TechPort ID*	Project Title*	Project Description*
96365	A Novel Optical Etalon for Precision Radial Velocity Measurements	Precise measurement of the Doppler shifts of starlight resulting from the radial velocity of planet-hosting stars is one of the first and most powerful methods of exoplanet detection. While spectrograph stability imposes limits on how precisely the radial velocity (RV) can be measured, spectral references play a critical role in characterizing and ensuring this precision. Only optical frequency combs and line-referenced Fabry-Perot etalons are capable of providing the stability needed for detecting Earth-like planets in the habitable zone of their Sun-like host stars. While both frequency combs and etalons can deliver high precision spectrograph calibration, the former requires relatively complex and sophisticated hardware in the visible portion of the spectrum. Specifically, ground-based, visible band astrocombs are large instruments that require multiple stages of filtering to achieve the line density resolvable by astronomical spectrographs. Other methods for achieving the desired mode spacing between 400 nm and 800 nm with frequency combs may entail second harmonic generation from NIR combs, which then must circumvent phase matching issues, or nonlinear spectral broadening of longer wavelength combs that requires high pulse power owing to the nonlinearity of materials that function in this regime. Etalons promise a simpler, more elegant, and smaller size, weight, and power (SWaP) alternative to visible band, high repetition rate frequency combs. While mirror-based etalons have previously struggled with implementation due to factors such as thermally induced instability and dispersion, sensitivity to polarization and alignment of input light, and mirror coating degradation, recent breakthroughs in engineering thermally insensitive whispering gallery mode (WGM) microresonators [1] make their use as novel etalons for visible-band RV calibration achievable. We propose to demonstrate a compact, reliable , and environmentally insensitive line-referenced etalon calibrator capable of operating in space and on the ground. The etalon will help next generation spectrographs to successfully detect Earth-mass Habitable Zone exoplanets. The proposed work builds on our experience developing compound microresonators with an engineered thermorefractivity. The broadband etalon (e.g. 400 nm to 800 nm) operation and comb-like spectrum is enabled by a crystalline CaF_2 or MgF_2 WGM resonator integrated with ceramic layers characterized by a negative coefficient of thermal expansion. We will first demonstrate the technology in a laboratory setting to show long-term stability, and then ultimately at an observatory. This work directly addresses the Exoplanet Exploration Program's Technology Gap List element M-2 to provide a robust, low SWaP precise calibration source for extreme-precision radial velocity measurements in the visible spectrum. We draw on our collective capabilities in precision radial velocity detection, expertise in engineering composite WGM microresonators, creating small, rugged, packaged devices, precision metrology, and etalons to demonstrate this technology for future NASA instruments and missions. 1. Matsko,A., Savchenkov, A, J. Opt. 20 (2018) 035801

96366	Large format, high dynamic range UV detector using MCPs and Timepix4 readouts	Large area microchannel plate (MCP) detectors have been identified as the leading candidates for upcoming NASA UV missions such as LUVOIR and HabEx. MCP detectors combine noiseless photon counting with good UV quantum efficiency, high spatial resolution, low intrinsic background and resistance to radiation damage. The large size of the instruments proposed for the focal planes (e.g. the Large Ultraviolet Multi-Object Spectrometer, LUMOS) require very large format detectors that must accommodate a very high dynamic range to handle the spectra from distant galaxies to nearby FUV bright B stars. Recently, MCPs have been fabricated in very large formats (200 x 200 mm). Much of the excellent imaging performance of these detectors is made possible by various types of readout anodes, which either utilize charge division or charge propagation time to encode the position of each event (e.g. Cross Strip [XS], Cross Delay Line [XDL] readouts) and associated electronics that determine the position of the incident UV photon. Over the past decade, our group at the Space Sciences Laboratory at Berkeley has been developing a new type of MCP readout based on the family of read out integrated circuits (ROICs) developed at CERN called Medipix/Timepix. The pixelated (256x256) Timepix ROIC can sample the MCP charge clouds to determine event centroids. Because the sampling pixels are small (55 micron), the amplifier noise is very low (<75e- rms) allowing a very low MCP gain (~50,000) to achieve spatial resolutions on the order of the MCP pore spacing. Since all the pixels are independent, this resolution is independent of the number of readout ROICs used to support larger MCPs. Unfortunately, the original Timepix and its successor, the Timepix3, could only be abutted on 3 sides, the fourth side used for I/O wirebonds. Therefore only 2xN arrays of these 17 x 14mm chips could be used, limiting the area of such an MCP detector, so it was never proposed for use in the large format NASA applications mentioned above. However, the Timepix readout has been used in many of our detectors in the field, specifically 2x2 arrays for a 28x28mm readout for neutron detection in many neutron beamlines around the world. The latest generation of this family of ROICs is the Timepix4 (Tpx4), which has many new features that make it an excellent candidate for large format MCP detectors. The Tpx4 is four times larger in area (28 x 25 mm), still with 55 microns pixels (512x448 array). It is also abuttable on 4 sides, allowing unlimited tiling of a mosaic. This was enabled by "through chip via" technology, negating the need for wirebonds, as all signals and power can come from the rear side of the chip. The Tpx4 has an event driven readout, with the capability of 250MHz event rate per chip, well beyond the high rate requirements of any proposed NASA mission. Finally, the Tpx4 can be operated in an ultra-low power mode such that a future array of 7 x 8 (196 x 196 mm) Tpx4 chips could be operated for less than 28 Watts. The Tpx4 design by the CERN Microelectronics Group is currently in its final stage and is expected to be submitted for fabrication in late spring with the first dies to be tested by the end of 2019. As a founding member of the Timepix4/Medipix4 collaboration, our group has access to the chips along with the expertise of CERN and other collaborators in this

		joint ROIC development. Our goal is to design and fabricate a 100 x 100 mm MCP detector with a 3x3 array of Tpx4 ROICS, demonstrating its imaging performance in a four-side abutted array of ROICs. This device will be environmentally tested in our thermal/vacuum chambers at SSL as well as our vibration facility. We also plan to test its radiation tolerance, which is expected to be better than the excellent resistance of its precursors. This effort will result in a TRL5 detector that can be scaled to the ultimate design of the 200mm detectors needed for NASA's next generation of UV telescopes.

96367	High performance, stable, and scalable UV aluminum mirror coatings using ALD	This proposal aims to further develop mirror coating technologies that can meet the needs of future large aperture space telescopes on mission concepts such as the Large UV/Optical/IR Surveyor (LUVOIR) and the Habitable Exoplanet Observatory (HabEx), with a thin film coating technology that can offer several advantages over the current state-of-the-art. In previous programs, work at NASA's Jet Propulsion Laboratory (JPL) has resulted in the development of new atomic layer deposition (ALD) processes for ultraviolet protective coating materials such as MgF2, AlF3 and LiF. This has led to the demonstration of protected aluminum mirror coatings by combining these ALD materials with evaporated aluminum. To date, these are the only high performance FUV mirrors (>80% R at 120 nm) with protective coatings that are not deposited by conventional physical vapor deposition methods like evaporation and sputtering. The self-limiting nature of the ALD process holds the promise of improved reflectance uniformity and improved coating stability. In this proposed effort we will take these laboratory demonstrations and fully characterize their environmental stability and investigate scaling trends toward the meter-class by utilizing the combined expertise of team members at NASA JPL, the University of Colorado Boulder (CU), and the University of California Santa Cruz (UCSC). The main objectives of this proposal are: 1. Perfecting the combination of ALD processes and Al PVD to produce wide band pass (90-2500 nm) aluminum mirror coatings with high reflectivity (~90%), placing particular emphasis on high reflectivity performance in the FUV. We will demonstrate full mirror coatings on shaped optics relevant to sounding rocket and cubesat programs at CU. 2. Studying and ensuring long term performance stability by comparing the most promising ALD coating methods directly with PVD-based mirrors for the first time under identical accelerated aging tests. 3. Demonstrating scalability trends towards large (>1 m) size mirrors. In part, this will utilize the unique large area ALD system developed at UCSC specifically for astronomical mirror systems. 4. Work with industry partners to refine our understanding of aluminum deposition with respect to form birefringence, microstructure, and overcoat stability in the context of compatibility with ALD overcoats as well as the future needs of LUVOIR or HabEx. 5. Measurement and modeling of reflectance uniformity, wavefront error, and polarization retardance over the full aperture of shaped optics in the wavelength bands of interest to exoplanet coronagraphs. The advancement in Technology Readiness Level (TRL) achieved by meeting these objectives will allow this new mirror coating technology to reach TRL 5 from its current TRL 3 status.

96368	Toward Fast, Low-Noise, Radiation-Tolerant X-ray Imaging Arrays for Lynx: Raising Technology Readiness Further	The most recent biennial Physics of the Cosmos Program Annual Technology Report (PATR) identifies 'fast, low-noise, megapixel X-ray imaging arrays' as a top-priority technology development need for future PCOS strategic astrophysics missions. The Lynx large mission concept now under study by NASA for presentation to the Astro2020 Decadal Survey, in particular, includes a High-Definition X-ray Imaging instrument requiring a combination of readout rate, noise, spatial resolution and size that cannot be furnished by currently mature technologies. We intend to continue to raise the technical readiness of advanced 'digital' CCD technology to meet the requirements of Lynx and other strategic high-energy astrophysics missions. This work will build on our current SAT-funded, MIT-led effort to demonstrate sensors with high-speed, low-noise amplifiers and low-power CCD charge transfer, and on a companion APRA-funded, Stanford-led effort to develop low-power signal processing application-specific integrated circuits (ASICs) compatible with our CCD technology. At the midpoint of our current digital CCD sensor development effort, we have reported very encouraging progress, with read noise reduced to 4.2 electrons, RMS at 2.5 MHz readout rate, and with CCD clock power per unit area only ~4% of that of legacy (Chandra) CCDs. By the end of this year we expect to have met Lynx requirements for read noise, and to be poised to mate our small, single-channel test sensor with a prototype signal processing ASIC. Our proposed continuation will leverage prior MIT Lincoln Laboratory and NASA investment to test a large (2k x 1k pixel) device with 8 outputs adapted to exploit fully the low-noise potential of the ASIC signal processor. We will first characterize the fast readout performance of this sensor using laboratory electronics and then demonstrate fast, multichannel, low-noise and low-power operation with the ASIC. We will also characterize the radiation tolerance of this device. This effort will raise the technology readiness of digital CCD and associated low-power signal-processing technology for Lynx further toward TRL 4.

96369	Superconducting Antenna-Coupled Detectors and Readouts for CMB polarimetry in PICO	We propose to develop high-sensitivity millimeter-wave detector arrays for CMB polarimetry. The detector arrays use planar antennas to implement optical coupling, polarization discrimination, and spectral band definition. The array architecture relies exclusively on lithographed thin film structures and eschews three-dimensional and massive fore-optics such as contacting lenses or feed horns. The antenna arrays' coherent microstrip feeds can tailor synthesized beams that would not be possible with lenses and feed horns. In particular, antenna arrays can couple to top-hat (uniform) illuminations resulting in substantially higher packing of pixel densities than can be achieved with coupling optics with Guassian profiles. The received optical signals couple to transition-edge sensor (TES) bolometers, read with multiplexed SQUID current amplifiers This program will advance technology readiness for the Inflation Probe mission in NASA's Physics of the Cosmos (PCOS) program and specifically the NASA PICO mission, recently studied by an international team of CMB scientists. PICO is a fourth-generation CMB satellite that will measure the polarization of the CMB to astrophysical limits, characterizing the inflationary potential, mapping large scale structure through polarization induced by gravitational lensing, and mapping the Galactic magnetic fields through polarized emission of galactic dust. Gravitational waves produced in the early universe's inflationary expansion may have generated detectable odd symmetry B-mode polarization patterns in the CMB whose amplitude can constrain inflation's energy scale. These degree-scale B-modes are distinct from the even symmetry E-modes sourced by inflationary scalar field variations. Intervening large scale structure also induces arcminute B-modes, spatially correlated at degree scales. This large scale structure is sensitive to the dark energy equation of state and the neutrino mass hierarchy. Observations with these detectors in suborbital experiments have placed the world's leading constraints on inflationary B-modes, limiting $r<0.06$. Ground based experiments using these detectors have demonstrated precise control of systematic errors subdominant to statistical errors. The achieved map depths on small patches of the sky are comparable to PICO's target depths over the entire sky. In a long duration balloon flight in 2015, these detectors demonstrated instantaneous sensitivity, stability, and cosmic ray immunity approaching PICO's needs. New arrays at 220 and 270GHz are now providing the most sensitive characterization of galactic dust through millimeter wave polarization. Beginning in 2020, new 30GHz and 40GHz arrays will produce the most sensitive characterization of galactic synchrotron emission through millimeter wave polarization. We propose to advance specific aspects of the detectors to ensure their technology readiness for space applications, including both PICO and other international satellite opportunities. We will increase pixel densities with circular footprint antennas, we will extend the range of multi-color pixels into the mid-frequency range with 150-220GHz dual color prototypes, we will develop 100mK bolometers and test cosmic ray susceptibility, we will modify our time division readout system to read 128 rows in a set with a chopped voltage

		bias, and we will demonstrate arrays of antenna-coupled TKIDs as an enhancing technology for PICO.

96370	A Single Photon Sensing and Photon Number Resolving Detector for NASA Missions	The goal of the proposed project is to pave the way for single photon counting gigapixel focal planes through a CMOS detector characterization and redesign program that leverages exciting recent advancements pioneered by the proposing team. The detectors, dubbed the "Quanta Image Sensor," was recently invented by Co-I Eric Fossum. We expect that device performance will match, or exceed, the performance level of existing state of the art detectors in metrics that are critical for NASA Astrophysics missions. This development program will give scientists extraordinary capabilities, enabling science programs that are not possible today. In the near term, the devices represent an excellent match between delivered performance and requirements for next generation large telescope missions. In addition to having ultra-low noise, they consume low power, are resilient against radiation, and operate as a digital focal plane, relieving many requirements for post-detector electronics. The key feature of the device that enables single photon counting is a high gain pixel design provided by pixels that have very small sense capacitance. The resulting gain per electron is much greater than the noise in the readout circuit. While initial development is for optical detectors, the basic architecture of the proposed technology can be directly extended to UV detectors using proven processes. The plan of work starts with a short functional characterization program at Dartmouth College using existing devices, followed by an extensive characterization program in the Center for Detectors at the Rochester Institute of Technology. We will measure performance at a large range of cryogenic temperatures in the laboratory, both before and after irradiation in a high energy proton beam, and also at a telescope. We believe that most of the performance characteristics that are relevant for such applications have already been established in this technology, but we will specifically test existing devices, and those with small modifications, for the most extreme demands of space Astrophysics missions. The testing will include read noise, dark current, quantum efficiency, intrapixel sensitivity, persistence, linearity, and radiation testing. We will investigate new data reduction and analysis schemes that are matched to the technology. Based on information from this program, Co-I Fossum will lead an effort to design a new version of the device. Output products of the proposed activity include simulations, designs, detectors, characterization data, and published papers in conference proceedings and refereed journals.

96371	Optimal spectrograph and wavefront control architectures for high-contrast exoplanet characterization	In this proposal, we aim to explore and demonstrate optimal spectrograph and wavefront control architectures for high-contrast exoplanet characterization with future space-based observatories. Once a candidate exoplanet has been detected and its position measured, follow-up spectroscopy over a wide range of wavelengths and spectral resolutions is necessary to characterize its atmosphere in details. According to the most recent Design Reference Missions for WFIRST CGI, HabEx and LUVOIR, the time required for spectroscopic characterization is typically two orders of magnitude larger than for detection. The metrics used to optimize instrument and wavefront control architectures for exoplanet searches are however sub-optimal for follow-up spectroscopy. Indeed, planet searches necessitate large dark holes to be cleared out of residual starlight and put a strain on the wavefront control system that results in contrast, throughput and bandwidth trade-offs. However, once the position of the planet is known, wavefront control degrees of freedom can be re-allocated by reducing the dark hole size and used to improve contrast, throughput and bandwidths, potentially reducing the spectroscopic exposure time by orders of magnitude. Moreover, we recently showed that the use of single-mode fibers to feed the planet light to a single or few-objects spectrograph can also lead to substantial gains in efficiency. Our proposed program will explore the dark hole size, contrast, throughput, and bandwidth trade space in detail by undergoing detailed end-to-end numerical simulations and laboratory demonstrations in the Exoplanet Technology Lab and High Contrast Spectroscopy Testbed at Caltech.

96372	Development of an Ultra-Stable Mid-Infrared Detector Array for Space-Based Exoplanet Transit Spectroscopy	Summary The discovery of the Trappist-1 system, which consists of an ultra cool M-dwarf star orbited by 7 planets, 3 of which are located in the habitable zone, has demonstrated that these types of planetary systems around dwarf stars are very common. Such systems are well suited for the study of exoplanets. In particular the search for biosignatures in the atmosphere of planets in the habitable zone around M-stars will be a high-priority science goal of future space missions. The mid-infrared (mid-IR) band between 5 and 15 microns is probably the best available band for this science, because the band contains spectral lines of methane, ozone, and nitrous oxide. The coexistence of those in a planet's atmosphere would be a very strong indicator for life on the planet. Mid-IR transit spectrometers on future space missions such as Origins Space Telescope (OST) will be the instrument of choice to detect these bio-signatures in exoplanets around M-dwarfs. However, current mid-IR detectors are based on impurity band conduction (IBC) devices such as Si:As detectors, which have significant problems with stability. As a result, those detectors are not expected to provide the required stability of ~ 5 ppm needed for a reliable detection of the aforementioned spectral lines. While efforts are under way to improve IBC detectors, it is unclear how far the performance can be improved. Here we propose the development of an ultra-stable mid-IR Array Spectrometer demonstration for Exoplanet Transits (MIRASET), which includes a calibration system that, as we show, is required to achieve the minimum sensitivity for the detection of atmospheric bio-signatures in habitable-zone planets around M-dwarfs. The spectrometer will be demonstrated with arrays of Transition Edge Sensor detectors (TES). These devices are known to be intrinsically very stable and the required detector parameters (sensitivity, dynamic range) for space based mid-IR transit spectroscopy can be easily met with existing devices. No new detector developments are required. This project will include the development of a high-accuracy calibration system with a stable reference source which itself will be monitored by an out of band (0.5 µm) photo-diode at a wavelength at which the precision of this measurement exceeds that of an in-band calibration. This scheme will allow for real time monitoring of the detector gain, which we anticipate will result in a background limited performance with the required stability of better than 5 ppm for the detection of bio-signatures in a designated spectrometer flying e.g. on the OST space telescope, and as such will help to answer one of NASA's main questions: "are we alone?"

96373	Development of low power FPGA-based readout electronics for superconducting detector arrays	We propose to design, build and demonstrate the performance of a low power FPGA-based readout electronics system for use with arrays of superconducting detectors such as transition edge sensors (TES) and kinetic inductance detectors (KIDs). Future space astrophysics missions such as PICO, the Galaxy Evolution Probe, the Cosmic Dawn Intensity Mapper and the Far-Infrared Explorer will require arrays of thousands of superconducting detectors. The complexity of the instrument can be reduced by implementing a multiplexing readout electronics system with high multiplex factor. Current superconducting arrays in operation on ground-based and balloon-borne instruments use either time-domain multiplexing (TDM) or frequency-domain multiplexing (FDM) at MHz frequencies with multiplex ratios of tens-hundreds. One way to increase the multiplex factor to 1000's of detectors is to increase the bandwidth of FDM by using GHz frequencies - this technique is called microwave multiplexing. Microwave multiplexing systems are being developed for ground-based applications and are planned for use in the next generation CMB experiments. A version of this electronics will be used to read out the KID arrays on the BLAST balloon-borne telescope. Typically existing systems have a power consumption of on order 100 mW per detector which also corresponds to 100 mW per MHz of bandwidth. However, a new family of FPGA-based chips called System On a Chip (SOC) that include all of the required inputs and output components (i.e. A/D and D/A converters) inside the device, have recently been released and offer much larger bandwidth at a lower power dissipation than existing systems. We propose to develop readout systems based on the algorithms implemented in existing readout systems with these new chips and demonstrate their performance reading out arrays of superconducting detectors. Estimates of the power dissipation required with the new system indicate that we could read out 10,000 detectors with < 30 W of power corresponding to < 3 mW per detector. We will perform thermal vacuum testing of these systems in environments relevant for balloon-borne applications. We will also investigate rad-hard firmware and ASIC implementation of the algorithms for future space-based missions.

96374	Laboratory Demonstration of Multi-Star Wavefront Control in Vacuum.	We propose to continue the technology advancement of Multi-Star Wavefront Control (MSWC), which is a method to directly image planets and disks in multi-star systems such as Alpha Centauri. This method works with almost any coronagraph or external occulter and requires little or no change to existing and mature coronagraph and wavefront control hardware. With an additional super-Nyquist mode, it also enables high contrast imaging beyond the nominal outer working angle of a deformable mirror, allowing imaging of wider separated multi-star systems, as well as larger disks and wider planetary systems around single stars. We have previously identified off-axis star leakage induced by surface aberrations as the fundamental starlight suppression challenge for multi-star systems. Aberrations are usually removed using a wavefront control system based on deformable mirrors, and MSWC enables doing this in the presence of multiple stars. We have advanced MSWC to TRL 3, and are on track to advance it to TRL 4 before the start of this work. This consisted of computer-based demonstrations of high contrast on binary stars using MSWC with WFIRST, LUVOIR, and HabEx; lab demonstrations of dark zones in two-star systems; validated simulations; as well as simulated predictions demonstrating that with this technology, contrasts needed for Earth-like planets are in principle achievable on LUVOIR and HabEx. The work proposed here aims to advance MSWC to TRL 5 (component-level) by testing it with a simple generic coronagraph and layout, making it ready for system-level TRL5 tests specific to different missions and their specific coronagraphs and layouts. As our "simple generic" coronagraph, we plan to use the classical Lyot coronagraph at JPL's High Contrast Imaging Testbed (HCIT). It has recently achieved better than <4e-10 in 10% broadband for single stars, and we will leverage this performance to test the operation of MSWC with binary stars at deep contrasts. At the end of year 1, our goal is to demonstrate at least 3e-9 raw contrast in monochromatic light, and at the end of year 2, in 10% broadband light. Our tests will simulate several potential binary star targets of interest to HabEx, LUVOIR, and WFIRST, including Alpha Centauri. Our work plan is also compatible with a variety of coronagraphs being tested at HCIT. If there is time remaining after reaching our milestones, we can proceed to demonstrate MSWC with additional coronagraphs towards system-level TRL5 for specific missions. The main impact of this work is that it enables existing mission concepts to image planetary systems and disks around binary star systems, as well as extends high contrast capability beyond the Nyquist-limited outer working angle of the DM, with little or no hardware modifications. This will improve the quantity and quality of available targets, and enhance the science output. Furthermore, it enables the detection of biomarkers on potential Earth-like planets around our nearest-neighbor star, Alpha Centauri. The ability to directly image the aCen system in high contrast also represents an opportunity to study an exo-planetary system in much higher detail and SNR than for any other sun-like star, because aCen is many times closer and brighter than the next closest sun-like star.

96375	Photon Counting NIR LmAPD Arrays for Ultra-low Background Space Observations	Two of NASA's four large mission concepts for the 2030's, HabEx and LUVOIR, identify a requirement for large format near infrared - 0.8 to 1.8, 2.5 or 5 microns - arrays with read noise << 1 e- and dark current <0.001 e-/s/pix. Linear-mode avalanche photo-diode (LmAPD) 320 x 256 @24-micron pitch 'SAPHIRA' arrays manufactured by Leonardo approach this performance. In HgCdTe, the LmAPD process provides noiseless multiplication of photo-electrons within the photo-diode, reducing the relative contribution of read noise to sub-electron levels. SAPHIRA arrays have achieved dark current~ 0.001 e-/s/pix at avalanche bias up to 10 volts (an avalanche gain ~ 10) and have a been operated in photon counting mode at higher avalanche gain (and dark current). UH is now funded by NASA's ROSES APRA program to develop a 1k x 1k @15-micron pitch LmAPD array, the L1RG-15, optimized for ultra-low-background operation. The ME1070 read out integrate circuit (ROIC) has been produced and the first engineering grade LmAPD arrays will be available in 2019. Although the SAPHIRA is estimated to already be at TRL-5, these new LmAPD arrays will start at TRL-3. Description of the key, central objectives. The central objective of the proposed investigation is to advance the Technical Readiness Level of these L1RG-10 arrays from TRL-3 to TRL-6. Secondary objectives are to characterize their dark current vs avalanche bias voltage and to further investigate their photon counting properties. Methods/techniques to accomplish these. Our current cameras and test facilities are all set up for either very low background measurements in the lab or for high background observations at telescopes on Mauna Kea with SAPHIRA arrays. We propose to refurbish an existing camera to allow operation of the L1RG-10 arrays at low background both in the laboratory and at the telescope. Among several options, our preferred choice is to upgrade the United Kingdom Infra-Red Telescope (UKIRT) Fast-Track Imager (UFTI), a facility instrument at UKIRT, which is now owned and operated by UH and will be available throughout the duration of the proposed project. In order to achieve TRL-6, this new camera will utilize an ASIC controller in place of the conventional controllers used with the SAPHIRA systems. The proposal will be baselined for the SIDECAR ASIC developed for JWST but will keep open the option of upgrading to the ACADIA ASIC currently being developed for the WFIRST mission. We will develop camera controller software as part of this. The radiation properties of the ROIC at L-2 can be extrapolated from similar arrays in missions such as JWST. We will investigate the radiation properties of the metal organic vapor phase epitaxial HgCdTe used in the LmAPD arrays at the same UC Davis cyclotron. The investigation will also involve characterization the 1k x 1k arrays relative to the requirements of read noise << 1 e- and dark current <0.001 e-/s/pix along with their photon counting properties. Significance of the proposed work. Achievement of TRL-6 for a 1k x 1k @15-micron pitch LmAPD array with read noise << 1 e- and dark current <0.001 e-/s/pix will qualify a new technology meeting the very demanding NIR array requirements of the HabEx and LUVOIR missions. As it is closely based on the traditional source follower HAWAII arrays being flown on JWST, Euclid and WFIRST, there is a direct route to

		the scaling of the LmAPD arrays to the 4k x 4k @15-micron pitch of the WFIRST arrays and their incorporation into large mosaic focal planes. These LmAPD HgCdTe arrays also have the potential to benefit other NASA missions.

96376	Microwave Multiplexing Readout Development	As NASA telescopes push for ever greater sensitivity, one of the primary hurdles is reading out the large arrays of sensors. Many of the next generation of space telescopes, including the Origins Space Telescope and Lynx, will require reading out thousands of superconducting sensors on a single line. Microwave multiplexing is a technology that has already begun enabling high-density readout. Microwave multiplexers rely on superconducting resonators that shift frequency due to input signals. The resonator frequencies are measured with warm electronics by sending and measuring probe tones. A team centered at SLAC and Stanford University designed and deployed a microwave multiplexing system named SMuRF. Microwave multiplexing requires fast digital signal processing, which is currently implemented on FPGAs. The FPGAs communicate with ADC and DACs via a high speed serial link called JESD. The JESD layer has high power demands. Devices called Radio Frequency Systems-on-Chip (RFSoC) have recently been introduced to the market. The RFSoC combines the FPGA, ADC, and DACs onto one device, eliminating the JESD layer. We propose to replace the current FPGAs, ADCs, and DACs with the RFSoC, dropping the energy requirements of the microwave multiplexer. A key technical hurdle for microwave multiplexing is the development of tone tracking, an algorithm designed to track resonator frequencies and ensure that probe tones always lie at the resonator minimum. This reduces the power transmitted to amplifiers. Nonlinearities in the amplifiers generate large numbers of third-order harmonics which act as a pseudo-noise floor. By lowering the input power to the amplifier, tone tracking enables multiplexing factors in the thousands. SMuRF is the only microwave multiplexing system to successfully demonstrate tone tracking. Both the current SMuRF FPGA and new RFSoC are built on the Xilinx Ultrascale+ firmware architecture. This will make it simpler and less expensive to port the existing tone tracking code to the new devices. In this proposal, we outline a plan to develop the RFSoC boards, integrate the new multiplexer with X-ray sensors, measure X-rays, and test the radiation hardness of the system. This elevates the SMuRF microwave multiplexing electronics from TRL 3 to TRL 5. The schedule is designed to align with the Lynx development schedule. The SLAC and Stanford team is well positioned to successfully develop an RFSoC-based microwave multiplexer. The engineers have experience building the hardware and firmware. SMuRF is currently on a CMB telescope at the South Pole, which will provide a unique venue to test for subtle systematic effects. The RFSoC-based SMuRF microwave multiplexer will help unlock the next generation of telescopes used to study our cosmic origins. Whether through an X-ray telescope or infrared spectrometer, the future of observational astrophysics relies on ever increasing sensor counts. SMuRF will provide the critical technology to read them out.

96329	Continuing Development of Bragg Reflector Optics and Gratings for Polarimetry	We propose to continue laboratory work to test multilayer mirrors and reflection gratings, as well as to develop and test novel twisted crystal Bragg reflectors as a higher energy and much more efficient alternative to multilayer mirrors. With previous NASA/APRA funding, we demonstrated the performance of transmission gratings and laterally graded multilayer mirrors (LGMLs) with polarized and unpolarized X-rays up to 0.4 keV. One goal of this proposal is to advance the state of laterally graded multilayer coated mirrors to higher X-ray energies. We also aim to test a new concept for polarizing reflection by using Bragg reflection off of crystals, which will then be twisted to satisfy the Bragg condition at different energies across their surface. Finally, we plan to test off-plane, blazed reflection gratings for polarization sensitivity. The astrophysical prospects of X-ray polarimetry are currently limited by instrumentation. Above 2-3 keV, photoelectron tracking and Thomson scattering methods can be used, the basis of the Imaging X-ray Polarization Explorer and X-Calibur. Below 0.4 keV, the Rocket Experiment Demonstration of a Soft X-ray Polarimeter implements multilayer-based polarimetry, proposed elsewhere for development as a sounding rocket payload. Between 0.4 and 2 keV, no methods have demonstrated sufficient efficiency. Here, we propose to develop methods to close this gap in order to support designs for more advanced polarimetry instrumentation such as an X-ray Polarization Probe. We have constructed a source of polarized X-rays in the lab that operates at a wide range of energies with a selectable polarization angle for testing prototype components of our proposed instrument. In 2013, we demonstrated that the polarimetry beam-line can provide 100% polarized X-rays at 0.525 keV with a single period multilayer. In 2014, we upgraded the source by installing a mirror with a laterally graded multilayer (LGML) coating, providing a wide energy range. In 2015 and 2017, we tested new LGMLs with two more material combinations (C/CrCo, La/B4C, and Cr/Sc) in order to obtain higher efficiencies in different soft X-ray bands than our early LGML made of W and B4C. In 2018 we tested the polarization sensitivity of critical angle transmission (CAT) gratings across a wide energy range. The existing LGMLs are highly efficient up to 0.40 keV and we are still working with APRA funding to extend the capability to 0.46 keV. Improving beyond the O-K edge at 0.54 keV requires different materials and better layer interfaces that we propose to develop under this program. We also are planning to test and develop the concept of using twisted crystals as Bragg reflectors in this energy range. Another approach to bridge the gap is to use blazed reflection gratings in the off-plane configuration. While Marlowe et al. showed that unblazed gratings show no significant polarization sensitivity, we would test blazed gratings.

