing partner, two choices surfaced a few years after Finland became ESA's 14th member state [D45]: VTT Information Technology, of Espoo, Finland and *Physikalisch-Technische Bundesanstalt* (PTB), of Berlin, Germany.

VTT is a not-for-profit research organization under Finland's Ministry of Employment and Economy. [D46] 30% of their funding stems from direct government investment and the majority from contracts, some of these between VTT and ESA or the EU. Previously, VTT had some experience with high-T_C superconductors and SQUIDs for single electron transistors, which placed them on the map for SRON. [I13]

PTB is Germany's national metrology institute and is, in some ways, the German equivalent of NIST. [I18] PTB's mandate calls for research into SQUIDs for precision electrical measurements in resistance metrology or temperature. This research was ongoing prior to any contact with SRON. Perhaps not surprisingly, SQUID development only plays a small part in a larger context for both organizations.

SRON staff met with both VTT and PTB representatives separately, and it was clear at the time that VTT staff were in a stronger position to respond to SRON's needs in the selection of the readout scheme explained in 3.6 A Bold Choice. The first meeting with VTT was described as closely resembling a design meeting: VTT was very receptive and offered up interesting, conceptual approaches to SRON's problem, showing a proactiveness which left a very positive impression on the SRON team. [I8; I10; I11] PTB's briefing was not as engaging, where the staff took a passive approach to the collaboration opportunity. [I11] In the words of a PTB staff member who was involved with this first encounter, despite some institutional experience with SQUIDs, they “weren't prepared” for the devices that SRON was looking for. [I8; I18]

In the end, SRON and VTT collaborated on a trade-off study comparing the different multiplexing schemes, leaving PTB out of the multiplexing equation for the time being.

3.6 A Bold Choice

The aforementioned trade-off study, completed in 2001, compared Frequency Domain Multiplexing (FDM), Time

Domain Multiplexing (TDM), and the direct readout method. [D13; D14; D26; D27] The direct readout method is the most straightforward and non-optimal approach: each TES pixel is connected by wires to a SQUID device, which in turn, is connected to a readout device: a 1-to-1-to-1 ratio. Because of the heat output of the SQUIDs, a separate cooling stage is required in order for correct operation of both devices. [D26] This combined with the wiring requirements quickly make this choice unfeasible.

In both FDM and TDM, the signals from multiple pixels can be transported along the same medium to a single SQUID. [D26] Several of these SQUIDs can then be read by a single readout device; a many-to-few-to-1 ratio. [I11; D26] TDM employs the technique of sampling the each input for a certain amount of time, then switching to the next one in line. FDM uses signal modulation techniques widely employed in the telecommunications field to achieve this reduction in overhead. [D26] Moreover, FDM has distinct advantages - with respect to the SQUID requirements - when X-rays are involved. [I8; I11] One can make use of the fact that inactive pixels do not consume bandwidth and additional pixels can be added without needing extra dynamic range. [I11]

In the trade-off, TDM and FDM scored the same in terms of theoretical performance. The most critical factor in this study was the foreseen complexity between the three choices: FDM scored highest (i.e. FDM was the simpler method). [D26] The perceived practicality of implementation was also an important factor in the decision:

> *"Ultimate theoretical performance of FDM and TDM does not differ from each other, and the choice between the two should be based on implementability considerations." [D28]*

Further differences between FDM and TDM are elaborated on in 3.16 The AC-Bias Problem.

3.7 The LC Filter Problem

Once the FDM choice was made, the team started to take inventory of the unknowns, one of which was the LC band pass filters: a special capacitor required per pixel. [D14] At the time, these were seen as "trivial from [an] IC fabrication point of view" [I13] and could be made at SRON using their lithographic capabilities. [I1; I8; I10] As recounted by the staff:

> *"We estimated that it was not such a big deal to make these capacitors." [I10]*

As such, SRON began manufacturing these filters, taking cues from the semiconductor industry (using Ta_XO_Y and Nb_XO_Y). [I1] They quickly ran into application-specific problems:

