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# Scientific/Technical/Management Plan

We propose to develop and mature a transformative photon counting silicon detector with high efficiency in the ultraviolet (UV) and ultra-low noise properties for future flagship missions. The unique stability and precision of the proposed delta-doped Skipper CCD addresses a key technology need of the highest-priority mission recommendations of Astro2020, the flagship-class infrared/optical/ultraviolet (IROUV) Great Observatory which was recently named Habitable World Observatory (HWO). The Astro2020 Decadal Survey report predicts that this observatory will create a “transformational leap in capability” to discover and explore earth-analog exoplanets. By combining high-resolution imaging and multi-object spectroscopy, “the same observatory will be transformative for general astrophysics…especially at ultraviolet wavelengths.” To achieve these goals, the Survey calls on NASA for significant advances in detector technology over the next six years, in order to ahieve “1-2 order of magnitude leaps in sensitivity and performance over HST…This telescope will be capable of achieving breakthrough discoveries across nearly all of astrophysics…[and] will become one of the most scientifically versatile astronomical telescopes ever flown.”

In this proposed effort, we leverage previous SAT investments in delta doped detectors and associated techniques such as detector-integrated bandpass filters, in order to create a new type of UV photon counting, solar blind detector. Delta-doped Skipper CCDs offer the transformative performance and scalable architecture needed by NASA to build multigigapixel focal planes for a flagship-class IROUV space observatory. Invented by Jim Janesick at JPL in 1990 (Janesick 1990), Skipper CCDs achieve single photon sensitivity and photon-number-resolving capability by using correlated multi-sampling to reduce the read noise by several orders of magnitude. Skipper CCDs recently achieved an unprecedented noise level of 0.068 e- rms/pixel after 4000 samples per pixel (Tiffenberg 2017). Our delta-doping technology will extend the spectral range of Skipper CCDs into the far UV (and indeed extreme UV and soft X-ray) by using nanoscale surface engineering for stable, radiation-hard surface passivation of back-illuminated detectors in space radiation environments. By combining delta-doping and multilayer coatings for the highest and most stable UV sensitivity with Skipper CCD’s ultralow noise, photon counting, and photon-number resolving capabilities in a single, easy to manufacture and operate device, we respond to the call for transformative detectors and their fabrication.

Resolving photon number with high precision at the pixel level is an enabling capability for precision astronomy and astrophysics, especially in studies of the ultra-faint and challenging parts of UV where members of our team specialize and where low sky and noise backgrounds make photon-counting critical. These areas include determining habitability of worlds around other stars, understanding the underlying rules for star formation, measuring how a galaxy interacts with its gaseous halo environment, and mapping how primordial hydrogen enters a galaxy to create stars.

Our team comprises members with complementary expertise in materials, device physics, detector characterization, instrument design and development, and observational astronomy. Several members of our team were involved in the LUVOIR and HabEx design team and have first-hand understanding of the requirements of the next Great Observatory (GO) and the Astrophysics Program Office Technology Gap priorities. Our group has pioneered the development of UV and UV-NIR detectors using nanoscale engineering of surfaces and interfaces in back-illuminated charge-coupled devices (CCDs), electron multiplying CCDs (EMCCDs), and complementary metal-oxide-semiconductor (CMOS) imaging detectors Our delta-doping and custom coating technologies have demonstrated high, stable, and tailorable QE, including recent developments in antireflection (AR) coatings and metal-dielectric filters for UV bandpass optimization (Hoenk 2014, Hennessy 2015, Hennessy 2018, Nikzad 2017).

## Objectives and Expected Significance

In this effort we propose to develop a photon counting, photon number resolving silicon detector with high efficiency in the UV by leveraging the ultra-low noise of Skipper CCDs with the high UV quantum efficiency and exceptional stability of delta-doped (2D-doped) silicon detectors. The proposed detector technology addresses the transformational performance and scalable architecture that NASA needs to deliver a flagship-class Habitable World Observatory. It is essential that we begin this development immediately in order to meet the schedule envisioned in the Astro2020 report.

Skipper CCDs will open a window into areas of astrophysics that have previously been difficult to observe due to their intrinsic faintness, such as determining habitability of worlds around other stars, understanding the underlying rules for star formation, measuring how a galaxy interacts with its gaseous halo environment, and mapping how primordial hydrogen enters a galaxy to create stars. The photon-number-resolving capability of Skipper CCDs is incredibly valuable in many fields, especially in studies of the ultra-faint parts of the UV spectrum where members of our team specialize, and will be a critical technology for future Flagship missions (Augustin 2019; Chung 2021; Hamden 2019, Hamden 2020, Hamden 2013, Martin 2019, O’Sullivan 2020).

### Goals

The main objective of this proposed work is to develop and mature an ultraviolet solid-state photon counting and photon-number resolving detector with high and stable response extending from the far ultraviolet to near infrared. The combination of Skipper design, block integrated bandpass filters, and delta doping constitutes a TRL 3 and we will mature this technology to TRL 4 by the end of this three-year effort. ***We will develop and mature ultraviolet-optimized Skipper CCDs by the end of this three-year task by***:

1. **Demonstrating ultra-stable, high efficiency, photon counting, photon number resolving UV detectors using two types of Skipper CCDs:**
   1. Skipper CCDs will be sourced from Semiconductor Technology Associates (STA) and Lawrence Berkely National Lab (LBNL)
   2. 2D-doped Skipper CCDs: We will demonstrate single photon counting and UV QE>50% on existing Skipper CCD arrays by 2D doping and AR coating (Yrs. 1-3, iterative, first demo year 1).
   3. After the initial demonstration, a new lot run will be fabricated and processed incorporating feedback for optimized performance (Yrs. 2-3)
2. **Demonstrating ultra-stable, high efficiency broadband photon counting detectors with variable response across the array for spectroscopy applications**:
   1. Incorporate integrated UV bandpass filters on 2D-doped Skipper CCDs: As part of this effort, we will develop integrated visible-rejection filters for the above detectors that maintain high QE in the near-UV (NUV) and/or far-UV (FUV) (Yrs. 2, 3)
   2. Use techniques developed by CoI-Jewell and her team under an APRA to incorporate block-filter and graded coatings on 2D-doped Skipper CCDs(Yr 3)*.*
3. **In-depth characterization to validate performance:**
   1. Evaluate two types of 2D-doped Skipper CCDs (STA and LBNL): using existing team-wide testing capabilities at the University of Arizona (UA) and the Jet Propulsion Lab (JPL) we will evaluate noise, depletion capability, required voltage, breakdown, and modulation transfer function of devices (Yrs 1-2).
   2. Evaluate QE, noise, and uniformity and PRNU (Pixel Response NonUniformity): Using JPL’s UV CCD characterization lab and precision projector facility, we will characterize critical detector performance parameters including QE, noise (e.g., read, dark) and assess uniformity and linearity across each 2D-doped device for the revised design fabricated and 2D doping in the second year (Yrs 2-3).
   3. **Performance Comparison**: We will evaluate critical Skipper CCD performance parameters and quantify their stability in comparison with other low noise 2D-doped detector arrays such as EMCCDs. (Yrs 2 & 3).
4. **On-sky study**: The UA team will lead this effot using the Circumgalactic H-alpha Spectrograph (CHαS) at the MDM Hiltner 2.4 m telescope on Kitt Peak, Arizona by substituting the proposed 2D-doped Skipper devices for the existing detector on the system. This will significantly improve on the existing performance specifications, allowing CHαS to achieve its science goals in 2-4x less exposure time. (Yr 3).

*The quantative goals of this effort are summarized in the Science Traceability Matrix (Table 1-1) in section 1.1.2.*

### Expected Significance

Our effort is focused on a the technology needs of the 6-meter HWO Great Observatory Mission for UV and UV/Visible photon counting detectors. We are also guided by large telescope decadal studies of LUVOIR and HabEx where the need for photon counting from UV to NIR has been highlighted. Significant QE gains, solar-blindness, and stable detector performance, coupled with large formats, will enable a new class of instruments with increased sensitivity and decreased complexity and will significantly impact science return for future GOs as well as missions of all classes.

Because the proposed detectors are silicon based, they benefit from significant leverage from commercial development—*a billion dollar industry*. JPL has formed strategic partnerships with several prominent members of industry to enable high performance devices of all types of designs to be available to the community for a variety of atronomical applications. This proposed effort leverages our partnership with STA as well as our previous collaborative efforts with LBNL. JPL’s 2D doping encompasses delta doping and superlattice doping—otherwise known as multilayer delta doping and an elegant yet natural extension of delta doping. Superlattice doping has all the advantages of delta doping and has shown unprecedented stability in the deep and far UV, including resilience to ionizing radiation-induced surface damage on silicon devices (Hoenk 2014). JPL’s end-to-end post fabrication processing development and maturation has been and will continue to be highly leveraged by industry’s interest in stable EUV and FUV detectors for semiconductor inspection as well as industry’s interest in aligning their development roadmap—e.g., for large format photon counting detectors— to the future observatories.

Key detector metrics are anchored to the representative mission error budgets including a 6-m aperture HWO-GO mission requirements summarized in Science Traceability Matrix in Table 1-1. This table highlights the flagship and representative mission concept and illustrates the broad suite of potential mission applications and their relation to NASA’s key science goals and objectives. Our approach, described in section 1.4, is accomplished through a series of measured steps and quantified metrics that are tied to the error budgets of these representative mission concepts.

**Table 1-1: Traceability Matrix for UV/Visible Detectors**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NASA Science Objective/ Questions | Science Sub-goal | Mission (+Instrument) Concept | UV/Visible  Detector Requirement | SAT Deliverable and/or Key Milestone |
| Understand the many phenomena and processes associated with galaxy, stellar and planetary system formation and evolution from the earliest epochs to today: How did the universe originate and evolve to produce the galaxies, star and planets we see today? | Absorption-line spectra of IGM, CGM, warm ISM. Composition of hot, warm and cold gas, atomic & molecular. | UVOIR: 4-15m w/ high-R spectrograph, (e.g., R~30k-100k). Bright/faint QSO | 2x (50k x1k) focal plane, high FUV, NUV QE w/ multi-AR, photon counting | *2D doped photon counting* Skipper with ALD-grown AR coatings  QE>50% @100-1000nm, selected wavelengths |
| Map and study star-forming regions, deep galaxy surveys, nearby galaxies/stellar populations  Exoplanet characterization | UVOIR: 4-15m w/ wide field imager, high ang. res. | >500 Mpix focal plane, high QE + Broadband resp., low noise fast readout, possibly visible rejection | 1. NUV-NIR *2D-doped* Skipper w/ graded response:  QE > 50% @200 nm,  >60% @ >372 nm;  80% @656.3 nm |
| Map IGM, CGM, ISM, outflows. Investigate signatures of star formation across galaxy types &redshift. | UVOIR: 4-15m w/ multi obj. spect (e.g., R~2.5k-5k, FOV~8', 0.05”-1" bin) | Multi-slit/IFU >100 Mpix focal plane w/ high QE, multi-AR, photon counting, visible rejection | 1 *2D-doped* Skipper NUV  QE>50% @200-300 nm,  2. *2D-doped* Skipper FUV  QE>50% @100-200 nm |
| Deep exoEarth Follow-up and characterization using UV-NIR imaging and spectroscopy  Emphasis on UV-Vis | LUVOIR-B ECLIPS [11.2.1.9-10,11.2.3.9]  HabEx [11.4.4.1] | Detector parameters: Dark current ≲ 2×10−2 to 10-4 e-/pix/s; Read noise ≲ 5 e- (rms); CIC: 3×10-3 e-/pix; QE: >50% (Fig H-26 in LUVOIR report) End of mission req. | Projected performance after tech development: Dark current ≲ 3×10−5 e-/pix/s; Read noise < 0.1 e- (rms); CIC: 1.3x10-3 e-/pix  QE > 50% (200-1000 nm) |
| Deep exoEarth Follow-up and characterization using vis-NIR imaging and spectroscopy  Emphasis Vis-NIR | HabEx 11.4.4.2 / LUVOIR 11.2.1.12-13 | QE >80% at 0.940 μm, thicker silicon (up to 200 μm thick layer), deep depletion devices, 4k×4k format for starshade IFS | Improvement over current state of the art as in EMCCDs |
| General Astrophysics (e.g., CGM) | HabEx Spectrograph – Low noise detectors | High UV QE ~60–80% in 0.1–0.3 μm, dark current of 3×10-5 e-/pix/s beginning of life. 4k×4k EMCCD fabricated. Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime, ≥4k×4k format fabricated | Same noise and QE performance as requirement: UV QE ~60–80% in 0.1–0.3 μm, dark current of 3×10-5 e-/pix/s beginning of life. 4k×4k Skipper fabricated. Dark current <0.001 e-/pix/s, in a space radiation environment over mission lifetime, ≥4k×4k format fabricated |

## Perceived Impact to State of Knowledge

The proposed technology will enable a new class of UV instruments with increased sensitivity and decreased complexity for future NASA missions. The reduction of complexity is due to the use of photon-counting silicon detectors with low operating voltages and broad applicability for multiple instruments.

