# Enabling Technologies for the High-Resolution Imaging Spectrometer of the Next NASA X-ray Astronomy Mission – Options, Status, and Roadmap

A response to RFI NNH11ZDA018L: Concepts for the Next NASA X-ray Astronomy Mission

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Category:
ENABLING TECHNOLOGIES:  We present the development trajectories of technologies that enable the imaging spectroscopy  needed by many of the IXO science goals.

Questions:
Willing to present?   – Yes, if appropriate for technologies (in contrast with missions and instruments).
Sensitive or controlled information? - No, the information is provided at a high level only.

Abstract:

The ability to perform broad-band imaging x-ray spectroscopy with high spectral and spatial resolution was an essential capability of the mission concept for the International X-ray Observatory.  High-resolution imaging spectrometers also feature prominently in a large number of the alternative mission concepts that are being put forward in response to this NASA Request for Information (RFI) for concepts that meet some or all of the original IXO science objectives.  The purpose of this white paper is to present the technology development needed to enable the original IXO X-ray Microcalorimeter Spectrometer (XMS) as well as a range of other instrument concepts presently being formulated to fill some of the same niche.  We present the technology options, the projected trajectories of their development, and the investment needed to bring them to fruition.

# 1. OVERVIEW

The ability to perform broad-band imaging x-ray spectroscopy with high spectral and spatial resolution was an essential capability of the mission concept for the International X-ray Observatory. High-resolution imaging spectrometers also feature prominently in a large number of the alternative mission concepts that are being put forward in response to this NASA Request for Information (RFI) for concepts that meet some or all of the original IXO science objectives. The purpose of this white paper is to present the technology development needed to enable the original IXO X-ray Microcalorimeter Spectrometer (XMS) as well as a range of other instrument concepts presently being formulated to fill some of the same niche. We present the technology options, the projected trajectories of their development, and the investment needed to bring them to fruition.

In an imaging spectrometer, the individual pixels map to spatial coordinates and thus must determine energy directly. Direct measurement of x-ray photons with eV-scale spectral resolution requires an operating temperature below 0.1 K. The required spectral resolution and the constraints of thermodynamics dictate the temperature regime nearly independently of the details of the sensor or the read-out technology. Various schemes for performing sensitive energy measurements have come together to form the field of low-temperature detectors (LTDs) over the last twenty-five years. The need for high-resolution, non-dispersive, x-ray spectrometers, particularly for cosmic targets, has been one of the main driving forces in this field.

LTD spectrometers can be divided into two broad classes – equilibrium and non-equilibrium. In the equilibrium devices, or calorimeters, the energy is deposited in an isolated thermal mass and the resulting increase in temperature is measured. At the time of the measurement, all of the deposited energy has become heat and the sensor is in thermal equilibrium. The ultimate energy resolution is determined by how well one can measure this change in temperature against the background of temperature fluctuations. While many temperature-dependent phenomena have been considered for transducing the resulting small temperature changes into a signal, the most successful have been the use of a highly temperature-dependent resistance (doped semiconductors and superconducting transitions) and magnetization. For photons in the x-ray band, these leading variations of calorimeters are reaching similar energy resolution: 2 – 3 eV FWHM at 6 keV.

Because calorimeters require complete equilibration to get their good energy resolution, they are slower than non-equilibrium devices, such as superconducting tunnel junctions (STJs) and microwave kinetic inductance detectors (MKIDs), in which the absorbed energy produces quantized excitations (quasiparticles) that are counted to determine the energy. Since some of the energy goes into heat or excited states, the ultimate energy resolution in such non-equilibrium devices is determined by the statistics governing the partition of energy between the system of excited states and everything else. Fair comparison would require a detailed presentation of specific design optimizations, but, generally, STJ resolution is a factor of 5 worse at 6 keV than that achievable with transition-edge sensor (TES) calorimeters, but the calorimeters can only handle fluxes in the several 100/s, whereas STJs maintain their performance up to several $10^4$/s. Thus, the relative importance of count rate and spectral resolution to a given class of observation dictates the sensor technology.

