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Introduction

This first Astrophysics Technology Update (ATU) highlights 12 examples of developments in technology maturation projects, from early 2022 to date, funded by NASA's Astrophysics Division. These and dozens more technology projects are funded through multiple programs: Strategic Astrophysics Technology (SAT), Astrophysics Research and Analysis (APRA), Internal Scientist Funding Model (ISFM), Segmented Mirror Technology Program (SMTP), and others (e.g., one of the highlighted projects, NEID, was funded in collaboration with the National Science Foundation). These ATUs will appear in between issues of the Astrophysics Biennial Technology Report (ABTR). The coming ABTR will be published this September and the next ATU should come out in September 2025. To learn more, visit the Astrophysics Projects Division technology website by scanning the following QR code:

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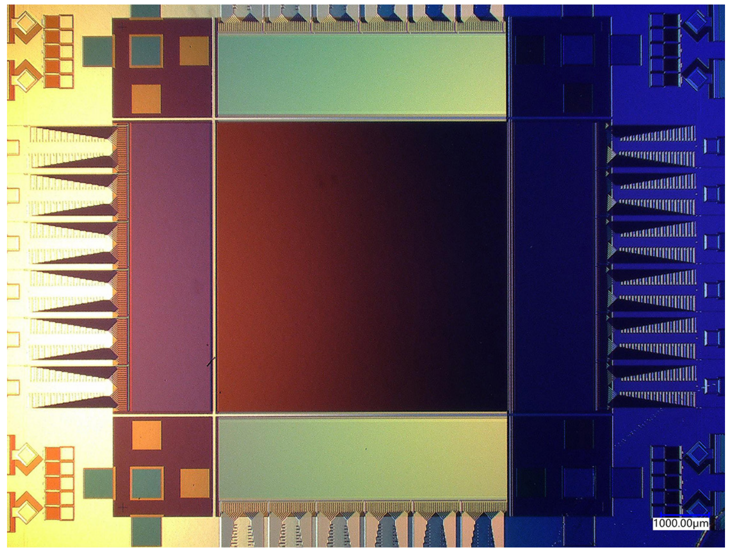
Cover Image: Tarantula Nebula. **Credit:** James Webb Space Telescope

Quantum Detection: Superconducting Nanowire Single-Photon Detectors

When imaging faint objects such as distant stars or exoplanets orbiting them, cameras must capture every single photon with extremely low noise. Superconducting cameras excel in both criteria but have historically not been widely applicable because they rarely exceeded a few thousand pixels, limiting their ability to capture high-resolution images. A team of researchers recently shattered that barrier with a 400,000-pixel superconducting camera that could detect faint astronomical signals from the ultraviolet (UV) to the infrared (IR). For every billion photons captured by these superconducting cameras, fewer than ten may be due to noise. Because these detectors are so sensitive, it's hard to pack them densely without causing interference between pixels. In addition, since these detectors need to be kept cold, only a handful of wires can be used to carry signals from the camera to its warm readout electronics.



A 400,000-pixel superconducting camera based on SNSPDs. Image credit: Adam McCaughan

To overcome these limitations, researchers at the National Institute of Standards and Technology (NIST), NASA's Jet Propulsion Laboratory (JPL), and the University of Colorado Boulder applied time-domain multiplexing to interrogating two-dimensional superconducting-nanowire single-photon-detector (SNSPD) arrays. Individual nanowires are arranged as intersecting rows and columns. When a photon arrives, the detector identifies which pixel sent the signal by measuring the times it takes to trigger a row detector and a column detector. This lets the camera efficiently encode its many rows and columns onto just a few readout wires.

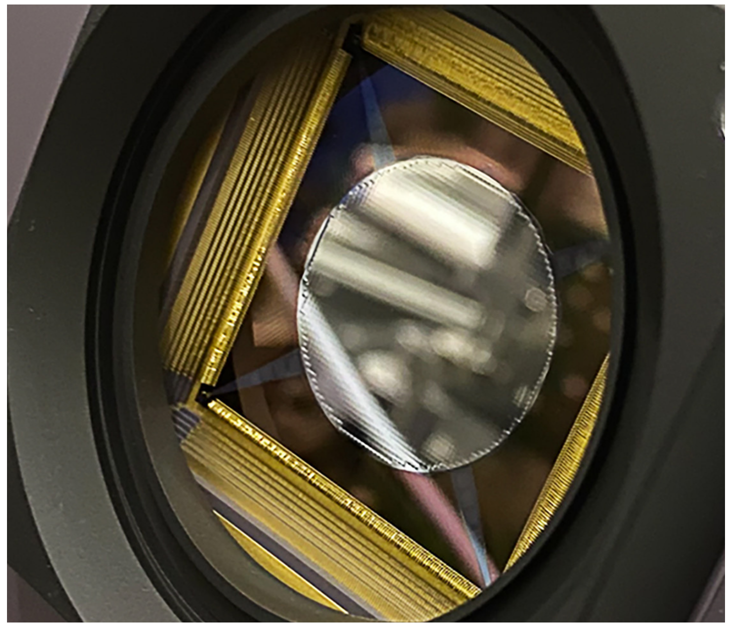
SNSPDs are one among many superconducting detector technologies, including microwave kinetic inductance detectors (MKIDs), transition-edge sensors (TESs), and quantum capacitance detectors (QCDs). SNSPDs are unique in that they operate much warmer than the millikelvin (mK) temperatures required by other technologies and have extremely good timing resolution, although they can't resolve the color of individual photons. NIST, JPL, and others have researched SNSPDs collaboratively for nearly two decades. This most recent work was only possible thanks to advances generated by the wider superconducting-detector community.

