Technology Roadmap for the X-ray Microcalorimeter Spectrometer of the International X-ray Observatory

Prepared by the XMS Consortium

1. Introduction

The XMS instrument is based on x-ray microcalorimeter technology, which has been developed over the last 25 years for high-resolution, high-throughput, x-ray spectroscopy for astrophysics and laboratory measurements. The first implementation of a microcalorimeter for astrophysics was on a suborbital payload (X-ray Quantum Calorimeter, XQC) for measuring the spectrum of the diffuse x-ray background (McCammon et al. 2002). This research program continues today, with the fifth flight planned for early next year. A major benchmark for the XMS technology readiness was the XRS instrument on the Suzaku Observatory. This instrument featured a 32-channel microcalorimeter array operating at 60 mK, a single-stage adiabatic demagnetization refrigerator (ADR), and digital processing electronics capable of on-board optimal pulse height analysis. An improved, detector system based on the XRS design is planned for the SXS instrument of Astro-H, scheduled for launch in 2014. These implementations have used ion-implanted Si for the thermometer with separately attached X-ray absorbers. This technology, though different in detail from the superconducting transition-edge sensor (TES) calorimeters baselined for the XMS, is described by the same resistive-calorimeter theory, operates in the same temperature regime, relies on many of the same low-temperature properties of materials, and requires the same signal processing. Thus, the XRS flight heritage is highly relevant to XMS. Before the launch of IXO, the micro-X sub-orbital experiment, which will use a TES-based calorimeter, will be flown.

The main tasks of the technology development for the XMS are to

- increase the array size (from the current few tens of pixels to few 1000 pixels)
- improve the energy resolution (from the current ~3 eV at low count rates in small multiplexed TES arrays to 2.5 eV while allowing for higher count rates).

In this document we describe the roadmap to achieve this improved performance and reach TRL 6. Section 2 details the technology roadmap that is well underway in the US for development in support of the NASA XMS reference design. It is provided as a representative and self-contained example that illustrates the type of milestones and level of effort remaining for XMS. Although the US roadmap is self-sufficient, supplementary activities are being carried out in Japan and Europe, and these may provide components or subsystems with similar or better performance. X-ray calorimeter groups in Europe (SRON, INAF), Japan (JAXA/ISAS and university collaborators) and the US (GSFC, NIST) are planning a joint response to the anticipated instrument AO, but the division of responsibility and the technical implementation of each subsystem have not yet been determined. Therefore, in Section 3 we list the XMS technology development planned and underway in Europe and Japan to illustrate the strength and flexibility of the international XMS collaboration.

