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Report of the Sensor Readout Electronics Panel

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INTRODUCTION

In many existing sensor arrays, it is the readout electronics that limits the overall system noise floor, rather than the detector itself. This is particularly the case for low-background imaging typically encountered in astrophysical missions. While the signal-to-noise ratio can be increased by increasing detector quantum efficiency, historically a substantially smaller effort has been applied to reducing the sensor readout electronics noise floor. A second general observation is that recent advances in materials, integrated circuit processing and circuit design techniques offer the possibility for significant enhancement in sensor readout performance for almost all imaging wavelengths. Thus it becomes imperative that any analysis of sensor requirements and development schedule include a coordinated analysis of readout issues. (See Fig. 1.)

Historically this has not been the case for NASA and SDI supported sensor development programs, where the effort was focused on the transducer part of the sensor, with the readout considered a conventional part of the control circuitry, and relegated to the later stages of system development. SDI has now recognized that readout technology may require comparable development effort, especially for large arrays and ultra-low noise applications, and sensor development programs must include a closely coupled effort on readout development from the start. This evolution in emphasis is apparent in SDI's new MODIL approach for infrared focal plane array development, and in their support of superconducting readout electronics. This panel strongly recommends that NASA adopt a similar approach, and support parallel, closely coupled efforts in sensor and readout development.

The focus of the Sensor Readout Electronics Panel was to assess the technology requirements for on-focal-plane signal processing and readout electronics for the Astrotech 21 mission set, and to generate a technology development plan to meet these needs. This analysis was to include all types of sensors for all regions of the electromagnetic spectrum. After examining the mission requirements, and comparing them to state-of-the-art technology, five major elements emerged as primary development needs in the area of sensor readout electronics. These elements are, in approximate priority order, (1) low-noise cryogenic readout electronics, (2) sub-electron read noise, (3) advanced packaging, (4) advanced focal-plane interface, and (5) advanced readout electronics architectures. For the most part, development of each of these elements stands to impact multiple missions and various sensor types, as summarized in Tables I and II, respectively.

In addition, a number of more generic issues were considered by the panel, including:

- What are the VLSI technology needs to enable low-noise, low-power sensor readout?
- How will very-low-temperature readout circuits required for very-long-wavelength IR detectors be achieved?
- What role will 3-D microelectronics play in future sensor readout electronics?
- What hybridization technology will be needed to achieve small pixels and large arrays?
- What will be the role of superconducting materials and circuits on the focal plane?
- What will be the role of "smart" readout architectures?
- What role is there for focal-plane signal processing?
- What are the limits of CCD multiplexer technology?

Table I. Technology Areas Recommended for Development

Technology Area	Desired Performance	Applicability Missions	Technology Freeze date
Low-noise cryogenic readout	0.1, 2 - 4 K	SIRTF	'92
	Micropower circuits	LTT	'95
	Reduction of 1/f noise	NGOVLBI	'00
		NGST	'02
Sub-electron read noise	< 1 e^- read noise	SIRTF	'92
		NAE, XST, HST III *	'95
		AXAF II, III	'95, '00
		AIM	'97
		HXIF	'99
		NGST	'02
		VHTF	'03
		GRSO	'04
		HST II, III	
Advanced packaging	Buttable-format arrays	SIRTF	'92
	Thermal compartmentalization	LTT, HST III	'95
		Imaging Int	'04
Advanced focal-plane interface	On-focal-plane A/D	SIRTF	'92
	Optical fiber link	XST, NAE	'95
		SMMI, HST III	'95
		AIM	'97
		NGOVLBI	'00
		NGST	'02
		VHTF	'03
		AXAF II, III	'95, 00
Advanced readout architectures	Event-driven readout	AXAF II, III	'95, '00
	Digital imager pixel	HXIF	'99
		VHTF	'03

* Terminologies II & III refer to 2nd and 3rd generation instruments.

