Radiation Tolerant, Photon Counting, Visible and Near-IR Detectors for Space Coronagraphs and Starshades

A Sub-Package within the Exoplanet Spectroscopy Technologies Work Package

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7 November 2019 (Rev. 4)

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1 Objective

This project is a sub-package within the Exoplanet Spectroscopy Technologies Work Package at NASA Goddard Space Flight Center.[*] Its purpose is to enhance the technology readiness of photon counting, radiation tolerant, visible and near-IR (VISIR)[†] detectors for spectroscopic biosignature characterization using space coronagraphs and/or starshades. To accomplish this, we focus on adding photon counting outputs to Lawrence Berkeley National Laboratory's (LBNL) thick, fully depleted, p-channel CCDs. The underlying p-channel CCDs are known to be radiation tolerant from a previous Technology Readiness Level (TRL) 6 demonstration for the Department of Energy's (DoE) SuperNova Acceleration Probe (SNAP) Dark Energy mission concept.[1] The photon counting outputs optimized for space coronagraphs and low background astrophysics are new.

To these ends, we have defined three years of work that culminate in the Technology Milestones that are defined in § 4. In a previous version of this document, we interpreted the word "Milestone" as it would be used when discussing a Gantt Chart: *i.e.* the zero-duration endpoint of a task. With this revision, we break the Technology Milestones out separately from the tasks. Roughly speaking, work will proceed as follows.

- Year 1. <u>Test</u> existing Hole Multiplying Charge Coupled Devices (HMCCD; see § 2.4.6) with reference to peer reviewed[‡] performance requirements for spectroscopic biosignature characterization. We will develop the requirements as part of this project. This will define the TRL of existing Gen-IV HMCCDs.
- Year 2. <u>Design and build</u> new CCDs. These may include improved HMCCDs and/or "Skipper" (see § 2.4.7) CCDs with enhancements to better adapt the readout times to space.
- Year 3. <u>Test</u> all new CCD designs against the same requirements as before and document any improvement and/or advances in TRL.

Upon fully successful completion of this project, there will exist at least one VISIR detector technology for space coronagraphs and/or starshades that: *i*) is expected to be inherently radiation tolerant, *ii*) has been demonstrated to count individual photons, and *iii*) has a path to an operational concept consistent with space use. Broadly speaking, we are aiming to mature at least one inherently radiation tolerant, photon counting, VISIR CCD to TRL-4. If either technology

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[†] See Appendix A for a List of Acronyms

[‡] Here the phrase "peer review" refers to an informal review within the broader Exoplanet Spectroscopy Technologies Work Package team. Although we are authors on some of the journal articles that are establishing these requirements,[4,10] we do not plan to write a new journal article specifically describing detector performance requirements as part of this sub-package.

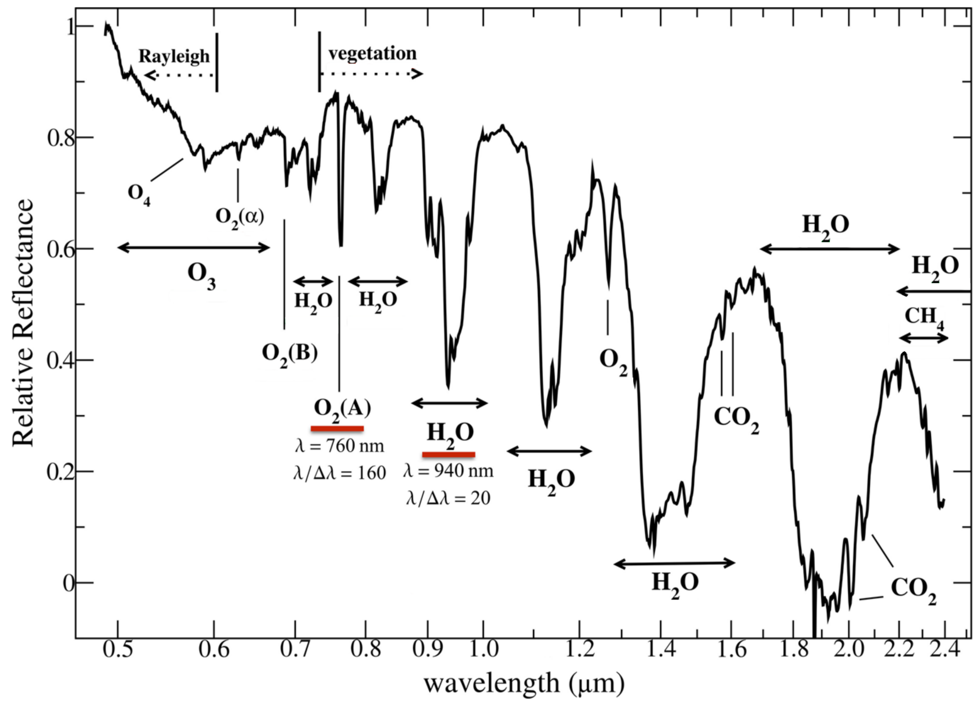


Figure 1. Earth seen as an exoplanet. To make this figure, Turnbull et al. (2006) observed the night side of the moon. Then, using knowledge of the solar spectrum, lunar surface reflectance, and Earth's atmospheric transmission, they modeled the earth's reflectance spectrum. Biosignatures are atmospheric spectral features that are thought to be necessary for life or that can be caused by it. For LUVOIR and HabEx, the 940 nm H_20 and 760 nm O_2 features are particularly important. Credit: Based on Figure 7 of Turnbull et al. (2006) and Figure 1 of Rauscher et al. (2016).

is successful, this project will have fulfilled its objectives. The interested reader is referred to Appendix B for a more detailed description of the exit criteria from TRL-3 to TRL-4 in the context of VISIR detectors.

This project is a partnership with DoE groups to build new detectors for NASA astrophysics, DoE Quantum Information research, and a DoE Dark Energy detection experiment. Prior to selection, we were asked by NASA Headquarters (HQ) to reduce the cost by 15%. To comply with this request, we had to eliminate the CCD design cycle and silicon foundry run that was needed to build new CCDs to our requirements. By partnering with DoE, NASA and DoE together have sufficient funds to pay for at least one design cycle with foundry run (and possibly two within the three year period of performance). However, being a partnership, NASA does not uniquely control the design/fabrication cycle, including its specific timing and contents. Nevertheless, because there is substantial overlap in the requirements for these three applications, we are confident that this partnership provides excellent value to NASA.

2 Introduction/Background

2.1 Scientific Context

After finding a promising exoEarth candidate, future space missions will use biosignature characterization to study the planet's potential habitability. Biosignatures are atmospheric spectral features that are thought to indicate the possible presence of life.[2] Figure 1 shows the VISIR spectrum of the earth as it would appear to an observer located in a distant star system.[3,4] Important biosignatures for the NASA Large UV-Optical-IR (LUVOIR)[5] and Habitable Exoplanet Imaging Mission (HabEx)[6] mission concepts include H_2O at $\lambda = 940$ nm and O_2 at $\lambda = 760$ nm.

H_2O is required for life (as we know it), and the 940 nm H_2O feature is deep and wide, making it comparatively easy to detect with a detector having sufficiently high near-IR QE. The O_2 line is important because, together with other information, it can indicate the presence of life. The interested reader is referred to Rauscher *et al.* (2016)[4] and references therein for more information on these specific biosignatures and an introduction to the extensive literature on this topic.

