

Candidate detector assessment for the CASTOR mission

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ABSTRACT

The Cosmological Advanced Survey Telescope for Optical and UV Research (CASTOR) is a proposed Canadian Space Agency (CSA) mission that would provide panoramic, high-resolution imaging of 1/8th of the sky in the UV/optical (150-550 nm) spectral region. This small-satellite class mission would provide high angular resolution ultra-deep imaging in three broad filters to supplement data from planned international dark energy missions (Euclid, WFIRST) as well as from the Large Synoptic Survey Telescope (LSST). One of the leading technical risks on this mission is the UV sensitivity required to approach 26th magnitude in the near UV band. We are planning to characterize a selected candidate technology down to 150 nm. We will review the main scientific and technical drivers for the mission and show how they constrain the available detector options. We will compare the sensitivity and general applicability of CCD, EMCCD, hybridized and monolithic CMOS FPA options.

Keywords: UV astronomy, detectors, focal plane arrays, astronomy, space telescope, NUV, silicon

1. INTRODUCTION

COM DEV is currently working with the CSA on a study to review available Focal Plane Array (FPA) technology and its application to the CASTOR mission. In support of this work the CASTOR science team are reviewing the science case and providing support for the requirements flow-down and detector selection trades. The goal of this project is to provide the Canadian Space Agency with a broad assessment of available UV-sensitive detector technologies for future astronomical space missions. This work is aimed to develop a scientifically relevant and technically achievable FPA specification addressing vacuum ultraviolet (NUV) sensitivity risks identified on the earlier CASTOR concept study. The team are evaluating state-of-the-art technology, selecting a supplier, and plan to leverage their existing James Webb Space Telescope (JWST) cryogenic detector test hardware to cost-effectively characterize the performance of the selected FPA.

This project is intended to provide an experimental demonstration of a high-speed, low-noise silicon array sensor with low power dissipation—critical for the operation of the huge focal plane needed for the CASTOR mission. The detector will be ‘back-illuminated’ so no gate structures will be present on the input surface to absorb signal photons. COM DEV is hoping to work with manufacturers to incorporate optimized surface treatments of the detector for improved quantum efficiency in the NUV spectral region, while investigating the trade space surrounding anti-reflection coatings in this region.

1.1 Mission Overview

The CASTOR mission is a proposed Canadian-led 1-m class, unobscured off-axis free-flying observatory targeted at a polar low earth orbit (LEO)¹. CASTOR would make a unique, powerful, and lasting contribution to astrophysics by providing panoramic, high-resolution imaging of 1/8th of the sky in the UV/optical (0.15-0.55 μm) spectral region over its first 5 years. This versatile small satellite-class mission would far surpass any ground-based optical telescope in terms of angular resolution, and would provide ultra-deep imaging in three broad filters to supplement longer-wavelength data from planned international dark energy missions (Euclid, WFIRST) as well as from the ground-based LSST.

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Imaging in the blue and NUV over a fully paved field of $\sim 1 \times 0.5$ degrees, CASTOR will be diffraction limited at 300 nm at $\sim 0.1''$ pixel scale (10 μm). This will require an array of 9 x 5 detectors, each with 16 Megapixels, or similar total size in alternative format. The wide field imager will take ~ 3 -10 minute exposures sampling up the slope in 3 colours: u, g, and NUV. A fine pointing mirror will use 10 Hz guiding data from a few bright stars on the main array to stabilize the image to $< 0.05''$, and a series of 4 dithers will be used at half integral offsets to fill in the gaps in the image array. One of the requirements is to do photometry on stars to levels of $< 1\%$ accuracy. This impacts requirements on gain linearity knowledge and allowable levels of inter-pixel capacitance (IPC). A secondary goal of the mission will be to provide high speed photometry on a set of ~ 300 bright stars at a refresh rate of > 20 Hz. This corresponds to at least 10 bright stars per array.

One of the leading technical risks on this mission is the UV sensitivity of the large area focal plane arrays required to approach 26th magnitude in the near UV band over the full survey area. This paper provides an assessment of different candidate detector and bandpass filter coating technologies against the preliminary mission requirements. The selection criteria include FPA packaging, thermal dissipation, and system impact in order to address challenging budgetary limitations. Opportunities for international partnership are also discussed.