These questions helped to focus the evolution of the recommended development plan. In the remainder of the report, the technology assessment and development plan for each of the five elements will be described in detail.

LOW-NOISE CRYOGENIC READOUT ELECTRONICS

A. Technology Assessment

Many of the missions described in the mission set, particularly in the infrared, require low-noise cryogenic readout electronics. There is a major, fundamental problem with conventional semiconductors operating at cryogenic temperatures. This is because the impurity atoms' electrons "freeze out" due to lack of sufficient thermal agitation. At moderately low temperatures (20-40K), the partial freeze-out of electrons results in excess noise, as electrons are unpredictably energized or frozen out of the conduction band. At lower temperatures, devices can cease to operate altogether.

There are several technical approaches to the problem. First, silicon can be fabricated to increase the number of impurity atoms. This decreases the freeze-out temperature and extends the device operating range. Acceptable silicon device performance has been demonstrated down to 12 K using a cryogenic process developed by TRW. (Lower temperature performance can be obtained with silicon p-type metal-oxide semiconductor (PMOS) technology but at an unacceptable cost in power.) A second approach is to use a semiconductor technology which doesn't require impurity atoms. Such a technology has been demonstrated at 77 K for digital circuits using gallium arsenide (GaAs) complementary heterojunction insulated-gate field-effect transistor (CHIGFET) technology, and is currently under exploratory investigation for very low temperature analog applications at JPL in a small contract with Honeywell. A third approach is the use of superconducting circuits. Some preliminary work has been performed at some aerospace companies for DoD applications.

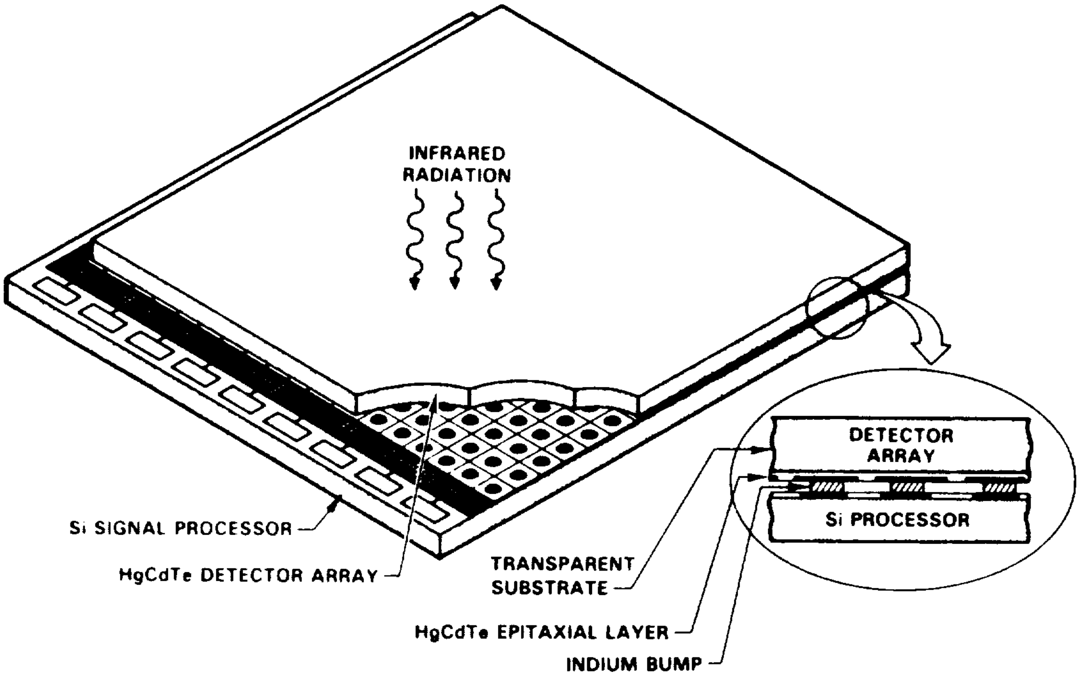

Figure 1. Hybrid focal plane architecture illustrating the intimate relationship between detectors and readout electronics. (From Bailey et al, IEEE Transactions on Electron Devices, **38**, page 1104, 1991.)

