Antimonide Unipolar Barrier Infrared Detectors for Earth Science Applications

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NASA Jet Propulsion Laboratory, California Institute of Technology

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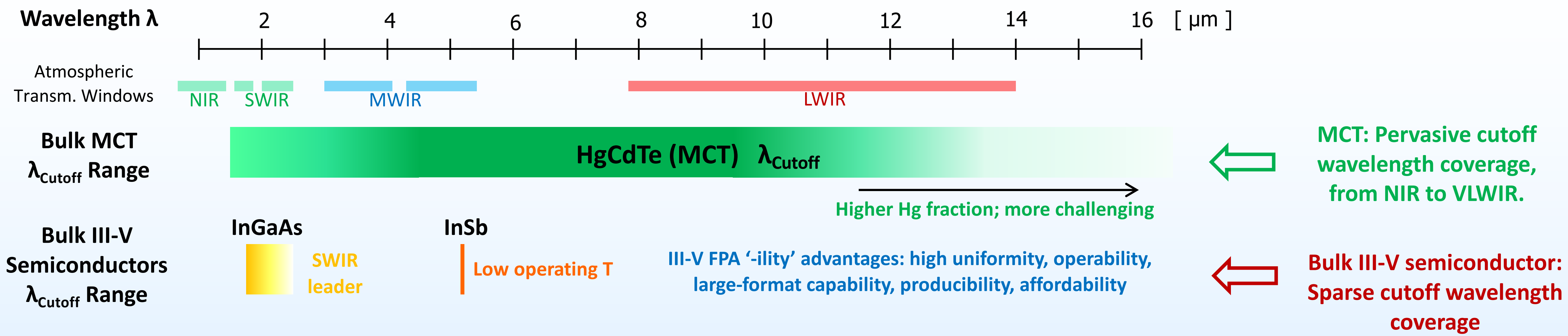
Outline

- III-V semiconductor barrier infrared detector (BIRD) technology development
- Barrier infrared detectors for ESTO applications
  - Land imaging technology, CIRAS, HyTES, HyTI, cFIRST

Motivation for III-V Semiconductor Infrared Detector Technology Development



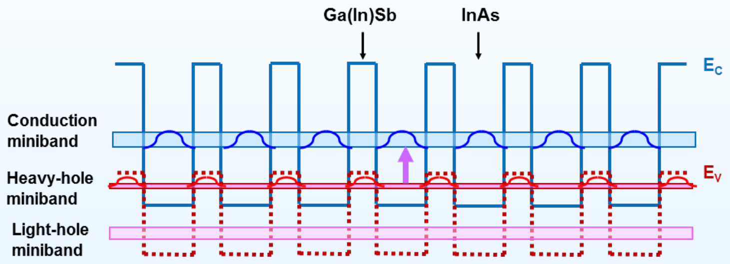
- **$Hg_xCd_{1-x}Te$** alloy (**MCT**) is the most successful high-performance infrared detector material to date
  - Varying alloy composition provides continuously adjustable cutoff wavelength coverage, ranging from NIR to VLWIR
  - Soft and brittle. Requires expert handling in growth, fabrication, storage. Costly.
  - Weak Hg-Te bond. Longer λ_{cutoff} , higher Hg fraction, progressively more challenging
- FPAs based on (near) lattice-matched bulk **III-V** semiconductor photodiodes are highly successful, but only in a few cases where suitable substrates are available.
  - SWIR **InGaAs** performs at near theoretical limit. Single color, limited cutoff wavelength adjustability.
  - **InSb** dominated MWIR market, despite lower operating temperature than MCT. Fixed cutoff wavelength.
  - Lacking the continuous cutoff wavelength adjustability of MCT

Goal: Develop high-performance infrared photodetectors based on robust III-V semiconductor, with wide-range cutoff wavelength adjustability.

