OST Technology Roadmap

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14-June-2017

List of Technology Gaps

1. Direct Detectors –
    - 1a. higher sensitivity, high dynamic range, and larger arrays
    - 1b. cryogenic multiplexing and pre-amps
    - 1c. room temperature readout-lower power {assessed at TRL4}
2. Compact Far-IR Spectrometer {labeled as enhancing}
3. Heterodyne Improvements {labeled as enhancing]
4. Sub-Kelvin Cooler (funded SAT for CADR) {assessed at TRL4}
5. Cryogenic Mirror Technology (actuators and material studies) {TRL4}
6. 4 K mechanical coolers {assessed at TRL4}
7. Mid–IR Coronagraph (need breakdown of components that need development)

- Send any additions/updates to Mike DiPirro by June 23 for inclusion in this year's PATR

Origins Space Telescope

	Total Gaps	TRL 2 Gaps	TRL 3 Gaps	TRL 4+ Gaps
Enabling+ enhancing	11	3	4	4
Enabling only	5	1	1	3

ID	Technology Gap	TRL	Note
1.1	Far-IR (FIR) detectors	3	NEP requirements relaxed, but main challenge is in multiplexing.
1.2	Cryogenic readouts for large-format FIR detectors	2	If speed requirement chosen to be enhancing then TRL may rise.
1.3	Warm readout electronics for large-format FIR detectors	4	May need further assessment; existing technology could likely limit number of channels
2*	Compact integrated spectrometers	3	
3*	Heterodyne FIR detector arrays	3	
4	Sub-K Coolers	4	
5	Cryogenic FIR mirror segments	4	Assumes Be segments, otherwise TRL decreases; other materials may require cryo-figure actuators
6*	Advanced Cryocoolers	4	SOA is acceptable
7.1*	Coronagraph optics and architecture	2	An optical design with masks and mirrors compatible with a segmented primary mirror
7.2*	Cryogenic deformable mirrors	2	Deformable mirrors that operate at cryogenic temperatures
7.3*	Mid-IR detectors	3	SOA may be OK, pending analysis

