Title:

HgCdTe Optical & Infrared Focal Plane Array Development in the Next Decade.

Abstract:

We lay out a comprehensive plan for OIR FPA technology development over the coming decade that promises order-of-magnitude breakthroughs in sensitivity coupled with dramatically simplified detector system architectures. ***Its ultimate goal is to achieve near perfect performance for all types of OIR observation in much larger FPAs at much lower cost/pixel.*** It impacts all areas of OIR astronomy, benefiting missions and observatories both large and small. It is focused entirely on HgCdTe, the material used in both the H1R FPA's flown on the Deep Impact comet mission (and soon to be launched to HST) and the H2RG FPAs selected for JWST and already in widespread use in ground based telescopes. It has three central objectives:

1) To greatly increase the pixel counts of the largest individual arrays without any increase in cost. A fourfold jump from the 4 Mpxl H2RG to the 16 Mpxl H4RG-15 is feasible right now and technology developments outside astronomy could well allow another leap to a 64 Mpxl H8RG-15 later in the decade. These dramatically reduce the cost per pixel for all observations and greatly simplify the large mosaic focal planes required by many of the more ambitious projects. Improvement of the readouts, ASIC controllers and mosaicing techniques to optimize the use of these larger FPAs will also be required.
2) To extend the wavelength coverage of HgCdTe FPAs down towards 0.4 μm and out to beyond 10 μm and even to 15 μm.
3) To utilize the unique electron and hole initiated avalanche properties of HgCdTe to develop ***e-***APD and ***h-***APD arrays allowing photon counting in the OIR entirely free of excess noise, to very high fluxes and, as required, striving for picosecond time resolution.

Based on our experience with similar developments we provide estimates for time frame and intermediate milestones for individual program elements, along with projections of time frame and cost.

Primary Author:

Donald N. B. Hall	Institute for Astronomy, University of Hawaii
Phone: (808)932-2360	email <hall@ifa.hawaii.edu>

Co-Authors:

Bernard S. Rauscher	NASA Goddard Space Flight Center
Judith L. Pipher	Dept of Physics and Astronomy, University of Rochester
Klaus W. Hodapp	Institute for Astronomy, University of Hawaii
Gerard Luppino	GL Scientific inc

HgCdTe OPTICAL & INFRARED FOCAL PLANE ARRAY TECHNOLOGY DEVELOPMENT IN THE NEXT DECADE.

Over the coming decade, it is within our grasp to realize near perfect OIR focal plane arrays (FPA) spanning wavelengths from 0.4 μm to 10 or even 15 μm. During the closing decades of the 20th century the advent of CCDs on 4 meter class telescopes and the Hubble Space Telescope (HST) led to a renaissance in extragalactic astronomy and large-format HgCdTe and InSb infrared arrays forever altered the basic nature of IR observational astronomy! In this decade, the demanding detector requirements of the near infrared (NIR) instruments of the James Webb Space Telescope (JWST) have driven spectacular improvements in the performance of FPAs for the 0.6 – 5 μm spectral region. The HAWAII-2RG (H2RG) HgCdTe arrays selected for all three NIR instruments, already in use at most large (4 – 10 m) ground based telescopes, provide high (~ 90%) quantum efficiency and extremely low (~0.002 e^-/sec) dark current in large format 4 Mpxl (2048 x 2048 @ 18 μm pitch) arrays. For a limited class of OIR observations they, along with CCDs in the optical, now provide near ultimate performance! However, this in no way implies that OIR FPA technology for astronomy is a mature field, with the future holding only incremental gains at prohibitive cost.

In this general technology development white paper, we lay out a comprehensive plan for OIR FPA technology development over the coming decade that promises order-of-magnitude breakthroughs in sensitivity coupled with dramatically simplified detector system architectures. ***Its ultimate goal is to achieve near perfect performance for all types of OIR observation in much larger FPAs at much lower cost/pixel.*** It impacts all areas of OIR astronomy, benefitting missions and observatories both large and small, new or refurbished. It is focused entirely on HgCdTe, the material used in both the H1R FPA's flown on the Deep Impact comet mission (and soon to be launched to HST) and the H2RG FPAs selected for JWST and already in widespread use in ground based telescopes. It has three central objectives:

4) To greatly increase the pixel counts of the largest individual arrays without any significant increase in cost. A fourfold jump from the 4 Mpxl H2RG to the 16 Mpxl H4RG-15 is feasible right now and technology developments outside astronomy could well allow another leap to a 64 Mpxl H8RG-15 later in the decade. These dramatically reduce the cost per pixel for all observations and greatly simplify the large mosaic focal planes required by many of the more ambitious projects. Improvement of the readouts, ASIC controllers and mosaicing techniques to optimize the use of these larger FPAs will also be required.
5) To extend the wavelength coverage of HgCdTe FPAs down towards 0.4 μm and out to beyond 10 μm and even to 15 μm.
6) To utilize the unique electron and hole initiated avalanche properties of HgCdTe to develop ***e-***APD and ***h-***APD arrays allowing photon counting in the OIR entirely free of excess noise, to very high fluxes and, as required, with down to picosecond time resolution.