Once they implemented this readout architecture, constructing superconducting cameras with extremely large numbers of pixels became straightforward. Dr. Bakhrom Oripov says, "The big advance here is that the detectors are truly independent, so if you want a camera with more pixels, you just add detectors to the chip." The researchers note that while their recent project was a 400,000-pixel device, they plan to demonstrate a device with over a million pixels and have yet to find an upper limit.

SNSPD cameras can also detect optical signals from missions in deep space. Optical links can transmit data at far higher rates than radio-frequency links from interplanetary distances. They can also be optimized for biomedical imaging to detect previously undetectably faint signals from cells and molecules and for quantum computing.

This Astrophysics Research and Analysis (APRA) team, led by NIST's Adam McCaughan and JPL's Boris Korzh, is now planning to optimize their camera for space applications, including both the UV and IR.

Deformable Mirrors in Space: Enabling Direct Imaging of Exo-Earths



A Boston Micromachines Corporation (BMC) 2k DM with 2040 actuators on a 400-μm pitch. Image credit: Eduardo Bendek

Finding and studying Earth-like planets orbiting nearby stars is critical to understanding if we are alone in the universe. To study such planets and assess if they can sustain life, they must be directly imaged. However, glare from the host star is ten billion times brighter than the light reflected by the planet, overwhelming the signal. A coronagraph can remove that glare. Deformable mirrors (DMs) are essential components of coronagraphs, as they can correct the tiniest of imperfections in the telescope, down to under half a billionth of an inch, 10 picometers (pm) –a fraction of the size of a hydrogen atom– removing any remaining starlight contamination.

DMs adjust the optical path of incoming light by changing the shape of a reflective mirror using precisely controlled piston-like actuators. These adjustments "correct" the wavefront that's perturbated by optical aberrations upstream and downstream of the DM, such as defects and/or optical misalignments internal to the telescope that may be driven by changing thermal gradients as the telescope and detectors are heated or cooled.

The DM's main characteristics are: 1) the number of actuators, proportional to the correctable field of view; 2) the actuators' maximum stroke; 3) the DM speed, or time required to modify its surface; 4) the surface-height resolution, defining the smallest wavefront control step; and 5) the stability of the DM surface.

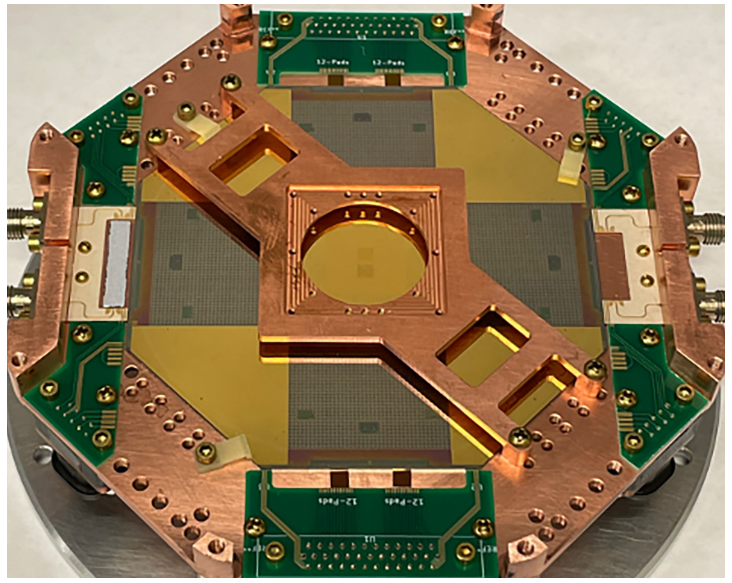
DMs will be demonstrated in space on a coronagraph instrument on NASA's Roman Space Telescope, planned to launch in 2027. This technology will enable a future flagship mission recommended by the 2020 Decadal Survey in Astronomy and Astrophysics (Astro2020), provisionally called the "Habitable Worlds Observatory" (HWO).

HWO DMs will require imaging contrast on the order of ten billion, 10,000× deeper than those used in ground-based telescopes, and strokes of under a micrometer (μm). However, the driving requirements for the DM and its control electronics are surface-height resolution (<10 pm) and surface stability (<10 pm/hour). The large number of actuators, up to ~10,000, is also a challenge, requiring a large number of high-voltage (~100 V) connections. The control electronics will likely require very high (>20-bit) depth and filters to remove electronics noise.

Several DM actuator technologies are considered for space missions: 1) Electrostrictive technology, such as AOA Xinetics's, with 1-mm pitch, in which actuators are mechanically connected to the DM's reflective surface; when a voltage is applied the actuator contracts and modifies the mirror surface. 2) Electrostatically forced Micro-Electro-Mechanical-System (MEMS) DMs, such as BMC's 2k DM (image) with 400-μm actuators, where the mirror surface is deformed by electrostatic force between an electrode and the mirror. 3) Inductive voice-coil technology, such as ALPAO, with a 1.5–2.5 mm pitch, whose actuators inductively drive the surface in a mechanically decoupled fashion.

A survey of DM vendors was conducted by a team led by Eduardo Bendek, Duncan Liu, and Tyler Groff.

New X-ray Detectors to View the High-Energy Universe



Prototype 100,000-pixel MMC array developed via collaboration between GSFC and MIT/LL. Image credit: Wonsik Yook

High-energy-resolution imaging X-ray spectrometers are crucial for studying galactic cores, needed for understanding galaxy formation. Large, high-angular-resolution imaging X-ray spectrometers help study the essential drivers of galaxy evolution, which leave imprints in the warm-to-hot plasma that cosmologists believe exists in the spaces between galaxies, making up to half of the universe's "normal matter."