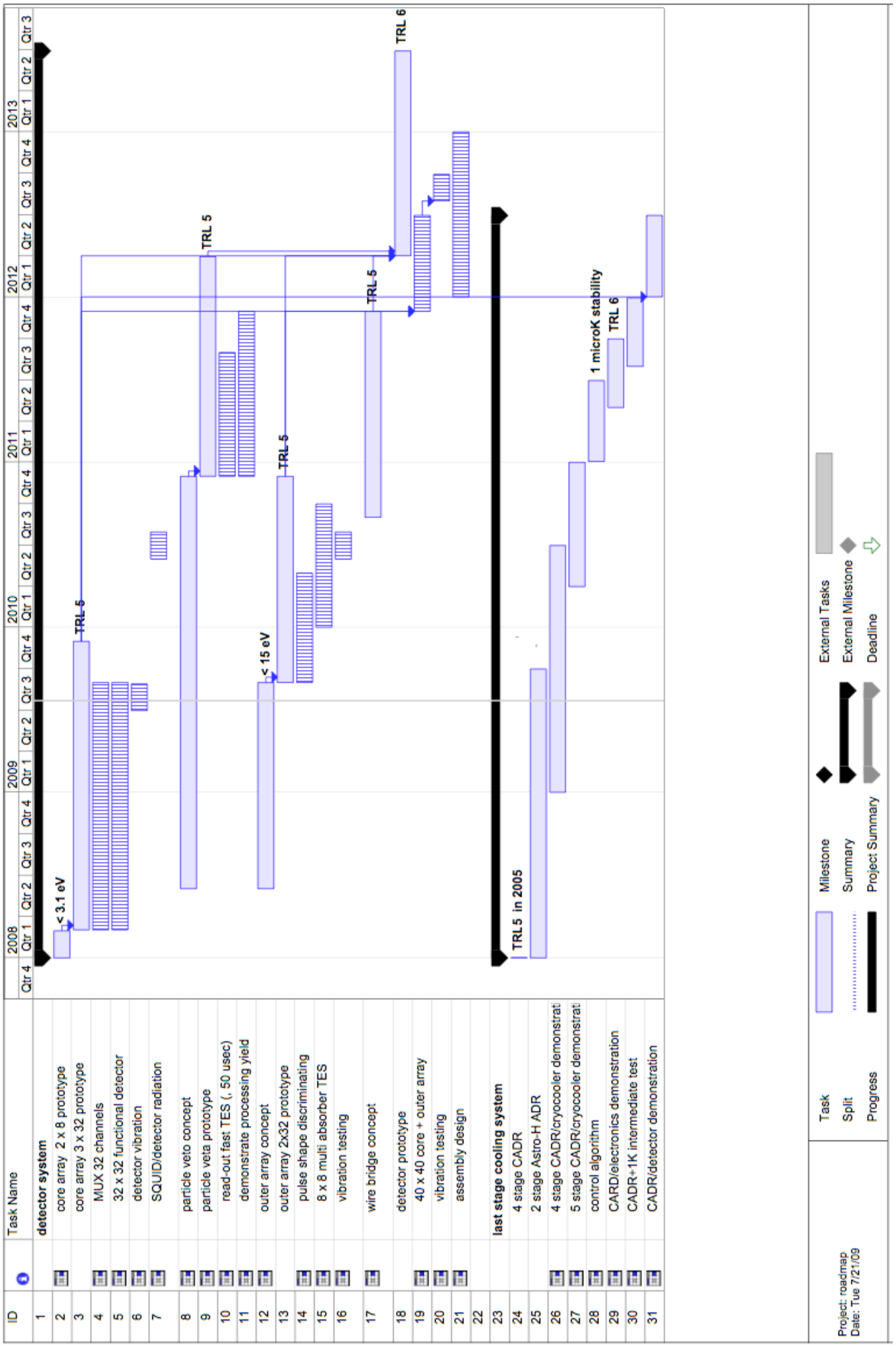

Fig 1. Planning of the US XMS roadmap as described in sections 2.1 and 2.2.

2. Technology Roadmap for the NASA Reference Configuration

The XMS technologies that are not yet at TRL 6 are the detectors and their readout (the detector system) and the continuous ADR. Since the roadmaps for the detector system and the CADR are largely independent, they are presented here sequentially. Each has its own subsystem TRL 6 demonstration. There is no plan for an integrated demonstration of the TRL 6 CADR and TRL 6 detector system until breadboarding activities during Phase B. However, operation of the TRL 5 core array with the TRL 6 CADR has been included in the CADR roadmap in order to confirm that the part of the XMS focal plane with the most demanding requirements can perform to specifications when cooled by the CADR. This logic is shown in figure 1.

2.1 XMS Detector System Technology Roadmap

The XMS detector system technology development roadmap consists of major milestones tied to significant demonstrations of the integrated detectors and read-outs, each fed by supporting demonstrations in the detector and superconducting electronics subsystems separately. Three of these major milestones bring individual components of the focal plane to TRL 5, and the final milestone establishes TRL 6. In addition to these major and supporting milestones, there are two concept demonstrations scheduled for the outer array and anti-coincidence detector to vet these components of the detector system that have not received investment comparable to close-packed arrays of independent TES calorimeters and SQUID multiplexer technology. These concept demonstrations are precursors to the TRL 5 demonstration of these components.