96330	Phase 2 of the Off-plane Grating Rocket Experiment (OGRE)	Future X-ray astronomy missions will require large advancements in many key technologies. Current state-of-the-art telescopes are achieving finer foci on lightweight substrates while diffraction gratings are more efficient and capable of higher resolving powers than ever before. Furthermore, detectors are more sensitive with lower noise and better energy resolution. However, most of these advancements have only been made in the laboratory on low to medium fidelity systems that do not address the entirety of issues involved with incorporation of these technologies into a flight-ready telescope. Here we propose continuation of funding for the Off-plane Grating Rocket Experiment (OGRE). This suborbital rocket payload comprises a combination of high performance optics, gratings, and detectors for the first time as an X-ray astronomical mission. OGRE employs polished silicon optics fabricated at NASA's Goddard Space Flight Center. These optics are the baseline optic technology for Lynx and have produced the highest resolution X-ray test results of any optic to date. OGRE also utilizes reflection gratings fabricated using novel methods at the Pennsylvania State University (PSU) to produce the highest measured efficiencies and resolving powers achieved for reflection gratings. Finally, the payload incorporates electron-multiplying CCD detectors fabricated by collaborators in the UK that amplify low-energy events and increase the sensitivity of soft X-ray observations. Using these cutting-edge, high-performance technologies, OGRE will obtain the highest resolving power spectrum in the soft X-ray to date. The astronomical target for observation is Capella, which is a giant binary system with prodigious coronal line emission. The high resolving power spectrum obtained by OGRE will help identify previously blended and unidentified lines while constraining the plasma properties of density and temperature to create a more accurate emission measure model for Capella. Furthermore, proper ground calibration combined with coincident observation of Capella with Chandra could provide a cross-calibration for Chandra's low energy response. The PSU-led team has heritage in designing and launching X-ray spectrometers onboard NASA suborbital rockets. The PSU program provides necessary hands-on training of young researchers in the fields of high energy instrumentation and observation. This research exposes these young trainees to the full experiment cycle of design, fabrication, integration, testing, launch, and data analysis. Continuation of the OGRE program not only supports the launch of a capable payload filled with critical technologies, but also supports a university-based suborbital program that represents an exciting mix of compelling science, heritage, cutting-edge technology development, and training of future scientists in the field.

96332	Observations of Neutron Stars and Black Holes with the Second-Generation Hard X-Ray Polarimetry Mission XL-Calibur	X-Calibur is a balloon borne X-ray polarimetry mission which uses a pointed 8 m long telescope bench, a focusing mirror, and a scattering polarimeter to measure the arrival times, energies, and linear polarization properties of 15-60 keV X-rays. X-Calibur was launched on December 29, 2018, for a Long Duration Balloon (LDB) flight from McMurdo (Antarctica). During the first 1 1/2 days of the flight, X-Calibur achieved a high signal-to-noise detection of the accreting X-ray pulsar GX 301-2. The X-Calibur observations gave a rich data set with detailed information about the light curve and energy spectrum of the source, as well as the first constraints on the polarization properties of the hard X-ray emission from an accreting pulsar. Unfortunately, the balloon constantly lost altitude owing to a helium leak, and the flight was terminated after 2 1/2 days, severely limiting the science return from the mission. We propose here the first two of a series of three LDB flights of the X-Calibur follow-up experiment XL-Calibur. The instrument achieves a more than one order of magnitude higher signal-to-background ratio than X-Calibur owing to several improvements. Most importantly, the 8 m long optical bench and the InFOCµS X-ray mirror will be replaced by a 12 m long optical bench and the spare mirror of the Hitomi hard X-ray telescope. In the energy range between 15 and 60 keV, the mirror provides a three to ten times larger effective collection area than the InFOCµS mirror. We will furthermore modify the polarimeter and shield assembly to reduce the background by a factor between six and fourteen. The XL-Calibur flights will allow us to measure the 15-75 keV polarization of a sample of archetypical X-ray sources, including but not limited to stellar mass black holes in X-ray binaries such as Cyg X-1 and GX 339-4, accretion powered neutron stars such as Her X-1 and GX 301-2, the Crab nebula and its rotation-powered pulsar, and a sample of flaring binaries. We will schedule simultaneous observations with XL-Calibur and NASA's Imaging X-ray Polarimetry Explorer (IXPE) mission to be launched in 2021, allowing us to disentangle and measure the polarization of different emission components. The XL-Calibur mission can be carried out at low costs and with minimal risks as the pointing, telescope and detector technologies were fully tested with X-Calibur, and the Hitomi spare mirror will be contributed to the mission at no costs to NASA by the Japanese co-investigators.

96334	Development of sub-arcsecond x-ray telescope optics	We propose to develop new high-precision x-ray telescope mirror technology that is critically necessary for planned NASA missions with sub-arc-sec HPD angular resolution goals, including, for example, explorer class missions such as STAR-X and FORCE, probe class missions such as AXIS, TAP, and HEX-P, as well as large missions such as Lynx. The proposed effort builds on previous research at MIT and complements NASA-supported research at other institutions. We proposed work plan includes (1) improved methods for stress-field mirror correction, (2) compensation of mirror distortion caused by coating stress, (3) stabilization and smoothing of mirror coatings, and (4) improved mirror figure metrology. Thin shell mirrors with resolution in the sub-arc second domain require significant advances in mirror shaping, coating and correction technology. For the proposed work we will focus our efforts on the polished silicon mirrors being fabricated by the Next Generation X-ray Optics (NGXO) group at Goddard Space Flight Center. We chose these particular mirrors for our research simply because these are the best available at the present time. Over the last year the NGXO group has provided mirrors for us to develop improved mirror correction techniques, which has allowed us to successfully demonstrate, for the first time, coated x-ray mirrors with sub-arc-sec slope errors, approaching Lynx requirement. We propose to further develop on-going research in mirror stress-based figure correction using MeV ion beam, silicon microfabrication, and femtosecond lasers. Since progress in the field into the sub-arc sec domain is now strongly limited by metrology error, we also propose to develop radically improved metrology tools. We also propose to continue work on a variety of beam-based mirror fabrication, coating and correction techniques, targeted specifically to the proposed Lynx mission.

96340	Advanced SiPM readout for the AMEGO CsI Calorimeter	We propose a program to advance the silicon photomultiplier (SiPM) readout for the CsI(Tl) calorimeter subsystem on the All-sky Medium-Energy Gamma-ray Observatory (AMEGO). AMEGO is a Probe-class mission concept, formerly known as ComPair; NRL is the PI institution for the CsI calorimeter – one of three major AMEGO subsystems. The other subsystems include a stack of double-sided silicon strip detectors (DSSD) and the CZT calorimeter. The AMEGO team, comprising over 200 scientists and 80 different institutions, has recently submitted 15 science white papers for inclusion in the Astronomy and Astrophysics Decadal Survey (Astro2020). This proposed program is a follow on to a previously funded APRA (PI J. E. Grove & Co-I R. Woolf, NRL - CsI Calorimeter for the ComPair Balloon Prototype, FY17-18) and companion to the currently-funded APRA (PI: J. McEnery, GSFC & NRL PI: R. Woolf - ComPair: Steps to a Medium-Energy Gamma-ray Mission, FY16-20). During the program led by PI Grove, we developed and built a hodoscopic, CsI (with SiPM readout) prototype calorimeter for a balloon flight, in conjunction with the other subsystems developed during the McEnery APRA. Aside from the prototype, the main goals were to understand the performance of a commercial SiPM array and an ASIC readout for SiPMs. Our work revealed multiple topics that demand further investigation going forward in order to advance the CsI calorimeter towards a full flight instrument. The first component of this proposal will be to design, fabricate and test a custom SiPM readout array. The array will be comprised of a mixture of small (1mm^2 or 9mm^2) square and large (36mm^2) square SiPMs, with each SiPM containing an optimized microcell size. The commercial SiPM arrays used during Grove's APRA do not provide adequate dynamic range needed for a single crystal in the calorimeter (desired 30 keV – 300 MeV). The mixture of small and large SiPMs will expand the dynamic range; this is the same dual gain range technique used by the Fermi LAT calorimeter with PIN diodes. Additionally, we found that the commercial SiPM array coupled to CsI demonstrated non-linear behavior when exposed to high-energy (>10 MeV) gamma rays. We will mitigate the non-linearity by testing with varying-sized SiPM microcells, ranging from 10 µm to 50 µm. This work will allow us to understand how the SiPM microcell size affects the non-linearity and will enable us to assess the dynamic range using different-sized SiPMs. Next, we will develop a customized readout board designed to integrate multiple commercial SiPM ASICs. This is considerably more complex than using an off-the-shelf product, but a necessary step to advance the CsI calorimeter program moving forward. During the Grove's APRA, we used a single 16-channel SiPM ASIC that performed well. The next logical step is to transition from a single ASIC readout board (with limited I/Os and channel count) to a custom readout board, incorporating multiple ASICs per board, that can interface with the other AMEGO subsystems. These readout boards will be compatible with a CsI calorimeter the size of a full-scale flight unit. Lastly, we will construct a two-layer deep calorimeter, comparable in size to a flight-like unit. The hodoscopic calorimeter will consist of flight-length CsI bars, dual gain range custom SiPMs, and

		multiple custom readout boards, integrated into a working instrument.

96342	AstroPix: Developing Silicon Pixel Detectors for Gamma-ray and Cosmic-ray Astrophysics	This technology advancement proposal will develop already mature Silicon (Si) technologies in ground-based detectors for use on space-based instruments. The particle physics community is developing monolithic (combined readout and detector medium) CMOS (Complementary Metal-Oxide-Semiconductor) Si pixel detectors with improved spatial resolution and lower power requirements per channel. We plan to leverage the expertise in the ground-based development of these high-spatial-resolution pixel detectors and optimize them for space-based future gamma-ray and cosmic-ray missions. The goal is to increase the technical readiness level (TRL) of monolithic CMOS Si pixel sensors from 4 to 5 enabling their use on future space-based gamma-ray and cosmic-ray missions supported by the Astro2020 Decadal Survey. The goals of this proposal are: 1) Acquire monolithic Silicon pixel detectors designed for the ground-based ATLAS experiment. For the first time, we will use these detectors to observe gamma-rays in the keV range to measure their performance. 2) Leverage our team's expertise to design a silicon pixel detector (AstroPix) based on the technology developed for the ATLAS experiment, but optimized for a medium energy gamma-ray telescope. The same technology will be suitable for multiple space-based applications. 3) Characterize, package and integrate the detectors for a beam-line test to demonstrate the ability to reconstruct gamma-ray events. 4) This technology will enable a suite of future missions from SmallSats to Probe scale. The science drivers encompass extreme astrophysics such as: 511 keV emission at the Galactic Center, nuclear lines in the Galaxy, and the prompt emission (Gamma-ray Bursts) from neutron star mergers

96345	Fast Timing ASIC for Germanium Strip Detectors	Large-area, tracking, semiconductor detectors with excellent spatial and spectral resolution enable exciting new access to soft (0.2-5 MeV) gamma-ray astrophysics. The improvements from semiconductor tracking detectors come with the burden of high density of strips and/or pixels that require high-density, low-power, spectroscopy quality readout electronics. CMOS ASIC technologies are a natural fit to this requirement and have led to high-quality readout systems for all current semiconducting tracking detectors. The Compton Spectrometer and Imager (COSI) at University of California Berkeley and the Gamma-Ray Imager/Polarimeter for Solar flares (GRIPS) at Goddard Space Flight Center utilize germanium cross-strip detectors and are on the forefront of NASA's Compton telescope research with funded missions of long duration balloon flights. A germanium strip detector ASIC requires excellent energy resolution and precise timing of the signals at the anode and cathode of the device to allow the depth of the interaction within the crystal to be determined. The previous APRA program produced an ASIC that meets the minimum science requirements for the missions and retired the primary risk of adding a timing circuit to the ASIC while maintaining excellent energy resolution. The current ASIC uses on analog shaper for both the energy and timing which leads to compromise shaping times that reduce instrument sensitivity. We propose to design an updated ASIC that has two shapers per channel, a fast shaper to produce accurate timing measurements and a slow shaper for germanium quality energy resolution. Dr. De Geronimo has other ASIC designs with this capability and the design can copy the current shaper for reuse in the fast shaper. COSI and GRIPS both target detectors with ~0.5 mm strip pitch so that the strip pitch is not the dominant term in the angular resolution of the instrument. At this pitch, charge sharing between neighboring strips is the predominant type of event. Using a reasonable energy threshold of 12 keV per strip, it would be common to see shared charge events in the neighboring strips that is less than the threshold. The current ASIC does not read out channels that are under threshold so the measured energy can differ from the actual interaction energy by up to two times the threshold. COSI avoided this issue with their discrete analog electronics by reading out neighboring strips even if they were under threshold. We propose to port Dr. De Geronimo's neighboring strip readout scheme from other ASIC designs to the germanium front-end ASIC. This should be a relatively risk-free change as it only modifies the digital backend of the chip without needing to modify the analog chain. Making these modifications to the current germanium front-end ASIC will produce an ASIC designed for future NASA missions with all of the functionality of the current COSI discrete electronics. It will enable instruments using this ASIC to have sensitivities approaching the limits of germanium detectors.

96348	Fabrication and Testing of Novel Hybrid CMOS X-ray Detectors for Future Large-Area and High-Resolution X-ray Astronomy Missions	In the coming years, X-ray astronomy will require new soft X-ray detectors that can be read very quickly with low noise and can achieve small pixel sizes over a moderately large focal plane area. These requirements will be present for a variety of X-ray missions that will attempt to address science that was highly ranked by the 2010 Decadal Survey, including missions with science that overlaps with that of IXO and Athena, as well as other missions addressing science topics beyond those of IXO and Athena. An X-ray Surveyor mission, Lynx, was chosen by NASA for study by a Science & Technology Definition Team (STDT) so it can be considered as an option for an upcoming flagship mission. A mission such as this was endorsed by the NASA long term planning document entitled "Enduring Quests, Daring Visions," and a detailed description of one possible realization of such a mission has been referred to as SMART-X; more recently, the Lynx STDT has released an initial/interim report on the concept design for an X-ray Surveyor. This provides an ex-ample of a future mission concept with these requirements since it has high X-ray throughput and excellent spatial resolution. The HDXI instrument on this mission re-quires a detector with the characteristics that we are developing with this proposal. We propose to further the development of our latest active pixel sensor designs, in particular the hybrid CMOS detectors that we have been working with for several years, and implement our newest in-pixel and on-chip technologies that will allow us to achieve these ambitious and realistic requirements on a timeline that will make them available to upcoming X-ray missions. This proposal is a continuation of our program that has been working on these developments for the past several years. The first 3 years of the program led to the development of a new circuit design for each pixel, and the following 3-year program led to the design of a ROIC readout array for full-size detectors that contain on-chip digitization. The program is now ready for the phase that includes fabrication and subsequent testing of a full-size detector. The proposed activity for the next four years will be to in-corporate this pixel and ROIC array design into a 1k x 1k pixel full-size device so it can be thoroughly tested and characterized.

96351	Detector development for high spectral resolution observations of diffuse hot gas	We propose to develop microcalorimeter detectors based on superconducting transition edge thermometers specifically aimed at constructing a sounding rocket instrument to investigate hot gas in the Galactic interstellar medium. Current observations show that gas at temperatures of 800,000 to ~2 million kelvin is widely distributed in and perhaps around the Galaxy, but little is actually known about its location, structures, and geometry, nor about its role in Galactic evolution. Material near 1 million degrees seems particularly abundant and apparently fills much of the Galactic disk in the Solar neighborhood. Further study of this gas requires disentangling multiple emissions sources along a line of sight, including substantial foreground emission from charge exchange on the Solar wind. This spectral region around 150 to 350 eV is so line-rich that resolving individual emission lines to properly understand the different components requires better than 2 eV spectral resolution. Collecting enough photons to obtain a scientifically useful spectrum in a sounding rocket flight will require a total detector area of 2–3 square centimeters; to get this with an affordable number of readout channels for a sounding rocket budget calls for individual pixels around 1mm x 1mm. The development of these detectors is quite orthogonal to the extensive and very good current work on arrays for XRISM, Athena, and Lynx. The requirements that the pixels must be large and very high resolution, but need be optimized only for energies up to 600 eV puts them in a quite different regime with a different figure of merit for the transition edge sensors, probably leading to different construction and geometry. We do work closely with the major developers of more conventional arrays and will take advantage of their knowledge and insights, but this is really a different development problem. Current work suggests that a sensor geometry without the usual 'zebra stripes' and careful attention to superconducting contact geometry and external B fields can produce the required high thermometer sensitivity with acceptable levels of current sensitivity and excess noise. But no one has really pushed in this direction before. Beyond our goal of building a rocket payload with these detectors, the same pixels in a larger array would be optimal for a future NASA mission to study diffuse hot gas in circumgalactic and intergalactic space. Knowledge of the movement and metallicity of hot gas in circumgalactic environments is crucial to understanding material transport into and out of galaxies. Athena will technically be able to do such observations, but this is not what it is optimized for, and it will not do a significant number of the extremely long exposures required. With the more specialized detectors developed for our rocket experiment, a straightforward probe-class mission could be constructed with 20 times the mapping speed of Athena for emission lines, about half the speed for absorption lines, and a small fraction of the cost.

96352	Development of a CdZnTe Imaging Calorimeter for Gamma-ray Astronomy	Building on our previous APRA work, we propose to advance the capabilities of CdZnTe bar detectors for use in future medium-energy g-ray missions. The largely unexplored MeV energy range offers great potential for astrophysics discovery, including aspects of nucleosynthesis, multimessenger/gravitational waves, jets, and compact objects. This field has been constrained by low cross sections, high backgrounds, and limitations in technology. With current APRA funding that ends this year, our team in collaboration with Brookhaven National Laboratory has been working on the development of a CdZnTe bar detector that can be used in next-generation g-ray telescopes to explore the MeV gap. Initial measurements of the detector performance are encouraging and have exceeded the predicted response. At the same time, based on the results obtained, we identified several opportunities for further improvements of the calorimeter performance and increased potential utilization in space instruments. With its impressive energy and position resolution and good efficiency, the proposed CdZnTe Imaging Calorimeter will be a mission-enabling technology in the next generation of g-ray telescopes, for example the Probe-class concept AMEGO being submitted to the Astro2020 Astronomy and Astrophysics Decadal Survey. In this APRA, we are proposing to continue development of the promising CdZnTe bar detector with the following objectives: • Design, optimize and develop a prototype of a modular CdZnTe calorimeter (Sec 4.1) o Confirm detector parameters of energy resolution and position resolution. o Investigate the improvement of the calorimeter performance by using a wave-front-sampling ASIC which offers the digitized waveform processing. • Perform bench and beam tests of the complete CdZnTe calorimeter (Sec 4.2) o Investigate and optimize the imaging calorimeter operation with high-energy photons (above 2 MeV) where multi-interaction events dominate and the Compton and Pair regime compete. o Perform activation tests of the CdZnTe at a proton beam facility to understand the dominating background component at MeV energies: activation. o Develop the event reconstruction, calibration and data analysis algorithms for the proposed calorimeter, based on the MEGAlib toolkit. • Validate higher-level instrument requirements (Sec 4.3) o Confirm the operation of the CdZnTe Imaging Calorimeter as a standalone Compton detector, with capability of measuring polarization of g-rays. o Simulate a coded aperture mask instrument with the proposed Imaging Calorimeter as the focal plane. Such a system could achieve high angular resolution, on the order of arcminutes, which is not possible with any other high TRL method. This work will elevate overall TRL of the CdZnTe calorimeter from the current level of 2-3 to 4-5 allowing the proposed imaging calorimeter to enable future g-ray missions.

96357	Dark Matter Searches with the Micro-X Rocket	Experimental observations, studying a variety of cosmological scales with a multitude of detector technologies, converge on a composition of the Universe that is 5% normal matter, 26% dark matter, and 69% dark energy. The nature of these dark components remains elusive, and multiple dark matter candidate particles are being sought in colliders (which try to produce them), direct detection experiments (which look for dark matter interactions in the detector medium) and indirect detection experiments (which look for standard model products from dark matter interactions, annihilation, or decay). Understanding the composition of dark matter is one of the most compelling scientific questions today, one which spans the fields of physics, cosmology, and astronomy. Micro-X is the first space program to fly X-ray Transition-Edge Sensor (TES) microcalorimeters, opening up sensitivity to new physics from high spectral resolution observations of extended X-ray sources. The payload's first flight on July 22, 2018 was a success from the payload and instrument point of view; unfortunately a failure of the NSROC-supplied Attitude Control System (ACS) led to no time on target and no science data. NASA has fully funded a re-flight, which is on schedule for August 25, 2019. This four-year proposal seeks funding for: 1) Analysis and publication of the second flight data, 2) Design and implementation of payload modifications to optimize Micro-X for a dark matter flight from White Sands Missile Range (WSMR) in late 2021, 3) A subsequent dark matter flight in late 2022, and 4) Data analysis and publications from both flights. The main scientific goal of this proposal is an indirect search for keV-scale galactic dark matter with unprecedented sensitivity. The instrument will detect a signal from galactic dark matter decay or annihilation, or it will place world-leading limits on multiple dark matter models. Maximizing the instrument's dark matter sensitivity requires modifications that will advance the technology readiness of TES microcalorimeters while enhancing the science capability of the payload. For the first flight in this proposal, we will adapt the payload to fly without the mirror in a large FOV mode appropriate for dark matter searches and studies of the soft-X-ray background (SXB), and for the second flight in this proposal we will upgrade to a new TES array to further enhance the sensitivity of the dark matter search. In addition to this compelling science, we will perform the analysis of the observation of the Cas-A supernova remnant from the 2019 flight. As mentioned above, this flight in August 2019 is fully funded, but the data analysis and publication of those results will fall under this grant. This data will be the first scientific data set from a TES-based X-ray microcalorimeter taken in space.

96320	Continued operations of HaloSat	HaloSat is a CubeSat that is performing an all-sky survey of line emission from highly ionized oxygen in order to measure the baryonic mass of the Milky Way's halo and help determine if hot halos with temperatures near a million degrees bound to galaxies make a significant contribution to the cosmological baryon budget. HaloSat was deployed in July, 2018, and began science operations in October, 2018. As of this writing, the HaloSat spacecraft and all three of its silicon drift detectors are operating well. We have calibrated the detectors using observations of the Crab Nebula, Cassiopeia A, and Vela supernova remnants and demonstrated that the instrument meets the performance requirements. We propose to continue operations of HaloSat until 30 June 2020. This will enable us to 1) measure the O-He interaction cross-section using the solar wind and the He-focusing cone to better understand X-ray emission via solar wind charge and the foreground emission that currently limits the accuracy of halo line emission measurements making our results on the halo more robust, 2) perform deeper observations that will improve the accuracy of the halo measurements, 3) probe galactic feedback and the relation of the Galactic center X-ray emission to the Fermi bubbles by performing a deep study of the Galactic bulge region, and 4) continue training junior researchers (undergraduates, graduate students, and a postdoc) for future leadership roles on NASA space flight missions. Modest funding will leverage the investment already made in HaloSat to significantly increase its scientific return.

96325	Advanced Filter Solutions for Multiband and Broadband Imaging	The proposed is a two-year effort to develop multiband and broadband imaging detectors by advancing optical detector coatings technologies. Astrophysical applications from cosmology to nucleosynthesis would benefit from high-throughput, wide-wavelength imaging and spectroscopy on a single detector. For broadband and multiband observations, multiple detectors or optical filters are typically used, each optimized for a specific band of interest. The proposed development will dramatically reduce the complexity required for UV-Visible instruments while also improving throughput. Our proposal offers an innovative solution to the limitations and compromises inherent in traditional optical coating technologies by combining well-established lithographic patterning techniques with atomic layer deposition (ALD). We have previously reported on the use of ALD in the development of antireflection coatings for various bands of interest spanning UV to visible wavelengths. In all cases, as is typical for most device manufacturers, a single coating was applied to the entire device, resulting in uniform response across the detector. Under the proposed effort, we will demonstrate new methods for selective-area ALD to develop sensor systems and optical components with spatially varying coatings, resulting in spatially varying response optimized for a given system. Using our approach a detector could be patterned with antireflection coatings of the same material at different thicknesses or even with different materials, thus offering more flexibility in terms of system-level optimization of optical performance and spectral sensitivity. The proposed effort is synergistic with ongoing instrument, detector, and coating development at JPL and can be evaluated at system level using existing instrumentation, such as JPL's Advanced UV Imaging Spectrometer (AUVIS).

96326	High-Resolution UV Detectors for Large Focal Plane Instruments	Potential future NASA satellite missions in the ultraviolet (e.g., LUVOIR (LUMOS) and HabEx (UVS) have baselined MCP detectors) will require very large format (up to 400 cm2), high-resolution detectors for both imaging and spectroscopy. The objective of this program is to move the current state of the art in UV detectors closer to fulfilling these requirements. We propose to exploit several emergent technologies including microchannel plates functionalized by atomic layer deposition, large area refractory cross strip anodes compatible with current readout electronics developments, large format square vacuum tube sealing, and high efficiency/low noise photocathodes. The end goal is to develop these technologies to enable a practical solution for a high spatial resolution, 100 x 100 mm2 detector in a hermetic sealed tube package. Atomic layer deposition (ALD) techniques and novel glass materials provide a new generation of enhanced performance microchannel plates (MCPs) being produced in very large formats (up to 400 cm2 with 20 µm pores and 160 cm2 with 10 µm pores). Using the basic technique of functionalizing (resistive and emissive layers) borosilicate micro-capillary arrays with ALD has resulted in significant achievements. These include producing large 20µm pore MCP formats with background rates of ~0.04 events/cm2/sec, and stable extended lifetimes ≥ 7 C/cm2 that are compatible with high temperature sealed tube integration. There has been recent success in the production of low resolution, very large square sealed tubes (200 x 200 mm2), albeit with significant dead area allotted to internal vacuum support structure. Non-refractory cross strip anodes have been produced in 100 x 100 mm2 formats and achieve >5 MHz single photon counting rates with position resolution <20 µm and timing resolution <100 ps. A current SAT synergistic project is also funded to develop a low power/mass ASIC to read them out and improve overall performance. Photocathodes (alkali halides, bialkali, GaN) have been used to establish high UV detection efficiency for MCP detectors and investigations to optimize the QE of these as solar blind photocathode materials is ongoing. Specific issues to be addressed in this investigation include an analysis of the design, materials, and techniques needed for a large area, high-resolution sealed tube as a hermetic refractory "system" that contains all of the necessary elements. The recent success with very large square ceramic based tube seals is promising. However incorporation of a high-resolution anode and establishment of the internal support structures presents their own set of structural and functional challenges to be overcome. The designs will need to be modeled for thermal and mechanical robustness and large area trial tubes need to be produced. Issues that need to be addressed include topics such as migration of the large format cross strip anode design to ceramic materials compatible with sealed tube manufacturing and that give the prerequisite imaging performance characteristics. In addition large MgF2 windows in >100 x 100 mm2 format, the window sealing process, dead area minimization between detector "panels", vacuum enclosure materials and processes, electrical integration of MCPs and anodes in large format configurations all play a part in

		the successful realization of detectors for the decadal study mission concepts.

96328	Ultraviolet Imaging and Spectroscopic Instrumentation for Future NASA Astrophysics Missions	We propose a five-year suborbital research program to develop and flight-qualify the instrument designs and components required to realize NASA's ambitious space instrumentation objectives of the next decade. This proposed work builds on previous University of Colorado efforts to support technological readiness for a future, highly multiplexed ultraviolet (UV) instrument with imaging and spectroscopic capabilities, e.g., the LUVOIR/LUMOS instrument or other future UV/optical mission. Our existing program successfully fabricated and will soon flight test a medium resolution imaging spectrograph for the 100 – 160 nm bandpass that demonstrates LUMOS technologies and spectrograph design. We propose to advance these efforts with a new multi-band ultraviolet imaging system that demonstrates the necessary component-level technology specified for the LUMOS far-UV Imager. We perform this work in the framework of a university-led program where undergraduate, graduate, and postdoctoral training is paramount. In the proposed effort, we will optimize the ultraviolet efficiency of our high-throughput imaging spectrograph (SISTINE) by characterizing and flight-testing aluminum mirror coatings employing protected fluoride overcoats (e.g., hot Al/eLiF + MgF2 or AlF3 capping layers). SISTINE is the first sub-arcsecond imaging, medium spectral resolution (R = 10,000), spectrograph ever flown with spectral coverage over the entire 100 – 160 nm bandpass. It is also the design prototype for the multi-object spectroscopy channel of the LUVOIR/LUMOS instrument. We will fly this upgraded SISTINE instrument in Years 1 and 2 to measure the ultraviolet radiation environment in the habitable zones around nearby stars. In parallel with the proposed science flights of SISTINE, we will design, fabricate, and calibrate a new FUV imaging payload (FLUID) that will enable the development, characterization, and flight testing of prototype narrow- and medium-band interference filters for the LUVOIR/LUMOS imaging channel. We will work with our collaborating institutions to 1) optimize a filter set that meets the science requirements identified by the LUVOIR STDT's community science program, 2) calibrate these in the laboratory, and 3) integrate them into the first simultaneous, multi-band imaging system operating from 100 – 180 nm. FLUID will fly in Years 4 and 5 to investigate massive star-formation in nearby galaxies and obtain the first morphological classification of nearby galaxies in the 100 – 120 nm bandpass. These observations will provide z ~ 0 references for JWST images of high-redshift galaxies and perform an essential calibration of the LUMOS filters while advancing their technology readiness from TRL 4 to TRL 6. SISTINE and FLUID incorporate several advanced optical technologies highlighted as major hardware drivers for NASA's next large UV/optical/near-IR observatory by the 2017 Cosmic Origins Technology Report, including 1) high-reflectivity far-UV-to-near-IR mirror coatings, 2) large-format, photon-counting UV detectors, and 3) ultraviolet band-shaping filters. Both SISTINE and FLUID address high-priority science questions identified in the 2010 Astronomy and Astrophysics Decadal Survey and 2013 NASA Astrophysics Roadmap. The hardware demonstrated on these pathfinder instruments is a crucial step towards meeting NASA's technology

		needs for UV-capable flagship, probe, and Explorer missions in the 2020s and beyond.