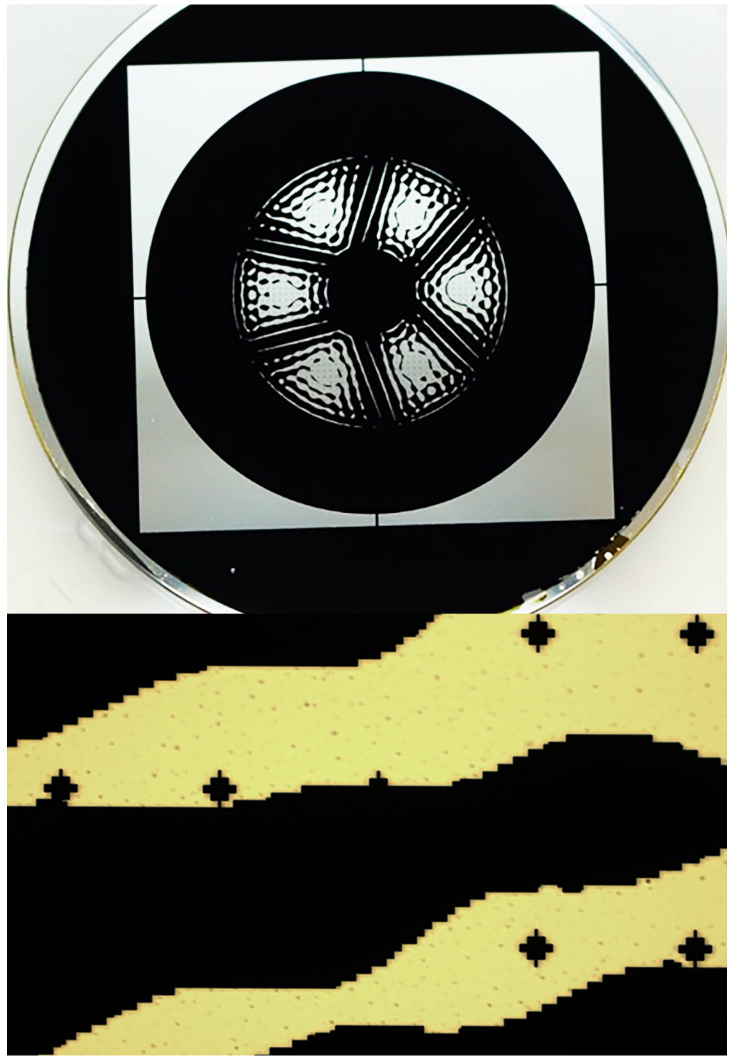
Microcalorimeters are a class of X-ray spectrometers operating at very low temperatures, a few percent of a degree Kelvin above absolute zero. Over the past five years, groups at Goddard Space Flight Center (GSFC), Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL), and NIST in Boulder, Colorado have been developing an ambitious new X-ray camera with unprecedented imaging and spectroscopic capabilities. This camera is based on a new type of X-ray detector, magnetic microcalorimeters (MMCs), which significantly extends the technology's capabilities. For example, the Japan Aerospace Exploration Agency/NASA's XRISM has a 36-pixel microcalorimeter array. The European Space Agency's flagship ATHENA mission, planned to launch in 2035, will fly a 2000-pixel microcalorimeter array. The NASA/MIT/NIST effort is working on a 100,000-pixel array, targeting angular scales and array sizes normally associated with CCD cameras, but with an energy resolution two orders of magnitude better.

When an incoming X-ray hits an MMC absorber, its energy converts into heat. Paramagnetic thermometers, where magnetization is inversely proportional to temperature, provide high-precision temperature sensing. MMC arrays can be attached to multiple X-ray absorbers with different thermal conductances. The unique temporal response of each pixel to X-ray events helps identify event position. This kind of thermal multiplexing device is called a "Hydra" after the multi-headed monster in Greek mythology.

The main challenge in creating large MMC arrays is fabricating high-density, high-yield, microstrip superconducting wiring to connect all the pixels. MIT/LL developed an innovative process that allows over eight layers of superconducting wiring with high yield. A four-layer array was fabricated, and the next generation of devices currently in fabrication has seven layers of buried wiring. By combining this buried wiring process with the 25-pixel, 'thermally multiplexed' MMCs developed at GSFC, the team produced large-format arrays that includes pixels with 25-μm and 50-μm pitches.

The final development needed to make this detector suitable for future astrophysics missions is the multiplexed readout needed for such large arrays. With NASA funding, NIST is developing a microwave-multiplexer Superconducting QUantum Interference Device (μMUX SQUID) readout in a form factor suitable for direct integration with this detector. Four two-dimensional (2D) chips carrying this readout will be bump-bonded to the four large green rectangular areas in the detector's outer regions (image). NIST recently demonstrated low-noise μMUX SQUIDs in small one-dimensional resonator arrays suitable for the new MMCs. These μMUX SQUIDs measured magnetic flux noise corresponding to just 20 quanta (photons) at signal frequencies, meeting the challenging design requirements. Soon, 2D versions of this readout will be bump-bonded to the detector, and the team hopes to demonstrate a ground-breaking new astrophysics instrumentation capability. GSFC's Simon Bandler leads a direct-funded project developing these devices.