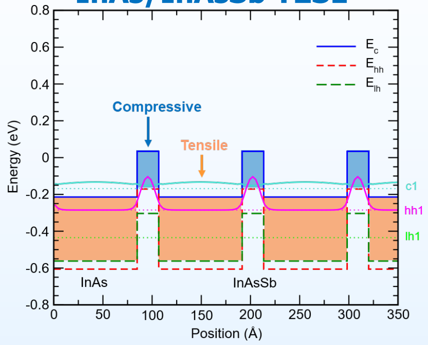
Advances in III-V Semiconductor IR Photodetectors

Antimonide infrared absorbers

InAs/GaSb Type-II superlattice

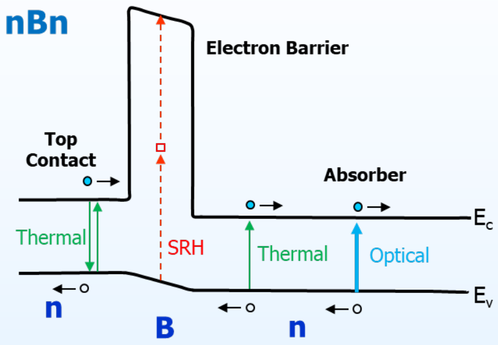


InAs/InAsSb T2SL

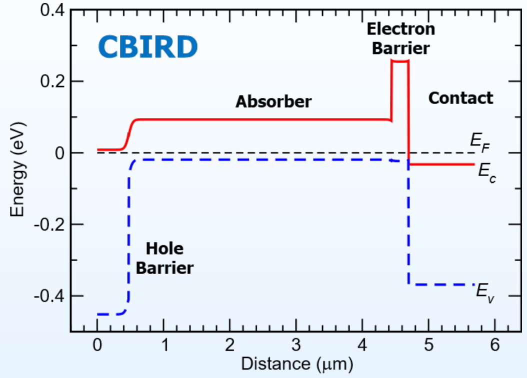


- InGaAsSb alloy: 2 - 4 µm cutoff wavelength
- Type-II superlattices (artificial IR material)
  - Continuously adjustable bandgap provides cutoff wavelength coverage from 2 µm to >15 µm
  - Tunneling and Auger dark current suppression
- All can be grown on GaSb substrates
  - 2″, 3″, 4″ diameter format commercially available.