96331	Demonstration of Pointing Stability to Enable Astrophysics with Rotating Synthetic Aperture Telescopes	Novel rotating synthetic aperture telescope designs have been proposed for space to maximize telescope resolution and collecting area given the available volume on launch vehicles. These large aperture diameter, low mass systems have applications in exoplanet detection as well as planet surveying and have been proposed as a way to maximize the aperture of missions from CubeSats to future great observatories. A deployable strip-like telescope has the potential to increase the light gathering power and resolution of a 3U CubeSat to hundreds of square centimeters, increasing the sensitivity to events such as exoplanet transits, astroseismology, and active galactic nuclei. Additionally, a deployable telescope allows resolutions exceeding ground-based observatories at a fraction of the cost of comparable ground systems. The proposed effort will mature the pointing control needed for a spinning strip aperture telescope through laboratory demonstration. The state-of-the art for current nanosatellite body pointing is approximately 1 arcsecond for conventional aperture. We will design a system to meet or exceed this pointing stability with a larger aperture and demonstrate pointing performance both in simulation and with hardware. This work builds on an architecture study of a strip aperture telescope developed by an MIT student team and will leverage the strong student hardware program at the MIT Space Systems Laboratory. The pointing and control demonstration will complement collaborative efforts led by University of Maryland focusing on high-contrast imaging and image reconstruction and Raytheon focusing on performance scaling laws to enable architecture trades. A primary objective of this work is to mature an existing strip aperture dynamics and controls testbed (DCT) designed and built by the student team. The DCT is designed to test the controllablity of the spinning strip aperture satellite, demonstrate the necessary pointing capability and explore the dynamic effects of spinning on the optical geometry. The testbed sits on an air bearing inside a Helmholtz cage to allow 3-degree of freedom angular motion and simulate the effects of the Earth's magnetic field. The testbed is controlled by four reaction wheels and includes an inertial measurement unit (IMU) and star tracker to close the loops around the satellite pointing. Mirror surrogates and mass tuning stages are used to simulate the inertia and mass properties of a spinning strip aperture telescope. A second objective is to demonstrate sensing and control in a laboratory environment, given a deployed strip aperture. Dynamical problems of large asymmetric structures include control of bending modes as well as dynamic loading due to photon pressure and solar wind and reaction wheel driven harmonics. We propose to develop an analytic control solution encompassing these problems, starting with a simple star tracker coupled to the dynamical model. We will translate this control model to an optical testbed using a CubeSat scale model, injecting jitter and higher order perturbations from realistic attitude determination and control systems to validate control system performance using a star tracker as the control signal. The final objective is a simulation that combines data from the DCT at MIT with that from optical testbeds at University of Arizona to validate

		end-to-end system pointing performance. This work will include design of an optical sensor which uses the strip aperture both for science observations and to sense the system state, measuring deformation and orientation relative to a target star or astrophysical scene and providing appropriate control signals to maximize the image quality. The end product of the proposed study is a validated dynamical model of a deployable strip aperture CubeSat telescope that can serve as the starting point for future astrophysics CubeSat missions and feasibility studies of larger strip aperture mission concepts.

96341	BlackCAT CubeSat: A Soft X-ray Sky Monitor, Transient Finder, and Burst Detector for High-Energy and Multimessenger Astrophysics	We propose a CubeSat with a wide field of view soft X-ray imager for high-energy and multi-messenger astrophysics. The BlackCAT CubeSat would use an X-ray Hybrid CMOS Detector (HCD) and a coded aperture mask to rapidly image a large region of the soft X-ray sky in the 0.2-20 keV band. The instrument would be the first of its kind utilizing an HCD and providing alerts and source localizations in the scientifically critical soft X-ray regime. It would detect and enable studies of gravitational wave X-ray counterparts, Gamma Ray Bursts (particularly at cosmological redshifts), and other X-ray transients and high emission states. The mission would thus function as a multi-wavelength and multi-messenger complement to several major present and future facilities including LIGO, VIRGO, IceCube, KM3NET, LSST, LOFAR, SKA, and CTA.

96344	Advanced silicon diffractive optics for cross-dispersed spectroscopy	Our group manufactures diffractive optics directly in silicon. These include transmissive gratings (grisms) and reflective gratings (immersion gratings). These gratings make possible compact medium and high-resolution infrared spectrometers with broad wavelength coverage for airborne (SOFIA), space-based (JWST), and ground-based (IGRINS, iSHELL) infrared spectrometers. We propose here to extend the capabilities of these optics in two important ways that will significantly broaden the usefulness of silicon dispersers for future space infrared instruments: we will create integrated cross-dispersed grisms for medium resolution transmission spectroscopy and we will extend the capabilities of diffraction-limited immersion gratings to the shortest possible wavelengths. Silicon grisms are not only compact at a given dispersive power but also can send dispersed light along an unbent path. This capability makes it possible to contemplate instruments with a single "filter" wheel that permits imaging, and low and medium resolution spectroscopy for planetary transit studies and other observations. In collaboration with JPL, we will develop a medium resolution, monolithic, double-sided silicon grism. This optic combines methods we developed at UT (UV lithographic and wet etching techniques to produce coarse blaze gratings) and at JPL (gray-scale electron beam lithography and plasma transfer etching to produce fine blazed gratings). These devices will enable cross-dispersed spectrographs continuously covering up to an octave in wavelength at R=5000—20,000, and add significantly to the design toolbox for transmission instruments. Silicon immersion gratings reduce instrument volumes by an order of magnitude compared to conventional grating instruments with the same resolving power. We will improve our immersion grating manufacturing precision in several ways to permit good performance down to the newly identified short wavelength cutoff of cryogenic silicon optics (down to 1.065 µm). These improvements will also allow very high resolving power (R>100,000—200,000) throughout the near-IR. With these improved high-R devices, we will open new methods for characterization of exoplanet atmospheres and a different approach to future detection of biosignatures.

96349	The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2): Trailblazing the Discovery of CGM Emission in the low-redshift universe with ground-breaking instrumentation and innovative UV technology (Columbia University Co-I Proposal)	Columbia University is a Co-I institution in a collaborative research program with Caltech, the Lead Institution (PI: Christopher Martin). The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2) is de- signed to discover and map faint emission from the circumgalactic medium of low redshift galaxies (0.3<1.0). This balloon is a upgrade of FIREBall-1 (FB-1), a path-finding mission built by our team with two successful flights (2007 Engineering, 2009 Science). FB-1 provided the strongest constraints on intergalactic and circumgalactic (IGM, CGM) emission available from any instrument at the time (Milliard et al., 2010). FIREBall-2 had a first flight in the fall of 2018 from Fort Sumner, NM, but the flight was cut short due to a hole in the balloon, which subsequently caused a loss in altitude to well below our UV transmission window. The 2018 flight of FIREBall-2 has demonstrated the successful performance of all subsystems and provided a test flight for several technology innovations: the UV-optimized EMCCD, the anamorphic UV grating, a wide-field UV multi-object spectrograph on a balloon payload, and a gondola with sub-arcsecond pointing stability. Given the success of the instrument, we are determined to refurbish the instrument and re-fly FIREBall-2 at least two more times between 2020 - 2022. We have a detailed schedule for a Palestine re-flight in 2020 and anticipate exciting science results from this campaign. Between the two proposed flights, we will test, install, and demonstrate a new, visible light-blocking filter on our UV-optimized EMCCD, a critical technology development for future UV missions seeking CCD support. We request three additional years of funding to support the FIREBall-2 team between 2020 - 2022 and fund an additional flight in 2022 which fully utilizes an upgraded UV detector technology. Supplementary funds after our proposed grant period may be sought to propel a third flight of FIREBall-2 from the southern hemisphere (Alice Springs, Australia; ∼2023 - 2024). FIREBall-2 will test key technologies and science strategies for a future space mission to map emission from CGM and IGM baryons. The FIREBall-2 team is comprised of an international consortium of experts in suborbital scientific ballooning and IGM/CGM physics, and includes several female graduate students and postdocs in key roles, in addition to being overseen by a female postdoctoral scholar (supported by a Caltech Experimental Prize Fellowship). Its flights will continue to provide vital training for the next generation of astrophysicists working on UV and space instrumentation. Additional funding is necessary to keep this highly qualified balloon team together and to fulfill the promise of this incredible instrument. FIREBall-2 combines several innovations and noteworthy goals: − Simultaneously addresses high-priority science questions stated in NASA's 2014 Strategic Plan and UV technology development emphasized by New Worlds New Horizons (NWNH) and AURA; − Demonstrates the first ever multi-object UV spectrograph suitable for future UV missions; − Demonstrates the first high quantum efficiency, low-noise, photon-counting, UV-optimized CCDs for space missions; − Flies a 1-m class UV telescope, enabled by low cost optics and innovative mounts; − Demonstrates a state-of-the-art, arcsecond-precision balloon pointing system; −

		Builds on a multi-international space agency partnership between NASA & CNES; − Benefits from the expertise found in a long-running, multi-institutional collaboration between Caltech/JPL, Columbia University, LAM (France), CNES (France), and University of Arizona; − Utilizes innovative optical solutions, such as a Schmidt corrector built into UV grating, which provides superior optical performance and throughput; − Trains the next-generation of instrumentation PIs, with a total of 11 Ph.D. students graduated or currently supported between FB-1 (3) and FIREBall-2 (8).

96353	Stable, solar-blind ultraviolet III-nitride photocathode imagers with high quantum efficiency	Currently, many detectors used in ultraviolet (UV) instruments utilize a photocathode to convert UV photons into electrons that are subsequently detected by microchannel plate or CCD. UV photocathodes provide low dark count rate combined with high out-of-band rejection. The performance of these detectors critically depends on the efficiency and stability of their photocathodes. In particular, photocathode instability is responsible for many of the fabrication difficulties commonly experienced with this class of detectors. In this effort, we will advance to TRL-4 a new type of cesium-free photocathode using III-nitride materials (GaN, AlN, and their ternary alloy Al(1-x)Ga(x)N) to achieve highly efficient, solar blind, stable UV response. In recent years, group-III/nitride (in particular GaN) photocathodes have been demonstrated with high quantum efficiency (QE) (>50%) in the UV spectral range. In particular, GaN photocathodes have promise to substantially surpass the QE of photocathodes fabricated from other materials. Moreover, due to the tunable wide bandgaps of III-nitride materials, photocathode response can be tailored, and can be made intrinsically solar-blind. However, these photocathodes still rely on reactive materials (such as cesium) for activation, necessitating in many cases all-vacuum fabrication and sealed-tube operation. In addition to the expense, mass, and fragility of the sealed-tube configuration, QE has been observed to degrade with cesiated photocathodes, even in the vacuum environment. The photocathode/microchannel plate structure proposed here achieves activation through methods for band structure engineering such as delta-doping and polarization field engineering. Compared to the current state-of-the-art microchannel plate sealed tubes, they will provide high QE and significantly enhance stability, fabrication yield, and reliability. We have demonstrated III-nitride photocathode operation without the use of cesium. We have implemented III-nitride polarity control, polarization charge engineering, and alloy fraction control to demonstrate high-QE UV photocathodes. However, further work is needed to provide improved stability over time, even higher QE, and truly tunable response enabled by AlGaN heterostructures. These improvements will be achieved by employing novel designs, surface passivation methods, and heterostructure growth techniques, and by continued optimization of placement of internal fixed charge. We will demonstrate the performance of these detectors in a system that includes either conventional micro-channel plate instruments (MCPs) or solid-state arrays with gain such as electron-bombarded CCD arrays. This technology will be enabling for future large UV spectroscopic and imaging missions such as HabEx and LUVOIR, as well as smaller orbital and sub-orbital missions where low mass, high QE, high out-of-band rejection, low dark count rates, and robustness are of primary importance.

96358	The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2): Trailblazing the Discovery of CGM Emission in the low-redshift universe with ground-breaking instrumentation and innovative UV technology University of Arizona Co-I	This is an institutional proposal as part of a larger collaboration. The main proposal is submitted by PI Chris Martin (Caltech). The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2) is de- signed to discover and map faint emission from the circumgalactic medium of low redshift galaxies (0.3<1.0). This balloon is a upgrade of FIREBall-1 (FB-1), a path-finding mission built by our team with two successful flights (2007 Engineering, 2009 Science). FB-1 provided the strongest constrains on intergalactic and circumgalactic (IGM, CGM) emission available from any instrument at the time (Milliard et al., 2010). FIREBall-2 had a first flight in the fall of 2018 from Fort Sumner, NM, but the flight was cut short due to a hole in the balloon, which subsequently caused a loss in altitude to well below our UV transmission window. The flight of FIREBall-2 did not meet the minimum mission requirements for success. The 2018 flight of FIREBall-2 has demonstrated the successful performance of all subsystems and provided a test flight for several technology innovations: the UV-optimized EMCCD, the anamorphic UV grating, a wide-field UV multi-object spectrograph on a balloon payload, and a gondola with sub-arcsecond pointing stability. Given the success of the instrument, we are determined to refurbish the instrument and re-fly FIREBall-2 at least two more times between 2020 - 2022. We have a detailed schedule for a Palestine re-flight in 2020 and anticipate exciting science results from this campaign. Between the two proposed flights, we will test, install, and demonstrate a new, visible light-blocking filter on our UV-optimized EMCCD, a critical technology development for future UV missions seeking CCD support. We request three additional years of funding to support the FIREBall-2 team between 2020 - 2022 and fund an additional flight in 2022 which fully utilizes an upgraded UV detector technology. FIREBall-2 will test key technologies and science strategies for a future space mission to map emission from CGM and IGM baryons. The FIREBall-2 team is comprised of an international consortium of experts in suborbital scientific ballooning and IGM/CGM physics, and includes several female graduate students and postdocs in key roles, in addition to being overseen by a female postdoctoral scholar (supported by a Caltech Experimental Prize Fellowship). Its flights will continue to provide vital training for the next generation of astrophysicists working on UV and space instrumentation. Additional funding is necessary to keep this highly qualified balloon team together and to fulfill the promise of this incredible instrument. FIREBall-2 combines several innovations and noteworthy goals: − Simultaneously addresses high-priority science questions stated in NASA's 2014 Strategic Plan and UV technology development emphasized by New Worlds New Horizons (NWNH) and AURA; − Demonstrates the first ever multi-object UV spectrograph suitable for future UV missions; − Demonstrates the first high quantum efficiency, low-noise, photon-counting, UV-optimized CCDs for space missions; − Flies a 1-m class UV telescope, enabled by low cost optics and innovative mounts; − Demonstrates a state-of-the-art, arcsecond-precision balloon pointing system; − Builds on a multi-international space agency partnership between NASA & CNES; − Benefits from the expertise

		found in a long-running, multi-institutional collaboration between Caltech/JPL, Columbia University, LAM (France), CNES (France), and University of Arizona; − Utilizes innovative optical solutions, such as a Schmidt corrector built into UV grating, which provides superior optical performance and throughput; − Trains the next-generation of instrumentation PIs, with a total of 11 Ph.D. students graduated or currently supported between FB-1 (3) and FIREBall-2 (8).

96359	The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2): Trailblazing the Discovery of CGM Emission in the low-redshift universe with ground-breaking instrumentation and innovative UV technology	The Faint Intergalactic-medium Redshifted Emission Balloon (FIREBall-2) is de- signed to discover and map faint emission from the circumgalactic medium of low redshift galaxies (0.3<1.0). This balloon is an upgrade of FIREBall-1 (FB-1), a path-finding mission built by our team with two successful flights (2007 Engineering, 2009 Science). FB-1 provided the strongest constraints on intergalactic and circumgalactic (IGM, CGM) emission available from any instrument at the time [33]. FIREBall-2 had a first flight in the fall of 2018 from Fort Sumner, NM, but the flight was cut short due to a hole in the balloon, which subsequently caused a loss in altitude to well below our UV transmission window. The flight of FIREBall-2 did not meet the minimum mission requirements for success. We propose to re-fly FIREBall-2 during two more campaigns over the next three years (2020 - 2022). In the cutting-edge field of CGM/IGM astrophysics, ground-based facilities are taking advantage of state-of-the-art IFUs to make ground-breaking discoveries of CGM and IGM emission at high (z>2) redshifts. FIREBall-2 is the only UV instrument currently proven and able to make these necessary discoveries in the low-redshift universe. Multiple flights of this very valuable facility will pave the way for low-redshift CGM physics alongside high-redshift CGM detections with ground-based surveys! FIREBall-2 will continue to serve as a platform to test cutting-edge technologies and science strategies for future space missions. The 2018 flight of FIREBall-2 demonstrated the successful performance of all subsystems and provided a test flight for several key technology innovations: the UV-optimized EMCCD, the anamorphic UV grating, a wide-field UV multi-object spectrograph, and a gondola with sub-arcsecond pointing stability. Between this program's two proposed flights, we will fabricate, characterize, and demonstrate a new, visible light-blocking filter on our UV- optimized EMCCD, a critical technology development for future UV missions seeking to use a CCD at UV wavelength. UV CCDs are notoriously prone to "red light leak," and this new filter will cut visible light sensitivity of these detectors to virtually 0%! The FIREBall-2 team is comprised of an international consortium of experts in suborbital scientific ballooning and IGM/CGM physics. The team includes several female graduate students and postdocs in key roles and is managed by a female postdoctoral scholar (supported by a Caltech Experimental Prize Fellowship). FIREBall-2's flights will continue to provide vital training for the next generation of astrophysicists working on UV and space instrumentation. FIREBall-2 combines several innovations and noteworthy goals: − Simultaneously addresses high-priority science questions stated in NASA's 2014 Strategic Plan and UV technology development emphasized by New Worlds New Horizons (NWNH) and AURA; − Demonstrates the first ever multi-object UV spectrograph suitable for future UV missions; − Demonstrates a high-QE, low-noise, photon-counting, UV-optimized CCD for space missions; − Flies a 1-m class UV telescope, enabled by low cost optics and innovative mounts; − Demonstrates a state-of-the-art, arcsecond-precision balloon pointing system; − Builds on an international space agency partnership between NASA & CNES; − Benefits from the expertise found in a long-running

		institutional collaboration between Caltech/JPL, Columbia University, LAM (France), CNES (France), and University of Arizona; − Utilizes innovative optical solutions, such as a Schmidt corrector built into UV grating, which provides superior optical performance and throughput; − Trains the next-generation of instrumentation PIs, with a total of 11 Ph.D. students graduated or currently supported between FB-1 (3) and FIREBall-2 (8).

96317	CALET: Extended Mission and Flight Data Analysis	This proposal is for the CALET Collaboration lead institution Louisiana State University with T. Gregory Guzik as the project Principal Investigator. Co-Investigator proposals will be provided Washington University at St. Louis (Institution PI Brian Rauch), and Goddard Space Flight Center (Institution PI John W. Mitchell). The CALET space experiment, which was developed by collaborators in Japan, Italy and the United States, has been mounted as an attached payload on the International Space Station (ISS) Japanese Experiment Module – Exposed Facility (JEM-EF) since August 2015. Over the >1,000 days of data taking the instrument has accumulated more than ~630 million triggered events > 10 GeV with a live time fraction of 84%. These data have been used to study electrons to ~5 TeV, gamma rays above 10 GeV and nuclei with Z=1 to 40 up to 10 - 20 TeV per nucleon. The instrument is performing well and has been shown to have an in-flight energy resolution of 2% for electrons > 100 GeV with a < 5% proton contamination for energies up to 1 TeV. Since CALET achieved orbit, ten peer-reviewed journal articles (with two more expected to be published soon) plus 28 conference papers detailing CALET flight results have been published. Work in the U.S. over the last several years have included development / operation of the U.S. CALET Data Center to distribute CALET data to U.S. collaborators, analyzing the ultra-heavy composition, establishing the efficiencies and event selection criteria for studying gamma-rays in the range ~1 GeV to over 10 TeV, analyzing the energy spectrum of light nuclei, working to establish a CALET data archive at the HEASRC facility at GSFC, and taking advantage of HPC facilities at U.S. institutions to improve the CALET simulated dataset. Further, with the confirmed observation of gravitational waves using the LIGO facility (one interferometer located in Livingston parish near Louisiana State University), CALET is now part of the LIGO-Virgo Gravity Wave electromagnetic counterpart alert network and potentially could provide gamma-ray observations associated with compact object mergers. JAXA is committed to CALET on the ISS, assuming continued instrument health and scientific productivity, until about March 2021 with the possibility of an extension beyond this date. With close to 5 ½ years of on-orbit operations our understanding of statistically limited scientific data products (e.g. electron spectrum to 10 TeV, ultra-heavy composition, B/C up to TeV/n, etc.) will be significantly improved. Under this proposal, we ask for continuing support for flight operations, data processing, and science analysis for the CALET mission in the United States. The U.S. Team consists of Louisiana State University (lead institution), Goddard Space Flight Center, and Washington University in St. Louis. We expect to continue with the CALET scientific investigations already started in the U.S, to expand our scientific analysis effort into areas such as Space Weather, and CALET gamma-ray burst detector observations with CAL measurements, plus coordinating these analyses with our Japanese and Italian colleagues.

96318	CALET: Extended Mission and Flight Data Analysis - Washington University Co-I	This is a Co-I proposal that should be cross-referenced to the Louisiana State University proposal titled "CALET: Extended Mission and Flight Data Analysis", for which T. Gregory Guzik is the Principal Investigator. The CALET space experiment, which was developed by collaborators in Japan, Italy and the United States, has been mounted as an attached payload on the International Space Station (ISS) Japanese Experiment Module – Exposed Facility (JEM-EF) since August 2015. Over the >1,000 days of data taking the instrument has accumulated more than ~630 million triggered events > 10 GeV with a live time fraction of 84%. These data have been used to study electrons to ~5 TeV, gamma rays above 10 GeV and nuclei with Z=1 to 40 up to 10 - 20 TeV per nucleon. The instrument is performing well and has been shown to have an in-flight energy resolution of 2% for electrons > 100 GeV with a < 5% proton contamination for energies up to 1 TeV. Since CALET achieved orbit, ten peer-reviewed journal articles (with two more expected to be published soon) plus 28 conference papers detailing CALET flight results have been published. Work in the U.S. over the last several years have included development / operation of the U.S. CALET Data Center to distribute CALET data to U.S. collaborators, analyzing the ultra-heavy composition, establishing the efficiencies and event selection criteria for studying gamma-rays in the range ~1 GeV to over 10 TeV, analyzing the energy spectrum of light nuclei, working to establish a CALET data archive at the HEASRC facility at GSFC, and taking advantage of HPC facilities at U.S. institutions to improve the CALET simulated dataset. Further, with the confirmed observation of gravitational waves using the LIGO facility (one interferometer located in Livingston parish near Louisiana State University), CALET is now part of the LIGO-Virgo Gravity Wave electromagnetic counterpart alert network and potentially could provide gamma-ray observations associated with compact object mergers. JAXA is committed to CALET on the ISS, assuming continued instrument health and scientific productivity, until about March 2021 with the possibility of an extension beyond this date. With close to 5 ½ years of on-orbit operations our understanding of statistically limited scientific data products (e.g. electron spectrum to 10 TeV, ultra-heavy composition, B/C up to TeV/n, etc.) will be significantly improved. Under this proposal, we ask for continuing support for flight operations, data processing, and science analysis for the CALET mission in the United States. The U.S. Team consists of Louisiana State University (lead institution), Goddard Space Flight Center, and Washington University in St. Louis. We expect to continue with the CALET scientific investigations already started in the U.S, to expand our scientific analysis effort into areas such as Space Weather, and CALET gamma-ray burst detector observations with CAL measurements, plus coordinating these analyses with our Japanese and Italian colleagues.

96356	Ultra-Heavy Cosmic-Ray Observations with SuperTIGER-2: Flight, Recovery and Data Analysis	This proposal is the lead proposal for the suborbital investigation titled "Ultra-Heavy Cosmic Ray Observations with SuperTIGER-2: Flight, Recovery, and Data Analysis". We submit here a proposal for a SuperTIGER-2 (hereafter ST-2) balloon flight over Antarctica in December of 2019 with the primary objective of measuring the abundances of individual elements with atomic number $41 \le Z \le 60$ (when combined with data from ST-1) for the first time, and to substantially increase the number of $30 \le Z \le 40$ nuclei already measured by ST-1. With reduced interactions in the instrument, flying near solar minimum, and flying for 60 days, we should detect ~1.7× the number of nuclei detected in our first flight with $41 \le Z \le 60$, thereby nearly tripling our total statistics. The proposal covers the December 2019-November 2021 period for integration and test at McMurdo preceding the flight, the flight itself, data analysis, and instrument recovery. We were originally funded (beginning December 2014) to fly ST-2 over Antarctica in December 2017. However, we were not able to fly due to uniformly bad weather. We were then selected for flight in the 2018-2019 season. Our balloon launch initially appeared to be good. However, the balloon went up to ~80,000 feet and then descended, resulting in no data from the flight. We were able to recover ST, reassemble, and successfully test the instrument at LDB in Antarctica. We are confident that it can be refurbished in time for integration and test at CSBF in Palestine in mid-July and flight over Antarctica in December, 2019. By flying ST-2, we propose to substantially extend the scientific reach of the already highly successful SuperTIGER. SuperTIGER is a large-area instrument designed to make precision measurements of the elemental composition of ultra-heavy cosmic rays (UHCR) with atomic number $Z \ge 30$. The principal objective of the first phase of the SuperTIGER program was to measure the abundances of nuclei with $30 \le Z \le 42$ with clear individual element resolution and high statistical precision. The excellent data from this flight have enabled us to achieve the initial goals of the program. The demonstrated high performance of the instrument, both in charge resolution and collecting power, makes a compelling case to expand our primary objective to include additional flights to measure the abundances of nuclei up to Z=60. Galactic cosmic rays (GCR) play an important role in the dynamics of matter and magnetic fields in the interstellar medium, and probably also play an important role in star formation. In spite of their importance, and despite much recent progress, significant questions about the origin of cosmic rays remain. Prior to the current decade, we "knew" that the neutron-rich nuclei heavier than Z=30 (r-process nuclei) in the contemporary cosmic rays were made in supernova explosions. But now, after observation of gravitational waves from neutron-star mergers, electromagnetic observations of those events, and models of r-process production in binary neutron star mergers, we recognize that a substantial fraction of r-process nuclei may be made in such mergers. Data from this proposed flight will enable us to constrain models of r-process production in supernovae and binary neutron star mergers.

18526	Primordial Inflation Polarization Explorer (Phase 3)	This is the Lead Proposal for the investigation "Primordial Inflation Polarization Explorer (Phase 3)". We propose to complete and fly the Primordial Inflation Polarization Explorer (PIPER) to measure the polarization of the cosmic microwave background (CMB) and search for the imprint of gravitational waves produced during an inflationary epoch in the early universe. Detection of the inflationary signal would have profound consequences for both cosmology and high-energy physics. Not only would it establish inflation as a physical reality, it would provide a direct, model-independent determination of the relevant energy scale, shedding light on physics at energies twelve orders of magnitude beyond those accessible to direct experimentation in particle accelerators. The recent detection of CMB polarization by the BICEP2 instrument brings new urgency to the field. The BICEP2 detection at degree angular scales is consistent with inflation, but the amplitude is a factor of two higher than upper limits set by unpolarized data. A critical test is the rise in power at large angular scales predicted by inflation. Detecting this rise would confirm the signal's inflationary origin, fulfilling a long quest for cosmology while providing new insight into physics at the highest energies. PIPER is the only suborbital instrument capable of measuring CMB polarization on the large angular scales needed to test an inflationary origin for the BICEP2 detection. PIPER is a balloon-borne instrument, optimized to detect the inflationary signal on large angular scales. It consists of two co-aligned telescopes cooled to 1.5 K within a large liquid helium bucket dewar. A variable-delay polarization modulator (VPM) on each telescope chops between linear and circular polarization to isolate the polarized signal while rejecting the much brighter unpolarized emission. Four 32 x 40 element detector arrays provide background-limited sensitivity. A series of flights from mid-latitude sites will map the full sky at frequencies 200, 270, 350, and 600 GHz to allow separation of CMB signals from the dominant dust foreground while providing new information on the diffuse dust cirrus. PIPER's innovative architecture combines cryogenic optics with kilo-pixel detector arrays to provide unprecedented sensitivity to CMB polarization. The fast modulation between linear and circular polarization takes advantage of the lack of astrophysical circular polarization to eliminate common sources of systematic error while enabling mapping on the largest angular scales. The sensitivity and control of systematic errors in turn enable measurements over most of the sky from mid-latitude launch sites; long-duration Antarctic flights are not required. With sensitivity $r < 0.007$ at 95% CL, PIPER will either confirm the inflationary signal or rule out nearly all large-field inflation models. The combination of sensitivity, sky coverage, and systematic error control provides unprecedented sensitivity to CMB polarization on angular scales greater than 20 deg, providing a critical test of the BICEP2 results against inflationary models. PIPER began development in 2009 and is nearly complete. End-to-end testing of detector arrays demonstrates the pixel yield, electrical, and thermal properties required for background-limited sensitivity. Cryogenics, gondola, and flight electronics use components flown on the successful ARCADE mission. The PIPER team has exceptional

		experience in all aspects of the proposed work, including detector development, polarization modulation, instrument integration, and cryogenic ballooning. The cryogenic optics provide instantaneous sensitivity comparable to a space mission while the full sky coverage tests systematic error control in ways not possible with restricted coverage: PIPER will probe the limits of sensitivity from a suborbital platform while developing instrumentation, observing techniques, and foreground models for an eventual space mission.