Table 1.
Stark et al.'s Yield Model Assumptions[a]

Parameter	Value	Comment
Pixel size[a]	15 μm	Practical size for coupling to optics
Format[a]	> 1024×1024 pix^2	Desirable for integral field spectroscopy
Operating temperature[a]	> 30 K	Passive cooling desired
Dark current	< 3×10^{-5} e^- pix^{-1} s^{-1}	
Read noise	Zero	
τ_{read}^{b}	<= 20 s	Limited by cosmic ray disturbance
τ_{pix}^{a}	< 1.2 ms	See § 2.4.5
CIC	< 1.3×10^{-3} e^- pix^{-1} frame^{-1}	Clock induced charge
QE	> 90%	

[a] *These demanding model assumptions reflect what theorists assume the detectors will meet upon reaching TRL-6. Some are well beyond where the detectors are today (TRL-3 demonstration in progress) and are provided as an indication to what will eventually be required.*
[b] Addition to Stark et al.'s model assumptions

Even with large telescopes, biosignature characterization is photon starved. The 760 nm O_2 line is particularly challenging because optimal detection requires spectral resolution matched to the line width, *i.e.* $R \stackrel{\text{def}}{=} \lambda/\Delta\lambda > 100$. At this resolution, even with an 8-m class space telescope, the photon arrival rate is only a few photons per hour per pixel (if using dispersive optics).

For these reasons, photon counting detectors with excellent near-IR QE and negligible false count rates are highly desirable. For use in space, the detectors must be radiation tolerant and capable of being read out sufficiently quickly (see § 2.4.5) that cosmic rays corrupt only a small percentage of pixels. Finally, the LUVOIR Team strongly desires the detector to operate at temperatures, T > 30 K, that are compatible with passive cooling.

2.2 Performance Needs for Exoplanet Spectroscopy

In recent years, several authors have studied detector performance needs for exoplanet-focused space missions. These include Bolcar *et al.*[7,8], who describe technology requirements for LUVOIR-like missions and Wang *et al.*[9], who describe requirements for HabEx-like (and LUVOIR) missions from a science perspective. Rauscher *et al.*[4] provide an overview of potential detector technologies, including superconducting detectors, and the associated cooling systems. More recently, Stark *et al.*[10] discuss detector needs in the context of mission yield models for coronagraph and starshade mission concepts.

For biosignature characterization, all of these authors concluded that essentially noiseless detectors are required. For purposes of this Sub-Package, we take Stark *et al.'s* model assumptions (Table 1) to be indicative of the desired performance in the VISIR. Although some of Stark *et al.'s* assumptions may prove to be unpractical in real devices (*e.g.* > 90% QE at all wavelengths), they are indicative of the level of performance that is being built into mission exoplanet yield models today.

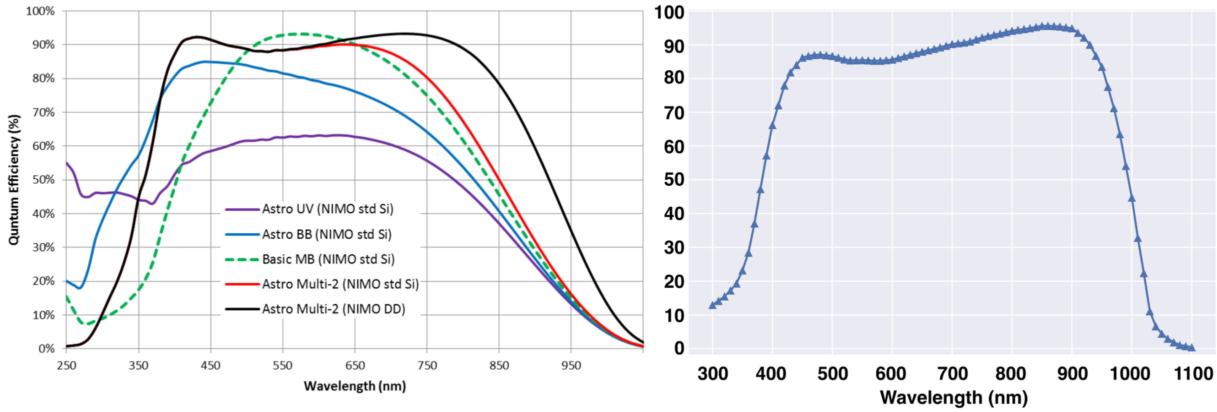
2.3 Today's Choice: The EMCCD

Today's leading detector for space coronagraphs is Teledyne-*e2v*'s Electron Multiplying CCD (EMCCD). Harding *et al.* (2016)[11] describe the comprehensive detector trade study that was done before selecting the EMCCD for the WFIRST coronagraph. This thorough study included seven specific detector models drawn from four competing technologies (CCD, EMCCD, hybrid CMOS, and monolithic CMOS). It included simulations of the comparative scientific yields, assessments of the relative TRL, and an assessment of the detector risks and opportunities. Compared to the competing detector technologies at the time, only the EMCCD offered read noise $\ll 1\ e^-$, as is required for photon counting.

The EMCCD achieves deeply sub-electron read noise by multiplying charge packets before they reach the output amplifier. This is done by using high voltage to achieve a small amount of impact ionization gain during each serial charge transfer in a specialized charge multiplier (CM; this is our term, not *e2v*'s).[12,13] Although the impact ionization gain from any one transfer is very small, when several hundred or more transfers are cascaded, multiplication gains sufficient to overwhelm the output amplifier's read noise and count individual photons are achieved.

By virtue of ongoing development for the *WFIRST* coronagraph, EMCCDs are TRL-6 for WFIRST today.[§] However, they are not necessarily ideal detectors for future strategic missions such as

[§] VISIR detectors are often considered to be TRL-5 upon meeting the required scientific performance requirements for the intended application (read noise, dark current, QE, pixel format, etc.). They are often considered to be TRL-6 upon successful completion of environmental testing, including especially radiation testing. If a future mission concept like LUVOIR or HabEx were to have more challenging performance requirements than WFIRST's coronagraph, than EMCCDs would not necessarily be TRL-6 for that application.



a) Advertised QE of some Teledyne-e2v CCDs *b) Measured QE of a recent LBNL CCD*

Figure 2. This figure shows: (a) the advertised QE curves for some Teledyne-e2v's CCD design variants and (b) the measured QE of a recent 250 µm thick, fully depleted, LBNL p-channel CCD. The LBNL CCD achieved about 84% QE at the scientifically important 940 nm H_2O feature. To achieve low dark current, the Teledyne-e2v CCDs were operated at about -100℃ while the LBNL CCD was operated at -135℃. Credit: Panel a is reproduced (with only the legend position moved) from Teledyne-e2v's website: https://www.teledyne-e2v.com/content/uploads/2014/02/QE-curve-100.png. Panel b is based on Figure 4 of Bebek et al. (2017).

LUVOIR or HabEx. For future missions, the biggest challenges are arguably radiation tolerance and near-IR QE.

2.3.1 Radiation Tolerance

Harding *et al.* (2016)[11] provide a thorough discussion of proton irradiation damage mechanisms, effects, and mitigations in EMCCDs. For astronomy, charge transfer efficiency (CTE) degradation is particularly important. It manifests as charge trailing when astronomical images are read out. CTE degradation is mediated by charge traps in the CCD channels. The silicon in n-channel CCDs, including EMCCDs, is doped with phosphorous. Unfortunately, phosphorous doped silicon does not interact well with proton irradiation.

The CTE degradation mechanism is therefore that protons damage the silicon, creating electrically active charge traps. The newly created traps capture charge as it passes, only to release it a little while later into trailing pixels. Unfortunately, there is nothing that can be done to fix the traps once they have been created. Although the effects can be mitigated somewhat using techniques including a pre-flash before readout,[14] these mitigations are generally incompatible with the modes of operation that would be used in an exoplanet spectrograph.