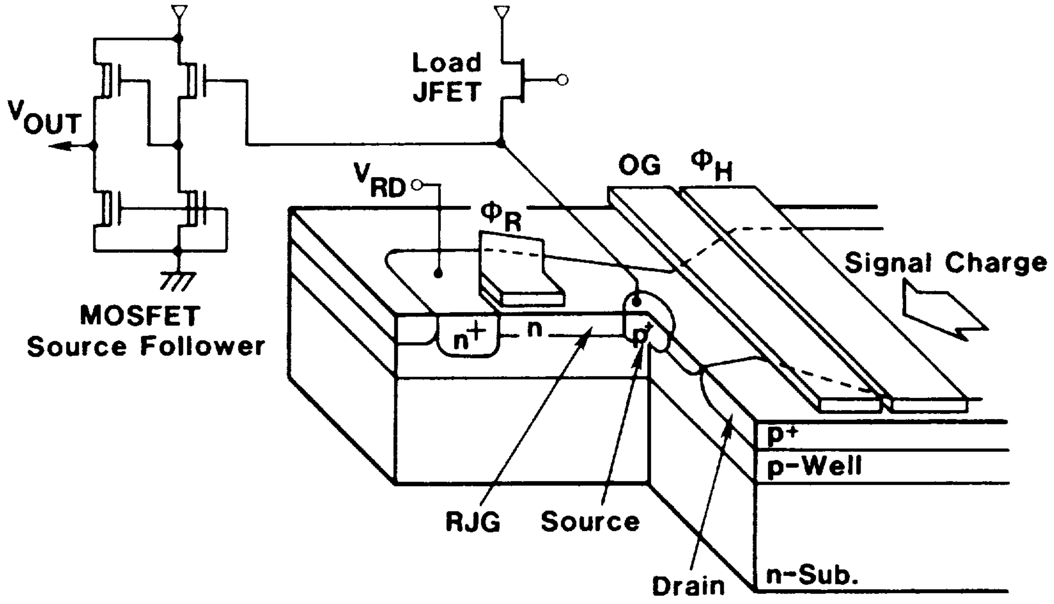

Figure 2. Low-noise JFET CCD output amplifier with high sensitivity. (From Mutoh et al, IEEE Transactions on Electron Devices, **38**, page 1048, 1991.)

Table II. Readout Electronics Technologies: Areas of Applications

Readout Technology Development Area	X-Ray & Gamma Ray	Ultraviolet & Visible	Direct Infrared	Heterodyne submillimeter
Low-noise cryogenic readout - 0.1 & 2-4 K - Micropower circuits - Reduction of 1/f noise	Bolometers, superconductors & Ge detectors	Cryogenic visible photodiode arrays	Bolometers & IBCs	IF amplifiers
Sub-electron read noise - Floating-well circuits - Source-follower MOS MUX	CCDs & superconducting X-ray detectors	CCDs & photodiode arrays	All very-low-background & spectroscopic measurements	N/A
Advanced packaging - Buttable format arrays - Thermal compartmentalization	Large mosaics	Large mosaics	Very long wave IR detectors	SIS arrays
Advanced focal-plane interface - On-focal-plane A/D - Optical fiber link	All cryogenic systems	All cryogenic systems	All cryogenic systems	All cryogenic systems
Advanced readout architectures - Event driven readout - Digital pixel imager	All low-signal applications	All low-signal applications	All low-signal applications	N/A

Operation at higher cryogenic temperatures is dominated by l/f noise. This noise, investigated for decades, is still poorly understood yet can limit system performance in applications such as gamma ray detector preamplifiers. We have broken the area of cryogenic readout electronics into four sub areas:

(i) Operation at 2-4 K

Very long wavelength, direct detectors need to operate at extremely low temperatures, and are anticipated for inclusion in missions such as SIRTF, NGIR and NGOVLBI. At the present time, no viable technology has been demonstrated for operation at such low temperatures. We recommend an immediate augmentation of efforts in this area.