2. REQUIREMENTS

Assuming random noise sources can be constrained to < 2.5 electrons on a 600 second integration, the CASTOR system requires a high quantum efficiency in the NUV band ($> 25\%$) to meet its targeted survey magnitudes. The sensitivity requirements are apportioned between the filter and the detector systems in the following subsections. A significant advantage would be gained by a manufacturer with a demonstrated ability to deposit a high throughput 'solar-blind' NUV bandpass coating directly onto the silicon FPA. This approach, if successful, would avoid the multiplicative coating losses at the filter and detector surfaces, taking advantage of the high internal efficiency of modern back-illuminated silicon detectors.

2.1 Detector Requirements

The CASTOR detectors need a high quantum efficiency in the NUV band ($> 50\%$) combined with a low dark current (< 0.01 e/p/s) in a large format array compatible with the power resources of a small satellite bus. Also required are:

- Gain knowledge of $< 0.5\%$ to achieve photometric accuracy.
- Low power dissipation on the focal plane (< 20 mW/cm²) is needed for the cryocooler to stay within the tight power budget of a small satellite, assuming cooling to < 170 K is required for end-of-life dark current after proton irradiation in LEO.
- IPC should be constrained to be within the optical point spread function of the telescope, and must be linear with flux to be removable from the data
- A detector pitch of 10 microns ($0.1''$) hits all the major science goals, if dithered to $0.05''$ sampling.
- Ability to do 10 Hz fine guiding on the main array without disrupting long science integrations would be a benefit.

It would ease procurement, qualification, and readout electronics design for future astronomy missions if the selected detector were to be available to be used for the entire NUV/Visible waveband, providing commonality of electrical interfaces and drive software. Detectors could be procured with varied anti-reflection coatings optimized for their target wavebands with minimal system impact in this case. Detector type should therefore be selected to have good sensitivity over the entire waveband.

2.2 Filter Requirements

CASTOR supports three filter wavebands: NUV (150-325 nm), 'u' (325-425 nm), and 'g' (425-550 nm). 'Red leak' is a major issue for UV science. The NUV-band filter will need to suppress the longer out-of-band wavelengths by 4 or more orders of magnitude (vs. 3 orders in 'u' and 'g' bands). In-band throughput needs to be $> 50\%$.

3. DETECTOR COMPARISON

We have ruled out ultra-low temperature detectors as infeasible within the resource envelope for a small satellite. Multi-channel plates with wide-bandgap solar-blind nitride photocathodes have gain uncertainties on the order of +/-30%, and cannot meet the photometric accuracy requirements, except when used as photon counters for the dimmest sources.

High resistivity silicon-based photovoltaic array detectors are known to have high internal quantum efficiency/absorptivity over the full NUV/Visible range down to 120 nm². Suitably mature silicon detector choices include monolithic Back Illuminated CMOS (BICMOS), silicon PIN hybridized to CMOS Readout Integrated Circuit (ROIC), and various flavours of back illuminated CCD (BICCD), including electron multiplying CCD (EMCCD). Since CCD technology has advanced to the point where photon detection has almost reached the ideal limit (ie. >90% quantum efficiency and <5 electrons readout noise), these are the imaging detectors most typically used in astronomy applications.

3.1 CCD-based options

CCDs shift collected charge off of the device at common readout stages. This means that the CCD photoresponse non-uniformity is typically very low from pixel-to-pixel because the same readout circuitry is used for each read. CMOS, on the other hand, often suffers from gain and offset non-uniformity over the surface of the detector chip because each pixel has a 'unique' output amplifier on-board with its own offset bias and gain characteristics.

Drawbacks associated with a CCD design include the fact that the efficiency of charge transfer degrades with radiation dose, and the power and off-chip circuitry required to shift the charge becomes a big penalty, especially at high readout rates.