In reviewing the science objectives of the International X-ray Observatory (IXO), the need for broad-band high-resolution spectroscopy underscores the need for continued progress in low-temperature detectors, and the emphasis on resolution < 2.5 eV, without comparable emphasis on high counting rate, points to calorimeters. Superconducting transition-edge sensor (TES) calorimeters were baselined for the X-ray Microcalorimeter Spectrometer (XMS) on IXO, and

Constellation-X before that. In this white paper, we present the state of the art for the baseline technology and other leading LTD technologies. The sensor technologies are considered hand-in-hand with the read-out technologies, because it is the combination of detectors and read out that determines whether a detector technology can be implemented with the required performance within the allocated resources. This white paper only addresses technology options for the detector system (detectors and their read-outs). The IXO Phase A study for Cosmic Visions selected a cooling system based on the Astro-H cooling chain as its baseline [den Herder et al., 2010]; by definition this requires no technology development outside of the Astro-H program itself. A myriad of other cooling chain options exist, with different balance between redundancy and mass/cost; discussing these is beyond the scope of this document.

## 2. MICROCALORIMETERS

The Soft X-ray Spectrometer (SXS) on Astro-H, expected to launch in 2014, uses silicon thermistors. Both semiconductor and superconductor calorimeters have been implemented in small arrays. Kilopixel arrays of the superconducting calorimeters are being produced, and much larger arrays may require the non-dissipative advantage of magnetically coupled thermometers.

### *Semiconductor Thermistors*

The SXS calorimeter operates at 50 mK and consists of a 6x6 array of silicon thermistors with HgTe X-ray absorbers on a 0.83 mm pitch. The SXS engineering-model and first flight-candidate calorimeter arrays have been completed, and the resolution at 6 keV ranges from 3.6 – 4.6 eV across the arrays.

This technology has been used for the XQC (X-ray Quantum Calorimeter) sounding rocket program [McCammon et al, 2002], on Astro-E and Astro-E2 (Suzaku) [Kelley et al., 2000], and at a facility at the Lawrence Livermore Electron Beam Ion Trap (EBIT) to carry out laboratory astrophysics [Porter et al, 2008]. This is a very well understood technology that has achieved an energy resolution of 3.2 eV FWHM at 6 keV [Porter et al, 2006]. If designed specifically to meet the IXO requirements, this technology does have the potential to meet the energy-resolution requirements. The drawback, in comparison with other options, is the lack of a demonstrated read-out technology that would enable arrays of greater than a few hundred pixels. However, electronics using GaAlAs/GaAs high-electron-mobility transistors and SiGe ASIC devices to read out, amplify and multiplex thermistor signals is under development. [Aliane et al., 2008] Further investment in the development of semiconducting thermistors would be of benefit to the IXO science objectives if this or another low-noise technique for multiplexing high-impedance sensors is demonstrated.

### *Superconducting Transition-Edge Sensors (TES)*

In a TES calorimeter, the temperature and current dependence of the transition from the zero-resistance to normal-resistance state of a superconductor is used for thermometry. The XMS baseline technology developed at Goddard incorporates a microns-thick Au or Au/Bi absorber, designed to thermalize the absorbed energy quickly, with a superconducting transition-edge sensor (TES) made from a Mo/Au proximity-effect bilayer. The Mo and Au layer thicknesses are tuned to achieve a superconducting transition around 0.1 K. The absorber makes direct contact with the TES only in normal-metal regions that are used to reduce noise in these sensors, which allows the use of a high-quality electroplated gold layer as the foundation for the absorber. A further constraint, that the high-conductance absorber not electrically short out the sensor, limits contact to only one point along the flow of current in the TES. Arrays of such pixels optimized for XMS have demonstrated energy resolutions of 2–3 eV FWHM at 6 keV.

The key strengths of this technology are that it has already achieved a world record energy resolution 1.8 eV FWHM at 6 keV in an 8x8 array [Bandler et al., 2008], and that a multiplexed SQUID (superconducting ammeter) read-out has been developed that is close to meeting the requirements of the few-thousand-pixel array for IXO [Kilbourne et al, 2008]. Fig. 1 shows a prototype for the XMS core array.
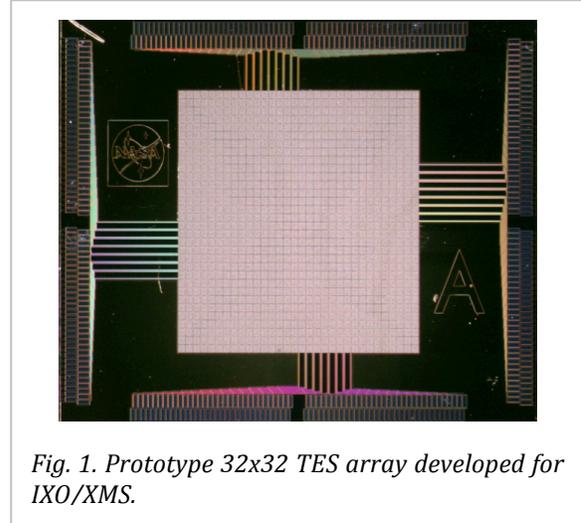
Recent TES calorimeter development has been enhanced by new understanding that many TES properties can be explained by quantum effects acting over length scales comparable to the device extent. [Sadleir et al., 2010; Sadleir et al., 2011] In small TES devices, the effective superconducting