Although the program draws heavily on the heritage of the University of Hawaii (UH) – Teledyne Imaging Systems (Teledyne – formerly Rockwell Scientific Co), the program is in no way limited this partnership or Teledyne as a vendor. The University of Rochester (UR) – Raytheon Vision Systems (RVS) team was a strong contender in NASA's rigorous JWST down- select and RVS was selected to provide the FPA for the mid-IR instrument (MIRI). RVS subsequently won the competition to provide the sixteen 4 Mpxl HgCdTe FPAs for the mosaic focal plane of ESO's VISTA telescope. A number of other vendors, notably DRS Infrared Technologies in Dallas TX and CEA LETI in Grenoble France are actively developing HgCdTe FPA technologies for astronomical applications.

1. Larger, better FPAs at greatly reduced cost per pixel.

The goal of this low risk aspect of the program is to make available FPA's with four, and possibly sixteen, times the pixels of the H2RG with a corresponding decrease in cost per pixel. This will benefit all OIR science but is particularly valuable for programs such as surveys that require large mosaic focal planes or cloned focal plane instruments.

1.1 A 16 Mpxl 4K x 4K building block for large mosaic focal planes.

For most observations the number of pixels in the focal plane factors into the **A-Ω** the same as the area of the telescope! The size of astronomical OIR arrays, both CCDs and hybrid IR CMOS, has grown at a rate far more gradual than Moore's law. The pixels of astronomical arrays must match the telescope scale and cannot be shrunk in size as the technology advances – instead the number of pixels of a given pixel size must be increased with a corresponding increase in the size of the array. There is inevitably a very step technical (and hence cost) limit above a set physical size, defining a "building block" array from which to assemble large mosaics. The 4 Mpxl H2RG is currently the building block in the 1 – 5 μm infrared. Within the current technical envelope, many of the costs of array fabrication are independent of the size or the numbers of pixels. Thus as technological advances allow larger arrays (usually in factors ~2 in dimension or 4 in pixel count) the cost per pixel is significantly reduced. With only a quarter of the arrays to mount, the cost of a mosaic FPA of a given pixel count can be reduced even faster. This reduction in price per pixel is critical to be able to afford to achieve the potential **A-Ω** gains of next generation telescopes.

Teledyne and UH have defined a 42 month roadmap to demonstrate full production of a high performance 4Kx4K infrared array, the H4RG-15, with integrated ASIC controller, at about one third to one quarter the cost per pixel of the current H2RG. The program is built upon both the SIDECAR ASIC controlled H2RG arrays selected for all three JWST NIR instruments and also the 4Kx4K mosaic FPAs already adopted by numerous ground based telescopes – UH 2.2 meter, CFHT, Gemini south, Carnegie, ESO etc.

The key areas involving significant extension of existing technology, or incorporation of new technology, are all well understood. They are:

- The 4Kx4K @ 10 μm pitch readout: *Teledyne has produced and successfully hybridized the H4RG-10 readout – it utilizes the same unit cell design- unfortunately too small for best IR performance.*

- Scaling to 62.5x62.5 mm active area: *This is at the limit of available size for cadmium Zinc Telluride (CdZnTe or CZT) substrates but is a cost, rather than a technical issue. The transition to Si substrates will mitigate the cost issue and simplify the technical process. Performance of MBE on Si material will be verified to be fully comparable to the best MBE on CZT as part of this development.*