Detecting Exo-Earths in Multi-Star Systems



Optical mask enabling suppression of starlight in multi-star systems, revealing planets in such systems (top). Microscopic detail showing mild periodic grating ("+" shapes) that enables MSWC (bottom). This mask is planned to fly as a contributed mode on the Roman Space Telescope coronagraphic instrument. Image credit: Eduardo Bendek

Imaging exoplanets in single-star systems requires a ten-orders-of-magnitude starlight suppression to avoid losing the dim reflected light from the exoplanet in the star's glare. This challenge is even greater in the many nearby star systems, such as Alpha Centauri, that are home to multiple stars. To image exo-Earths in such systems and search them for signs of life, we need a multi-star wavefront-control (MSWC) technology to suppress the light from all the stars in that system.

MSWC, invented at NASA's Ames Research Center (ARC) in 2014, relies on two innovations. The first is a way to control a DM to suppress light from two stars independently using two different sets of shapes (spatial frequency modes) on the DM for different stars. The second technique, "super-Nyquist wavefront control," allows DMs to suppress starlight beyond their normal limits by using a special "mild grating" (image).

Normally, a DM can only suppress starlight in a small region around a star – a DM control region. This poses a problem when imaging binary stars because a typical DM can only suppress starlight from both stars if those stars' control regions overlap. However, binary stars tend to be far apart, so there's no overlap. The mild grating solves this problem by creating a grid of faint copies of the second star ("diffraction orders"), extending the DM's reach to a much larger region around each star. Merging the two techniques, a coronagraph can overcome cross-contamination and increase starlight contrast to image exoplanets in binary star systems.

Because DMs will be present in all future coronagraphic mission concepts, MSWC is compatible with any coronagraphic mission, in principle. This compatibility enabled MSWC to be accepted as a contributed mode on the Roman Space Telescope's Coronagraph Instrument, with only slight modifications of the single-star instrument masks. Testing MSWC on the sky in this context will demonstrate this important technology to enable imaging of exoplanets in binary star systems, including Alpha Centauri.

The MSWC team, led by ARC's Ruslan Belikov, has been steadily maturing the technology through simulations and demonstrations at the Ames Coronagraph Experiment Laboratory and on the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument on Japan's ground-based Subaru Telescope. Over the past few years, the team extended MSWC testing to the High Contrast Imaging Testbed (HCIT) at JPL, a state-of-the-art facility for high-contrast demonstrations in vacuum.

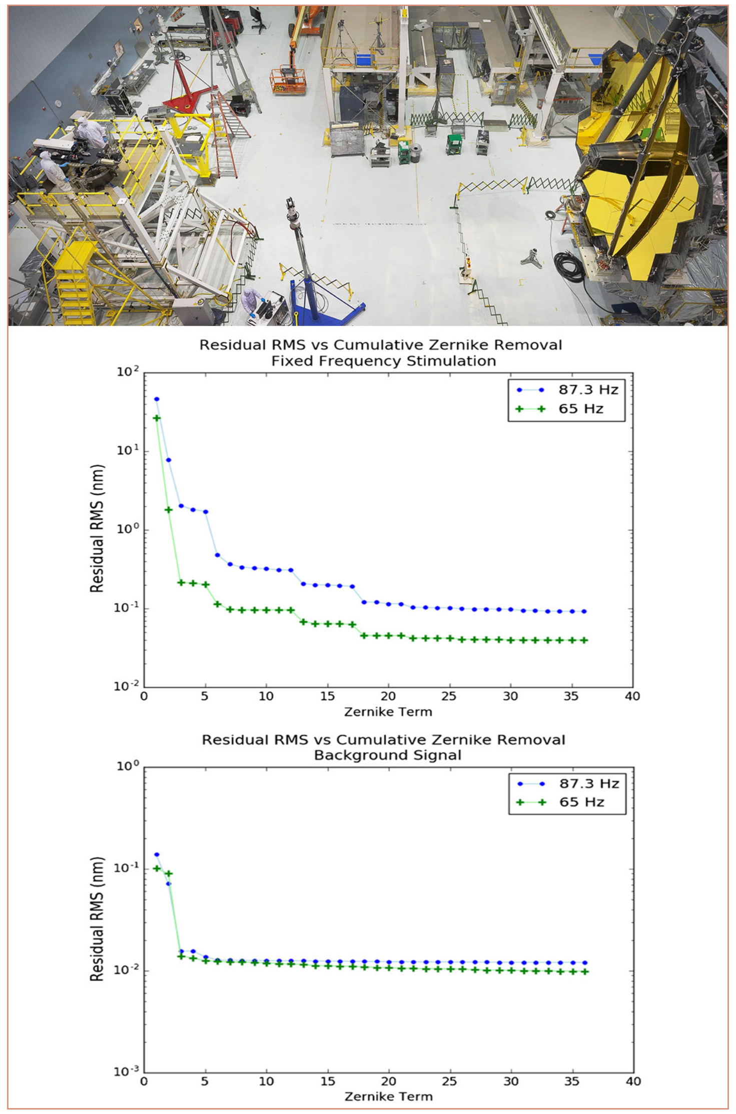
MSWC has demonstrated the basic feasibility of suppressing starlight from more than one star, including where stars are separated beyond DMs' conventional limits.

Ultra-Stable Testbed: Enabling Development of the Habitable Worlds Observatory

HWO, recommended by Astro2020, will directly image 25 exo-Earths in search of biosignatures. This requires high contrast, 10^{-10}, and even more demanding contrast stability, 10^{-11}. Contrast stability requires maintaining a stable telescope prescription, defined by the shape and position of all optical elements, affected by environmental effects such as mechanism vibrations and slow thermal drift of the metering structure and optical elements. To achieve such remarkable contrast stability, the primary mirror must be stable to 10 pm, a fraction of a hydrogen atom size, over a seconds-to-minutes telescope control cycle.