Fig. 1. Prototype 32x32 TES array developed for IXO/XMS.

transition temperature depends sensitively on current, one effect of which is to extend the linear operating range of such pixels. Pixels with a 0.035 mm TES and 0.057 mm absorber have demonstrated better than 2 eV resolution over a wide energy range (shown in Fig. 2). Such small pixels operate well without membrane isolation, allowing fabrication on a robust substrate with built-in heat sinking. These pixels are also about a factor of six faster than the ones optimized for IXO; with use of an appropriate filter in the TES bias circuit, the rise and fall times will both be approximately 30 µs. Thus, with this newly obtained understanding of TES physics, the basic TES architecture can be optimized for a variety of observing goals.
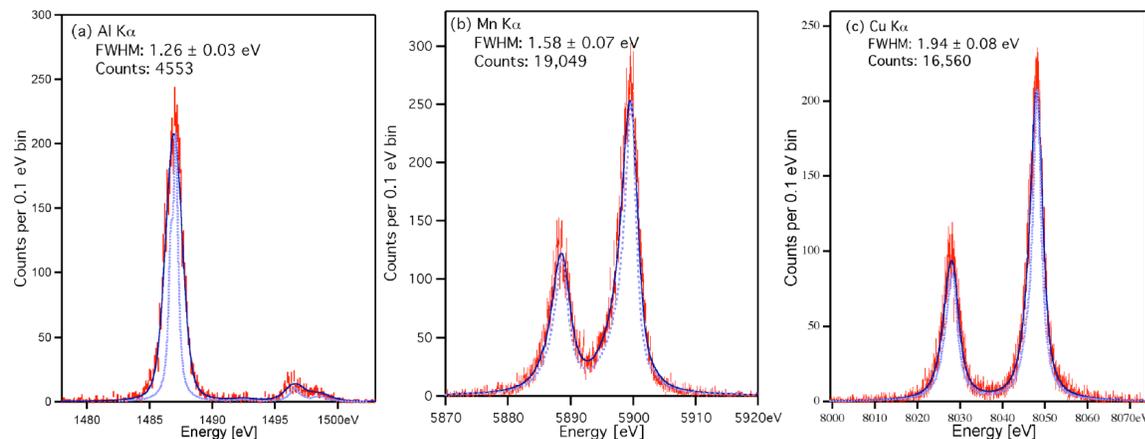


Fig. 2. Energy resolution of a small TES calorimeter measured at three different energies using x-ray fluorescence. The pixel dimensions are 57 µm x 57 µm x 4.5 µm, with an underlying 35 µm TES. In each spectrum, the light blue dotted line shows the intrinsic line shape of the K transition. The red lines represent the data, and the darker blue line is the intrinsic line shape convolved with the best fit instrumental broadening (assumed to be Gaussian).

## Magnetically Coupled  Calorimeters

Metallic magnetic calorimeters (MMCs) utilize the temperature dependence of the magnetization of a paramagnetic metal in a weak magnetic field to detect the temperature rise resulting from the absorption of a photon. Gold doped with a small amount of erbium (Au:Er) is an effective sensor

[Fleischmann, 2005]. The temperature rise causes a change of magnetization ($M \propto 1/T$) of the Er spins, which is measured as a flux change in a SQUID magnetometer.