Detectors with high efficiency spanning the spectral range from soft X-ray and EUV to NIR with improved radiation tolerance are game changing, as they leverage cutting-edge silicon imaging technologies to offer capabilities previously only available in photoemissive devices (e.g., microchannel plates or MCPs) or low TRL devices based on the GaN family of materials. JPL’s model of working with industry and picking up where industry leaves off provides a powerful resource for the astronomy community, allowing a wide variety of device architectures customized to suit mission requirements. Our previous work under an SAT, as well as other synergistically funded efforts by industry and JPL, have established the manufacturability of 2D-doped detectors that can be available to the scientific community and future missions at an affordable cost (Nikzad 2017). This work leverages JPL internal investments on infrastructure and technology development as well as non-NASA funded developments, and builds on the success of our previous SAT and APRA work to provide the astronomy and astrophysics instrument designer with important new detector capabilities.

## Relevance to Element Programs and Objectives

This proposal primarily addresses the Astrophysics Science Theme of Cosmic Origins (COR) with strong relevance to Exoplanet Exploration program (EXEP). The proposed technology is anchored to the Astro2020-recommendation for the HWO Great Observatory, which is Astro2020’s top priority (6-m IROUV observatory). The roadmap of our development and the milestones achieved is directly responsive to the Astrophysics Program Office’s Technology Gap Priorities (Astrophysics Technology Gaps 2022) as shown in Table 1-2.

Table 1-2-Technology Gaps and Relevance of Proposed Technology to the gap.

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| Technology Gap | Proposed Technology  & Roadmap |
| *Large-format, High-resolution FPAs* | Photon counting and exceeds noise requirements, the delta doping and filters developed here applicable to all Si detectors, high QE in both FUV &NUV |
| *Large-Format, Low Darkrate, High Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors* | High Efficiency, Solar blind, Delta-doped Skipper CCDs are viable alternative to MCPs –low voltage, large format, scalable, leverages silicon industry, high QE in both FUV and NUV |
| *High-Throughput Bandpass Selection for UV/VIS - Single Filter and Detector Integrated* | Specifically names delta doped detectors with integrated UV bandpass metal-dielectric filters |
| *Vis/NIR Detection Sensitivity (EXEP)* | Skipper CCDs demonstrated in fully-depleted thick format with extended NIR response. With delta doping high efficiency and ultrahigh stability achielved |
| *UV Detection Sensitivity (EXEP)* | Meets and exceeds the UV detection requirements |
| *Photon Counting Large-format UV Detectors* | Photon Counting and high QE, Delta doped, with block filters on Skipper; scalable format |
| *High-QE, Solar-blind, broad-band NUV detector (COR)* | Gap identifies delta doped performance in FIREBall-2 and SPARCS, |

The HWO flagship mission and other classes of missions will benefit from the combination of high, uniform, and stable QE, solar blindness, extended spectral response, and radiation tolerance of delta-doped Skipper CCDs with customized AR and UV bandpass filters. It should be noted that because our 2D-doping processes are versatile and agnostic to the detector architecture, they can be applied to a variety of detector formats and architectures, including Skipper CCDs, quantized CMOS (e.g., Quanta Image Sensor), EMCCDs for photon counting spectroscopy, standard CCDs for survey missions, and scientific CMOS imagers for missions requiring ultralow noise, high sensitivity, higher speed, and versatile readout.

## Technical Approach and Methodology

Our technical approach will consist of a straightforward development process, using the techniques and workflows already perfected for UV optimized EMCCDs. We will first delta dope Skipper CCDs for UV performance, working with LBNL and STA as sources of existing Skipper wafers. Once devices are delta-doped and packaged, we will characterize key performance metrics, including measuring dark current, read noise, readout time for given SNR, quantum efficiency, and quantum yield, and explore how Skipper’s readout functionality can be optimized for faster astronomy readout. In parallel with the UV-optimization processing, we will obtain several standard visible Skipper CCDs from the same sources (STA and LBNL) and begin characterization of the devices. After a first round of exploration, we will develop an updated Skipper CCD architecture and fabricate a new lot of wafers through a contract with either DALSA or Microchip in Chandler, AZ. These modifications will include increasing the numbers of readout amplifiers, incorporating low noise amplifier design, and adding more readout amplifiers for faster readout. We will also explore additional strategies for reducing dark current and improving readout speed. We will adjust our readout software to allow for dynamic readout—a process in which the signal level in the first sample determines how many samples are ultimately needed to reduce readout time. For each step, we will evaluate the performance at a system level and compare with EMCCD approaches. Finally, if performance is promising, we will collect initial on-sky data using telescopes accessible at UA. Details of these steps are described below.

### Skipper CCDs

Skipper CCDs have extremely low detector noise, meaning signals from faint astrophysical sources can be measured precisely without large errors, i.e., photon counting. A Skipper CCD uses a non-destructive read-out amplifier, allowing for multi-sampling pixels to reduce the read noise by several orders of magnitude. Invented by Jim Janesick at JPL (Janesick 1990), Skipper CCDs recently achieved unprecedented read noise of 0.068 electrons rms to enable the photon-number resolving performance required for NASA’s transformative goals for the HWO Great Observatory (Tiffenberg 2017 and Bredthauer 2022). This means a Skipper CCD can distinguish between 0 and 1 electrons in a pixel, which is the typical expectation for photon counting and is something EMCCDs and MCPs can also do. But the Skipper CCD is unique in that it can also distinguish between 1 and 2 photons, and between 2 and 3 photons, and between 3 and 4 photons, and so on all the way up to the saturation limit of the detector. This means a Skipper can perform true photon counting and is not limited by the typical rate requirements of an EMCCD.

STA has produced a 1kx2k, 12 µm pixel Skipper CCD in frame transfer format; it’s design layout is shown in Figure 1-1. These Skipper CCDs have a Skipper output at one end of the serial register (2.5 uV/e-, 5.5 e- noise single sample at 100 kHz), and a standard single stage output at the other end (5 uV/e-, 3 e- noise at 100 kHz). The Skipper output structure has the typical summing well and output transfer gate (OTG )s, but instead of a floating diffusion as the sense node, it uses a floating gate for non-destructive readout. A reset gate is used to set the floating gate bias, and a dump gate is used to remove the charge after sampling. Summing well and OTG are clocked high and low to move the charge on and off the floating gate to permit multiple nondestructive reads, with the read noise falling as the square root of the number of cycles. This output achieved an 0.19 e- read noise using 2000 samples per pixel.

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| **Figure 1-1**: 1kx 2k, 12-µm pixel Skipper n-channel CCD operated in frame transfer, shown in the dewar (left) and design of the sense node to enable multiple non-destructive read to achieve ultralow noise (right), (adapted from Bredthauer 2022). | |

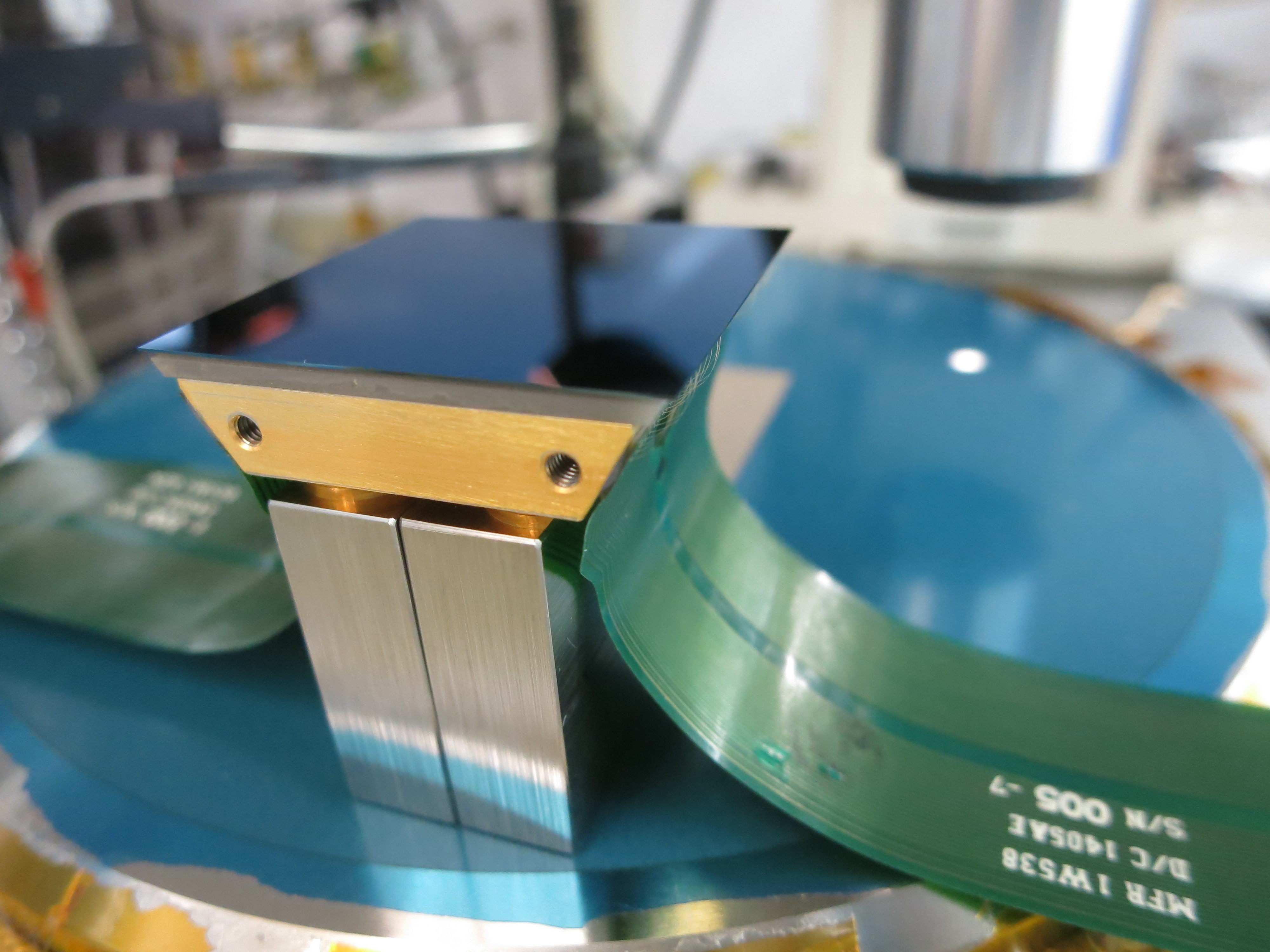
Figure 1-2 shows the photon counting performance measured in this device. As shown in the figure, the histogram shows photon counting resolving ability of this device.

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| **Figure 1-2**: Histogram obtained in the visible from the above 1kx 2k, 12-µm pixel Skipper CCD showing the photon counting and photon number resolving capability of Skipper CCD. (adapted from Bredthauer 2022). |

### 2D-doped Skipper CCDs with integrated filters for optimized QE and Photon Counting

This proposed effort combines advanced single photon counting Skipper CCDs developed at STA and LBNL with the performance of JPL’s 2D doping processes and integrated, multilayer antireflection (AR) coatings and UV bandpass filters. 2D doping encompasses the nanoscale surface engineering techniques of delta doping and superlattice doping (multiple delta layers) that have been developed and matured over the years at JPL for ultra-stable and uniform response with nearly 100% internal quantum efficiency (QE) on silicon detectors of various designs and formats (Hoenk 1992, Jones 2000, Hoenk 2009, Nikzad 2012, Hoenk 2014, Nikzad 2017).

Figure 1-3 shows the process flow for JPL’s end-to-end post fabrication processing. These processes include bonding, thinning, 2D doping, AR coatings/UV bandpass filters, packaging, and testing. Typically, device wafers are received at JPL from the foundry, fully fabricated and complete with metallization. Prior to thinning, device wafers are bonded to a blank “handle” wafer using direct wafer-wafer bonding processes at temperatures low enough to avoid any harm to the devices. Device wafers are back-thinned using a series of chemical etch and chemical-mechanical polishing steps to remove the substrate and expose the epilayer for back illumination. After thinning, the device wafers are atomically cleaned using processes developed at JPL (Hoenk 1992, Jones 2000, Hoenk 2009). Wafers are then 2D doped in JPL’s silicon molecular beam epitaxy (MBE) system with 8-inch-diameter wafer handling capacity (Nikzad 2017). AR coatings or UV bandpass filters are deposited after dicing using precision atomic layer deposition (ALD) and thermal physical vapor deposition (PVD) processes (Hennessy 2015). Applying the coatings after dicing allows for iteration and optimization within the resources of the task. JPL’s processes have been developed for both n-channel devices with boron delta doing (Nikzad 2017) and p-channel devices with antinomy delta doping (Nikzad 2017, Blacksberg 2008, Jewell 2018)

**Figure 1-3.** Process flow of JPL’s back illumination fabrication processes including bonding, thinning, 2D doping, AR coating/integrated metal-dielectric filters, and packaging.On the right**,** steps of theprocess flow are shown pictorially.