Each of the technologies supporting the XMS is at Research and Development Degree of Difficulty (R&D^3) II, which means that there remains a significant amount of development work, but that the path to success is sufficiently straightforward that parallel development of significantly different alternate technologies will not be necessary. This approach is low risk as long as sufficient investment in the primary development path is made early in the program.

Core array pre-prototype demonstration:

Multiplexed (2x8) read-out of 16 different flight like pixels in an 8x8 array with better than 4-eV resolution at 6 keV and pulse fall time < 1 ms. [accomplished MARCH 2008]

Discussion:
Reaching this milestone showed that the baseline technology approach for the XMS core array is fundamentally sound. The detector pixels were sufficiently uniform to permit good performance to be achieved under common bias, and the modest degradation of the detector performance while multiplexed was consistent with models. Resolution across 16 multiplexed pixels ranged from 2.6 eV to 3.1 eV, and the pulse time constant was 0.28 ms, far exceeding the requirements of this milestone. Additionally, 12-channel and 16-channel multiplexing were accomplished with degraded resolution (average resolutions of 3.0 and 3.2 eV, respectively).

Core array prototype (TRL 5) demonstration:

Multiplexed (3x32) read-out of 96 different flight-like pixels on a 0.3 mm pitch in a 32x32 (or greater) array with > 95% of pixels achieving better than 3-eV resolution at 6 keV and pulse fall time < 0.5 ms. Verification must also be accomplished at count rates up to 60 counts/s/pixel, in those pixels located in a valid test environment (either surrounded by other biased pixels or by unbiased pixels that are shielded from x-rays). [DECEMBER 2009]

Supporting milestones:

- 32-channel MUX switching speed and low noise demonstration [SEPTEMBER 2009]

- verification of 32x32 close-packed (flight-like, 0.3 mm pitch) array, in test of at least 16 randomly distributed pixels, each meeting XMS requirements for the core array when tested individually (or via lower degree of multiplexing, e.g. < 8 row). Verification must be accomplished at count rates up to 60 counts/s/pixel, in those pixels located in a valid test environment (either surrounded by other biased pixels or by unbiased pixels that are shielded from x-rays). [SEPTEMBER 2009]

- successful vibration testing of 32x32 array [SEPTEMBER 2009]

- successful radiation testing of SQUIDs and detectors [JULY 2010]
  (Note that vibration and radiation testing, while necessary for full realization of TRL 5, are not required for the actual core array prototype demonstration. Thus, it is acceptable for the radiation testing to be scheduled later.)

Discussion:
This demonstration requires the SQUID multiplexer to be at the ultimate design speed (12 MHz open loop bandwidth), which will be realized with straightforward design changes from the successful 2x8 demonstration. The development required in scaling the core array from 8x8 to the present 40x40 baseline lies mainly in routing of the signal leads through the array (fine-line micro-striplines are now required) and in heat sinking the array structure to handle the bias power of 1600 pixels and minimize thermal crosstalk. These elements can be adequately verified in a 32x32 array, thus the milestone does not require the full 40x40 of the baseline. The micro-stripline technology is already in hand, and the process of integrating it into the TES array fabrication is in progress. Proper heat sinking must be accomplished on the scale of the core array before the more complex integration of the TRL 6 demonstration is attempted. The concepts are straightforward, however, thus the associated risk is small.

Extended field-of-view concept demonstration:

Verify the feasibility of extending the field of view beyond the 2-arcmin core array to 5 arcmin, while increasing the number of electronics channels by less than 50%. This milestone requires demonstrating a resolution on each outer pixel of better than 15 eV, in a design that is readily arrayed in a close-packed configuration.