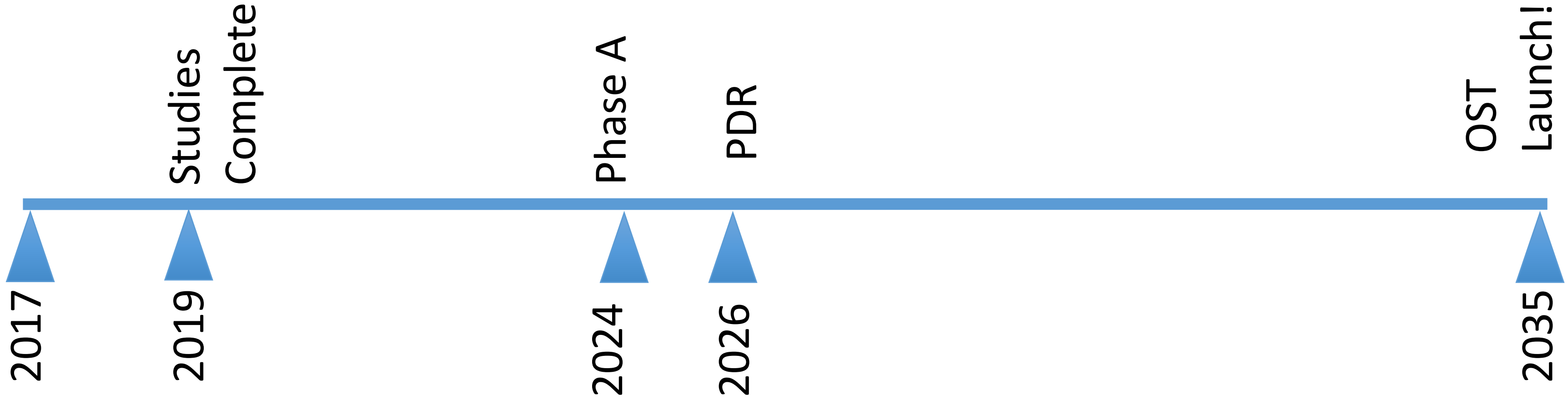
*** Enhancing technology**

60 second tutorial on TRL definitions from Pause and Learn

TRL	TRL	Definition in NPR 7123.1B	Summary
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	**Concept**
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	**Proof-of-concept**
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality in critical test environments, and associated performance predictions are defined relative to final operating environment.	**Low-fidelity prototype demonstrated in a lab**
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	**Medium-fidelity prototype demonstrated to meet performance in the relevant environment**

Road to TRL-6

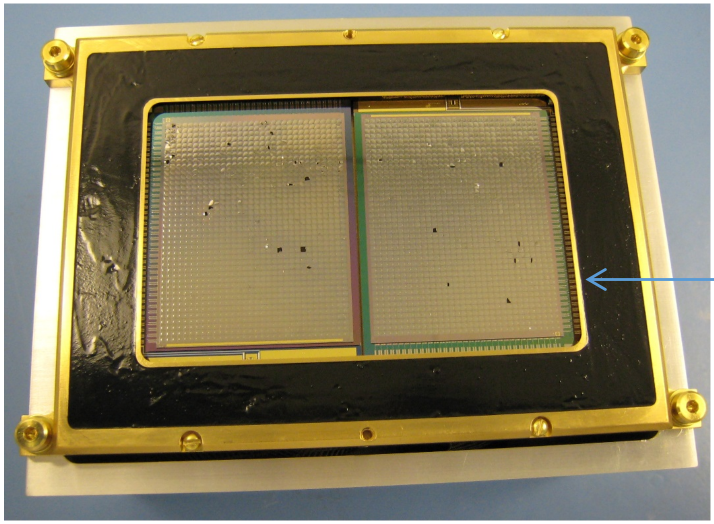
- Mature the Key Technologies to TRL 4 by 2019, TRL 5 by 2024, and TRL 6 by 2026
  - From the Pause and Learn we found that OST was in the best shape of the 4 STDTs with only two enabling technologies below TRL 4
    - Stated “goal” is 3 or fewer TRL <4 <u>enabling</u> technologies
    - Enabling vs. Enhancing needs further discussion



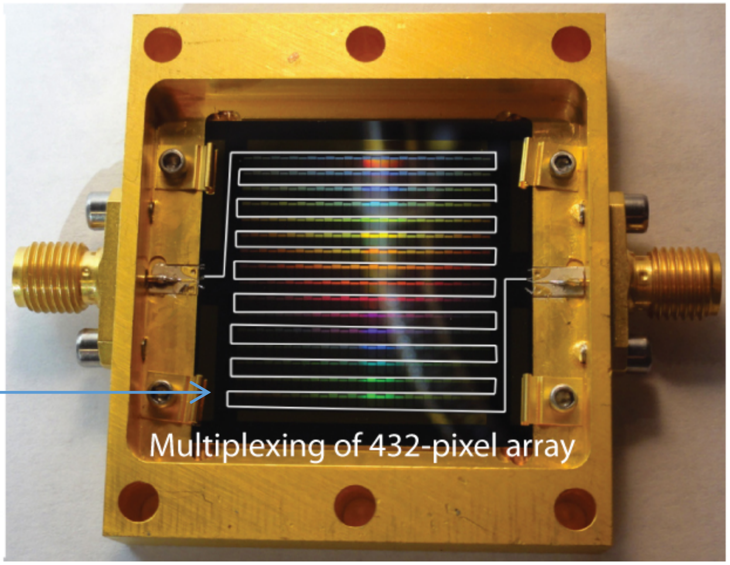
1a. Detector Details-1

- Enabling noise equivalent power (NEP) 1e-19 W/√Hz
- Enhancing NEP to 3e-20 W/√Hz or better
- Enabling 10^4 pixels per array
- Enhancing 3x10^4 pixels per array
- Must be compatible with cryogenic multiplexers