Designing such a telescope requires a new spatial metrology system and new environmental controls to measure component and system stability to a corresponding level. A GSFC Strategic Astrophysics Technology (SAT) team, led by Babak Saif and Lee Feinberg, with representatives from the Space Telescope Science Institute and the Smithsonian Astrophysical Observatory, is developing the Ultra-stable Structures Laboratory to enable the design and development of large ultra-stable telescopes.

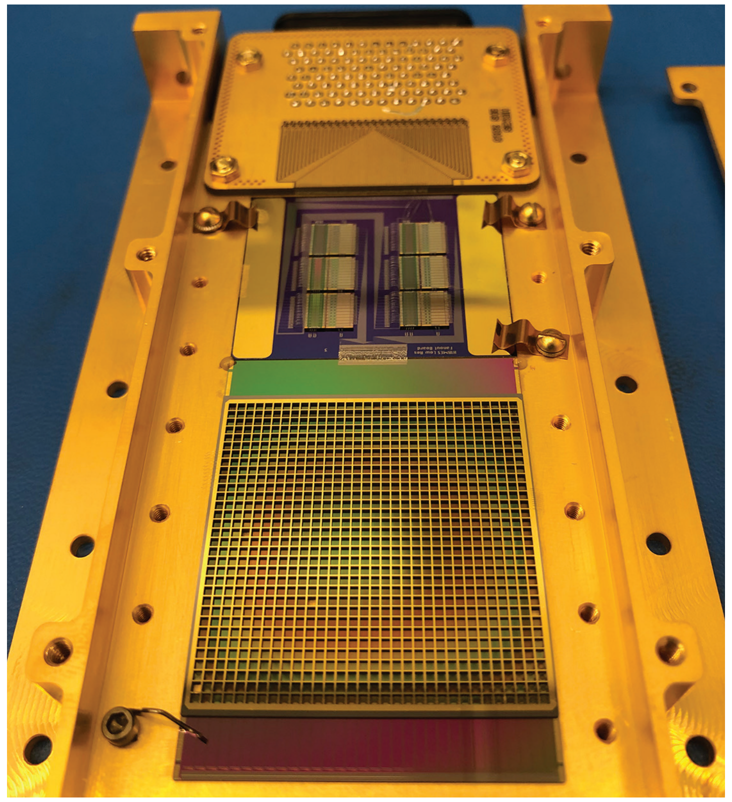
The lab can measure pm dimensional stability of both dynamic and temporal disturbances for diffuse and specular surfaces at rates up to 5.9 kHz and temperature control <±1 mK – very challenging precision. By comparison, jet engine components are controlled to tens of μm, 10^7× less stringent, and the James Webb Space Telescope's (JWST) stability requirements are a few nanometers, 1000× less stringent.



The first version of the High-Speed Interferometer was used to measure JWST mirror-segment responses to very small dynamic stimuli (top). The residual spatial root-mean-square after subtracting the first N dynamic Zernike terms is shown with stimulus (center) and without stimulus (bottom). Photo: Chris Gunn, Graphics: Babak Saif, et al.

Systems behave very differently at pm scales than at nanometers or larger scales. For example, pm-amplitude vibrations may not propagate over mechanically fastened joints; instead, adhesives are needed to transmit disturbances. Internal stresses and external environments also play a role. Thus, unlike with JWST, the team emphasizes measuring pm spatial changes without testing over larger temperature changes. They successfully measured pm-level dynamic spatial changes, and recent work focused on the more difficult measurement of drift (slow changes, like small thermal changes). Their approach is to develop new metrology methods and equipment as required and incrementally test ultra-stable telescope building blocks, such as actuators, composite materials, joints, etc. Over time, lab infrastructure will be expanded to enable the characterization of large subsystems and structures. An initial version of this new stability metrology was used on in-situ JWST mirror segment measurements in 2015 – 2016 via very-low-amplitude dynamic stimulation of the entire telescope (image). Those tests identified surface aberrations at pm-level amplitudes. Recently, the team measured thermally induced drifts < 3±2 pm/sec in the surface profile of a flat glass plate.

Large Superconducting Sensor Arrays Enabling Far-IR Observatories



The interface between a "Double Stack" detector (bottom component) and cryogenic readout SQUID multiplexers (above the detector). Image credit: Felipe A. Colazo Petit

Astro2020 recommended a series of flagships and Probe-class missions, including far-IR imaging or spectroscopy ones, requiring cryogenic telescopes with unprecedented sensitivities and mapping speeds. Such missions could measure the masses of protoplanetary disks; track the role of water, ice, and volatiles in planet formation; investigate the interplay between the interstellar medium and star formation across the Milky Way; and diagnose the state of gas and its radiation environment in nearby galaxies, including outer galaxy disks and extra-planar material associated with feedback and gas accretion. These advanced telescopes could also study the evolution of galaxies and the matter they're made of throughout the history of the universe, from the formation of the first dust clouds to star-forming galaxies at the cosmic noon (when significantly more stars were formed per time unit than today) and perform detailed investigations of the matter making up the Milky Way. Far-IR observatories can see through layers of matter that block visible light. They can observe the supermassive black holes embedded in the dense central regions of many galaxies, allowing astronomers to determine how black-hole creation proceeded throughout the universe's history.