95094	Superconducting Nanowire Single-Photon Detectors for Exoplanet Spectroscopy in the Mid-Infrared	Superconducting nanowire single-photon detectors (SNSPDs) have emerged as the highest-performing single-photon detectors from the UV to the mid-infrared. These detectors combine very high efficiencies (> 90% in the infrared at 1.55 um), ultralow jitter (~100 ps or less), zero readout noise, and very low dark count rates (< 10-4 Hz) . Recently, we have developed SNSPDs operating in the mid-infrared from 2 - 7 um. Basic models of the physics of the detection process suggest that by reducing the width of the nanowires to ~ 10 - 20 nm, and tuning the composition of the superconducting material, one may be able to demonstrate single-photon detection at wavelengths extending to 60 um. In addition, recently-developed multiplexing techniques should allow the fabrication of small arrays consisting of ~ 1000 pixels or more, which could potentially be useful for spectroscopy and imaging. The primary advantages of using SNSPDs in this wavelength range are high stability of detector gain as a function of temperature and bias current, true single-photon sensitivity, zero readout noise, and extremely low dark count rate. In addition, SNSPDs would not suffer from many of the problems inherent with arrays of currently used blocked impurity band (BIB) detectors such as reset anomaly, last-frame effect, droop, drift, multiplexer glow, and latent images. One of the many goals of the Origins Space Telescope (OST) is the study of exoplanets. This study makes up roughly one-third of the science case for OST. In particular, part of OST's mission is the detection of biosignatures such as ozone, nitrous oxide, and methane in the atmospheres of Earth-sized planets transiting the habitable-zones of nearby stars. The spectroscopy of exoplanet atmospheres requires mid-infrared detector arrays combining high stability over time (a few ppm over several hours), high sensitivity (ideally single-photon sensitive), high system efficiency, and low noise. We propose to develop kilopixel-scale arrays consisting of single-photon-sensitive superconducting nanowire detectors that are sensitive in the range of 6 - 20 um wavelengths that would meet the requirements for any future instruments directed towards exoplanet transit spectroscopy, for example the mid-infrared spectrometer and coronagraph (MISC) planned for the Origins Space Telescope. As outlined above, the excellent stability and single-photon sensitivity of these detectors would be ideal for such an application requiring data collection over the course of hundreds of transits of an exoplanet across its parent star, each of which can last several hours or longer.

95112	The Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE): a Next-Generation Experiment for Galaxy Evolution Studies	Understanding the formation and evolution of galaxies over cosmic time is one of the foremost goals of astrophysics and cosmology today. The cosmic star formation rate has undergone a dramatic evolution over the course of the last 14 billion years, and dust-obscured star forming galaxies (DSFGs) are a crucial component of this evolution. A variety of important, bright, and unextincted diagnostic lines are present in the far-infrared (FIR) which can provide crucial insight into the physical conditions of galaxy evolution, including the instantaneous star formation rate, the effect of AGN feedback on star formation, the mass function of the stars, metallicities, and the spectrum of their ionizing radiation. FIR spectroscopy is technically difficult but scientifically crucial. The FIR waveband is impossible to observe from the ground, and spans a crucial gap in the spectroscopic coverage between the Atacama Large Millimeter/submillimeter Array (ALMA) in the sub/mm, and the James Webb Space Telescope (JWST) in the mid-IR. Stratospheric balloons offer a platform which can outperform current instrument sensitivities and are the only way to provide large-area, wide-bandwidth spatial/spectral mapping at FIR wavelengths. We propose an aggressive program of instrumentation development and experimental study called the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE), with the goal of demonstrating the key technical milestones necessary for FIR spectroscopy. STARFIRE will provide a technological stepping stone to the future space-borne instrumentation such as the Origins Space Telescope (OST, formerly the Far-IR Surveyor) or a Probe mission. STARFIRE will address the two key technical issues necessary to achieve this: 1) Low-emissivity, high-throughput telescope and spectrometer optics for the FIR; 2) Background-limited detectors in large format arrays, scalable to >10,000 pixels. We will do this by constructing an integral-field spectrometer from 240 - 420 microns coupled to a 2-meter low-emissivity carbon-fiber telescope. The development of the optics will utilize the capabilities of the Arizona Steward Observatory mirror lab and the unique expertise of our spectroscopic experts to create high-throughput optics. For the detectors, we will leverage the highly advanced development work of the Caltech / JPL group to develop and field kinetic-inductance detectors (KIDs). KIDs represent the most promising route to economical, large format submillimeter detector arrays. In addition to the development and demonstration of crucial technologies for the FIR, STARFIRE will perform groundbreaking science. We will survey two 0.1 square degree fields centered on GOODS-S and the South Pole Telescope Deep Field, both of which have rich ancillary data. Scientifically, we will: 1) Obtain spectroscopic line detections of ~100 galaxies in the atomic fine structure lines [CII](158 microns) (at 0.5

95117	Frequency-agile and high-power terahertz laser local oscillators	Many molecular species that comprise the interstellar medium have strong spectral features in the 2-5 THz range, and heterodyne spectroscopy is required to obtain ~km/s velocity resolution to resolve their complicated lineshapes and disentangle them from the background. Understanding the kinetics and energetics within the gas clouds of the interstellar medium is critical to understanding star formation processes, validate theories of galactic evolution, and to probe protoplanetary disks. The next frontier for heterodyne spectroscopy is the 2-6 THz region - a spectral range which is well matched to the use of terahertz quantum-cascade (QC) lasers as local oscillators (LOs). This proposal looks beyond the state-of-the-art, to the development of large format heterodyne arrays which contain on the order of 20-200 elements. LO powers on the order of 10-100 mW delivered in a high-quality Gaussian beam will be needed to pump the mixer array - not only because of the mixer power requirement, but to account for large losses in LO coupling and distribution. Large format heterodyne array instruments are attractive for a dramatic speedup of mapping of the interstellar medium, particularly on airborne platforms such as the Stratospheric Observatory for Infrared Astronomy (SOFIA), and on long duration balloon platforms where observation time is limited. In our recent work, we demonstrated a new architecture for terahertz quantum-cascade (QC) lasers capable of delivering scalable output power a near-diffraction limited output beam: the quantum-cascade vertical-external-cavity-surface-emitting-laser (QC-VECSEL). The enabling technology for this proposed laser is an amplifying metasurface reflectarray, which is made up of a sparse array of low-quality-factor antenna-coupled sub-cavities loaded with QC gain material. The sub-cavities on the metasurface radiate coherently into a high-quality-factor external cavity mode, which sets the beam shape and allows for scalable power combining. In previous work, we made two key proof-of-concept demonstrations: (a) a 3.4 THz QC-VECSEL which emitted continuous-wave power of 5 mW in a single-mode and in a high-quality beam at a temperature of 83 K with a wall plug efficiency of approximately 0.13%, and (b) the ability to continuously tune the frequency of QC-VECSEL by changing the cavity length, albeit with inconsistent beam pattern, power levels, and occasional multi-moding. Our overarching research goal in this successor proposal is demonstrate the QC-VECSEL as a credible frequency-agile local-oscillator. In the first theme, we propose to achieve 10x improvement in continuous-wave wall-plug efficiency from ~0.1% to 1% at 77 K, to allow generation of 10-100 mW with 1-10 W power dissipation at frequencies of 2.7 and 4.7 THz. In the second theme, we propose to demonstrate robust and repeatable tunability of a single mode over 15% of its center frequency near 2.7 THz while maintaining beam quality and power. In the third theme, we will demonstrate frequency-locking of the QC-VECSEL to a microwave reference over its tuning range, which is necessary to stabilize the LO output to resolve complicated lineshapes and allow long receiver integration times. This will be a critical demonstration, as the VECSEL cavity is very different than the monolithic THz QC-lasers that have been frequency/phase locked in the past.

		Furthermore, demonstration of this level of performance in terms of power, efficiency, beam quality, and tunability will be firsts for any type of stabilized THz QC-laser under consideration for a local oscillator, and would enable new possibilities for frequency-agile heterodyne instruments that could access multiple lines of interest. Additionally, in the course of the program, we will demonstrate the first QC-VECSELs at 4.7 THz which is close to the important OI line 4.745 THz (a major coolant for photo-dissociation regions in molecular clouds).

95118	Advanced on-chip, submm-wavelength spectrometers using superconducting detectors.	This program will develop and characterize ultra-sensitive on-chip spectrometers covering the sub-mm and mm-wavelength observing bands from 3 mm to 230 microns. This builds upon a successful program, SuperSpec, which has demonstrated the basic filterbank operation, a proof of principle that large-format spectrographs for the far-IR and submillimeter can be miniaturized onto silicon chips. Using superconducting mm-wave transmission line components and extremely small-volume kinetic inductance detectors (KIDs), we have constructed and are currently preparing to deploy a ground-based demonstration instrument covering the 1 mm atmospheric band. This is a key enabling technology for the next-generation cryogenically-cooled far-IR flight missions as well as near-future sub-orbital platforms such as balloon-based spectrometers and future SOFIA instruments. However, obtaining full scientific return from these powerful future far-IR missions requires 3 crucial advances in the SuperSpec filerbank technology: (1) improving filterbank loss by a factor of >10; (2) improving the detector sensitivity in order to meet the requirements of the low-background space platforms; (3) extending operation from the mm-wave to 230 microns. In order to meet these goals, we will build on our experience with superspec, as well as advances in dielectric material quality, fabrication techniques, and kinetic-inductance detector (KID) design approaches to accomplish each of these goals. A successful demonstration of these technologies will not only benefit future spectroscopic instruments, but will be immediatly useful for instruments operating in the submm and for KID-based instruments designed for a wide range of science targets. We will begin by adjusting the filterbank electromagnetic design for a silicon inner layer dielectric as this promises factors of up to 50 times lower loss than the current materials. We will build and test silicon-dielectric prototypes, beginning at the current 200--300 GHz band, but then moving up to the 400--700 GHz band. We will explore both deposited amorphous silicon (a-Si) using a new low-loss recipe as well as a crystalline silicon (c-Si) ''fliped-SOI" process using silicon-on-oxide (SOI) wafers. Meanwhile we will develop more sensitive KIDs to embed in the spectrometers. In particular, we will adapt our spectrometer design to accommodate very small volume aluminum KIDs, which promises significant improvements in sensitivity required for low-loading applications. Finally, we will explore superconducting transmission lines made from both sputtered and atomic layer deposited (ALD) NbTiN and NbN. These materials have a transition temperature much higher than niobium and should allow us to extend the operation of our basic filterbank architecture to THz frequencies. In addition to a number of test structures sample devices, we will produce a series of four demonstration pixels: [FB-1]: a prototype covering the full 200-300 GHz band with resolving power (R) of at least 1000 and negligible dielectric loss. [FB-2]: a similarly low-loss submm prototype covering the 850-650 micron bands with similar resolving powers. [FB-HR]: a mm-wavelength device designed to achieve the highest possible resolving powers, targeting R~5000. [FB-T]: a sparse filterbank covering regions of the 0.8-1.3 THz filterbank to demonstrate high-frequency operation. The first three of these

		devices are intended to be field-ready at the conclusion of this program, and the fourth easily adapted for future instruments.

95119	Sensitive Mid and Far-IR Kinetic Inductance Detector Arrays for Space Astronomy	Over the past several years, NASA has been intensively studying future astrophysics missions at mid- and far-infrared wavelengths, including the flagship-class Origins Space Telescope (OST) and the probe-class Galaxy Evolution Probe (GEP). These mission studies follow the broad endorsement of a "Far-Infrared Surveyor" mission in the 2013 30-year roadmap study chartered by NASA, and the 2010 Decadal Survey recommendation for NASA participation in the JAXA/ESA SPICA far-IR mission. Not surprisingly, the OST and GEP studies have identified detector arrays as the highest-priority technology needing development. In this proposal, we offer to address essentially all of the fundamental detector needs for OST and GEP and for sub-orbital precursors, including the full 10-400 micron wavelength range, the varied sensitivity requirements, scalability to the desired array formats, and even to open a path toward highly stable photon-counting detectors needed for mid-IR biosignature characterization of terrestrial exoplanets with OST. We address all of these needs in a timely, integrated, highly efficient program by focusing on a single underlying technology, namely direct-absorption (microwave) kinetic inductance detectors (MKIDs or KIDs) using aluminum as the superconducting material. Our proposal aims squarely at the needs for OST and GEP: 1) sensitivity at or below 1e-19 W/root(Hz); 2) array architecture that enables efficient absorption at wavelengths from 10 to 350 micron, and 3) scalability to focal planes of >10^5 pixels. We will begin by increasing the sensitivity of our existing 350 micron feedhorn-coupled devices (which comfortably meet sub-orbital sensitivity requirements) by 1.5 orders of magnitude with a combination of lower operating temperature, higher quality films, and a reduced volume absorber. We will also push to shorter wavelengths, targeting first 30 micron and then 10 micron detectors, through use of new, efficient, and practical absorber geometries illuminated by scalable microlens arrays. This mid-IR capability will substantially reduce the cost and complexity of GEP and provide photon counting capability for high-stability mid-IR spectroscopic characterization of terrestrial exoplanets with OST, extending the initial work with JWST/MIRI. A successful conclusion to our proposed program would represent a substantial reduction of technological risk for future NASA mid- and far-IR missions such as OST and GEP, with demonstration of the sensitivity, wavelength range, and array formats needed for the baseline designs developed by these study teams. It would also open a path to high-stability mid-IR exoplanet characterization with OST via photon counting.

96319	Aerogel Scattering Filters for Millimeter and Sub-Millimeter Astrophysics	We propose to develop novel infrared-blocking filters made by embedding scattering particles in an aerogel substrate. Infrared-blocking filters are needed to minimize the heat load on receiver cryogenic systems, stabilizing the instrument and extending mission lifetime. Future instruments require that they do so over increasingly larger apertures, while maintaining high in-band transmission. Aerogel scattering filters have ultra-low density and index of refraction (n<1.07), removing the need for anti-reflection coatings that limit bandwidth and increase filter complexity. By choosing the size distribution of the silicon particles embedded as scatterers in the filter, the cutoff frequency of the filter is tunable with strong rejection across all frequencies above the cutoff. Aerogel scattering filters would enable a broad range of missions, including the Probe of Inflation and Cosmic Origins (PICO) and future SOFIA instruments.

96322	ASTHROS - Astrophysics Stratospheric Telescope for High spectral Resolution Observations at Submillimeter-wavelengths JHU/APL Co-I	This is a Co-I Institution proposal for "ASTHROS - Astrophysics Stratospheric Telescope for High Spectral Resolutions Observations at Submillimeter-wavelengths". We propose a stratospheric balloon mission to enable detailed 3D mapping of ionized gas in star forming regions in the Milky Way via simultaneous observations of the [NII] 122µm (2.46THz) and 205µm (1.46THz) fine structure lines. These observations are critical for understanding the structure and dynamics of ionized gas in star forming regions, the effect of radiative feedback from massive stars on their progenitor cloud, and the energy input of massive stars into the interstellar medium. These processes play a key role in the regulation of star formation in galaxies, which in turn drives galaxy evolution. ASTHROS will be a 2.5m telescope on a long-duration balloon that will produce high spectral resolution, high spatial dynamical range maps of the ionized gas component in a selected sample of Galactic and extra-galactic star forming regions during a flight from Antarctica in 2023. ASTHROS will produce the first high-spectral resolution images of the [NII] 122µm line, which is obscured by the atmosphere even at SOFIA altitudes and can only be observed at balloon altitudes or from space. This line provides an important diagnostic of the ionized gas in star forming regions and together with the [NII] 205µm line can be used to derive the 3D structure of the ionized gas density in star forming regions. Additionally, ASTHROS will have the capability to observe numerous other lines, for example, the HD line at 2.67THz, enabling its observation in a variety of astrophysical environments. ASTHROS is an important step in the path to demonstrate key technology and science applications that are part of future NASA space missions being currently studied, such as the Origins Space Telescope (OST). By providing key information on the process of galaxy evolution and by studying the HD line in a variety of environments, the scientific case for ASTHROS is aligned to NASA's goal in Astrophysics which is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." In particular, the proposed science investigation will help answer the key question "How did we get here?" by exploring the origin and evolution of the galaxies, stars and planets that make up our universe. The ASTHROS team is experienced in balloon flights based on previous work on the STO Antarctic flights. ASTHROS's project manager/technical lead (Jose Siles, JPL), has completed two Antarctic campaigns including STO-2's. System Engineer (Jonathan Kawamura) has also participated in two Antarctic campaigns including STO-1&2. The Deputy PI (Chris Groppi, Arizona State U.) participated in 7 Antarctic Campaigns, again including the STO-1&2 balloons. The gondola manager (Pietro Bernasconi; APL - J. Hopkins U.) delivered the STO-1&2 gondola. ASTHROS will use similar gondola design to STO-2. The ASTHROS instrument consist of 4-pixel receivers in the 1.5 THz & 2.5 THz range based room-temperature frequency multiplied local oscillator sources and cryogenically cooled Hot Electron Bolometer mixers. This receiver technology was successfully flown in HIFI/Herschel and STO-2. Unlike HIFI and STO-2, ASTHROS will fly for the first time a low-power 4K space-compatible cryocooler (available at JPL), which will not require liquid helium. This

		approach is essential for extended lifetime FIR space missions, such as OST, a future NASA PROBE mission, or a SmallSat. We will fly for the first time the CMOS-based System-on-Chip digital spectrometers developed by JPL in collaboration with UCLA. These spectrometers exhibit an order-of-magnitude reduction in dc power consumption compared to the spectrometers flown on STO-2 and used on the SOFIA/GREAT instrument (1W vs. 10W). This technology is also crucial to enable multi-pixel spectral-line imaging terahertz space missions/instruments.

96333	Integrated Silicon Micromachined SIS-Heterodyne Array Instrument at 557 GHz	We propose to develop a highly integrated low power and low-mass 450-570 GHz silicon micromachined 16-pixel SIS-mixer based high-resolution spectrometer. This integrated component development technology at submillimeter wavelengths that will dramatically simplify the fabrication, assembly, and integration of large focal plane arrays. This technology has the potential to significantly increase the pixel count of detector arrays and reduce the mass, volume, and complexity of arrays for a broad range of applications in astrophysics. Since it is getting increasingly difficult to field submillimeter-wave heterodyne array instruments due to the lack large mission opportunities, it is high time we demonstrate the technology viability using SmallSat and CubeSat platforms. Towards that goal, this development will also include a ~15 cm aperture diameter spiral leaky-wave planar metasurface-based antenna with a circular waveguide feed, which can easily be integrated on the sidewalls of a CubeSat or SmallSat. The 16-pixel array spectrometer development includes SIS mixer-based receiver front end, integrated low-loss waveguide switch for differential radiometric calibration, and will use existing CMOS based low-power synthesizer and spectrometer. The scientific importance of high-resolution spectroscopic observations at submillimeter wavelengths is underscored by the key role of heterodyne spectrometers in the ESA cornerstone Herschel Space Observatory as well as the ground-based ALMA and airborne SOFIA. Star formation and key phases of galaxy evolution occur in region enshrouded by dust that obscures them at infrared and optical wavelengths, while the temperature range of the interstellar medium of ten to a few thousand Kelvin in these regions excites a wealth of submillimeter-wave spectral lines. With high-resolution spectroscopy, resolved line profiles reveal the dynamics of star formation, directly revealing details of turbulence, outflows, and core collapse. Observations of emission from ionized species such as water (557 GHz) and carbon (490 GHz) with a high-resolution array instrument with hundreds of pixel will change the way mapping is done for this important species. While the primary motivation to develop multi-pixel array technology arises from the need for future missions to study a wide range of astrophysical topics ranging from planet formation to the large-scale structure of the universe to the monitoring of the earth's atmosphere, this technology effort will also spawn synergistic systems involving other imaging sensors for reconnaissance usage and will help pioneer the emerging uses of the submillimeter-wave spectrum in the homeland security applications. Possible Reviewers: (i) Prof. Philip Mauskopf – Arizona State University (Philip.Mauskopf@asu.edu), (ii) Dr. Sander Weinreb – Caltech (sweinreb@caltech.edu), (iii) Dr. Theodore Reck – Virginia Diodes Inc. (theodore.reck@vadiodes.com), (iv) Dr. Berhanu Bulcha – NASA Goddard Space Flight Center (berhanu.t.bulcha@nasa.gov)

96335	Highly multiplexed acoustic resonator detector arrays (Hi-MARs) for space applications	Advances in detector technologies have time and time again helped us to radically improve our understanding of the Universe. An example of this is seen in the progression of our knowledge of the Cosmic Microwave Background (CMB) through improved detector technology. NASA's Cosmic Background Explorer (COBE) generated the first maps of the CMB, providing evidence for black-body distribution. It also detected several previously unknown far-infrared emitting galaxies. Further detector improvements on Wilkinson Microwave Anisotropy Probe (WMAP, 2001) and ESA's Planck spacecraft (2009) gave increasingly detailed maps of density and distribution of matter in the universe and a higher precision measurement of the age of the universe. The upcoming James Webb Space Telescope will give unprecedented information of the time just after recombination, yielding insights into star and galaxy formation. These improvements in detector technology have proven immanently useful in the fields of astronomy, astrophysics, and cosmology. The vast majority of photons in the universe are in the millimeter and submillimeter wavelength ranges. These photons carry clues to many of our most profound questions set out in NASA's astrophysics roadmap: "Are we alone?," "How did we get here?," and "How does the universe work?" Bolometric detectors remain the state-of-the-art (SOA) for space-based studies, but creating large arrays is challenging with this technology. The NIKA2 Camera installed at Pico Veleta represents the current Earth-based SOA for continuum detector technology, utilizing highly sensitive kinetic inductance detectors (KIDs). KIDs typically give a NEP performance of E-17~E-18 W/√Hz with beneficial multiplexing capabilities, something not possible with the previous SOA bolometric detectors. This capability generates a convenient platform for large arrays of detectors. Ongoing improvements to KIDs are eminent, with SuperSpec KIDs and SRON's SPACEKIDS achieving E-19 W√Hz. While KIDs clearly have offered a path forward towards improved sensitivity with multiplexing capabilities, there are known challenges associated with these detectors. Missions such as Origins Space Telescope (OST) or Large UV/Optical/IR Surveyor (LUVIOR) would benefit from the advancement of an alternative technology to ensure that mission success is not fully reliant on a single technology that is not yet fully developed. An alternative technological solution to highly sensitive Far-IR detection would greatly help mitigate mission risk and offer an independent path to mission success. We propose to implement an array of resonant detectors sensitive to a broad range of spectra from UV to far-IR with ultralow-noise performance with frequency multiplexing capability. The frequency of the detectors shifts proportional to the amount of absorbed radiation power. Each pixel of the detector array is composed of an acoustic resonator with ultra-high quality factor in the order of E5. The pixels exhibit slightly different resonance frequencies defined by optical lithography processes. To improve sensitivity, the temperature coefficient of frequency of these detectors can be engineered to be >100 ppm/K. When operated at typical low temperatures (<300mK) to limit thermal noise, their Qs become even higher generating further improvements in the NEP. Thus,

		depending on the application, they can be cooled to any temperature to meet the science need, with expected achievable NEP values of E-18 W√Hz at 60mK. Nanofabrication and multiplexing allows integration of thousands of pixels to form a large imaging array. These detectors combine the detection principles of resonant bolometers with the frequency multiplexing capabilities of KIDs, generating an independent and alternative detector technology with existing infrastructure.

96337	Superconducting Nanowire Single-Photon Detectors for Exoplanet Spectroscopy in the Mid-Infrared: Phase 2	Superconducting nanowire single-photon detectors (SNSPDs) have emerged as the highest-performing single-photon detectors from the UV to the mid-infrared. These detectors combine very high efficiencies (> 90% in the infrared at 1.55 µm), ultralow jitter (~100 ps or less), zero readout noise, and very low dark count rates (< 10^-4 Hz) . Recently, we have developed SNSPDs operating in the mid-infrared from 2 - 7 µm. Basic models of the physics of the detection process as well as recent experimental results suggest that by tuning the composition of the superconducting alloy, one may be able to demonstrate efficient single-photon detection at wavelengths extending from 2 - 11 µm. In addition, recently-developed multiplexing techniques have now allowed the fabrication of small arrays consisting of 1024 pixels, which could potentially be useful for spectroscopy and imaging. The primary advantages of using SNSPDs in this wavelength range are high stability of detector gain as a function of temperature and bias current, true single-photon sensitivity, zero readout noise, and extremely low dark count rate. In addition, SNSPDs would not suffer from many of the problems inherent with arrays of currently used blocked impurity band (BIB) detectors such as reset anomaly, last-frame effect, droop, drift, multiplexer glow, and latent images. One of the many goals of the Origins Space Telescope (OST) is the study of exoplanets. This study makes up roughly one-third of the science case for OST. In particular, part of OST's mission is the detection of biosignatures such as ozone, nitrous oxide, and methane in the atmospheres of Earth-sized planets transiting the habitable-zones of nearby stars. The spectroscopy of exoplanet atmospheres requires mid-infrared detector arrays combining high stability over time (a few ppm over several hours), high sensitivity (ideally single-photon sensitive), high system efficiency, and low noise. We propose to develop kilopixel-scale arrays consisting of single-photon-sensitive superconducting nanowire detectors that are sensitive in the range of 2.8 - 11 µm wavelengths that would meet the requirements for any future instruments directed towards exoplanet transit spectroscopy, for example the mid-infrared spectrometer and coronagraph (MISC) planned for the Origins Space Telescope. As outlined above, the excellent stability and single-photon sensitivity of these detectors would be ideal for such an application requiring data collection over the course of hundreds of transits of an exoplanet across its parent star, each of which can last several hours or longer.

96338	Precision Imaging Technique to Enable Time-Domain Far-IR Astrophysics	Far-infrared astronomy is on the verge of a revolution in which giant gains in sensitivity will allow unprecedented use of the time domain to reveal the inner workings of protostars, solar systems, and distant galactic nuclei. To do so will require advancement in data analysis methods beyond Herschel and Spitzer as well as careful consideration of observing modes and science traceability — all especially timely as the next far-IR missions are being formulated. The project proposed here pushes the state-of-the-art forward for far-IR imaging, particularly targeting cutting-edge time-domain astrophysics with Origins Space Telescope (OST), and with broader benefits. Specific goals for the research are driven by key questions in far-IR astrophysics for the next decades and the capabilities of future far-IR missions currently under study — OST, the Galaxy Evolution Probe (GEP), and SPICA. Starting from the state-of-the-art established by archival data products from Herschel, Spitzer, and other NASA missions, we propose to achieve improvements in four key aspects of imaging precision by 1—2 orders of magnitude. We highlight three classes of astrophysical objects requiring far-IR observations with exquisite precision on minute to decade timescales. 1) Repeated far-IR observations of protostars surrounded by protoplanetary disks will provide crucial and unique statistical constraint to models of mass assembly and uncover a wealth of phenomena, including instabilities in the accretion disk and Quasi-Periodic Oscillations driven by orbiting mass concentrations. 2) Precise far-IR observations play a key role in determining the sizes and surface properties of Trans-Neptunian Objects (TNOs) — which comprise a reservoir of frozen water and a fossil record of the early Solar System. OST will be competitive with the large ground-based optical survey telescopes of its generation for discovery of TNOs, but unprecedented precision will be needed to detect them amidst the extragalactic background. 3) Far-IR extragalactic surveys with OST, GEP, and SPICA will for the first time determine rates and distributions of far-IR variability among samples of up to 10^8 galaxies, discover classes of highly variable AGN, and use reverberation mapping to characterize nuclear dust distributions at high redshift. Beyond the measurement of flux densities, a substantial improvement to precision has additional benefits to the community using NASA's far-IR data — for example, much better spatial and spectral separation of debris disk emission from stellar photospheric emission. We will also provide quantitative feedback on the observing strategies used on Herschel and Spitzer, looking ahead to OST. Our work on this project follows the example of a past effort by several of us to re-calibrate and re-process Herschel imaging data on Sgr A*. Using several experimental methods beyond the standard pipeline, pioneered by our team, we were able to achieve a factor of 10 improvement in precision and a new science result. For this broader project, we have added personnel with years of experience with the detectors, science data, and pipelines for Spitzer, Herschel, and JCMT submillimeter telescope. We have identified demonstration data sets from Herschel, Spitzer, and SOFIA which we will run through multiple iterations of algorithm development, data processing, and image study, allowing us to test periodically versus project goals.

		We will seek independent feedback on our results and approaches, including peer review and outside conferences and workshops. The main deliverables from this three-year project are: 1) a detailed written description of algorithms, quantitative performance data, and other lessons learned, in the form of a report and technical/science papers; 2) improved science images posted on the public IRSA archive at IPAC. This work has the potential to discover time-domain signals that were hiding in the existing NASA far-IR data archives.

96339	Quantum-limited Amplifiers for Large Array Readout of Superconducting Detectors	We propose to develop broadband, quantum-limited amplifiers based on parametric amplification to enhance the readout of highly multiplexed arrays of Transition Edge Sensor (TES) detectors and Microwave Kinetic Inductance Detectors (MKIDs). A substantial fraction of NASA's portfolio consists of challenging photon-detection applications across the electromagnetic spectrum, for which arrays of cryogenic sensors of either TES or MKIDs are a key enabling technology. However for many important applications, the sensor array is limited by the noise temperature of the follow-on amplifier. In the proposed research effort, we aim to reduce the noise of the follow-on amplifier by a factor of 10-20 relative to the current state-of-the-art, while maintaining the large bandwidth needed for the readout of highly multiplexed arrays. By doing so, we will enhance the capability and increase the scalability of existing low temperature detector technologies in a cost-effective way. Specifically, we will realize novel implementations of kinetic inductance traveling-wave (KIT) parametric amplifiers that explore artificial transmissions, discrete resonator phase matching, microstrip geometries, and 3-wave mixing. In addition, we will develop Josephson junction traveling-wave parametric amplifiers (JTWPAs). For most of these ideas, we have already published encouraging proof-of-principle demonstrations. Our overarching goal is to create an amplifier with noise near the standard quantum limit, greater than 1 GHz bandwidth, greater than 15dB gain, and high saturation power well-suited to the needs of large array detector readout. We will than implement our best performing amplifier in detector readout demonstrations of both TES and MKID arrays with 100s to 1000s of sensors. We focus our efforts on applications in the mm/submm/FIR part of the spectrum. Nevertheless, the proposed quantum-limited amplifiers have application from mm-waves to x-rays. The proposed research effort will enable a broad range of NASA flagship mission concepts including OST, LUVOIR, and Lynx and is also directly applicable to recent probe-class studies the Probe of Inflation and Cosmic Origins (PICO) and the Galaxy Evolution Probe (GEP).