When energetic protons interact with phosphorous doped silicon, phosphorous displacement vacancies are formed. Falling about 0.46 eV above the valence band (*i.e.* near the middle of the bandgap), the phosphorous displacement vacancy complex tends to be particularly troublesome. Fortunately, the WFIRST Project is already implementing and testing several EMCCD design modifications to mitigate the effects of radiation damage. However, none of WFIRST's planned mitigations actually removes the phosphorous from the channels. As such, there is a risk that the resulting EMCCDs may meet WFIRST requirements, but still fail to meet the more stringent science requirements of a LUVOIR or HabE*x* -especially after a few years of radiation damage on orbit.

LBNL's p-channel CCDs address the radiation tolerance issue by using boron as the channel dopant instead of phosphorous. Although boron doped silicon still degrades somewhat under proton irradiation, the adverse effects are significantly less pronounced than in phosphorous doped silicon.

2.3.2 Quantum Efficiency

The < 50% QE of EMCCDs near the 940 nm H_2O feature is also challenging. Figure 2a shows the advertised QE of some Teledyne-*e2v* CCDs and EMCCDs. For comparison, we also show (Figure 2b) the QE of a recent 250 µm thick LBNL p-channel CCD.[15] Due in part to its comparatively thicker silicon, the LBNL CCD achieves about 84% QE at this wavelength.

With regard to better radiation tolerance and near-IR QE, our efforts complement the ongoing *WFIRST* EMCCD work by focusing on LBNL's thick, fully depleted, p-channel devices.

2.4 Photon Counting, Thick, Fully Depleted P-Channel CCDs

All of the CCDs (HMCCDs and Skippers) that we are building and testing are thick, fully depleted p-channel devices. The thick silicon gives them excellent QE for the scientifically important 940 nm H_20 feature. The p-channel architecture makes them inherently more radiation tolerant than comparable EMCCDs.

2.4.1 Current State of the Art

Both HMCCDs and Skippers leverage LBNL's approximately 20 year heritage building thick, fully depleted, p-channel CCDs for ground and space. The underlying p-channel CCD architecture that completely determines the photonic interaction is already TRL-6 by virtue of prior development for SNAP.[1] Moreover, p-channel CCDs are understood to be inherently more radiation tolerant than n-channel CCDs including EMCCDs.[16–19]

Table 2 summarizes the performance requirements that LBNL is delivering to for the ground based Dark Energy Spectroscopic Instrument (DESI).[20] These represent essentially the state of the art for LBNL CCDs with conventional outputs. The DESI CCDs were not designed for photon counting. They therefore have four conventional output amplifiers rather than the new output configurations that are being developed here. Apart from read noise, most other parameters (pixel size, QE, *etc*) are broadly consistent with what we aim to achieve. Although today's dark current (Table 2) is still high compared to what is desired (Table 1), we plan to explore deep cooling as a way to improve on today's state of the art. By building on the strong foundation afforded by LBNL's TRL-6 p-channel CCDs, this project can focus on photon counting with confidence that most other performance parameters can be made acceptable.

Table 2. DESI CCD Requirements

Parameter	Specification	Comment
Format		
Pixel size	15 µm	
Pixel count	≥ 4096 × 4096	
Readout channels	4	
Photonic		
Dark current	< 10 e^-/pix/hr	
Read noise	< 3 e^-	At 100 kpix/sec; See 2
Full well	> 75,000 e^-	3% Linearity deviation
Non-Linearity	< 1%	From 200 e- to 75% full
Charge transfer efficiency		
Parallel	> 0.99999	
Serial	> 0.99999	
Quantum efficiency		
360 – 400 nm	> 75%	
400 – 600 nm	> 85%	
600 – 900 nm	> 85%	
900 – 980 nm	> 60%	
Lateral diffusion		
rms at surface	< 5 µm	
Cosmetics		
Column defects	< 10 max	black or white
White spots	< 800 max	
Total (black and white) spots	< 1500 max	
Traps > 200 e^-	< 15 max	
Flatness		
Blue channel	< 20 µm P-P	
Red and NIR channel	< 15 µm P-P	
Metrology		
Corner pixels location knowledge	± 50 µm	

[1]Photon counting not required, conventional CCD outputs
[2]Read noise = 1.2 e^- has been achieved. See Bebek *et al.* (2017)

In this project, we plan to explore two complementary output amplifier architectures that aim to make LBNL's CCDs function as nearly ideal photon counters. These are the HMCCD (§ 2.4.6) and Skipper (§ 2.4.7).

2.4.2 Recent Design Improvements

Recently, LBNL tested two design improvements for DESI that pay dividends here. These are a lower noise "buried contact" output amplifier and an improved 3-layer AR coating. Bebek *et al.* (2017)[9] describe these developments.

The buried-contact amplifier reduces the read noise from about 3 e^- rms at 100 kHz to roughly 1.2 e^- rms. The noise reduction is accomplished because the buried contact design enables use of a smaller floating-diffusion area, reduced output-transistor width, and eliminates additional area needed to accommodate the metal contact (and its spacing to the edge of the implanted region). The net effect is to significantly reduce the input capacitance, thereby increasing the transimpedance gain and reducing the readout noise.

2.4.3 Road to Photon Counting P-Channel CCDs

As part of this project, and building on the buried contact amplifier, we are exploring two potential paths to achieving deeply sub-electron read noise and photon counting. These are:

1) Hole multiplication analogous to the electron multiplication in an EMCCD yielding the Hole Multiplying CCD (HMCCD), and
2) "Skipper" readout using multiple non-destructive reads.

HMCCD and Skipper are two compatible output architectures for p-channel CCDs. The HMCCD multiplies charge packets before they reach the output amplifier with the aim of overwhelming readout noise. In contrast, Skipper uses multiple non-destructive reads with the aim of averaging the readout noise down to $\ll 1\ e^-$. The HMCCD and Skipper use compatible design processes. As such, both can be combined in the same production lot, thereby providing two very different ways of achieving deeply sub-electron read noise.

Throughout this document, we follow the established practice in astronomy of reporting read noise in electrons, even though it is actually holes that are collected and multiplied in p-channel CCDs. If either the HMCCD or the Skipper achieves $\sigma_{rd} \ll 1\ e^-$, and thereby photon counting, while comprehensively meeting the other requirements, then this project will have been successful.

2.4.4 Specific Design Variants and Risks

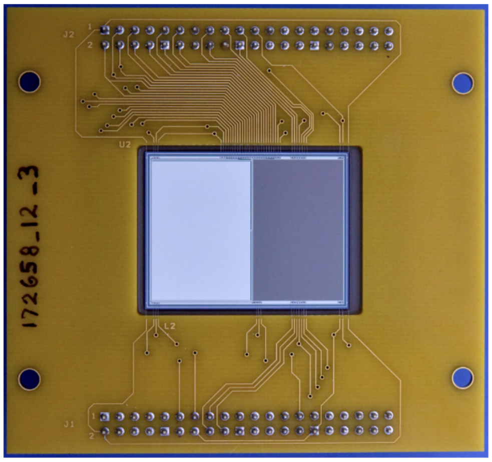
We plan to test existing Gen-IV and Gen-V HMCCDs during the first approximately eighteen months of the project. The main change between Gen-IV and Gen-V is going from 1,444 gain stages to 2,268 gain stages. The aim is to be able to achieve the same gain as before, but using lower voltage. The only changes made to the gain stages were those needed to package them onto the die. The main risk is that the Gen-V HMCCDs many not function for some TBD reason. In this case, the mitigation is to proceed with Plan B, Skipper testing.