(ii) Cryogenic readout electronics at 0.1 K.

With the exception of low-temperature superconducting electronics, whose development is still at a very early stage, no technology exists at 0.1 K. Such a technology would represent a breakthrough and have a significant impact on broadband very long wavelength IR detector readout and thermal packaging. The CHIGFET technology may also represent a possible approach. We recommend a breakthrough thrust in this area.

(iii) Analog Micropower Circuits

For high-background applications, and for large arrays, the readout/multiplexer circuitry can constitute the dominant power drain in the focal plane. And since this dissipation occurs in a low-temperature part of the instrument, it is imperative that this dissipation be kept as low as possible, so as to avoid unreasonable demands on the cooling system. Thus the development of cryogenic readout electronics requires not only the development of low-noise devices but also of low-power circuits. The panel finds this to be a critical element of a cryogenic readout electronics plan. The circuits are typically customized for a particular detector application. Applications include all cryogenic IR missions.

(iv) Reduction of 1/f noise.

As described above, 1/f noise is an age old problem in semiconductor analog circuits. However, because it continues to limit amplifier performance the panel recommends renewed attempts to understand and reduce this noise. Operating temperature regimes of importance are 60-80 K (NAE, GRSO), 10-20 K (SIRTF, NGIR) and 2-4 K (SIRTF, NGIR).

B. Development Plan

This element requires very rapid resolution, as the results are needed in time for SIRTF. The desired characteristics are low-noise, low-power, radiation tolerant, cryogenic readout multiplexer arrays for device operating temperatures of 0.1, 2 - 4, and 80 K. The first step is to evaluate the contribution from different noise sources, in order to determine methods to reduce them. An early assessment of the feasibility of low-temperature superconductors for bolometer readout arrays is also recommended. Finally, 2 - 4 and 80 K readouts with < 1 e^- rms read noise need to be demonstrated prior to the '94 technology freeze date for SIRTF. The development plan is summarized in Table III.

SUB-ELECTRON READ NOISE

A. Technology Assessment

Many of the missions call for one electron rms read noise, or less. These include HST, LTT, FUSE, AIM, NGST, II, SIRTF, AXAF, XST, HXIF, AND VHTF. Sub-electron read noise means that the probability of correctly measuring a single electron is greater than 50%, or that a given collection of electrons is converted to a voltage with an rms noise less than the electron-to-voltage conversion gain. The major limitation is obtaining sufficient sensitivity on the output amplifier to overcome white thermal and 1/f noise. The technical approaches are thus to either increase the sensitivity of the single node (i.e., reduce its capacitance) or reduce the conversion noise.

One source of conversion noise in CCD output amplifiers is the so-called kTC noise occurring when a capacitor is charged to a reset voltage, and then disconnected and left floating. In the past few years, an output amplifier design called the floating well amplifier (Fig. 2) has been developed in Japan which eliminates kTC noise. It also has high output sensitivity. Thus far, it has not been adopted by U.S. CCD manufacturers, but the method is understood. In source-follower MOS switched-array multiplexers (used in IR imagers) the noise level obtained is in the 10-50 electron rms range. It is generally believed that with development and possible use of floating well techniques, these readout circuits can also be brought to the one electron or less read noise level.

B. Development Plan

The panel recommends two thrusts in this area: (1) the development of the floating-well output amplifier, and (2) the development of ultra-low-noise source-follower MOS switched-array multiplexors. As for cryogenic readouts, these capabilities are required for SIRTF instruments, and thus must be developed before '94, as summarized in Table IV. However, additional optimization can be continued through the decade to benefit later missions.