This milestone will be met by demonstrating an array scheme that is readily arrayed in a close-packed configuration in which a single read-out channel of the outer array reads the signals from an area on the focal plane that is at least a factor of 16 larger than an individual pixel of the inner array, using spatial resolution elements no bigger than 6 arc sec (twice the width of the pixels of the core array). [SEPTEMBER 2009]

Discussion:
In the reference design for the outer array for the XMS, there are four 6-arc-sec pixels per TES. Each pixel is a distinct x-ray absorber coupled to the TES by a different thermal conductance, and discrimination between the four pixels is achieved by pulse-shape analysis. In this baseline, 32-channel multiplexing is presumed, with the same speed as for the core array. Although the pulse fall-time requirement for the outer array is 2 ms (compared with 0.3 ms for the inner array), using the same architecture for the multiplexed read-out preserves sensitivity to the variations in the pulse shape, and allows the outer array to be read with 18 electronics channels identical to the 50 used to read out the core array. Thus, the concept demonstration only needs to validate the detector technology, via demonstrating operation of a four-absorber TES in which each absorber is 0.6 mm wide. In four-absorber TES devices with 0.25 mm pixels, 6 eV resolution has already been achieved. Variations in which sixteen, 0.3-mm pixels are attached to a single TES, or separate single-TES pixels are coupled with different electrical time constants to the same input SQUID will be evaluated and could also be used to satisfy this milestone. Going forward, the option of increasing the scale of multiplexing for the outer array, from 32 rows to 128 rows but at the same line rate, will also be evaluated.

Outer array prototype (TRL 5) demonstration:

Multiplexed (2x32) read-out of 8x8 array of multi-absorber TES devices (same physical area covered as 32x32 core array demo) with better than 12 eV resolution at 6 keV, pulse fall time < 2 ms, and position discrimination down to energies as low as 150 eV. [DECEMBER 2010]

Supporting milestones:

- demonstration of pulse-shape discrimination and 32-channel multiplexing at compromise choice of input filtering [MARCH 2010]

- verification that 8x8 or greater array of close-packed, multi-absorber TES devices can be fabricated with sufficient uniformity for common biasing, meeting the requirements for the extended array on all pixels [OCTOBER 2010]

- successful vibration testing of outer-array prototype [JUNE 2010]

Particle veto concept demonstration:

Demonstrate proof-of-principle one-sided anti-coincidence detector for particle veto and design a feasible scheme for its integration behind the microcalorimeter array. [DECEMBER 2010]

Discussion:
An anticoincidence detector has been presumed for XMS, but very little work has been done towards its realization for XMS at this time. The Suzaku/XRS had an antcoincidence detector based on charge collection in Si. The detector was situated just behind the calorimeter array and was operated at the same temperature (60 mK), and it was read-out using a similar JFET amplifier scheme to the pixels of the array. For the XMS, a similar design scheme is under consideration that uses the same read-out as the detector array, in this case SQUID technology. In the current baseline concept, TES are placed on the surface of a silicon crystal to read the non-thermal phonon signal resulting from particle interaction; this is an approach that is already in use in terrestrial dark matter searches and that would be readily adaptable for the XMS anticoincidence detector. At the time of designing the engineering unit, schemes for 5-sided anti-coincidence that incorporate the veto detector into the detector housing will be investigated, but demonstration of a one-sided veto is adequate for technology verification. Successful demonstration includes verifying that a threshold can be set as low as necessary to reject > 99.8% of minimum ionizing particle interactions depositing < 12 keV in the calorimeter array.

Particle veto prototype (TRL 5) demonstration:

Demonstrate particle veto prototype on scale appropriate for full XMS array (~36 x 36 mm) with pulse time constant < 50 micro-seconds, energy resolution better than 1 keV, and ability to reject > 99.8% of minimum ionizing particle interactions depositing < 12 keV in the calorimeter array. [MARCH 2012]

Supporting milestones:

- demonstration of read-out of fast TES signals and determination of the number of read-out channels needed to provide position information as a means of classifying background events [JUNE 2011]

- demonstration of processing yield of TES devices and phonon-collection features on 36 x 36 mm device [DECEMBER 2011]

