NASA SBIR 2020 Phase I Solicitation

S1.04 Sensor and Detector Technologies for Visible, IR, Far-IR, and Submillimeter

Lead Center: JPL

Participating Center(s): ARC, GSFC, LaRC

Technology Area: TA8 Science Instruments, Observatories & Sensor Systems

Scope Description

NASA is seeking new technologies or improvements to existing technologies to meet the detector needs of future missions, as described in the most recent decadal surveys:

- Earth Science and Applications from Space: http://www.nap.edu/catalog/11820.html
- New Frontiers in the Solar System: http://www.nap.edu/catalog/10432.html
- Astronomy and Astrophysics in the New Millennium: http://www.nap.edu/books/0309070317/html/

*Technologies for visible detectors are **not** being solicited this year*.

LOW-POWER & LOW-COST READOUT INTEGRATED ELECTRONICS

Photodiode Arrays: In-pixel Digital Readout Integrated Circuit (DROIC) for high dynamic range infrared imaging and spectral imaging (10-60 Hz operation) focal plane arrays to circumvent the limitations in charge well capacity, by using in-pixel digital counters that can provide orders of magnitude larger effective well depth, thereby affording longer integration times.

MKID/TES Detectors: A radiation tolerant, digital readout system is needed for the readout of low temperature detectors such as Microwave Kinetic Inductance Detector (MKIDs) or other detector types that use microwave frequency domain multiplexing techniques. Each readout channel of the system should be capable of generating a set of at least 1500 carrier tones in a bandwidth of at least 1 GHz with 14 bit precision and 1 kHz frequency placement resolution. The returning frequency multiplexed signals from the detector array will be digitized with at least 12 bit resolution. A channelizer will then perform a down-conversion at each carrier frequency with a configurable decimation factor and maximum individual subchannel bandwidth of at least 50 Hz. The power consumption of a system consisting of multiple readout channels should be at most 20 mW per subchannel or 30 W per 1 GHz readout channel. That requirement would most likely indicate the use of an RF System on a Chip or ASIC with combined digitizer and channelizer functionality.

Bolometric Arrays: Low power, low noise, cryogenic multiplexed readout for large format two-dimensional bolometer arrays with 1000 or more pixels, operating at 65-350 mK. We require a superconducting readout capable of reading two Transition Edge Sensors (TESs) per pixel within a 1 mm-square spacing. The wafer-scale readout of interest will be capable of being indium-bump bonded directly to two-dimensional arrays of membrane bolometers. We require row and column readout with very low crosstalk, low read noise \, and low detector Noise Equivalent

Power degradation.

Thermopile Detector Arrays: Mars Climate Sounder (MCS), the Diviner Lunar Radiometer Experiment (DLRE), and the Polar Radiant Energy in the Far Infrared Experiment (PREFIRE) are NASA space-borne radiometers that utilize custom thermopile detector arrays. Next-generation radiometers will use larger format thermopile detector arrays, indium bump bonding to hybridize the detector arrays to the Readout Integrated Circuits (ROICs), low input-referred noise, and low power consumption. ROICs compatible with 128x64 element Bi-Sb-Te thermopile arrays with low 1/f noise, an operating temperature between 200-300 K, radiation hardness to 300 krad and on-ROIC analog-to-digital converter (ADC) will be desirable.

LIDAR DETECTORS

Development of single-mode fiber-coupled extended-wavelength integrated InGaAs detectors/preamplifiers for heterodyne detection lidar at 2-2.1 um wavelengths with near shot-noise-limited performance for less than 3 mW local oscillator power, quantum efficiency > 90% over 2-2.1 um wavelengths, and bandwidth > 5 GHz. Specifications should be demonstrated in heterodyne detection experiments.

IR & Far-IR/SUBMILLIMETER-WAVE DETECTORS

Novel Materials and Devices**:** New or improved technologies leading to measurement of trace atmospheric species (e.g., CO, CH4, N2O) or broadband energy balance in the IR and far-IR from geostationary and low-Earth orbital platforms. Of particular interest are new direct detector or heterodyne detector technologies made using high temperature superconducting films (YBCO, MgB2) or engineered semiconductor materials, especially 2-Dimensional Electron Gas (2DEG) and Quantum Wells (QW).

Array Receivers**:** Development of a robust wafer level packaging/integration technology that will allow high-frequency capable interconnects and allow two dissimilar substrates (i.e., Silicon and GaAs) to be aligned and mechanically 'welded' together. Specially develop ball grid and/or Through Silicon Via (TSV) technology that can support submillimeter-wave (frequency above 300 GHz) arrays.