ADVANCED PACKAGING

A. Technology Assessment

The Sensor Readout Electronics panel identified

Table III. Low-Noise Cryogenic Readouts

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Process technology noise evaluation (1/f, thermal)	Indefinite	Evaluation Noise reduction	92 - 94 94 - 95	Small Small
2 - 4 K readout circuits	15 K	Demonstration	92 - 95	Moderate
0.1 K low-temperature superconductor readout	Concept	Demonstration	92 - 93	Moderate
Analog micro-power device/circuit	500 mW input power	$\leq$ 10 mW input power	92 - 94	Moderate
80 K, < 10 e^- rms MUX	50 e^-	Demonstration	92 - 95	Small

Table IV. Sub-Electron Read Noise

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Floating-well output & amplifier	Exists in Japan	Elimination of kTC noise	92 - 93	Moderate
Source-follower MOS switched array MUX	$\leq$ 50 e^- read noise	< 1 e^- read noise	93 - 95	Small

advanced packaging as a critical component of sensor technology. While not falling into the sensor readout electronics panel's predefined area, for a sense of completeness it is included in our report. We see advanced packaging having three thrust components critical to ensuring that the mission set requirements can be met. These are large area infrared focal-plane arrays, large-area visible (CCD) focal-plane arrays, and thermal compartmentalization.

(i) Large area infrared focal-plane arrays.
The mission description for NGST suggests that array sizes of ≥ 10k x 10k are desired. While techniques to form a mosaic of focal-plane arrays have been explored in a DoD context, a methodology of such large arrays must be developed. For example, if hybrid IR imagers of size 512 x 512 can be demonstrated, then to achieve a size 20k x 20k will require some 1600 imagers in a focal-plane mosaic. Many of the panel members expressed reservations regarding the feasibility of such an approach. Nevertheless, significantly less ambitious mission requirements will still require an advancement in packaging methodology to achieve viability. A buttable mosaic array, as described above, is one approach to this problem. A more advanced solution would be the semi-monolithic integration of sensor readout electronics with a detector. For example, HgCdTe grown on a GaAs multiplexer substrate might be an approach to be considered. This is desirable because of the intrinsic match of thermal expansion coefficients between the materials. A third approach is the fully monolithic integration of the detector and multiplexer. For example, a GaAs quantum well infrared photodetector (QWIP) might be integrated with GaAs readout electronics to form the image sensor. This approach has not yet been demonstrated.

(ii) Large area/large format visible (CCD) arrays.
In conjunction with the visible detector panel, the sensor readout electronics panel considered the NGST mission requirement for 10k x 10k or larger pixel arrays. While CCD multiplexers/imagers have exhibited remarkable progress in the past years, array sizes of 10k x 10k will require significant improvement in the already near-perfect charge transfer efficiency and readout rate without degrading noise performance. In this case, use of a mosaic array of CCD imagers would be a more prudent readout strategy, with each imager having, say four-quadrant readout. (A buttable mosaic array also alleviates semiconductor fabrication yield concerns.) A methodology for packaging such a mosaic array may already exist in DoD applications. We recommend advanced development by NASA.

(iii) Thermal Compartmentalization
In many infrared focal-planes requiring low temperature operation, detector thermal isolation and readout electronics form conflicting requirements. There is a need to keep detectors at very low temperatures, yet maintain readout electronics at higher temperatures, to insure low noise readout and avoid self-warming of the sensor during readout. If the readout can be operated at higher temperatures, there is also a savings in cooling capacity at the sensor temperature, and a relaxation of the requirements for cryogenic readout technologies. It is also useful to keep the readout electronics at higher temperatures to ensure low-noise readout and avoid self-warming of the sensor during readout. Innovative approaches to thermal isolation and compartmentalization are required. The panel feels this is outside our area of expertise, but that it should be included in the report.