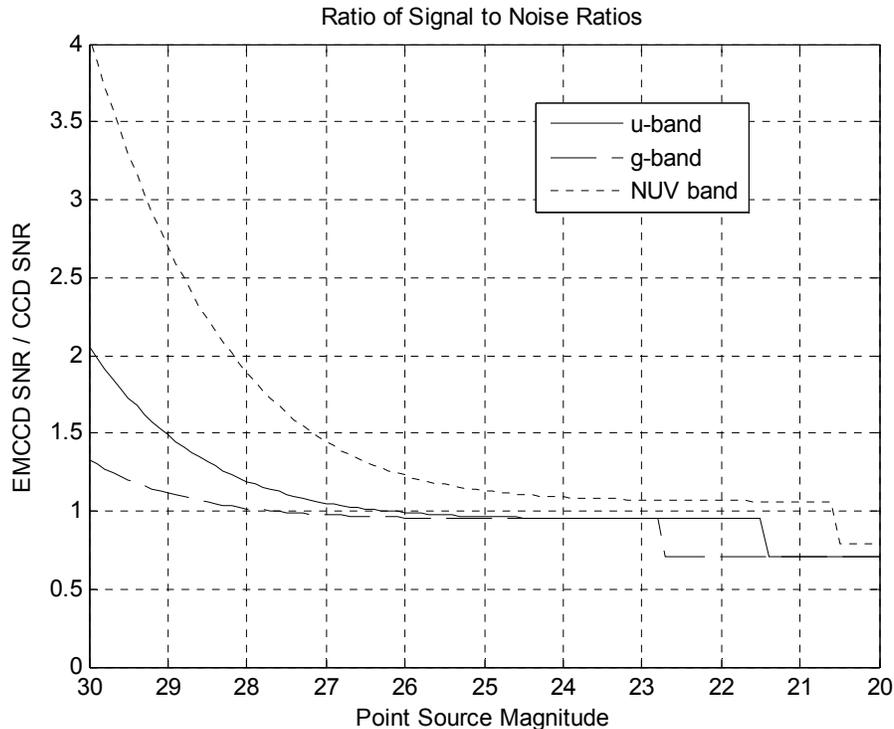


Figure 1 CASTOR mission EMCCD signal to noise comparison to CCD as a function of magnitude

EMCCDs can provide a signal-to-noise advantage over classical CCDs in photon-counting mode for the dimmest sources under consideration. For bright signals of more than a few collected electrons/pixel, the EMCCD, however, operates at a photometric noise penalty. In order to keep the pixel fluence low for the majority of sources, an EMCCD would need to be operated at very high frame rates. This would exacerbate the power penalty over that of a classical CCD. The signal

to noise ratio tradeoff is summarized in Figure 1 as a function of the target magnitude for the CASTOR mission. The discontinuous drop at the bright end of the scale is an indication of where the source brightness exceeds the single photon/pixel limit for useful photometry at the maximum frame rate of existing large EMCCDs (~15 Hz). For object magnitudes above this point the data from the EMCCD would be processed in analog mode, at which point the gain dispersion reduces the effective signal to noise ratio, compared to a typical CCD.

When the energy of the UV photons exceeds twice the bandgap energy in silicon, there is a chance that multiple charge carriers will be created on absorption. The CCD signal-to-noise shown for the NUV band in Figure 1 has been corrected for an estimated quantum yield factor of 1.3, which is applicable to e2v CCDs operating near 150 nm (see Figure 3). Dispersion in this gain will affect the photometric accuracy of the CCD measurements whereas the signal-to-noise ratio for the EMCCD in photon counting mode is not affected by creation of multiple charge carriers by energetic photons.

Using the magnitude limits where photon counting is still feasible and the SNR ratio from Figure 1, the potential benefits of the EMCCD are readily calculated as shown in Table 1. For this comparison, we noted the brightest source that would be consistent with accurate photon counting while maintaining power dissipation similar to the original CMOS FPA consistent with a small satellite resource allocation. In this case, the maximum frame rate would be <0.15 Hz and this corresponds to photon counting saturation >5 magnitudes earlier than presented in Figure 1.

Table 1 CASTOR Limiting Magnitude or Survey Time Improvement with EMCCD's

	Survey	CASTOR Survey Band		
		NUV	u	g
SNR Factor Improvement (from Figure 1)	Wide	1.20	1.06	1.00
	Deep	3.10	1.94	1.30
Limiting Magnitude Improvement	Wide	+0.2 (26.0)	+0.06 (27.2)	+0.01 (27.8)
	Deep	+1.2 (27.5)	+0.7 (28.3)	+0.3 (28.6)
Photon Counting Saturation Magnitude		25.6	26.5	27.8
Survey Time Improvement Factor	Wide	0.7	0.9	1.0
	Deep	0.1	0.3	0.6

It is immediately apparent from Table 1 that the main benefit from EMCCDs would be in the NUV band deep survey, extending it by more than a magnitude. Because of the power limitations on a small satellite bus, the source brightness window for non-saturating photon counting is quite narrow. For photon counting to address a useful range of source magnitudes it needs to be operated at maximum frame rates and high voltages, and this significantly complicates the readout electronics design. In addition, an unfeasibly large deployable solar panel would need to be added to the satellite to provide a few extra kilowatts of readout and cryocooler power.