> *"[...] We looked more careful in the books, and the dielectric loss would never be sufficient," [I1]*

and these materials were abandoned. Subsequent trials in 2004 employed materials used by SRON partners, such as Si_XN_Y [D16], which was used by VTT. [I1] Though these did produce better capacitors, SRON was unsuccessful in creating ones suitable for their application. UTwente's facilities seemingly offered a solution to SRON's situation by providing equipment capable of low pressure chemical vapor deposition. UTwente's technical staff, being weary of contamination in their equipment, conducted the required experiments very carefully, but also very slowly. This forced SRON to discontinue the Si_XN_Y route as well. [I1]

That same year, Al_XO_Y was employed in SRON's trials [I1; D16], yet after approximately four years, their results were still disappointing and this method was also abandoned. [I1; D51] Al_XO_Y was kept as the working material and further experimentation occurred in cooperation with a group in Nijmegen using atomic layer deposition; a technique also used in the semiconductor industry. This led to even worse results. [I1; D51]

In the end, the successful technique that led to the required LC filters specifications used hydrogenated amorphous Si deposited by plasma assisted chemical vapor deposition [D51], which allows SRON to scale up to bigger arrays. [I1] But by the time this problem was solved in 2011, SRON had already shifted its major focus from the X-ray regime to the IR regime (see 4.4 A Future in IR).

In contrast to this intensive trial and error phase, NIST, with its in-house access to SQUID manufacturing equipment and expertise, pursued a TDM implementation for its multiplexing. [I5] With this scheme, modulation of the signal occurs in the SQUID, negating the need to develop and produce the LC filter.

At the start of this process, SRON's gamble was easy to understand; if FDM was not successful, SRON would have engaged with NIST and enlisted their help in switching to TDM. It would have been superfluous to redo their work while SRON lagged far behind NIST in the TDM field. Nevertheless, the choice to continue down the FDM path is equally understandable, foreseen to produce larger pay-offs. First, having VTT heavily invested in the success of the project created an institutional inertia, which favored continuing the research rather than taking a completely different approach. Second, it was impossible to predict whether their work would have led to a breakthrough sooner rather than later, as some SRON employees attest. Third, halting their original research would effectively mean borrowing heavily from what other labs had accomplished (both research and potentially samples), which would have been a hit to their institutional pride and would have nullified their chances of being the “best in Europe” with respect to this specific application of FDM. This differentiation and demonstration of success plays a very important role in political negotiations as described next in 3.8 Informal Relationships.

3.8 Informal Relationships

Initially, resolutions with TES were not as good the theoretical goal of 1 eV. In fact, SRON’s measurements only surpassed the 10 eV mark circa 2000-2001, thus engendering recognition in the wider community. [I4]

In SM2's experience, as the brief example shows, this community is very results based. This could mean that you and your works are not considered at the community’s conferences until a certain results threshold is reached. SM2's opinion on Americans in particular is very poignant:

> *“[...] as long as you're not good enough, [American groups] are not interested in you.” [I4]*

Once this threshold is reached and cooperation is established, however, the contact between the groups can be described as pleasant and the information flows freely. This is particularly apparent at the LTD conferences, first mentioned in 2.4 The Spark. This conference sees participation of players from around the world, including Goddard, NIST, and European and Japanese groups. In the experience of ST1, this community is very open, and collaboration occurs in a very friendly way, to the point where samples are sometimes shared across borders, e.g. SQUID samples from NIST, described in 3.12 A Mixed Bag from NIST.

Throughout the SRON X-ray microcalorimetry history, the human factor has played a very positive role in facilitating discussions and collaborations; of particular note, a SRON team member spent a sabbatical at NIST, facilitating not only SRON's cooperation with NIST, but also opening up an alternate avenue for SQUID production (see 3.17 PTB Returns).

