Detectors and Cooling Technology for Direct Spectroscopic Biosignature Characterization

Bernard J. Rauscher and Avi Mandell

The search for life on other worlds looms large in NASA's 30-year strategic vision, and several mission concept studies are underway that would use UV-Optical-IR space telescopes equipped with a coronagraph or starshade to characterize potentially habitable exoEarths (e.g. LUVOIR, HabEx). Our aim in this note is to discuss a short list of detector technologies that are thought to be potentially capable of biosignature characterization for either coronagraph or starshade missions.

Once a rocky exoplanet in the habitable zone has been found, biosignature characterization will be the primary tool for determining whether we think it harbors life. Biosignature characterization uses moderate-resolution spectroscopy, $R = \lambda/\Delta\lambda > 100$, to study atmospheric spectral features that are thought to be necessary for life, or that can be created by it (e.g. H_2O, O_2, O_3, CH_4, CO_2). Even using a very large space telescope, biosignature characterization is extremely photon-starved. The emerging technologies for ultra-low-noise detectors fall into two broad categories: (1) low noise detectors (including "photon counting") that are compatible with passive cooling and (2) true energy resolving single photon detectors that require active cooling. Table 1 shows expected performance requirements for a detector used for exoplanet biosignature characterization.

Table 1: Strawman Detector Characteristics for Biosignature Detection

Parameter:	**Goal:**
Operational Bandpass	0.4 - 1.8 μm (need) 0.4 - 5 μm (goal)
Read Noise	<< 1 e^-
Dark Current	< 0.001 e^-/pix/s
Spurious Count Rate	Small compared to dark current
Quantum Efficiency (Peak)	> 80% over bandpass (conventional) > 50% over bandpass (energy resolving)
Format	> 2K × 2K (conventional) > 30 × 30 (energy resolving)
Spectral resolution	$R = \lambda/\Delta\lambda > 100$ at 1 μm (energy resolving only)
Other	Rad-hard, minimum 5-year lifetime at L2. Non-cryogenic operation strongly preferred

Today's State of the Art

The most mature VISIR detector candidates are semiconductor-based. These technologies are attractive because of their comparative maturity, low risk, and the possibility that their performance might be sufficient for biosignature characterization, even if they do not function as single photon detectors.

EMCCDs – Electron multiplying charge coupled devices (EMCCD) are widely regarded as the most mature detector technology for visible wavelength biosignature characterization today. A 1K × 1K pixel EMCCD has been selected for the WFIRST coronagraph's imaging camera and integral field spectrograph.

Advantages: They are operational now, and are being space-qualified for use in WFIRST. Significant investment will be made as part of this process, making the subsequent TRL level attractive for risk reduction.

Disadvantages: A major concern with the current EMCCD design is radiation induced performance degradation. This may include decreased charge transfer efficiency, decreased pixel operability, and increased clock induced charge (CIC). An EMCCD that is deemed "good enough" for WFIRST may not be satisfactory for LUVOIR biosignature characterization.

HgCdTe Near-IR Photodiode Arrays – HgCdTe is today's most mature material for astronomical near-IR instruments. It is possible to tune its cutoff wavelength from about 1.7 μm out to 5 − 10 μm while still achieving performance that enables low background space astronomy.

Advantages: HgCdTe arrays have substantial heritage for NASA astronomy, having been used in JWST, Euclid, WFIRST, etc. When cooled sufficiently, the dark current of today's 2.5 μm cutoff flight grade HgCdTe arrays already achieves the < 0.001 e− s^{-1} pix^{-1} that is needed for biosignature characterization.

Disadvantages: The read noise floor of the existing generation of HgCdTe photodiode arrays is a few e− RMS per pixel, higher than what is needed for biosignature detection, and significant work is needed to understand exactly where, and why, the read noise and dark current originate.

Emerging Non-Cryogenic Technologies for Astrophysics

VISIR detectors have many other applications besides astrophysics. Moreover, NASA has already made initial investments into maturing some detector technologies for exoplanet missions. Although the technologies in this section are less mature for astrophysics than EMCCDs and HgCdTe photodiode arrays, they are being (or have recently been) explored as potential photon counting detectors.

CMOS Arrays – Complementary metal-oxide-semiconductor (CMOS) arrays have evolved substantially over the past 20 years, to the point where they have now become the dominant sensor for consumer applications including cell phone and digital SLR cameras, and can have read noise of a few electrons. Several groups are exploring advanced concepts for photon counting. The best individual CMOS pixels have achieved read noise ~0.2 e^- (although ~ 1 e^- is more typical).

Advantages: The devices promise to count individual photons. The cost is low, requiring no exotic processing. The power is ultra-low, e.g. a single Gigapixel array would require ~a Watt of power. In most implementations, the data are fully digital at the focal plane. There are no known problems with regard to radiation tolerance.

Disadvantages: Published dark count rates are too high for biosignature characterization (although this is likely to improve with cooling). Comprehensive characterization for astrophysics and biosignature characterization is needed. It is unknown how radiation will affect CMOS sensors at sub-electron noise levels.