Unipolar barrier detector architecture



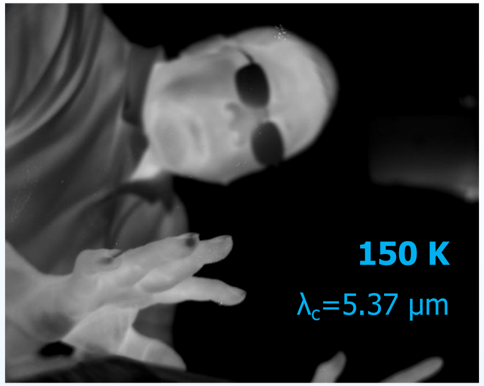
Complementary Barrier InfraRed Detector

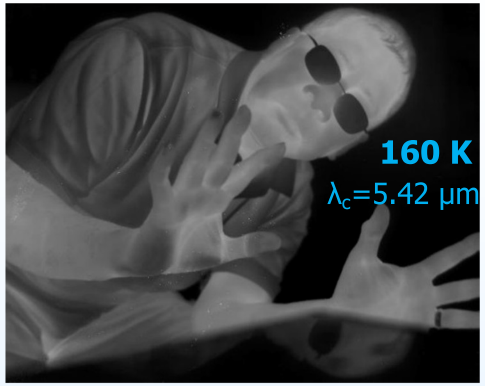


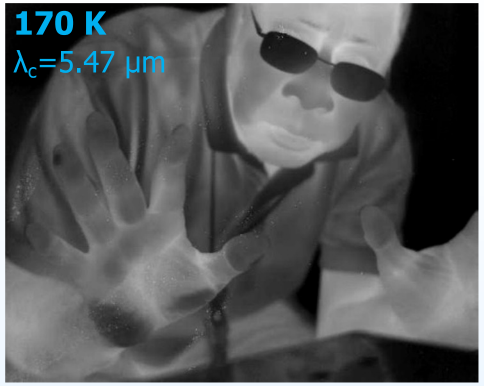
- Unipolar barrier detector architecture
  - Unipolar Barriers block electrons but not holes (or vice versa)
  - Examples: nBn, XBn, XBp, CBIRD
- Can suppress G-R and surface leakage dark current, w/o impeding photocurrent
- Higher operating temperature / sensitivity

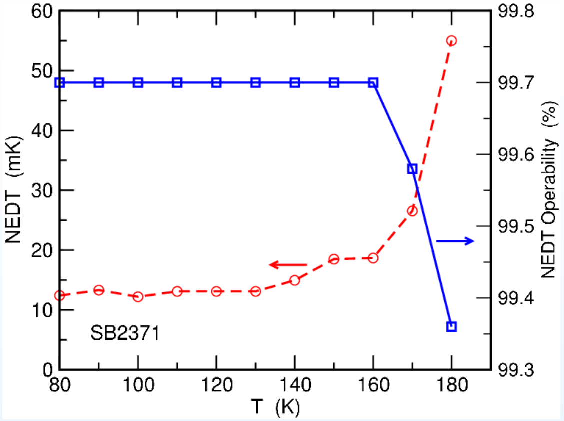
The confluence of these two developments has led to a new generation of versatile, cost-effective, high-performance infrared detectors and focal plane arrays based on robust III-V semiconductors, with wide-range cutoff wavelength coverage.

(HOT) MWIR InAs/InAsSb Type-II Superlattice (T2SL) FPA









IEEE Photonics Journal **10**(6), 6804106 (2018); *Appl. Phys. Lett.* **113**, 021101 (2018); U. S. Patent No. 8,217,480 (2012).

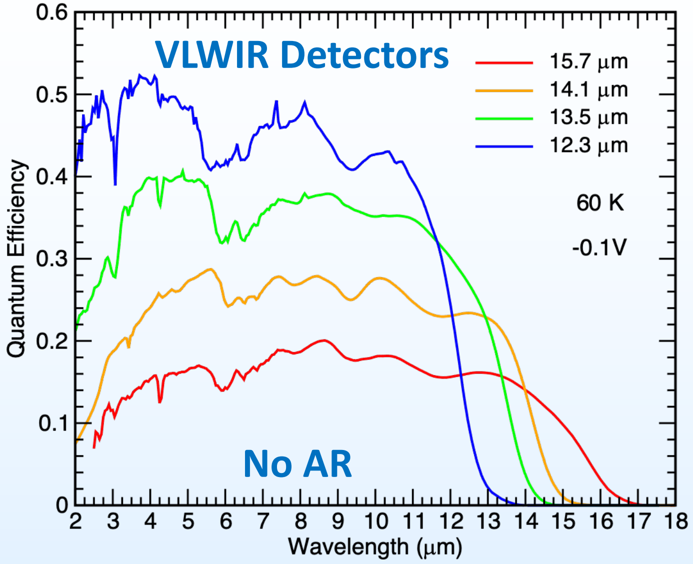
SBF-193 ROIC: 24-µm pitch, 640×512 format. 300K background, f/2 optics. 160K (170K): NEDT 18.7 mK (26.6 mK), Operability 99.7% (99.6%)