3.9 Synergy Through IR Projects

By March of 2002, a handful of groups in Europe were developing IR direct detectors and their readout electronics. Their major shortfall, however, was their inability to produce TES bolometers and/or SQUID electronics in-house, and as such, were sourced from outside Europe. At that time, SM2's SRON colleague from Groningen attended the “Second Workshop on New Concepts for Far-Infrared and Submillimeter Space Astronomy” conference in Maryland. [D29] After this conference, both agreed that SRON should restart research on IR bolometers. Since SRON had made breakthroughs with TES sensors for X-ray detectors and the multiplexed readouts, a branching out into TES bolometers seemed to be a good and straightforward investment; one that would potentially cross-pollinate with ongoing TES research. [D29]

3.10 Further Funding for X-ray Research

The first articulated external contract in support of the X-ray microcalorimeter program was in the form of a Technology Research Program (TRP) grant awarded by ESA in 2002. [I5; D7; D30] The TRP is a broad program, covering the first part of the technology readiness scale [D42]: Technology Readiness Level (TRL) 5, typically up to TRL 4. The TRP covers all domains; in so doing, all directorates in the agency, and is managed by the technical directorate. [I15]

The Cryogenic Imaging Spectrometer (CIS) proposal, tendered at the end of 2001 for 1.2 MEuro among six partners [D30], brought SRON approximately 600 kEuro [I5] in research funds. The major aim of this contract was to produce and test the arrays of 5 x 5 pixels envisioned by the IXMA project, with a final goal of 32 x 32 pixels. Production of these arrays was done via wet etching, using a technically straightforward process called bulk micromachining [D52], though surface micromachining techniques were tested as well. [D7; D30; D31] In comparison, the Americans required the expensive deep reactive ion etching technique for their array production, which allowed them to produce higher quality parts. At a later date, SRON put in a proposal to NWO for this piece of equipment, but was turned down. SRON's wet etching technique is still used to fabricate their detectors.

In the original proposal, the detectors were to be fabricated with the help of the MESA+ group. [D14; D30] Nevertheless, after the Si_XN_Y technology was established within SRON, both groups agreed that the MESA+ technology and expertise were to be transferred to SRON, and the collaboration was stopped. From then on, the detectors could be manufactured within SRON, without outside help. [I6]

3.11 Funding Delays Hamper Progress

The funds received through the CIS contract needed to be sensibly apportioned among the partners, as the full sum did not meet their collective expectations. For VTT, this meant that the theoretical aspects of the work could make substantial progress, but work on a SQUID device could not. [I7; I10] The sum received as part of the CIS TRP was insufficient to cover SQUID fabrication on top of the ongoing detector research. [I10; I13] The team then assumed that, as major inroads into the multiplexing arena had already been made, ESA would provide funds through a subsequent (SQUID production) contract. In the end, the release authorization for the call for proposals for multiplexing work was delayed for an untenable period of approximately six years. [I2; I7; I10; I11; I13] This delay was perhaps the biggest setback the project had seen, both technically and politically.

> *“It hampered [the work] a lot.” [I13]*

Financially, SRON was hamstrung and could not employ other funds towards the project outside of those already allocated internally for the prioritized detector work. [I11] The multiplexing work was merely “kept alive” by VTT's staff who found ways of incorporating parts of this project into their other ongoing work; essentially doing this project during their off hours. [I13] The delay also slowed the development of sorely needed high(er) frequency devices mentioned in 3.12 A Mixed Bag from NIST.

Nevertheless, SRON pursued experimentation and building equipment (LC filters, modulation equipment) to the extent that their internal funding would allow. [I7; D16]

3.12 A Mixed Bag from NIST

Seeing that the contract for the production of the SQUIDs was being held back, the SRON team was forced to look elsewhere for SQUIDs that could be used for experimentation.

NIST developed SQUIDs in-house and had given its first, non-optimized recipe and mask layouts to a third party, who took in orders and produced these for groups that required them. SRON received SQUIDs from this third party at no cost, but these were not without issues of their own. Limitations included a specification mismatch (SRON needed a coil of a few nH, the NIST coil was approximately 300 nH) and dynamic range (SRON could not achieve frequencies above 1 MHz, which was limited by these SQUIDs). [I4; I10] But with little funding available for alternative options and with a strong drive to get any results, SRON saw no choice but to employ these devices in their initial experiments. This is yet another example of the “McGuyvered” setup that the SRON staff contended with:

> *“...rather primitive electronics, built with the smallest amount of means available [...] which we tied together, [...] try[ing] to prove things.” [I10]*