1a. Detector Details-2

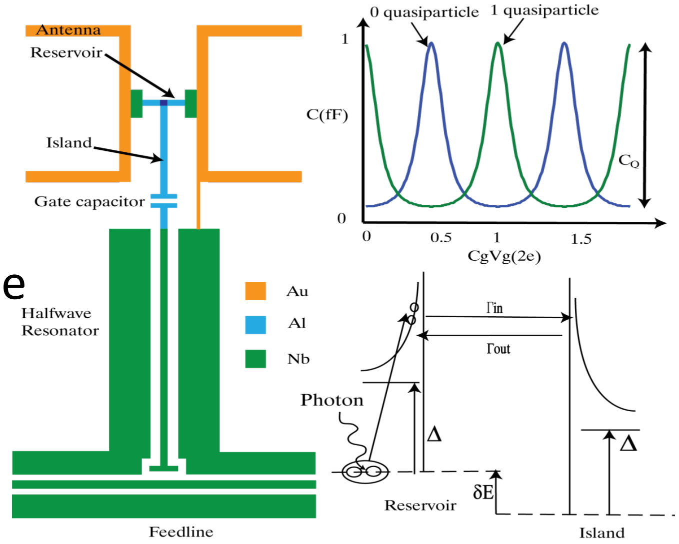


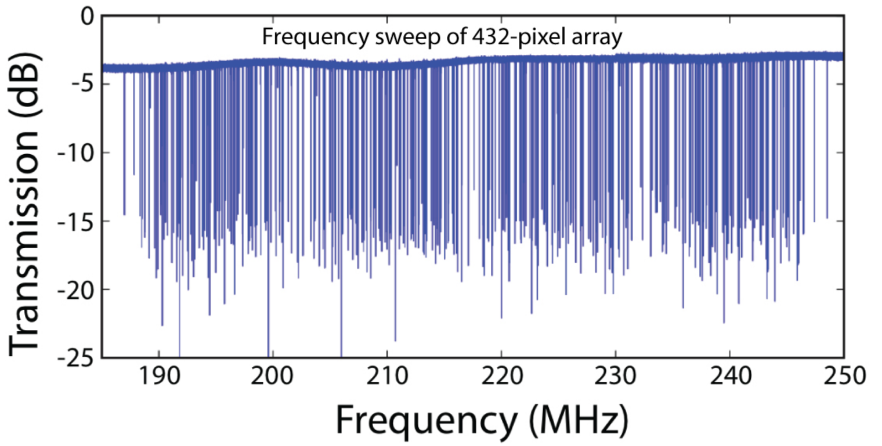
HAWC+
40x32x2
1 mm pixel
1e-18 W/√Hz



KID 432 pixel
Array
1e-18 W/√Hz

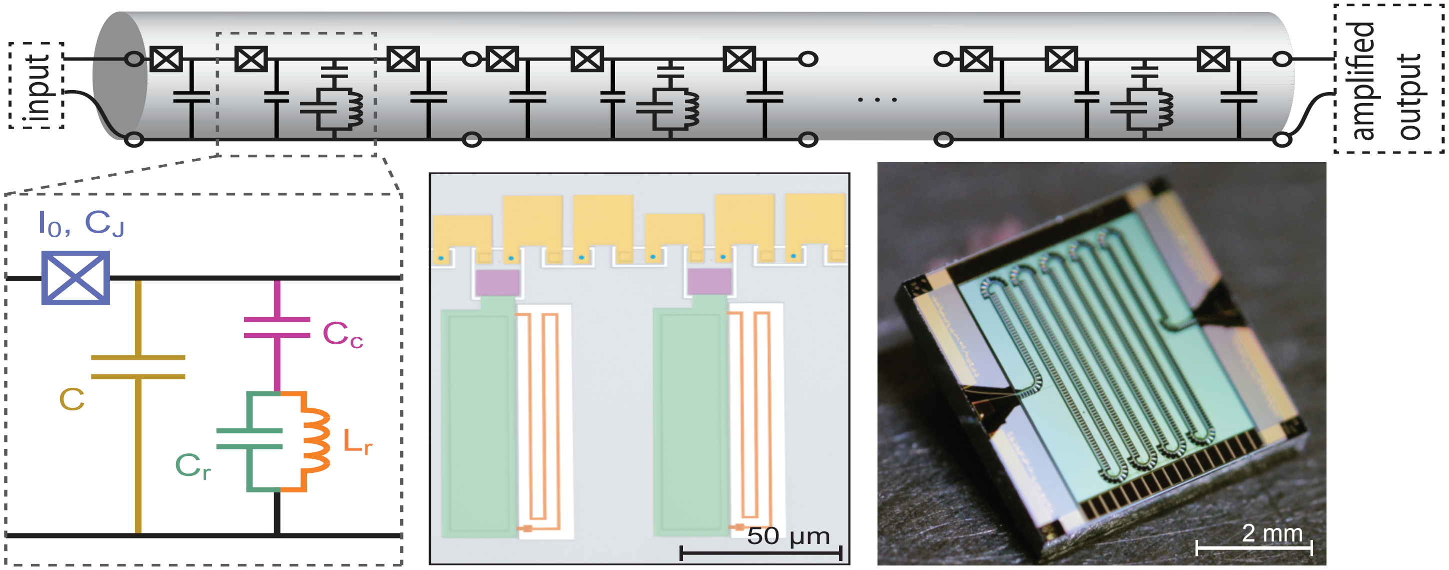
Quantum
Capacitance
Detector





1b. Multiplexing & Preamp Details

