Development of Fast Readout Technology in Support of Future X-Ray Astronomy Missions

Submitted by

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in response to the PCOS 2011 RFI NNH11ZDA018L,

Concepts for the Next NASA X-ray Astronomy Mission

Category of Response: Enabling Technologies

Answer to Questions:

1) Yes, we are willing to participate at the workshop and to present our concept
2) Our organizations have some sensitive/controlled information that we can discuss with NASA if appropriate arrangements can be made to protect this information.

Introduction

The *IXO* mission included a Wide Field Imager (now part of *ATHENA*) designed to perform imaging over a wide field of view with moderate X-ray resolution, and to cope with very high count rates from bright sources. This instrument employed a type of Active Pixel Sensor (APS), by which we mean a detector with active in-pixel electronics that permits, among other things, random-access readout of the image data. In order to cope with bright sources observed by a high-throughput telescope, the readout rate of this imager is extremely high, and the image processing requirements are similarly high. Future US missions are likely to have similar requirements (e.g., *SMART-X*, which also plans to use APS detectors operated at very high speeds). In order for the US X-ray astronomy community to be able to contribute to missions such as *ATHENA* and *SMART-X*, we need to develop technology for very high-speed data transmission, as well as very high-speed event recognition and data compression. A modest funding stream can satisfy this need.

Science Drivers

Science drivers for the *SMART-X* mission are presented in a different response to this RFI. Here, we will briefly discuss the science drivers for the *ATHENA* WFI that are directly relevant to this RFI. Because this instrument is virtually identical to the *IXO* WFI, it by definition satisfies some of the *IXO* science requirements.

1) **When and how did SMBHs grow?** *IXO* was designed to find young, growing supermassive black holes (SMBHs) at the cosmic dawn (z~ 6 – 10) through deep surveys. One of the many fascinating mysteries related to the origin of the universe is how SMBHs could form in the few hundred million years between the Big Bang and the oldest quasars we can find (currently the most distant known quasar is at z~7, corresponding to only 700 Myr after the Big Bang). The wide field of view and excellent sensitivity of the *ATHENA* WFI will use X-rays to probe the formation rate of SMBHs in the young Universe, by measuring the density of SMBHs as a function of redshift. Since the X-ray sky is dominated by AGN, X-rays provide the best window
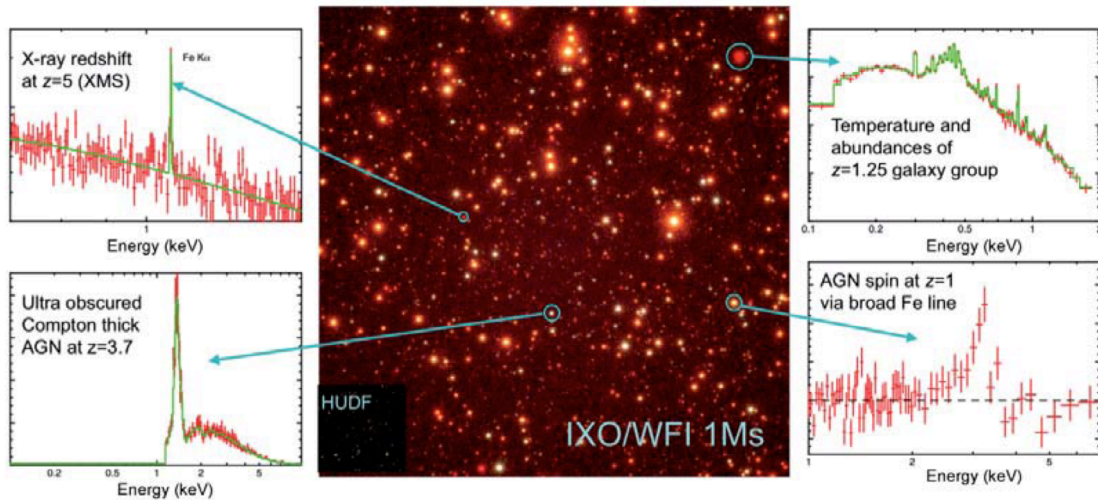

Fig. 1: Simulation of a deep WFI observation of the Chandra Deep Field South (from the IXO Assessment Study Report by ESA, arXiv:1102.2845 [1]). The simulated spectra show the WFI ability to (clockwise from upper left): measure redshift of faint sources, measure temperatures and abundances of clusters to z>1, measure spin of SMBHs in distant AGN, and find heavily obscured AGN at high z.

in the electromagnetic spectrum for making this measurement (Fig. 1).