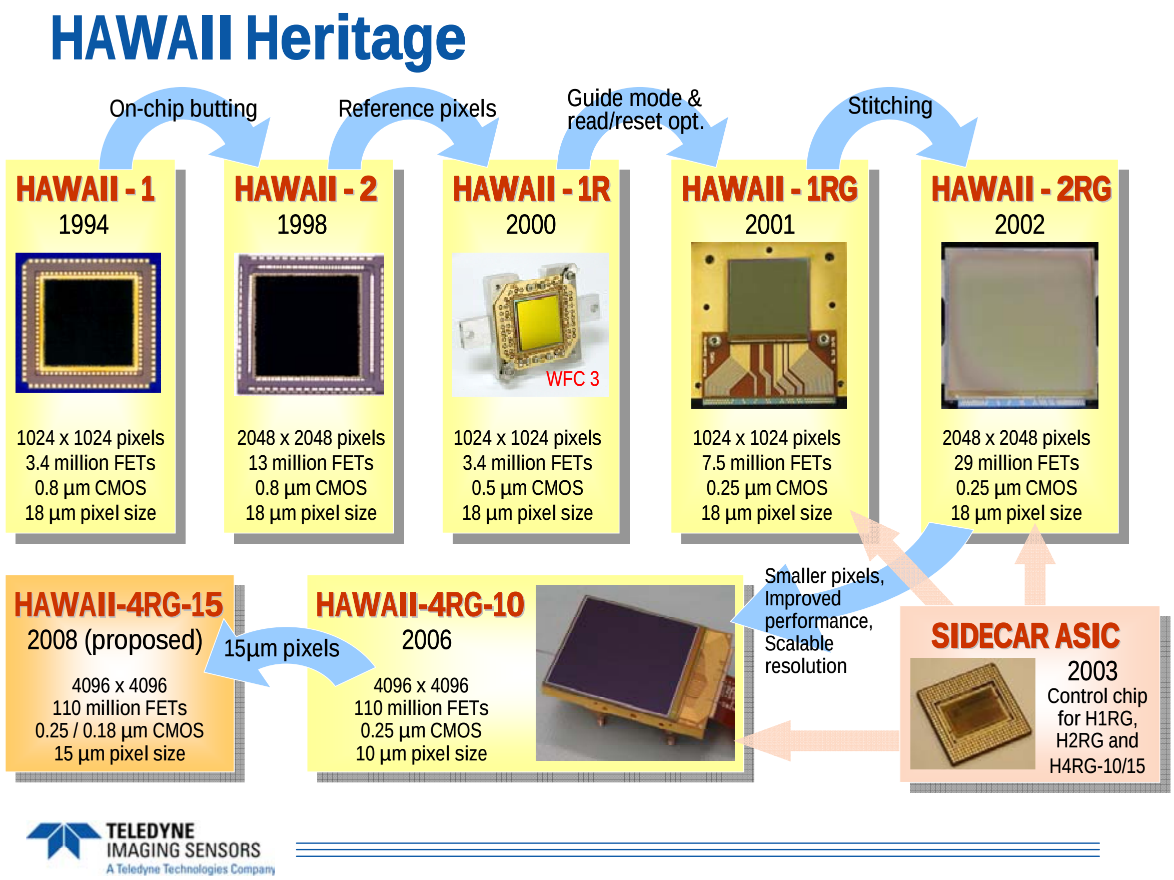


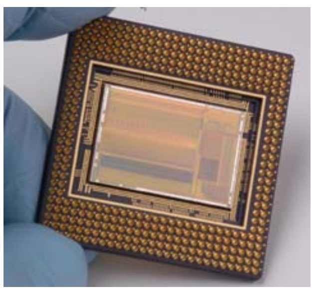
Figure 1: Approaching twenty years of development of the HAWAII series of infrared arrays.

- Hybridization at 4Kx4K @ 15 µm pitch: *Teledyne has successfully hybridized the H4RG-10 with high pixel interconnectivity and the HIGH STARE program will scale hybridization to 2Kx2K @ 30 µm pitch arrays. Teledyne now routinely achieves near perfect interconnect operability in flight H2RGs.*
- Design incorporating integral SIDECAR ASIC: *The SiC carrier is an excellent CTE match to both the Si ASIC itself and also to the AIN ceramic on which it will be directly mounted. ASIC's on AIN ceramics similarly mounted into Invar carriers have been flight qualified for both the Hubble Advanced Camera repair and for all three NIR instruments on JWST.*

The overall objective of the proposed program is to fully demonstrate, in 3 - 4 years, an affordable workhorse 4K x 4K NIR array. The program could commence as early as 2009 with completion in 2012. Ideally it would be followed by a redesign of the H4RG-15 and in the last half of the decade by the jump to a 64 Mpxl 8Kx8K "building block" array. The H4RG-15 redesign could range from relatively minor upgrading of capability and functionality to a complete redesign of the unit cell and readout architecture, taking full advantage of advances in CMOS fabrication, to provide major new capabilities.

1.2. Second generation ASICs.

The 1st generation SIDECAR ASIC has been an extraordinary success. It has enabled the JWST NIR focal planes, and also the rescue of the ACS on HST. It has displaced conventional array controller and data acquisition systems at a growing number of ground based telescopes. Moreover, all of this was accomplished within only a few years of the SIDECAR's conception, development and introduction!