3.13 A Demonstrator as a Focal Point

The delays for funding the multiplexing work notwithstanding, the CIS funding set the detector and array aspects as high priorities [D14] and development continued well into 2004. At the same time, a potential merger of the XEUS and NASA's Constellation-X mission was being discussed within ESA. [D27] The possibility of including NASA in any X-ray mission added a major competitor to the equation, seeing that NASA's X-ray microcalorimeter efforts were significantly further along than SRON's. In an attempt to allay this uncertainty both within SRON and internationally, SRON launched its EURECA project in October of 2004 with the following objectives [D27]:

- To show that a European-Japanese collaboration is willing and able to deliver a cryogenic instrument for imaging X-ray spectroscopy to the future XEUS or XEUS/Con-X mission; and
- To show in about 2½ years that this collaboration had the technical capability to develop, build, and test a cryogenic instrument for space with the requirements set by the XEUS mission. The (ultimate) instrument was described as a 5 x 5 pixel TES microcalorimeter array, read-out by FDM electronics, and cooled down to 70 mK in an Adiabatic Demagnetization Refrigerator (ADR), pre-cooled by a compressor driven pulse-tube cooler. [D18]

Despite the ambitious goals set out by EURECA, SRON lagged behind NASA in their development of the microcalorimeters and the researchers were very well aware of this situation.

> *“[...] obviously, everybody knew that the American groups were ahead of us.”* [7]

3.14 Cooling Issues

Though an integral part of the system, developing a cooler for XEUS in-house was not one of SRON's priorities. Mullard Space Science Laboratory was developing a suitable cooler under an ESA contract and this was to be made available to the EURECA project, according to project documents. [D27] At the same time, a CNES group out of Grenoble was also developing combination of absorption cooling and ADR. Apparently, despite being mentioned in the EURECA plan, the partner for cooling was not set in stone. SRON kept both groups interested and delayed making a selection between the two. [I8]

3.15 Disappointing Results

Initial measurements with EURECA used a single pixel microcalorimeter and the central Cu absorber, without the Bi mushroom[8] and showed a resolution of 6 eV, as well as phase dependent effects: not in line with expected values. [I10] For this reason, the team wanted to pursue higher frequencies, but needed other electronics to

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[7] Name omitted.

[8] This is an assumption, since the subsequent BESSY II test did not have Bi portion either. [I10]

accomplish this. Simultaneously, the higher frequencies that they were aiming for were outside of the operating frequencies of the NIST SQUIDs, as mentioned in 3.12 A Mixed Bag from NIST. [I10]

> *“[It was like] fighting a problem with one hand tied behind your back.” [I10]*

Further hampering progress was the less-than-ideal laboratory environment described in 3.13 A Demonstrator as a Focal Point. SRON staff decided that an improvement was necessary and the lab equipment was revamped in a “more appropriate” way. [I10; D16] It was thought that this upgrade would reduce the level of noise observed during previous experiments.

> *“We have been very lucky to have measured anything decent, without all the shielding measures which we have now.” [I10]*

Unfortunately, even after the switch to the new electronics and its accompanying software, the team still measured a resolution of 6 eV. According to one of the researchers, this revamp

> *"[...] took too big of a step away from where we were experimentally [...]" [I10]*

and it became difficult to distinguish whether the 6 eV was caused by bugs in the new equipment, or whether this was a fundamental limitation of the detectors. [I10] The origin of the (perceived) problem became hard to trace.

3.16 The AC-Bias Problem

In FDM, the TES acts as a modulator requiring an AC bias for the TES. This contrasts with TDM where the SQUID acts as the modulator and a DC bias is employed. [I9; I10; D26] SRON staff theorized that measurements using either method would be approximately equal, and conducted experiments using both AC and DC bias on the same pixel in order to ascertain whether this was true. [I10]

The resolution of 6 eV mentioned in 3.15 Disappointing Results corresponded to experiments conducted under AC bias. Unfortunately for the SRON team, the same pixel measured under DC bias reported a different result: a resolution of 4.5-5 eV. [I10] As previously mentioned, it was believed that the lab setup was non-ideal, yet after the upgrade to new equipment, the best results only showed a minor improvement. [I10]

The question of whether the X-ray TES pixel will demonstrate the same resolution under both AC and DC bias remained unresolved for a number of years, but SRON personnel, to their credit, have since all but closed this gap. [I1]