A geometry suitable for making arrays of MMC microcalorimeters consists of superconducting niobium meander inductors onto which a layer of magnetic material is deposited. When a current is passed through the meander, a magnetic field is produced in the region of the magnetic material. When an x-ray is absorbed, the temperature of the magnetic material changes, as does its magnetic permeability, and therefore the inductance of the meander. In the read-out circuit the meanders are in parallel with input coils of the SQUIDs. From the change in inductance of the meander, there will be a change in the current both through the meander and through the input coil of the SQUID. An outgrowth of this development has been yet another type of calorimeter, the magnetic penetration thermometer (MPT), which uses the same geometry but replaces the magnetic material with a superconductor in its transition. The MPT potentially combines the best of the magnetic calorimeter and TES technologies, providing the sensitivity of a TES in a dissipationless configuration. MMCs have achieved just better than 2.0 eV resolution at 6 keV [Fleischmann, 2011], and the Goddard group has recently obtained 2.3 eV resolution in a Mo/Au MPT at this energy.

Magnetically coupled calorimeters are intrinsically dissipationless. The read-out does not heat the thermometers; thus, very large-format focal-plane arrays can be built without the difficulty of removing the bias power from the detector array. (The SQUIDs do dissipate power but are not located at the focal plane and hence are much less of a problem.) Furthermore, because the sensor material itself is not connected to an electrical circuit (only the meander is, which is electrically isolated from the sensor), the thermometers can be directly connected to a metallic heat sink without affecting the way in which they are read out, greatly simplifying the management of thermal crosstalk. On the other hand, dissipation in TES calorimeters allows electrothermal feedback, which works to stabilize the operating temperature, relaxing the temperature stability required at the heat sink. Dissipation also allows easy signal filtering, simplifying multiplexing. Therefore, parallel investment in both TES and magnetic calorimeters is needed.

## *Position-Sensitive Calorimeter Elements*

Some degree of thermal multiplexing can be engineered into microcalorimeter arrays through the use of position-sensitive detectors. The basic element of such arrays is a macro-pixel (which may be continuous or made of interconnected discrete elements) read out by one or more thermometers. The element is designed such that the shape of the temperature pulse depends on the location of absorption on the macro-pixel.

The main advantage of such devices is that they reduce the total number of electronic channels required to read out a given number of pixels. This eases the requirements on the wiring and the number of readout channels. The associated increase in the complexity of the analysis electronics, from the added task of determining the sub-pixel event location, is minimal [Smith, 2009]. The last IXO/XMS baseline included an outer array of large position-dependent elements to extend the field of view.

Macro-pixels with internal position sensitivity can be implemented with any thermometer technology. Both TES and MMC macro-pixels have been successfully demonstrated in the Hydra design, in which one thermometer is coupled to discrete separate absorbers via varied thermal links. For example, a single TES with 6 differently coupled 0.3-mm absorbers (a case intermediate between the Constellation-X outer-array and the IXO baselined outer array) was tested at Goddard. Resolutions across the 6 pixels ranged from 5.4 eV to 7.8 eV; the layout and distinguishing pulse shapes are shown in Fig. 3.
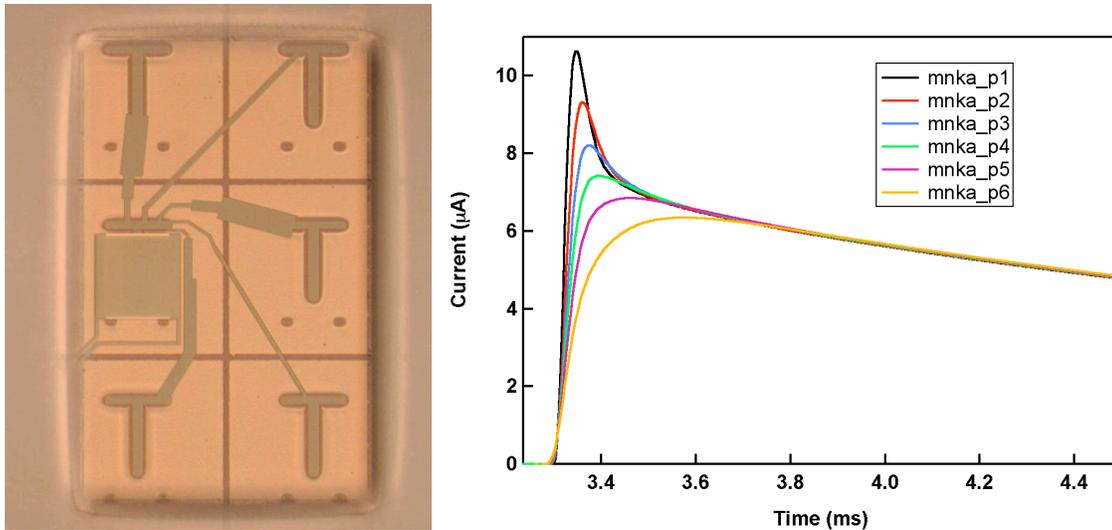
*Fig. 3: left:  6-pixel macro-pixel from the back (looking through the nitride membrane), showing 6 absorbers, single TES, and the links between them, right: the characteristic pulse shapes that distinguish the 6 pixels; resolutions across the 6 pixels ranged from 5.4 eV to 7.8 eV.  A single pixel of the same heat capacity and TES properties would have had a resolution of about 4 eV.*