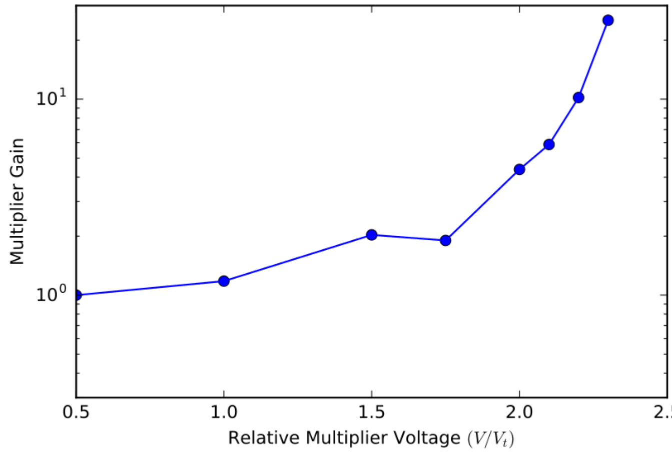
In comparison to the Skippers that were used by Tiffenberg *et al.* (2017),[21] The new skippers will have 16 output amplifiers instead of 4. There will also be Skipper CCDs with the low noise (buried contact) DESI output amplifier. Finally, there will also be a version that has *n* (TBD) amplifiers in series to further reduce the readout time. Broadly speaking, by these design changes we are aiming to reduce the readout time by a factor of about 1/8x compared to Tiffenberg *et al*.

For the new Skippers, the risks are the same as for any foundry run using a new design. We may not yield as expected, or the newly fabricated parts might reveal a design problem that was not identified at the design stage. If this risk were to materialize, we would work with our DoE partners to arrange another foundry run. By pooling our resources, we believe it is likely that we could afford another foundry run in this unfortunate situation.

2.4.5 Exposure Time Limit for Thick CCDs

Cosmic rays limit the maximum useful exposure time for thick CCDs. As protons pass through the CCD, they leave approximately linear tracks of corrupted pixels in their wake. To a first approximation, one would expect the number of corrupted pixels to scale linearly with CCD thickness. At the Sun-Earth L2 point, the underlying galactic cosmic ray (GCR) rate is about





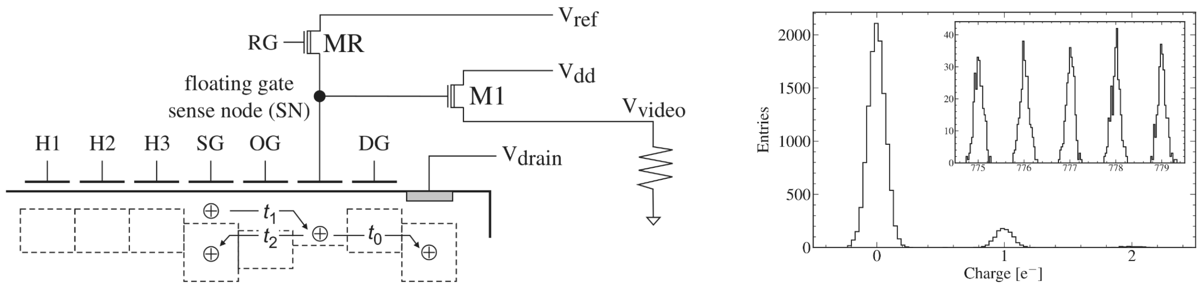
a) Gen-IV HMCCD *b) Best (Gen-IV) HMCCD gain so far*

Figure 3. This Gen-IV frame transfer HMCCD has 512×1024 imaging pixels. These appear in the dark gray area to the right of the centerline. The shiny area to the left of the centerline is a metal mask. We currently have four (improved) Gen-V HMCCDs in the queue for testing at Goddard. The Gen-V HMCCDs are also frame transfer. They have a larger 1024×1622 pixel imaging area with 1361 gain stages. Panel b) shows the best hole multiplication gain that has been achieved so far by an older Gen-IV part. When used with the $\sim 1\ e^-$ read noise amplifier (see Bebek et al. 2017), multiplication gain $\gtrsim 10\ e^-$ should be sufficient to achieve photon counting.

5 ions $cm^{-2}\ s^{-1}$.[16] As the primary cosmic rays pass through the instrument shielding, they produce secondary electrons that can also disturb the detectors. For requirement development purposes, we therefore assume a total disturbance rate, GCR plus secondaries, = 10 $cm^{-2}\ s^{-1}$.

To bound the problem, we did a Monte Carlo simulation of cosmic rays striking a 250 µm thick LBNL CCD having $(15\ \mu m)^2$ pixels. The simulation included protons striking at random locations and random angles. Any pixel that a proton passed through was flagged as corrupted. For our requirement, we assume that it is acceptable for 10% of the pixels to be affected. From the Monte Carlo simulation, the maximum tolerable exposure time is, $\tau_{\rm read} \leq 20$s. This requirement applies to both HMCCDs and Skippers. For Skippers, we furthermore impose $\tau_{\rm pix} < 1.2$ ms, the maximum tolerable pixel dwell time that allows readout of the full 1024×1024 pixel image area within the allowed exposure time using up to 64 video channels.

If a larger image area were to be required, then there is a new Goddard concept for Skipper-like CCDs that would approximately halve the readout time. We have dubbed this new concept "hopper".[22] Depending on the interests of our DoE partners, it may or may not be possible to build hoppers as part of this project, although doing so is not currently planned and would constitute an increase in scope.



a) Skipper Operational Concept *b) Cleanly resolved charge packets*

Figure 4. a) A Skipper CCD uses multiple non-destructive samples to average down the read noise. Phases H1, H2, and H3 are normal CCD clock phases. In operation, the Skipper repeatedly shuffles charge packets between the FGA's sense node (SN) and SG, all the while acquiring correlated double samples. After many non-destructive correlated double samples, charge can be dumped using the dump gate (DG). b) As described by Tiffenberg et al. (2017), existing p-channel skippers are capable of cleanly resolving individual charge packets if read out sufficiently slowly. Credit: This figure (panels a and b) is reproduced from Tiffenberg et al. (2017).

2.4.6 HMCCD

An HMCCD (Figure 3) functions like an EMCCD, although holes are multiplied rather than electrons. Compared to an EMCCD, the HMCCD aims to accomplish two important things: (1) significantly increased radiation tolerance and (2) enhanced near-IR sensitivity for important spectral features including the 940 nm H_2O line.

The HMCCD concept was born in about 2006, shortly after Rauscher and Goddard DCL colleagues demonstrated single electron counting with an EMCCD.[23] Although we understood that the EMCCD showed excellent promise as a low-light level photon counter, we realized that the underlying n-channel CCD architecture would degrade in the space radiation environment. Moreover, it was clear that the near-IR contained several important spectral features for exoplanet studies, and that better near-IR QE was therefore desirable. For these reasons, Rauscher called Holland to enquire about the possibility of making HMCCDs.

The first HMCCD, which was made shortly thereafter, failed to function. However, leveraging internal NASA Goddard, internal DoE, and other funds, Holland continued development until the first working HMCCDs were made circa 2014 (the HMCCD shown in Figure 3 is from this generation).[24] These HMCCDs have achieved impact ionization gains of 10-20x, which would be adequate for counting photons if coupled with the ultra-low noise buried contact amplifier that is described in § 2.4.2.

2.4.7 Skipper

A Skipper CCD (Figure 4) uses a floating gate amplifier (FGA) in a specific way to enable multiple non-destructive sampling of charge packets, and thereby deeply sub-electron read noise. David

D. Wen of Fairchild Research and Development Laboratories published the first descriptions of a CCD floating gate amplifier that we are aware of in 1973 and 1974 (although Wen's focus was not astronomy).[25,26] In his 1973 paper, Wen credits J.M. Early with developing the "basic concept". The initial idea required clocking a charge packet through multiple sequential floating gate amplifiers to accomplish multiple non-destructive correlated double sampling.