B. Development Plan

To meet the needs of mega-pixel readout, the panel suggests support in three areas. First, there should be support at a moderate level to develop hybrid, large-format IR array mosaics. Second, both hybrid and monolithic mosaicking of large-format CCD systems should be developed. Finally, innovative approaches to resolve the conflict between thermal isolation and readout interconnections should be addressed. The lead time for this development is rather short, as the capabilities are desired for missions such as XST, NAE, SMMI, and HST refurbishments with technology freeze dates starting in '95. However, additional development could also benefit missions with longer lead times. The development schedule is summarized in Table V.

ADVANCED FOCAL PLANE INTERFACE

A. Technology Assessment

Two elements of an advanced cryogenic system were discussed. Since cryogenic systems are, by nature, isolated from their surroundings, electrical signals are driven from the focal-plane, through long cables, to warm external electronics. From individual experience of panel members, it was noted that system performance often degrades by a factor of 2 to 4 between the focal-plane and the external world. It was also noted that a significant portion of dissipated heat on the focal-plane is due to the need to drive the cabling. While not called out as a requirement by particular missions, two technical approaches to

Table V. Advanced Packaging

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
IR detectors on Si or GaAs				
Develop various options	Concepts	Feasibility	92 - 94	Small
Develop best option	512 x 512	≥ 10k x 10k	94 - 97	Moderate
Integration of MUX & array				
Mechanical hybrids	512 x 512	1k x 1k	92 - 95	Moderate
Monolithic	Concepts	≥ 10k x 10k	94 - 97	Moderate
Compartmentalization				
Thermal isolation	Ad-hoc, situation-specific solutions	Generic solution, 2 - 5 times improvement in performance	92 - 93	Small
Implementation experiments			93 - 94	Small
Optimization			94 - 96	Moderate

reducing this scientific information degradation and Dewar heat load should be brought to the reader's attention. These are focal-plane data conversion and optical links.

(i) Focal-plane data conversion (A/D)
Relocation of the analog-to-digital conversion process from outside the Dewar will result in the benefits of increased immunity from electromagnetic interference (EMI) and a reduction in off-chip drive power, and offers the promise of increased scientific data return by lowering the system noise floor. In exchange, it adds back power dissipation on the focal plane for data conversion, and requires electrical isolation from the sensor multiplexer electronics. The panel was particularly intrigued by the possibility of superconducting A/D electronics since they consume little power and operate well at cryogenic (i.e., Dewar) temperatures.

(ii) Focal-plane Optical Fiber Links
Currently, electrical wires connect the cryogenic environment with the external warm environment. Optical fiber links offer intriguing opportunities to enhance system performance in several ways. First, optical fiber being small diameter glass "wire" reduces the parasitic heat load on the focal plane. Second, optical fibers are virtually immune from EMI, thus preventing external noise from infiltrating the focal-plane electronics. Third, focal-plane readout using optical means can reduce power dissipation on the focal plane. We see optical fiber potentially performing the following functions:

(a) Provides a link for external clock signals to the focal plane.

(b) Provides a readout channel to the external environment.

(c) Provides power optically to the focal plane. (Requires energy conversion on the focal plane.)

In particular, option (ii) in conjunction with a focal-plane A/D converter might significantly enhance overall system performance. We must emphasize that in each of these options we are not advocating putting an optical source (e.g., laser) on the focal plane. This would dissipate too much power and add system complexity. Rather, the source can be external, and in the case of option (ii), be modulated on the focal plane using very little power. A possible configuration is sketched in figure 3.

B. Development Plan

The two areas described above are recommended for support. The specific performance requirements are summarized in Table VI.

ADVANCED ARCHITECTURES

A. Technology Assessment

In most visible and IR sensor systems, the multiplexer is used to connect each detector to the output amplifier sequentially, one-at-a-time in some sort of raster scan mode. While this performs the readout function, in systems of increasing throughput requirements such a methodology may be less than optimum. Our panel has two recommendations for advanced sensor readout electronics architectures which do not fall into this category. We believe that exploration of advanced architectures may impact all sensor-based missions.