2) **What happens close to black holes?** The same survey measurements with the WFI will measure the line shape of the broad Fe lines around SMBHs, providing a unique probe of the extreme conditions in the near vicinity of massive black holes. Such measurements probe gravity in regimes not otherwise attainable. Similar measurements of Galactic stellar-mass black holes will provide corresponding data over a wide range of gravitational field and gravitational gradients.

The wide field of view needed for the first science question requires a physically large detector. The *ATHENA* WFI instrument uses a 1024x1024 detector array. The high count rate requirements imposed by the second science question above (physics close to black holes) imposes a very high readout requirement on the detector (1.28 – 2.56 ms per frame), far in excess of anything previously demonstrated with X-ray silicon arrays. (By contrast, X-ray CCD cameras on *Chandra*, *Swift*, and *Suzaku* have readout rates of order 50-100 kilopixels/s per readout node, for total readout times of a few seconds per frame.)

If ATHENA is selected for launch by ESA, its capabilities will be complementary to whatever mission NASA subsequently selects for development. US participation in the WFI will provide access to these critical measurements. Such participation is welcomed by the WFI PI, who has invited our groups to contribute to this instrument.

If ATHENA is not selected by ESA, the technology development discussed below will still be needed for future US X-ray astronomy missions, which are likely to include instruments based on APS detectors and high-throughput optics.

High Speed Readouts

The readout and data transfer speeds required by these missions are quite high. The *SMART-X* Active Pixel Sensor Imager (APSI) spec is 100 frames per second, in order to a) handle the very high count rates of bright sources without pileup, and b) minimize optical loading (which otherwise would require thick X-ray absorbing optical blocking filters, reducing low energy response). The WFI frame rate is even higher, with rates of order 500-1000 frames per second foreseen. Both missions will require very high data transfer rates from the detector housing to the supporting electronics box (ICU or equivalent), a very high speed event recognition processor capable of handling up to $(10^8 – 10^9)$ pixels per second, and very fast processing of events to achieve cosmic ray/particle rejection and a high quality data stream for telemetry processing. While the high data transfer speeds discussed here are technically feasible in ground-based applications, they have not yet been demonstrated in space-based applications to our knowledge. Further development of this technology is required to advance the TRL level to $5 – 6$ in preparation for these future missions.

Active Pixel Sensors (APS) have significant advantages over CCDs and are being baselined for several future missions, including *ATHENA* and *SMART-X*. Compared with CCDs, APS detectors are significantly more resistant to radiation damage (by factors of $100 – 1000$) and can accommodate much higher readout rates due to the absence of high-capacitance clock electrodes. In an APS the signal is read out by amplifiers located in each pixel, thus eliminating the requirement for charge transfer across the device. However, each pixel must still be read out in order to search for X-rays, and the entire array must be scanned for event patterns characteristic of X-ray interactions in order to obtain the low background rates characteristic of CCDs, which are required for the science goals of both *ATHENA* and *SMART-X*. Both *ATHENA* and *SMART-X* plan to perform the event recognition in firmware using high-speed FPGAs and software algorithms optimized to rapidly screen candidate X-ray events and discard charged particle background. The readout rates of these missions require that this processing must occur at speeds orders of magnitude faster than current missions such as *Chandra*, *Swift*, and *Suzaku*. Here we take the WFI requirements as the limiting case for what must be achieved.

The WFI readout rate is projected to be as high as 1000 frames per second, providing millisecond timing over the entire field of view in order to accommodate high-speed timing requirements and the high count rates anticipated during studies of Galactic black holes. Because of the very large collecting area of the IXO telescope ($> 1m^2$), and the requirement that individual photons be detected and counted for even moderately bright sources, the WFI is designed to have a very high readout rate of 2.5μs per row. The sensor is split into two "hemispheres" of 1024 columns of 512 rows each. The two hemispheres are read out in parallel with 16 bits per pixel, for a total data rate of 1.6 GBytes/s (0.8 GB/s per hemisphere). Each hemisphere has a set of front-end ASICs located adjacent to the camera housing that process the analog signals from the 1024 columns at high speed [2,3,4], multiplexing 64 columns onto each output channel. The 16 channels from each hemisphere are digitized locally and sent to the Instrument Control Unit (ICU), located several meters from the camera head.

