Ultraviolet Detectors for Cosmic Origins and Exoplanet Science with LUVOIR

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The LUVOIR Surveyor is envisioned as the `Space Observatory of the 21st Century'. With 10 – 40 times the geometric collecting area of the *Hubble Space Telescope* and highly sensitive, multiplexed instruments, LUVOIR is poised to provide transformative scientific measurements of a broad range of astrophysical objects. Ultraviolet imaging and spectroscopic capabilities are central to the majority of the key scientific goals of LUVOIR, from quantifying the flows of matter between galaxies and the intergalactic medium to understanding how host star's UV radiation regulates the atmospheric photochemistry on habitable planets.

Carrying out high-precision ultraviolet astronomy across such a wide range of sources requires detector systems working below the atmospheric cut-off (90 – 400 nm) with low-noise and/or photon-counting capability, high quantum detection efficiency, large format size, and high temporal resolution. Ideally, all of these characteristics would be encompassed in a single detector, but multiple technologies may be required to accomplish LUVOIR's suite of science investigations.

We present an overview of UV detector technologies so the LUVOIR STDT and NASA can make informed recommendations for directed technology investment to support first generation UV instrumentation for LUVOIR. We note that with the goal of serviceability, some technologies that are less mature today may be optimized by the time second generation LUVOIR instruments are proposed, and as such, a long-term but adaptable technology maturation plan would be desirable for UV detectors.

Microchannel Plate Devices – Micro-channel plates (MCPs) with "solar-blind" photocathodes, low dark rates, and zero read noise have a rich flight heritage on astronomy, heliophysics, and planetary science missions.

Advantages: MCP-based detectors are inherently photon-counting, operate at room temperature, can be ruggedized for 10+ year lifetimes in space, are scalable to large formats, and offer relatively high quantum efficiency at short UV wavelengths ($\lambda < 130$ nm).

Disadvantages: MCPs have limited dynamic range for bright objects that require instrument safety protocols, do not regularly support signal-to-noise (S/N) > 100 observations owing to fixed pattern noise, and experience issues with long-term "gain-sag" (burn-in at locations of prolonged high illumination).

CCD and sCMOS – Charge coupled devices (CCDs) have significant heritage in space and on the ground, can be δ-doped to improve UV performance, and anti-reflection coatings can be further optimized to offer higher QE over a selected bandpass. Research is on-going to extend the range of QE enhancements.

Advantages: UV-optimized CCDs have flight-heritage on astrophysics suborbital missions as well as solar missions at shorter UV wavelengths. The large dynamic range and flat-field characteristics are well-suited for high S/N observations. CCDs are moving to larger formats and advancements in electron-multiplying CCDs (EMCCDs) offer the prospect of ~zero read noise photon-counting operation, although they must be operated at cryogenic temperatures (< 173 K) to achieve dark count rates comparable to MCPs. Other silicon-based technologies such as low-noise scientific complementary metal-oxide-semiconductor (sCMOS) are now being optimized for the UV using similar processing techniques as those being used for CCDs.

Disadvantages: CCDs are not inherently "solar-blind", due to the low band-gap of silicon, so care must be taken to mitigate sensitivity to scattered visible-band radiation in UV applications. Testing / optimization of these devices for radiation hardness in an L2-like environment is also an active area of research. Initial results show good radiation tolerance, but this has yet to be demonstrated in a rigorous testing environment. sCMOS devices require similar investigation into radiation hardness and low-temperature operation.

Advanced Concepts – Less mature UV detector technologies, such as microwave kinetic inductance detectors (MKIDs), offer the possibility of energy resolution at the pixel level. Uncertainties in the scalability to significant pixel/spaxel counts and cryogenic operation currently limit the utility of these devices for LUVOIR, but these issues may be quantified and possibly overcome with additional technology investment.

Challenges unique to UV – Key technology challenges that remain unique to the UV involve boosting efficiency and reducing noise, along with several other issues linked to these goals:

Quantum Efficiency: UV sensitive detectors have quantum efficiencies at or below 20-50% within the band, leading to the possibility that future technologies may provide factors of up to 2-5× improvement in overall UV sensitivity. Some UV sensor technologies have a comparable or higher QE in the visible, raising potential "red leak" issues that may require additional filtering. A related challenge is the low transmittance of UV band-pass filters, which limits options for efficient red-blocking or band selection.

Noise: The sky background is several magnitudes fainter in the UV than in the visible which presents both an opportunity and a challenge. The opportunity is the exploitation of a low-background window for the study of faint objects. For example, for broadband FUV observations, the sky background is 28.5 mag/sq. arcsec, or fewer than ~1 photon per resol for 10-30 min exposure times on a 10-m LUVOIR, even less for narrowband observations or spectroscopy. The challenge is that taking full advantage of this low background requires detectors that do not themselves limit faint observations, motivating low noise or photon-counting technologies, with read noise and/or dark current typically lower than required for standard broadband visible observations.

Dynamic Range: These same photon-counting detectors may also have limited dynamic range, particularly in the large formats required for LUVOIR, and is a challenge that needs to be addressed by all technologies being considered. A detailed comparison of the dynamic range performance for each of the leading detector technologies, given realistic instrumentation and observing programs would be a valuable exercise for the LUVOIR study.

Improving performance in these areas can significantly impact science return. The required exposure time to reach a given S/N for a particular target in a sky-background-limited observation scales as $t \sim QE$, and increases to $t \sim QE^2$ in the detector dark current-limited regime, motivating efficiency gains. Similarly, the required exposure times decrease linearly with improvement in dark current and/or read noise, down to the very low sky-background limit. No single technology leads performance in all three areas (efficiency, read noise and dark current), at this point the optimal UV detector is likely to be application or instrument-specific.

Table 1: UV detector targets for LUVOIR and a comparison with the state-of-the-art in laboratory and flight technology (adapted from Bolcar *et al.* 2016).

Parameter:	**Goal:**	**State-of-the-Art:**	
Operational Bandpass	90 nm – 400 nm	< 90 nm – 300 nm	MCP
		< 90 nm – 400 nm	EMCCD
		TBD	sCMOS
Read Noise	0	0	MCP
		N/A for multi. mode	EMCCD
		0.8 – 1.0 e$^-$	sCMOS
Dark Current and/or Spurious Count Rate	≤0.1-1 counts/cm^2/s ≤1-10e-3 e$^-$/resol/hr	0.05-0.5 counts/cm^2/s	MCP
		> 0.005 e$^-$/resol/hr	EMCCD
		> 0.005 e$^-$/resol/hr	sCMOS
Quantum Efficiency (Peak)	75% (Far UV – Near UV)	45-20% FUV - NUV	MCP
		30-50% FUV - NUV	EMCCD
		TBD	sCMOS
Resol Size	≤ 10 μm	20 μm	MCP
		20 μm	EMCCD
		10-20 μm	sCMOS
Dynamic Range (Max. Count Rate)	≥ 10^4 Hz / resol (as needed)	2kHz / resol 5 MHz global	MCP
		Readout dependent	EMCCD
		10^5 Hz / resol	sCMOS
Time Resolution	≤ 100 ms (as needed)	<< 1 ms	MCP
		< 10 ms	EMCCD
		< 10 ms	sCMOS
Format	≥ 8–16k pixels per side with high fill factor	8k × 8k	MCP
		3.5k × 3.5k	EMCCD
		3.5k × 3.5k	sCMOS
Radiation Tolerance	Good	Good	MCP
		TBD	EMCCD
		Good	sCMOS