3.17 PTB Returns

PTB's collaboration with SRON did not end with the first meeting in 1999. In fact, their interest in creating SQUIDs for SRON was rekindled during the sabbatical referred to in 3.8 Informal Relationships, where, fortuitously, a PTB staff member was also on assignment during the same time. [I8; I18] Discussions surrounding a SQUID component that could meet SRON's needs morphed into full on development work in 2003-2004 [I18], and ultimately coalesced into a device with a performance better than VTT's. [I8; I11]

Rather surprisingly, VTT personnel welcomed some competition with regards to SQUID development on the same project; it has spurred them to perform in the face of collegial scrutiny from other partners. [I13] With regards to a key piece of the interface between room temperature and the operating temperature of the SQUIDs:

> *“I had actually had the [cryogenic Si/Ge transistors] in my desk drawer for a couple of years, [and PTB's involvement] pushed me to actually do the experiment and it turned out to be a key ingredient in the FDM readout.” [I13]*

In 2007, testing of the single pixel unit, with a Cu absorber on top of a Ti/Au TES, took place at PTB's beamline at BESSY II. [I10: D19; D32] The detector's behavior was tested to investigate crucial issues like calibration of the energy scale, non-linearity, large signal analysis, and energy resolution retrieval from pile-up events. [D32] Testing was done, as previously stated, with a Cu absorber alone, proving to be insufficient to capture all incoming photons. [I10; D32] This notwithstanding, SRON showed an energy resolution of 2.5 eV at 1 keV and a resolution between 1.52 eV and 1.78 eV was reached at 250 eV for 50 and 500 photons/sec respectively. [D32]

After the BESSY campaign, SRON integrated the results from the tests and started using PTB's SQUIDs. [I10]

4 The Future of X-ray Microcalorimeters at SRON

4.1 XEUS becomes IXO

The uncertainty regarding the NFI2 instrument selection described in 3.2 First Steps was, in essence, a question of whether NFI2 was to be delivered by the US or Europe; the option of entering into a partnership and using the further developed Goddard detectors was on the table around 2008. [I14] Naturally, having this option would have caused ESA's grant apparatus to pause, possibly in a coordinated effort, and ascertain whether further research investment on the European side was merited. The uncertainty at the mission level thus translated into a stall at the project level.

This had a different impact on the each of the partners involved: SRON, with its stable internal funding and previous grant award elaborated on in 3.10 Further Funding for X-ray Research was able to continue work on non-multiplexing aspects of TES, but VTT, which was only slated to provide multiplexing services, was not. This effectively negated any lead that VTT had over other laboratories with respect to this research at that time. [I13] VTT did manage to obtain some funding from their technology and innovation agency [I13], TEKES, who, upon hearing XEUS' uncertainties, decided not to invest more capital. [I7]

It seemed that even though XEUS was selected for the Cosmic Vision program and nominated as a candidate for the next L-class mission selection, realizing the full project was still outside of the reach of the original partners.

> *"[XEUS] clearly could not be implemented by ESA and JAXA alone, [and] NASA, ESA, and JAXA agreed to embark on the study of an integrated mission called the International X-ray Observatory (IXO)." [D47]*

At this point, NASA had its own next-gen X-ray observatory in the works. Constellation-X, itself a merger of three other mission concepts, ranked second behind the James Webb Space Telescope (JWST) in the 2000 Astronomy and Astrophysics in the New Millennium Decadal Survey. [D33; D34] Its science goals being "very similar" to XEUS, it was thought that a merger could provide a [more] cost effective mission and a higher science return for all parties. [D1; D34]

A merger of the two projects started to take shape in early 2009. [I8] The SRON lead for the XEUS project was a part of the steering group and the chairman of the instrument working group, both of which contained American, European, and Japanese representatives, adding a tangible political tinge to the selection of the instruments. [I8] To those at NASA, IXO became an upgraded Con-X, by tacking some of XEUS' goals onto the existing mission. [D34]

To some extent, the inclusion of NASA into the IXO mission made sense: it was still a very ambitious concept, but it was hoped that the existing risks and the gaps in the technology could be mitigated by including additional international partners, and a superb satellite delivering superb results would be the outcome. [I15]

> *"In a way we recognized that the Goddard detectors were significantly better, at that moment, then ours. [And] that we did not have the manpower to do both [detectors and readout]." [I8]*