96343	ASTHROS - Astrophysics Stratospheric Telescope for High spectral Resolution Observations at Submillimeter-wavelengths ASU Co-I	This proposal is a co-investigator proposal for the lead proposal "ASTHROS - Astrophysics Stratospheric Telescope for High spectral Resolution Observations at Submillimeter-wavelengths" with PI Jorge Pineda. We propose a stratospheric balloon mission to enable detailed 3D mapping of ionized gas in Galactic and extra-galactic star forming regions via simultaneous observations of the [NII] 122µm (2.46 THz) and 205µm (1.46 THz) fine structure lines. These observations are critical for understanding the structure and dynamics of ionized gas in star forming regions, the effect of radiative feedback from massive stars on their progenitor cloud, and the energy input of massive stars into the interstellar medium. These processes play a key role in the regulation of star formation in galaxies, which in turn drives galaxy evolution. ASTHROS will be a 2.5m telescope on a long-duration balloon that will produce high spectral resolution, high spatial dynamical range maps of the ionized gas component in a selected sample of Galactic and extra-galactic star forming regions during a flight from Antarctica in 2023. ASTHROS will produce the first high-spectral resolution images of the [NII] 122µm line, which is obscured by the atmosphere even at SOFIA altitudes and can only be observed at balloon altitudes or from space. This line provides an important diagnostic of the ionized gas in star forming regions and together with the [NII] 205µm line can be used to derive the 3D structure of the ionized gas density in star forming regions. Additionally, ASTHROS will have the capability to observe numerous other lines, for example, the HD line at 2.67 THz, enabling its observation in a variety of astrophysical environments. ASTHROS is an important step in the path to demonstrate key technology and science applications that are part of future NASA space missions being currently studied, such as the Origins Space Telescope (OST). By providing key information on the process of galaxy evolution and by studying the HD line in a variety of environments, the scientific case for ASTHROS is aligned to NASA's goal in Astrophysics which is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." In particular, the proposed science investigation will help answer the key question – "How did we get here?" - by exploring the origin and evolution of the galaxies, stars and planets that make up our universe. The ASTHROS team is experienced in balloon flights based on previous work on the STO Antarctic flights. ASTHROS's project manager/technical lead (Jose Siles, JPL), has completed two Antarctic campaigns including STO-2's. System Engineer (Jonathan Kawamura) has also participated in two Antarctic campaigns including STO-1&2. The Deputy PI (Chris Groppi, ASU) participated in 7 Antarctic Campaigns, again including the STO-1&2 balloons. The gondola manager (Pietro Bernasconi; APL - J. H. U.) delivered the STO-1&2 gondola. ASTHROS will use similar gondola design to STO-2.

96346	ASTHROS - Astrophysics Stratospheric Telescope for High spectral Resolution Observations at Submillimeter-wavelengths - University of Miami Co-I	This is a Co-I proposal for "ASTHROS - Astrophysics Stratospheric Telescope for High Spectral Resolutions Observations at Submillimeter-wavelengths" We propose a stratospheric balloon mission to enable detailed 3D mapping of ionized gas in Galactic and extra-galactic star forming regions via simultaneous observations of the [NII] 122µm (2.46 THz) and 205µm (1.46 THz) fine structure lines. These observations are critical for understanding the structure and dynamics of ionized gas in star forming regions, the effect of radiative feedback from massive stars on their progenitor cloud, and the energy input of massive stars into the interstellar medium. These processes play a key role in the regulation of star formation in galaxies, which in turn drives galaxy evolution. ASTHROS will be a 2.5m telescope on a long-duration balloon that will produce high spectral resolution, high spatial dynamical range maps of the ionized gas component in a selected sample of Galactic and extra-galactic star forming regions during a flight from Antarctica in 2023. ASTHROS will produce the first high-spectral resolution images of the [NII] 122µm line, which is obscured by the atmosphere even at SOFIA altitudes and can only be observed at balloon altitudes or from space. This line provides an important diagnostic of the ionized gas in star forming regions and together with the [NII] 205µm line can be used to derive the 3D structure of the ionized gas density in star forming regions. Additionally, ASTHROS will have the capability to observe numerous other lines, for example, the HD line at 2.67 THz, enabling its observation in a variety of astrophysical environments. ASTHROS is an important step in the path to demonstrate key technology and science applications that are part of future NASA space missions being currently studied, such as the Origins Space Telescope (OST). By providing key information on the process of galaxy evolution and by studying the HD line in a variety of environments, the scientific case for ASTHROS is aligned to NASA's goal in Astrophysics which is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." In particular, the proposed science investigation will help answer the key question – "How did we get here?" - by exploring the origin and evolution of the galaxies, stars and planets that make up our universe. The ASTHROS team is experienced in balloon flights based on previous work on the STO Antarctic flights. ASTHROS's project manager/technical lead (Jose Siles, JPL), has completed two Antarctic campaigns including STO-2's. System Engineer (Jonathan Kawamura) has also participated in two Antarctic campaigns including STO-1&2. The Deputy PI (Chris Groppi, ASU) participated in 7 Antarctic Campaigns, again including the STO-1&2 balloons. The gondola manager (Pietro Bernasconi; APL - J. H. U.) delivered the STO-1&2 gondola. ASTHROS will use similar gondola design to STO-2. The ASTHROS instrument consist of 4-pixel receivers in the 1.5 THz & 2.5 THz range based room-temperature frequency multiplied local oscillator sources and cryogenically cooled Hot Electron Bolometer mixers. This receiver technology was successfully flown in HIFI/Herschel and STO-2. Unlike HIFI and STO-2, ASTHROS will fly for the first time a low-power 4K space-compatible cryo-cooler (available at JPL), which will not require

		liquid helium. This approach is essential for extended lifetime FIR space missions, such as OST, a future NASA PROBE mission, or a SmallSat. We will fly for the first time the CMOS-based System-on-Chip digital spectrometers developed by JPL in collaboration with UCLA. These spectrometers exhibit an order-of-magnitude reduction in dc power consumption compared to the spectrometers flown on STO-2 and used on the SOFIA/GREAT instrument (1 W vs. 10 W). This technology is also crucial to enable multi-pixel spectral-line imaging terahertz space missions/instruments.

96347	ASTHROS - Astrophysics Stratospheric Telescope for High spectral Resolution Observations at Submillimeter-wavelengths	This is the lead proposal for "ASTHROS - Astrophysics Stratospheric Telescope for High Spectral Resolutions Observations at Submillimeter-wavelengths". We propose a stratospheric balloon mission to enable detailed 3D mapping of ionized gas in Galactic and extra-galactic star forming regions via simultaneous observations of the [NII] 122µm (2.46 THz) and 205µm (1.46 THz) fine structure lines. These observations are critical for understanding the structure and dynamics of ionized gas in star forming regions, the effect of radiative feedback from massive stars on their progenitor cloud, and the energy input of massive stars into the interstellar medium. These processes play a key role in the regulation of star formation in galaxies, which in turn drives galaxy evolution. ASTHROS will be a 2.5m telescope on a long-duration balloon that will produce high spectral resolution, high spatial dynamical range maps of the ionized gas component in a selected sample of Galactic and extra-galactic star forming regions during a flight from Antarctica in 2023. ASTHROS will produce the first high-spectral resolution images of the [NII] 122µm line, which is obscured by the atmosphere even at SOFIA altitudes and can only be observed at balloon altitudes or from space. This line provides an important diagnostic of the ionized gas in star forming regions and together with the [NII] 205µm line can be used to derive the 3D structure of the ionized gas density in star forming regions. Additionally, ASTHROS will have the capability to observe numerous other lines, for example, the HD line at 2.67 THz, enabling its observation in a variety of astrophysical environments. ASTHROS is an important step in the path to demonstrate key technology and science applications that are part of future NASA space missions being currently studied, such as the Origins Space Telescope (OST). By providing key information on the process of galaxy evolution and by studying the HD line in a variety of environments, the scientific case for ASTHROS is aligned to NASA's goal in Astrophysics which is to "Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars." In particular, the proposed science investigation will help answer the key question – "How did we get here?" - by exploring the origin and evolution of the galaxies, stars and planets that make up our universe. The ASTHROS team is experienced in balloon flights based on previous work on the STO Antarctic flights. ASTHROS's project manager/technical lead (Jose Siles, JPL), has completed two Antarctic campaigns including STO-2's. System Engineer (Jonathan Kawamura) has also participated in two Antarctic campaigns including STO-1&2. The Deputy PI (Chris Groppi, ASU) participated in 7 Antarctic Campaigns, again including the STO-1&2 balloons. The gondola manager (Pietro Bernasconi; APL - J.H.U.) delivered the STO-1&2 gondola. ASTHROS will use similar gondola design to STO-2. The ASTHROS instrument consist of 4-pixel receivers in the 1.5 THz & 2.5 THz range based on room-temperature frequency multiplied local oscillator sources and cryogenically cooled Hot Electron Bolometer mixers. This receiver technology was successfully flown in HIFI/Herschel and STO-2. Unlike HIFI and STO-2, ASTHROS will fly for the first time a low-power 4K space-compatible cryo-cooler (available at JPL), which will not require

		liquid helium. This approach is essential for extended lifetime FIR space missions, such as OST, a future NASA PROBE mission, or a SmallSat. We will fly for the first time the CMOS-based System-on-Chip digital spectrometers developed by JPL in collaboration with UCLA. These spectrometers exhibit an order-of-magnitude reduction in dc power consumption compared to the spectrometers flown on STO-2 and used on the SOFIA/GREAT instrument (1 W vs. 10 W). This technology is also crucial to enable multi-pixel spectral-line imaging terahertz space missions/instruments.

96361	Stacked Wafer-Bonded Gradient Index Silicon Optics with Integral Antireflection Treatment	A wide range of applications in submillimeter and millimeter wavelength astronomy, on the ground and in space, would benefit from silicon optics with broadband antireflection treatment. Silicon's high refractive index and low loss make it an ideal optical material at these wavelengths. It is even possible to use silicon for ambient temperature vacuum windows. Antireflection treatment of silicon optics is essential, however, and has proven a major challenge for the 150 mm to 1000 mm diameter optics required for current and future applications. Moreover, multilayer antireflection treatments are necessary for wide spectral bandwidths, with wider bandwidths requiring more layers. It is difficult to find low loss dielectrics with the correct refractive index and other properties to match silicon well, especially if more than one layer is required. Textured surfaces are an attractive alternative to dielectric antireflection coatings. This approach has been most successfully applied for silicon lenses in the ACTpol experiment at mm wavelengths using a dicing saw to cut a two-layer AR structure that gave a < -23 dB reflection intensity over a spectral bandwidth of 1.3:1. The same group has an unpublished prototype of a 5-layer structure. Others have used the dicing saw approach to produce smooth-sided pyramids. Laser machining has also been applied to produce circular holes, sharp cones, concentric circular grooves, and pyramids. Extending to submm wavelengths and increasing the bandwidth requires finer and more accurate features than conventional machining, and perhaps laser machining, can produce. Depth control is also a challenge for laser machining. An alternative is to use a photolithographic fabrication process to etch features onto the silicon's surface. Deep reactive ion etching (DRIE) is a mature micromachining technique that can create deep features (up to 30:1 in aspect ratio) in arbitrary patterns, and it was previously used in demonstrations of flat single-layer coatings at THz frequencies. We have extended this approach on flat surfaces using a unique, multi-depth DRIE technique. We have published excellent results on a two-layer, 1.6:1 bandwidth AR structure patterned using multi-depth DRIE. This is the first *optical* demonstration of an *etched*, two-layer structure of which we are aware. We are fabricating a four-layer structure with an expected 4:1 bandwidth, incorporating wafer-bonding to assemble the AR structure, and our approach is scalable to a bandwidth of 6:1 with a 7-layer structure. Here, we propose to build on this work to realize powered optics with such integral AR structures. To circumvent applying the above process to a curved surface, or to slumping a flat structure onto a curved surface, we will *construct* a silicon optic by stacking flat patterned wafers. The starting point is a multilayer optical design incorporating both an axial gradient in the refractive index for antireflection and a radial index gradient for focusing. For each optical layer, we will use a radially varying hole pattern to achieve the required effective index of refraction. Using our multi-depth DRIE process, we will fabricate multiple layers of the optical structure on each individual flat wafer. Using our demonstrated wafer-bonding technique, we will stack several of these wafers and bond them together to produce the completed optic. Our experience so far with flat AR structures provides

		positive evidence this approach will work. The estimated costs for "production mode" are reasonable. We are in the midst of producing a first-generation gradient index optic. We will add to this proof-of-principle optic design AR structures and then extend the approach to larger bandwidths, building on the demonstrated flat, wide-bandwidth AR structures. The work will culminate with a demonstration optic having a 6:1 bandwidth, 100 mm in diameter. This work will advance the TRL from 2 to 4.

96363	COronal Diagnostic EXperiment (CODEX) - CSR	NASA Goddard Space Flight Center (GSFC), in collaboration with the Korea Astronomy and Space Science Institute (KASI) plans to develop a coronagraph and to install it on the International Space Station (ISS). The primary goal of CODEX is to Understand the physical conditions in the solar wind acceleration region. Solar wind source and acceleration models are highly under constrained due to current data limitations. CODEX will provide the first global, comprehensive data sets allowing us to provide these crucial constraints on a daily basis, and answer targeted essential questions such as: Are there signatures of hot plasma released into the solar wind from previously closed fields? What are the velocities and temperatures of the density structures that are observed so ubiquitously within streamers and coronal holes? The coronagraph is externally occulted with a field of view from ~3-10 solar radii ($R_\odot$), simultaneously covering all latitudes. The observation wavelength is ~400 nm. As demonstrated at total solar eclipse opportunities, photometric filter ratio observations around this band enable the estimation of the 2D electron temperature and electron velocity distribution in the corona. This will be the first time electron density, temperature, and velocity have been measured simultaneously for this field-of-view, and we will do it globally for 6 months! This regular, systematic, comprehensive dataset will test all theories of solar wind acceleration and source region as well as serve to validate and improve space-weather/operational models in the crucial source region of the solar wind. The coronagraph consists of an optical assembly, an external and internal occulter, a polarization camera, command and data handling electronics and a pointing system (gimbals, sun sensor, gyroscopes, drive electronics). The coronagraph itself will have only three mechanisms: an aperture door, filter-wheel rotator, and a launch latch. The polarization camera utilizes a grid directly in front of the detector that eliminates the need for a polarization wheel mechanism and enables obtaining images in close temporal proximity as required for the filter-ratio technique. This proposal will exploit the expertise at GSFC, Wallops Flight Facility, and KASI. The proposal team has extensive experience in coronagraphy, ISS payloads, and solar wind studies and hence is well suited to successfully complete the proposed work. CODEX directly builds upon the Balloon-borne Investigation of the Temperature and Speed of Electrons in the Corona (BITSE), a NASA scientific balloon technology demonstration mission currently under development by the same proposal team and expected to fly for ~8 hours from Ft. Sumner, NM in September 2019. Although BITSE and ground-based eclipses provide some insight, such investigations are too short in duration and limited by sky brightness to obtain all the data needed to achieve CODEX's science objectives. The remote-sensing data from the CODEX mission will augment the in situ and remote sensing measurements from the Parker Solar Probe and Solar Orbiter. The CODEX mission will also exploit the synergy with the currently operating NASA missions such as SOHO, STEREO, and SDO to enhance the science return by combining coronal imagery in overlapping fields of view. Data returned from CODEX will be deposited in the Solar Data Analysis

		Center web site, a publicly accessible NASA repository. CODEX is highly relevant to the HTIDeS program. The proposed mission is a complete investigation including payload development, instrument calibration, launch, and data analysis. The proposed project offers well-defined technology and science breakthroughs. CODEX's origins of the solar wind investigation will help achieve Strategic Objective 1.1 of the NASA Strategic Plan 2018: "Understand the Sun, Earth, Solar System, and Universe," in particular, the core context of "Discovering the Secrets of the Universe."

96364	Dione: A pathfinder mission for understanding the Ionosphere-Thermosphere responses to magnetospheric forcing	Advances toward deploying the highly capable 6U cubesat, along with the culmination of our team's miniaturized particle and field sensor development efforts offers the most efficient, cost-effective approach to addressing one of the most urgent questions in Geospace science today: How, and where is energy transmitted between the magnetosphere and ionosphere? Just like the ancient Greek goddess Dione that presided over the oracle, the mission Dione will demonstrate with a comprehensive sensor package in a low cost, flexible assembly a path for better specification and prediction of Ionosphere-Thermosphere (IT) responses to geomagnetic phenomena. Dione's sensor package includes four instruments: a miniaturized fluxgate magnetometer system that will provide science-grade magnetic field measurements with two sensor heads, GRIDS that will measure vector plasma drifts and deduce the in-situ E-fields, DESA (Dual ElectroStatic Analyser) that will measure precipitating particles as well as upgoing secondary electrons, and NMS (Neutral Mass Spectrometer) measuring total neutral density and composition. Dione will be 3-axis stabilized in a circular LEO, high-inclination orbit, traversing the auroral precipitation and high latitude currents in every orbit. Dione will use the design of the 6U Dellingr bus, which was developed at NASA GSFC, and which is scheduled for flight in August 2017. The primary science objective is to quantify how the ionosphere and thermosphere respond to electromagnetic and kinetic energy inputs from the magnetosphere. This energy input is a key parameter in all physics-based models of the IT system and has long been identified as one of the parameters with the largest uncertainties. Dione will, for the first time since the DE2 mission, provide simultaneous measurements of energy input and IT responses. The energy inputs will be quantified as Poynting flux and electron fluxes, while the IT responses will be quantified as ion drifts and temperatures and neutral density and composition. Dione will provide in situ measurements and through its precession will sample all local times and latitudes and under various geomagnetic conditions. Dione will also establish conjunction passes over key ground instrumentation, specifically auroral imagers and radars, and use conjunction observations to study theories of magnetosphere-ionosphere coupling and IT heating. We will use global MHD models, kinetic models of precipitating electron fluxes, and models of ionospheric conductivity to understand how the incoming electron fluxes and Poynting flux heat the upper atmosphere and result in the observed aurora and neutral heating. Dione targets the community's need to understand how energy is coupled from the magnetosphere down to the ionosphere and thence into the neutral thermosphere, a focus of the 2012 Heliophysics Decadal Survey, and also addresses aspects of the objectives in future NASA strategic missions DYNAMIC and GDC.

96293	Quantifying Uncertainty and Kinematics of Earthquake Systems (QUAKES-A) Analytic Center Framework	We propose to develop an analytic center framework for creating a uniform crustal deformation reference model for the active plate margin of California by fusing InSAR, topographic, and GNSS geodetic imaging data. We will quantify uncertainties for the reference model, which can serve to improve earthquake forecast models and be used to improve understanding of the physical processes leading to and following earthquakes. Users will be able to access and generate custom crustal deformation products for further analysis. Our approach will be to 1) infuse GNSS network solutions into UAVSAR baseline estimation and extract features from InSAR images, 2) develop cluster analysis to identify crustal blocks and rank active fault systems spatially and temporally, 3) interpolate the analyzed InSAR and GNSS data to provide an adaptively sampled deformation field, and 4) assimilate and correlate the crustal deformation products into geodetic/seismicity-based earthquake forecasts and test against past data. All tools and products will be open source (Apache Software License, version 2) and available through geospatial web map services. The key technical challenge will be harmonizing data products with widely varying spatial and temporal resolutions that provide one or more components of the 3D time-dependent deformation field and have unique error sources and intrinsically different accuracies. Spatial resolutions range from cm to sub-meter for topography, ~10 m for airborne InSAR (UAVSAR), ~100m spaceborne InSAR, and ~10 km for GNSS. Temporal sampling can range from minutes (GNSS) to weekly, monthly, or yearly for the other geodetic imaging techniques. Processing assumptions can weaken solutions that would be strengthened using knowledge from other data types. For example, repeat pass interferometry requires an estimation of the position of the instrument at each pass and tectonic deformation can add error to baseline estimation if not properly incorporated. Error sources can bias each data set in unique ways and must be understood and accuracies quantified in order to best establish a gridded crustal deformation model that is dense in areas of rapid changes and sparse where little changes occur. Our project is divided into three main tasks: 1) Data fusion and uncertainty quantification, 2) Data management and geospatial information services (the analytic center framework) and 3) collaboration and infusion into target communities. This work is directly relevant to NASA's Earth Surface and Interior program and adds value to NASA supported GNSS and UAVSAR results. It is also relevant to the NISAR mission scheduled for launch in early 2022. Products from this project can serve to validate NISAR and methodologies developed here can be applied to NISAR data when the mission is operational. The earthquake geophysics community will benefit the most from this work, followed by disaster responders. Target users for earthquake geophysics are the multi-institutional Southern California Earthquake Center community and the US Geological Survey. Target applications communities are the Federal Emergency Management Agency (FEMA), State of California Office of Emergency Services, and local California jurisdictions.

96294	Supporting Shellfish Aquaculture in the Chesapeake Bay using Artificial Intelligence to Detect Poor Water Quality through Sampling and Remote Sensing	Aquaculture in the Chesapeake Bay and around the world is the fastest growing food-producing sector, now accounting for almost 50% of the world's fish harvest according to the FAO. Yet waterways face increasing pressures as the world's population grows near the coasts and extreme weather leads to greater run-off from land. Pollutants such as agricultural fertilizers, livestock waste, and overflowing sewage make their way into streams and rivers, with detrimental impacts on water quality in the Bay and elsewhere [e.g. 2019 Chesapeake Bay Foundation Report Card; MD DNR, 2019; Schollaert Uz et al., 2019]. Responsible management of aquaculture requires access to reliable information on a variety of environmental factors that are not currently available at optimal scales in space and time. To address this challenge, we propose to expand the use of Earth observations from satellites and other data sets by using an Analytic Center Framework (ACF) Artificial Intelligence (AI) tool to improve efficiencies in managing diverse environmental datasets. Computationally-intensive AI algorithms trained with many sources of observations have potential to detect patterns of poor water quality not previously possible through traditional techniques. Our team of experts in remote sensing, aquatic ecology and biogeochemistry, along with Maryland Department of the Environment (MDE) shellfish regulators, has been conducting a scoping study of this problem since last fall in search of optical signatures in the water around leaking septic systems. We have been collecting and analyzing biological, chemical, and physical variables in and above the water at target sites and in the lab. Although toxins that typically cause shellfish bed closures are not discernable by traditional multispectral techniques, we are looking for hyperspectral proxies covarying with such toxins. One promising result of our pilot study has been the detection of a shifted fluorescence emission from dissolved organic matter along with emission by phycoerythrin pigments associated with high fecal coliform counts. Now we propose to team up with computer scientists to apply an AI model to this problem, using datasets collected monthly at 800 sites around the Bay for decades, in combination with remotely sensed satellite and aerial data during targeted field work to support an applied research need to more effectively and rapidly sort through disparate data sets to identify areas of poor water quality resulting in shellfish bed closure. While this project is a proof-of-concept in the well-sampled Chesapeake Bay, the long-term goal is for a global application on a satellite platform. This is aligned with several goals of NASA for this decade, namely through the development of applications that contribute to managing water quality, one of the essential but overlooked elements of regional and local sustainable water resources management. This proposal is relevant to the AIST Program Element by integrating previously unlinked datasets and tools into a common platform to address this previously intractable science problem.

96295	A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design	Observing System Simulation Experiments (OSSE's) are used to design mission and instrument constellations and evaluate the science return. A critical component in this process is the simulation of both measurements and retrievals, and the assessment of candidate measurement configurations. The trade space that consists of all possible instrument and spacecraft configurations has expanded tremendously with the recent miniaturization of instruments, and the rise of small-sat (and cube-sat) technology. An exhaustive search through all possible instrument configurations is computationally infeasible with our current tools and infrastructure. Our approach allows quantification of elements in a science and applications traceability matrix (SATM), making it distinct from other mission design toolkits. We propose to develop a fast-turnaround, scalable OSSE Toolkit that can support both rapid and thorough exploration of the trade space of possible instrument configurations, with full assessment of the science fidelity. The capability to rapidly explore various instrument configurations is enabled through the use of both lower fidelity and state-of-the-art simulators and radiative transfer codes, along with a scalable parallel computing framework utilizing the Apache PySpark (Map-Reduce analytics) and xarray/dask technologies. The toolkit will automate the entire mission simulation workflow and scale to large analyses by parallelizing many operations, including the search of the parameter space by an ensemble of runs (30 to 1000x speedups), using cluster computing either on-premise or in the Cloud. The toolkit will consist of: - An Apache Spark & xarray Map-Reduce compute framework with pluggable modules in the form of Docker containers for measurement and retrieval simulation, with the flexibility to plug in other instrument simulators and retrieval codes - A scalable system, tested in the cloud, capable of examining large numbers of potential measurement configurations with the Map/Reduce framework - A front end GUI for easy configuration, plotting, and computation of statistics, and a set of "live" python Notebooks that use JupyterLab and Jupyter Hub, a Python client library, and a web services API. - A Knowledge Base (ElasticSearch JSON doc database) set up to track the simulations performed to facilitate rapid exploration of simulation results and ensure reproducibility The target application is quantitative evaluation of science return from candidate measurements made in the Decadal Survey Aerosols, Clouds, Convection, and Precipitation (A-CCP) mission. In our OSSE workflow, many instrument configurations are simulated in parallel (the Map step), including measurements (e.g., from spaceborne radar) and retrievals (e.g., ice water path and precipitation content profile). Then metrics are aggregated that allow quantitative comparison of the possible configurations (the Reduce step). The majority of the computational work is highly parallelizable by segmenting over time (each instrument view) and the ensemble of parallel runs needed to search and characterize the mission parameter space to evaluate tradeoffs. We utilize instrument simulators that have already been packaged for use within virtual machines, and as such are already capable of running on the Cloud. Our toolkit will enable a breakthrough in the number and fidelity of

		mission simulations undertaken by: automating the entire pipeline, parallelizing many of the steps, and providing fast turnaround for iterative exploration.

96296	Development of the High Performance Version of GEOS-Chem (GCHP) to enable broad community access to high-resolution atmospheric chemistry modeling in support of NASA Earth Science	Global modeling of atmospheric chemistry is a grand scientific and computational challenge because of the need to simulate large coupled systems of order ~100-1000 chemical and aerosol species interacting with transport on all scales. Atmospheric chemistry models must be integrated online into Earth system models (ESMs) to address a range of fundamental Earth Science questions but must also be able to operate offline, where the chemical continuity equations are solved using meteorological data as input. The offline approach has advantages of simplicity, accessibility, reproducibility, and application to inverse modeling. It is thus highly attractive to atmospheric chemistry researchers. The GEOS-Chem global 3-D model of atmospheric chemistry, developed and managed with NASA support, is used offline by hundreds of research groups worldwide with meteorological fields from the NASA Goddard Earth Observing System (GEOS), and the exact same model also operates online as a chemical module within the GEOS ESM at the NASA Global Modeling and Assimilation Office (GMAO). Through partnership with GMAO, we have recently developed a high-performance version of GEOS-Chem (GCHP) using the Earth System Modeling Framework (ESMF) in its Modeling Analysis and Prediction Layer (MAPL) implementation, that permits GEOS-Chem to operate offline in a distributed-memory framework for massive parallelization consistent with the NASA GEOS system. GCHP allows GEOS-Chem to exploit the native GEOS cubed-sphere grid for greater accuracy and computational efficiency. Global simulations of stratosphere–troposphere oxidant–aerosol chemistry at very high resolution such as cubed-sphere C720 (∼12 km) become feasible. Here we solicit support from AIST to make this high-performance version of GEOS-Chem highly accessible by the atmospheric chemistry community in sustained partnership with GMAO. This will allow the atmospheric chemistry community to better exploit the GEOS system through the use of GEOS-Chem, and to advance atmospheric chemistry knowledge for the benefit of the GEOS system and NASA's mission. Specifically, we propose to: 1) Update to current version of MAPL and enable seamless updates to benefit from future software engineering advances at GMAO for ESM coupling and data transfer, and to contribute MAPL enhancements produced by the GEOS-Chem community for atmospheric chemistry applications. MAPL developments at GMAO will increase GCHP functionality and capabilities, such as the use of stretched-grid simulations. 2) Improve GCHP performance and portability to promote usage across the large GEOS-Chem community and beyond. This effort includes (a) fully parallelizing the model to remove current bottlenecks, thus enabling finer resolution simulations that better emulate the GEOS system, (b) improving the build system and using software containers to facilitate access and ease model configuration, and (c) supporting a mature multi-node capability on the Amazon cloud. 3) Generate an operational cubed-sphere archive of GEOS assimilated meteorological data for driving GCHP. This task will increase accuracy in modeling transport and will provide a better foundation for collaboration between the GEOS-Chem community and GMAO. This project will greatly increase the accessibility and value of NASA

		GEOS products and GEOS-Chem to the atmospheric chemistry community worldwide, from academic researchers to air quality managers and policy analysts. It will not only exploit NASA's investment in atmospheric modeling to benefit the atmospheric chemistry community, but also engage that community in long-term partnership with GMAO to advance atmospheric chemistry within the NASA Earth modeling and data assimilation system. Thus, this project is at the core of NASA's ACF mission to develop powerful, re-usable tools to support scientific analysis of large volumes of data, often from disparate sources, as needed by the Earth Science Division in the 5-20 year timeframe.

	96297	Valid time-series analyses of satellite data to obtain statistical inference about spatiotemporal trends at global scales	(a) Objectives and Benefits As remote sensing has matured, there is a growing number of datasets that have both broad spatial extent and repeated observations over decades. These datasets provide unprecedented ability to detect broad-scale changes in the world through time, and to forecast changes into the future. However, rigorously testing for patterns in these datasets, and confidently making forecasts, require a solid statistical foundation that is currently missing. The challenge presented by remotely sensed data is the same as its remarkable value: remotely sensed datasets consist of potentially millions of time series that are non-randomly distributed in space. We propose to develop new statistical tools to analyze large, remotely sensed datasets that will give statistical rigor to conclusions about patterns of change and statistical confidence to forecasts of future change. Our focus is providing statistical tests for regional-scale hypotheses using pixel-scale data, thereby harnessing the statistical power contained within all of the information in remotely sensed time series. (b) Proposed Work and Methodology We will develop both a framework and software tools for incorporating spatial correlation (non-independence) into analyses of remotely sensed time-series data. Our framework will apply to different types of time-series models that are currently used to analyze pixel-level or small-scale data including continuous changes (e.g., directional trends) and abrupt changes (e.g., breakpoint analyses). Specifically, we will address: i. Patterns in annual trends in time series. Our tools will identify where there are significant time trends. ii. Causes of trends. Our tools will examine which variables explain observed changes best (e.g., climate, elevation, human population, etc.). iii. Within-year patterns of seasonal trends and phenological events. Forecasts for future change are only useful if they include an uncertainty in the forecasts. Thus, statistical models are necessary. Our statistical approach is based on models that, once fit to data, can be used for forecasting. These forecasts will use the spatio-temporal correlations estimated from the data and therefore can account implicitly for regional differences in the past time series that are likely to be perpetuated into the future, even if the underlying drivers for these changes are unknown. We will test our algorithms with AVHRR/GIMMS3g, MODIS, AMSR-E, JAXA/JASMES, and Landsat data at global to regional scales to provide a proof-of-concept, demonstrate the feasibility, and highlight the value of our approach to the remote sensing community at large. Our project will make substantial contributions to the AIST Goal of Increasing the Accessibility and Utility of Science Data by providing appropriate statistical tools for large remotely sensed time-series datasets. There are no available, easy-to-apply methods for testing hypotheses explaining regional patterns of past change and predicting future change that can be scaled to the size of remotely sensed datasets. We propose to remedy this, thereby making a major contribution to both remote sensing science and the application of satellite imagery for decision making. Our proposal fits under the AIST Core Topic of Data-Centric Technologies. (c) Period of Performance Our project will span two years. (d) Entry

		and Planned Exit TRL Our proposal will enter at Software TRL 2 and exit at TRL 5.