### Custom Antireflection Coatings and Detector-Integrated Filters for Broadband, Narrowband, and Tailored UV Response and Out of Band Rejection

Our group has arguably been the first team to make extensive and efficient use of unique properties of ALD for UV AR coatings and UV bandpass filters (Figure 1-4). With atomic level precision and control, stoichiometric films, ultrathin films, and sharp interfaces, ALD is particularly suited for UV coating applications. In the past decade we have developed ALD processes for UV-relevant materials and designed and demonstrated a variety of single- and multi-layer AR coatings as well as detector-integrated metal-dielectric UV-bandpass filters. We will design optimized AR coatings and filters and incorporate them on 2D-doped Skipper CCDs for tailored UV response.

Spectroscopy applications often benefit from a spatially varying detector response optimized according to the instrument’s optical dispersion. However, because of silicon’s varying optical properties there is often no “one size fits all” coating/filter solution that can span the entire UV to NIR wavelength range. Spatially varying the detector response to correspond with instrument dispersion requires that different coatings be applied to different portions of the detector. Under an internally-funded task (PI: Hennessy), we have developed new ALD processes that, through careful control of process parameters including working pressure and dose time/pressure, result in coatings that continuously vary in thickness as a function of lateral position on the substrate. Under an ongoing APRA-funded task (PI: Jewell), we are developing detectors with a butcher-block style response profile with each portion of the device targeting a specific bandpass. We have successfully demonstrated the intentional and controllable patterning of an AR coating deposited by ALD as shown in Figure 1-5, and we are in the process of refining the patterning process for implementation with 2D-doped arrays [Jewell 2022]. A similar approach of using a separate, stand-alone butcher-block style linear variable filter above the focal plane is being used for the upcoming SPHEREx infrared astrophysics mission [Crill 2020]. The uniqueness of our implementation is that the filters are integrated directly onto the detector surface, which allows for better index matching and higher overall throughput.

Much of our previous patterned/graded filter work has focused on optimizing UV response. Under the proposed task we will extend our work to span the visible and NIR wavelength ranges in order to take full advantage of the spectral sensitivity offered by the full-depletion LBNL-type Skipper devices.

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| **Figure 1-4**: Examples of delta-doped detector responses possible using existing coating and filter designs from JPL’s filter catalog. Left: With simple, single layer AR coatings we can achieve >50% QE is bands throughout the UV (adapted from Nikzad 2012). Center: Multilayer AR coatings often allow for higher in-band QE than a single-layer coatings (adapted from Hamden 2019). Right: For red-blocking filters, the in-band peak position can be varied depending on the dielectric material used in the MDF stack, while still maintaining good red rejection (adapted from Hennessy 2018). |

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| **Figure 1-5**: Left: Measured film thickness across a 4 cm × 3 cm substrate with a graded thickness profile. Here, the graded AlF3 film ranges in thickness from ~10 nm to ~38 nm, which would result in a UV QE peak shift from ~125 nm to ~235 nm. *Right*: Example of a silicon detector with a butcher block AR coating. The purple and blue outlined regions are coated with 14 nm and 32 nm Al2O3, respectively; the rest of the detector is bare. The device is a 1056 × 2069, 13 µm pixel, EMCCD. Each coated region is 300 × 300 pixels and the regions are separated by 30 pixels. The test image was acquired at ambient pressure under visible light illumination and at room temperature; the uneven flat field is due to non-uniform illumination conditions. Even under these un-optimized conditions, the AR coated regions are clearly visible and distinct. |

### Characterization and optimization of Skipper CCDs for astronomy

The proposed characterization work will take place at JPL’s UV detector characterization laboratory, Precision Projector Laboratory (PPL), and in the laboratory of Co-I Hamden at UA . Devices will be integrated into dewars/cameras and key detector performance parameters will be characterized, including QE, dark current vs. temperature, noise, stability, uniformity, linearity, intrapixel response, image lag and crosstalk. Devices selected from the batch will be sent to our industry vendors for further laboratory system testing. Devices will be again tested for QE (in the UV—only at JPL and UA), noise, power consumption, dark current, uniformity, pixel response nonuniformity vs. temperatures and signal level.

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|  | Screen Shot 2015-03-04 at 1.20.50 PM.png | |
| **Figure 1-6**: Example PPL image data. LEFT: Arrays of 3µm point sources (“stars”) covering the detector rapidly probe subtle systematics at a range of focal ratios (f/8 or slower). RIGHT: A mask emulating a simplistic spectrum with a few widths and heights. More sophisticated masks can be fabricated as needed to enable science-driven tests of detector systematics. | | |
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| **Figure 1-7:** LEFT: Flat field calibration image from a hybrid CMOS detector with a pronounced crosshatch pattern. RIGHT: PPL reconstruction of a 20x20 pixel region at 1/3 pixel (6µm) resolution. Scanning thousands of undersampled point-sources confirmed that the entire pattern varies on scales smaller than 1 pixel and thus causes photometric errors that are not removed by conventional flat-field calibration. (Shapiro et al. 2019) | |  |

PPL is a JPL/Caltech facility originally established for the evaluation of VIS/NIR detectors used in challenging, high-precision astronomical measurements such as weak gravitational lensing or extreme precision exoplanet radial velocities. The PPL testbed projects customizeable scenes (e.g. tens of thousands of point sources or other shapes like galaxies or spectra, see Figure 1-6) onto detectors to emulate data that can be analyzed with realistic photometry or astrometry analysis pipelines, enabling testing detectors with a stimulus representative of missions and instrument requirements such as those needed for detecting the IGM in the FUV and NUV. Systematics that affect these measurements are thus probed directly with high statistical significance rather than modeled from analyses of darks, flats or simpler test patterns (Figure 1-7). The data generated by combining these capabilities will be uniquely comprehensive.

### On-sky observations with ground-based telescope

The UA team (Institutional-PI Hamden and postdoc, Dr. Nicole Melso) has previously led the development of a ground-based instrument, the Circumgalactic H-alpha Spectrograph (CHαS) that has been commissioned at the MDM 2.4-m Hiltner telescope on Kitt Peak, AZ. CHαS incorporates a microlens array slicer to feed a fast spectrograph that, together with a narrowband filter, is capable of obtaining extremely deep, wide-field velocity-resolved maps of H-alpha and other emission line gas from the circumgalactic medium of nearby galaxies. Currently CHαS is using the MDM Blue 4K CCD detector (STA0500A) with 15 micron pixels, 5 e- read noise and 0.01 e-/s/pixel dark current @-124°C (Melso 2022) during standard operating conditions. Our proposed Skipper devices would significantly improve on both performance specifications, allowing CHαS to achieve its science goals in 2-4x lower exposure time. As an easy to access on-sky testbed, with significant availability (the MDM telescopes are typically undersubscribed), full frame coverage, and tooled with calibration lamps and sky calibration targets, CHαS is an ideal platform for demonstrating device performance in a realistic and demanding astrophysical measurement. We propose to test at least one device (in the visible) on CHαS during the proposed period. Scientific results will include astrophysical findings of the CGM of nearby galaxies, complemented by technical characterization of efficiency, noise and photometric accuracy, readoute times, and stability of the device.

### Maturation of Skipper CCDs through radiation testing

L2 is a likely orbit for a future HWO, making high energy solar protons and galactic cosmic rays the dominant source of damage with a split of approximately 90% and 10% respectively [Crowley 2016]. High energy protons damage the underlying bulk silicon, creating defects that result in increased mean thermal dark current and the formation of isolated ‘hot pixels.’ The protons also form bulk traps that can result in increased Charge Transfer Inefficiency (CTI).

Finally, devices accumulate a Total Ionizing Dose (TID) while in flight as a result of ionizing energy loss due to protons and cosmic rays forming traps within gate oxides. TID results in a flat band voltage shift, increased dark current, image lag, read noise and RTS [Soman 2015]. TID effects are characterized using irradiation with gamma rays, where a negligible displacement damage dose is introduced compared to the total delivered TID.

We will plan radiation testing based on L2 environment—the likely orbit for a future 6-m HWO Great Observatory. We will focus on the effects of total ionizing dose (TID) and displacement damage dose (DDD) with exposure to gamma ray and MeV protons, and will assess the effect of irradiation on key parameters of the detector such dark current, QE, trap density, and CTI through two sets of tests: 1) room temperature, unbiased devices will be irradiated and will be evaluated for the above-mentioned parameters before and after irradiation; 2) we will operate the devices cold and will irradiate the devices and evaluate parameters before and after irradiation.

We will use previously-developed customized test dewar for simultaneous operation of two 2D-doped detectors (Figure 10-4). This dewar and associated hardware and controllers have been used under prior SAT programs for radiation testing of delta-doped EMCCDs at Loma Linda University—a facility capable of providing the needed radiation environment. We will use JPL radiation group facilities for TID testing.

## Contributions of Principal Investigator and Key Personnel

Principal Investigator

Dr. Shouleh Nikzad will provide the overall direction for the task and coordinate the work of all the co investigators. She is a condensed matter physicist and materials, detector, and instrument expert with over 30 years of experience in detector and instrument development and delivery.

Key Personnel

Prof. Erika Hamden, CoI has extensive experience in photon counting detectors, and has acted as project scientist for a sub-orbital balloon flight and submitted several Explorer proposals as PI. She is a Roman Technology Fellow and will lead the noise and dark current evaluation protocol in terms of science requirements and future instrument needs. She will also lead the on-sky observation as a reach goal.

Dr. April Jewell, CoI is a chemist with 10+ years’ experience with the development and deployment of 2D-doped detector and coatings technologies and will perform wafer preparation and MBE processing, and lead the ALD graded coating development.

Dr. Gillian Kyne, CoI is an expert in detector characterization and has been the detector scientist on FIREBall-2 for the past seven years. She delivered the detector system to FIREBall-2 for the 2018 flight and is a recognized expert on NuVu controllers. She has had a key role in Roman-CGI environmental testing of EMCCDs baselined for CGI and is an expert in single photon counting detectors and their characterizaiton. She will lead the characterization and environmental testing of the detectors.

Dr. John Hennessy, CoI is an expert in developing ALD processes, AR coatings, and development of integrated bandpass filters on detector. He will lead the effort and design and implementation of ALD AR coatings and filters.

Dr. Chaz Shapiro, CoI is director of the Precision Projector Laboratory (PPL). He will lead hardware setup and data acquisition and will participate in data analysis.

### Collaborators and Consultants

Mr. Roger Smith, Collaborator, is an expert in detectors with extensive experience in detailed characterization of detectors and their use in focal planes and systems. He will assist CoI-Shapiro on the PPL measurements and will use synergistic programs to provide Skipper characterization.

An advisory group at JPL comprising John Ziemer, David Redding, Rhonda Morgan and other members of large telescope studies (LUVOIR, HabEx, and HDST) will serve as consultants for development path toward requirements of future Great Observatory—the 6-m HWO Telescope.

## Work Plan

The proposed technology aims to address the technology gaps (Astrophysics Technology Gaps 2022). The photon counting capability as evidenced by the SNR, the photon resolving properties through histograms, QE in the UV spectral range, and uniformity will be measured in the work plan described below. The measured detector metrics and performance will be compared with and evaluated against the quantitative goals as summarized in the STM (Table 1-1). The stepwise, methodical approach to developing this new detector will be accomplished through the work plan described below.

In the first year, we will procure detectors and perform extensive characterization to establish data on quantum efficiency, read noise, dark current as a function of temperature, linearity and pixel response nonuniformity (PRNU). We will work with both vendors to have access to their latest devices, with analog to digital converter (ADC) esign and noise data from those devices. Because our MBE growth and ALD deposition technologies are performed on the back surface, the work done on basic devices will carry to the more advanced designs. We will procure two wafers each of the STA Skipper CCD and LBNL Skipper CCD detectors for post fabrication processing at JPL and begin the processing. Wafer level processing and optimization will be performed serially and will include thinning, surface preparation, and 2D doping. We will design AR coatings and detector-integrated UV bandpass filters for optimized performance in the NUV-NIR spectral range. Wafers will be probed and diced, and die will be packaged for testing. Detailed characterization will be performed at UA and JPL both for absolute measurments and with different emphasis—for example, while both organizations will measure the noise, QE, dark current, and uniformity, JPL’s QE characterization capability spans FUV to near infrared and is better equipped for absolute measurements while UA’s has the infrastructure and capability for high precision dark current measurement. Additionally, our collabortors at Caltech will use synergistic programs and provide addtional characterization of our devices. We will begin working with UA to incorporate a 2D-doped Skipper CCD into the ground-based instrument at Kitt Peak observatory.