Reduction of this high-speed digital data stream poses challenges in three areas that must be addressed before the mission can proceed: data transfer from the camera head to the ICU, event recognition within the ICU, and event processing. We address these three stages in sequence.

High-speed Data Transfer: PSU conducted a trade study in 2010 (as part of the WFI consortium) that examined several competing technologies for the high-speed data link between the camera and the ICU and concluded that the best option is a space-rated fiber optic cable (such as the rad-hard DrakaElite fibers, which are specially fabricated to exhibit minimal radiation-induced attenuation in meter-length fibers for doses exceeding 100 krad) and Space Photonics FireFiber transceivers (rated at up to 2.5Gbps speeds and 1Mrad Si radiation dose). While this approach looks good on paper, some effort is required to advance the concept to TRL 5 or TRL 6.

Event Recognition: Most of the pixel data read out of a CCD or APS are noise (empty pixels; see Fig. 2). Only a few pixels in each frame of data will contain charge from X-ray events. The purpose of the Frame Builder is to extract the candidate X-ray signals from this high- speed data stream (a process we refer to as "event recognition") and pass them on to the flight software for characterization and transmission to the ground. The distribution of charge from X-ray interactions between adjacent pixels has characteristic features: charge is usually deposited in 1–4 pixels, depending on exactly where the photon lands within the pixel [5]. For example, if a photon lands near a pixel boundary, the charge cloud produced in the detector is likely to be split between the two adjacent pixels (Fig. 2). By contrast, background events due to charged particle interactions in the detector tend to deposit large amounts of charge across many adjacent pixels (Fig. 3). Thus, by classifying the "morphology" of an event, it can be interpreted as either an X-ray or a background event with high confidence [6]. This is usually done using an event recognition algorithm with a sliding 3 x 3 (or 5 x 5) window (referred to as a "neighborhood" or "island") that is virtually scanned across the data stream. Each neighborhood is searched for a local maximum (that exceeds an adjustable threshold) in the central pixel. When a local maximum is found, this pixel is identified as a possible X-ray event, and the neighborhood is passed to the next processing stage. Typically, events with charge patterns that can be produced by photoelectric absorption of single X-rays are "graded" (to describe their shape) and telemetered, while those with shapes characteristic of charged particles are discarded on-board. The event recognition algorithms used on the *Chandra*/ACIS and *Swift*/XRT instruments reject particle background with ~99.9% efficiency [6, 7, 8, 9, 10]. Because these event recognition algorithms are based on the characteristics of photoelectric absorption in pixelated silicon detectors, the same techniques are applicable to APS detectors.
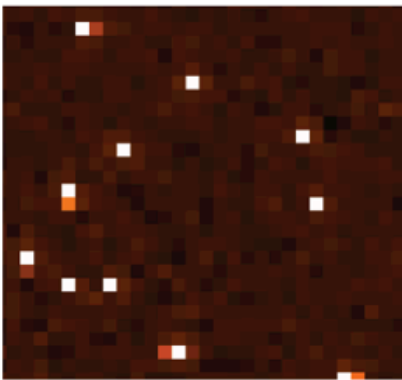