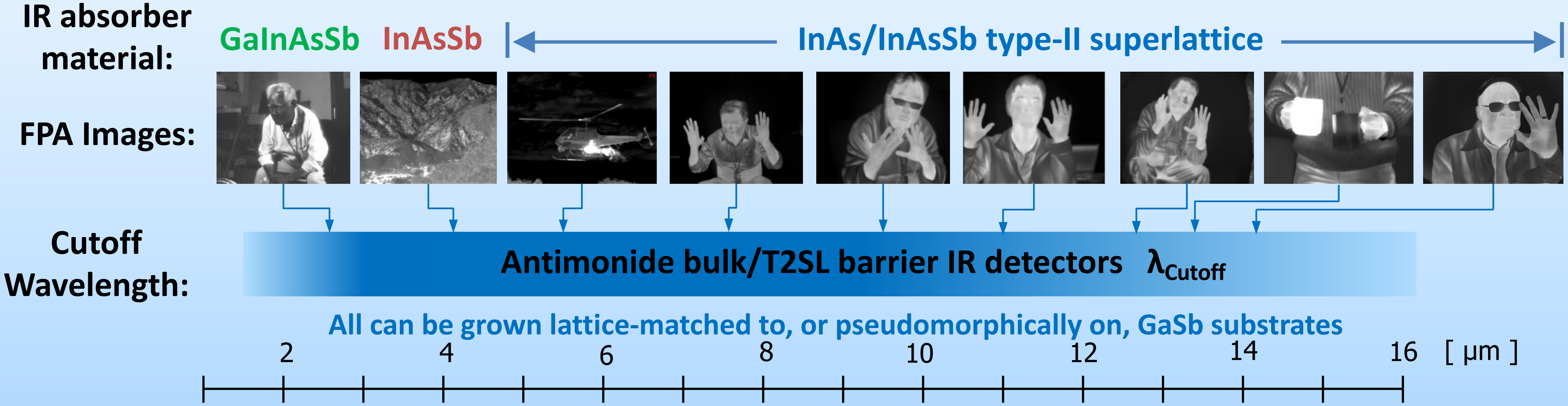
- Antimonide T2SL **h**igh **o**perating **t**emperature **b**arrier **i**nf**r**ared **d**etector (**HOT-BIRD**)
  - Customized cutoff wavelength to match InSb. Excellent FPA imaging performance at 160K
- T2SL FPA with ~same cutoff wavelength, but **much higher operating temperature than InSb**
  - Planar InSb (ion implant) ~ 80K. MBE epi InSb ~ 95-100K (can image up to 110-120K)
    - Klipstein et al., Infrared Phys. & Technol. 59 (2013) 172–181
- Reduces demand on cryocoolers – Enables longer cooler lifetime, or the use of compact coolers.
- Retains the same III-V semiconductor manufacturability & affordability benefits as InSb
- T2SL FPA demonstrating a clear advantage over a **major incumbent technology (InSb)**
  - In 2018, InSb FPA led all photodetector FPA market in volume, with >50% market share (units sold).

InAs/InAsSb type-II superlattice absorber + unipolar barrier architecture => Breakthrough MWIR detectors

Unipolar Barrier IR Detectors – SWIR to VLWIR

- Unipolar barrier infrared detectors
  - IR absorbers: GaInAsSb, InAsSb, InAs/InAsSb T2SL
  - All grown on GaSb substrates
  - Cutoff wavelengths ranging from 2.5 to 15.7 µm demonstrated
- Focal plane arrays
  - Cutoff wavelengths ranging from 2.6 to 14.1 µm demonstrated
  - High uniformity and operability