In year two we will complete wafer processing and implement broadband and NUV coatings and filters. Using JPL facilities at the UV detector characterization lab and the PPL, we will perform detailed characterization of devices produced in years 1 and 2 and optimize the design of coatings as we apply them to devices and characterize devices. We will use existing dewars and characterization setup that had been developed for the testing silicon devices and characterizing of UV QE, response uniformity, stability, and visible rejection ratio for the NUV devices. Noise, photon counting, and other device parameters will be characterized at UA and Caltech. Feedback from these will be used in the revised design and a lot run of wafers will be fabricated using Microchip foundry.

In years two and three, we will process the devices with revised design, characterize and advance the technology readiness level of 2D-doped Skipper detectors with integrated AR coatings and UV bandpass filters fabricated in years 1 and 2 will be characterized in JPL’s detector characterization lab and PPL. Radiation testing will be performed to evaluate the stability of key detector parameter parameters in a realistic radiation environment for NASA’s Great Observatories. We will continue to support UA in their ground-based astronomical observations using a 2D-doped Skipper CCD.

### Key Milestones

The schedule in Figure 1-8 shows the workflow to achieve the key milestones (triangles).

### Management Structure

Dr. Shouleh Nikzad of JPL is the PI of the proposed investigation. She is solely responsible for the quality and direction of the proposed research and the proper use of all awarded funds. She is also responsible for all technical, management, and budget issues and is the final authority for this task. As detailed in the proposal’s *Inclusion Plan*, PI-Nikzad will ensure that best practices are implemented for running an inclusive team while also positively impacting a future workforce that is diverse in a community that is inclusive. The Co-Is report to and take direction from the PI and will provide all the management data needed to ensure that she can effectively manage the entire task. She will direct and coordinate the efforts of the co-investigators and collaborators at JPL and University of Arizona, and Caltech as well as the subcontractors and vendors. The Co-Is report to the PI, and will provide the data to ensure effective overall task management by the PI.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Milestone | Year 1 | | | | Year 2 | Year 3 |  |  |
| Q1 | Q2 | Q3 | Q4 |  |  |  |
| Demonstrate and Evaluate UV-Vis Photon Counting (PC) Detectors using Skipper Artchitecture |  |  |  |  |  |  |  |  |
| Procure: Skipper CCD Wafers from two sources |  |  |  |  |  |  |  |  |
| End to end post-fab process thru 2D doping (iterative) |  |  |  |  |  |  |  |  |
| Characterize 2D doped Skippers (Vis) and Standard |  |  |  |  |  |  |  |  |
| Fabricate New Lot Run of Devices |  |  |  |  |  |  |  |  |
| Procure lot run from one source based on feedback |  |  |  |  |  |  |  |  |
| End to end post-fab process thru 2D doping (iterative) |  |  |  |  |  |  |  |  |
| Characterize at UA for noise, uniformity, cross talk, photon counting |  |  |  |  |  | d |  |  |
| Demonstrate UV and Solar Blind PC Detectors |  |  |  |  |  |  |  |  |
| Design graded coatings for Vis-NIR range |  |  |  |  |  |  |  |  |
| Implement on 2D-doped Skipper CCDs |  |  |  |  |  |  |  |  |
| Characterize Lot Run |  |  |  |  |  |  |  |  |
| Characterize for noise characterization, optimize for photon counting, MTF, system level testing |  |  |  |  |  |  |  |  |
| Characterize QE, uniformity, rejection ratio, & dark (iterate with filters, coatings) |  |  |  |  | d |  |  |  |
| System Testing Comparison with Other Photon Counting Approaches |  |  |  |  |  |  |  |  |
| Compare 2D-doped Skipper w 2D-doped EMCCD |  |  |  |  |  | d |  |  |
| On Sky Testing |  |  |  |  |  |  |  |  |

**Figure 1-8**. Schedule and Key Milestones

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# Inclusion Plan

## Potential Barriers to Creating an Inclusive Environment

Our team comprises experts from three different institutions, which are both geographically and culturally separated. For example, there are possibilities of JPL personnel dividing their time between research and flight projects (or multiple research projects), whereas students typically work on a signle project. While this brings more knowledge and experience to the collaboration, it does mean that more deliberate planning for meetings and communication has to be in place for students to have access to the team members.

In general, in a project such as this, potential barriers to an inclusive environment include the dispirate locations for the work, as well as the wide variety of scientific specialites of the team. In such a situation, it is easy for people to become silo’ed off from one another or to not be clear about what tasks others are working on and why.

## Approach to Overcoming Potential Barriers to an Inclusive Environment

Our team will overcome the barriers listed in 3.1 by setting up clear communication channels for all team members. This will be done via regular meetings of the entire team, in addition to regular sub-team meetings as needed. In-person team meetings will happen annually. All documents will be shared via GoogleDrive (as allowable) and accessible to all team members via their institutional login. Finally, PI Nikzad will check in regularly with each team member to ensure they feel connected and part of the team.

For additional development, early career team members, including postdocs and students, will take the lead on papers presenting results. This will provide them with critical training and allow them to grow as scientists and leaders.

## Contributions to the Development of an Inclusive Workforce

Our collaboration is well known as an inclusive team, with good representation of female scientists and people of color—including the PI and three of the CoI’s. Additionally, our team has members with diverse backgrounds in chemistry, physics, cosmology, astrophysics, and electrical engineering.

PI-Nikzad is recognized for forming successful and productive teams of scientists and engineers with diverse backgrounds. She is committed to best practices in diversity, inclusion, equity, and accessibility. She was selected through a highly-competitive process to the inaugural JPL Inclusion Advisory Committee where she co-chaired the subcommittee for internal communications. She also served on the SPIE’s Equity Diversity, and Inclusion Committee. While she had learned from personal experience—the first woman to head JPL’s Science Division and one of only four female JPL Fellows—and through her leadership experience—hiring, nurturing, and mentoring a diverse team—she has also been training and educating herself in running inclusive meetings, how to be an inclusive leader, and how to be an effective advocate and bystander ally.

The University of Arizona is an MSI (more specifically a Hispanic Serving Institution) and Co-I, Prof. Hamden’s group there consists of >50% female scientists and >50% people of color. Her students are part of the next generation of instrument builders, and will be trained on both detector development as well as astronomical observing, data analysis, and leadership. In addition, the team members will have the opportunity to go to JPL and explore opportunities there which would not otherwise be available to them.

There is no substitute for seeing what you want to be and having women and minorities in leadership positions is a powerful way to help develop an inclusive workforce of the future. With any other endeavor, no doubt, we are still learning to make better teams and we will share our experience both in successesses and lessons learned.

# Biographical Sketch(es)

## Principal Investigator

**Shouleh Nikzad**

Fellow, Senior Research Scientist, Principal Engineer, Science Division Lead

Jet Propulsion Laboratory, California Intitue of Technology

4800 Oak Grove Drive • Pasadena, CA 91109; MS 183-335

[shouleh.nikzad@jpl.nasa.gov](mailto:shouleh.nikzad@jpl.nasa.gov); (818) 354-7496

Relevant Experience

Nearly 30 years of experience in ultraviolet detectors, detectors, UV instrument technologies and UV spectrometers and cameras research, development, and deployment. She leads a team in developing UV systems including spectrometers, and ultraviolet devices. Has led the successful delivery ultraviolet detectors and technologies to suborbital flights, ground-based observatories, and CubeSats.Initiated, developed and managed successful detector and imaging array research and development funded in collaboration with JPL groups, universities, and industrial partners.

Education

* Ph. D., Applied Physics, Caltech, 1985-1990
* M.S., Electrical Engineering, Caltech, Dec 1983
* B.S., Elecrical Engineering, Honors, University of Southern California, 1982

Professional Experience:

JPL Science Division Lead (2022-), Fellow (2020-), Senior Research Scientist (2012-), Principal Engineer (2006-), Technical Supervisor and Lead, *Advanced Detector Arrays, Imaging Systems, & Nanoscience Group (2001-22),* Senior A Member of Technical Staff (2000), Senior Member of Technical Staff (1998), Technical Group Leader (1996), Member of Tech Staff (1992)

Caltech Visiting Assoc, Astrophysics (2011-); Lecturer Eng. & Applied Science (2015-)

Caltech Post-Doctoral Research Fellow (1990-1992)

ANL Graduate Research Fellow at Argonne National Laboratory (1988-1990)

Caltech Research Assistant/Teaching Assistant (1985-1990)

Kratos Aviation Electrical Engineer; analog circuit design (1984)

Pacific Infrared Electrical/Optical Engineer: digital design, optics (1982-1984)

Selected Professional Activities and Service

COPAG-Eexecutive Committee Chair (2022-)

NASA SBIR Subtopica Manger, Detectors Gamma Ray to Ultraviolet

Optica Fellow (2022); IEEE Fellow (2020); SPIE Fellow (2016); APS Fellow (2012)

Selected Professional Honors, Awards, and Recognitions

IEEE *Aron Kressel Award*, 2022; Scientific Detector Workshop Board’s *Lifetime Achievement Award Asteroid Nikzad, 2022*; SPIE *Luminary, Detector Technology for Astrophysics*, 2021; SPIE *Aden and Marjorie Meinel Technology Achievement Award*, 2021; IEEE *Distinguished Lecturer Award—Image Sensors for Space Exploration*, 2019-2020

NASA Outstanding Leadership Medal, 2020

JPL Fellow (2020);

National Academy of Inventors, 2017

Selected Relevant Patents

“Using a Delta-doped CCD to Determine the Energy of a Low-energy Particle”, S. Nikzad, D. Croley, and G. Murphy, US patent # 6278119

“Hybrid Advanced Detector for Low-energy Particle Detection”, S. Nikzad, T. Cunningham, E. Fossum, and G. Soli, US patent #6346700

“Delta-doped CCDs as low-energy Particle Detectors and Imagers”, S. Nikzad, M.Hoenk, and M. Hecht, US patent # 6403963.

“Piezoelectrically Enhanced Photocathode”, S. Nikzad, R. Beach, R. Strittmatter, L. D. Bell, US Patent # 7,592,747.

Refereed Publications

Nikzad, S., et al., "High-efficiency UV/optical/NIR detectors for large aperture telescopes and UV explorer missions: development of and field observations with delta-doped arrays," J. Astron. Telesc. Instrum. Syst.3(3), 036002 (2017), doi: 10.1117/1.JATIS.3.3.036002.

Nikzad, S. et al., "High-Performance Silicon Imaging Arrays for Cosmology, Planetary Sciences, and other Applications," Invited Paper in International Electron Devices Meeting, 2014.

Nikzad, S., et al. (2012). Delta doped EMCCD with Absolute Quantum Efficiency over 50% in the near to far Ultraviolet Range for Single Photon Counting Applications, Applied Optics, 51, 365, 2012.

Kyne, G. Hamden, E.T., Nikzad, S., et al., “Delta doped Electron Multiplying CCD for FIREBall-2,”, J. of. Astronomical Telescopes Instruments, & Systems 6(1), 011007 (2020).

Nikzad, S. et al., “High Performance Silicon and III-Nitride-Based UV and UV/Optical Imaging Detectors,” in the World Scientific Publishing Company Handbook of Astronomical Instrumentation Ed. Anna Moore and David Burrows, WS, 2021.

Nikzad, S. et al. (2014), "High-Performance Silicon Imaging Arrays for Cosmology, Planetary Sciences, and other Applications," Invited Paper in International Electron Devices Meeting.

Hamden, E., Greer, F., Blacksberg, J., Hoenk, M.E., Nikzad, S., and Schiminovich, D. (2011). Anti-Reflection Coatings for use in UV detector design, Applied Optics, 50, 4180–4188.

Nikzad, S. (2014). High Performance Silicon Imagers and their Applications, in High Performance Silicon Imaging. Ed., D. Durini, Woodhead Publishing, Elsevier.

Shouleh Nikzad, et al. (2014). Digital Imaging for Planetary Exploration, in Handbook of Digital Imaging. Ed., Michael Kriss. Whiley Books.

S. Nikzadand M.E. Hoenk, “High-performance silicon imagers, back illumination using delta and superlattice doping, and their applications in astrophysics, medicine and other fieldsin *High Performance Silicon Imaging: Fundamentals and Applications of CMOS and CCD Image Sensors, Second Edition,* D. Durini, ed. (Elsevier), pp. 473–500 (2020).

S. Nikzad*, M.E. Hoenk, J.J. Hennessy, and L.D. Bell,* “Ultraviolet and Optical Instrumentation Technologies for Astrophysics and Astronomy,” *in Handbook of Astronomical Instrumentation,* Eds. A. Moore, D. Burrows, World Scientific Publishing Company, 2021.