4.2 IXO Becomes ATHENA

At this point, with three official stakeholders now forming the IXO consortium and their precise roles yet to be determined, it can be assumed that the funding delay on the ESA side regarding the multiplexing work was extended, or maintained, until a clearer picture of responsibilities surfaced. [I14]

The outlook on the American side was no better. IXO ranked second after the JWST in the New Worlds, New Horizons Decadal Survey in 2010, citing “medium high” technical risk [D35], and the Decadal Survey costs estimates were $1.3B USD off previously available numbers, largely due to technology development and mission complexity concerns. [D34] Undergoing its own financial crunches, NASA decided not to fund its proposed contribution and put a much smaller sum of money towards further developing IXO in preparation for the next Decadal Survey. In the same vein, NASA also withdrew its (proposed) funding from the other L-class mission candidates Laser Interferometer Space Antenna (LISA), later Next Gravitational wave Observatory (NGO); and Europa Jupiter System Mission (EJSM/Laplace), later Jupiter Icy Moon Explorer (JUICE). [D34]

Faced yet again with the need for a European-only mission, IXO was restructured and simplified in March 2011 to become the Advanced Telescope for High-Energy Astrophysics (ATHENA); its science case was once again reconsidered with two main instruments, a cryogenic imaging spectrometer, led by SRON, and a wide-field imager. [D36; D48]

4.3 JUICE Selected

After the Europe-only reformulation, ATHENA, NGO, and JUICE were the candidates for ESA's first L-class mission selection. On May 2nd, 2012, it was announced that JUICE was the L1 selection. [D49; D50] The selection committee's report stated that their main concerns which affected their decision were the mirror modules, the TES detector and its cooling system not achieving TRL 5, thus stating that the launch take place in 2023. [D36]

> *“Naturally [the ATHENA team members] felt disappointed that they invest time and effort into something that has become, at least to mission outsiders, a bit of a dead end.” [I14]*

The tumultuous history that the project has seen from the mission perspective certainly did not help ATHENA's case at the selection, most egregious perhaps the American detector performance in comparison to SRON's. Not surprisingly, the ESA funding delay had hamstrung any development of the multiplexing technology, which could have closed this gap before the selection. Furthermore, the FDM choice had left SRON to prove whether biasing the detectors under AC produced the same measurements as the DC bias, which, up to that point, was not the case for the X-ray regime.

It is likely that ATHENA, or its variant, will be proposed once more at the next L-class mission selection. However, there are still significant concerns working against its selection. Even if the detector funding stream was guaranteed, there is no guarantee that the mission will be politically viable for the selection committee at that time. In the words of one SRON staff member:

> *“[...] there is no 1-to-1 relation between how much you invest and the probability of being selected. Sometimes it's a way of selling yourself more than what you really have done.” [I12]*

This political aspect can be considered as an unknown-unknown and adds significant strain to an already uncertain future of X-ray research.

Also factoring against the ATHENA selection is the fact that NGO received the highest science rating during the first L-class selection [I14; D36], making it a strong candidate for the second round. If this occurs, it could significantly delay a possible TES mission.

> *“[...] this could mean that the X-ray astronomy would become the 3rd L-class mission in 2035”. [I14]*

And if one takes the funding delays and uncertainty back into account, the technology development cycles start to extend past feasible time frames.

> *“[...] the [mission] spacing in time becomes so large that it starts to be comparable with the lifetime of a person in his career”. [I11]*

> *“I don't think you can sustain all these labs over that period of time”. [I14]*

With such long development cycles, other, better-funded labs have a chance to pursue newer, better performing technologies, potentially usurping any other ongoing research projects. At the same time, one must recognize that there are still unknowns with any R&D pursuit and just because one theoretical result seems more promising than the next, it does not imply that it will turn into a feasible subsystem.

> *“[...] you expect to have a certain development cycle, [...] then you say that you can do it in five years, then it turns out that in 10 years... You really have to be right, work hard, push it. And you get there, or you may not get precisely where you want to be.” [I12]*

SRON and the other partner labs avoid this situation by broadening and diversifying their research, leveraging their previous work into new and emerging fields. IR research in particular is a recurring theme for this group.