The distributed-absorber approach does come with a penalty of reduced energy resolution, however.  The resolution will always be somewhat worse than that of a single pixel with the heat capacity and temperature sensitivity of the macro-pixel because decoupling parts of the absorber to introduce position variation introduces thermal fluctuation noise between parts of the absorber.

## 3.  NON-EQUILIBRIUM LOW-TEMPERATURE DETECTORS

### Superconducting Tunnel  Junctions

In superconducting tunnel junctions (STJ), Cooper pairs in a narrow-gap superconductor are broken by incoming radiation into quasiparticles that are collected (sometimes after multiplication) as the signal.  STJs have the intrinsic advantage that they are very fast and thus can accommodate extremely high counting rates. Having intrinsic rise-times of 2-3 μs, and decay times around 20 μs, reasonably high energy resolution has been demonstrated under 1 keV (<10 eV at 277 eV) for count rates up to 10,000 s^{-1} [Frank et al., 1998]. However, they have not achieved a competitive energy resolution in the 1-10 keV band-pass.  Even the theoretical limits for most materials from which they can be made do not meet the requirements at 6 keV, and actual performance, though good, has only come close to the theoretical limits at energies below 1 keV. STJs could fill a niche for future applications requiring only moderate energy resolution and the ability to accommodate very high counting rates.  It should be possible for the SQUID read-out of STJs to be multiplexed using the microwave multiplexing described in Section 4.

### Microwave Kinetic Inductance Detectors

Microwave Kinetic Inductance Detectors (MKIDs) [Day et al., 2003; Mazin, 2004] are also based fundamentally on measuring a quasiparticle signal produced in a superconducting absorber, but they have the inherent major advantage that their basic read-out can multiplex thousands of channels into a single amplifier.  This is achieved via trapping the quasiparticles in the sensitive element of a resonator.   The energy resolution is fundamentally Fano-noise-limited such that an energy resolution of better than 3 eV at 6 keV is impossible in most superconductors, except,

theoretically, though use of small-gap superconducting absorbers such as Re (1.7 eV), Mo (1.3 eV) or Hf (1.1 eV). The potential use of such absorbers would necessitate the use of even lower energy gap superconductors for trapping quasiparticles (to control losses), necessitating lower temperatures of operation than baselined for calorimeters. In addition to fundamental energy resolution there are other processes that could potentially degrade the energy resolution for reasons that are almost the same as for STJs. The quasiparticles can also become trapped, either temporarily of permanently, at surfaces, defects, or impurity sites. For an x-ray astrophysics mission, the most important gate for this technology would be demonstrating a moderate to high resolving power. If this is achieved, then this technology could become an attractive option for a future very large-scale imaging x-ray spectrometer.

## 4. MULTIPLEXED READ OUT

### *Switched SQUID Multiplexing*

The time-division multiplexing (TDM) reference concept for the TES baseline for XMS was pioneered at NIST. In TDM, the outputs from the dedicated input SQUIDs of individual TES pixels are coupled to a single amplifier, and multiplexing is achieved by sequential switching of these input SQUIDs. [Reintsema et al., 2003; Doriese et al., 2004; Beyer and Drung, 2008]. This technology was used in March 2008 for the successful demonstration of multiplexed (2x8) read-out of 16 different pixels (in an 8x8 array) similar to what is needed for the XMS reference design [Kilbourne et al., 2008]. 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. Additionally, 12-channel and 16-channel multiplexing were accomplished with degraded resolution (average resolutions of 3.0 and 3.2 eV, respectively).