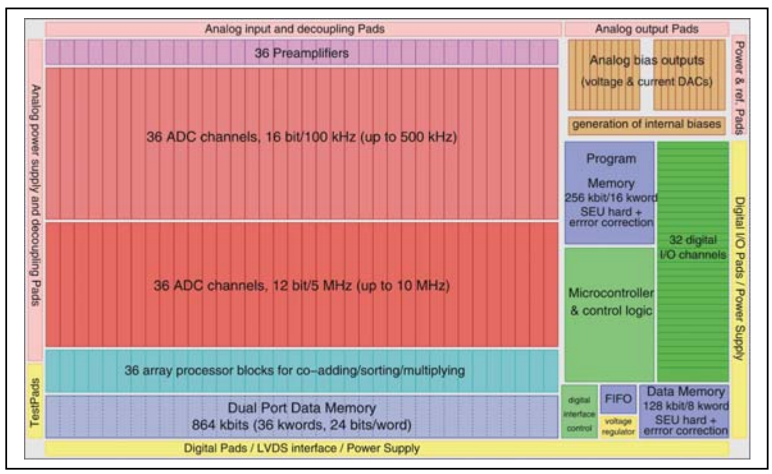


Figure 2: The SIDECAR ASIC in a ground-based package (left) and chip "floorplan" (right); complete focal plane electronics capability in a circuit that is 14.5 × 22 mm.

The SIDECAR is an application-specific integrated circuit (ASIC) that interfaces directly with the H1RG, H2RG and H4RG-15, providing all of the functionality required from focal plane electronics with a significant reduction in the size, weight, and power of the focal plane electronics (Fig. 2). The SIDECAR contains a programmable microprocessor, bias generators, clock generators, amplifiers, and analog-to-digital converters. Up to 36 analog inputs can be accommodated in parallel, and digitized at up to 500 kHz sample rate (16-bit resolution) or up to 10 MHz sample rate (12-bit resolution). The SIDECAR interfaces digitally with instrument electronics, and with low-voltage differential-signal communication. It can be placed several meters from the instrument electronics and operation is programmable via the communication line.

The SIDECAR ASIC operates with very low power over the entire temperature range from ambient down to < 35K. Reading 32 ports continuously at 100 kHz sample rate will use about 150 mW at 70K. Low power operation enables placement of the SIDECAR within the instrument cryostat and even integrated into the detector package.

Based on experience with the present SIDECAR we foresee the need for a redesign at the outset of the coming decade. This would be focused on maturing the ASIC from a developmental device to an operational, user-friendly product. The redesign would also remedy some unanticipated shortcomings, such as not being able to co-add full frames within it, and improve some aspects of technical performance, such as noise in voltage and current sources that has been identified by the JWST project. The SIDECAR is already fully optimized to operate the H4RG series of readouts (a second, slaved SIDECAR allows use of all 64 outputs) and this philosophy would be carried over into any redesign. With advances in technology, we anticipate the need for a complete redesign of the ASIC in conjunction with the 8Kx8K development although operation with 3 slaved ASICs in 128 output mode is certainly not ruled out.

It is a remarkable tribute to the versatility and power of the multiple HRG readouts operated by the SIDECAR ASIC that they can be operated at high frame rate in photon counting mode to utilize the unique properties of HgCdTe ***e-***APD and ***h-***APD detectors.

1.3. Enabling technology for large mosaic FPAs at cryogenic temperatures.

The technology for mosaics of H2RGs is mature with standard 16 Mpxl 2x2 mosaics in extensive use on ground based telescopes; several 2x2 mosaics will be flown on JWST. Detailed conceptual designs exist for H2RG mosaics as large as 5x7, approaching 150 Mpxl! The H4RG-15 carrier has been designed to facilitate simple integration into very large mosaic arrays – the 5x7 format would scale to nearly 0.6 Gpxl. We foresee a need to develop detailed conceptual designs and demonstrate technology for at least a 2x2 H4RG-15 (64 Mpxl) mosaic and also a larger 3x3, or preferably 4x4, configuration where some arrays are embedded within the mosaic. This effort would facilitate use in ground based telescopes, planning for space missions and eventual space qualification.

2. Extending OIR Wavelength Coverage.

Substrate-removed HgCdTe photo-diodes are already used down through the visible as well as in the NIR. By changing the mole fraction of cadmium in the HgCdTe, the wavelength cutoff can also be tuned to provide response throughout the LWIR. The goal in this area of development is to extend the wavelength interval over which HgCdTe is fully optimized for OIR astronomy to both shorter and longer wavelengths.