Wire-bridge concept demonstration:

Demonstrate proof-of-principle superconducting wire-bridge scheme that can be used for high-density wiring between the 50 mK and 1 K stages, and possibly also between the 1 K and 4.5 K stages. [DECEMBER 2011]

Discussion:
The detector assembly houses and provides the thermal staging at 50 mK (for the TES arrays, the particle veto, and the SQUIDs), at 1 K (for heat intercepts on the wiring), and at 4.5 K (for the termination resistors used on the SQUID feedback and address lines). The 50 mK, 1 K, and 4.5 K sections are held rigidly with respect to each other so that the assembly can be inserted as a single unit with minimized thermal conduction between the stages. The assembly includes mechanical suspension systems, heat sinks, wiring interconnects, high density wiring feedthroughs, and magnetic shielding. Although the design of the detector assembly itself is part of the TRL 6 milestone, the wiring interconnects between the temperature stages requires advance research. The conducted load to 50 mK from the ~1100 wires must be kept to < 1 μW. The leading concept is based on the silicon microbridges of Spitzer/IRAC, except that the conductors would be Nb microstrips, and the substrates would be polymer films. Schemes for incorporating flat woven cables of twisted pairs of fine round wire, as will be used for the TRL5 demos, should be investigated as a back-up.

Detector assembly prototype demonstration (TRL 6):

Multiplexed (6x32) read-out of portion of full focal plane array – 128 different single-TES pixels in a 40x40 core array with better than 2.7-eV resolution at 6 keV and pulse fall time < 0.3 ms and 64 multi-absorber TES (256 0.6-mm pixels or 1024 0.3-mm pixels) of a full-sized outer array with < 12 eV resolution at 6 keV. A particle-veto has been integrated into the test set-up. Electrical and thermal interconnects and staging are approaching a flight-worthy design, but a flight design is not fully realized. All pixels are biased though not read out, in order to validate the thermal design. Performance of the core array at count rates up to 200 counts/s/pixel will be demonstrated. [JUNE 2013]

Supporting milestones:

- verification of expanded focal plane array comprising 40x40 core array and array extension, either in a monolithic array or a composite structure. [MAY 2012]

- composite detector vibration tests passed (using detector fixturing approximating that needed in focal plane assembly) [SEPTEMBER 2012]

- electrical/thermal/mechanical assembly designed and fabricated [JANUARY 2013]

Discussion:

The difference between this demonstration and the Engineering Unit is that only the focal plane array will be of a flight-like design. The detector assembly will not be designed to accommodate every electronics channel, nor will it be engineered to vibration or mass specifications. The purpose of this demonstration is to bring the various components of the focal plane assembly together to develop the technologies needed for their thermal and electrical integration into the focal plane assembly. The design of this assembly includes mechanical suspension systems, wiring interconnects, high-density wiring feedthroughs, thermal sinks, and kinematic mounts. The assembly must maintain the following at an acceptable level: 1) thermal stability, thermal gradient across array, and thermal crosstalk, 2) electrical crosstalk, microphonics, magnetic shielding, and susceptibility to interference, and 3) conducted and radiative heat loads on all the temperatures stages. The design of this assembly will be guided by experience with Suzaku/XRS, the X-ray Quantum Calorimeter sounding rocket program, and our test platforms. The design does not require new physics, but will require systematic quantification of materials parameters and a careful balancing of the competing needs of the electrical, thermal, and mechanical elements of the integration. The risks associated with this development can be minimized by allocation of adequate resources to this development.

2.2 CADR Technology Roadmap

The Continuous ADR (CADR) technology development roadmap establishes milestones for component-level and subsystem-level demonstrations that will culminate in a TRL 6 cooler capable of meeting all XMS performance requirements. The plan leverages concurrent development of multi-stage ADRs for other projects – principally Astro-H – to first achieve flight-worthy demonstrations of all component technologies and relevant sub-assemblies. In parallel, an existing full-scale CADR and control electronics will be modified and optimized to demonstrate compliance, with adequate margin, with all XMS cooling requirements, using components that have been qualified at the mechanical and structural level. This will establish a TRL of 6 for the CADR system.