In the early 1990s, Janesick and others associated with NASA's JPL revisited FGAs for astronomical CCDs.[27–29] In 1993, Janesick patented the modern Skipper concept that uses a single FGA per output.[27] However, the read noise of the early devices unfortunately bottomed out at around 0.5 e^- rms per pixel, which is not low enough for exoplanet spectroscopy.

The LBNL p-channel Skipper is an outgrowth of the earlier Goddard-DoE HMCCD development. Co-I Holland was interested in screening out large charge packets before feeding them into the hole multiplier. His idea was that we could non-destructively sample each charge packet prior to multiplication, and discard those that were undesirably large. Once Holland had implemented the FGA structure in an LBNL p-channel CCD, its use for ultra-low noise readout came about naturally. Compared to the comparatively noisy amplifiers that were used in the early 1990s, today's CCD amplifiers are capable of achieving deeply sub-electron read noise in the p-channel Skipper.

Today's state-of-the-art Skipper read noise, σ_{rd} = 0.068 e^- rms/pixel (see also Figure 4b), was achieved by our DoE partners at FermiLab.[21] In 2017, a FermiLab group demonstrated deeply sub-electron read noise using a thick, fully depleted LBNL p-channel CCD with Skipper outputs.[21]

3 Work Plan

Work focuses on testing, designing, building, and re-testing thick fully depleted p-channel CCDs with two or more output amplifier designs for photon counting. All detailed performance characterization of photon counting p-channel CCDs for astronomy will be done in the Goddard DCL. Goddard will also lead development of space astronomy packages. The first CCDs will be designed at LBNL, fabricated at Teledyne DALSA and LBNL, packaged at LBNL, and sent to Goddard for characterization.[**]

We originally envisioned working only with HMCCDs. The several hour readout time of then-existing Skippers (when used as photon counters) was far too long for space astrophysics. However, as described in § 1, an HQ mandated cost reduction unfortunately resulted in the elimination of the dedicated CCD design cycle that was required to make new HMCCDs starting in FY19. We subsequently recovered this design cycle, and possibly another, by partnering with DoE. Moreover, with DoE, we became aware of other groups that shared our potential interest

[**] If a second batch of CCDs is made, we will use another silicon foundry as DALSA has informed us that they will not accept new orders for the process that we require after 31 December 2019. Co-I and CCD designer Steve Holland is already in discussion with two foundries that have compatible processes. These are Microtek and Tower-JAZZ.

in greatly reducing the readout time of Skippers. Moving forward, we now plan to make both reduced readout time Skippers and HMCCDs.

One benefit of partnering with DoE groups is that we will also be able to build and test Skipper p-channel CCDs. The Technology Milestones that we define in this Section adapt those that were proposed in 2018 to account for the possibility of also evaluating Skippers. By partnering with DoE on the foundry run, we save sufficient funds to pay for the additional testing and analysis, and potentially an additional foundry run in years 2-3.

In order to partner with DoE, we must place the order for the first foundry run before the end of the year (*i.e.* before we will have completed evaluation of the existing HMCCDs). The immediate benefit is that we will be able to collaborate in evaluating the new Skippers in Year 2. If new HMCCDs are made, then this will happen in Year 3. The process for making HMCCDs is compatible with making Skippers.

In the following, the tasks-by-year describe the work that will be done to achieve the Technology Milestones.

3.1 Year 1 Tasks

1) Demonstrate function of Goddard high speed / high resolution electronics card. This has already been done, and the card is delivering clean clocks with the intended $\lesssim$ 10 ns resolution.
2) Testing to define TRL of existing HMCCDs in DCL
3) Begin design of Skipper test set
4) Begin layout of improved, faster readout, Skipper CCDs

3.2 Year 2 Task

5) Document describing baseline performance of Gen-V HMCCDs in regard to space coronagraph requirements.
6) Begin fabrication of improved, faster readout, Skipper CCDs
7) Complete modifications to DCL test setup for Skipper CCDs
8) Begin testing Skipper CCDs in DCL
9) Begin layout/design of improved HMCCDs and/or Skippers (TBC)
10) Testing to demonstrate <2 e^- read noise (goal <1 e^-) in conventional CCD mode using the ultra-low noise buried contact output (either HMCCD or Skipper).

3.3 Year 3 Tasks

11) Testing to demonstrate photon counting, *i.e.* a low light level laboratory test image in photon counting mode that substantially has Poisson noise statistics.
12) Integrate detector characterization results into the cross-package integrated model analysis and evaluate design trades in terms of spectral retrieval yields.

4 Technology Milestone Definitions

We have defined three Technology Milestones that determine success for these technologies.

4.1 Technology Milestone 1 Definition

Technology Milestone 1 will occur when we document that the HMCCDs that we have in the DCL now meet the exit criteria for TRL-3. Per NPR 7123.1B Appendix E, the definition of TRL-3 is, "-Analytical and experimental critical function and/or characteristic proof-of- concept". The exit criteria for TRL-3 are, "Documented analytical/experimental results validating predictions of key parameters." The key parameters that are relevant for this project are: (1) hole multiplier gain >10x and (2) hole multiplier charge transfer efficiency (CTE) > 0.9999. Gain >10x is the minimum that we believe will be required to count photons. CTE > 0.9999 is a steppingstone toward the > 0.99999 that we believe will likely be required for biosignature characterization. We plan to first document these achievements in a Monthly Status Report submitted to the ExEP Office. We cannot claim TRL-4 at this stage of the project because this level of performance still falls significantly short of what is being assumed for mission planning purposes (*cf.* Table 1).

4.2 Technology Milestone 2 Definition

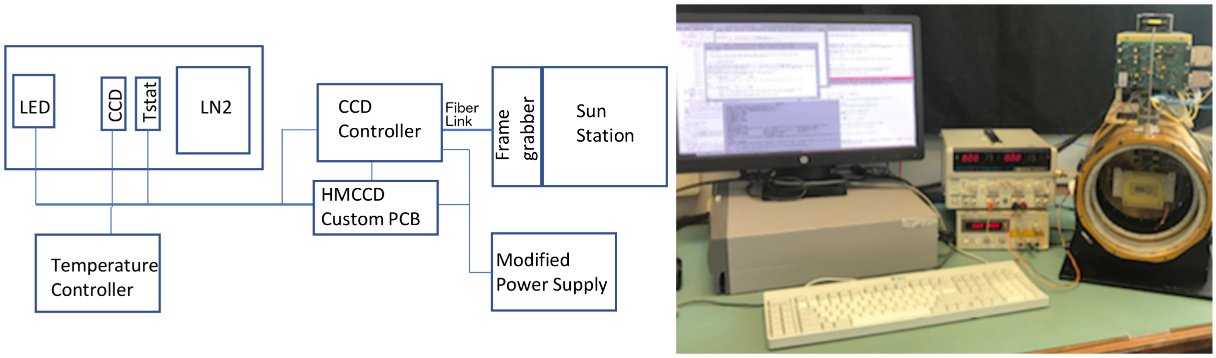
Technology Milestone 2 is documented proof that the ultra-low noise buried contact amplifier can be implemented in a p-channel CCD architecture that is, in principle, capable of photon counting. For this, we require <2 e- read noise (goal <1 e-) in conventional CCD mode using the ultra-low noise buried contact output (either HMCCD or Skipper). We plan to first document these achievements in a Monthly Status Report submitted to the ExEP Office.

For the HMCCD, the lower noise amplifier is important because it means that lower hole multiplication gain is required to count photons. The anticipated benefits include less clock induced charge and improved CTE in the multiplication register. For Skipper, the benefit is that fewer non-destructive samples are needed to achieve deeply sub-electron read noise and thereby photon counting.

Although achieving this Technology Milestone is a very important step, we do not believe that by itself it is sufficient to claim a TRL advance.