96298	NASA Evolutionary Programming Analytic Center (NEPAC) for Climate Data Records, Science Products and Models	We propose to develop an Analytic Center Framework (ACF), called the NASA Evolutionary Programming Analytic Center (NEPAC), that will enable scientists and engineers to rapidly formulate algorithms for satellite data products using both satellite and in situ observations. ACFs are one of two primary thrusts of the NASA Advanced Information Systems Technology (AIST) Program. NEPAC's primary scientific goal is to discover and apply new and novel algorithms for ocean chlorophyll a (Chl-a), the key biological state variable for ocean and inland water ecosystem assessment, historically the first-order proxy for phytoplankton biomass estimates (Cullen, 1982) and necessary inputs for contemporary carbon-based productivity estimates (Behrenfeld et al., 2005), making Chl-a observations a critical element for global phytoplankton climate assessment (Behrenfeld, 2014). The ACF will initially focus on generating Chl-a algorithms to target improvement of the uncertainties and for annealing these estimates across multiple Ocean Color (OC) satellite data sets, a needed step for establishing a coherent Chl-a climate data record. Ocean phytoplankton are primary components of the global biogeochemical cycle, generating nearly half of the global atmospheric oxygen supply, and are drivers of the global ocean carbon sequestration processes (Dutkiewicz et al., 2019). The core element for this ACF is a Genetic Programming (GP) application that generates either prognostic equations, such as satellite algorithms, or coupled systems of equations, such as those used in ocean ecosystem models. The proposed design of the ACF's work environment centers on providing ocean scientists, the ACF target community, easy-access through a web-enabled, user-friendly, Graphical User Interface (GUI) to an evolutionary search algorithm toolbox which will connect data and applications to high end computer resources. This GUI-based environment will be the portal through which users will: i) select the independent and dependent variables from relevant satellite and in situ data sets; ii) select the performance metrics from a range of traditional and improved techniques; iii) set the GP application's free parameters and options, and; iv) select the computational infrastructure to which the work will be submitted to. The GUI will operate outside of the high end computational and data storage infrastructure. A set of Application Programming Interfaces (APIs) will be developed, or a pre-existing and compatible one modified, to link the GUI application to the computational infrastructure that will carry out the GP computations using the chosen data sets. The overall technology goal is to enable the ocean science community to use computers to objectively, efficiently and rapidly generate algorithm-based satellite products that will have improved outcomes (lower errors, bias and uncertainty) necessary for answering key science questions regarding the sensitivity of ocean ecology to relevant issues, such as global climate variability. The initial target satellite product for this proposal is Chl-a. However, we, and others, have demonstrated that satellite observations are capable of retrieving pigments (Moisan et al., 2011), phytoplankton functional types (Hirata et al., 2011; Moisan et al., 2017), and primary production estimates (Behrenfeld, 2005), all important

		components for ecosystem and carbon cycle studies. Algorithms for these and other potential satellite products (new production, carbon flux) can also be generated using this ACF. In addition, this ACF will be extensible so that it can support other algorithm development needs within and outside of the NASA community. NEPAC will lead to considerable time and cost savings, and yield improved algorithms that will enable improved science results.

96299	An Analytic Center for Biodiversity and Remote Sensing Data Integration	Novel and rapidly growing biodiversity data streams from a range of sensors and sources now enable a much improved capture of geographic variation in status and trends of biodiversity. The combination of these data with remotely sensed information powerfully extends this assessment into environmental space and, with the right workflows and infrastructure, holds the potential for near real-time monitoring of the biological pulse of our planet. Successful integration needs to account for the differing spatiotemporal resolution and uncertainty in both data as well as biodiversity data biases, and support analysis, visualization and change detection across scales. These complexities require a range of tasks and decisions by scientists and communities who wish to benefit from new opportunities at the interface of biodiversity and remote sensing. The proposed Analytic Center will provide analysis products, visualizations, interactive analytical tools, and guidance, all combined in an online dashboard, that will support a large community of users interested in linking environmental and biodiversity information. This project will leverage prototyped tools developed in a first-phase AIST grant (16-AIST16-0092) and specifically i) improve their technological readiness and usability, ii) add a range of analysis and visualization options, iii) strongly expand the breadth of remote sensing products and pre-annotated biodiversity products, and iv) scale up the on-demand biodiversity-environment annotation service. In-situ biodiversity has intrinsic spatiotemporal grain and associated uncertainty that varies with methodology. The Center will provide this service to a broad community. Specifically, the Center online dashboard will i) allow users to perform a guided selection among a large suite of biodiversity-relevant remote sensing-supported biodiversity layers (including MODIS, Landsat, Sentinel, Airbus One Atlas, and others), ii) access available spatial biodiversity data (ca. 1 billion records) from repositories such as GBIF (publicly shared data), Movebank (movement data), Wildlife Insights (camera-trapping data) and Map of Life (additional data sources and types, including inventories and expert maps) and visually explore these data in multi-dimensional environment space, iii) support decisions around the most appropriate environmental characterization of these data, iv) support user-driven visualizations, reports, and data download, v) provide visual niche data coverage and niche change reporting, and vi) support these same services for user-uploaded data or user-driven annotation algorithms for up to 0.5M points. The proposed platform will fill an important technological gap between biodiversity and remote sensing data and their associated communities. Specifically, it will lower the barrier of entry for the use of remote sensing data for a range of user communities in biodiversity science and conservation and enable them to access, use, and interpret biological signals enriched with remotely sensed environmental data. The proposed Center will provide the thousands of users of GBIF, Movebank, or Wildlife Insights data with the option to work with environmentally enriched biodiversity data or drive custom annotations. The workflows developed under this grant will provide a scalable solution to environmental annotation that is central to species environmental niche

		assessment, distribution modelling, and the development of species population EBV products. Together with additional visual reports this will directly benefit the biodiversity monitoring and assessment community, including GEO BON, and support EBV development and change assessment in Map of Life. The planned entry TRL for this project is 5 and the exit is aimed at TRL 7.

96300	Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals	The central objective of this proposal is to create a terrestrial hydrology mission planning tool to help inform experimental design with relevance to terrestrial snow, soil moisture, and vegetation using passive and active microwave remote sensing, LiDAR remote sensing, passive optical remote sensing, hydrologic modeling, and data assimilation. Accurate estimation of land surface states and fluxes – including soil moisture, snow, vegetation, surface runoff – has been identified as a priority in the most recent decadal survey and can only be viewed globally (in an operational sense) with the use of satellite-based sensors. The development of a simulation tool that can quantify the utility of mission data for research and applications is directly relevant to these planning efforts. Leveraging the existing capabilities of the NASA Land Information System (LIS) and the Tradespace Analysis Tool for Constellations (TAT-C), a comprehensive environment for conducting observing system simulation experiments (OSSEs) will be developed to quantify the added value associated with different sensor and orbital configurations as related to snow, soil moisture, and vegetation and the subsequent hydrologic response of the coupled snow-soil moisture-vegetation system. It will allow for quantitative assessment of different orbital configurations (e.g., polar versus geostationary), number of sensors (e.g., single sensor versus constellation), and the associated costs with installing space-based instrumentation. In addition, the integrated system will provide insights into the advantages (and disadvantages) of different configurations including simultaneous measurements. The goal of the OSSE is to maximize the utility in experimental design in terms of greatest benefit to global, freshwater resource characterization. The integrated system will enable a true end-to-end OSSE that can help to quantify the value of observations based on their utility to science research and applications and to guide mission designs and configurations. Synthetic passive microwave (radiometry), active microwave (RADAR), passive optical (VIS/NIR), and active infrared (LiDAR) observations will be generated to provide information related to the coupled snow-soil moisture-vegetation integration in the terrestrial environment. This suite of synthetic observations will then be assimilated into NASA LIS to systematically assess the added value (or lack thereof) associated with an observation in space and time. Science and mission planning questions addressed as part of this proposal include, but are not limited to: 1. How can sensor viewing be optimized to best capture and characterize the integrated snow-soil moisture-vegetation response? Further, how would the efficacy of these sensors behave during extreme (e.g., flood, drought, rain-on-snow, post-wildfire, atmospheric river) events and non-extreme (e.g., climatological) events? 2. How might observations be coordinated (in space and time) to maximize utility, inform experimental design, and mission planning? 3. What is the added utility associated with an additional observation? Further, what is the marginal gain associated with adaptive (a.k.a., dynamic) viewing relative to a more traditional, fixed (a.k.a., static) viewing strategy? 4. What is the tradeoff space between different mixes of sensor types (i.e., passive MW, RADAR, and LiDAR), swath widths, fields-of-view, and error characteristics that maximizes scientific

		return while minimizing mission cost and mission risk? This project is relevant to several current and planned NASA research interests. This project will leverage a suite of existing NASA data products and models, and therefore, add value to previously incurred costs associated with their development.

96301	AMP: An Automated Metadata Pipeline	A core function of the AIST Analytic Center Framework is to facilitate research and analysis that uses the full spectrum of data products available in archives hosting relevant, publicly available data. Key to this is making data "FAIR" (findable, accessible, interoperable, and reusable), not just for humans, but for automated systems. Effective data discovery services and fully automated, machine-driven transactions require metadata that can be understood by both humans and machines. But such metadata are uncommon. More commonly, metadata records are inadequately contextualized, incomplete, or simply do not exist. When they do exist, they often lack the semantic underpinnings to make them meaningful. The goal of the Automated Metadata Pipeline (AMP) project is to (1) Develop a fully-automated metadata pipeline that integrates machine learning and ontologies to generate syntactically and semantically consistent metadata records that advance FAIR objectives and support Earth science research for a diverse group of stakeholders ranging from scientists to policy makers, and (2) Demonstrate the application of AMP-enhanced data to automate and substantially improve the use and reuse of NASA-hosted data in environmental/Earth systems models in the ARtificial Intelligence for Ecosystem Services (ARIES; Villa et al. 2014) platform, a distributed network of ecosystem services and Earth science models and data that relies on semantics to assemble network-available data and model components into ecosystem services models, built on demand and optimized for the context of application. ARIES is a context-aware modeling system that, given adequate, semantically-grounded metadata, is capable of finding and assessing the suitability of candidate data sets for use with a particular model, and automatically establishing linkages between data sources and model components, performing a variety of mediation and pre-processing tasks to integrate heterogeneous data sets. The AMP project aims to use machine learning techniques to auto-generate semantically consistent, variable-level metadata records for NASA data products and, in collaboration with the ARIES developer and user communities, demonstrate their value in supporting scientific research. In so doing, we hope to achieve several objectives: • Address usability and scalability issues for data providers and metadata curators in connection with tools for generating robust variable-level metadata records; • Improve the semantic interoperability of target NASA data products by linking concepts in AMP-generated metadata records to terms from well-established, external vocabularies such as the Environment Ontology (ENVO), thereby taking advantage of existing term mappings between ENVO and ontologies developed by other communities of practice, including NASA's Semantic Web for Earth and Environment Technology (SWEET) Ontology; • Demonstrate the benefits of semantically interoperable, FAIR data across communities of practice. AMP will provide a platform for auto-generating robust, FAIR-promoting, semantically consistent metadata records using neural nets to assign variables to ontological classes in the AMP Ontology. Our approach recognizes that there is a wealth of information contained within the data itself, which can be exploited to generate accurate and consistent

		metadata. We will work with the Goddard Space Flight Center's (GSFC) Earth Science (GES) Data and Information Services Center (DISC), which will provide access to data via its OPENDAP servers for training and testing the AMP pipeline, and for use by the ARIES platform. AMP advances the Analytic Center Framework objectives of allowing seamless integration of new and user-supplied components and data; increasing research capabilities and speed; handling large volumes of data efficiently; and providing novel data discovery tools.

96302	On-Demand Geospatial Spectroscopy Processing Environment on the Cloud (GeoSPEC)	The 2017-2027 Decadal Survey prioritizes a spaceborne imaging spectrometer to advance the study of Surface Biology and Geology (SBG) globally. It would generate large volumes (~20 TB/day) of high dimensional (>224 bands) data, with a wide range of measurement objectives spanning vegetation, hydrology, geology, and aquatic studies. Many of the observables identified for SBG have been demonstrated using airborne imaging spectroscopy, but there is a potentially very large set of products that may be asked of a mission like SBG, and the algorithms, L1-to-L3+ processing flows, and intermediate products may vary considerably by application. Further, multiple well-vetted algorithms in the processing chain may exist for the same observables (and are ever-improving), and users may wish to tune the retrievals based on parameterizations particular to an application or using constraints from field measurements to improve algorithm performance in localized settings. Because of the demand for products from imaging spectroscopy from a wide range of users as well as the dynamic nature of the algorithms, our basic premise is that in the future science data systems for imaging spectrometer data will differ dramatically from current approaches. We propose an On-Demand Geospatial Spectroscopy Processing Environment on the Cloud (GeoSPEC) as a necessary information technology innovation required to meet the needs of both users and distributors of the products of imaging spectroscopy in the forthcoming era of widespread and possibly global hyperspectral data availability. We will develop the technology using terrestrial vegetation use cases for mapping vegetation foliar traits and fractional cover. We will provide users with options for new atmospheric correction protocols, other corrections (such as BRDF and topography), and options for algorithm selection. GeoSPEC will also include off- and on-ramps in the processing workflow for users to implement their own code or commercial programs on their own systems, thus facilitating flexibility in the application of vetted algorithms for product distribution. The proposed project will leverage existing NASA-funded technologies:EcoSIS for spectral libraries, EcoSML for spectral models, the SWOT/NISAR cloud-based science data system (HySDS), as well as data analysis services (Apache SDAP), interactive visualization and analytics (Common Mapping Client, CMC) and open-source python packages HyTools for hyperspectral processing and ISOFIT for atmospheric correction.The platform will be developed using Level 1 calibrated radiance from two imaging spectrometers with large and diverse data records: NASA AVIRIS-Classic and AVIRIS-NG. Ultimately, development of flexible, on-demand cloud-based processing of hyperspectral imagery- which does not currently exist -will reduce barriers to usage of complex imaging spectroscopy data and its products, such as NASA's vast airborne AVIRIS archives at present, and data from EMIT and HISUI in the near future, and eventually SBG. Finally, there is a large potential user base for the L3+ outputs of SBG-like measurements, which for our use case includes ecologists and ecosystem scientists interested in using the high-level products to predict processes related to carbon uptake and nutrient processing, or to characterize biodiversity based on spatial variation in functional traits. These

		potential users represent a new constituency for imaging spectroscopy data products who previously would not have had access to such measurements across broad spatial and temporal extents. GeoSPEC is a necessary Analytic Center Framework development both for a scientific community wishing to use the high-level products of imaging spectroscopy (we have three letters of endorsement representing Map of Life, distribution modeling, and evolutionary biology) as well as two mission communities (letters from SBG mission study leadership and NEON). GeoSPEC enters at TRL 3 and exits at TRL 5.

96303	Multi-scale Methane Analytic Framework	We propose to mature and integrate methane data analysis capabilities spanning multiple observing systems and spatial scales into an analytic center framework. The Multi-scale Methane Analytic Framework (M2AF) will address the needs of public and private sector stakeholders for improved decision support and also help the science community fully exploit emerging and planned airborne and space-based methane observations. We will develop an analytic center framework that: 1. Provides workflow optimization and management tools that help methane science investigations and applications proceed in an efficient (low latency) and repeatable manner. 2. Provides analytic tools to characterize methane fluxes and the physical processes that control them. 3. Facilitates data search and discovery relevant to specific methane science investigations and applications from diverse data sets. 4. Leverages our prototype methane data portal to provide collaborative, web-based tools for enabling scientific discussion and application of data analysis and modeling results. This framework will significantly mature and integrate component capabilities we developed under previous and ongoing methane projects including NASA's Carbon Monitoring System (CMS) program (Jacob-2013, 2016, Duren-2012, 2015) and ACCESS Methane Source Finder project, the interagency California Methane Survey project (CARB/CEC/NASA funded), and the interagency Megacities Carbon Project (NIST, NASA, NOAA, CARB funded). Those capabilities currently involve primarily standalone experimental demonstrations with surface, airborne and satellite observations (TRL 3-4) and uncoordinated data processing and modeling systems. We assess the TRL levels of these capabilities to be mostly in the TRL 3-4 range, with some (data portal) in the TRL-5 range. We propose to further develop and mature these capabilities (with additional testing with airborne and satellite observations) with input from our technology recipients, achieving exit TRLs in the 5-6 range.

96304	Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS	Objectives and benefits: Snow is a critical component of the natural earth system and it has significant socio-economic effects. Snow provides a natural reservoir for water resources that billions of people rely on; it is a key link between the global energy and water cycles; it plays a major role in both plant and animal habitats; it has the power to shut down economic activity; and yet it also provides the foundation for a massive recreation industry. While the importance of snow is often considered on regional to global scales, one of the most important horizontal length scales for snow processes can only be represented with model grid spacings of 100 meters or less. The snow science community has made great advances in understanding and representing these critical scales in small scale snow models; however, the software infrastructure does not yet exist to perform such fine spatial resolution simulations on continental scales. This presents a significant constraint on NASA when planning and operating future snow science missions. The snow community has determined that the optimal future snow product must combine modeling with remote sensing, and to achieve this it must be possible to perform simulations on approximately a 100-meter grid while representing the processes that operate on that scale, e.g. preferential deposition, snow redistribution, enhanced radiation load. The goal of this proposed project is to improve NASA's capability to plan and operate a future snow mission by coupling an advanced snow modeling system (SnowModel) into NASA's Land Information System Framework (NASA-LISF). This work will provide the tools necessary to plan and operate a more cost-effective snow mission, yielding better snow products for the research and applications communities. Proposed work and approach: We propose to increase the readiness of NASA's snow modeling capability by extending the LISF to include an explicit representation of spatial variability (LISF-SnowModel). The specific work elements in the proposal are: (1) Incorporate and enhance fine scale wind field and precipitation modifications from SnowModel's MicroMet tool into the NASA-LISF forcing engine. (2) Couple SnowModel's snowpack and snow redistribution components into LISF and the Noah-MP land surface model in LISF. (3) Improve the computational infrastructure supporting LISF-SnowModel to provide parallel performance sufficient to run continental domain simulations at snowdrift resolving scales (100-m). This includes coupling snow transport processes represented in SnowModel with the MPI communications in LISF. (4) Perform a mission trade-off analysis based on high-resolution continental scale SnowModel simulations within LISF-SnowModel. Period of performance: December 1st 2019 – November 30th 2021. Technical Readiness Level Advancement: Entry TRL: 2; Exit TRL: 5.

96305	Cloud-based Analytic Framework for Precipitation Research (CAPRi)	Researchers at the University of Alabama in Huntsville (UAH) Information Technology and Systems Center (ITSC) and Earth Systems Science Center (ESSC), in collaboration with NASA Marshall Space Flight Center (NASA/MSFC), propose to leverage cloud-native technologies explored in the AIST-2016 VISAGE (Visualization for Integrated Satellite, Airborne and Ground-based data Exploration) project to develop a Cloud-based Analytic framework for Precipitation Research (CAPRi). CAPRi will host Global Precipitation Measurement Validation Network (GPM-VN) data integrated with a Deep Learning framework to provide an analysis-optimized cloud data store and access via on-demand cloud-based serverless tools. CAPRi services will automate the generation of large volumes of high-quality training data for successful deployment of Deep Learning models. The research focus will be to develop a Deep Learning application to enhance the resolution of GPM data for improved identification of convective scale precipitation features, particularly outside the range of ground-based weather radar. This resolution enhancement technology is called super-resolution or downscaling. Deep Learning Convolutional Neural Networks (CNNs) will be used to learn features that can infer high-resolution information from low-resolution variables, building on a prototype developed by the PI of this proposal in collaboration with GPM mission scientists. The research focus addresses NASA AIST program's Analytic Center Framework (ACF) thrust Water and Energy Cycle domain. To conduct this research, we have assembled a multi-disciplinary team that includes leaders in Machine Learning/Deep Learning, atmospheric/earth science, precipitation, data analytics, remote sensing, and information technology: PI Dr. John Beck (UAH/ITSC), Deep Learning and remote sensing lead; Co-I Dr. Patrick Gatlin (NASA/MSFC), precipitation science and GPM GV subject matter expert; Co-I Mr. Todd Berendes (UAH/ITSC), GPM VN network and cloud-based tools and analytics lead; Co-I Dr. Geoffrey Stano (UAH/ITSC) atmospheric science and information technology; Co-I Ms. Anita LeRoy (UAH/ESSC) precipitation features subject matter expert (SME); and collaborator Dr. Walt Petersen (NASA/MSFC), GPM subject matter expert. The GPM-VN, having already identified and extracted coincident low-resolution satellite radar and high-resolution ground radar observations of a variety of precipitation events, provides an ideal source of training and test data for this proposal. We propose to develop cloud-based tools within CAPRi to automate the development of this type of training data directly from the VN and results will be used within an extended CNN architecture to downscale the spatial resolution of satellite-based GPM DPR precipitation products from ~5km to ~1km radar resolution and thus advance precipitation measurements from space. CAPRi will simplify the access to and the processing of these data, leading to practical applicability of these techniques to improve rainfall retrieval estimates from GPM DPR data in areas where ground-based scanning radar data and reliable precipitation gauge observations are lacking. As a science use test case, CAPRi will be used to develop a precipitation features demonstration database to support the precipitation science community. In prior research, Co-I LeRoy developed a method to identify convective

		scale precipitation features from a larger scale precipitation features database (developed at the University of Utah). This research will be expanded to identify 3D convective scale precipitation features in the GPM era, leveraging the VN database of precipitation observations from GPM including super-resolution GPM data to improve the identification and refine the scale of 3D precipitation features beyond the scope of the VN.

96306	Creation of a Wildland Fire Analysis: Products to enable Earth Science	Wildland fire science and related applications have benefitted from a wide range of space-based and airborne fire observations, each with different spatial resolutions and revisit frequencies, as additional sensors and constellations continue to be added by both the public and private sector. Greater use of such observations for analysis and modeling of wildland fire occurrence, behavior, and effects such as emissions is hampered by limitations including: (1) the observations' disparate resolutions and extent, (2) temporal or spatial gaps due to cloud cover, satellite revisit timing, and other issues, and (3) partial fire mapping resulting from (1,2) with crudely mosaicked image segments. Our purpose is to develop the methodology to create, test, and assess the first wildland fire analysis (sometimes called "reanalysis") products - standardized, gridded outputs of desired wildfire products produced at regular intervals. The idea is to develop fire products analogous to atmospheric analyses -- powerful products used across atmospheric science to initialize atmospheric models and support many types of scientific studies. Reanalyses integrate dissimilar, disconnected, asynchronous observations using the physical consistency of a model and data assimilation system to fill gaps in time and space, estimate variables that are not directly observed, and create a physically balanced, more complete image of reality and how it changed over time. Similar needs exist for sectors of wildland fire science and operations but no analogous process or product exists; instead, investigators have attempted to numerically interpolate between widely separated observations or to estimate or retrieve information from spatially and/or temporally coarse data. We aim to develop the fire reanalysis methodology using fire detection products (e.g. Suomi-NPP VIIRS, Landsat OLI, Sentinel-2, Terra/Aqua MODIS, AVHRR, and Sentinel-3 SLSTR), and other products (e.g. ASTER). Subsequently, we will investigate assimilation of supplementary infrared observations from small satellite constellations and private sector products (e.g. DigitalGlobe WorldView-3), airborne observations such as USDA's National Infrared Operations (NIROPs), or experimental platforms (e.g. German Aerospace Center TET-1) that reflect the growing number of remote sensing observations. The CAWFE coupled numerical weather prediction - wildland fire model, which has been successfully used to model many wildfire events, will assimilate this remotely-sensed fire detection data to simulate fires' evolution while minimizing variance from those observations. In this exploratory study, we will produce reanalysis products for a sample of different types of wildfire events. Products would include 2-D gridded variables including cumulative burned area extent, active burning areas, and heat release rate (related to Fire Radiative Power) in common data formats at hourly intervals (or other frequency to be determined by users - team members who develop additional products, e.g. biomass burning emissions inventories, for the research community and decision makers). As part of the project, users will test the products and assess their utility in smoke and emissions modeling, where the infrequency of fire detection observations (e.g., 2 per day for the original VIIRS) currently creates errors in predicted fire emissions due to the diurnal variability in

		fire activity. Also, 3-D products will be considered, including atmospheric state variables and smoke concentration, which could indicate injection height, and smoke concentration profiles needed to initialize air quality models. Data, software, documentation, products, and metadata will be released in a publicly accessible repository, allowing the community to further develop the methods and product library, and outreach will be made by initiating workshops and sessions at scientific conferences.

96307	Mining Chained Modules in Analytic Center Framework	NASA is building Analytic Center Framework (ACF) as a collaboration platform for community users to harmonize existing tools, data and computing environments. In the next 5-10-year timeframe, it can be anticipated many data analytics tools and models will be published onto the NASA ACF as reusable software modules. However, a large number of software modules will make it difficult for Earth scientists to choose from as components to build their new data analytics experiments (workflows). How to help Earth scientists find suitable software modules from a sea of available candidates and use them productively will soon become a big challenge for ACF thus demands a systematic study. Therefore, we propose this AIST project preparing for the next 5-10-year timeframe, aiming to build a workflow tool as a building block for ACF, which is capable of recommending multiple software modules, already chained together, based on their past usage history. We propose to study how software modules collaborated, or could collaborate, to serve various workflows. Based on such investigations, we aim to develop a recommend-as-you-go technique to assist Earth scientists in designing data analytics workflows to address previously intractable scientific questions. The ultimate goal is to reduce time-to-experiment, share expertise and avoid reinvention of wheels. It should be noted that in recent years, many Earth scientists have adopted the Jupyter Notebook to conduct interactive data analytics. Thus, we will leverage the Jupyter Notebook as the environment to focus on the following three objectives: (1) to develop algorithms to mine software module usage history and dependencies from Jupyter notebooks, and construct a knowledge network to store and retrieve data effectively; (2) to develop algorithms to explore and extract reusable chain of software modules from the knowledge network; and (3) to develop an intelligent service that provides personalized recommend-as-you-go support to help Earth scientists design workflows.

96308	The bridge from canopy condition to continental scale biodiversity forecasts, including the rare species of greatest conservation concern	Emerging remote sensing tools have the potential to track biodiversity changes that are happening now are anticipated for coming decades, with new insights on the foundations of terrestrial food webs, particularly high-quality masting fruits, nuts, and seeds that make up 30-100% of herbivore diets. The need for scientific progress on the foundations of terrestrial food webs is most acute for the threatened species of greatest conservation concern. Lidar and hyperspectral imagery provide a high-dimensional representation of canopy structure and its changing spectral reflectance properties over time that are only just beginning to be explored. Emerging insights on canopy condition must be linked to the production of mast that supports herbivores. The Masting Inference and Forecasting (MASTIF) network, coupled with remote sensing and herbivore monitoring at National Ecological Observatory Network (NEON) sites, provides a first opportunity to fully calibrate changes in canopy condition, mast production, and herbivore responses at a continental scale. Building on NASA-AIST support to initiate joint analysis of NEON and remote sensing products, this proposal confronts three main prediction challenges for ecological forecasting, i) translating the most recent remote sensing products into the canopy condition and drought stress metrics having greatest promise for predicting the supply of mast resources to herbivores, ii) leveraging information from the full community of species to improve prediction for the rare species of greatest conservation concern, and iii) resolving the big-data challenge represented by spatio-temporal dependence in large, raster-based arrays of remotely sensed canopy variables and climate. We will create a web visualization portal that provides display and interaction with model results as well as visualization of biodiversity trends. The three elements of our proposed study lead from canopy characterization to mast production by individual trees to continent scale prediction of mast and the consumers that depend on it, jointly as a community. First, we characterize canopy condition at NEON locations, where hyperspectral and lidar data are paired with mast-production and consumer data. Second, new canopy condition variables enter as covariates (predictors) for tree fecundity, including coarser-scale remotely-sensed drought stress indices (e.g., a new thermal stress index developed from MODIS LST (DroughtEye, 4 km), and NASA/JPL's new ECOSTRESS sensor for validation and downscaling). This second step uses MASTIF and Generalized Joint Attribute Modeling (GJAM) for joint community prediction. Third, we use US Forest Inventory and Analysis plots with the fitted MASTIF to project mast production nationally. This third step engages dimension reduction techniques developed specifically for dependence in large spatio-temporal arrays. Finally, all canopy condition and drought indices, habitat, and mast predictors are used to predict consumer abundances nationally. These predictive distributions include conditional prediction of rare species to reevaluate ecological forecasting for conservation goals. We will provide public access to our results and visualization of the NEON biodiversity trends, indices of ecosystems that characterize community and physical habitat structure, energy flow, herbivore food webs, and their vulnerability to climate change by drought

		stress (http://pbgjam.org). Products of this analysis will take the form of i) software for dimension reduction in ecological forecasting, available as an R package, ii) remotely sensed canopy condition and drought-stress maps iii) community predictions of biodiversity change and iv) conditional prediction of threatened species. The goals of this project parallel those of The Decadal Survey in tracking flows of energy and changes in ecosystem structure, function and biodiversity, and relying on national field data collection and space-borne NASA mission data.