Vincent Picouet, et. al., “End-to-end ground calibration and in-flight performance of the FIREBall-2 instrument,” Journal of Astronomical Telescopes Instruments, and Systems 6(4), 044004 (2020). <https://doi.org/10.1117.JATIS.6.4.044004>

E. Hamden, et al., “FIREBall-2: The Faint Intergalactic Medium Redshifted Emission Balloon Telescope,” *The ApJ,* ***898*** *170, 2020.* <https://doi.org/10.3847/1538-4357/aba1e0>

T. Greffe, et al., “Characterization of Low Light Performance of a CMOS sensor for Ultraviolet Astronomical Applications,” [J. of Astronomical Telescopes, Instruments, and Systems, 8(2)](https://www.spiedigitallibrary.org/journals/Journal-of-Astronomical-Telescopes-Instruments-and-Systems/volume-8/issue-2), 026004 (2022). <https://doi.org/10.1117/1.JATIS.8.2.026004>

## Co-Investigator (s)

Erika Hamden

University of Arizona, Steward Observatory, Department of Astronomy • 933 N Cherry Ave, Tucson, AZ 85719 • 520-621-9524 • hamden@email.arizona.edu

|  |  |  |
| --- | --- | --- |
| **Education:** | | |
| Columbia University | Ph.D Astronomy, 2014 | |
| Columbia University | M.Phil. Astronomy, 2010 | |
| Columbia University | M.A. Astronomy, 2009 | |
| Harvard College | A.B. Astronomy and Astrophysics, 2006 | |
| **Professional Experience:** | | |
| * Assistant Professor, University of Arizona, Steward Observatory | | 2018-Present |
| * Postdoctoral Fellow, California Institute of Technology, Astronomy Department | | 2014-2018 |
| * Graduate Research Fellow, Columbia University, Astronomy Department | | 2007-2014 |
| **Relevant Project Experience:** | | |
| * PI of *Hyperion*, a Medium Explorer Mission Concept proposed in 2021. A FUV long slit spectrograph designed to observe fluorescent emission from molecular hydrogen in galactic star forming regions. Rated Category I but not selected. * Deputy PI of *Aspera*, a Pioneers SmallSat mission selected in 2021, PI: Carlos Vargas. An EUV spectrograph designed to observe OVI emission from edge-on galaxy halos. * High efficiency UV detector development and EMCCD detector development. Roman Fellow. * Institutional PI of FIREBall-2 (PI: Chris Martin), previously Project Manager, Project Scientist. Currently overseeing optical re-alignment and calibration. In her past role, Prof. Hamden oversaw all aspects of the FIREBall-2 project, including the detector and associated subsystems, designed critical hardware, and coordinated a team of over 30 people across 5 institutions and 2 countries for a 2018 flight. * Founder and organizer of the PI Launchpad | | |
| **Selected Honors, Awards, Professional Achievements:** | | |
| * Group Achievement Award to FIREBall-2 Detector Team, 2020- NASA * NASA Early Career Public Achievement Medal, 2020 * Presidential Early Career Award for Scientists & Engineers, 2019- NASA * TED Fellow, 2019- TED; IF/THEN Ambassador, 2019- AAAS * Nancy Grace Roman Technology Fellowship, 2015- NASA * R.A. & G.B. Millikan Prize Postdoctoral Fellowship in Experimental Physics, 2017- Caltech * NSF Astronomy and Astrophysics Postdoctoral Fellowship, 2014- NSF * Group Achievement Award to Advanced UV/Optical Detector Team, 2014- NASA | | |
| **Selected Publications:** | | |
| 1. “FIREBall-2: The Faint Intergalactic Medium Redshifted Emission Balloon Telescope .E. T. Hamden, et. al. The Astrophysical Journal, Volume 898, Issue 2, id.170, 2020. 2. “Multi-filament inflows in forming protogalaxies”. D. C. Martin, D.O. Sullivan, M. Matuszewski, E. T. Hamden, A. Dekel, P. Morrissey, J. D. Neill, S. Cantalupo, J. X. Prochaska, C. Steidel, R. Trainor, A. Moore. NatureVolume 3, p. 822-831, 2019. 3. “The Diffuse Galactic Far Ultraviolet Sky”. E. T. Hamden, D. Schiminovich, and M. Seibert. Astrophysical Journal, 799:180H, Dec. 2013 7. 4. “Ultraviolet anti-reflection coatings for use in silicon detector design”. E. T. Hamden, F. Greer,M. E. Hoenk, J. Blacksberg, M. R. Dickie, S. Nikzad, D. C. Martin, and D. Schiminovich. Applied Optics, 50:4180–4188, July 2011. | | |

John Hennessy, Ph.D.

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91109

M/S 300-315, (818) 354-4808, john.j.hennessy@jpl.nasa.gov

Proposed Role in the Investigation

Dr. Hennessy will be a co-Investigator on the proposed effort. His primary roles will be to participate in project and process planning, model and develop detector coatings using atomic layer deposition processes, and contribute to data analysis and interpretation.

Relevant Experience

Technologist in the Advanced Detectors, Systems, and Nanoscience Group at JPL with more than 10 years of experience in the development of atomic layer deposition (ALD) systems and processes for optical and microelectronic applications. Dr. Hennessy has investigated the use of ALD films as coatings for advanced UV/visible detector applications, FUV mirror coatings, and as passivation layers for III-nitride avalanche photodiodes. He has led research efforts in JPL and NASA R&D programs for metal fluoride thin films with particular emphasis on improving the optical performance of detector-integrated filters and reflective coatings in the far ultraviolet.

Education

* Ph.D., Electrical Engineering, Massachusetts Institute of Technology, 2010
* M.S., Electrical Engineering, Massachusetts Institute of Technology, 2004
* B.E., Electrical Engineering, The Cooper Union, 2002

Profession Activities & Honors

* NASA Early Career Public Achievement Medal (2020).
* JPL Voyager Award. For individual achievements related to the development of new ALD materials and processes (2017, 2018, & 2019).
* SPIE Rising Researcher Award (SPIE Defense + Commercial Sensing, 2017)
* NASA Group Achievement Awards, achievements in UV imagers (2014 & 2020).
* Senior Member IEEE (EDS & Photonics), Member AVS, SPIE

Selected Relevant Publications

J. Hennessy, and S. Nikzad, “Atomic Layer Deposition of Lithium Fluoride Optical Coatings for the Ultraviolet,” Inorganics 6(2), 46 (2018).

B. Fleming, M. Quijada, J. Hennessy, A. Egan, J. Del Hoyo, B. A. Hicks, J. Wiley, N. Kruczek, N. Erickson, and K. France, “Advanced environmentally resistant lithium fluoride mirror coatings for the next generation of broadband space observatories,” Appl. Opt. 56 (36), 9941-9950 (2017).

J. Hennessy, K. Balasubramanian, C. S. Moore, A. D. Jewell, S. Nikzad, K. France, and M. Quijada, “Performance and prospects of far ultraviolet aluminum mirrors protected by atomic layer deposition,” J. Astron. Telesc. Instrum. Syst. 2 (4), 041206 (2016).

J. Hennessy, A. D. Jewell, M. E. Hoenk, and S. Nikzad, “Metal-Dielectric Filters for Solar-Blind Silicon Ultraviolet Detectors,” Applied Optics 54, (2015).

J. Hennessy, A.D. Jewell, F. Greer, M.C. Lee, and S. Nikzad, “Atomic layer deposition of magnesium fluoride via bis(ethylcyclopentadienyl)magnesium and anhydrous hydrogen fluoride,” JVST A 33, 01A125 (2015).

April Jewell

Jet Propulsion Laboratory

4800 Oak Grove Drive, Mail Stop 300-315; Pasadena, CA 91109

818-354-3474; april.d.jewell@jpl.nasa.gov

Proposed Role in the Investigation

Dr. Jewell will be a co-Investigator on the proposed effort. Her primary roles will be to participate in project and process planning, perform the 2D-doping processing work, and contribute to data analysis and interpretation.

Experience Related to the Investigation

Dr. Jewell has 10+ years’ experience working with, producing, and characterizing delta-doped, silicon-based devices. She also has extensive experience using atomic layer deposition to develop optical coatings for device-integrated coatings and filters, as well as standalone optical components.

2015–present Microdevices Engineer/Technologist; Jet Propulsion Laboratory

Education

Ph.D., Chemistry, Tufts University, 2012

B.S., Chemistry, George Washington University, 2002

Honors/Awards

2019 Charles Elachi Award for Outstanding Early Career Achievement, JPL

2019 Rising Researcher Award, SPIE

Related Publications

A.D. Jewell, et al., "Optimizing silicon UV detector response with antireflection coatings, solar-blind bandpass filters and linear variable filters," in *Proc. SPIE* **12181**: Space Telescopes and instrumentation 2022: Ultraviolet to Gamma Ray, (2022) 121810G.

A.D. Jewell, et al., “Toward Ultrafast, Ultra-stable Imaging Arrays: Superlattice doping to enhance the performance of Backside-illuminated 3D-hybridized Silicon Photodetectors.” *JVSTA*; **38** (2020) 023203.Special Collection 30 Years of the Nellie Yeoh Whetten Award – Celebrating the Women of the AVS

A. D. Jewell et al., “Low-temperature homoepitaxial growth of two-dimensional antimony superlattices in silicon,” *JVSTA* **36**(6), 061513 (2018)

A. D. Jewell et al., “Ultraviolet detectors for astrophysics missions: a case study with the star-planet activity research cubeSat (SPARCS),” in *Proc. SPIE* **10709**: High Energy, Optical, and Infrared Detectors for Astronomy VII, (2018) 107090C:8

A. D. Jewell et al., “Detector performance for the FIREBall-2 UV experiment,” in Proc. SPIE 9601: UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XIX **9601**, O. Siegmund et al., Eds., p. 0N:8, San Diego, CA, USA (2015)

**Gillian Kyne**

Jet Propulsion Laboratory, California Institute of Technology

Tel: (626) 497-3610, gillian.kyne@.jpl.nasa.gov

Proposed Role in the Investigation

Dr. Kyne will be a co-Investigator on the proposed effort. Her primary roles will be to participate in project planning, lead the characterization, and contribute to data analysis and interpretation.

**RELEVANT EXPERIENCE**

Detector scientist for 8 years for a balloon mission called FIREBall-2 with extensive experience in detector characterization, specifically for photon counting detectors, EMCCDs as well as experience with standard CCDs and CMOS arrays. In-depth knowledge of nuanced detector behavior and in using the special Controller and using for CCD clocking optimization. Full development of the camera flown Sept. 2018 and funded for sflight in 2023 and 2034. Extensive experience with cryo and vacuum development and building software for detector operations. In charge of detector characterization in detector development and for ground-based observing as well as future space-based missions.

**EDUCATION**

Ph.D. Physics & Astronomy, 2014.

B.S. Applied Physics, 2009.

**EMPLOYMENT**

2020-: JPL Technologist II in *Advanced Detector Systems and Nanoscience* and Roman-CGI2019-2020: JPL Postdoctoral Research Scholar & Detector Scientist in Advanced Detector Systems and Nanoscience (389E) and WFIRST CGI.

2015-2019: Caltech Postdoctoral Research Scholar & Detector Scientist for FIREBall-2

**SELECTED RECENT PUBLICATIONS**

**Kyne, G.,** Hamden, E.T., Nikzad, S., Hoadley,K., Jewell, A., Jones,T., Hoenk, M., Cheng, S.D., Martin, C., Lingner,N., Schiminovich,D., Milliard, B., Grange, R., Daigle,O., "Delta-doped electron-multiplying CCDs for FIREBall-2," *J. Astron. Telesc. Instrum. Syst.***6**(1), 011007 (2020). **Kyne, G.**, Hamden, E. T., Lingner, N., Morrissey, P., Nikzad, S., and Martin, D. C. (2016a). The faint intergalactic-medium red-shifted emission balloon: future UV observations with EMCCDs. In High Energy, Optical, and Infrared Detectors for Astronomy VII, volume 9915, page 91507.

**Kyne, G.**, Lara, D., Hallinan, G., Redfern, M., and Shearer, A. (2016b). An investigation of the Eigenvalue Calibration Method (ECM) using GASP for non-imaging and imaging detectors. Experimental Astronomy, 41:43–66.

Moran, P., **Kyne, G.**, Gouiffès, C., Laurent, P., Hallinan, G., Redfern, R. M., and Shearer, A. (2016). A recent change in the optical and γ-ray polarization of the Crab nebula and pulsar. Monthly Notices of the Royal Astronomical Society, 456:2974–2981.

Nikzad, S., Jewell, A. D., Hoenk, M. E., Jones, T., Hennessy, J., Goodsall, T., Carver, A., Shapiro, C., Cheng, S. R., Hamden, E., **Kyne, G.**, Martin, D. C., Schiminovich, D., Scowen, P., France, K., McCandliss, S., and Lupu, R. E. (2016). High Efficiency UV/Optical/NIR Detectors for Large Aperture Telescopes and UV Explorer Missions: Development of and Field Observations with Delta-doped Arrays. ArXiv e-prints

Dr. Charles Shapiro

Jet Propulsion Laboratory • California Institute of Technology

4800 Oak Grove Drive • MS 300-315 • Pasadena, CA 91109

(818) 354-7894 • Charles.A.Shapiro@jpl.nasa.gov

Proposed Role in the Investigation

Dr. Shapiro will be a co-Investigator on the proposed effort. His primary roles will be leading the Projector Precision Laboratory characterization, contribute to data analysis and interpretation.