The CADR development has drawn on considerable flight heritage from the Astro-E, Suzaku (formerly Astro-E2) and SOFIA/HAWC projects, and a cooler that meets (with greater than 100% margin) the cooling power requirements anticipated for IXO has been operational for more than 4 years. The remaining development focuses on adding an intermediate stable temperature stage at ~ 1 K for wire heatsinks and cooling a thermal shield, and on stabilizing the base temperature throughout the CADR's cycle to the level required by the detectors. Based on its operating principles, the CADR is able to achieve better temperature stability at the expense of modestly lower cooling power. Consequently, there is no fundamental barrier to meeting XMS requirements, which justifies a Research and Development Degree of Difficulty ($R\&D^3$) rating of II. The proposed approach is low risk as long as sufficient investment is made early in the program.

4-stage CADR TRL 5 demonstration:

Operational multi-stage CADR achieving greater than 5 microwatts of cooling power at 50 mK while rejecting heat to a 4.2 K heat sink. [accomplished 2005]

Discussion:
Reaching this milestone demonstrated for the first time a cooling technology that could meet the required 50 mK operating temperature of the XMS detectors with sufficient cooling power within acceptable mass limits. The CADR's revolutionary architecture enabled it to achieve more than an order of magnitude increase in cooling power per unit mass over existing single-shot ADRs. The CADR also has inherently higher efficiency, higher heat rejection capability and lower peak heat output; characteristics that are necessary for IXO and future missions that will use mechanical cryocoolers as an upper cooling stage. Moreover, all CADR components, especially suspension systems for structurally supporting the salt pills within their magnets, incorporated heritage designs from flight ADRs built for XRS2 on Suzaku and HAWC. This was done to make the design as flight-like as possible, and ensure that internal parasitic heat flows were representative of eventual flight designs. The TRL 5 unit has therefore demonstrated the *capability* to meet all XMS cooling requirements.

2-stage Astro-H ADR demonstration:

Operational two-stage ADR that meets the cooling requirements of the Astro-H detectors with flight mechanical and structural components [OCTOBER 2009]

Discussion:
Although it does not directly support the development of CADR technology, the production of a 2-stage ADR for Astro-H will contribute to its technical maturity through the qualification testing of components and designs that are similar to those used in the CADR. The Astro-H ADR does not operate continuously, but in a "single-shot" mode. This difference requires more massive salt pills than is required for comparable stages in a CADR. Consequently the mechanical and structural design of these components is more challenging. At the same time, the thermal requirements are more demanding in terms of allowable parasitic heat leaks. The performance and environmental testing of the Astro-H ADR will therefore qualify component and sub-assembly designs that can be incorporated into future CADR designs. This will provide a stronger basis for developing a 5-stage CADR for XMS, and conducting a TRL 6 demonstration (targeted for late 2011, as discussed below).

4-stage CADR and cryocooler demonstration:

Assemble a 4-stage CADR with a commercial cryocooler and characterize performance [JULY 2010]

Discussion:
This combined system will form a test bed for subsequent development of CADR components and control electronics. ADRs (and the XMS) are potentially susceptible to low levels of vibration from the cryocooler, and the CADR's performance is affected by the stability of the heat sink temperature through radiation and heat conduction. This demonstration will verify the inherent compatibility of the two cooler types, as well as provide a test facility for modifications to the ADR stages, control algorithms, and control electronics.

5-stage CADR and cryocooler demonstration:

The XMS requirement of a stable 1 K node for staging a thermal shield and for heat sinking wiring and possibly other components will be demonstrated by coupling a 5th ADR stage to the warmest stage in the 4-stage CADR. [DECEMBER 2010]

Discussion:
The same principle that enables continuous cooling at 50 mK will be used to achieve continuous cooling at 1 K. This involves adding a 5th stage that couples to the warmest stage of the CADR via a heat switch. This stage will cool a shield that will eventually surround the entire 4-stage CADR, providing a stable intercept for higher temperature radiation, as well as establishing a platform for heat sinking leads. The 50-Ohm termination resistors for the SQUID feedback and address lines could also be staged there. This will complete the demonstration of all cooler functionality required for IXO.