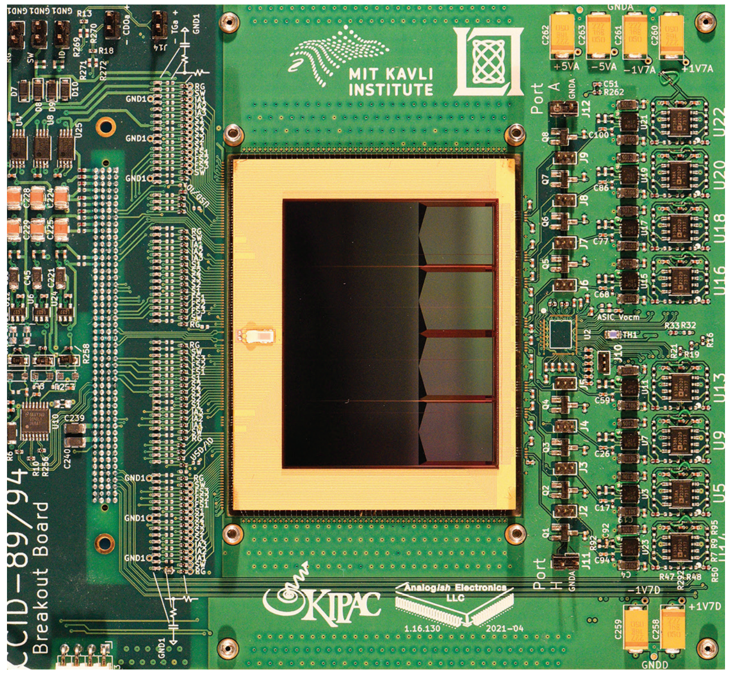
Such observatories require robust, high-sensitivity, 100,000-pixel arrays operating over the entire far-IR spectrum, with integrated readout multiplexers meeting the ultra-low-noise requirements of space missions. Some key technologies needed for these arrays were previously demonstrated on the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA). Those detectors provided excellent performance for suborbital far-IR applications, but their production was labor-intensive with low yields.

Johannes Staguhn of GSFC and Johns Hopkins University leads an SAT team from GSFC and NIST in Boulder, Colorado, addressing this need. The team is maturing and streamlining the processing required to produce arrays with large numbers of pixels (10,000) that can be tiled to deliver the desired 100,000 pixels.

The team successfully developed detector wafers that could be bonded together to produce a detector with the required 100,000 pixels, each containing one AlMn TES superconducting detector. Developing a kilopixel detector required "hybridization," a process allowing detector wafers to be bonded together. Indium "bumps" are deposited on dedicated landing spots on each wafer, after which the wafers are pushed together. The bumps on one wafer stick to those on the other, creating a superconducting connection between the wafers. Using this method, the team developed the first kilopixel detector, consisting of a hybridized "Double Stack" detector, a readout board, and 64 channels of ultra-sensitive SQUIDs (image). The project's end product was the demonstration of a fully bump-bonded "Triple Stack" detector array. A so-called "interposer board" was bump-bonded to the detector array. This "double stack" was then bump-bonded to a fanout board. Using this new detector, the team successfully measured several devices, the first demonstration of a triple layer of superconducting bump bonds.

Fast, Low-noise X-ray Sensors for Investigating Supermassive Black Holes

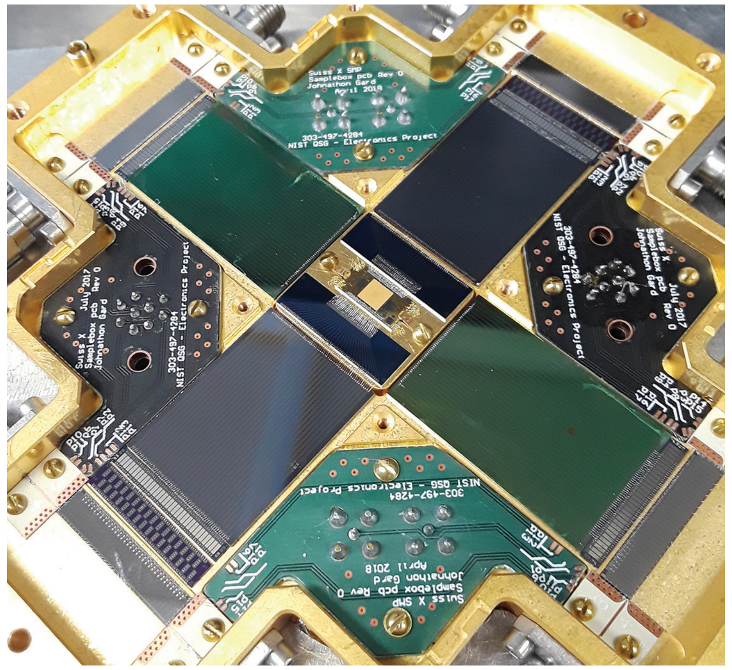
New imaging technology will enable future large X-ray missions recommended by Astro2020 to trace the origin and growth of black holes and the ways they shaped the cosmos. X-ray photons carry 1000× more energy than visible-light photons, so special sensors are needed to sense them and measure their energies. Future X-ray sensors must be able to record and process photons 10–30× faster than Chandra, with high sensitivity and low internal noise; and meet stringent size, mass, and power constraints. An MIT team led by Mark Bautz, working with MIT/LL and Stanford University, is developing and operating X-ray CCDs and applying the latest micro-fabrication and micro-electronics developments to achieve and exceed the required performance. The team is also developing chips to provide fast, low-noise, low-power, analog signal processing. The team demonstrated noise levels better than Chandra's sensors while operating 20× faster with the same power per unit detector area. With a new 8-channel chip, they demonstrated high-speed, low-noise X-ray imaging 40× faster than Chandra (image). The team is working on a further 2.5× increase.