2.1 Shorter wavelengths: ~ 0.4 μm with substrate removal.

Substrate removed $\boldsymbol{\lambda_{co} \sim 1.7\ \mu m}$ and ***2.5 μm*** HgCdTe is already used at visible wavelengths and its spectral response extends below 0.4 μm. Detection of photons more than three times the band gap energy (~ 0.6 μm for $\boldsymbol{\lambda_{co} \sim 1.7\ \mu m}$ material and ~ 0.45 μm for $\boldsymbol{\lambda_{co} \sim 1.35\ \mu m}$ material) exhibits modest QE enhancements. These effects require further study and further development is required to fully optimize its performance, particularly QE, over the 0.4 to 1 μm interval for OIR astronomy. For the best visible wavelength performance, proper passivation after removing the substrate is the key. Although the JWST passivation provides excellent QE (>70%) for wavelengths as short as 0.6 *μm,* surface traps limit the utility of this passivation for shorter wavelengths. For non-astronomical applications, Teledyne has shown that excellent QE can be achieved to wavelengths as short as about 0.4 *μm* using improved passivation (Fig. 3).

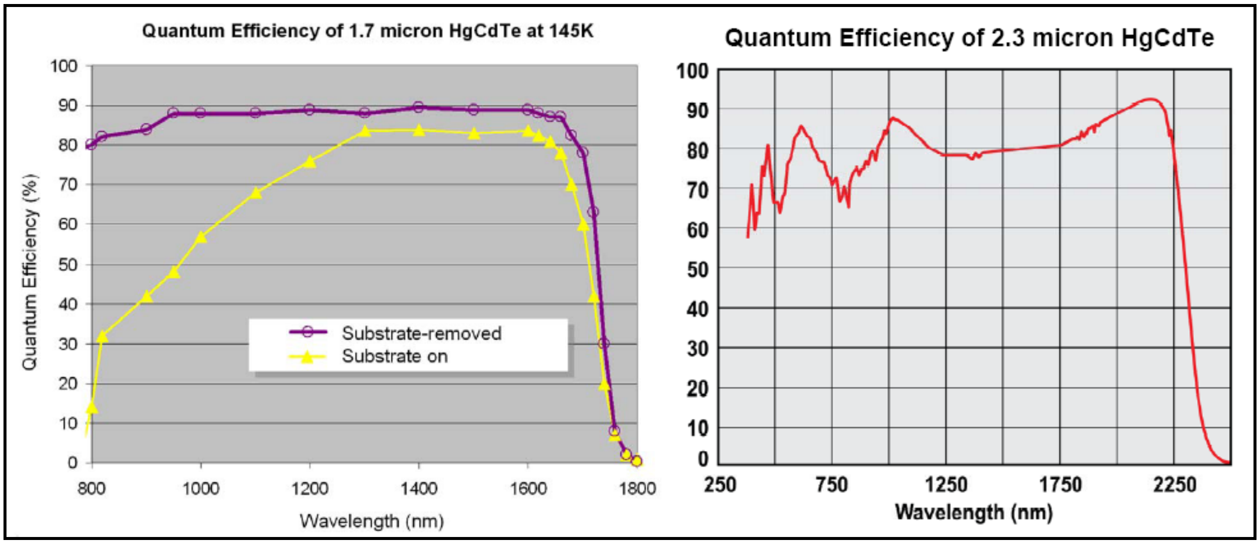


Figure 3: When properly passivated, substrate-removed HgCdTe has excellent QE at visible wavelengths. Although these data are from a non-astronomical application, there is no fundamental reason why similar performance could not be achieved with an astronomical vis-NIR array. The technology development plan that is outlined in this white paper includes passivation studies aimed at achieving this level of performance in astronomical arrays. These data are from substrate-removed parts produced by Teledyne.

2.2 Longer wavelengths: λ_{co} ~ 10 - 15 μm.

LWIR HgCdTe arrays (to cut-off wavelengths as long as 20 μm) have long been used in *very* high background applications, e.g. tactical. On the other hand, space astrophysics experiments often demand very low, zodiacal background radiation limited operation. For example, with a cryogenic 4-m telescope, the background generated photocurrent at a wavelength of 10 μm is 2000 e-/s for diffraction limited pixels, QE = 70%, optical efficiency 48%, and spectral resolution ***R*** = 3. The longest wavelength HgCdTe detector arrays in use for astrophysics, the Teledyne **λ_{co} ~ 5 μm** H2RGs for JWST, took 5 years to develop to JWST specifications, a huge leap from the reported 1998 status (Bailey et al. SPIE 3354, 77). However, the lessons learned in the JWST development, in particular specialized processing, architecture and novel bonding techniques, led to Teledyne development of vastly improved, 10 μm cut-off arrays suitable for low background radiation levels, in collaboration with UR (Bacon, PhD thesis 2007).