3.2 CMOS ROIC-based options

Recent advances have shown that there is no intrinsic reason that silicon CMOS ROICs cannot match or even outperform CCDs in all areas of performance³. Modern multi-read sampling techniques effectively eliminate the problem of fixed pattern offset noise and variable gain characteristics can be calibrated with a suitable flat field test. This, combined with their non-destructive readout capability, simplified low-power readout electronics, and intrinsic proton radiation tolerance make scientific CMOS a better choice for future space astronomy applications. CMOS readouts have the additional important operational benefit that many of them support high speed random-access subwindowing without affecting the rest of the scientific data collecting area. This would allow using the main scientific camera as the source for fine guidance information. An additional advantage is that the Silicon PIN can be hybridized to familiar infrared astronomy ROICs such as the HXRG family, recently used by COM DEV and the CSA in the JWST program.

One competing drawback, however, is that the PIN material needs extra thickness to retain structural integrity during indium bump bond hybridization, and this leads to a larger dark current than otherwise necessary at fixed operating

temperature and results in higher transient sensitivity to cosmic rays and trapped proton flux. For a silicon detector, the displacement damage processes that affect bulk dark current generation rates are well understood and scale with the sensitive volume of the pixel⁴. The main risk is that a 5 year LEO trapped proton dose up to $\sim 5 \times 10^{10}$ p/cm² @10 MeV equivalent non-ionizing fluence under reasonable shielding levels will create sufficient displacement damage in thick silicon PIN pixels to require the baseline FPA to operate near 160-170 K. This will keep the dark current at or below the expected read noise levels on a 10 minute exposure. A custom BICMOS detector would have a much smaller thickness of silicon from which to collect dark current, and would allow the CASTOR FPA to operate at a higher temperature.

Another drawback of the hybridized detector is enhanced IPC. IPC is an effect that can occur in bump-bonded hybrid FPAs that employ a source follower pixel amplifier. IPC can result in the signal in one pixel being sensed by adjacent pixels that are capacitively coupled. IPC effect is more pronounced in fully-depleted silicon hybrid CMOS focal plane arrays than in infrared arrays because of the stronger coupling path through the silicon detector layer. IPC can degrade the image resolution and it can cause an overestimation of conversion gain (electrons per mV) determined from the conventional photon-transfer method because the IPC "blur" reduces the variance of photon noise⁵. This effectively smears a few percent of the signal from a bright pixel into its surrounding neighbours. Image processing methods have been developed on previous instruments to deconvolve IPC from data collected using HXRG detectors⁶. Good photometric accuracy can be achieved after IPC correction as long as the IPC is stable and well characterized. This is a concern because of the recent reports of significant IPC change with integrated signal levels⁷.

The trade off between BICMOS and Si PIN hybridized to CMOS that was considered in the original study¹ was ultimately tilted in favour of the Teledyne H4RG-10 due to its maturity, familiarity, and the fact that an appropriate SiC package was undergoing flight qualification.

3.3 Silicon surface treatments

Another driver for future astronomical applications is the quantum efficiency, especially at the shortest wavelengths. Driven in part by semiconductor fabrication requirements, there has been excellent progress in optimizing the short wavelength quantum efficiency of silicon detectors. Work will be needed to determine the best type of surface treatments to use that would maximize NUV response. A standard option is to use photon down-conversion through scintillating coatings such as sodium salicylate, or Lumogen, but this results in >50% of the photons being lost to scattering at the focal plane.

Energetic ion-assisted hard coating processes used in typical AR-coatings tend to create surface defects in crystalline silicon. Care must be taken in developing reliable methods of applying robust anti-reflection coatings to back-thinned silicon detectors without creating a high concentration of surface defects that might serve as recombination centres for photo-generated electron-hole pairs⁸. A couple of European companies have been developing back-thinning and surface passivation methods for large format NUV BICMOS detectors for the proposed ESA Solar Orbiter mission^{9,10}. JPL has developed a well-demonstrated molecular beam epitaxial process called δ -doping that has already moved from the laboratory into some commercial foundries. Figure 2 shows the improvements associated with this advancement, described as follows:

"Delta-doped CCDs were developed at the Microdevices Laboratory at the Jet Propulsion Laboratory in 1992. Using molecular beam epitaxy, fully-processed thinned CCDs are modified for UV enhancement by growing 2.5 nm of Boron-doped silicon on the back surface. Named delta-doped CCDs because of the sharply-spiked dopant profile in the thin epitaxial layer, these devices exhibit stable and uniform 100% internal quantum efficiency without hysteresis in the visible and ultraviolet regions of the spectrum."¹¹

Other manufacturers have developed similar proprietary UV sensitizing processes with varying levels of demonstrated success and stability.