Relevant Experience

Shapiro has 10 years of experience in precision characterization of image sensors for astronomy. He works on detector characterization in the JPL Advanced Detectors, Systems, and Nanoscience group, which innovates detector technologies for NASA missions. He specializes in understanding detector behavior that impedes challenging astronomical measurements such as gravitational lensing or exoplanet detection. As a former theoretical cosmologist, he brings a broad perspective to detector characterization, understanding devices in terms of their intended science measurements and mission figures of merit. He leads the Precision Projector Laboratory, a facility designed to study detector-induced measurement errors by emulating realistic data. Novel PPL experiments performed using hybrid CMOS near-infrared detectors have led to unique findings (such as intra-pixel response and inter-pixel nonlinearity), which influenced projects such as WFIRST, Euclid, and JWST. Shapiro oversees PPL upgrades, data-acquisition, and detector analysis by staff, postdocs, and students from JPL and Caltech campus.

Education

* Ph. D., Physics, University of Chicago, 2008
* B.S. with Honors, Physics, The Pennsylvania State University, 2002
* B.S., Mathematics, The Pennsylvania State University, 2002

Professional Experience:

**Current Positions:**

2016 – present Co-Lead of WFIRST Detector Working Group

2014 – present Manager and PI; Precision Projector Laboratory, JPL

2013 – present Staff Technologist; Advanced Detectors, Systems & Nanoscience, JPL

**Previous Positions:**

2016 – 2020 Visiting Faculty Associate; California Institute of Technology

2014 – 2016 Lead of WFIRST Detector Requirements Working Group

2011 – 2013 NASA Postdoctoral Fellow; JPL

2008 – 2011 Postdoctoral Researcher; Institute of Cosmology & Gravitation, Portsmouth,UK

Selected Publications

* Shapiro, C. et al., “Precision Projector Laboratory: Detector Characterization with an Astronomical Emulation Testbed.” JATIS, Vol 5, id. 041503 (2019).
* Shapiro, C., et al. “Intra-pixel response characterization of a HgCdTe near infrared detector with a pronounced crosshatch pattern.” SPIE Proceedings, 2018.
* Plazas, A., Shapiro, C., et al., “Laboratory Measurement of the Brighter-fatter Effect in an H2RG Infrared Detector.” PASP, 130, 065004 (2018).
* Hamden, E., Jewell, A., Shapiro, C., et al. ``CCD detectors with high QE at UV wavelengths.’’ JATIS, Volume 2, id. 036003 (2016).

**Roger M. Smith**

Member of Professional Staff

Caltech Optical Observatories, California Institute of Technology

MC 11-17, 1200 E. California Blvd, Pasadena, CA 91125

Phone: (626) 395-8780 Fax: (626) 568-1517 E-mail: rsmith@astro.caltech.edu

Proposed Role in the Investigation

Roger Smith will be a collaborator on the proposed effort. His primary roles will be assisting the Projector Precision Laboratory characterization and general characterization.

Relevant Experience

Roger has spent 43 years developing instrumentation and detector systems for astronomy, and researching sources of systematic errors in NIR and optical sensors, most notably to develop the theory for image persistence. He currently leads the detector team at Caltech Optical Observatories which produces custom instruments for Palomar and Keck Observatories and TMT. He has collaborated with JPL to develop facilities in his lab to emulate proposed space missions using HgCdTe detectors: SNAP, JDEM, WFIRST, ELEKTRA, ZEBRA, HALO, FINESSE, and advisor to JPL for Kepler, Chemin, MMM, OCO, and SAGE projects. He has worked on EUCLID NIR detector testing. He is a member of the science team for SphereX and the UV Imager lead for the UVEX mission now in Phase A. He led development of the 600 megapixel ZTF CCD mosaic, and was a regular reviewer of DOE’s DECam and LSST acmeras, and DESI spectrographs. He is system architect for Next GenertaionPalomar Spectrograph, aand iss being active in sensor systems for IRIS and WFOS for TMT, and HISPEC and KPF for Keck. He is PI for an NSF-ATI grant, “Prototyping a new telescope design for unprecedented survey speed in the infrared” and has submitted an NSF proposal for development of a new skipper amplifier configuration to reduce readout time by a factor of ~250.

Education

1979 B.E, Electrical Engineering, University of Sydney, Australia

1977 B.Sc., Physics, University of Sydney, Australia

Professional Appointments

2001– present Lead Electronics Engineer, Caltech Optical Observatories

1983–2001: Engineering Project Manager, Cerro Tololo Inter-American Observatory

1979–1983: Electronics Engineer, Anglo-Australian Observatory.

Related Publications

Greffe, T.,  Smith, R.,  Sherman, M.,  Harrison, F., Earnshaw, H.,  Grefenstette, B., Hennessy, J., Nikzad, S., (2022) JATIS 8(2), 026004, “Characterization of low light performance of a complementary metal-oxide semiconductor sensor for ultraviolet astronomical applications”,  https://doi.org/10.1117/1.JATIS.8.2.026004

R. Smith, S. Kaye, “CCD speed-noise optimization at 1 MHz”, SPIE 10709, 2018

R. Smith, R. Dekany, et al. “The ZTF Observing System”, SPIE 9154, 2014

R.Smith, D.Hale, “Read noise for a 2.5μm cutoff Teledyne H2RG at 1-1000Hz frame rates”, SPIE 8435 (digital archive only), 2012.

R. Smith, M. Zavodny, G. Rahmer and M. Bonati, “A theory for image persistence in HgCdTe photodiodes”, SPIE 7021, 2008

R. Smith and G. Rahmer, “Pixel area variation in CCDs and implications for precision photometry”, SPIE 7021, p. 70212A, 2008

# **Table of Personnel and Work Efforts**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Name | Organization | Role | Work Commitment | | |
| Year 1 | Year 2 | Year 3 |
| Dr. Shouleh Nikzad | JPL | Principal Investigator | 0.21 | 0.20 | 0.20 |
| Dr. John Hennessy | JPL | Co-Investigator | 0.11 | 0.18 | 0.06 |
| Dr. April Jewell | JPL | Co-Investigator | 0.15 | 0.17 | 0.20 |
| Dr. Gillian Kyne | JPL | Co-Investigator | 0.35 | 0.48 | 0.50 |
| Dr. Chaz Shapiro | JPL | Co-Investigator | 0.10 | 0.10 | 0.10 |
| Prof. Erika Hamden | U of Arizona | Co-Investigator | 0.05 | 0.05 | 0.05 |
| Mr. Roger Smith | Caltech | Collaborator | diminimus | diminimus | diminimus |

# Current and Pending Support

## Current Awards

Shouleh Nikzad

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| S. Nikzad | Large Format, High Efficiency, UV/Optical/NIR Photon Counting Detectors | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | 12/01/22–  09/30/23 | 0.5 |
| E. Shkolnik | Monitoring the High-Energy Radiation Environment of Exoplanets around Low-mass Stars with SPARCS (Star-Planet Activity Research CubeSat) | APRA/NASA  Michael R. Garcia  +1 202 358 1053 Michael.R.Garcia@nasa.gov | 11/11/21–  06/30/24 | <1 |
| S. Nikzad | UV/VISIBLE PHOTON COUNTING AND IMAGING SILICON DETECTORS FOR PLANETARY SCIENCE INSTRUMENTS | PICASSO/NASA  Michael Lienhard  michael.a.lienhard@nasa.gov | 09/01/20  09/30/23 | 0.5 |

April Jewell

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| A. Jewell | Advanced Filter Solutions for Multiband and Broadband Imaging | APRA/NASA  Michael R. Garcia  +1 202 358 1053 Michael.R.Garcia@nasa.gov | 01/10/20–  09/30/23 | 3 |
| J. Hennessy | High performance, stable, and scalable UV aluminum mirror coatings using ALD | SAT/NASA  Nasser Barghouty  nasser.barghouty@nasa.gov +1 +1 202 358 1211 | 01/10/20–  09/30/23 | 1.8 |
| S. Nikzad | Large Format, High Efficiency, UV/Optical/NIR Photon Counting Detectors | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | 12/01/22–  09/30/23 | 2 |
| E. Shkolnik | Monitoring the High-Energy Radiation Environment of Exoplanets around Low-mass Stars with SPARCS (Star-Planet Activity Research CubeSat) | APRA/NASA  Michael R. Garcia  +1 202 358 1053 Michael.R.Garcia@nasa.gov | 11/11/21–  06/30/24 | <1 |
| M. Hoenk | High Performance FUV, NUV, and UV/Optical CMOS Imagers | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | 12/01/22–  09/30/25 | 2.4 |

John Hennessy

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| J. Hennessy | High performance, stable, and scalable UV aluminum mirror coatings using ALD | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | FY20-FY23 | 3.6 |
| F. Harrison | UVEX – MIDEX (Phase A) | Explorers/NASA  Linda S. Sparke  +1 202 358 7335  linda.s.sparke@nasa.gov | FY23 | 3.6 |
| M. Hoenk | High Performance FUV, NUV, and UV/Optical CMOS Imagers | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | FY23-FY25 | 1.8 |

Gillian Kyne

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| L. Harding | HTIDS / Development of a delta doped EMCCD space camera for UV spectroscopy: probing space weather with a CubeSat | HTIDS/NASA  Roshanak Hakimzadeh  [hakimzadeh@nasa.gov](mailto:hakimzadeh@nasa.gov) | FY 21-24 | 1 |
| Chris Martin | FIREBall-2 Detector | APRA/NASA  Michael R. Garcia  Michael.R.Garcia@nasa.gov  +1 202 358 1053 | 10/19-09/23 | 6 |
| E. Shkolnik | Monitoring the High-Energy Radiation Environment of Exoplanets around Low-mass Stars with SPARCS (Star-Planet Activity Research CubeSat) | APRA/NASA  Michael R. Garcia  Michael.R.Garcia@nasa.gov  +1 202 358 1053 | 06/22-12/22 | 0.5 |

Erika Hamden

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| Erika Hamden | Advanced Photon-Counting Detectors for UV-VIS Astronomical Use | APRA / NASA / Michael Garcia, 202-358-1053, Michael.R.Garcia@NASA.gov | 11/15/19–11/14/23 | 3.0 |
| Erika Hamden | The Faint Intergalactic-Medium Redshifted Emission Balloon (FIREBall-2): Trailblazing the Discovery of CGM Emission in the Low-Redshift Universe with Ground-Breaking Instrumentation and Innovative UV | APRA / NASA / Michael Garcia, 202-358-1053, Michael.R.Garcia@NASA.gov | 11/15/19-11/14/23 | 2.0 |
| Erika Hamden | Advance Photon-Counting Detectors for UV/VIS Astronomical Use | RTF / NASA / Mario Perez, 202-358-1535, Mario.Perez@NASA.gov | 07/14/20-07/13/23 | 0.12 |
| Erika Hamden | Understanding the Dark Current Plateau in Silicon CCDs | ASTRO (Aafaque Khan) / NASA / Hannah Jang-Condell, 907-484-1682, Hannah.Jangcondell@NASA.gov | 09/01/21-08/31/24 | Mentor |
| Erika Hamden | SURP FY2021 Proposal 26-Advancing Ultraviolet Detectors: Dark Current Characterization Towards Fundamental Understanding of Silicon Detectors for Future Astronomical Missions | SURP / JPL / Dr. Shouleh Nikzad, 818-354-7496, Shouleh.Nikzad@jpl.nasa.gov | 11/13/20-12/31/22 | 0.16 |
| Keri Hoadley | High Efficiency, High-Dynamic Range UV Blazed Gratings for NASA's Next Generation Space Observatories | APRA / U. Iowa (NASA) / Michael Garcia, 202-358-1053, Michael.R.Garcia@NASA.gov | 03/01/22-11/09/24 | 0.10 |
| Erika Hamden | Taming the Sharks: Dynamics and Dust in the High-Latitude 3D ISM with GALEX | ADAP / AURA & STScI / Cathy Donnellan, 410-338-2444, donnellan@stsci.edu | 09/19/22-04/30/25 | 1.0 |
| Erika Hamden | PI 101: Training in Mission Concept Development Across SMD | Heising-Simons Foundation / Kelly Hayashi, 650-887-0277 | 06/01/20-11/30/23 | 1.0 |
| Carlos Vargas | Aspera: Unveiling Missing Gas | Pioneers / NASA / Michael Garcia, 202-358-1053, Michael.R.Garcia@NASA.gov | 04/01/22-06/30/26 | 0.60 |
| Peter Milne | Studying Space Explosions in the Ultra-violet from the Ground: Installing a NUV CCD Camera on the Super-LOTIS Telescope on Kitt Peak | Mount Cuba Astronomical Foundation / J. Lang, jlang.MCAF@comcast.net | 12/01/22-11/30/23 | 0.14 |
| Chris Martin | FIREBALL-2: The Next Generation of UV Science, Technology and Leadership | APRA / Cal Tech (NASA) / Samantha Westcott, 626-395-6826, westcott@caltech.edu | 09/01/22-08/31/26 | 0.66 |
| Haeun Chung | Revisiting FUSE: O VI Emission Survey in Nearby Galaxies | ADAP / NASA | 01/01/23-12/31/25 | 0.50 |