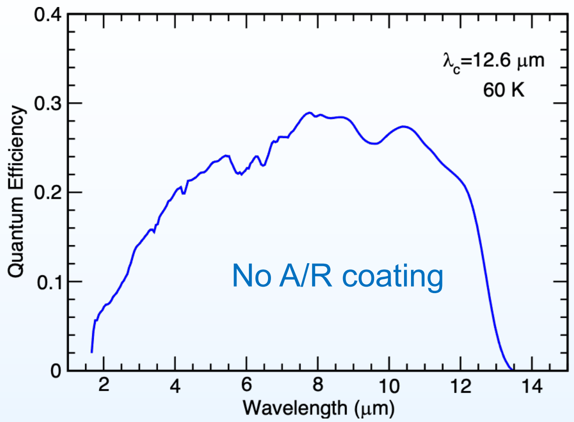


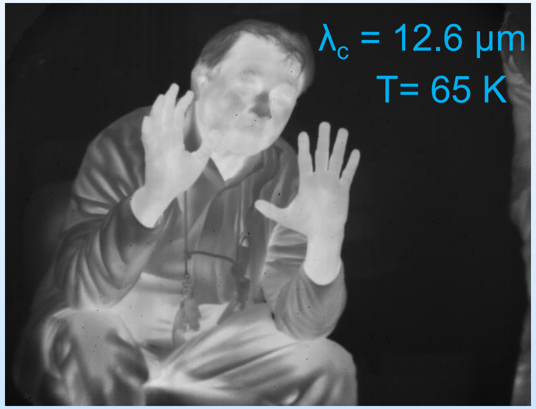


JPL antimonide alloy and type-II superlattice unipolar barrier infrared detectors have demonstrated high uniformity & operability FPAs, with cutoff wavelengths covering SWIR to VLWIR.

Long Wavelength Infrared FPA for Land Imaging

- QWIP FPAs with response up to 12 µm used in NASA HyTES & LandSat-8 TIRS for hyper/multi-spectral land imaging
  - High spatial uniformity & temporal stability
  - No need for frequent system recalibration
  - Relatively low conversion QE & high dark current density
  - Low FPA operating temperature (~43 K)
- Developed type-II superlattice (T2SL) barrier infrared detector (BIRD) FPAs to meet NASA Sustainable Land Imaging (SLI) interests in thermal IR bands in the 8 – 12 µm range.
- LWIR FPA Results:
  - FPA with λ_{cutoff} ~ 12.6 µm T2SL absorber material and SBF-193 ROIC
  - J_{dark}(65K)~3×10^{-5} A/cm^2 ; QE ~ 27%, no A/R coating. FPA operability ~ 99.98%
  - Estimated 20K operating temperature advantage over QWIP FPA.
  - Reduce cooling demand for favorable SWaP.
- LWIR T2SL FPA have also been fabricated using L3 "silicon sandwich" process, paving the way to multi-megapixel LWIR FPAs for high-resolution land imaging applications.



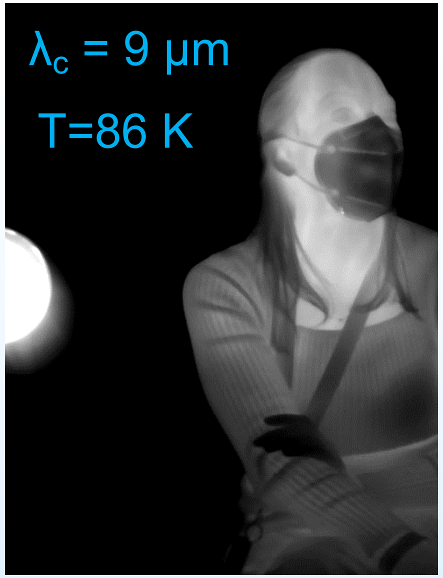


Ting et al., *Infrared Phys. & Technol.*, **123**, 104133 (2022)

Long wavelength type-II superlattice (T2SL) barrier infrared detector (BIRD) FPAs can provide an estimated 20 K operating temperature advantage over existing QWIP FPAs.

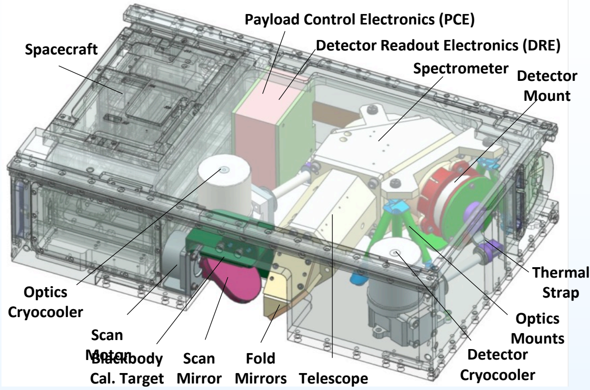
Digital FPA for Higher Sensitivity and Dynamic Range