UV photons having more than twice the silicon bandgap energy have a chance of creating multiple electron/hole pairs on absorption. While this increases the detectability of a faint source above the noise floor, this process also increases the photometric noise by significantly increasing the variance in gain. This implies two separate methods of quantifying QE. Detective QE (DQE) is the fraction of incoming photons detected, whereas Responsive QE (RQE) is the ratio of

collected charge carriers to the number of incoming photons. RQE is always larger than DQE in the UV where photons have sufficient energy to excite multiple charge carriers.

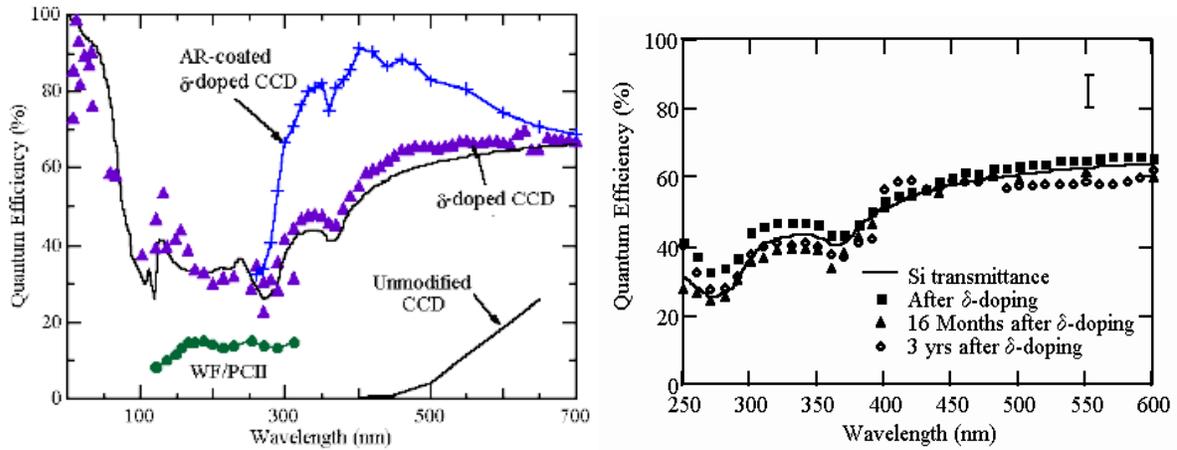


Figure 2 Typical QE levels of delta-doped silicon back-illuminated detectors¹¹

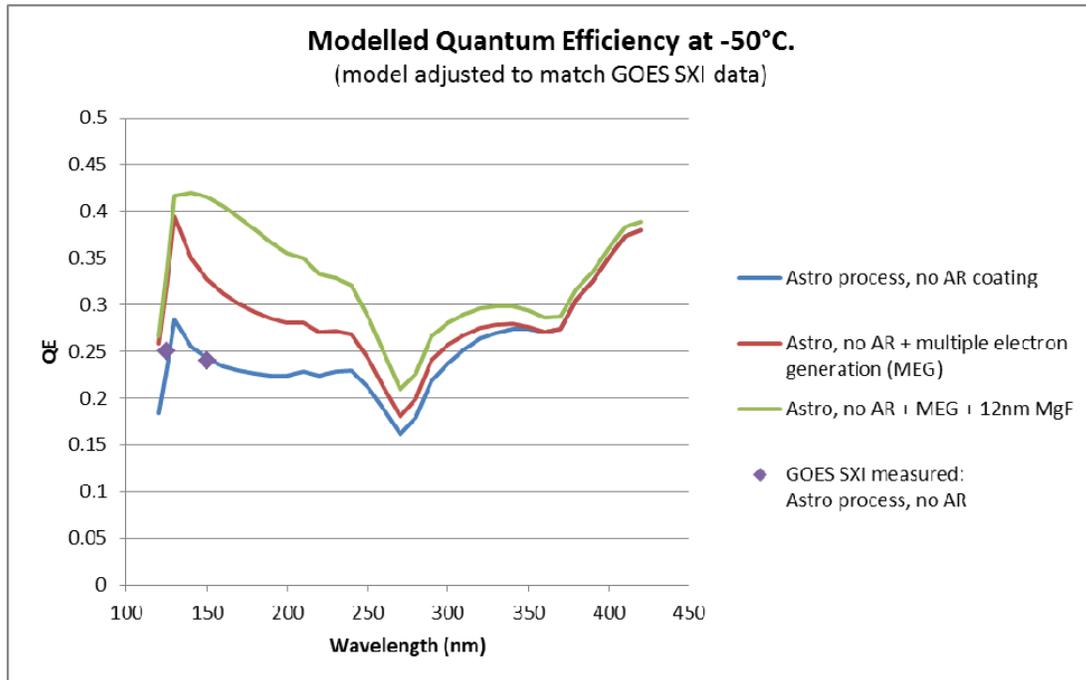


Figure 3 e2v back-illuminated silicon detector performance predictions with GOES SXI data points[†]

E2v have demonstrated a response on back-illuminated, uncoated CMOS devices down to 120 nm in the vacuum ultraviolet as shown in Figure 3. JPL has done similar work as shown in Figure 4. There is a strong linkage between coating technology and the survey strategy. Since silicon detector coatings cannot offer optimum QE over all three bands simultaneously we have settled on a focal plane layout with fixed spectral bands applied to each detector. This eliminates the need for a large filter wheel, and improves overall system reliability and throughput. It should be noted,

[†] e2v private communication 2014.

however, that although the sensitivity is good with these simple coatings, they provide little blocking of the red leak. Additional multi-layer coatings are required to block the rest of the silicon waveband to the required levels.