4.3 Technology Milestone 3 Definition

Technology Milestone 3 is documented proof of photon counting using either an HMCCD or Skipper. We plan to acquire a low light level laboratory test image in photon counting mode that substantially has Poisson noise statistics. This Technology Milestone is achieved if any of detector architectures does this using $\tau_{\rm pix} < 6 \text{ ms pix}^{-1}$. This value of $\tau_{\rm pix}$ is a stepping stone between the desired $\tau_{pix} < 1.2$ ms, and $\tau_{pix} = 12$ ms as used by Tiffenberg *et al.* (2017)[21] in their photon counting demonstration. We plan to first document these achievements in a Monthly Status Report submitted to the ExEP Office.



a) Block diagram *b) Test setup*

Figure 5. The a) DCL's HMCCD test system is based on a Gen-II Leach Controller (here labeled "CCD Controller"). It includes a DCL-designed printed circuit board (PCB) to generate the specialized voltages that the HMCCD requires. Panel b) shows most components, with the dewar faceplate removed so that the HMCCD is visible.

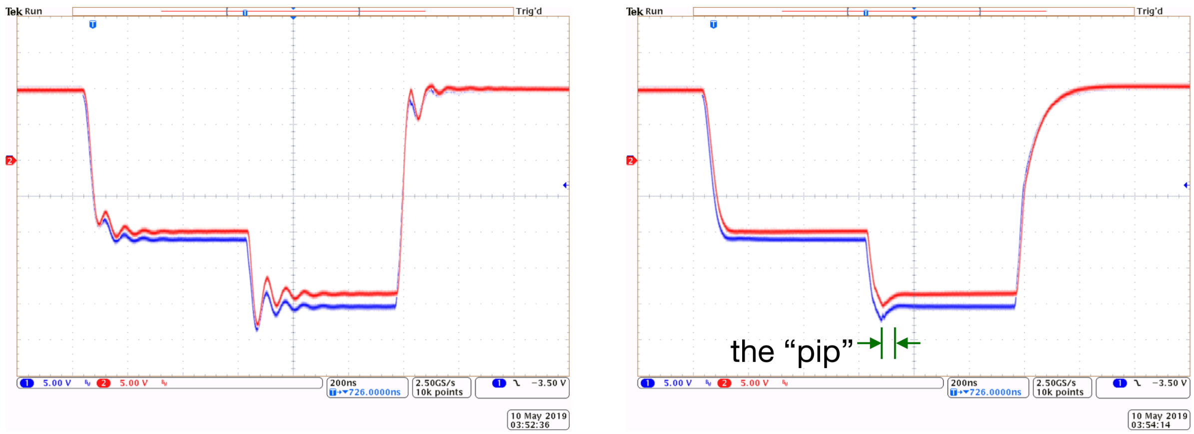
Technology Milestone 3 is important because it establishes the existence of a photon counting p-channel CCD with a readout time that is compatible with the space radiation environment. Upon completion of this Technology Milestone, one or both detector architectures will be at least TRL-4 for exoplanet spectroscopy.

Per NPR 7123.1B Appendix E, the definition of TRL-4 is, "Component and/or breadboard validation in laboratory environment." The exit criteria for TRL-4 are, "Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment." Here the critical analytic prediction is that photon counting is achievable with $\tau_{\rm pix} < 6~{\rm ms~pix}^{-1}$.

5 Experiment Description

The HMCCD test system is housed in the Goddard DCL, which is itself part of Goddard's Detector Systems Branch. The DCL provides a comprehensive suite of detector characterization services to NASA and other Government customers including flight characterization for missions such as (most recently) the *WFIRST* WFI, *Euclid*, *JWST* NIRSpec, and *HST*. The DCL's experience with LBNL's thick, fully depleted, p-channel CCDs goes back more than a decade, to early characterization done in support of the DoE SuperNova Acceleration Probe (SNAP) Dark Energy mission concept. The DCL's experience with charge multiplying CCDs (EMCCD & HMCCD) goes back to one of the first demonstrations of individual charge counting using an EMCCD circa 2005.[23]

At its core, the DCL's HMCCD test setup (Figure 5) is built around a Gen-II Leach Controller from Astronomical Research Cameras, Inc. The DCL's Lead Engineer selected a Gen-II controller rather than a newer Gen-IV or Gen-III controller because he thinks that it will be technically better for



a) High voltage (HV) clock ringing *b) HV clock waveform with line compensation*

Figure 6. This figure shows actual oscilloscope traces. Although the oscilloscope legend is difficult to read, our intent is to show the shape of the waveforms rather than the numeric values in the legend. The HV clock card showed a) ringing when first turned on. The ringing was eliminated by b) treating the cable harness as an impedance compensated transmission line. The little upside-down shark fin feature is known as the "pip". It is by design. Hole multiplication occurs only during the rising edge of the pip as indicated by the green bracket.

generating the required high speed clocks. The controller includes a DCL-designed bias and clock board that provides a set of unique control voltages for the HMCCD. These include negative biases for the p-channel clock phases, a high voltage substrate bias that is required to fully deplete the silicon, and a high voltage, high speed clock for the hole multiplication register. Although design of the Skipper test set has not started yet, we envision that it too will be built around a Leach controller with a custom printed circuit board (PCB) to provide the specialized voltages and clocks.

The HMCCD is a p-channel CCD. As such, it requires negative bias voltages for the output amplifiers. Further, it requires an approximately 100 V positive bias voltage to fully deplete the ≳200 µm thick high resistivity Si wafer. Monte Carlo simulations at LBNL previously showed that hole multiplication requires high negative voltage clocking with 20 ns (or better) time resolution. These parameters cannot be supported by typical CCD controllers.

For this reason, the DCL developed a custom PCB to interface the HMCCD with a DCL-standard Gen-II Leach CCD Controller (hereafter "Leach controller"). The PCB is synchronized and controlled by the Leach controller. The PCB provides the required negative biases and high voltage, high slew rate clock. All CCD signals are programmable through the Leach controller's DSP56000 processor. Although the Leach controller itself is standard, the DCL had to modify the power supply by adding negative voltage modules to generate the negative voltages that the PCB requires.

The CCDs' video output is processed and digitized by the Leach controller's video/ADC card. The resulting digital data are transmitted to the host computer through a standard fiber optic link. The host computer incorporates a custom frame grabber that places the data into dual port RAM memory. The DCL has an IDL application, running on the host computer, that formats the data into FITS format before storing it on the host computer's hard drives. Analysis of the resulting data is done using a combination of IDL and python-3 running on separate data analysis servers (depending on the analyst).

The HMCCD operates at a temperature of about $\mathrm{T} \approx -140\,\mathrm{C}$, a temperature that is easily achievable using an LN2 cryostat. The detector temperature is actively maintained at a set point within $< 2\ \mathrm{mK}$ using a thermostat (Tstat in Figure 5). The CCD can be illuminated by an LED that is mounted in the dewar and controlled by the Leach controller, or by an xray source (^{55}Fe). The ^{55}Fe source provides a direct measure of the conversion gain, $g_c(e^-/\mathrm{DN})$, that is independent of visible wavelength light.

The CCD electronics are mounted directly to the cryostat to minimize the length of the wiring for all control signals, but primarily for the high-speed clock. Prior HMCCD testing suggests that distortion of the clock waveform may negatively impact the noise and gain of the hole multiplier. Although the short cable length reduced reflections, it was still not sufficient to generate a clean high voltage waveform. But, by carefully tuning the line impedance we were able to eliminate the ringing that was initially seen (Figure 6).

The current status is that the full test system has been fully integrated and tested. We plan to begin characterization of the first Gen-V HMCCDs within the next few weeks.