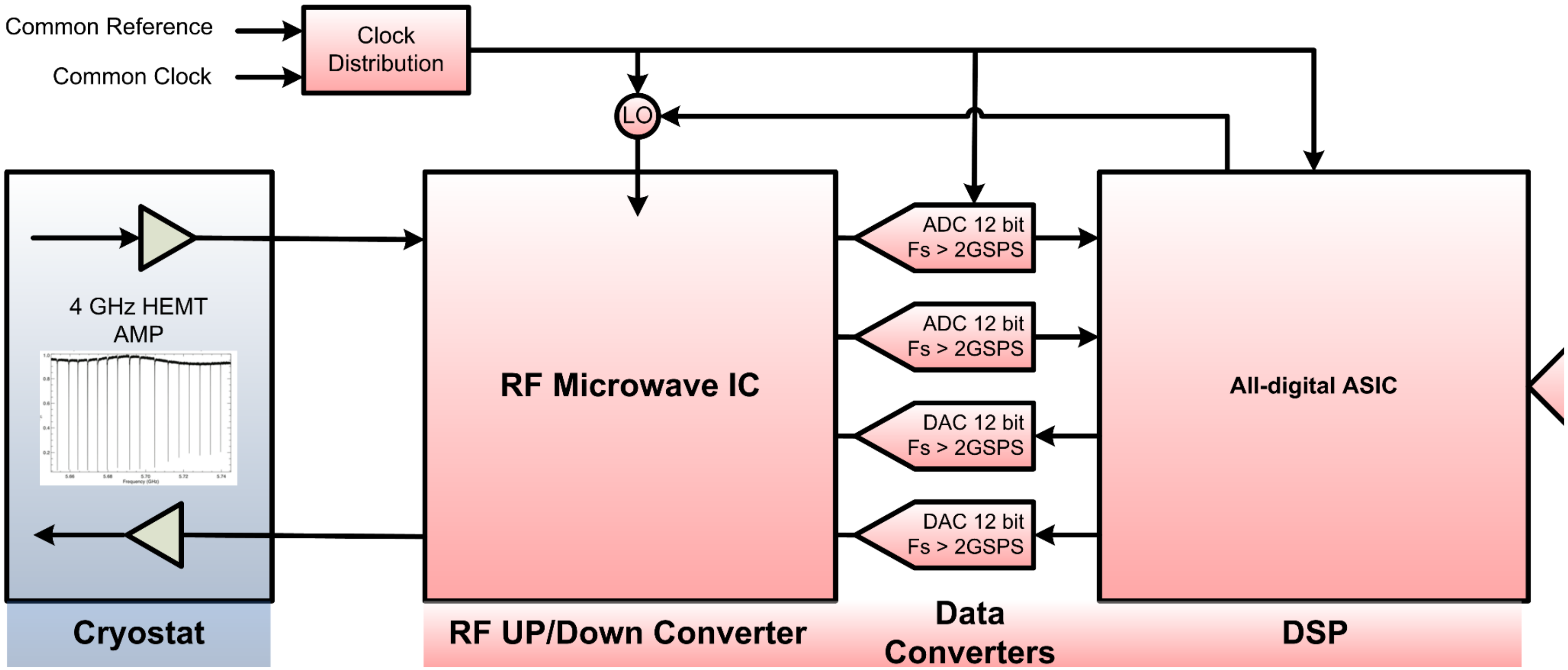
- Multiplexing using rf resonator circuits
  - Enabling goal is >1000 pixels per channel without loss of sensitivity or cross-talk
- Preamplifiers using µwave SQUIDs and/or parametric amplifiers and/or HEMTs
  - Enabling is < 0.7 mW per channel
  - Enhancing is < 0.3 mW per channel