Receiver Components**:** Local Oscillators capable of spectral coverage 2-5 THz; Output power up to > 2 mW; Frequency agility with > 1 GHz near chosen THz frequency; Continuous phase-locking ability over the THz tunable range with < 100 kHz line width. Both solid-state (low parasitic Schottky diodes) as well as Quantum Cascade Lasers (for f > 2 THz) will be needed. Components and devices such as mixers, isolators, and orthomode transducers, working in the THz range, that enable future heterodyne array receivers are also desired. GaN based power amplifiers at frequencies above 100 GHz and with PAE > 25% are also needed. ASIC based SoC (System on Chip) solutions are needed for heterodyne receiver backends. ASICs capable of binning > 6 GHz intermediate frequency bandwidth into 0.1-0.5 MHz channels with low power dissipation < 0.5 W would be needed for array receivers

References

1. Meixner, M. et al., “Overview of the Origins Space telescope: science drivers to observatory requirements,” Proc. SPIE 10698 (2018).
2. Leisawitz, D. et al., “The Origins Space telescope: mission concept overview,” Proc. SPIE 10698 (2018).
3. Allan, L. N., East, N. J., Mooney, J.T., Sandin, C., “Materials for large far-IR telescope mirrors,” Proc. SPIE 10698, Paper 10698-58 (2018).
4. Dipierro, M. et al., “The Origins Space telescope cryogenic-thermal architecture,” Proc. SPIE 10698, Paper 10698-44 (2018).
5. Sakon, I., et al., “The mid-infrared imager/spectrometer/coronagraph instrument (MISC) for the Origins Space Telescope,” Proc. SPIE 10698, Paper 10698-42 (2018).
6. Staguhn, J. G., et al., “Origins Space Telescope: the far infrared imager and polarimeter FIP,” Proc. SPIE 10698, Paper 10698-45 (2018).
7. Risacher, C. et al., “The upGREAT 1.9 THz multi-pixel high resolution spectrometer for the SOFIA Observatory,” A&A 595, A34 (2016). How about TST paper?
8. Goldsmith, P., Sub--Millimeter Heterodyne Focal-Plane Arrays for High-Resolution Astronomical Spectroscopy,'' Goldsmith, P. 2017, The Radio Science Bulletin, 362, 53.
9. Performance of Backshort-Under-Grid Kilopixel TES arrays for HAWC+", DOI 10.1007/s10909-016-1509-9

10. Characterization of Kilopixel TES detector arrays for PIPER", Bibliographic link: http://adsabs.harvard.edu/abs/2018AAS...23115219D
11. A Time Domain SQUID Multiplexing System for Large Format TES Arrays": https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=31361
12. Mellberg, A., et al, “InP HEMT-Based,Cryogenic, Wideband LNAs for 4-8 GHz operating at very low DC Power”, https://ieeexplore.ieee.org/document/1014467
13. Montazeri, S. et al, “A Sub-milliwatt 4-8 GHz SiGe Cryogenic Low Noise Amplifier, https://ieeexplore.ieee.org/document/8058937
and
14. Montazeri, S. et al, “Ultra-Low-Power Cryogenic SiGe Low-Noise Amplifiers: Theory and Demonstration” , IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 64, NO. 1, JANUARY 2016.

Schleeh, J. et al, “Ultralow-Power Cryogenic InP HEMT with Minimum Noise Temperature of 1 K at 6 GHz”, IEEE ELECTRON DEVICE LETTERS, VOL. 33, NO. 5, MAY 2012.

Desired Deliverables of Phase II

Prototypes and analysis

Desired Deliverables Description

- All of the detectors and associated readout and other technologies can be built as prototypes to advance TRL. Detailed analysis of the operation and tradeoff space would also be very helpful.

State of the Art and Critical Gaps

Efficient multi-pixel readout electronics are needed both for room temperature operation as well as cryogenic temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice would not exist. The Moore's Law corollary for pixel count describes the number of pixels for the digital camera industry as growing in an exponential manner over the past several decades, and the trend is continuing. The future of long-wave detectors is moving toward tens of thousands of pixels and beyond. Readout circuits capable of addressing their needs do not exist, and without them the astronomical community will not be able to keep up with the needs of the future. These technology needs must be addressed now, or we are at risk of being unable to meet the science requirements of the future.