Code Division Multiplexing (CDM) developed at NIST will soon replace TDM on the XMS roadmap. CDM's chief distinction from TDM, and its chief advantage, is that all detector pixels are "on" all the time. TDM employs low duty-cycle boxcar modulation functions that switch on and off the input SQUIDs of the TESs one row at a time. In contrast, CDM uses Walsh codes, in which the coupling of the pixel signals is alternated in polarity. Fig. 4 shows the four-pixel Walsh codes and compares them with the TDM modulation. To extract the individual signals, multiplication by the inverse Walsh matrix is required. Because signal is measured from every detector at each sample, instead of once per frame for TDM, CDM has a sqrt(N) noise advantage over TDM, where N is the scale of the multiplexing. The IXO/XMS noise budget was extremely tight. Investment in CDM, and its eventual replacement of TDM in the roadmap, will enable more capable implementations of XMS by enabling a much larger number of rows per read-out amplifier without degradation of energy resolution.

Flux-matrixed CDM, which encodes the Walsh matrix in hard-wired coupling to the switched SQUIDs, has been demonstrated as a drop-in replacement for TDM. Using a high-resolution NIST TES array not designed to meet the XMS requirements for pixel size, speed, and fill factor, a resolution of better than 3 eV on all switched pixels was achieved using flux-matrixed CDM. Work is also in progress on switched CDM, which uses superconducting switches to apply the Walsh code [Irwin, 2011].
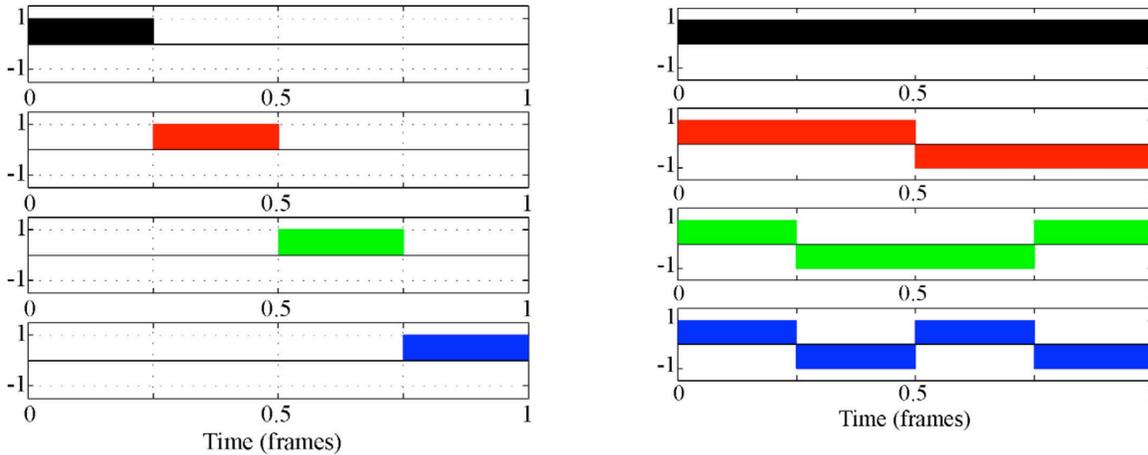
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*Fig. 4: Left:  Modulation functions for four-row TDM.  Each pixel is off (in the 0 state) for three rows, and on (in the 1 state) for one.  Right:  Walsh-code modulation functions for four-row CDM.  The polarity of each pixel's coupling is modulated between +1 and -1.*

## Microwave Multiplexing

Read-out consisting of a microwave multiplexer offers a path to mega-pixel arrays.  Several different versions of this type of multiplexer exist, depending upon whether it is adapted for the read-out of TESs, MMCs, or MKIDs. The detector technology most easily implemented with microwave read-out is the MKID, since the sensor is part of a resonator and no SQUIDs or modulation techniques are necessary.  For TESs and MMCs, unshunted, non-hysteretic rf SQUIDs are incorporated into the read-out that have negligible power dissipation even for extremely large arrays [Mates, 2008]. Furthermore, rf SQUIDs can be coupled to high-Q microwave resonant circuits fabricated from superconducting coplanar waveguides with resonant frequencies of several gigahertz. In this approach, the bandwidth of each microcalorimeter is limited by the resonant circuit after amplification by the rf SQUID. A single high-electron-mobility transistor amplifier has the bandwidth and dynamic range to read out many hundreds of rf SQUIDs operated in superconducting microresonators tuned to different frequencies, all coupled to the same coplanar-waveguide feedline.  For TESs and MMCs, the essential components of this technology are the same but their optimization is slightly different. Even larger multiplex scales are achievable via use of CDM as the front end to a microwave multiplexer.  Microwave multiplexing will be necessary for array scales greater than  ~10,000 thermometer elements.