Achieved 20+ dB gain over 4.5 GHz instantaneous bandwidth with near-quantum-limited noise temperature < 400 mK (Lincoln Labs)

1c. Room Temperature Readout Details

- ASICs to perform frequency demultiplexing task with low power requirement
  - Current state of the art is 60 W/channel using FPGAs
  - Enabling is <30 W/channel using ASICs assessed at TRL4



Common Reference
Common Clock
Clock Distribution
LO
4 GHz HEMT AMP
RF Microwave IC
ADC 12 bit Fs > 2GSPS
ADC 12 bit Fs > 2GSPS
DAC 12 bit Fs > 2GSPS
DAC 12 bit Fs > 2GSPS
All-digital ASIC
Cryostat
RF UP/Down Converter
Data Converters
DSP

Discussion

- Please provide Input for Next COR and PCOS PATR
- Have we used enabling and enhancing properly?
- What updates are there to the technolgy in the last year?
- Can we make it to TRL 4 with enabling technologies by 2019?

ORIGINS
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Present OST Technology Gap Matrix

Dec adal								Crosscutting Applicability					
Gap	STDT	Technology Item	Brief Description	Key Performance Capability Requirement (Flight)	Current State of the Art	TRL Today per STDT	Enabling (Mission Won't Launch Without This) or Enhancing (Desirable)	Applicability for Other Missions and/or Programs within Astrophysics	Applicability for Other NASA Divisions or Directorates, Other Agencies, and/or Private Sector	STDT Comments	TRL Today per PO	PO's Rationale	APD SATs and Directed Funding
1	OST	Large format Far-IR detectors	Large-format detectors which operate with high efficiency (≥80%), low noise, and relatively fast time constant. Readout schemes including cryogenic multiplexing and room temperature ADCs and rf electronics for these arrays also need development	Detector sensitivities with noise-equivalent powers (NEPs) of ≈ 3E-20 W/√Hz are needed for spectroscopy, available in a close-packed configuration in at least one direction. The detector system should be scalable to enable ~a million-pixel total format in a large mission. Fast detector time constant (~200 µsec) is needed for Fourier-transform spectroscopy. Readout schemes using HEMT amplifiers and frequency multiplexed resonant circuits are in development. Near term this scheme should result in 1000-3000 pixels per HEMT channel. Recovering the signal to noise with lower power room temperature electronics needs to lower the input power by up to a facotr of 10.	Single detectors are at TRL ~5, but demonstrated array architectures are lagging at TRL ~3.	3-5	Detector NEP of 3e-19 is eanbling, 3e-20 is enhancing. Array size of 10^4 pixels is enabling, 3x10^4 is enhancing. Readout of 1000 pixels per channel is enabling, 3000 pixels per channel is enhancing	Readout technology is applicable to microcalorimetry in X-ray missions such as Athena and Lynx.			2	The principal challenge is to achieve both low NEP (~3E-20) and scalability to ~million pixels in an array. Some detector architectures that are getting close to the required NEP are quantum capacitance detectors (QCD), electron-phonon isolated transition edge sensors (TESs), and kinetic inductance detectors (KIDs). For KIDs, NEP performance is 10× short of the requirement, but there is a credible path to achieve 3E-20 by reducing superconducting absorber volume by a factor of 100. Multiplexing over 1,000 channels has been demonstrated in KIDs and TESs. Thus it is the opinion of the PO that this technology is nearly at TRL 3.	Jonas Zmuidzinas at JPL has been working on an SAT titled "Kinetic Inductance Detector Imaging Arrays for Far-Infrared Astrophysics" since 2013 and which is ending this year.