- FPAs made with in-pixel digital readout integrated circuit (D-ROIC)
  - Very large effective well capacity
  - Enables longer integration time for improved signal-to-noise ratio
  - Higher operating temperature
  - High dynamic range
- D-ROIC from Copious Imaging (Anduril)
  - MIT-Lincoln Lab heritage
  - 20 μm pitch, 640x480 and 1280x480 formats
  - Well depth: >400 Me^-
    - ~10 Me^- for typical analog ROIC
- D-FPAs with LWIR T2SL detector arrays hybridized to D-ROICs

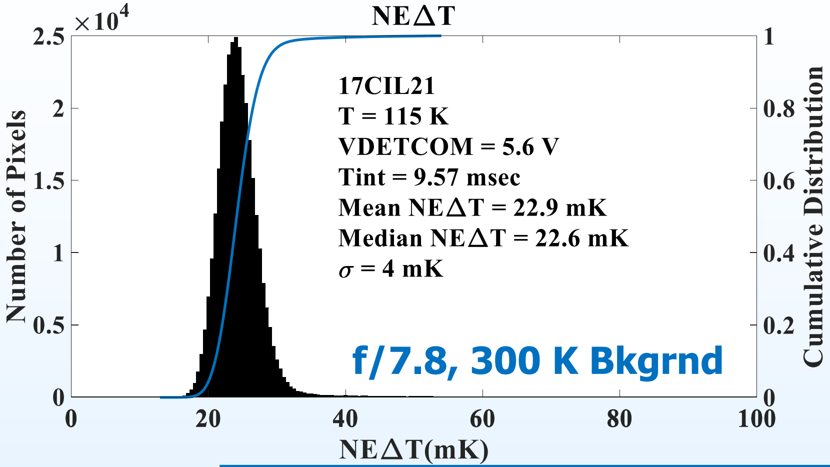


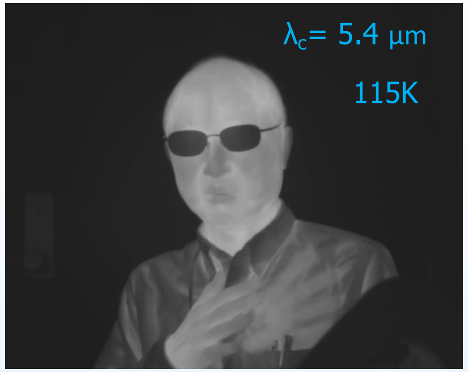
(SLI-T 19) Project co-I’s from Copious Imaging (Anduril): Chris David, Justin Baker, Mike Kelly

HOT-BIRD Focal Plane Arrays for The CubeSat Infrared Atmospheric Sounder (CIRAS)



T. Pagano et al., *Proc. SPIE* **11832**, 118320D (2021)





Ting et al., *IEEE Photonics Technol Lett.* **34**, 329 (2022)

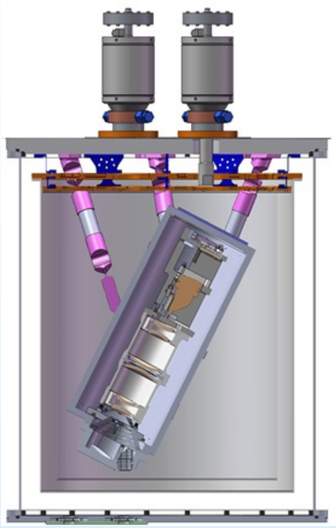
- Concept for space-borne MWIR hyperspectral instrument in 6U CubeSat
  - 625 channels in 4.08 - 5.13 μm range
    - Needs better sensitivity than for imaging applications
    - Cool detectors further for lower dark current
  - CubeSats SWaP limits cryocooling capabilities
    - Limits how low in temperature we can cool the FPA
- FPA Requirement
  - Cutoff > ~ 5.4 μm
  - Dark current density < 1×10^{-6} A/cm^2
  - Operating temperature > 110 K
  - Affordability is also important for relatively low-cost CubeSat missions