As can be seen in Figure 4, at a focal plane temperature of 30K, 25% of the pixels are either unresponsive to radiation, or exhibit dark currents in excess of 30 e-/s. Most of the responsive pixels exhibit dark currents close to 0 e-/s (the apparent negative dark current reflects a system offset) – 72% have dark currents < 1 e-/s. These devices are currently at a research level of performance that is approximately equivalent to the status in 1998 for the 5 μm devices. Taking the 10 μm development to a state where approaching 99% of the pixels showed low dark currents, and larger well size, would make them valuable for astronomy. Extending the cutoff wavelength to 15 μm, yet meeting background limited operation would be very difficult, but is entirely possible, since diagnostic information obtained by UR on high dark current pixels in the 10 μm arrays focuses attention on the defects responsible, which Teledyne is poised to address. Why is this development desirable? Optimized LWIR HgCdTe could be operated at focal plane temperatures of ~30K achievable with radiative cooling in space, decreasing the cost and increasing the lifetime of future space missions incorporating LWIR detector arrays – a huge improvement over current space missions which must employ IBC photoconductor arrays which require cooling to 6-8K. The use of HgCdTe would also allow this wavelength interval to benefit from the huge body of manufacturing and packaging technology already developed for shorter wavelengths.

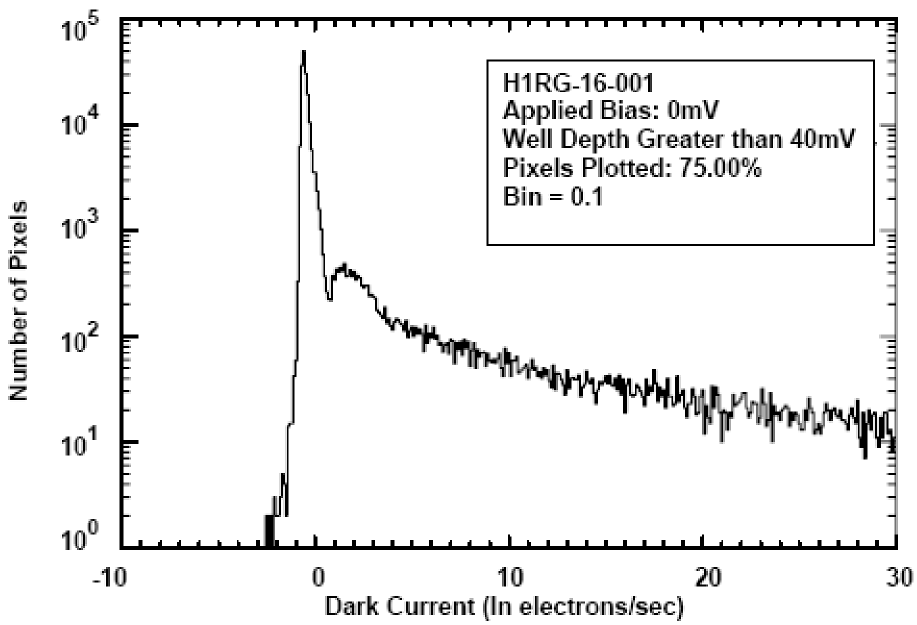


Figure 4: Histogram for 9.2 μm cut-off array (the x-axis has a negative offset of 1 – 2 e-/sec and 72% of pixels have dark current < 1e-/sec). The only pixels plotted have well depths 25Ke- or higher, that is pixels which are responsive to radiation.

3. HgCdTe *e*-APDs and *h*-APDs - perfect photon counting arrays for the OIR

Both ***e-***APD and ***h-***APD technologies in HgCdTe hold promise of dramatically improved performance of large format OIR FPAs over the entire 0.4 to 15 μm range. This is a challenging technical development program with the potential to remove essentially all constraints on performance due to detector performance.

3.1. HgCdTe *e*-APD and *h*-APD FPAs with existing readouts.

As shown in Figure 5, the avalanche properties of $Hg_{1-x}Cd_xTe$ vary dramatically with band-gap. This due to the unique crystal lattice properties of HgCdTe which allow two types of noise-free linear avalanche in quite distinct modes – pure electron initiated (***e-***

APD) for band-gaps $\leq$ 0.65 eV (***$\lambda_{co} \geq$ 1.9 μm)*** and pure hole initiated (***h***-APD) centered on a very specific band-gap of 0.938 eV (***λ_{co} = 1.32 μm***) corresponding to a resonance with spin-orbit splitting. Both utilize very similar architectures consisting of a separate avalanche multiplication (SAM) layer graded into a photo-detection layer of a lower band-gap. With the photo-detection layer cutoff wavelengths in the range ***1.35 μm $\leq \lambda_{co} \leq$ 2.5 μm,*** and higher operating temperatures, the ***h***-APD arrays are ideally suited to most ground-based applications and HST-like space missions – they have the potential to entirely supercede CCD's and charge-integrating IR FPAs in the visible and short – wave IR. For ***e***-APD arrays the cutoff wavelength options beyond 2.5 μm (***2.5 μm $\leq \lambda_{co} \leq$ 15 μm***) complement ***h***-APDs for JWST like space missions along with high resolution spectroscopy from the ground. In linear avalanche mode, ***e***-APDs and ***h***-APDs complement one another to offer noise free counting of multiple photons to high gain-bandwidth throughout the OIR in large format FPAs.