Geiger-Mode Avalanche Photodiode (GM-APD) arrays – A GM-APD array counts photons by amplifying a single photon into an avalanche of ~10^7 electrons which is then detected as a large voltage pulse. GM-APD arrays were the subject of a 2009 NASA Technology Development for Exoplanet Missions (TDEM) award.

Advantages: The devices count individual photons. The data are fully digital at the focal plane. There are no known problems with regard to radiation tolerance.

Disadvantages: In the current implementation, the sensitivity is peaked in the center of each pixel. Ultra-low dark currents at cryogenic temperatures have not been measured. The voltage has to be tuned in order to minimize dark current while maximizing quantum efficiency.

HgCdTe APD Arrays – HgCdTe APD arrays are a promising technology that initially entered astronomy for comparatively high background applications including adaptive optics, interferometry, wavefront sensing, and fringe tracking.

Advantages: The gain in APD arrays is built into the pixels before the first amplifier, they promise photon counting in the visible and near-IR and potentially even single photon detection if "dark current" can be reduced to acceptable levels. With an appropriately optimized fabrication process, the HgCdTe itself is potentially capable of the same quantum efficiency (QE) performance as the JWST arrays.

Disadvantages: "Dark current" is the most significant obstacle to using APD arrays for ultra-low background astronomy today. The ~10−20 e− s^{-1} $pixel^{-1}$ "dark current" that has been reported is almost certainly dominated by glow from the readout integrated circuit (ROIC). This dark current may be reduced with optimization of the ROIC.

Emerging Cryogenic Technologies for Astrophysics

Today's CCDs, EMCCDs, and HgCdTe hybrids are not single photon detectors in the context of biosignature characterization. All would add significant noise and thereby reduce mission exoEarth yields below what could be achieved with a noiseless detector. On the other hand, superconducting MKID and TES arrays already function as single photon detectors today. However, the use of these superconducting detectors by LUVOIR is contingent upon the development of ultra-low vibration cooling.

Transition-edge sensor (TES) microcalorimeter arrays – In a microcalorimeter, the energy of an absorbed photon is determined from the temperature rise of the detector. The energy resolution of such a detector is set by thermodynamic noise sources in the detector and amplifier noise.

Advantages: Thermal sensors simultaneously detect individual photons and use the thermal signal to measure photon energy – as such they enable non-dispersive imaging spectroscopy. For the designs discussed here, the minimum photon energy is well separated from the system noise, so the probability of dark events are near zero, and the read noise manifests itself as the limit to the energy resolution of the system.

Disadvantages: The energy resolution scales with temperature, so for VISIR applications with R > 100 the detectors must be operated at T < 100 mK.

Microwave kinetic inductance devices (MKID) – An MKID detects absorption of photons in a superconductor by a change in kinetic inductance.

Advantages: MKIDs are energy resolving detectors with zero dark count rate. In addition to high sensitivity, MKIDs have a natural means of multiplexing; systems have been demonstrated for simultaneous readout of up to 4000 MKID pixels.

Disadvantages: Operating temperatures are $\lesssim$ 1 K. Other, non-fundamental sources of MKID noise also exist, and are the subject of active research. Current resolving powers are R~10 at 0.4 μm. Improving VISIR MKIDs to R = 100 faces significant challenges.

Ultra-Low-Vibration Detector Cooling – In order to take advantage of super-conducting energy resolving detectors, detector cooling down to < 1 K must be achieved using a low-volume and ultra-low vibration space-qualified technology. Stored cryogen systems have been used in the past to provide cooling to observatories and instruments with near zero vibration, but they are impractically massive for missions with lifetimes greater than five years, and have largely been replaced by mechanical cryocoolers. Cryocoolers are far lighter and have lifetimes limited primarily by their control electronics.

Linear compressor cryocoolers: Almost all flight cryocoolers launched to date are based on linear motor-driven piston compressors. These devices have virtually unlimited lifetime. They also have inherently high vibration at their operating frequency, typically 20 to 70 Hz, which unfortunately is in a range that often contains important telescope and instrument structural mode frequencies. Many flight cryocoolers use a second, co-aligned piston and control electronics to provide active vibration cancellation along the axis of motion, but cancellation is imperfect, partially because the piston force couples into other degrees of freedom.

Low Vibration Cryocoolers: Alternative coolers with much lower exported vibration force in the critical 0 − 200 Hz band have been developed. Two examples are Joule-Thompson expansion coolers and reverse Brayton cycle coolers. In both cases, the operation is continuous, rather than oscillating, and the compressors can be mounted meters away from the instruments. These coolers are compact and low-vibration, but reaching the required level of cooling for ultra-low-noise detectors may be impossible.

Sub-Kelvin Coolers: On the ground, dilution refrigerators are most commonly used to reach temperatures as low as 0.002 K; however, no zero-g version has been demonstrated. Another option is magnetic coolers, or Adiabatic Demagnetization Refrigerators (ADRs). ADRs have no moving parts and are generally considered to be zero-vibration devices. However, the stresses in the magnetic components may generate disturbances at the relevant level and frequencies.

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