2	OST	Compact, Integrated Spectrometers for 100 to 1000 µm	Compact, integrated spectrometer operating in the 100 mm to 1 mm band which can provide a wide (e.g. 1:1.6) instantaneous bandwidth at resolving power (R = λ/Δλ = n/Δn) ~500 with high efficiency in a compact package ~10 cm package which could be arrayed in a focal plane to provide integral-field mapping or multi-object spectroscopy capability.	An integrated spectrometer + detector array system would demonstrate 1:1.7 bandwidth (or greater), high efficiency (>50%, including detector absorption), resolving power > 400, and a coupling scheme compatible with a telescope beam e.g. an f/4 Gaussian beam. To enable the observatories with hundreds of spectrometers, a single spectrometer + detector array would be a packaged on a silicon wafer on order tens of square cm in size (e.g. less than one 4" wafer).	Multiple compact spectrometers are under development: including compact silicon gratings and grating analogs, as well as superconducting filterbanks. These systems are promising, and in some cases are approaching photon-noise limited performance suitable for ground-based observations, but have not yet been demonstrated in a scientific application.	3	Enhancing. This technology will decrease the size, mass and cost of far infrared spectrometers.				3	Concur with STDT's assessment. While TRL 4 has not been achieved yet, there are multiple relevant detectors with hardware demonstration providing proof of concept.	
4	OST	Heterodyne FIR detector arrays and related technologies	Heterodyne focal-plane arrays are needed for high-sensitivity, spectrally resolved mapping of interstellar clouds, star-forming regions, and solar system objects including comets. These arrays require mixers with low noise-temperature and wide intermediate frequency (IF) bandwidth, local oscillators (LOs) that are tunable but which can be phase-locked, and accompanying system technology including optics and low-cost, low-power digital spectrometers. Specifically, LO sources at frequencies above 2 THz that can generate ≥ 10 microW (corrected from mW per Martina Wiedner) of power will be essential for large-format heterodyne receiver arrays to observe many spectral lines important for COR (e.g., HD at 2.7 THz and OI at 4.7 THz).	Tunable-bandwidth array receivers for operation at frequencies of 1-5 THz. Arrays of 10 to 100 pixels are required to build on the discoveries of Herschel and exploit the sub-millimeter/FIR region for astronomy. Should include optics and accompanying system components. For mixers, IF bandwidths of 4 GHz 8 GHz at shorter wavelengths (< 100 microns) are essential to analyze entire galactic spectrum in one observation. Sensitive mixers not requiring cooling to 4 K (e.g., based on high critical temperature superconductors) will be essential for application on space platforms, especially with the benefit of increased IF bandwidth. For LOs, sources with output power levels ≥ 10 microW (corrected from mW per Martina Wiedner) at frequencies above 2 THz. For digital spectrometers, 8 GHz bandwidth with > 8000 spectral channels, and < 1W power per pixel will be necessary for large arrays used in space missions	For SOFIA, only single-pixel receivers have been developed for flight; arrays of 16 pixels are approaching TRL ~4. LOs above 2 THz are at TRL 2.	2-4	Enhancing.				2	A COR SAT working with an array of 16 pixels at 1.9 THz was approaching TRL 4. Another SAT developing QCL LOs for 4.7 THz is also at TRL 3. However, the requirement for a "broad-tunable-bandwidth array receivers for operation at frequencies of 1-5 THz" leads us to the assessment that TRL 3 has not been met. Broad band tunability is not required for OST. Current state of the art is sufficient in "tunability" is adequate for OST.	Imran Mehdi at JPL had a SAT titled "A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping" that came close to TRL 4 but ended in 2016. Qing Hu at MIT has a SAT titled "Raising the TRL of 4.7 THz local oscillators" that is at TRL 3 and funded through FY18.