Advanced 2-megapixel X-ray image sensor (dark brown rectangle surrounded by gold frame) mounted on a test board (green). Image credit: David Volfson

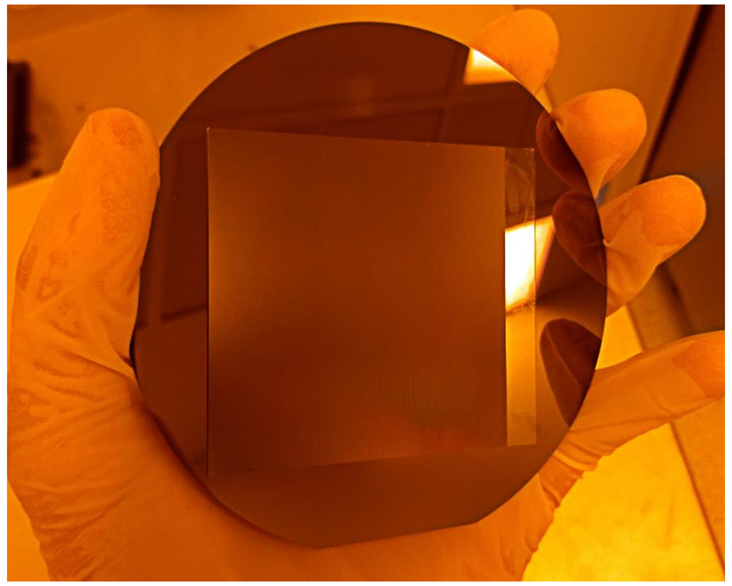
Microwave SQUID Multiplexing Enables Large X-ray Detector Arrays

Combining recent advances in X-ray mirrors and spectroscopic X-ray detectors, such as TES microcalorimeters, future X-ray observatories could transform our understanding of the cosmos. When cooled below 0.1 K, microcalorimeters can measure single X-ray photon energies with < 0.1% error. To achieve such cold temperatures with fixed power, signals from many sensors must be multiplexed to few wires. NIST pioneered the use of SQUID μMUX from cryogenic detectors to warm readout electronics. An X-ray Flagship requires multiplexing 100,000 pixels, for example by combining thermal and electrical multiplexing. μMUXs transform microcalorimeter signals into frequency shifts at GHz frequencies, taking advantage of the large bandwidth that microwave components can use to combine signals from thousands of sensors onto a single cable. This SAT team, led by NIST's Douglas Bennett, demonstrated μMUXs optimized to read out thermally multiplexed microcalorimeters (image), targeting the proposed Lynx X-ray Microcalorimeter requirements that could also work for future X-ray missions with large microcalorimeter arrays.



Microwave SQUID multiplexers (outermost chips) integrated with hydra TES array (innermost chip) fabricated by GSFC. Image credit: Kelsey Morgan

Nanofabricating Diffractive Optics for Future Great Observatories



A full-sized echelle grating after production in the PSU nanofabrication lab. This grating is over 50% more efficient than previous state-of-the-art echelles, with improved scattered-light performance. Image credit: Drew Miles

Advanced semiconductor fabrication methods help improve performance and may reduce the cost of the next major UV/optical space observatory, HWO, for example by fabricating advanced diffraction gratings with higher efficiency and more creative design flexibility than previously possible. Penn State University (PSU) researchers used electron-beam lithography and chemical etching to rule X-ray gratings onto flat silicon wafers, leveraging silicon's crystal properties, and creating exceptionally smooth, precise, and uniform blazed grooves across the grating surface. University of Colorado's Brian Fleming leads an SAT team that includes Johns Hopkins University and PSU, which applies these techniques to UV wavelengths. Echelle gratings are low-period, high-blaze-angle gratings designed to operate at a steep angle of incidence, enabling high-resolution spectrographs commonly used to characterize chemical abundances in stars or, more recently, exoplanet atmospheres. The team used the new technology to produce three etched silicon gratings that surpassed the state-of-the-art diffraction efficiency by ~50%, with 3× the efficiency of a similar grating on Hubble. The team is infusing the new technology on suborbital missions including the FORTIS and MOBIUS sounding rockets and the MANTIS EUV CubeSat.

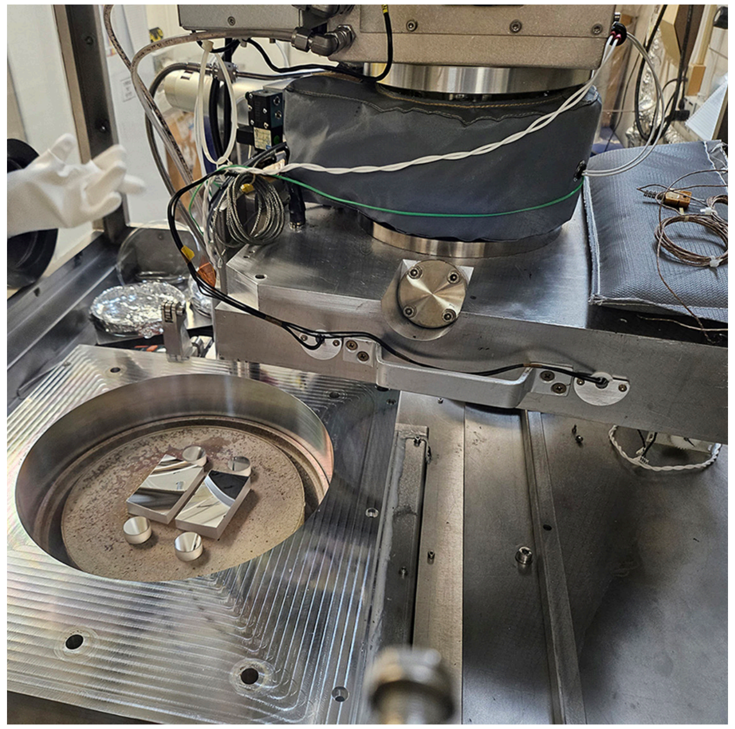
NEID: Opening an Ultra-Precise Window to Investigate Nearby Exoplanets