- Commercially available readout integrated circuits (ROICs) typically have well depths of less than 10 million electrons.
- 6-9bit, ROACH-2 board solutions with 2000 bands, <10kHz bandwidth in each are SOA.
- IR detector systems are needed for Earth imaging based on the recently release Earth Decadal Survey.
- Direct detectors with D~10^9 cm-rtHz/W achieved in this range. Technologies with new materials that take advantage of cooling to the 30-100K range are capable of D~10^12 cm-rtHz/W. Broadband (>15%) heterodyne detectors that can provide sensitivities of 5 to 10 times the quantum limit in the submillimeter-wave range while operating at 30-77 K are an improvement in the state or art due to higher operating temperature.
- Detector array detection efficiency < 20% at 532nm (including fill factor and probability of detection) for low after pulsing, low dead time designs is SOA.
- Far-IR bolometric heterodyne detectors are limited to 3dB gain bandwidth of around 3 GHz. Novel superconducting material such a MgB2 can provide significant enhancement of up to 9 GHz IF bandwidth.
- Cryogenic Low Noise Amplifiers (LNAs) in the 4-8 GHz bandwidth with thermal stability are needed for Focal Plane Arrays, Origins Space Telescope (OST) instruments, Origins Survey Spectrometers (OSS), microwave kinetic inductance detectors (MKIDs), Far-infrared Imager and Polarimeters (FIP), Heterodyne Instrument on OST (HERO), and the Lynx Telescope. DC power dissipation should be only a few mW.
- Another frequency range of interest for LNAs is 0.5-8.5 GHz. This is useful for Heterodyne Receiver for OST (HERO). Other NASA systems in the Space Geodesy Project (SGP) would be interested in

bandwidths up to 2-14 GHz.

- 15-20 dB Gain and <5 Kelvin Noise over the 4-8 GHz bandwidth has been demonstrated.
- -Currently, all space borne heterodyne receivers are single pixel. Novel architectures are needed for ~100 pixel arrays at 1.9 THz
- The current State of the Art readout circuit is capable of reading one TES per pixel in a 1 mm square area. 2D arrays developed by NIST have been a boon for current NASA programs. However, NIST has declined to continue to produce two-dimensional circuits, or to develop one capable of two TES-per-pixel readout. This work is extremely important to NASA’s filled, kilopixel bolometer array program.
- Two dimensional cryogenic readout circuits are analogous to semiconductor Readout Integrated Circuits operating at much higher temperatures. We can produce millions-of-pixel detector arrays at infrared wavelengths up to about 14 microns, only because there are readout circuits (ROIC) available on the market. Without these, high-density, large-format infrared arrays such as Quantum Well Infrared Photodiode, HgCdTe, and Strained Layer Superlattice would not exist.
- For Lidar detectors, extended wavelength InGaAs detector/preamplifier packages operating at 2-2.1 micron wavelengths with high quantum efficiency (> 90%) operating up to about 1 GHz bandwidth are available as are packages operating up to about 10 GHz with lower quantum efficiency. Detectors that have > 90% quantum efficiency over the full bandwidth from near DC to > 5 GHz and capable of achieving near-shot-noise limited operation are not currently available.

Relevance / Science Traceability

- Future short-wave, mid-wave, and long-wave infrared Earth science and planetary science missions all require detectors that are sensitive and broadband with low power requirements.
- Future Astrophysics instruments require cryogenic detectors that are super-sensitive and broadband and provide imaging capability (multi-pixel).
- Aerosol spaceborne lidar as identified by 2017 decadal survey to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide uptake. Additional applications in planetary surface mapping, vegetation, and trace gas lidar.
- Earth Radiation Budget measurement per 2007 decadal survey Clouds and Earth’s Radiant Energy System (CERES) Tier-1 designation to maintain the continuous radiation budget measurement for climate modeling and better understand radiative forcings.
- Astrophysical missions such as Origins Space Telescope (OST) will need IR and Far-IR detector and related technologies.
- LANDSAT Thermal InfraRed Sensor (TIRS), Climate Absolute Radiance and Refractivity Observatory (CLARREO), BOReal Ecosystem Atmosphere Study (BOREAS), Methane Trace Gas Sounder or other infrared earth observing missions.
- Current Science missions utilizing two-dimensional, large-format cryogenic readout circuits:
  (1) HAWC + (High Resolution Airborne Wideband Camera Upgrade) for SOFIA (Stratospheric Observatory for Infrared Astronomy)Future missions:

1) PIPER (Primordial Inflation Polarization Experiment), Balloon-borne

2) PICO (Probe of Inflation and Cosmic Origins, a Probe-class Cosmic Microwave Background mission concept

- Lidar detectors are needed for 3D wind measurements from space.