## 5.  Roadmap and Development Cost

It is a challenge to define a technology roadmap for an open-ended RFI such as this, for which new mission concepts that meet all or some of the original IXO scientific objectives are solicited.  Thus, we have kept close to the original XMS baseline for the detector system for the projected roadmap and cost, with an allowance for alternate technologies to merge into the flow.  Development of many of the alternate technologies is already funded for other applications.

The XMS detector system technology is at TRL 4.  The "2x8 demo" of 2008 of multiplexed read-out of part of a TES array achieved the most fundamental goal of a demonstration of TRL 4  – basic technological components were integrated to establish that they will work together. The performance approached the requirements of potential system applications (in terms of resolution, speed, pixel scale, and quantum efficiency.) However, consistent with the expectations for TRL 4,

the validation was relatively low-fidelity compared with the eventual system application. It was low fidelity in that it is not possible to scale up the technologies used in the demonstration to what is needed for the flight system without further technology development.

The XMS detector system technology development roadmap consists of major milestones tied to significant demonstrations of the integrated detectors and read-out electronics, each fed by supporting demonstrations in the detector and superconducting electronics components separately. Below, we present only the major milestones; much more detailed discussion of these and supporting milestones was generated for ESA's Cosmic Visions review [Kilbourne and Doriese, 2010].

The reference technology is on track for reaching TRL 6. Straightforward modifications to the TDM architecture can achieve the factor of 4 increase in switching speed needed to go from 8-row to 32-row multiplexing. Optimization of multi-absorber devices must also take place. Advances are also needed in detector fabrication process control, and architecture of the detector-system front end.

### IXO/XMS Core Array Prototype (TRL 5) Demonstration

Demonstrate multiplexed (3 columns x 32 rows) 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, when analyzed using a record length and pre-pulse exclusion interval consistent with the requirement of 80% live time at an x-ray rate of 50/s/pixel. Vibration testing of an array is required to validate the mechanical design of the pixels.

### IXO/XMS Outer Array Prototype (TRL 5) Demonstration

Demonstrate multiplexed (2 columns x 32 rows) read-out of 8x8 array of four-absorber devices (same physical area covered as 32x32 core array demo) with better than 15 eV resolution at 6 keV when analyzed using a record length and pre-pulse exclusion interval consistent with the requirement of 80% live time at an x-ray rate of 2/s/pixel, and position discrimination down to energies as low as 150 eV.

### IXO/XMS 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. (The particle-veto is presumed to be TES-based, along the lines of detectors developed for dark-matter detection.)

### Integrated Detector-System Prototype Demonstration (TRL 5)

Combine the requirements of the core-array and outer-array TRL 5 demonstrations into an integrated demonstration of both parts of the focal plane. An anti-coincidence detector will also be integrated into the test platform and operated. Radiation testing of SQUIDs and detectors is also to be performed.
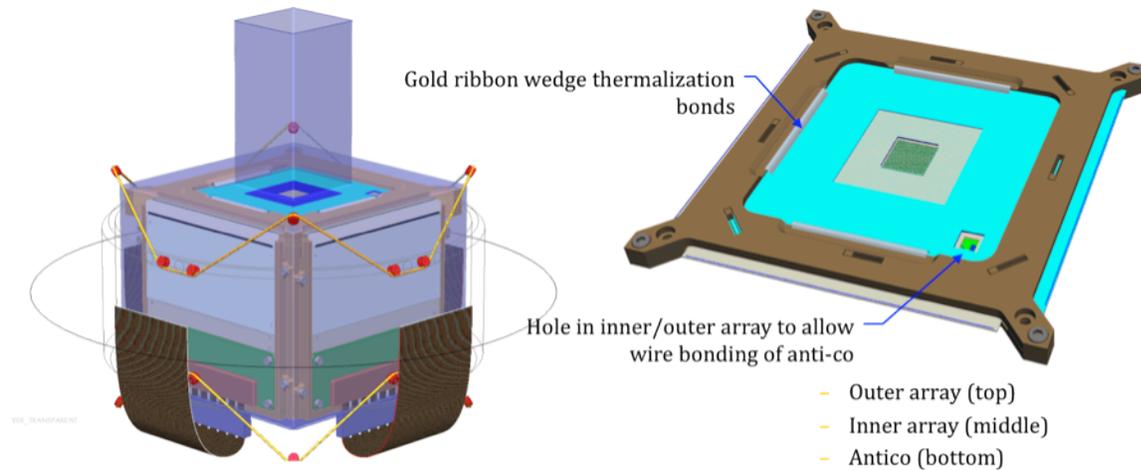
*Fig. 5: SRON/Goddard design for the focal-plane assembly for IXO/XMS. Demonstrating a flight-worthy design of these electrical, thermal, and mechanical interfaces is an important aspect of TRL 6.*