6 Data Measurement & Analysis

For either the HMCCD or Skipper, the interaction of photons with the silicon detector material is already understood from previous SNAP testing.[1] Likewise, the motions of charges under normal voltages in the parallel and (low voltage) serial directions is also inherited from SNAP. Our focus is on the new elements. For the HMCCD, these are the hole multiplier and the ultra-low noise buried contact amplifier. For Skipper, the new elements are photon counting using the ultra-low noise buried contact amplifier and reducing the readout time by using more and lower noise outputs.

For the HMCCD, the primary objective is to measure the hole multiplication gain of the multiplication register and to optimize the configuration to achieve the lowest possible noise with acceptable charge transfer. The planned test sequence is as follows.

1. Optimize HMCCD configuration
    - Measure noise and gain as a function of HV clock phase, shape, and duration of the "pip" that accomplishes multiplication gain

- Optimize phase 1 and 2 clocking for maximum gain[††]
- Measure noise and gain as a function of HV amplitude
- Measure noise and gain as a function of depletion voltage (VSUB potential)

2. Measure charge transfer efficiency (CTE) for and around the optimal configuration
3. Measure noise and gain at optimal operating point
4. Characterize excess noise, including clock induced charge

7 Success Criteria

For most Tasks, success is defined by maintaining schedule, or by passing a Peer Review during which the overall performance will be examined in the context of spectroscopic biosignature characterization. The best technical indicators of overall project success will be the completion of Technology Milestones 1-3 (See § 4).

8 Schedule

Appendix C shows the schedule.

9 Potential Follow-on Work

Upon fully successful completion of this project, the HMCCD, Skipper, or possibly both will be TRL-4. Advancing to TRL-5 will require making new devices having pixel formats and packages compatible with LUVOIR or HabEx. Advancing to TRL-6 will require environmental testing, and in particular radiation testing. However, both making flight format devices and radiation test are outside the scope of the current project.

References

1. Besuner, R. W. *et al.* A 260 megapixel visible/NIR mixed technology focal plane for space. in *Proc SPIE* 81550D--14 (SPIE, 2011). doi:10.1117/12.893777
2. Des Marais, D. J. *et al.* Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology* **2**, 153–181 (2002).
3. Turnbull, M. C. *et al.* Spectrum of a Habitable World: Earthshine in the Near-Infrared. *Astrophys. J.* **644**, 551–559 (2006).
4. Rauscher, B. J., Canavan, E. R., Moseley, S. H., Sadleir, J. E. & Stevenson, T. Detectors and cooling technology for direct spectroscopic biosignature characterization. *J. Astron. Telesc. Instruments, Syst.* **2**, 41212–41217 (2016).
5. The LUVOIR Team. The LUVOIR Mission Concept Study Interim Report. *arXiv e-prints* arXiv:1809.09668 (2018).
6. Gaudi, B. S. *et al.* The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Interim Report. *arXiv e-prints* arXiv:1809.09674 (2018).

[††] Four clocks must be correctly phased to achieve hole multiplication. Three of these use normal p-channel CCD clock amplitudes and relatively slow transition times. The HV clock uses very high voltage during the very short "pip" to accomplish hole multiplication at the correct time during serial charge transfer in the hole multiplier.

7. Bolcar, M. R. *et al.* Technology gap assessment for a future large-aperture ultraviolet-optical-infrared space telescope. *J. Astron. Telesc. Instruments, Syst.* **2**, 041209 (2016).
8. Bolcar, M. R. *et al.* Technology development for the Advanced Technology Large Aperture Space Telescope (ATLAST) as a candidate large UV-Optical-Infrared (LUVOIR) surveyor. *UV/Optical/IR Sp. Telesc. Instruments Innov. Technol. Concepts VII* **9602**, 960209 (2015).
9. Wang, J. *et al.* Baseline Requirements For Detecting Biosignatures with the HabEx and LUVOIR Mission Concepts. *JATIS* **4**, 1–9 (2018).
10. Stark, C. C. *et al.* ExoEarth yield landscape for future direct imaging space telescopes. *J. Astron. Telesc. Instruments, Syst.* **5**, 1–20 (2019).
11. Harding, L. K. *et al.* Technology advancement of the CCD201-20 EMCCD for the WFIRST coronagraph instrument: sensor characterization and radiation damage. *J. Astron. Telesc. Instruments, Syst.* **2**, 11007–11032 (2016).
12. Burt, D. & Bell, R. CCD imagers with multiplication register. *EP Patent 0,866,501* (2004).
13. Hynecek, J. CCM—A New Low-Noise Charge Carrier Multiplier Suitable for Detection of Charge in Small Pixel CCD Image Sensors. *IEEE Trans. Electron Devices* **39**, 1972–1975 (1992).
14. Dressel, L. Wide Field Camera 3 Instrument Handbook, Version 11.0. *https://hst-docs.stsci.edu/display/WFC3IHB* **(Baltimore**, (2019).
15. Bebek, C. J. *et al.* Status of the CCD development for the Dark Energy Spectroscopic Instrument. *JINST* **12**, C04018--C04018 (2017).
16. Dawson, K. *et al.* Radiation Tolerance of Fully-Depleted P-Channel CCDs Designed for the SNAP Satellite. *IEEE Trans. Nucl. Sci.* **55**, 1725–1735 (2008).
17. Bebek, C. *et al.* Proton radiation damage in p-channel CCDs fabricated on high-resistivity silicon. *IEEE Trans. Nucl. Sci.* **49**, 1221–1225 (2002).
18. Spratt, J. P. *et al.* Proton damage effects in high performance P-channel CCDs. *IEEE Trans. Nucl. Sci.* **52**, 2695–2702 (2015).
19. Marshall, C. J. *et al.* Comparisons of the proton-induced dark current and charge transfer efficiency responses of n- and p-channel CCDs. in *Proc SPIE* 542–552 (2004). doi:10.1117/12.551914
20. DESI Collaboration *et al.* The DESI Experiment Part II: Instrument Design. *arXiv e-prints* arXiv:1611.00037 (2016).
21. Tiffenberg, J. *et al.* Single-Electron and Single-Photon Sensitivity with a Silicon Skipper CCD. *Phys. Rev. Lett.* **119**, 131802–131806 (2017).
22. Rauscher, B. J. 'Hopper' Ultra-Low Read Noise Charge Coupled Device. *NASA e-NTR* **1549398893**, (2019).
23. Wen, Y. *et al.* Individual photon counting using e2v L3 CCDs for low background astronomical spectroscopy. *High Energy* **6276**, 44–48 (2006).
24. Rauscher, B. J. & Holland, S. Hole Multiplying Charge Coupled Device (HMCCD). *NASA e-NTR# 1456415060* (2016).
25. Wen, D. & Salsbury, P. Analysis and design of a single-state floating gate amplifier. in *1973 IEEE International Solid-State Circuits Conference. Digest of Technical Papers* **XVI**, 154–155 (1973).
26. Wen, D. D. Design and operation of a floating gate amplifier. *IEEE J. Solid-State Circuits* **9**,

410–414 (1974).
27. Janesick, J. R. U.S. Patent# 5,250,824: Ultra Low-Noise Charge Coupled Device. (1993).
28. Chandler, C. E., Bredthauer, R. A., Janesick, J. R. & Westphal, J. A. Sub-electron noise charge-coupled devices. in *Charge-Coupled Devices and Solid State Optical Sensors* (ed. Blouke, M. M.) 238–252 (International Society for Optics and Photonics, 1990). doi:10.1117/12.19457
29. Janesick, J. R. *et al.* New advancements in charge-coupled device technology: subelectron noise and 4096 x 4096 pixel CCDs. in *Charge-Coupled Devices and Solid State Optical Sensors* (ed. Blouke, M. M.) 223–238 (International Society for Optics and Photonics, 1990). doi:10.1117/12.19452