- HOT-BIRD FPA for CIRAS
  - SBF-193 ROIC: 24-μm pitch, 640×512 format
  - Mean QE = 53% for 3 – 5 μm band at 115 K, no ARC
  - Mean J_{dark}= 1.7 x 10^{-7} A/cm^2 at 115 K
  - Mean NEDT = 22.9 mK for 300 K background, f/7.8 optics.
  - NEDT operability 99.94%
- Meets CIRAS hyperspectral imaging requirements
- CIRAS based Pyro-atmosphere InfraRed Sounder (PIRS) recently selected for the ESTO FireSense Technology Program (FIRET-22)

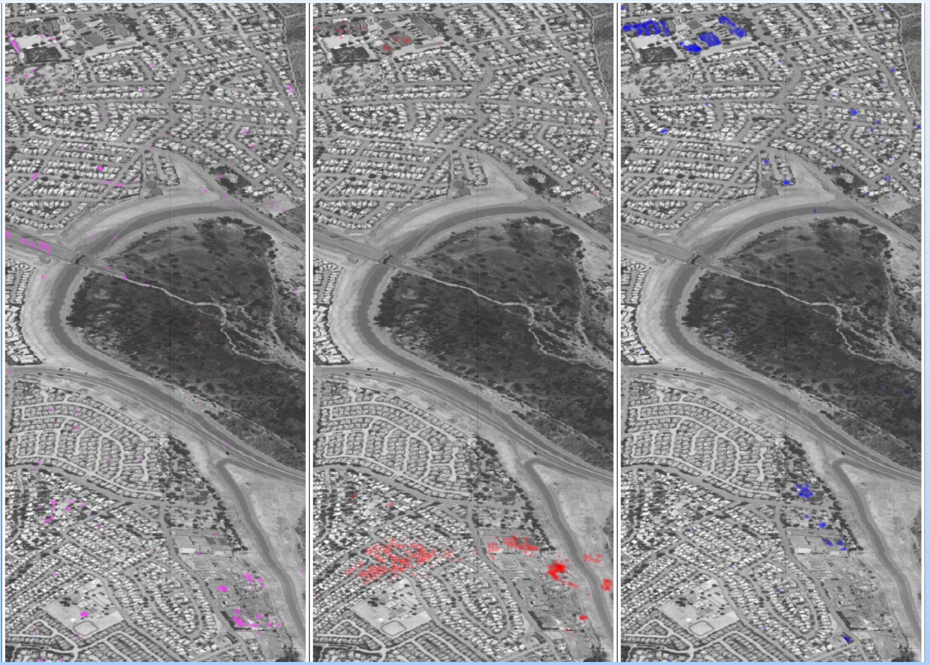
Hyperspectral Thermal Emission Spectrometer (HyTES)

- Airborne hyperspectral imaging spectrometer
  - 256 spectral channels between 7.5 and 12 µm
  - First flown in 2012, originally with LWIR QWIP FPA
  - Flying with LWIR InAs/InAsSb T2SL FPA since 2021
  - Both QWIP & T2SL FPAs exhibit good **temporal stability**; no in-flight recalibration (over several hours).