Cold stage and control algorithm development completed:

Modifications will be made to the coldest stage of the CADR and to control algorithms to improve the thermal stability of the base temperature. [MAY 2011]

Supporting Milestones:

- Fabricate a new salt pill for continuous stage of the CADR to achieve higher thermal conductance between the salt and the external interface

- Develop higher resolution temperature readout electronics, such as those being developed for the Astro-H ADR

- Characterize components parameters and heat transfer coefficients within the CADR

- Implement "feedforward" control routines to compensate for changes in heat flow in real time

Discussion:
For single-shot ADRs, heat loads during operational periods are essentially constant. As a result, the electronics can use simple feedback routines to achieve very stable temperature control. The CADR's cycle involves significant fluctuations in the heat loads during the continuous operational cycle, and this has a tendency to produce temperature fluctuations in the cold stage. One approach to minimizing the fluctuations takes advantage of the fact that an ADR's thermodynamic state can be computed in real time from measurements of temperature and magnetic field. With sufficiently accurate knowledge of certain parameters of each component (mass, heat capacity, thermal conductance, etc.) it is possible to implement temperature control algorithms that are predictive in nature, and which can compensate for changes in heat flow *as they occur*, rather than rely on reactive control *after they occur*. This will allow the CADR to achieve better temperature stability without affecting its cycle speed, and hence the cooling power. Recent implementations of this technique have been able to reduce fluctuations in the prototype CADR from 100 microkelvin rms to about 14 microkelvin rms. This was the best that could be achieved given some amplification of the approximately 8 microkelvin rms readout noise of the control thermometers. The XMS requires ~1 microkelvin rms stability. To achieve this, higher resolution thermometry readout is needed along with more finely tuned feedforward algorithms. Both commercial electronics and the Astro-H ADRC will be evaluated for this purpose, and control parameters will be tuned to demonstrate the ultimate stability of this technique. The CADR's cycle speed will also be adjusted as necessary to reach the XMS requirement.

CADR and control electronics demonstration (TRL 6):

Reassemble a CADR using structurally qualified components and high-stability control electronics [OCTOBER 2011]

Discussion:
The demonstration of a fully functional CADR meeting (with margin) the cooling requirements of the XMS, coupled to a commercial cryocooler and using flight-qualified designs, will constitute a TRL 6 demonstration of a detector cooling system for IXO.

CADR with 1-K intermediate stable stage in platform designed for detector system integration:

A 5-stage CADR will be assembled into a test dewar that will be designed for high-fidelity tests of cooler and detector performance. [DECEMBER 2011]

Discussion:
Existing CADR test dewars are not configured for combined CADR/detector tests, due to internal space constraints and the lack of suitable electrical access for detector array readout. Either after refurbishment of an existing facility or the development of a new

one, the TRL 6 CADR will be integrated into a test dewar that will enable it to provide an environment functionally identical to flight conditions for the detector array.

Combined CADR/detector-system demo:

Run detector system from TRL5 demo of core array with 5-stage CADR to confirm that the same detector performance can be achieved as with a single shot ADR. This will confirm the adequacy of the specifications for the temperature control, thermal environment, and magnetic field environment. [JUNE 2012]

3. European and Japanese Developments

In Europe and Japan, parallel developments are ongoing. The European technology development activities can be found in the response by a consortium of European groups that, together with the US (GSFC, NIST) and Japan (ISAS, MTU, Kanazawa University), responded to ESA's request for a Declaration of Interest in IXO technology development. As indicated earlier, these activities are largely parallel to the US roadmap. At the time of the instrument AO, this consortium will propose the best performing instrument, drawing from the best technology available in the different countries.