### IXO/XMS Detector System Demonstration (TRL 6)

Multiplexed (6x32) read-out of portion of full composite focal plane array – 128 different single-TES pixels in a 40x40 core array and 64 multi-absorber TES (256 0.6-mm pixels) of a full-sized outer array meeting the IXO XMS requirements. 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. Fig. 5 shows a possible design, developed by SRON with Goddard input, for the staging and magnetic shielding of the detectors and front-end electronics.

### Cost for Detector System to Reach TRL 6

The cost will depend on the actual mission goals (whether they are closer to the original IXO XMS or to a less ambitious implementation) and whether funding ramps up quickly or slowly. The range will be $10M to $20M, for which the first is for a focused development of the core-array technology only (32x32 TES array with 16-row TDM read-out) over ~4 years, and the latter is a slow development of the full IXO/XMS detector system with some investment in technology variations, such as CDM, that promise to increase the margin in the currently very tight noise budget. These estimates are based on the historical cost of advancing these technologies (through APRA, Constellation-X development, and other sources) to significant milestones. Fig. 6 is a schematic showing the approximate development cost needed for TRL 6 to be achieved at increasing array scales.

### Future State of the Art

It is likely that CDM will replace TDM in the technology roadmap in the next year or two. This technology will provide much needed margin on meeting the XMS performance requirements. Also in the next 2-4 years, new TES designs guided by our improved understanding of the physics likely will enable improvements in the intrinsic energy resolution of such devices, towards 1 eV, adding further margin. By 2017, magnetically coupled calorimeters and microwave multiplexing will be on solid footing, embarking on their own road map towards mega-pixel arrays.
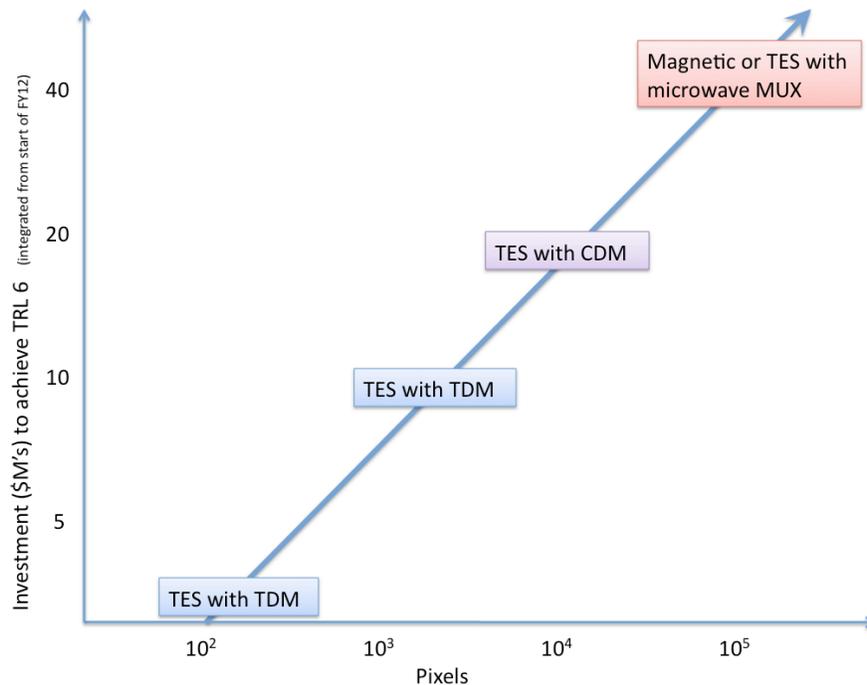
*Fig. 6: Schematic showing qualitative estimate of the investment needed to advance increasing array scales to TRL 6. The 100-pixel-scale array indicated is for the Micro-X sounding rocket. Though it is not clear at what scale magnetic calorimeters will replace TESs, it is probable that $10^5$ pixels will need microwave multiplexing.*

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