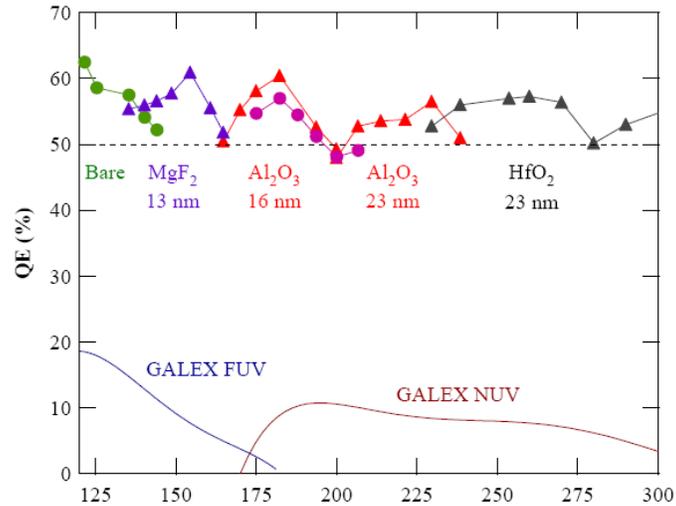


Figure 4 State-of-the-art in single layer UV AR coatings for silicon¹²

3.4 Packaging

The sheer size of the proposed CASTOR focal plane array poses a packaging challenge, although observatories with 4-side butttable packages have already reached the Gigapixel mark (eg. Gaia). The telescope and FPA structure will be manufactured from silicon carbide to provide a lightweight optical system that is structurally and thermally stable. Qualifying a custom package for a space mission can be a long and costly undertaking. A packaged pre-qualified SiC FPA from an international partner could be an enabling contribution for the CASTOR mission.

For the original mission concept study the detector baseline was a 9 x 5 array of H4RG-10 HyVisI (Si PIN/CMOS) from Teledyne, arranged in three spectral bands of 3 x 5 FPAs. These FPAs consist of 4096 x 4096 pixels at a pitch of 10 μm in 4-side butttable SiC packages. This is important for minimizing the gaps between nearby arrays in the FPA. The design allows for <3 mm gaps between active areas of subsequent arrays on 3 sides and <8 mm gap on the fourth bondpad side. These detectors are very similar in their readout characteristics to H2RG devices tested by COM DEV and incorporated into the JWST Guider and NIRISS instruments. The baseline FPA has already been built and space qualified to TRL6 for the NRL Joint Milli-Arcsecond Pathfinder Survey (J-MAPS), recently cancelled¹³. These detectors had been selected as the baseline due to their high TRL, space-qualified status, and mission criticality. Other packaging material options with similar thermo-mechanical properties, such as the Invar package currently being developed by e2v for TAOS, could be an option if detailed thermal analysis show promise.