96309	Surrogate modeling for atmospheric chemistry and data assimilation	Exposure to ambient concentrations of ozone (O3) is the second largest pollution-related risk of premature death in the US, leading to approximately 20,000 premature deaths annually. Tens of millions of US citizens live in areas where O3 concentrations exceed federal standards. While air quality forecasts could minimize these exposure risks and help develop attainment strategies, accurate and reliable O3 forecasts have been elusive owing to the computational complexity of O3 air quality modeling. From the prediction of urban-scale pollution distributions, to short-term O3 forecasts, to better understanding the relationship between O3 and climate change, a persistent challenge in the atmospheric community is the computational expense of chemistry within the models used to research these problems. To address these challenges, this project aims at building a robust and computationally efficient chemical DA system, merging research in compressive sampling and machine learning for large- scale dynamical systems. In particular, we will use low-rank tensor representations, demonstrated recently for the first time by Co-PI Doostan for surrogate modeling of chemical kinetics. This approach allows for efficient construction of a surrogate which itself is very computationally cheap to evaluate. Our approach will also draw from expertise in polynomial chaos expansions (PCE – a spectral representation of the model solution that can be constructed non-intrusively, i.e., by treating the chemical model as a black box) coupled with multiscale stochastic preconditioners (to address stiffness of the chemical system) to develop fast surrogate models for atmospheric chemistry. In particular, we will accomplish the following objectives: (1) Develop, test, and deliver a surrogate model for the chemical solver in a widely used AQ model (GEOS-Chem). (2) Generalize the surrogate model generation procedure within a software toolbox applicable to any user-provided chemical mechanisms. (3) Demonstrate the benefits of using a surrogate-based AQ modeling framework for assimilation of geostationary observations of atmospheric composition to improve O3 simulations. This project will advance computational tools available for AQ prediction, mitigation, and research. Not only do we aim to deliver a surrogate model for the chemical mechanism of an AQ model used by a very large research community (GEOS-Chem), we will provide a software toolbox for generation of surrogate models for any user-provided mechanism. The potential impacts though are much greater, as improvements in computational expediency could affect research in areas from urban air pollution modeling to long-term studies of chemistry-climate interactions. Eliminating the computational bottleneck associated with chemistry will in turn help to promote the broader use of data assimilation within other AQ forecasting systems. As a case study, we will explore and demonstrate the benefits of surrogate modeling for 4D-Var assimilation using geostationary measurements of NO2, which in the next few years will be available for the first time over North America, Europe, and East Asia. This supports a broader goal of facilitating the use of NASA remote sensing data for air quality forecasting here in the US. The proposed work is highly relevant to the AIST program and broader goals of the earth science and

		applied sciences programs. Our work directly responds to the NASA AIST proposal solicitation for "data-driven modeling tools enabling the forecast of future behavior of the phenomena" as well as "analytic tools to characterize the natural phenomena or physical processes from data" within the program thrust for Analytic Center Framework Development.

96310	SPCTOR: Sensing-Policy Controller and OptimizeR	This proposal outlines new technology concepts for multi-sensor infusion under the current AISTs New Observation Strategies (NOS) thrust with specific focus on (a) Integrated operation of different types of instruments or at different vantage points, (b) Evaluation/comparison of alternative observing [sensing] strategies, and (c) Estimation of science value to enable comparison of observing strategies. Specifically, we propose to develop technologies that coordinate the operations of networks of ground-based and Unmanned Aerial Vehicle (UAV)-based sensors, jointly referred to as Agents. When sensing Agents are coordinated, they can deliver ground-truth information to multiple end-uses that may have different application requirements, especially for different NASA remote sensing science products. We call the overall system achieving this technology vision "Sensing Policy Controller and OptimizeR (SPCTOR)." This technology concept is particularly relevant when considering the fact that existing ground networks have limited capabilities in terms of spatiotemporal sampling flexibility, multi-user coordination, and multi-sensor integration. These limitations are further compounded when multiple users, each with different application requirements, seek access to sensing networks that may have limited resources. Earth-looking remote sensing observatories, in particular, almost always require ground based in-situ networks for geophysical product validation and calibration. In the domain of soil moisture remote sensing, which is our target observable, current (e.g., SMAP and SMOS) and future (e.g., NISAR) missions have different spatial (100 m – 10s km) and temporal (daily to weekly) mapping requirements, resulting in complex and potentially conflicting demands on in-situ networks for validating their products. This proposal will directly address the aforementioned limitations. Building upon elements of existing high-TRL (up to 7) technology heritage of the Soil moisture Sensing Controller and oPtimal Estimator (SoilSCAPE), we propose a new framework to coordinate soil moisture sensing strategies across multiple battery-operated Agents by means of a new machine-learning-based entity called the Sensing-Policy Controller (SPC). In essence, the PC considers Agents' energy constraints, recent data and observations, and respective application (or science) based performance metrics, and then makes the determination on whether to update an Agent's observation strategy. We will further expand in situ sensor network capabilities to enable integration, interaction, and interoperability between ground sensor networks and UAV-based software-defined radars (SDRadars) for field-scale operations. UAVs have reached a level of technological maturity such that their inclusion within existing sensor networks with potential science applications can be feasibly considered. We therefore pursue two principal technology development and research objectives: Objective 1: Develop a Sensing-Policy Controller (SPC) for multi-Agent observation strategy coordination and optimization. (NOS elements b and c). Objective 2: Develop and demonstrate integrated operations between in-situ wireless sensors networks and networks of UAV-SDRadars (NOS element a) Our technology development plan includes analysis, computations, laboratory experiments, and field demonstrations. The entry

		Technology Readiness Levels (TRLs) for the above two objectives are 2 and 4 and exit TRLs are 4 and 6, respectively.

96311	StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science	We propose a two-year investigation to demonstrate higher-level onboard science data processing for more intelligent SmallSats and CubeSats to enable future Earth science missions and Earth observing constellations. Low-cost SmallSat architectures with limited numbers of ground stations generally suffer from downlink bottlenecks that present impediments to delivering large volumes of data to science algorithms implemented on the ground and generating timely science or operational products. When data compression and playback cannot provide a complete solution, data acquisitions per orbit must be sacrificed. This is highly undesirable for weather and climate objectives that require global-scale observations. Our approach to resolving this bottleneck is to disaggregate science data processing and embed science algorithms onboard. Our project leverages ESTO's investment in the SpaceCube family of onboard processors with Size-Weight-and-Power (SWAP) suitable for SmallSat and CubeSat applications. It is now important to focus on application development for these processors to realize the full benefit of this investment. We target our pathfinder application to an objective relevant to the 2017-2027 Earth Sciences Decadal Survey - atmospheric dynamics with 3D stereo tracking of cloud and moisture features using a Structure from Motion (SfM) technique that we call StereoBit. StereoBit is well suited to the hybrid SpaceCube architecture that includes Field Programmable Gate Arrays (FPGAs) that can be programmed for computation. Our StereoBit approach derives from our work in 3D Winds using the MISR instrument onboard NASA's Terra spacecraft together with imagery from NOAA's geostationary satellites. We envision implementing StereoBit onboard using multi-angle data from a sensor such as the ESTO-funded Compact Mid-wave IR System (CMIS) and exploiting information from other vantage points, including geostationary satellites. StereoBit enables large-scale data volume reductions to realize the full science value of each orbit without degradation or compromise. Our proposal includes a testbed to enable development of intelligent onboard systems and test them under flight-like conditions while running on actual spacecraft processors. The testbed has a cloud-hosted, FPGA-enabled component that is scalable to emulate computing capabilities implemented on other platforms for collaborative computing concepts and for off-premise development and testing. We will develop and prove the onboard StereoBit approach to stereo 3D winds to achieve TRL 6 capability by study completion. Best practices derived from our investigations will be valuable to other application areas in the Earth sciences and will be shared with the community.

96312	Smart On-Demand Analysis of Multi-Temporal and Full Resolution SAR ARDs in Multi-Cloud & HPC	We will build upon our cloud-native Advanced Rapid Imaging & Analysis (ARIA) science data system to help address pain-points in the complexities of large-scale algorithm development and on-demand analysis of handling voluminous SAR measurements at full resolution from L1 SLCs to L3 time series. We will increase multi-temporal and full resolution SAR data use as well as facilitate algorithm development and analysis for higher fidelity surface deformation and urgent response use cases. The approach will enable full resolution time series analysis, high-accuracy flood and damage assessments with remote sensing SAR Analysis Ready Data (ARD). We will be building upon our existing capabilities: * Generation and analysis of the SAR ARDs will be done using science notebook-based (e.g. Jupyter) algorithm development environment where algorithms are published into the SAR ARD algorithm analysis "appstore". * We will integrate in curated natural events from NASA's Earth Observatory Natural Event Tracker (EONET) to help users setup automated triggers of on-demand SAR ARD analysis using their own algorithms from algorithm analysis "appstore". * Handling on-demand analysis jobs are done across multi-cloud (AWS, Google Cloud Platform, and Microsoft Azure) and NASA HPC (Pleiades) environments. * Enabling "smart on-demand" where analysis are cost-model-informed to help address the cost of jobs across multi-cloud and HPC environments. E.g. optimizing for fast processing vs lower costs requests. We plan to use the system to develop and process data for the follow demonstration use cases: (1) multi-temporal and full resolution ARDs of L1 coregistered SLC stacks (2) full resolution time series for critical infrastructure monitoring use cases (3) multi-temporal flood extent maps (4) multi-temporal damage assessment maps

96313	D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions	Distributed Space Missions (DSMs) can increase measurement samples over multiple, spatio-temporal vantage points. Smaller spacecraft can now carry imager/radar payloads, even if constrained by power and data downlink. Large numbers of spacecraft increase responsiveness, revisit time and coverage, even with static payloads. Fully re-orientable payloads, tasked by autonomous decision-making, can further improve the capability to reactively observe phenomena. D-SHIELD is a suite of scalable software tools - Scheduler, Science Simulator, Analyzer. The goal is to schedule the payload operations of a large constellation, with multiple payloads per and across spacecraft, such that the collection of observational data and their downlink, constrained by the DSM's constraints (orbital mechanics), resources (e.g. power) and subsystems (e.g. attitude control), results in maximum science value for a selected use case. The constellation topology, spacecraft and ground network characteristics can be imported from design tools or existing constellations. D-SHIELD Scheduler is informed by D-SHIELD Science Simulator, that is based on a simplified Observing System Simulation Experiment developed for a relevancy scenario. It assimilates data from past observations of the DSM along with other sources, and predicts the relative, quantitative value of observations or operational decisions. We will also build a D-SHIELD Analyzer, to evaluate the performance of D-SHIELD for given user inputs, and compare options for its components (e.g., optimization algorithms). Analyzer will also assess the trades to run D-SHIELD onboard vs. ground vs. combination of both. D-SHIELD is thus a mission operations design tool that coordinates autonomous reactions to new events, observations of existing events with changed requirements, and off-nominal situations like failed observations or communications. To validate D-SHIELD, we will apply it to schedule representative constellations measuring spatio-temporal distributions of soil moisture, which varies on spatial scales of a few meters to many kilometers and time scales of minutes to weeks. Observations are accomplished most effectively via power-hungry microwave active and passive sensors (radars and radiometers) at frequency bands P to K. As soil moisture fields are sensitive to view geometry and dynamic, an ideal observational strategy requires that remote sensing instruments have a high degree of agility in their orientation and spatio-temporal sampling. Using a combination of prior/current observations and hydroecologic modeling predictions, the Science Simulator will task the next set of space assets based on anticipated events, such as heavy precipitation and flooding (rapid time scales) and droughts (not rapidly emerging but requiring well-planned long time series of observations). We will also ensure D-SHIELD's applicability to other relevancy scenarios like tropical cyclones, wildfires, urban floods. We have several ongoing projects complementing the proposed work. We have published an algorithmic framework that schedules the time-varying, full-body orientation of single-payload small spacecraft in a constellation. This scheduler can run at the ground station autonomously and schedules uplinked to the spacecraft, or onboard small spacecraft, such that the constellation can make decisions autonomously, without ground control. The algorithm

		also applies Disruption Tolerant Networking reliable and low-latency communication between constantly changing inter-satellite link. We are working on a flight mission which will demonstrate reactive measurements of plasma density by an autonomous swarm of four cross-linked spacecraft, due for launch in 2020-21. We have prototyped an agent-based simulator with centralized and decentralized planning algorithms. It can probabilistically assess the value of forming temporary coalitions to observe targets on the ground simultaneously from various platforms and sensors.

96314	Predicting What We Breathe: Using Machine Learning to Understand Air Quality	Every 7 seconds, someone dies from the effects of air pollution. Air pollution is responsible for 4.5 million deaths and 107.2 million disability-adjusted-life-years globally. With the percentage of the global population living in urban areas projected to increase from 54% in 2015 to 68% in 2050 and in the U.S. up to 89%, the prevention of a significant increase in air pollution-related loss of life requires comprehensive mitigation strategies, as well as forecast systems, to limit and reduce the exposure to harmful urban air. While some megacities like Los Angeles operate an extensive network of ground-based monitoring stations for ozone, particulate matter (PM) 2.5, and other pollutants, air quality (AQ) in many cities around the globe are poorly characterized at ground level. The main source of information on atmospheric environmental conditions in those cities is space-based monitoring of a limited set of AQ indicators. We propose the development of advanced Machine Learning (ML)-based algorithms and models that links ground-based in situ and space-based remote sensing observations of major AQ components, with the aim to (a) classify patterns in urban air quality, (b) enable the deduction and forecast of air pollution events related to PM2.5 and ozone from space-based observations, and ultimately (c) identify similarities in AQ regimes between megacities around the globe for improved air pollution mitigation strategies. Furthermore, this proposal will help us understand the correlation between air pollution and health conditions all over the City of Los Angeles, and predict individuals' health risks related to air pollution based on air quality measurements. Using the City of Los Angeles as a test case, this proposal work will focus on elements (a) and (b), with the extension to element (c) envisaged for follow-on studies. The objective of this proposal is to increase the accessibility and use of space data by using machine learning to help cities predict air quality in ways that can be acted upon to improve human health outcomes and provide better data to individuals and cities. Secondarily, the goal is to provide these tools and algorithms to future Earth science missions (e.g., MAIA) to provide rapid ground truth, combine multiple data sources, and support more rapid use of mission data. This proposal will focus on maturing the technologies involved in: --Developing machine learning algorithms for predictive models for air quality based on PM2.5 and other air pollutants --Build a big data analytics algorithm for integrating ground and space data --Provide predictive models for health risk using deep learning and machine learning --Build an open source PM2.5 stack for integrating ground and space data --Create a model for cities with shared attributes to understand predictions and effective interventions

96394	Metasurfaces for Compact, Next-Generation Polarimetric Remote Sensing of Aerosols and Clouds	Aerosols – suspensions of solid or liquid droplets in air – present a unique challenge in atmospheric science and are, together with their interactions with clouds, key sources of uncertainty in global climate models. Light's polarization state upon scattering from aerosols and clouds is known to carry information that can aid in determination of their mean size, droplet size uniformity, shape, and absorption properties. However, the current instrumentation for polarimetry (the measurement of light's polarization state) is bulky and/or reliant on moving parts. Metasurfaces – subwavelength spaced arrays of nanophotonic phase shifters, an emergent optical technology – have recently been shown to implement polarization imaging with all polarization analysis handled by a single optical element and thus hold promise for a new class of polarization instrumentation for remote sensing. To date, no past, current, or planned Earth Science airborne/spaceborne polarimeter has measured light's circular polarization. Metasurfaces easily yield information on the circular polarization of light, therefore, the utility this seldom-measured quantity can have for aerosol and cloud remote sensing will be investigated. The proposed IIP-ICD effort will evaluate whether metasurface-based polarimetry can achieve the accuracy mandated for cutting-edge aerosol and cloud remote sensing applications by partnering resources and personnel from Harvard University, leaders in the development of metasurfaces for polarimetric imaging, with aerosol and cloud remote sensing expertise at NASA GSFC. Our team proposes to examine the scientific feasibility of metasurfaces in this realm, whose compactness (when paired with this requisite accuracy) could enable a compact, next-generation remote sensing platform for application onboard a CubeSat. As part of this project we will fabricate several metasurface polarization camera prototypes in three wavelength bands relevant for aerosol and cloud remote sensing (550, 670, and 870 nm), characterize their accuracy, and investigate future applications of metasurfaces in polarimetry, advancing the technology from TRL 2 at entry and TRL 4 upon exit. Finally, the proposed effort will explore the utility of using new metasurface enabled observations of circular polarization for Earth Science applications; maturation of the technology has the potential to be cross-cutting with the Planetary Science community, as chirality, a potential indicator of complex biological life, contributes to the circular polarization signal.

96395	Digitally Enhanced Meta-surface Radar/Radiometer for Snow Remote Sensing	We propose to develop a Ku-band active and passive (radiometer/radar) microwave wavelength instrument capable of measuring the spatial distribution of snow-water-equivalent (SWE) from a space-borne platform using CMOS radar combined with metasurface antenna technology to overcome the isolation and dynamic range challenges associated with snow sensing. Traditionally remote sensing of SWE from a space-borne is prohibitive as it demands both a large aperture (>1m diameter) to maintain resolution in terms of ground footprint, and high dynamic range radar system (beyond 60dB) to accommodate the vast difference in reflectivity between the snowpack's top surface and the underlying ground. This dynamic range in particular requires that a radar have a very low transmit-to-receiver leakage (again beyond 60dB). Airborne remote sensing of snow addresses this leakage by employing bi-static radars where the transmitter and receiver operate using separate antennas. The separation of the two signals with separate antennas allows these systems to easily achieve the required transmit-to-receive isolation as the two are not required to share an aperture. While suitable for large airborne campaigns, the bi-static approach is prohibitive for spaceborne platforms as needing two large antennas (as opposed to a single antenna) makes the instrument prohibitively large. To overcome this we propose an instrument which employs a new metasurface antenna which enables simultaneous transmitting and receiving using the same antenna aperture and frequency, while still providing the high isolation required for sensing SWE from a spaceborne platform. This high isolation is achieved through a combination of the antenna's native design (approx. 20dB isolation), as well as a leakage cancelling pre-distortion technique where signals leaking between the two ports are digitally cancelled to provide an additional 50dB. Using this high dynamic range, the proposed instrument can provide critical information about snowpack features (depth, density, liquid water content) used to estimate and constrain SWE, but unlike ground-based or airborne measurements, can provide global coverage as it targets a spaceborne approach. The instrument also offers a passive radiometer mode (where the radar transmitter is disabled) which is an important measurement in constraining the amount of liquid water pooled at the bottom of the snowpack. To achieve the high level of signal processing performance required to enhance the isolation of the metasurface antenna, we employ CMOS system-on-chip (SoCs) technology (the same electronics technology used in modern smartphones) for all radar and radiometer electronics. CMOS SoCs offers approximately a factor of 100X in performance over FPGA platforms implemented with the same transistor size.

96396	Black Array of Broadband Absolute Radiometers for Imaging Earth Radiation	We propose to develop and demonstrate a novel instrument utilizing a linear array of electrical substitution microbolometers for imaging outgoing Earth radiation with low uncertainty. Our instrument will measure in several broad bands spanning the electromagnetic spectrum from 0.2 µm to 100 µm with a 1 km spatial footprint from a low Earth orbit vantage point. Accurate measurements of outgoing broadband radiation are critical for understanding Earth's climate. Our focus on beginning with an instrument of reduced volume, mass, and power, while enhancing spatial resolution and providing high accuracy supports key measurement objectives for use in the next generation of science missions. These objectives include broadened applicability to small satellite platforms and reduced risk from potential data record gaps. Our instrument, the Black Array of Broadband Absolute Radiometers (BABAR) Earth Radiation Imager (BABAR-ERI), capitalizes on linear detector array technology in development under an Advanced Component Technology (ACT) award (#ACT-17-0025). BABAR is an uncooled microbolometer electrical-substitution radiometer array with Vertically Aligned Carbon Nanotubes (VACNT) as the optical absorber. Electrical-substitution radiometers are used extensively in precision radiometry, but have never been used for imaging despite their many advantages. Relative to traditional microbolometer arrays, the BABAR detector allows for faster response, higher linearity, higher accuracy, and higher long-term stability. This is achieved by using closed-loop electrical substitution techniques in conjunction with electrical substitution radiometry. The VACNTs provide spectrally flat absorptance greater than 99.8% over the range from 0.2 µm to 100 µm. The combination of electrical substitution and broadband VACNT absorption provides a path to a compact, high resolution, and high accuracy instrument because on-board calibration hardware is not required. Absolute radiometry will be verified against the Planar Bolometric Radiometer for Irradiance (PBR-I) reference standard. These properties make BABAR-ERI ideal for space-based Earth energy budget and remote sensing applications. In order to accommodate the broad wavelength range desired for energy budget applications, an all-reflective imaging system will be implemented. A key aspect of this IIP will be generating a compact design which can fit onto a 6U CubeSat bus. This will enable a future, straightforward on-orbit demonstration as well as facilitate potential future deployment of multiple BABAR-ERI instruments on a constellation of small spacecraft. The proposing team has a long history of instrument development and deployment of radiometers in space-based and suborbital platforms. The proposed sensors draw heritage from: the Compact Solar Spectral Irradiance Monitor (CSIM), developed under a 2013 IIP award, that has been making daily solar irradiance measurements from a 6U CubeSat platform since early 2019; the Compact Total Irradiance Monitor (CTIM), in development for the In-Space Validation of Earth Science Technologies (InVEST) program with a planned launch in 2021; and the BABAR ACT project. The BABAR linear array detector is currently at a Technology Readiness Level (TRL) of 3. We are proposing an exit TRL of 6 at the end of this three-year project.

96397	SToRM SAR	Observations at 1km horizontal resolution are needed to resolve the fine thermodynamic phase structure present in many severe storms, and support the weather process research needed for future convection-resolving weather models. SToRM SAR is an approach developed by BAE Systems and Colorado State University for a space-based 3D multi-static precipitation radar that employs agile micro-satellites operating synchronously in a distributed configuration to provide 1km horizontal spatial resolution observations of a precipitation field using a new interferometric method. The focus of the proposed work is on next-generation space-based precipitation field observations at finer spatial scales. The horizontal resolution of the large GPM radar is 5 km-too coarse to resolve these phenomena. A real-aperture radar-scaled to pro-vide 1 km resolution at Ku band would have an aperture dimension of 15-30 meters–a funda-mentally unaffordable approach. SToRM SAR (Satellite Tomography of Rain and Motion using Synthetic Aperture Ra-dar) directly leverages the rapid developments in small satellite technology and launch capabil-ity to provide significant new capability at a mission cost more than 10x lower than other space-borne precipitation radars- with the ability to penetrate and characterize severe mid-latitude storms at the 1-km scale from space for the first time. The approach is compatible with both X-band and Ku-band operation, enabling full profiling through intense storms using transmitter power levels consistent with miniature solid state RF amplifiers. The approach employs range-encoded pulse sequences and strategically positioned receivers to enable a sim-ultaneous interferometric measure of the vertical and cross-track structure of the precipitation field. The along-track spatial structure is observed using a scene illumination approach simi-lar that used for the spotlight-mode employed in traditional 2D SAR. Along-track structure is recovered via a tomographic re-construction method. Radar observation locations are cued by passive IR and microwave mapping micro-satellites orbiting ahead, which indicate areas of immanent or ongoing severe weather. This cueing allows the duty-cycle of the radar to be low without sacrificing observations of the key storm regions of interest, thereby keeping the ac-commodation requirements within micro-satellite resource limits. The SToRM SAR method does not rely on the Doppler Effect for observing storm structure, but uses Doppler to sense field motions- as do ground-based Doppler-weather radars. Under a 3-year IIP-IDD, the overall mission and instrumentation risks will be reduced though detailed observing concept and instrument payload design, supported by a realistic sim-ulations of the complex 3D precipitation field observations and ground-based field demonstra-tions of the observation method. This work builds upon a successful NASA ESTO-Funded Fea-sibility Study that developed the mathematical framework. The envisioned hardware imple-mentation is TRL5. However, the overall readiness of this relatively complex observation method is currently low (TRL2-3), and improving this readiness to TRL5 through analysis, simulation, testing, and field demonstration would be a primary focus of the risk reduction work. The method is, in part, derived from methods applied by BAE Systems in RF signals in-telligence

		and navigation. The precipitation field modeling is based on substantial prior work by Colorado State University in reflectivity field simulation. Field tests of the interferometry method will be conducted at BAE Systems RF range and near Colorado State University's NSF-Funded CHILL multi-band (C-band-X-band)/dual polarization precipitation radar research and development facility near Ft Collins, CO which will enable the observation of storm structure using the new method (at X-Band) to be compared with the observations of a powerful ground-based precipitation radar.

96398	Smart Ice Cloud Sensing	We propose an instrument optimized for Smart Ice Cloud Sensing (SMICES) that will enable both multi-angle and multi-resolution measurements of cloud ice particles size and shape within the tropospheric temperature and water vapor profile context. This will improve understanding of tropospheric events including hurricanes, tropical deep convections, tornadoes and storms. SMICE will combine an active radar, with passive multi-band radiometers and sounders using an intelligent backend and control system. SMICES will maximize the scientific outcome by performing multi-angle and multi-resolution measurements of interesting tropospheric features and optimizing the volume of collected data by using a footprint overlap high resolution mode for the radiometers, a track-and-lock algorithm for the radar, and a reconfigurable wide-band high-resolution digital spectrometer to produce sounder channel spectra. These three system characteristics enable feature-dependent and incidence angle-dependent resolutions resulting in efficient acquisition of high resolution measurements. The intelligent feature detection enabled by SMICES, including observational locking capability and the multi-angle and multi-resolution measurements, will enable the detection of ice particles at different sizes, distribution and granularity with a fine vertical resolution of 500 meters. The use of the spectrometers enable collocated temperature and water vapor profiles measurements needed for evaluating and constraining climate model simulations of ice cloud processes. The SMICES instrument works in the following manner. During normal operation, the radiometers continuously scan the upper troposphere at 45° incidence angle. Passive instrument calibration will be performed on board, allowing for near real-time detection of tropospheric features. Once the passive sensors detect a tropospheric feature, the radar, which is nominally nadir pointed, will point towards the feature and examine the region of interest. As the satellite travels, the relative position between the feature and the instrument also changes. By locking the radar to the target, the radar will be able to obtain multi-angle data. This intelligent control of the radar enables high-resolution data for specific features of interest. Along with combination of active and passive sensing techniques, the "smart" functionality of SMICES is a key feature. This is enabled by calibration and feature detection algorithms using neural networks. The radiometric calibration and feature detection neural networks operation will be performed on-orbit. Antenna temperature will be estimated from the radiometric voltage reading and system operating condition using a multi-layer deep-learning neural network. The calibration neural network will have the capability to on-orbit training to account for non-stationary system effects including component aging. The feature detection neural network operation will be trained on ground using multiple datasets, and can be updated to the spacecraft as necessary. SMICES relies on significant technology to meet its mission goals. The calibration algorithm and feature detection is currently rated to be TRL 3, as well as the antenna focus and tracking. The high resolution digital spectrometer is currently TRL 4. The Sounders and radiometers operate at 240, 310, 380, 670 and GHz and are estimated to be at

		TRL 5 from IIP-13 TWICE and ACT-17 IRaST. Exit TRL level of the SMICES instrument will be TRL-5. TRL4 radar receiver and up-converter operate at 233 GHz and have been developed on the DARPA ViSAR program. The 233 GHz TWT will leverage work from the DARPA ViSAR program, with the magnet being changed from a fixed magnet to a PPM. We therefore rank the TWT as TRL3.

96399	Compact Hyperspectral Air Pollution Sensor-Demonstrator (CHAPS-D)	Air pollution is responsible for ~7 million premature deaths every year. Past and current satellite missions in low Earth orbit have characterized air pollution distributions and established trends at fixed local solar times but in most cases cannot resolve individual emission sources without statistical post-analysis. Current and planned geostationary satellites will add diurnal information but lack global coverage. The Decadal Survey calls for a robust, comprehensive observing strategy for the spatial distribution of air pollution at high spatial, high temporal resolution. This will not be possible in a sustainable way without technological advancements. The Compact Hyperspectral Air Pollution Sensor (CHAPS) is a hyperspectral imager (HSI) using free-form optics in a form factor suitable for accommodation on a small satellite or hosted payload. CHAPS will make measurements of air pollution at unprecedented spatial resolution from low Earth orbit (1 x 1 km2) and will characterize, quantify, and monitor emissions from urban areas, power plants, and other anthropogenic activities. The compact size and relatively lower cost of CHAPS makes a constellation feasible for the first time, with unprecedented spatiotemporal sampling of global point pollution sources. A CHAPS constellation represents a new observing system making science-quality measurements of air pollution, meeting new Decadal Survey requirements. The objective of the CHAPS–Demonstrator (CHAPS-D) IIP project is the airborne demonstration of a CHAPS prototype instrument. CHAPS derives heritage from the TROPOspheric Monitoring Instrument (TROPOMI) on the Sentinel-5 Precursor, which uses a free-form mirror telescope. Free-form optics is an emerging technology with potentially huge advantages over traditional optical designs, including fewer optical surfaces, less mass and volume, and improved image quality. The free-form optics design demonstrated by the CHAPS D IIP will be generalizable to other wavelengths between 270 and 2400 nm, making it applicable to a wide variety of Earth science problems, including public health, atmospheric composition, surface biology and geology, land use/agriculture, marine and terrestrial ecosystems, the cryosphere, volcanic eruptions, and natural disaster response. As a case study, we will focus this IIP project on the measurement of nitrogen dioxide (NO2). NO2 is a primary ingredient of air pollution, as it is a toxic gas at high concentrations, a marker for combustion-related pollutants and co-emitted air toxins, and the main precursor of tropospheric ozone and nitrate aerosols. CHAPS-D will combine a radiometrically calibrated HSI (300–500 nm @ 0.5-nm resolution) with associated detector and payload electronics. It will be as close to the ultimate space design as feasible within the scope of the IIP. For example, we will impose the design constraints for the payload of a 6U CubeSat. With these constraints in mind, we will introduce new technologies for on-board instrument calibration. With new, innovative passive metrology, we will be able to constantly monitor the instrument for continuous on-board correction of the measurement data. The project total period of performance is from January 2020 through December 2022. The first project year focuses on the instrument design and the fabrication of the free-form optics, detector, and electronics. The second year will see the

		integration of the instrument, laboratory calibration, and ground-based (zenith-sky) measurements. The third year features a series of aircraft flights, where we will validate the performance of CHAPS-D, retrieve NO2 vertical column densities from measured radiance spectra, and compare these retrievals with extant ground-based, airborne, and operational space-based NO2 products. This will raise the CHAPS-D TRL from 2 to 5, preparing the compact hyperspectral imaging technology to tackle numerous Earth science objectives.