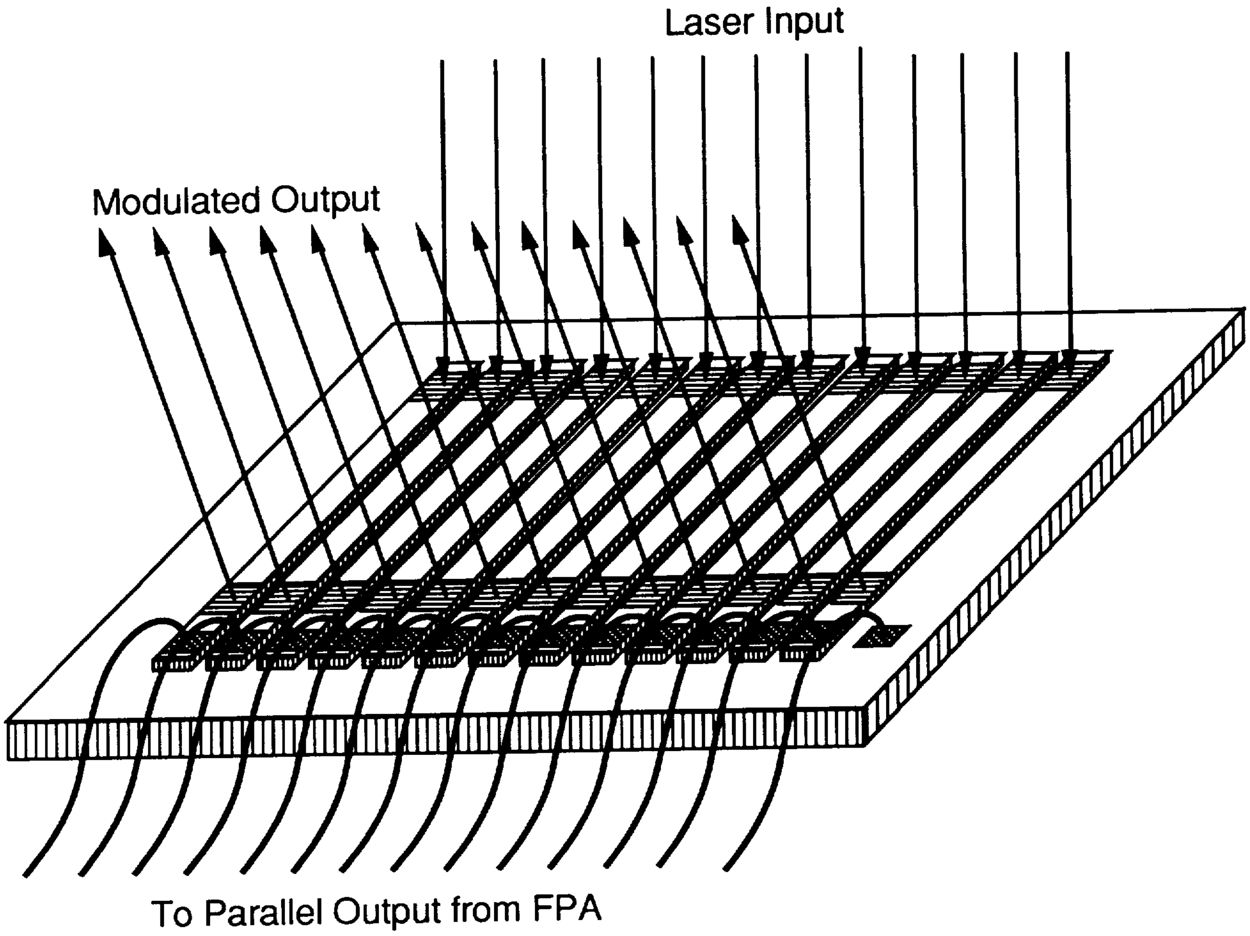

Figure 3. Schematic of an all-optical link between a cold focal plane and warmer system electronics. Optical fibers could be used to provide external clock signals and focal-plane power, as well as a signal readout channel. Advantages include a reduction in power dissipation and parasitic heat load on the focal plane, and immunity from electromagnetic interference.