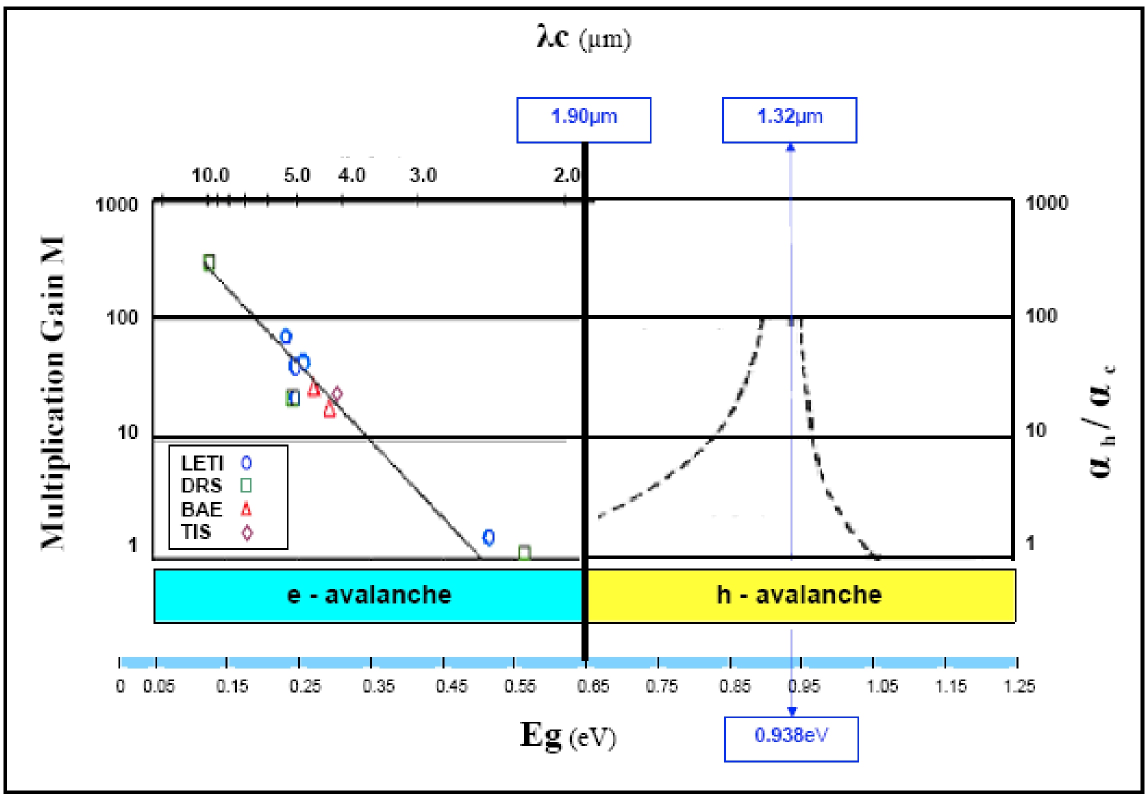


Figure 5: The distinct e-APD and h-APD regimes of HgCdTe cross over at Eg ~ 0.65 eV (λ_{co} ~ 1.9 μm). At lower band-gaps the e-APD gain increases exponentially - material for four manufacturers shows remarkably consistent results. To higher bandgap the ratio k = α_h / α_e asymptotically approaches pure h-APD at Eg = 0.938 eV – the ideal SAM layer.

We foresee a sequence of technology development programs (several of which are already underway) followed by use of the technology at the telescope utilizing existing readouts and ASICs in the early part of the coming decade. Development of optimized readouts and ASICs would follow later in the decade. If we can demonstrate infrared photon counting with QE comparable to the conventional charge integration mode, then the read noise constraint is completely eliminated and high spectral resolution, ultra low background and high time resolution measurements are limited only by natural constraints, usually photon statistics. With specialized readouts, the photon counting arrays can be designed to handle high photon fluxes so as to encompass the same parameter space as the current H2RG arrays. Such arrays would provide the perfect detector for both space and ground based astronomy with their huge dynamic range, high quantum efficiency, negligible dark current, noiseless readout and the potential for photon time-tagging to picosecond levels.