5	OST	High-performance, sub-Kelvin coolers	Optics and detectors for FIR, sub-millimeter, and certain X-ray missions require very low temperatures of operation, typically in the tens of milli-Kelvins. Compact, low-power, lightweight coolers suitable for space-flight are needed to provide this cooling.	A sub-Kelvin cooler operating from a base temperature of ~4 K and cooling to 30 mK with a continuous heat lift of 5 µW at 50 mK and 1 µW at 30 mK. Features such as compactness, low input power, low vibration, intermediate cooling, and other impact-reducing design aspects are desired.	Existing adiabatic demagnetic refrigerators with low cooling power at 50 mK are at TRL 7-9 (Hitomi/SXS) but high cooling power versions are at TRL 4, dilution refrigerators at TRL 3 and solid-state cooling approach based on quantum tunneling through normal-insulator-superconductor (NIS) junctions is at TRL 3.	3-4	Enabling. ADRs currently under development through the SAT will provide TRL 5-6.	SubKelvin coolers are also required for X-ray missions with microcalorimeters such as Athena and Lynx.			4	Concur with STDT that high-cooling power ADR development has achieved TRL 4.	Jim Tuttle at GSFC has a SAT titled "High-Efficiency Continuous Cooling for Cryogenic Instruments and sub-Kelvin Detectors" funded through FY19.
6	OST	Large Cryogenic Optics for the Far IR	Large telescopes (of order 10 m in diameter) provide both light-gathering power to see the faintest targets, and spatial resolution to see the most detail and reduce source confusion. To achieve the ultimate sensitivity, their emission must be minimized, which requires these telescopes be operated at temperatures, depending on the application, as low as 4 K.	Develop a feasible and affordable approach to producing a 10-m-class telescope with sufficiently high specific stiffness, strength, and low areal density to be launched, while maintaining compatibility with cryogenic cooling and FIR surface quality/figure of ~1µm rms. Material property measurements at cryogenic temperatures for structures and optics such as damping, emissivity, thermal conductivity, etc.	JWST Be mirror segments may meet requirements now, so TRL 5 with an extremely expensive technology; TRL 3 exists for other materials like SiC. Cryogenic low dissipation actuators exist at TRL 3-5.	3-5	Enabling. Lower cost materials and verification techniques are required to lower the cost for a future mission.				4	Gold-plated Be mirror technology is at high TRL from Spitzer and JWST's progress. Therefore, technology components have high TRL but together as a single system this technology is at TRL 4 for this set of requirements. Spitzer's Be mirror operated at 5.5 K with 67-nm RMS, and we don't expect significant impact from cooling to 4 K. JWST Be mirrors are at a high TRL, but for much higher temperature.	