Fig. 2: Small sample of a single frame of ground test data from hybrid CMOS detectors developed by Penn State, where the color indicates the signal in each pixel. Most pixels contain only read noise (dark red/black). A few isolated bright pixels (white) represent X-ray events depositing their energy into single pixels. Several events are also seen in which the charge is spread into adjacent pixels, indicating that the photon was absorbed near a pixel boundary [5].
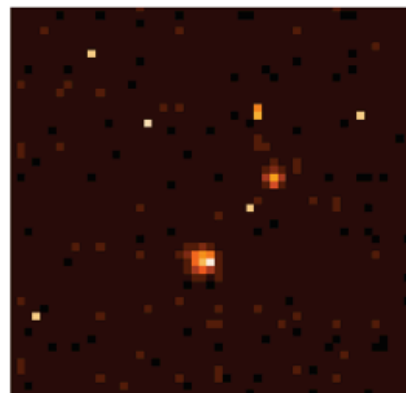
Fig. 3: Small sample of a single frame of flight data from the Swift X-Ray Telescope (XRT) CCD. Most pixels contain only read noise. A few isolated bright pixels (white/yellow) represent X-ray events depositing their energy into one or two pixels. Two broad, "blobby" events are from cosmic ray interactions in the detector, which produce wide charge clouds that are easily distinguished from X-rays.

To date, X-ray event recognition has been done in software (e.g., *Chandra*/ACIS and *Swift*/XRT) or in hardware (*XMM-Newton*/EPIC), but never at such high readout rates. The existence of high-speed, radiation-tolerant FPGAs makes this feasible, and PSU has developed a preliminary design concept for this circuitry that is at TRL3 (Fig. 4). Some development effort is needed to breadboard this design, test it in hardware, and verify that it meets the WFI processing specs, followed by advancement to TRL6. This development would address one of the key technologies identified in the 2010 Strategic Astrophysics Technology NRA for the Physics of the Cosmic program in the area of High Energy Astrophysics: readout devices for pixel sensor arrays.
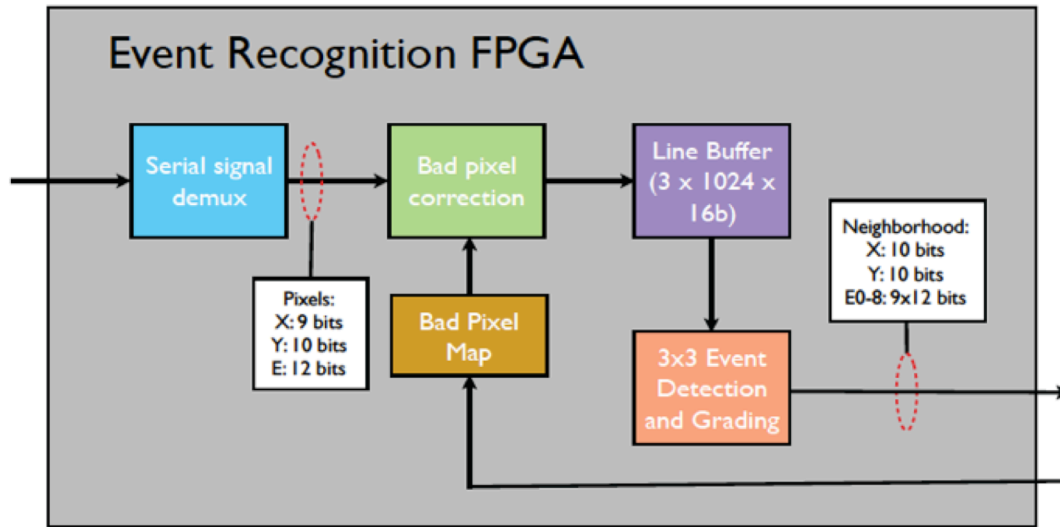

Fig. 4: The heart of the event recognition processor is a high-speed space qualified FPGA. This figure shows a simplified block diagram of the FPGA logic design. High-speed serial digital data are demultiplexed and bad pixels are zeroed as needed. The data are then inserted into a three line buffer that is scanned for valid X-ray events using a sliding 3×3 pixel window. Event grades are assigned based on an uploadable table of valid event shapes. Output data are 3×3 "neighborhoods" centered on candidate X-ray events.

Event Processing: The development of event grading schemes for the CCD cameras on ASCA, Chandra, and Swift was based on many years of laboratory testing and sounding rocket flights. APS detectors are just beginning to be used in the laboratory and are therefore less mature than CCDs were when first flown. Although the principles of the charge collection and charge distribution within APS detectors should be similar to that within CCDs, we expect that some development work is needed in the area of event processing in order to optimize signal, energy resolution, and charge particle rejection while retaining high processing speeds needed for *ATHENA*, *SMART-X*, and other future high-throughput X-ray missions. Comparisons between active pixel sensors from different groups with different design choices will be important for developing detailed simulations codes, as well as for choosing optimal detectors for specific future missions. Current funding levels from APRA are typically not sufficient to cover this work, and additional funding is needed over the next 4 – 5 years to ensure that both the detectors themselves, and the processing algorithms needed to optimize their performance, are ready for new mission starts.