Below we give a short overview of these activities as well as expected milestones (see also SRON-XMS-PL-2009-003 and the "IXO-XMS Technology Development Activities: workplan 2008-2011, annex 1", to be issued by ESA. Note that the time frame for this roadmap is somewhat different (2008 – 2011).

TDA	Activity	Milestone at technological Readiness Review
	European	
TDA1	Optimization of the TES-based micro-calorimeter array for IXO/XMS	Assessment present sensors + few new types: July 2009
		New TES geometries: Prod. + tests.: Dec 2009
		Arrays with new layout for X-ray tests (25 pixels): March 2010
		Demonstrate production 32 x 32 wafer
TDA2	Optimization of Frequency-Domain-Multiplexed read-out electronics for Micro-calorimeter arrays	FDM 2 pixels: July 2009
		FDM 8 pixels: Dec. 2009
		FDM: 2 x 8 pixels spanning full frequency domain: March 2010
TDA3	SQUID development for cryogenic sensor readout at PTB, funded through TRP5417, TDA3 will include follow up	Assessment 1st SQUIDs: Mid 2009
		Delivery 2nd SQUID version: December 2009
		Assessment 2nd gen. SQUIDs: March 2010
TDA4	SQUID development for cryogenic sensor readout at VTT	Delivery 1st gen. SQUIDs: Mid 2009
		Assessment 1st gen. SQUIDs: Autumn 2009
		Delivery 2nd gen. SQUIDS: Spring 2010
TDA5	Qualification activities on detector arrays	Thermal/mechanical test of 5 x 5 array: March 2010
		Radiation hardness test: March 2011
TDA6	Qualification activities on read-out electronics	> 2010
TDA7	Development of electrical interconnections	Proof of principle of bonding for 3D structures (dec 2009,

	for the (cold) detector components	TRL 3) Laboratory demonstrator (TRL 4, June 2010)
TDA8	Closed cycle dilution cooler	Breadboard (TRL 4) at Q1 2010
TDA9	Advanced 2K JT cooler	ESA TRP milestones
TDA10	15K Pulse Tube cooler	ESA TRP milestones
TDA11	50mK continuous cooler"He3-Sorption-ADR hybrid	Engineering model (dec 2009- Feb 2010) vibration tested
TDA12	50mK continuous cooler: dADR	Under discussion with ESA
TDA13	optimize full cooling chain	n/a > 2010
TDA14	Test & Verification of Sub-kelvin cooling chain	n/a > 2010
TDA15	Cryogenic anti-coincidence sensor development	First detector breadboard tested with commercial SQUID electronics selected to meet the requirements (march 2010)
TDA16	design of complex filterwheel for XMS	Assessment of rotating filters and electrical cal. sources: March 2010
TDA17	develop polarization sensitive filters	Demonstrate performance around Fe-K and provide estimates sensitivities
TDA18	demonstrate performance of beam diffusing optics	A working and characterized MCP diffusing optic
TDA19	Large area X-ray window development.	Carried out under ESA contract
	Japanese	
TDA_J1	Electronics for TES microcalorimeter Frequency-Domain-Mulitiplex	TES readout with analog BBFB at >= 1 MHz, Multiplex >= 2 pixels
TDA_J2	Design of TES microcalorimeter array	TES array designed to verify IXO array
TDA_J3	Design of full cooling chain	More detailed design including reliability assessment, ground operation plan, and initial cooling plan
TDA_J4	50 mK dADR and drive electronics	Assessment of present BBM dADR Study of "AC-bridge type" temperature-sensor electronics
TDA_J5	Long-lifetime 1 K cooler	Basic research for 10 year lifetime coolers
TDA_J6	Compressor for closed cycle dilution cooler	Clarifying requirements and conceptual study (with European partner)
TDA_J7	Digital Data processing	Conceptual study for optimum data processing for IXO with low power electronics