Left to right: Principal Investigator Suvrath Mahadevan, systems engineer Andy Monson, and project manager Fred Hearty install a massive prism into NEID. Image credit: Colin Nitroy

PSU's Suvrath Mahadevan led a team of astronomers funded by NASA and the National Science Foundation to develop the NEID spectrometer, installed on the 3.5-m WIYN telescope at Kitt Peak National Observatory, to precisely measure with sub-meter-per-second stability, the wobbles of stars caused by the planets orbiting them. NEID uses minute Doppler wavelength shifts in light reaching us from these stars, precisely measuring the mass of new exoplanets discovered by TESS and facilitating the discovery of nearby exoplanets to be targeted by observatories such as HWO. NEID's large-format, high-quality optics capture starlight across the visible range and beyond. The optics are encased in a vacuum chamber and temperature-controlled to sub-mK stability. Such strict maintenance of the instrument's environment eliminates measurement instability due to atmospheric index-of-refraction variability or optical-mount thermal expansion. The system is calibrated by a laser frequency comb to correct for inevitable baseline drifts due to effects such as atomic-level settling of the optics.

High-Performance, Stable, Scalable UV Mirror Coatings Using ALD

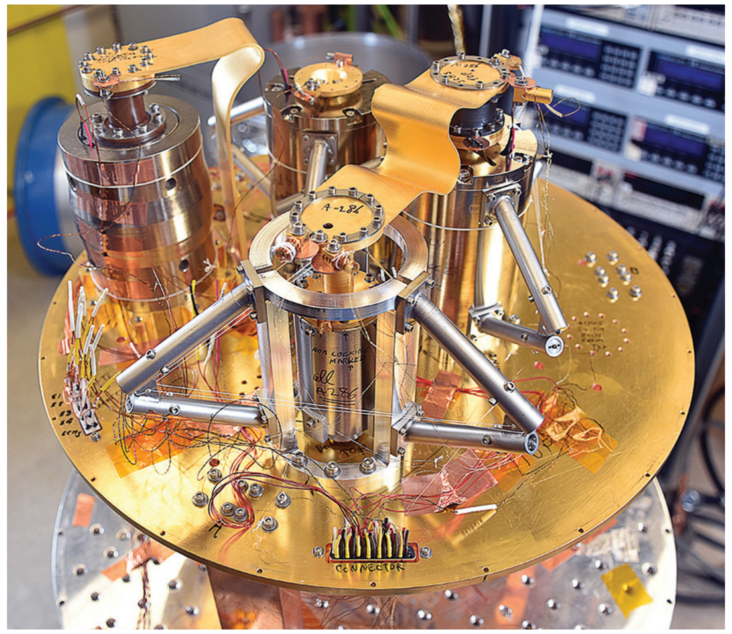
Enhancing UV reflectance is crucial for missions such as HWO, where the large number of reflections in the optical path lead to a nearly 20-fold higher throughput by increasing reflectance from 75% to 90%. JPL's John Hennessy leads an SAT project studying and enhancing the long-term performance stability of LiF/Al wide-bandpass (100–2500 nm) mirror systems using atomic layer deposition (ALD) and demonstrating scalability towards large (>1 meter) mirrors. The team uses JPL's low-temperature (~100°C) ALD metal fluoride processes with atomic layer etching (ALE) to maximize the performance of UV protected-aluminum mirror coatings and exploit the unique capabilities of ALD, including nanolaminate structures and mixed-composition fluoride overcoats. They measure and model reflectance uniformity, wavefront error, and polarization retardance over the full aperture of shaped optics in wavelength bands of interest to exoplanet coronagraphs. ALD-protected mirror coatings were fabricated at 150- and 200-mm sizes, with initial coupon tests over 0.9 meter underway. This technology is used as part of the mirror coatings for the SPRITE CubeSat and the Aspera SmallSat mission.



Flight-optic coating inside JPL ALD chamber for the Aspera Pioneers mission using a mirror coating that combines GSFC's eLiF process with thin ALD MgF_2 encapsulation. Image credit: John Hennessy

CADR: Enabling Ultra-Low-Noise Detectors

Continuous Adiabatic Demagnetization Refrigeration (CADR) is an enabling technology for multiple strategic Astrophysics missions, including far-IR and X-ray Flagships and Probes. A team led by GSFC's Mark Kimball is working to bring a CADR to Technology Readiness Level (TRL) 6 with continuous cooling of 3 microwatts (μW) at 35 mK simultaneous with 1.5 milliwatts (mW) of cooling at 1 K. The CADR uses paramagnetic salts heated/cooled by changing magnetic fields, with heat transferred between stages separated by heat switches. Magnetic shielding maintains the exported field to under 2 microtesla (μT); which, along with its efficient, highly reliable, vibration-free operation makes this a low-impact cooling solution. This technology promises to exceed the requirements of currently conceived cryogenic detector arrays. The team is completing the design of this new system and is currently working towards a demonstration of the 1-K continuous stage.



A four-stage 0.05 K to 4 K CADR installed in a cryogenic test facility. Image credit: Herbert Eaton