Table VI. Advanced Focal-Plane Interface

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Monolithic A/D converter	Concepts	≥ 10 bits, kHz - MHz sample rate, μW power for ≤ 10 K, mW power for 80 K Parallel-serial MUX Digital data driver	93 - 98	Moderate
Optical readout	Concepts	≥ 10 bits analog range, μW power for ≤ 10 K, mW power for 80 K low-power driver/modulator low-power optical trans/receiver	93 - 98	Small

(i) Event-driven readout

In certain sensor systems, and in particular in the case of high energy photon sensing (e.g., x-ray) the array illumination may be sparse, with photon activity occurring only in a small portion of the array. It would be inefficient, and perhaps impractical, to fully scan the entire array at sufficient rate to ensure that single photon events are read out prior to the next event in that pixel. We propose investigating event-driven readout where a photon event triggers readout of that pixel. As an alternative, locally variable frame rate read out might also serve the high-throughput, sparse-illumination mission requirement. Note, these schemes are not equivalent to data compression, and do not result in any loss of image information.

(ii) Digital Imager Pixel

As a breakthrough thrust, the panel recommends the development of a digital imager pixel. In this very advanced concept, the output of each pixel is a digital count rather than an analog value. Successful implementation of this concept could result in making CCDs and IR analog multiplexers obsolete. It could (in time) achieve noiseless readout, provide unprecedented radiation hardness, increase dynamic range, and pave the way for a host of smart sensor architectures. Such a breakthrough will require a successful marriage of advanced VLSI and materials processing, including the development of 3-D microelectronics.

In addition to these two advanced architecture thrusts, the panel also felt that the readout of MCP arrays for UV sensors might benefit from other focal-plane readout technologies. However, there was insufficient time during the course of this workshop to explore this concept.

B. Development Plan

As detailed in Table VII, the panel recommends the development of an event-driven readout architecture to replace conventional full-array sampling schemes with a device that performs peak detection, storage and self-addressing readout. This approach will become critical as array sizes expand to 1k x 1k and beyond, where sampling of the entire

Table VII. Advanced Architectures

Technology Development	Current Technology	Program Goals	Program Dates	Program Size
Event-driven readout				
Explore options	Concepts	Feasibility	93 - 95	Few small
Develop best option(s)		~ 1×10^4 / s event rate, ~ 1×10^3 amplitude resolution, < 1 electron noise, 1×10^6 - 1×10^8 pixels, 1×10^3 dynamic range	95 - 99	Moderate

pixel count becomes prohibitively slow. Development should start with investigations of a number of potential approaches, each on a small scale, and following a down selection in '95, the best option(s) should be developed.

SUMMARY

This report summarizes the findings of the Sensor Readout Electronics Panel in regards to technology assessment and recommended development plans. In addition to two specific readout issues, cryogenic readouts and sub-electron read noise, the panel considered three advanced technology areas that impact the ability to achieve large-format sensor arrays. These are mega-pixel focal-plane packaging issues, focal-plane to data-processing module interfaces, and event-driven readout architectures. Development in each of these five areas was judged to have significant impact in enabling the sensor performance desired for the Astrotech 21 mission set. Other readout issues, such as on-focal-plane signal processing or other high-volume data acquisition applications important for Eos-type mapping, were determined not to be relevant for astrophysics science goals, and are explicitly excluded from this report.

Some of the recommendations from this panel are duplicated in the reports of the panels that considered specific wavelength ranges. This is to be expected, as many of the readout issues are intimately related to the specific detector architecture. However, the existence of a separate readout panel also enabled the identification of more generic issues, which could then be addressed with a unified development plan, thereby avoiding unnecessary duplication. Thus the strong interaction between the readout and detector panels in this workshop, and the unified approach to readout issues, engendered a useful cross-fertilization of ideas among the different detector communities.