Required Funding Levels

We estimate that this work can be done with modest funding levels over a period of 4-5 years, depending on decisions made by ESA and NASA about future missions. For example, if *ATHENA* is selected by ESA, US participation will have to be via a Mission of Opportunity proposal and funds will be requested in that proposal to accomplish this work. On the other hand, if the next mission opportunity for APS sensors is *SMART-X*, then we argue that NASA should provide a modest funding stream now to prepare to meet *SMART-X* APS requirements so that the entire program is on sound technical footing once the mirror technology is ready for a new start. We estimate a work plan as follows:

Year 1:

Data Transfer (1/2 FTE):
1) Define data rate requirements
2) Develop signal test generation board to simulate X-ray data using fixed patterns (including some based on laboratory test data)
3) Develop test setup for optical fiber tests
4) Test optical fibers using simulated X-ray data, verify performance over expected data rates with margin

Event Recognition (1/2 FTE):
1) Develop FPGA design, test on commercial FPGA prototype board
2) Perform detailed FPGA simulations to show compliance with requirements and predict performance margins
3) Develop GSE for tests
4) Design brassboard version of circuits

Event Processing (1 FTE):
1) Collect laboratory data from existing APS detectors
2) Develop APS simulator
3) Tune simulator parameters to match data from multiple candidate detectors

Year 2:

Event Recognition (2 FTE):
1) Fabricate and test prototype event recognition board
2) Iterate design as necessary
3) Rigorous test program using test patterns as inputs
4) Produce and test 3 copies of final board for tests at PSU, MIT, JHU

Event Processing (1 FTE):
1) Develop processing algorithms optimized to provide best energy resolution and background rejection for APS sensors. This involves processing a large amount of APS data for X-rays at various energies spanning the instrument range, as well as gamma-rays and/or protons (simulating particle backgrounds), for several different APS types. We expect this to be a several year effort, based on experience with the same process for CCD data.

Year 3:

Event Recognition (3 x 1 FTE):
1) Rigorous testing of event recognition board at PSU, MIT, JHU, using data from test generator and in-house APS cameras. Results from board will be compared with results from standard

laboratory processing of the same data sets. Board performance is controlled by adjustable parameters located in registers; these will be optimized to obtain the best possible performance for each APS type.
2) Publish results

Event Processing (1 FTE):
1) Continue development of processing algorithms optimized to provide best energy resolution and background rejection for APS sensors. This involves processing a large amount of APS data for X-rays at various energies spanning the instrument range, as well as gamma-rays and/or protons (simulating particle backgrounds), for several different APS types. We expect this to be a several year effort, based on experience with the same process for CCD data.

Year 4:
Event Recognition (3 x 0.5 FTE):
1) Update testing with new APS results (assumes APS development ongoing in parallel)

Event Processing (1 FTE):
2) Continue development of processing algorithms optimized to provide best energy resolution and background rejection for APS sensors. This involves processing a large amount of APS data for X-rays at various energies spanning the instrument range, as well as gamma-rays and/or protons (simulating particle backgrounds), for several different APS types. We expect this to be a several year effort, based on experience with the same process for CCD data.

Total ROM budget in FY11 dollars (assuming fully burdened cost of $250K/yr for personnel plus $50K/yr equipment and miscellaneous expenses):
Year 1: 2 FTE * $250K + $50K = $550K
Year 2: 3 FTE * $250K + $50K = $800K
Year 3: 4 FTE * $250K + $50K = $1050K
Year 4: 2.5 FTE * $250K + $50K = $675K

Total: **$3,075,000 over 4 years**

We note that we have assumed that parallel development efforts will be underway on the APS detectors themselves. To ensure that those detectors are ready on a similar time-scale, NASA should at least double the current funding levels for APS detector development. This point is discussed in more detail in an Appendix to the *SMART-X* RFI response.

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