## Pending Awards

Shouleh Nikzad

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| S. Nikzad | This Proposal. A High-Performance Ultraviolet Photon Counting Detector for Strategic Astrophysics Missions | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | 10/01/23–  09/30/26 | 2 |

April Jewell

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| A. Jewell | Linear Variable Filters for Ultraviolet Spectroscopy | APRA/NASA  Michael R. Garcia  +1 202 358 1053 Michael.R.Garcia@nasa.gov | 10/01/23–  09/30/26 | 1.2 |

John Hennessy

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| A. Jewell | Linear Variable Filters for Ultraviolet Spectroscopy | APRA/NASA  Michael R. Garcia  +1 202 358 1053 Michael.R.Garcia@nasa.gov | FY24-FY26 | 1.2 |
| F. Harrison | UVEX – MIDEX | Explorers/NASA  Linda S. Sparke  +1 202 358 7335  linda.s.sparke@nasa.gov | FY24-FY26 | 3.0 |
| S. Tuttle | Maratus: Mapping the Circumgalactic Medium in the FUV | APRA/NASA  Michael R. Garcia  Michael.R.Garcia@nasa.gov  (202) 358-1053 | FY23-FY25 | 0.7 |
| N. Kruczek | The FLUID Rocket Payload: Far- and Lyman-Ultraviolet Imaging of High-Redshift Galaxy Analogs | APRA/NASA  Michael R. Garcia  Michael.R.Garcia@nasa.gov  (202) 358-1053 | FY24-FY25 | 0.6 |
| A. Kenter | Development of Advanced Pixelated Si Sensors for the Next Generation of X-ray Observatories | SAT/NASA  Mario Perez  +1 202 358 1535  mario.perez@nasa.gov | FY24-FY26 | 0.3 |

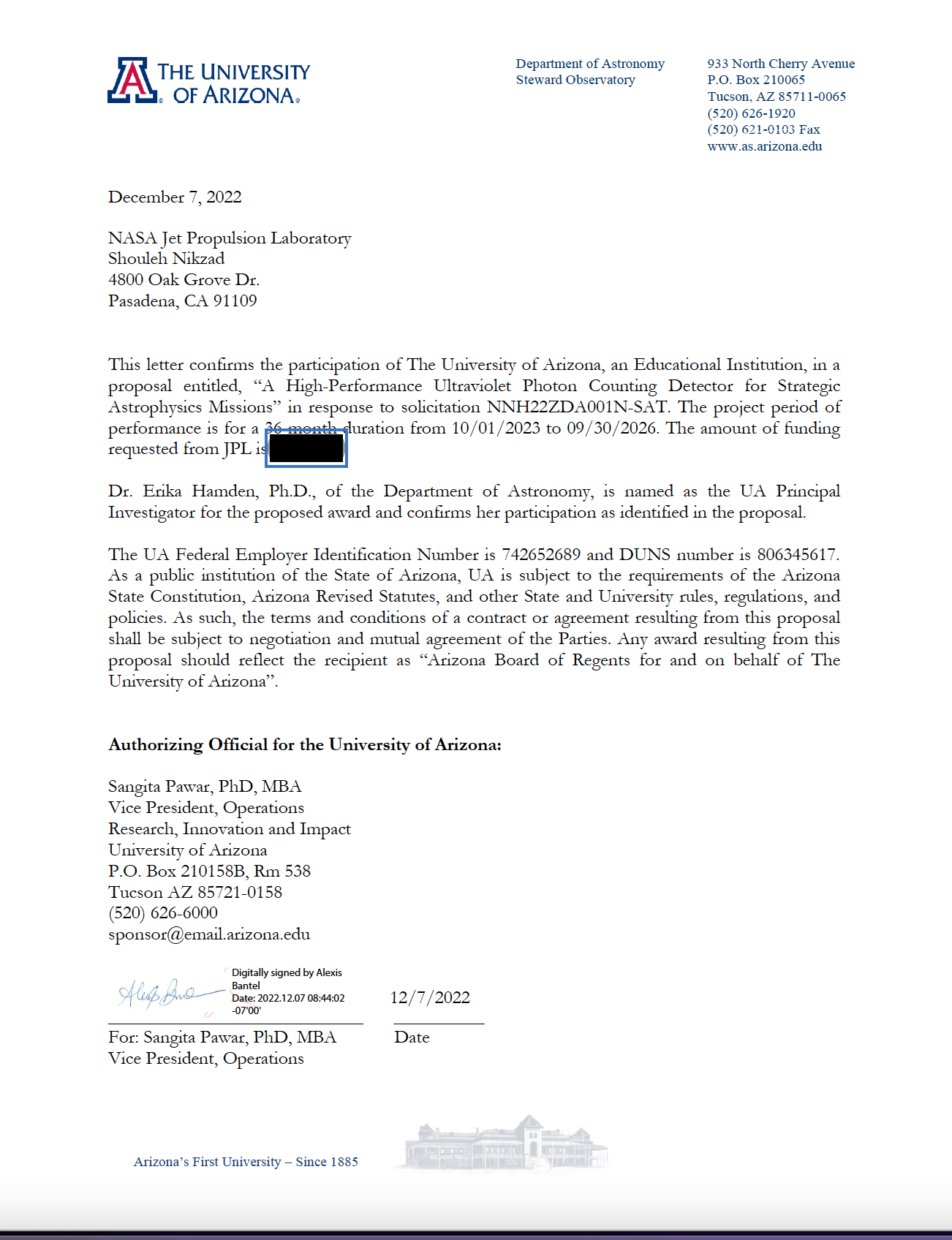
Gillian Kyne

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| J. Corliss | APRA/ High-Resolution Spectroscopy of Far UV Hydrogen Emission from Star Forming Regions using Spatial Heterodyne Interferometry | APRA/NASA  Dominic Benford  [Dominic.Benford@nasa.gov](mailto:Dominic.Benford@nasa.gov)  202-358-1261 | 10/23 – 09/26 | 1.2 |

Erika Hamden

| Name of Principal Investigator on Award | Award/Project Title | Program Name/ Sponsoring Agency/ Point of Contact telephone and email | Period of Performance | Commitment (Person-Months per Year) |
| --- | --- | --- | --- | --- |
| Erika Hamden | Observing the Faint Halos of Nearby Galaxies | Alfred P. Sloan Foundation | 09/15/23-09/14/25 | 0.50 |
| Erika Hamden | NUV Observations of Transients with the NUTRANS System: Providing NUV Data to the Time-Domain Community | ATI / NSF | 09/01/22-08/31/25 | 0.52 |

# Statements of Commitment and Letters of Support



# Budget Justification

## Budget Narrative

The “*A High-Performance Ultraviolet Photon Counting Detector for Strategic Astrophysics Missions”* cost proposal was prepared using JPL’s pricing/accounting system, which has been reviewed and approved by the DCAA. The rates applied in this proposal are JPL’s current published rate set (version FY23-1), dated October 3, 2022.

The derivation of the cost estimate is a grassroots methodology based on the expert judgment from a team of experienced individuals who have performed similar work. The team provides the necessary relevant experience to develop a credible and realistic cost estimate. The cognizant individuals identify and define the products and the schedule needed to complete the tasks for each work element. The team developed the grassroots estimate using estimating methods and techniques (analogy, vendor quotes, historical experience) appropriate for each element of work. These methods are used to generate the detailed schedule and resource estimates for labor, procurements, travel, and other direct costs for each work element. The resource estimates are aggregated and priced using JPL’s pricing/accounting system. JPL’s process assures that lower-level estimates are developed and reviewed by the performing organizations and their management who will be accountable for successfully completing the proposed work scope within their estimated cost.

As of proposal submission, NASA SMD’s open source policy set forth in SPD-41 dated August 4, 2021 is not included under Contract 80NM0018D0004 between NASA and Caltech/JPL. Therefore, JPL will perform the proposed work in accordance with SPD-41 on a best effort basis, and this proposal may not include cost for full compliance with SPD-41.

## Budget Details – Year 1

Direct Labor – Year 1

* Dr. Shouleh Nikzad is the PI and will oversee all aspects of the proposed work. Time Commitment is 0.21 wy.
* Dr. April Jewell will serve as a Co-Investigator on this effort. Time Commitment is 0.15 wy.
* Dr. John Hennessy will serve as a Co-Investigator on this effort. Time Commitment is 0.11 wy.
* Dr. Gillian Kyne will serve as a Co-Investigator on this effort. Time Commitment is 0.35 wy.
* Dr. Charles Shapiro will serve as a Co-Investigator on this effort. Time Commitment is 0.1 wy.
* .

Other Direct Costs – Year 1

Subawards:

* Subaward to University of Arizona for Prof. Erika Hamden. Time Commitment is 0.05wy.
* Desktop Network Chargebacks (calculated at $4.69/hr.). All JPL computers are subject to a monthly service charge that includes hardware, software, and technical support. ($9.827K)

Consultants:

* There are no consultants required for this task.

Equipment:

* There are no major equipment purchases necessary.

Services:

* Liquid Nitrogen for MBE ($36K)

Supplies and Publications:

* Publication and Documentation: Miscellaneous publication and documentation charges ($2K)

Travel:

* The PI and one CoI will travel to SPIE Astronomical Telescopes and Instrumentation, Japan ($6K/$3K each) Estimated costs include:
* Airfare: $700
* Lodging $1,000
* Registration $900
* Per diem $700
* Local transportation ($200)

## Budget Justification: Details – Year 2

Direct Labor – Year 2

* Dr. Shouleh Nikzad is the PI and will oversee all aspects of the proposed work. Time Commitment is 0.2 wy.
* Dr. April Jewell will serve as a Co-Investigator on this effort. Time Commitment is 0.17 wy.
* Dr. John Hennessy will serve as a Co-Investigator on this effort. Time Commitment is 0.18 wy.
* Dr. Gillian Kyne will serve as a Co-Investigator on this effort. Time Commitment is 0.48 wy.
* Dr. Charles Shapiro will serve as a Co-Investigator on this effort. Time Commitment is 0.1 wy.

Other Direct Costs – Year 2

Subawards:

* Subaward to University of Arizona for Prof. Erika Hamden. Time Commitment is 0.05wy.
* Desktop Network Chargebacks (calculated at $4.69/hr.): All JPL computers are subject to a monthly service charge that includes hardware, software, and technical support. ($10.108K)

Consultants:

* There are no consultants required for this task.

Equipment:

* There are no major equipment purchases necessary.

Services:

* Liquid Nitrogen for MBE ($36K)
* Radiation testing ($50K)

Supplies and Publications:

* Publication and Documentation: Miscellaneous publication and documentation charges ($2K)

Travel:

* The PI and one CoI will travel to International Image Sensor Workshop, Japan ($5K/$2.5K each) Estimated costs include:
* Airfare $800
* Registration $1200 (includes lodging and some meals)
* Per Diem $200
* Local transportation $300

## Budget Justification: Details – Year 3

Direct Labor – Year 3

* Dr. Shouleh Nikzad is the PI and will oversee all aspects of the proposed work. Time Commitment is 0.2 wy.
* Dr. April Jewell will serve as a Co-Investigator on this effort. Time Commitment is 0.20 wy.
* Dr. John Hennessy will serve as a Co-Investigator on this effort. Time Commitment is 0.06 wy.
* Dr. Gillian Kyne will serve as a Co-Investigator on this effort. Time Commitment is 0.50 wy.
* Dr. Charles Shapiro will serve as a Co-Investigator on this effort. Time Commitment is 0.1 wy.

Other Direct Costs – Year 3

Subawards:

* Subaward to University of Arizona for Prof. Erika Hamden. Time Commitment is 0.05wy.
* Desktop Network Chargebacks (calculated at $4.69/hr.): All JPL computers are subject to a monthly service charge that includes hardware, software, and technical support. ($9.251K)

Consultants:

* There are no consultants required for this task.

Equipment:

* There are no major equipment purchases necessary.