Appendix A List of Acronyms

Acronym	Definition
ADC	Analog to Digital Converter
CCD	Charge Coupled Device
CIC	Clock Induced Charge
CTE	Charge Transfer Efficiency
DoE	Department of Energy
DN	Digital Number
DSP	Digital Signal Processor
EMCCD	Electron Multiplying Charge Coupled Device
GCR	Galactic Cosmic Ray
GSFC	Goddard Space Flight Center
HMCCD	Hole Multiplying Charge Coupled Device
HST	Hubble Space Telescope
HV	High Voltage
JWST	James Webb Space Telescope
LBNL	Lawrence Berkeley National Laboratory
NASA	National Aeronautics and Space Administration
NET	No Earlier Than
NPR	NASA Procedural Requirements
NIRSpec	[JWST] Near Infrared Spectrograph
PCB	Printed Circuit Board
SNAP	SuperNova Acceleration Probe
TBC	To be Confirmed
TBD	To be Determined
TRL	Technology Readiness Level
VISIR	Visible and Near-IR
VSUB	The substrate voltage. A high voltage that fully depletes the Si
WFIRST	Wide Field Infrared Survey Telescope
WFI	[WFIRST] Wide Field Imager

Appendix B TRL-3 Exit Criteria for VISIR Detectors

The NASA procedural requirements (NPR; https://esto.nasa.gov/files/TRL.pdf) define Technology Readiness Levels (TRL). Table 3 describes the range from TRL-3 to TRL-4 (our focus in this project). For NASA astronomy missions, TLR-6 is the minimum that is generally considered acceptable for flight projects upon entry to Phase B, "Preliminary Design and Technology Completion Activities."

Table 3. NASA TRL 3-4 Definitions

TRL	Definition	Hardware Description	Exit Criteria
3	**Proof-of-Concept** - Analytical and experimental critical function and/or characteristic proof-of-concept	At this step in the maturation process, active research and development (RandD) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2.	Documented analytical/experimental results validating predictions of key parameters.
4	**Technology Demonstration** - Generic design demonstrating concept-enabling performance consistent with potential applications - Low-fidelity validation of critical functions using breadboards/brassboards with non-flight-like parts and packaging in a laboratory environment at room temperature or environment required for functional validation	Following successful "proof-of-concept" work, a single technological element is integrated to establish that the pieces will work together to achieve concept-enabling levels of performance for a component and/or breadboard/brassboard. This validation must be devised to support the concept that was formulated earlier and should also be consistent with the requirements of potential system applications. The validation is relatively "low fidelity" compared to the eventual system.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.

In the context of VISIR detectors, TRL-3 is essentially proof-of-concept. The critical new functionality of the HMCCD is hole multiplication. Figure 3b shows that hole multiplication functions, thus validating the overall concept and the simulations at LBNL that were done showing when and how hole multiplication is achieved during charge transfer.

For Skipper, Figure 4b constitutes the proof-of-concept. The skipper cleanly resolved individual charge packets and read noise = 0.068 rms e^-/pixel rms was achieved.[21]

The lead author was closely associated with the detector maturation activities for *JWST*, *Euclid*, and *WFIRST*. For these missions, TRL-4 was generally taken to mean that a detector existed that had about the right format and that exhibited functional performance not too far from meeting requirements for a specific mission and instrument. In other words, "performance consistent with potential applications" in a non-flight package.

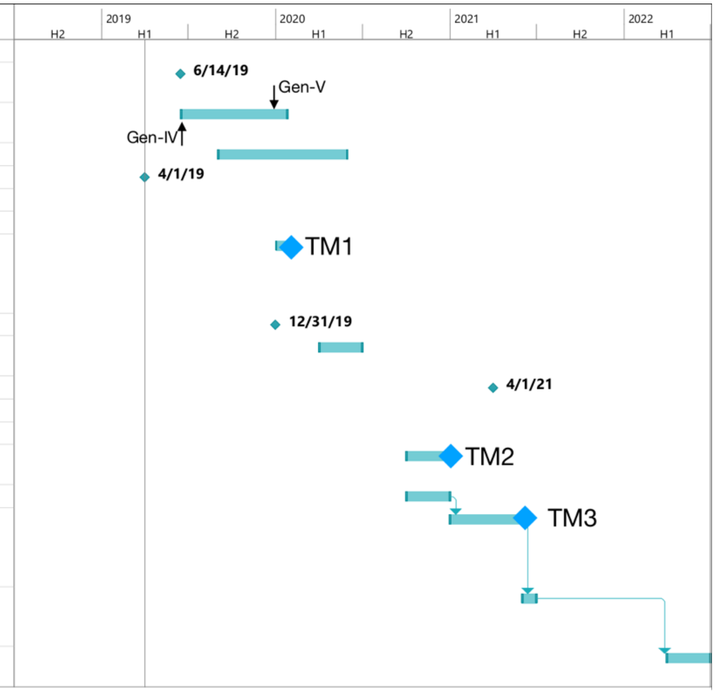
Although we do not aim for TRL-5 and 6 here, in the context of VISIR detectors these generally mean: (TRL-5) a detector exists that generally meets performance requirements and (TRL-6) the detector has passed environmental qualification. Within environmental qualification, radiation testing is arguably most challenging for today's VISIR detectors.

To summarize, and in the context of VISIR detectors, the following are true upon exiting a TRL.

TRL-3 = Demonstration of proof of concept
TRL-4 = Demonstration of performance consistent with intended application
TRL-5 = Essentially meets performance requirements
TRL-6 = Environmentally qualified, including end of life radiation tolerance

Appendix C Top Level Schedule

ID		Task Name	Duration	Start	Finish	Predecessors
1		**Year 1**				
2		Demonstrate function of GSFC high speed/ high resolution electronics card	0 days	Fri 6/14/19	Fri 6/14/19	
3		Begin testing improved, but already existing HMCCDs in the DCL	160 days	Mon 6/17/19	Fri 1/24/20	
4		Begin design of skipper test set up	195 days	Mon 9/2/19	Fri 5/29/20	
5		Begin layout of improved , faster readout, skipper CCDs	0 days	Mon 4/1/19	Mon 4/1/19	
6						
7		**Year 2**				
8		Document describing baseline performance of existing HMCCDs in regard to space coronagraph requirements. As proposed, this was an end of Year 1 Milestone. The 5 week government shutdown pushes it into early Year 2	23 days	Thu 1/2/20	Mon 2/3/20	
9		Begin fabrication of improved, faster readout, skipper CCDs	0 days	Tue 12/31/19	Tue 12/31/19	
10		**Complete any required modifications to DCL test setup for skipper CCDs and be ready for existing skipper testing**	65 days	Wed 4/1/20	Tue 6/30/20	
11		Begin layout/design of improved HMCCDs and / or skippers (TBC)	0 days	Thu 4/1/21	Thu 4/1/21	
12						
13		**Year 3**				
14		Demonstration of <2 e- read noise (goal <1e-) in conventional CCD mode using the ultra-low noise buried contact output	66 days	Thu 10/1/20	Thu 12/31/20	
15		Demostration of hole multiplication gain >10x (goal >20x)	66 days	Thu 10/1/20	Thu 12/31/20	
16		Achieve TRL-4. Demonstration of photon couting, i.e. a low light level laboratory image in photon counting mode that substantially has Poisson noise statistics. Milestone is met if any of detector architectures does this	107 days	Fri 1/1/21	Mon 5/31/21	15
17		Integrate detector characterization results into the cross-package integrated model analysis, and evaluate design trades in terms of spectral retrieval yields	22 days	Tue 6/1/21	Wed 6/30/21	16
18		Test 2nd run and report assuming 9 months after placing wafer order.	65 days	Fri 4/1/22	Thu 6/30/22	17



TM = Technical Milestone