3.5 State-of-the-art Assessment

We have selected appropriate FPA technologies in consultation with experienced high performance detector manufacturers, as the basis of this assessment. From e2v we have selected a BICMOS FPA similar to the TAOS II¹⁴ or CIS113¹⁵. From Sarnoff (SRI) we have selected their Mk x Nk expandable BICMOS technology¹⁶ similar to the SoloHi detector¹⁷. From Raytheon we have selected a custom silicon PIN direct-bonded hybrid¹⁸. The Teledyne RSC option is the H4RG-10 HyVisI¹⁹. A notional custom large format BICCD development is also included for comparison.

Key custom manufacturing processes that impact detector performance include:

- Back-thinning/ PIN hybridization
- Delta doping/UV sensitization
- Multi-layer dielectric AR-coating

Our investigations show that most manufacturers have processes available in-house for back-thinning their silicon FPAs, or else a process arrangement in place with a subcontractor. There are multiple independent sources of back-illuminated surface sensitization available, including JPL MBE δ -doping; Mike Lesser (U Arizona) chemisorption process; SRI patented flash gate process; Teledyne RSC in-house thinning process; e2v astronomy process. The qualification levels and NUV QE achieved by these processes are still under investigation.

Table 2 provides a comparison of proposed solutions for the CASTOR mission from leading detector manufacturers. Green squares indicate the best options, yellow squares indicate areas of concern, and red squares indicate areas of serious concern for the CASTOR mission.

The comparison provided in the end of life (EOL) dark current column of Table 2 is somewhat speculative, and is based on the universal response of silicon to the expected proton environment in a LEO orbit (see Section 3). All else being equal, the volume of depleted silicon that accumulates proton-induced displacement damage will be directly proportional to the end of life dark current at any fixed temperature. The Teledyne H4RG HyVisI requires about 10x more thickness of silicon than the other options, due to the pressure that is applied to the wafer during Indium bump bonding. This corresponds to an operating temperature penalty of about 10 Kelvin. The other impact on EOL dark current is surface related dark current from ionizing radiation damage at the silicon/oxide interface. This can be mitigated somewhat in the design of the pixel, but we do not have data on this aspect of detector performance.

Table 2: Detector types comparative analysis

Detector Type	ROE	# of Det	TRL UV	TRL Det	TRL Pkg	IPC	Sub-window	Up-ramp Sampling	Read Noise	EOL I_{dark}^{\ddagger}
E2V BICMOS TAOS II	Custom analog LVDS	36	5 ^{††}	4 [§]	4 ^{**}	None	Yes	Yes	~5 e-	
Teledyne H4RG HyVisI	JWST re-use	45	5 ^{††}	6	5 ^{††}	~5%	Yes	Yes	~10 e-	
Raytheon PIN hybrid	Custom analog LVDS ^{§§}	6 or 18	2	5	4	None	Yes	Yes	~5 e-	
SRI Mk x Nk	JWST re-use	12	2	4	2	None	Yes (by row)	Yes	<6 e-	
BICCD	Custom analog CCD	45	2	4	2	None	No	Not needed	<1.5 e-	

4. SUMMARY

Based on the comparison provided, it appears that there are multiple silicon detector candidates that could address the needs of the CASTOR mission. The best characterized UV sensitization process is molecular beam δ -doping available at JPL. A collaboration between JPL and one of the detector manufacturers would also provide a strong option for the CASTOR mission FPA. A comparative study assessing the NUV-band sensitivity of the various manufacturer processes with test diodes would also be useful. A significant advantage would be gained by a manufacturer with a demonstrated ability to deposit a 'solar-blind' NUV bandpass coating directly onto the silicon.

[†] Based on volume of radiation-sensitive active silicon assuming surface dark currents are minimized by design

[§] Expect TRL 5 by the fall

^{**} Current package is Invar vs. SiC

^{††} The internal QE of the Teledyne and e2v UV processes across the NUV band are under investigation.

^{†††} J-MAPS package may require adaptation to the larger CASTOR FPA

^{§§} Custom digital is available, but has unacceptable read noise

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