Services:

* Liquid Nitrogen for MBE ($36K)

Supplies and Publications:

* Publication and Documentation: Miscellaneous publication and documentation charges ($2K)

Travel:

* The PI and one CoI will travel to SPIE Astronomical Telescopes and Instrumentation, Europe ($6K/$3K each) Estimated costs include:
* Airfare: $650
* Lodging $1,000
* Registration $900
* Per diem $750
* Local transportation ($200)

# Supplementary External Co-I Budget Details

**University of Arizona**

**Budget Narrative**

Academic faculty and graduate student employee year is broken into academic and summer terms. The academic term is 1600 hours spanning a 9-month period. The summer term is a maximum of 464 hours over approximately 3 months. The academic faculty summer rate is calculated by taking the base salary \* .00072. Graduate students work at 0.50 FTE during the academic year (800 hrs.) and 420 hours for the summer term. Hourly rates for other named staff are calculated by dividing the annual salary by 2088 hours, or the average amount of available work hours in a fiscal year. The fiscal year runs from July 1st to June 30th, and while the hours in a fiscal year varies slightly, we used the average of 2088 hours in our calculations. Salaries are based on actual salaries and are projected to include a 3% annual cost-of-living adjustment (and merit, if applicable) effective each year.

1. Senior/Key Personnel
   1. PI Prof Hamden: Prof. Hamden will lead the University of Arizona team, including designing and performing testing strategies for the detectors designed during this effort, including both cross checks of QE and detector noise performance, as well as leading the on-sky testing. Prof. Hamden has worked extensively with CCDs, including the development of groundbreaking anti-reflection coatings for high UV efficiency, and overseeing initial noise and dark testing of the FIREBall-2 EMCCD and the first flight test of the EMCCD during the Fall 2018 flight of FIREBall-2. Her recent work on dark current testing and QE testing of EMCCDs will help in this project. Prof. Hamden will assist with bandpass and “color” selection of AR Coatings as needed, informed by potential science cases. Prof. Hamden devotes 0.52 summer months in years 1 and 3, and 0.65 summer months in year 2 to this APRA effort.
2. Other Personnel
   1. Postdoctoral Scholars- One postdoctoral scholar is funded at 4 calendar months for this project in years 1 and 3, and 6 months in year 3. They will oversee the development of the QE testing strategy for skippers to validate UV performance, advise on architecture developments for future skipper wafers, and work with ARCON for additional controllers.
   2. Graduate Students: We have requested funds for one graduate student for 3.4 months at 0.50 FTE during the academic year 1, 4.6 months in year 2, and 2.3 months in year3. Additionally, we request funding for 1.5 months during the summer for the three years proposed. The graduate student will work on detector characterization and analysis, on sky testing. Prof. Hamden will supervise this student.
3. Fringe Benefits

The University of Arizona defines fringe benefits as direct costs and estimates benefits as a standard percent of salary applied uniformly to all types sponsored activities, and charges benefits to sponsors in accordance with the Federally-negotiated rates in effect at the time salaries are incurred. The rates used in the proposal budget are based on the current Federally-negotiated Rate Agreement rate.

1. Equipment
   1. We request $40,000 for an STA Archon controller. We expect a typical 4 channel AC system, with some additional add ons. The Archon price list is found here: <http://www.sta-inc.net/wp-content/uploads/2014/06/ArchonPriceList.pdf>
2. Travel
3. Domestic: Travel is requested each year for project visits to JPL for two people for 5 days. These will provide opportunities for collaboration and intensive project development. Airfare is estimated at $300, lodging and meals at $236/day, and ground transportation at $50 for a total of $1,530 per person.
4. Domestic: Travel is also requested for attendance at the annual AAS meeting in year 3 of the award for PI and graduate student for 5 days. The graduate student will present the results of the work thus far in the project. Airfare is estimated at $300, lodging and meals at $218/day, and ground transportation at $50 and conference fee at $195/each for a total of $1,835 per person
5. Foreign: Travel is requested to present results of this work at the 2024 SPIE meeting, Astronomical Telescopes and Instrumentation. This meeting is the pre-eminent instrument meeting and the graduate student will present their work on the project. The PI will also attend for 5 days. Airfare is estimated at $1,200, lodging and meals at $339/day, and ground transportation at $50 for a total of $3,045 per person.
6. Participant/Trainee Support Costs - None
7. Other Direct costs
   1. Materials and supplies: We request $9000 in year 1, $9000 in year 2, and $5000 in year 3 for misc. lab hardware and supplies as needed for testing (custom controller boards, alignment fixtures, cleanroom garb, etc).
   2. PCB Printing: We request $6000 in year 1 and $5000 in year 2 for custom printed circuit board (PCB) printing. These boards are used to hold and interface the controller to the detector, and typically require several iterations to minimize noise and maximize performance. We anticipate between 2 and 3 printing runs in year 1 and 2 in year 2.
   3. Publication costs: We request $1000 a year in publication costs for page charges.
   4. Alterations and Renovations
   5. Graduate Tuition Remission: Graduate tuition remission is a mandatory benefit that is charged in proportion to the amount of effort a graduate student will work on the project.
8. Indirect Costs

The University of Arizona indirect rate agreement approved by DHHS on April 5, 2022 is based on Modified Total Direct Cost (MTDC). Equipment, capital expenditures, tuition remission, rental costs, participant support, scholarships and fellowships, and the portion of subgrants and subcontracts in excess of $25,000 are excluded from MTDC. A copy of the University’s DHHS-approved rate agreement dated April 5, 2022 is available online.

# Facilities and Equipment

## Jet Propulsion Laboratory

### UV Detector Fabrication and Processing: 2D doping, AR Coating, Integrated Red Rejection Filters

The proposed work will be performed in the JPL Microdevices Laboratory (MDL), which provides facilities for end-to-end fabrication and characterization of devices based on silicon, III-V compound semiconductors, amorphous semiconductors, and superconductors. MDL houses 38,000 square feet of office and laboratory space, including clean room environments ranging from class 100,000 to class 10.

Passivation and superlattice doping/delta doping is performed at wafer, section, or die level in JPL’s 8-inch wafer capacity silicon MBE, custom Veeco Gen200 equipped with a load lock for sample loading and unloading, ultrahigh vacuum chambers dedicated to loading, storage, sample preparation, and growth (Figure 10-1). A robot arm automates the sample loading and retrieval from any of these chambers. The growth chamber is equipped with electron-beam evaporators for silicon growth, boron and antimony k-cells for p and n-type doping (for n-channel and p-channel devices respectively). Radiative heating elevates sample temperature for outgassing and growth. The growth chamber is equipped with dual liquid nitrogen and water cooling shrouds to control the cleanliness of the environment around the sample.

The ALD work in this effort will be done using JPL’s Oxford OpAL Atomic Layer Deposition System or the JPL’s Beneq TFS 200 ALD System (Figure 10-2). The OpAL has a growth chamber equipped with inputs for up to three precursor compounds and six ports for reactive gases such as oxygen, water vapor, ammonia, and hydrogen; also it’s setup includes an integrated sample introduction glove box that can hold and store multiple samples under dry nitrogen. The TFS 200 includes a load-locked sample introduction mechanism and can accommodate up to six precursors in addition to the reactive gases already mentioned. In addition to the ALD facilities, there are several other major instruments currently available in MDL for film characterization including a high-resolution x-ray photoemission spectrometer, a field emission scanning electron microscope, an atomic force microscope, and an X-ray diffractometer. These will be utilized to judge the quality of the ALD coatings that are produced.

|  |  |  |  |
| --- | --- | --- | --- |
|  | | Description: Multiple_3inch_Si_wafer_MBE_glowing_sm  Description: 8inch_Si_in_chamber_glowing_sm |  |
| **Figure 10-1**. The 8-inch Silicon MBE facilities at JPL. On the right photographs of inside MBE show multiple three-inch wafers being heated prior to MBE growth (top right) and single eight-inch wafer being heated prior to the MBE growth (bottom right).  Analytical tools are used to monitor the quality of the MBE films grown for device passivation, spectral range extension and QE enhancement or ALD films grown for AR coatings.  The facilities required to produce quality chemically-polished detectors and custom packaging are located in the class-1000 cleanroom at MDL. Particulate control is further reduced with a class-100 laminar flow hood at each workstation. Ovens used for drying, curing, and outgassing are provided. In addition to stereoscopic bench microscopes, a videoscope is available under the laminar flow hoods. | | |  |
| :::::::private:var:folders:y0:y04DTlk8HwyLhC18HhnZ9E++0ok:TemporaryItems:ALDPicture2_mod.jpg | WP_20130320_004.jpg | | |
| **Figure 10-2.** Photographs of JPL’s Atomic Layer Deposition (ALD) Systems. | | | |

### Detector Characterization

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**Figure 10-3** Photographs of the far UV, visible, characterization setup at JPL. Left: side view of the 1-m vacuum monochromator, with dual sources and dewars on the right, NIST-calibrated photodiode for flux measurements, and control electronics for automated grating positioning and wavelength setup. Right shows the view oof the setup from the end were the differentially-pumped dewar (black on the left of photo) is shown. Dual Tungsten-Deuterium source with index mirror and filters is at the end of the arm on the right.

Ultraviolet quantum efficiency, visible rejection ratio, will be conducted at JPL’s UV characterization set up. The photograph in Figure 10-3 shows the measurement setup where the majority of in-depth studies will take place. The setup is located in a class 100,000 cleanroom and is equipped with a differentially pumped vacuum monochromator, two sources that can be indexed for measurement from Lyman alpha to the visible, and a differentially pumped detector chamber (Figure 10-3). The dewar contains a diffuser, a copper block for cooling, and socket for mounting the array. The chamber can accommodate arrays of different formats, size, and readout schemes.

Characterization has also included measurements of conversion gain and quantum efficiency, array response uniformity, linearity and noise. A specialized light source also allows a sub-pixel spot scan, allowing the PSF to be obtained.

For Skipper characterization we will use Archon controllers developed by STA and have quickly become standard for astronomical detector characterization. We have designed a small dewar to hold up to two detectors for testing in a previousl tasks funded by an SAT and an APRA (Figure 10-4). This dewar is also compatible with our 1-m monochromator for quantum efficiency data acquisition. Our test setup shown in the figure is testing two CCD201-20 EMCCD. However, the system can be used for identical conditions for two different types of detector to allow “apples-to-apples” comparison. We can used this set up for example to compare the performance of a delta doped EMCCD and a delta doped Skipper CCD. While we will use the Archon Controller for the Skipper CCD, we have used the NuVu V3 controller for the EMCCD.

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|  | **Figure 10-4** Photographs of JPL’s custom dewar showing two EMCCDs, flex cables to two NuVu controllers setup for simultaneous operation of two EMCCDs with two NuVu controllers. This set up has been used at Loma Linda University for proton irradiation testing of two detectors. |

The Precision Projector Laboratory (PPL) set up is shown in Figure 10-5

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| --- | --- |
| image_0.jpeg |  |
| **Figure 10-5** The Precision Projector Laboratory, a joint Caltech-JPL facility funded by JPL and led by CoI-Shapiro and assisted by Collaborator-Smith. The facility is used for detailed characterization of detectors using astrophysics scene emulation. | |

## University of Arizona Facilities

The development team has access to the well-equipped, 800 sq ft Hamden UV/Vis Detector Lab, that contains a clean room and several large optical tables. The lab is equipped with a UV monochromator (150 to 900 nm), two sources, a filter set, photodiodes and vacuum systems, in addition to standard lab hardware (scopes, lamps, tools, etc.). The HUVD Lab also has access to a McPherson VUV reflectance sample test chamber, which can measure reflected light at a range of angles of incidence from normal to 180 deg. This chamber can be connected to our UV monochromator or other hardware components as needed for grating testing.

**Testing Equipment and Systems:** The University makes available a wide range of equipment that support the verification and validation process of space flight hardware. The equipment includes small, medium, and large volume thermal-vacuum chambers and ovens. These systems support component to full-scale payload testing and are key infrastructure for UA space mission projects.

**Other University Cleanroom facilities:** UA maintains several on and off-campus cleanroom facilities. The majority of these facilities are actively maintained at a Class 10,000 level and are equipped with arrays of monitoring systems. The development project can access laminar flow benches capable of Class 1000 or better areas used for systems assembly as needed. These facilities were used in assembly of instrumentation and other hardware for HST, SPITZER, JWST, HiRISE, Phoenix-Mars, OSIRIS-REx missions.

UA has extensive lab facilities for space mission hardware development, including instruments on HST, Spitzer, JWST, and more. The University has a large scale machine shop, a team of engineers (mechanical, thermal, optical, etc), and extensive institutional experience in mission development.

**Computer Facilities:** Our Research Labs offer a variety of equipment for use in student and faculty research projects. These labs contain Mac, Windows, and Linux OS systems, specialized printers, graphics and visualization devices, and PC clusters. UA offers high performance computing resources in the Research Data Center (RDC), a state-of-the-art facility that hosts large computer clusters. Scientific research relies upon such systems to analyze massive amounts of collected data. Time on these systems is available at no charge to faculty, researchers, or students. The University provides full service administrative IT support to all faculty and staff.