3.2. Development of optimized photon counting readouts.

The versatility of the H1RG and 2RG readouts in tandem with the SIDECAR ASIC enables powerful photon counting arrays utilizing existing, space qualified devices. However the unique properties of HgCdTe ***h-***APD and ***e-***APD arrays can be far better utilized with custom readouts. For these the unit cell consists of a low input noise comparator to increment a counter each time an avalanche event occurs. At the end of the integration, the counts in each pixel are either transferred to a storage register, or simply held in the accumulation register. The contents of the register are then sequentially accessed and read during the frame read. With HgCdTe such readouts have much higher saturation fluxes than conventional CCD's or charge integrating IR arrays but in photon counting mode, resulting in a huge improvement in dynamic range. We foresee development of such readouts in the first half of the coming decade.

3.3 Picosecond time resolution – the field of quantum astrophysics.

In linear mode HgCdTe avalanche pulses are sharp, exhibiting typical rise times of 50 psec followed by sub-nanosecond decays, and are also self-quenching. This opens the way to time tagging photon arrival times to picosecond (0.3 mm travel distance) levels in arrays with sub-nanosecond dead times, allowing a huge leap in the developing field of quantum astrophysics (quantum photometry along with intensity interferometry and spectroscopy). It also enables 2nd generation photon counting readouts with far higher saturation fluxes and full well capacities than current optical CCDs and NIR arrays. However, significant design challenges will have to be overcome in the development of these readouts to fit all of the necessary circuitry into a pixel while keeping the power consumption at an acceptable level.

4. Milestones, schedules and costs.

The HST WFC3 development of the H1R readout hybridized to $\lambda_{co} \sim 1.7\ \mu m$ HgCdTe, the JWST development of the SIDECAR ASIC and the H2RG with $\lambda_{co} \sim 1.7\ \mu m$ and ***5 µm*** HgCdTe, the submission of the proposal for the H4RG-15 and initiatives for $\lambda_{co} \sim 10\ \mu m$ HgCdTe together provide a firm basis from which to estimate costs and schedules for the first two areas of the program. Although the APD element involves riskier, more open ended technical development, our understanding of ***e-*** and ***h-*** avalanching in HgCdTe has matured rapidly; we use our experience with one award in process, and a submitted proposal for another, on which to base the estimates for these areas of the program.

As stated at the outset, the ultimate goal of this HgCdTe based technology is "***to achieve near perfect performance for all types of OIR observation in much larger FPAs at much lower cost/pixel***". Component tasks along with their intermediate milestones are laid out in Table 1 together with estimates of when they will occur and very rough costs based on the authors' experience over the last decade. The overall cost impact in the decade depends heavily on whether the H4RG-15 is already funded and whether the H8RG-15 proceeds. If these are already funded or delayed, then the total drops to $25 million, weighted towards the first half of the decade

Task	Intermediate Milestones	Begin	End	$ (2010 - million)
H4RG-15	**1) Demo H4RG. 2) Production Run. 3) Comm Product. 4) TRL-6**	**7/09**	**12/12**	**10?**
2nd Gen ASICs	**1) Community input. 2) Demo. 3) Comm Prod. 4) TRL-6**	**1/11**	**12/13**	**2**
2nd Gen H4RG-15	**1) Community input. 2) Demo. 3) Comm Prod. 4) TRL-6**	**1/13**	**12/14**	**2**
H8RG-15	**1) Review mid-decade**	**1/15**	**12/17**	**10?**
H8RG-15 ASIC ?	**1) Review mid-decade**	**1/16**	**12/17**	**2?**
GPxl Mosaic FPA Technology Base	**1) H4RG-15 based 2x2 & 4x4 designs. 2) H8RG extension.**	**1/10**	**12/15**	**1**
Optimization of *0.4 – 1 μm* Properties	**1) Astro performance to 0.4 μm 2) Extend to λ?**	**1/11**	**12/14**	**2**
***λ_{co} ~ 10 - 15 μm* Development**	**1) Astro performance to 10 μm 2) Extend to 15 μm**	**1/11**	**12/14**	**4**
***e*-APD Technology Develop**	**1) Demo technology. 2) Astro FPAs. 3) Comm Product.**	**1/08**	**12/13**	**3**
***h*-APD Technology Develop**	**1) Technology demo. 2) Astro FPAs. 3) Comm Product.**	**1/10**	**12/13**	**3**
***e- & h-* APD Photon Counting Readouts**	**1) Technology demo. 2) Comm Product**	**1/14**	**12/15**	**4**
nsec to psec Timing Readout	**1) Technology Demo**	**1/16**	**12/17**	**4**

Table 1: Breakdown of intermediate milestones with cost and time frame.

The mandatory page limits leave no space to make a scientific case but the advantages of the proposed program seem apparent and widespread. They also extend far beyond OIR astronomy into both NASA areas such as planetary missions, earth remote sensing and space optical communications and also into more general fields such as fiber communications, 3D LIDAR imaging and tomography, night vision, quantum entangled encryption and broader homeland security and medical applications.