https://hytes.jpl.nasa.gov/



H_2S NH_3 SO_2



2021-05-25, Los Angeles, California

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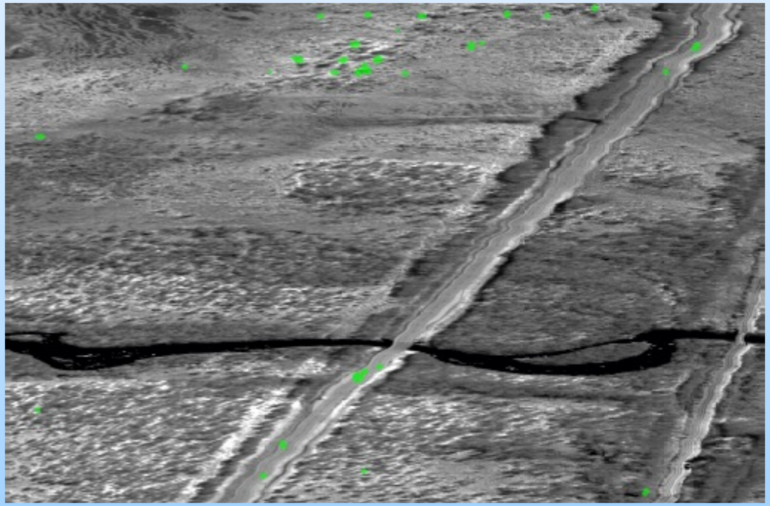
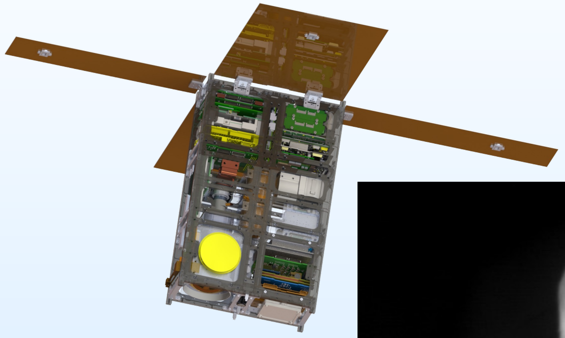


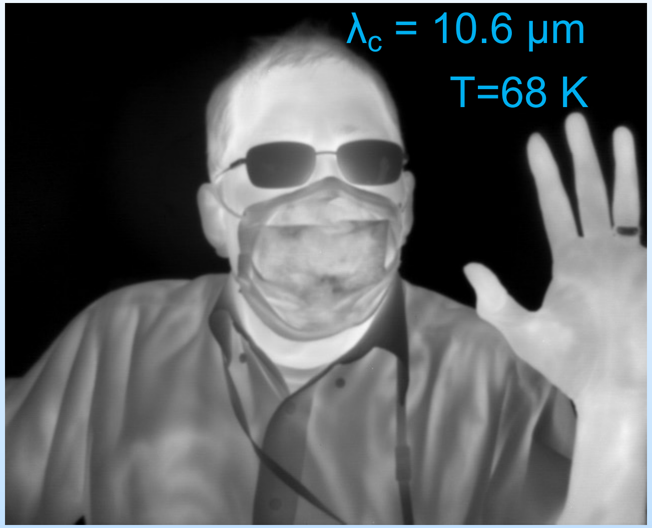
2021-08-27, Kiruna, Sweden

HyTI , c-FIRST

- HYTI: Hyperspectral Thermal Imager
  - PI: R. Wright, Hawaii Institute of Geophysics & Planetology (HIGP)
  - JPL LWIR T2SL BIRD FPA
    - SBF-193 ROIC: 24-μm pitch, 640×512 format
    - Cutoff wavelength: 10.6 μm
    - Mean J_{dark}= 2.3 x 10^{-5} A/cm^2 at 68 K.
    - Mean QE = 47% for 8.1 – 9.4 μm filter;
      28% for 8.2 – 10.7 μm filter
    - Mean NEDT = 33.4 mK for 300 K background, f/5.4 optics. NEDT operability 99.7%

https://esto.nasa.gov/invest/hyti/





- c-FIRST: Compact fire infrared radiance spectral tracker
  - PI: S. Gunapala (JPL). Presented earlier in Session 5.
  - MWIR HOT-BIRD digital-FPA

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Type-II superlattice barrier IR detectors

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