4.4 A Future in IR

In SRON's 2004 annual report, the Japanese SPICA mission, in part the successor to the Herschel satellite and a complimentary asset to JWST, was identified as a potential secondary application of TES technology. [D16] Rutherford Appleton Laboratory, a UK research laboratory, was initially tasked to be the PI for the SAFARI instrument on SPICA, but this was reconsidered after the withdrawal of their funding contribution by the UK government. Thus, the SAFARI consortium chose SRON as their new PI, and TES bolometers as the instrument’s detectors. [I2; I5] Though the immediacy for IR TES research at SRON has waxed and waned since their start in 1997, it saw a strong resurgence around 2007-2008 [I3], while seeing a gradual decline of the X-ray implementation at the same time.

As stated before, a substantial effort was required to equate the performance between AC and DC biasing of the X-ray TES detectors (3.16 The AC-Bias Problem). Equating this for IR TES detectors, on the other hand, proved to be much more straightforward due to the physics of the bolometer’s signals. The SRON team measured the same performance - to within 10% error [I11] - under both regimes. SRON scientists then used lessons learned during the IR trials to successfully narrow the AC/DC gap in the X-ray band, as the hardware and readout scheme employed was the same across both platforms. [I11] It is unlikely that SRON would have made these and other inroads without their prior experience with, and investment in, the X-ray variant of TES microcalorimeters.

Once the SAFARI instrument was selected to be TES bolometers in 2010 and taking into account the aforementioned nomination, considerable importance was placed on the SRON contribution, which drove all TES effort in the SRON lab, and thus in the partner labs, to focus on IR. [I3; I13; I18] Here, a disjoint between institutional priority and researcher motivation can be observed: some researchers in SRON and VTT would like to continue the X-ray detector work and see it to conclusion. [I9; I13] Naturally, there are others on the project who would simply like to see their intellectual investment put to good use on an approved mission. VTT, specifically, is hedging their bets on a new X-ray mission being proposed post-ATHENA, and is looking to obtain additional funding to continue this work. [I13] On the other hand, SRON's obligations dictate that it should focus its resources primarily on the IR work, slowing down any progress made on the X-ray front.

5 Closing Thoughts

At the pinnacle of their X-ray efforts, SRON developed a 5 x 5 pixel, Bi/Cu absorber, Ti/Au TES array, readout by FDM electronics. The array was tested without the Bi portion of the absorber and measured a resolution of 1.52 eV at 250 eV. [D32] The team's efforts were then gradually shifted towards the IR implementation of TES. Currently, SRON is close to meeting the sensitivity and multiplexing specifications for the SAFARI instrument on SPICA. SRON is also still collaborating with Goddard on an X-ray mission stemming from the American IXO team. Here, the aim is to produce an observatory within the budget limits proposed during the last Decadal Survey ($2B USD). [D34]

Space instrumentation research in the European context, regardless of mission, is now funded through the member states, as opposed to direct grants from ESA in previous decades. [I4] This leaves national institutions, such as SRON, in the somewhat difficult position of coordinating both funding and task division among other European research partners, and at the whims of their respective governments' funding cycles. The case study described in this document shows how uncertainties in mission priorities and funding delays can severely impact the competitiveness of a technology, though perhaps accentuated due to the brevity of this report. It might be too heavy-handed to refer to X-ray TES microcalorimeters as a project waiting to be shelved considering the work yet to be accomplished and the positive attitude of those involved. Yet, if one takes a current day snapshot from a top down view, it is difficult not to come to this conclusion. As one SRON employee stated:

> *"...we have no future in X-ray astronomy for quite a while, it looks like, because ATHENA is dead as well now, but we have a future still going on in IR astronomy, SPICA, the Japanese mission."* [9]

SRON is currently producing arrays and is waiting for the Japanese decision to proceed in earnest with the SPICA instrument. As previously noted, this mission is currently the most likely candidate for the first implementation of the TES technology, though of the IR variety. Those involved with the TES research should be credited for carrying out this research in parallel to the X-ray efforts. The future of X-ray microcalorimeters at SRON notwithstanding, the research team's flexibility and adaptability over the years has allowed them to navigate uncertainties, and keep their work relevant, regardless of external climate.

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[9] Name omitted.