7	OST	Advanced Cryocoolers	Cryo-coolers are required for achieving very low temperatures (e.g., ~4 K) for optics and as precoolers for sub-Kelvin detector coolers for COR missions. Eliminating the need for expendable materials (cryogens) will increase achievable lifetime and reduce system mass and volume. Improvements are needed in terms of performance, especially low power consumption and low vibration levels.	Several mission concepts require sustaining temperatures of a few Kelvin, with continuous heat-lift levels of a few dozen to ~200 mW at temperatures ranging from 4 K to 18 K. Other concepts could benefit from greater heat lifts at somewhat higher temperatures. All this needs to be accomplished with < 200 W input power. Such coolers need to be compact, and impose only low levels of vibration on the spacecraft. In some applications, a sub-Kelvin cooler will be implemented, and an advanced few- Kelvin cryo-cooler able to maintain the sub-Kelvin cooler's hot zone at a steady (e.g.) 4 K will be very beneficial.	For several-Kelvin temperature designs, the current state of the art includes pulse-tube, Stirling, and Joule-Thomson coolers which are at high TRL but are expensive, and do not yet have good enough performance. Changes in the working fluid have been shown to produce temerpatures in the range of 4.0 K which is required for OST	4	Enhancing. Currentl state of the art is high TRL cryocoolers that produce cooling to 4.5 K. Producing larger cryocoolers with improved efficiency will lower the input power required.	Cryocoolers are needed for a variety of Astrophysics missions. 4K class cryocoolers are necessary for the Athena and Lynx X-ray missions.	STMD is funding development of a high cooling power, low vibration, high efficiency 20 K class cooler for long term storage of cryogenic propellants. This would have some applicability to OST.		4	Concur with STDT assessment.	
8	OST	Mid-IR spectral coronagraph	Characterization of the atmospheres of cool exoplanets in wide orbits (>5 AU, ice giants and more massive) requires spectrally dispersed coronagraphy in the 7-30 micron range with contrasts of 1E-6 and IWA of 0.1" at the shortest wavelength. The spectral resolving power should be moderate (R~100-500).	A spectro-imaging instrument with and inner working angle of 0.1" at 10 micron. This is likely less than 2 λ/D for the available aperture. The best IWA is needed to detect a 300 K Neptune-sized planet at 10 pc at a 1-2 AU separation, and the contrast should be 1E-6 to detect Saturn at 10 pc (~1 microJy @ 24 micron, 3 λ/D for 16m aperture) with R~10. The maximum spectral dispersion should be sufficient to resolve the 15 micron CO_2 band (R~500).	The current state of the art for mid-infrared coronagraphs are the three four-quadrant phase masks of JWST-MIRI. These provide narrow-band imaging with contrasts up to 1E-4 in three narrow bands from 10.65-15.5 micron with inner working angles of 0.33-0.49". The MIRI coronagraphs do not offer spectral dispersion.	Laboratory devices have been laboratory tested by JAXA. Current TRL is TBD.	Enhancing. The coronagraph science will not drive the OST design.	Coronagraphy is applicable at other wavelengths, for instance in LUVOIR and HabEx.			3	Non-dispersive coronagraph mask for JWST is at TRL 6, but is not demonstrated to meet OST contrast requirements; A proposed SPICA coronagraph (JAXA-ESA; earliest launch 2027-2028) has been shown by analysis and lab demonstrations of masks to achieve better than 1E-6 contrast at 3.5 l/D (at 10 microns) with R~200. But for OST to claim TRL 4, basic functionality of a cryogenic deformable mirror would be demonstrated in the lab. In addition, a detailed analysis would show that the required contrast can be achieved at <2 l/D and the contrast can be met with a segmented primary mirror.	