96400	Breakthrough Technologies Enabling ESPA-Class SmallSat Implementation of Earth Science LIDAR Missions	Space-based lidars have made many key Earth science observations. They provide unique advantages of spatial, spectral and temporal resolution because they carry their own laser illumination source. Despite many highly successful missions, however, lidar instruments are not being flown regularly in Earth orbit due to their cost, size, power requirements, and risk. In this Instrument Concept Demonstration (ICD), our team proposes to develop an innovative combination of lidar technologies to help overcome these critical challenges. Our team will demonstrate key instrument capabilities to enable lower cost, more regular missions. This work targets three new technologies that address the most critical drivers of space lidar size, weight and power (SWaP). When successful these will enable SmallSat implementation of traditionally bulky, power-hungry lidar instruments. These technologies are: (1) miniaturized and efficient wavelength-tunable seed lasers using photonic integrated circuits (PICs) and hollow-core photonic crystal fiber (HC-PCF) gas cells; (2) compact, efficient, high peak power optical amplifiers using highly-doped, large-mode-area fiber laser technology; and (3) a lightweight deployable, membrane receiver telescope coupled with custom free-form optics aberration correction. These cutting-edge technologies address the major drivers for SWaP on a lidar mission, so combined they can enable a space lidar on a much smaller satellite that reduces cost but still meets stringent performance requirements. Although the technologies that our team will address are broadly applicable to many lidar concepts, our team will target those for GSFC's CO2 Sounder, a carbon dioxide (CO2) integrated-path differential-absorption (IPDA) lidar. The lidar measurement of CO2 serves as an important testbed for the technology. The Earth science community and NASA have long recognized the importance of laser-based spectroscopic measurements for greenhouse gases from space because it allows greater coverage and avoids several known bias errors inherent in passive measurements. Our team is uniquely positioned to do this work with years of experience developing the airborne CO2 Sounder as well as space-based, and other airborne lidars. Our team has partnerships with the University of California Santa Barbara (UCSB) for photonic integrated circuits and with NeXolve for membrane telescope component development. Our team has the critical expertise in understanding the science measurements, developing the component technologies, and in verifying the component performance. The proposed 18-month program will increase the technology readiness from level 2 to 3.

96401	Global L-band Active/Passive Observatory for Water Cycle Studies (GLOWS)	The value of L-band measurements from the Soil Moisture Active Passive (SMAP) and Soil Moisture Ocean Salinity (SMOS) missions have shown the importance of L-band data record in Earth Sciences. An obstacle to this is the high cost of designing and flying the large antennas required for L-band observations. A new technique based on reflectarray antennas provides a path to smaller, lower-cost, simpler, large-aperture antennas for low frequency microwave (L-band) observation. Using this key technology, we propose the Global L-band Active/Passive Observatory for Water Cycle Studies (GLOWS) instrument. The use of a reflectarray lens antenna enables L-band measurement capability from a significantly smaller spacecraft. This proposal to the Instrument Incubator Program (IIP) is to evaluate the radiometric performance of the new antenna design concept from TRL 2-3 to TRL 4 to advance the timeline of a GLOWS flight. The technology improvements can be applied to other remote sensing missions as well.

96402	Distributed Aperture Radar Tomographic Sensors (DARTS) to Map Three-Dimensional Vegetation Structure and Surface Topography	We propose to mature and demonstrate a set of relevant technologies that, when coupled with recent developments in miniaturized spaceborne radars, will enable formations of satellites to perform disruptive global vegetation structure and surface topography measurements. The recent report from the 2017-2027 US Decadal Survey for Earth Science and Applications from Space recommended the global mapping of surface topography and three-dimensional vegetation structure as one of the highest priority "incubator" measurements to undertake in the next decade. Despite its extremely high relevance, significant technological developments are needed to enable the implementation of a feasible and affordable space mission that can demonstrably retrieve vegetation structural characteristics, including the underlying ground topography, with the desired vertical and horizontal resolutions, accuracy and temporal sampling. Our concept, named Distributed Aperture Radar Tomographic Sensors (DARTS), is based on multistatic tomographic SAR (TomoSAR) observations. A notional architecture for measuring vegetation structure and surface topography globally every ~10-15 days includes a formation of ~5-10 spacecraft equipped with full-polarimetric, bistatic, L-band distributed radar instruments. One or more of the spacecrafts, the hub(s), transmits the radar signal while all remaining satellites receive the echo simultaneously. The relative position, attitude, timing, and clock are synchronized between all platforms to enable coherent, multistatic SAR observations of common scenes with nominally 50 m horizontal resolution and 3-5 m vertical resolution after multi-looking. The formation's relative orbital control requirement is <10 m but the knowledge of the relative positions is required to <1 cm to maintain coherent phase between the distributed radar receivers for tomographic reconstruction. Data from each spacecraft is transferred to the hub spacecraft(s) via inter-satellite communications for data reduction and downlink to Earth for tomographic processing and digital elevation model generation. The objectives of our investigation are to (1) Design, build and test a distributed system to synchronized timing, clock, relative position and sensor data for all of the distributed DARTS elements; (2) Miniaturize the distributed phase-coherent radar system by leveraging recent RF system-on-chip (RFSoC) technologies and implement compact L-band radars in order to achieve time-synchronization and phase coherence across the distributed elements. (3) Design the optimal distributed system architecture given the scientific requirements for surface topography and vegetation tomographic imaging, and analyze the tomographic signals acquired by both fixed-position and mobile small Unmanned Aerial System (sUAS) synchronized radars; (4) Design a SmallSat-compatible, L-band foldable patch antenna, including the electrical backend and the mechanical structure required to enable a cost-effective formation of satellites for the distributed DARTS system. A multistatic interferometric system enabling single-pass SAR tomography constitutes a disruptive measurement for ecosystem science because it can provide global, high-quality year-round measurements of 3D vegetation structure while being insensitive to

		dynamic changes in vegetation, soil and atmosphere. Coupled with fast repeat periods, such a measurement would provide a consistent 4D view of vegetation (3D in space + 1D in time) complementing and potentially overcoming the limitations of spaceborne lidar missions and other planned missions such as TANDEM-L and BIOMASS. This investigation responds directly to the Instrument Development and Demonstration sub-element of the IIP solicitation. The proposed period of performance is 3 years. The entry Technology Readiness Level (TRL) is 2, which we plan to increase by 1 every year, aiming for a TRL equal to 5 at the end of the investigation.

96403	CloudCube	We propose to develop a multi-frequency millimeter-wave radar system, named CloudCube, using a minimalistic architecture that vastly reduces mass, power, size, development time and recurring costs. The instrument will enable unprecedented mission concepts that would fill existing gaps in the observation of a variety of cloud and precipitation processes. Mission concepts include, but are not limited to, low-cost radar measurements from small spacecraft platforms relevant to observation of cloud, convection and precipitation processes, global monitoring of atmospheric winds and observations of critical elements of the planetary boundary layer. For the first time, CloudCube combines Ka-, W- and G-band (35/94/238 GHz, respectively) radar backscatter with Doppler velocity measurement capability at Ka-band to simultaneously observes key components of a variety of atmospheric processes; however, the CloudCube design is modular allowing for selection of different subsets of the radar frequencies to meet targeted mission observables from a resource-limited platform. This new radar instrument provides flexible and timely capabilities to complement other instruments (e.g. lidar/spectrometer/microwave radiometer) in the Cloud Convection and Precipitation (CCP) architecture and expands the science return for other mission concepts not primarily hinged on radar observations. The concept has an entry level TRL of 3, with many critical components and subsystems at higher TRL. We will raise to TRL 6 over a three-year effort. The instrument is designed and built from extensive heritage of JPL technology development for NASA. Some of the enabling technologies are: 1) a compact radar architecture utilizing offset I/Q with pulse compression which was demonstrated with RainCube (Radar In a Cube, NASA InVEST-15), 2) high-efficient Schottky diode frequency-multipliers, 3) a low-power, on-board digital processor and 4) the Displaced Phase Center Antenna (DPCA) approach to enable coherent measurements with small aperture antennas. The radar electronics will be developed under this project and consist of three transceivers that integrate all-solid-state transmit and receive devices inside compact modules. The transmit sources use waveguide power combining geometry with Schottky diodes at G-band and low voltage power amplifiers at both Ka- and W-bands to achieve the required transmitter power, which is kept at or below 10 W to avoid any complications from multipaction, breakdown, arcing and thermal dissipation. For the radar receivers, GaAs and InP low-noise amplifiers are used which have state-of-the-art noise temperatures. The CloudCube electronics are compatible with a number of specific antenna solutions and mission architectures to maximize its reconfigurability and tailor its resources to specific sets of science requirements.

96404	Formaldehyde Integrated Path Differential Absorption LIDAR	An improved understanding of the coupled chemistry-climate system is a key objective of NASA Earth Science. Central to this objective is the reactive photochemistry that controls the lifetime of greenhouse gases like methane, the production of ozone, and the growth of organic aerosols. Formaldehyde (HCHO) is a critical player in these processes: It is a key measure of the oxidative power of the atmosphere (it is produced in the oxidation of methane), an important intermediate in the production of ozone (it produces the species that make ozone), and an indicator for the abundance of the organic precursors that lead to organic aerosols (it is produced from the same organic precursors). HCHO is an important component of existing (OMI, TROPOMI, OMPS) and planned (TEMPO, GEMS, Sentinel-4) satellite missions. Each of these instruments measures reflected sunlight in the near ultraviolet (300-350 nm) to determine the column of HCHO. The difficulty with this technique is that the high level of scattering makes the retrieval of the column abundance strongly dependent on the assumed shape of the HCHO profile. The combination of the weak absorption signal (HCHO is present at parts per billion in the atmosphere), limited light due to scattering, and the dependence on a model-derived concentration profile, make HCHO difficult to measure accurately with passive spectroscopy. Our motivation is that this accuracy is not adequate to solve emerging science goals. Our team proposes to develop a new method to detect formaldehyde remotely with integrated path differential absorption (IPDA) LIDAR under the IIP instrument concept demonstration (ICD) call. Our concept uses a tunable narrow-linewidth fiber amplified laser to measure the absorbance of single rotational lines of the A-X transition at 339 nm. The concept will measure the column of formaldehyde in the laser path using a simple Beer's law analysis that is largely independent of the a priori assumptions needed in passive systems, providing improved capability in sensitivity and accuracy. In addition, since this is an active system with a small footprint, it can measure at night and in scenes partially obscured by clouds and aerosol. The challenge is to develop the experimental capability to detect the low abundances of formaldehyde in the UV where Rayleigh scattering is large. We now have the technology to meet this challenge. We will modify a new laser developed with ESTO and GSFC IRAD support to provide the laser light at 339 nm. We will demonstrate the capability to detect HCHO with a remote target on the ground using commercially available electronics for data acquisition. We will evaluate and optimize the technique and, at the conclusion of this effort, we will provide our recommendation for the best path towards an instrument design. We will advance the TRL from 2 to 3 over an 18-month period. At the conclusion of this IIP ICD, we plan to pursue the development of an airborne IPDA instrument with the instrument Development and Demonstration (IIP-IDD) or airborne instrument technology transfer (AITT) program. Our short-term (3-5 yr) goal is to demonstrate performance in an operational airborne configuration. Longer term (5-10+ yr), this concept can be applied to space-based measurements.

96405	Signals of Opportunity Synthetic Aperture Radar for High Resolution Remote Sensing of Land Surfaces	The goal of our proposal is to develop the Synthetic Aperture Radar (SAR) Technology based on a unique combination of P-band Signals of Opportunity (SoOp) technique and sparse array technology for high resolution satellite remote sensing of Snow Water Equivalent (SWE) and Root Zone Soil Moisture (RZSM). The SoOpSAR concept will potentially lead to a significant reduction of cost and risk by an order of magnitude in comparison with the current available SAR technologies, which require dedicated high power transmit source, large deployable antenna aperture, complex deployment and hence large satellites. Specifically, we target the second element of the IIP call on Instrument Concept Demonstration (ICD) to advance the TRL of SoOpSAR technology concept from 2 to 3. The objectives of the proposed research are: 1. Complete proof-of-concept demonstration of the SoOpSAR technology by ground-based experiments; 2. Advance system concept by performing trade studies for resolution, swath, sparse array optimization, and uncertainty analysis of receiver timing and positioning errors. The proposed SoOpSAR based on P-band Signals of Opportunity will provide an order of magnitude improvement in spatial resolution than the conventional SoOp technologies to enable applications, such as flood monitoring/forecasts and precision farming. Furthermore, the conventional spaceborne monostatic P-band SAR is currently not allowed to operate over North America and Western Europe due to frequency allocation by the International Telecommunication Union, which designates the US Space Objects Tracking Radar (SOTR) as the primary user of the 435 MHz band. The proposed SoOpSAR technology, operating at 260 and 360 MHz bands, could fill the gap for high-resolution radar imaging of land surfaces at P-band. High resolution (~100m) remote sensing of soil moisture/snow water content is critical for modeling of land surface hydrological processes and applications. Despite their importance, SWE and RZSM, which are critical water storage elements, are arguably two of the least measured hydrologic states in the Earth System, in part due to the challenges and high cost of current spaceborne SAR technologies, which require large antenna apertures and hence large satellites. The proposed SoOpSAR concept is highly relevant to NASA Earth Science, specifically motivated by the stated science goal in the 2014 NASA Science Plan to: "Enable better assessment and management of water quality and quantity to accurately predict how the global water cycle evolves in response to climate change." The ability of SoOpSAR will also address the needs of terrestrial snow water storage designated as one of the critical variables for the Earth Explorer Missions in the 2017 NASA Decadal Survey report. We have completed a preliminary system performance analysis. The expected signal to noise ratio is exceptional and will enable accurate soil moisture and snow water content retrieval. For the IIP-ICD SoOpSAR proof-of-concept testing, we will develop five receivers for testing using a ground-based moving vehicle. The receivers will be mounted with various horizontal spacings to acquire data to simulate and test the use of sparse array concept for high across-track resolution processing. We will also conduct detailed system error analyses to determine the requirements on sparse array position control and

		knowledge accuracy requirements. Our team members have demonstrated expertise in science algorithms, SoOp techniques, and SAR technologies and will complete the proposed tasks on cost and schedule.

96406	Integrated Inertial Sensors and Laser Ranging Instruments for Small Satellite Earth Geodesy Constellations	We plan to develop a compact inertial sensor and integrated laser interferometer for low-cost small satellite Earth geodesy constellations. Our concept has the potential to be disruptive, enabling dozens of satellite pairs at a cost that is comparable to previous Earth geodesy missions. The potential science return from the higher accuracy instruments and increased satellite constellation size would help resolve questions about how the global Earth system is changing. It would improve the accuracy and resolution of gravity field measurements, increasing our understanding of climate variability and change, including critically important temporal and spatial changes in the mass of Earth's ice cover and water. The instrument and satellite platform will take advantage of NASA and European Space Agency investments in technology for Earth geodesy and space gravitational wave detection. The inertial sensors (IS) will have an improved acceleration noise performance relative to the ONERA sensors employed in the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On (GRACE-FO) missions, achieving an acceleration noise of <10^–12 m/s^2Hz^1/2, a factor of 100 improvement over the ONERA sensors. To do so, the IS design will capitalize on technologies developed for LISA Pathfinder and performance models that were validated by flight data from that mission. With these models, we will tailor the design to meet the desired performance of next-generation geodesy missions, while minimizing the size, weight, and power of the sensor. The inertial sensor will incorporate a laser interferometer port for direct interrogation, and we will develop a strategy to modify the GRACE-FO laser ranging interferometer (LRI) to allow direct integration with the IS. An inertial sensor and spacecraft designed from the start with laser interferometry in mind will allow an LRI with a smaller mass and volume than that used on GRACE FO, for example, by eliminating components that were only needed to allow GRACE-FO to use the GRACE spacecraft and microwave ranging instrument. By integrating a compact inertial sensor and laser ranging interferometer, and eliminating the microwave ranging system used on GRACE and GRACE FO, a low-low satellite-to-satellite tracking geodesy mission could be realized on a small satellite, for example an ESPA-class platform or smaller. The reduced cost to develop and launch this small satellite and instrument would enable a larger number of pairs of satellites to be employed in future geodesy missions. Because of the higher frequency with which they observe any given location on the Earth, multi-satellite systems can increase the temporal resolution of gravity field maps. Mixed-orbit constellations can also markedly enhance observational strength, decorrelate gravity coefficient estimates, and help address the fundamental aliasing/modeling problem that exists with previous missions. The constellation approach is also scalable and could take advantage of improved technologies when they become available. We will develop the conceptual design of the inertial sensor and laser ranging interferometer considering the size, mass, and power constraints of small satellite platforms. The performance of the inertial sensor will be based on analytical models developed for the LISA and LISA

		Pathfinder missions and validated using noise measurements made with the University of Florida torsion pendulum, which is capable of measuring the performance of inertial sensors down to ~10^–13 m/s^2Hz^1/2 around a few mHz. We will also evaluate the science return for an optimized set of orbits for small satellite pairs in terms of the spatial, temporal resolution and accuracy of the recovered geopotential. In this analysis, we will consider both rideshare opportunities and Venture class launches that enable launches into desired orbits for each pair of satellites at relatively low cost.

96407	Frequency Comb Spectrometer for Satellite Atmospheric Remote Sensing	The dual frequency-comb spectrometer has recently emerged as a novel instrument to support precise retrievals of atmospheric trace gas column densities over long paths without systematic drifts. In this work, we propose the development of dual comb spectroscopy (DCS) for satellite measurements to 1) perform active-source integrated vertical column measurements to ground stations, which will substantially improve coverage in the high and low latitudes and provide ultrahigh-resolving-power spectra for TCCON and OCO-2 calibration and 2) perform active satellite-to-satellite occultation measurements to obtain vertical profiles of gases in the upper troposphere and stratosphere. Specifically, we propose to develop a dual-comb spectrometer in the 2.1 um region for measurements of CH4, 13CH4, CO2, C18OO, 13CO2, H2O, N2O, and O3, as well as temperature and line-of-sight wind. When incorporated into a satellite mission, this novel instrument could yield data on the integrated columns and vertical profiles of these gases and atmospheric parameters, which in turn could support global transport model validation, contribute to greenhouse gas measurements and source attribution, and finally monitor the recovery of the stratospheric ozone layer and the ozone hole. Additionally, the column measurements will enable a cross-calibration of satellite missions such as OCO-2 and GOSAT with TCCON and the WMO standard. Our proposed instrument is designed for active vertical column DCS as well as satellite-to-satellite DCS, as highlighted in a recent Keck Institute for Space Science report. DCS rests on the Nobel-prize winning technology of frequency comb lasers, whose collimated output comprises a set of evenly spaced narrow comb "teeth" covering a very broad spectrum. In DCS, these comb teeth are transmitted through the air and the resulting absorption is "read out" on a comb tooth-by-tooth basis with high accuracy and negligible instrument lineshape. This results in a resolving power of >10,000,000 -- orders-of-magnitude higher than achievable with a Fourier Transform or grating spectrometer. The sample point spacings of ~200-MHz (0.006 cm-1) can easily fully resolve narrow molecular features at high altitudes. Moreover, unlike conventional spectrometers, this exquisitely narrow instrument lineshape is not fundamentally linked to the instrument size. In fact, the receiver consists only of a telescope and photoreceiver, so that DCS could provide precise column gas measurements in a cost-effective and scalable approach. Finally, because DCS uses an active light source, rather than the sun, it can provide information at high/low latitudes and during night, unlike nadir-looking scattered-sunlight instruments. In this program, we will 1) develop the DCS instrument at the 2.1 um spectral region, selected to overlap with the above listed critical gas species and current technology, 2) evaluate its operation over a 35-km open-path from the Maua Loa to Mauna Kea observatory, 3) conduct a trade study of orbit and satellite system configuration, and finally 4) evaluate the feasibility of future DCS satellite missions to support Earth science applications. A satellite-based DCS system would increase NASA's measurement capability for several Explorer-level Targeted Observables: Greenhouse Gases, and Ozone and Trace Gases. The proposed missions will allow for global and

		regional CO_2 and methane trends over the seasonal and multi-year scales and would enable vertical profiles on the regional and global scales for the Explorer level trace gases H_2O, N_2O, O_3, and CH_4, as called for in the 2017 NASA Earth Science Decadal Survey. We propose a period of performance of 18 months. While we have operated DCS in the field at 1.6-um band for ground-based CO_2/CH_4 measurements (TRL level 5), the translation to the 2.1-um region and future satellite-based measurements is a new technology with an entry TRL level of 2 and exit TRL level of 4.

96408	Atmospheric Boundary-Layer Lidar PathfindEr (ABLE)	The 2017 Decadal Survey for Earth Science Applications from Space (ESAS) identifies water vapor (WV) observations as synergetic and cross-cutting over five of six ESAS science and applications priorities. High vertical resolution profiles of WV within the Planetary Boundary Layer (PBL), as well as in the free troposphere, were identified more frequently than any other geophysical observables within ESAS, and given distinction as a "Most Important Observable" across most of the science panels. WV profiling lidar, optimized for the PBL, was explicitly identified as a candidate measurement approach and recommended for continued technology advancements to be a candidate for implementation the next decadal survey. This project, through focused technology advances and a space instrument design concept, will retire the risk for a future space based WV lidar that will enable cross-cutting science across disparate NASA focus areas. This single multi-function lidar will be capable of rideshare launch on an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA), which drastically reduces mission costs over a dedicated launch vehicle. Technology advancement without context of the final implementation can be misguided, resulting in costly iterations to adapt to designs to a future instrument or mission. Our proposed approach integrates technology advancement with mission design to avoid costly adaptation for final implementation. We propose to advance technologies and develop a space instrument/mission concept to enable the world's first space-based WV DIAL optimized for PBL profiling with multi-function capability and cross-cutting application that is affordable within future EVI and EVM cost caps. A future satellite lidar based on these innovate technologies would revolutionize weather and climate research by providing three-dimensional distributions of water vapor profiles capable of delineating PBL from free tropospheric variations, estimates of total precipitable water vapor, distributions of PBL heights, profiles of aerosols and clouds, and high spatial resolution maps of methane columns. We propose to advance the TRL of pulsed Er:YAG solid state lasers, pump laser diodes, and photonic integrated circuit (PIC) seed lasers to TRL-5. We look to execute this project by partnering with our industry collaborators, in which we have ongoing SBIR development efforts, to cost-share and maximize the TRL advancements of new innovative technologies that will further enable new and more affordable DIAL missions. Under this IIP we will leverage the work performed over multiple NASA SBIR's (summing to >$1.3M) as well as through ongoing Department of Defense programs for the development of a space-qualifiable TRL-5 Er:YAG single-frequency laser compatible with operation on a SmallSat. The second key objective of this IIP is to substantially improve the electrical efficiency of 1532 nm pump laser diodes from the current <25% to >40% electrical efficiency. The proposed advance in pump diode efficiency is the single largest improvement to the overall lidar efficiency and enables operation on a SmallSat platform. The final objective of our IIP is to leverage an additional >$2M in SBIR and Game-Changing Technology funding to adapt existing high TRL seed laser technologies into a PIC to substantially reduce size, weight,

		complexity and power and enable operation on a SmallSat. The technology development is bracketed with a series of engineering design sessions between NASA Langley and ESPA SmallSat vendors to develop a high fidelity instrument design integrated on a SmallSat bus. We will conclude the program by leveraging our science collaborators respective areas of expertise to develop intelligent mission designs that integrate with existing missions and help inform the development of future observing systems. The period of performance is 36 months and the entry and exit TRL for the airborne laser subsystem is 3 and 5, respectively.

96409	Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS)	We propose to develop a brassboard version of a polar-orbiting SmallSat observing system which integrates adaptive lidar, hyperspectral imaging and on-board artificial intelligence (AI) technologies. The brassboard will demonstrate instrument performance required for space for key sub-systems. The technology, the Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS), will provide high-priority measurements which support scientific studies and societal applications related to the carbon cycle and ecosystems, cryosphere response to climate change, natural hazards and atmospheric clouds and aerosols. The lidar, with altimeter and atmosphere profiling channels, will adaptively distribute the laser beam to specified locations across a swath using a photonic integrated circuit seed laser, wavelength tuning circuitry, a high-power fiber amplifier and a wavelength-to-angle mapping dispersive grating. This capability will enable measurement continuity with the ICESat-2 and GEDI lidar missions and, for the first time from space, achieve 3-D lidar imaging of a swath. The receiver telescope will employ free-form optics to substantially reduce its volume compared to traditional designs. A novel broadband filtering approach will reject solar background noise using a second grating. The signal photons will be detected using a linear-mode, photon-sensitive detector array with time-domain multiplexing electronics to differentiate from which location the photons are returned. The receiver telescope will be shared by the lidar and MiniSpec, a visible-NIR-SWIR hyperspectral imaging sensor which will provide information on target properties. MiniSpec also uses free-form optics for volume reduction. AI-assisted machine learning will be used for real-time hyperspectral image classification to support autonomous decision making, including optimized lidar beam targeting and data volume reduction by means of spectral band subsetting, on-orbit generation of products and product compression. Together, the concurrent information on vertical structure from the lidar and target properties from the spectral data will enable new scientific and application capabilities not achieved separately. The results will address five Earth Science Decadal Survey observable recommendations: ecosystem structure, ice elevation, snow depth and water equivalent, topography and 3-D vegetation and the atmosphere boundary layer. Our work will advance several space system technologies, including combined active/passive sensing, photonic integrated circuits, emerging sensor technologies, free-form optics and compact electronics. We will demonstrate smart sensing methods coupled to emerging machine learning information processing technologies. On-platform computational capacity will be used to coordinate among instruments and models of physical phenomenon, and react to changing environmental conditions. The period of performance is from January 1, 2020 to December 31, 2022. The technical readiness level at the start will be 2 and achieve 4 upon completion.

96410	MLSCube – A Microwave Limb Sounder for continuity of stratospheric observations in a 6U-CubeSat form factor	We propose to develop technologies needed for a 6U CubeSat instrument measuring profiles of the composition, humidity, and temperature of Earth's upper troposphere, stratosphere, and mesosphere with the vertical resolution, spatial coverage, precision, and accuracy required to derive essential Earth System Data Records. The instrument will provide continuity for the Aura Microwave Limb Sounder (MLS, launched in 2004), generally considered to represent the "platinum standard" for such measurements. The composition of the upper troposphere and stratosphere (UT/S) plays many roles in influencing and responding to changes in surface climate. Factors such as potential injection of aerosols into the stratosphere for "geoengineering" and recently identified rogue emissions of ozone-depleting CFC-11 underscore the need for a robust quantitative understanding of those roles and their future evolution, founded on a continued record of reliable observations. Recent technology development efforts, including several funded by ESTO, have enabled dramatic reductions in mass/power/volume/cost for future such instruments. Presently, however, no viable route to making such observations from a CubeSat-class spacecraft exists, mainly because of the requirement for a large (e.g., 60cm) aperture. A CubeSat-class MLS-type instrument represents a much-needed advance, given the far more frequent opportunities that exist for CubeSat deployments compared to other mission profiles. "MLSCube" uses phased-array techniques to synthesize a 60cm electronically-steered aperture for limb emission observations, tunable over 316–358GHz, consisting of 24 individual receiver elements, each employing piezo-electrically-driven moving silicon lenses to aid in beam steering and sidelobe reduction. A set of identical custom System on Chip (SoC) devices will provide individual synchronized phase- and frequency-tunable 108–116GHz oscillators for each element. These will then be frequency-tripled and combined with the atmospheric signals in a Schottky diode mixer. Micromechanical switches and in-waveguide targets will be used for radiometric calibration of each element, replacing traditional but bulky switching mirrors and associated optics. The Intermediate Frequency signals will be amplified and sent through programmable attenuators, then combined for beam forming and analyzed with a 3GHz bandwidth SoC 4096 channel spectrometer that will produce spectra. Various schemes for in-flight active beamforming calibration will be developed and evaluated. While some components are high-TRL, the overall concept is currently TRL-3. The proposed three-year effort will include validation of a four-element 183GHz prototype based on devices nearing completion developed under other programs. This will be followed by fabrication of 12 of the 24 array elements needed for the 340GHz-MLSCube instrument. These will then be integrated, along with the previously developed backend spectrometer subsystem, into a 6U CubeSat form factor (leaving space for the remaining 12 elements and 2U for spacecraft components). The partial system will be extensively calibrated, and subjected to flight-like vibration, thermal vacuum, and radio frequency interference and compliance testing, followed by a re-calibration, demonstrating TRL-5. The recent Earth science Decadal

		Survey identified the parameters measured by MLSCube as key targeted observables within the "Ozone and Trace Gas" opportunity in the "Explorer" line. In addition, MLSCube is ideally suited for demonstrating potential continuity measurements in any suitably-targeted "Earth Venture-Continuity" opportunity.

96411	Multi-Spectral, Low-Mass, High-Resolution, Planar Integrated Photonic Imagers	We propose to demonstrate a new telescope concept that provides a low-mass, low-volume, integrated, and highly manufacturable alternative to the traditional bulky optical telescope. The proposed new instrument consists of millions of optical interferometers densely packed onto photonic integrated circuits (PICs) to measure the amplitude and phase of the visibility function at spatial frequencies that span the full synthetic aperture. This Segmented Planar Imaging Detector for Electro-Optical Reconnaissance (SPIDER) utilizes many photonic interferometric circuits each employing sub-micron scale optical waveguides and nano-photonic structures fabricated on a silicon PIC with micron scale packing density to form the necessary interferometers. The newly proposed method utilizes standard processes at a silicon photonic and silicon CMOS foundries for wafer-scale SPIDER PIC fabrication, CMOS readout circuit fabrication, and assembly into a functional and robust integrated SPIDER. Benefits to NASA missions are multi-fold: (a) reduction of weight by ~100 x and volume by ~1000x, (b) significant simplification of assembly and integration, (c) order of magnitude reduction in cost and manufacturing time utilizing commercial silicon photonic and CMOS foundries, (d) robust operation in challenging environments with large temperature variations, vibrations, and shocks, (e) modular scalability to larger apertures, and (f) simultaneously offering high-resolution and low-resolution images from groups of long and short baseline interferograms. NASA IIP provides a unique opportunity to add the new innovations to facilitate commercial transition opportunities with Lockheed Martin and commercial foundries.

96412	DEMETER: DEMonstrating the Emerging Technology for measuring the Earth's Radiation	DEMETER, which stands for DEMonstrating the Emerging Technology for measuring the Earth's Radiation, is a small sensorcraft that will demonstrate a revolutionary approach for measuring Earth's Radiation Budget Fundamental Climate Data Record (ERB-FCDR) from Low Earth Orbit (LEO). This measurement is comprised of global Top-Of-Atmosphere (TOA) broadband radiance fields which include total reflected solar and outgoing longwave radiation. DEMETER is a sensorcraft mission solution that goes beyond preserving observational and radiometric continuity of the existing multi-decadal FCDR; it exploits new technology, integrating it with existing high TRL capability assets, and capitalizes on concurrent investments in technology demonstration flight programs from multiple agencies. This greatly expands the scientific utility of the Earth Radiation Budget Thematic Climate Data Record (ERB-TCDR). Our solution increases the spatial resolution of the measurement by a factor of 10, which enables more accurate clear-versus-cloudy sky investigations, provides in-situ data processing capability on the sensorcraft, while also reducing mass, power and cost by an order of magnitude over current approaches and brings a potentially new data set of reflected solar polarimetric observations. Reduced accommodations enable insertion of the sensorcraft into multiple orbits for more complete global diurnal sampling of the radiation fields, while providing robustness against a possible gap in the observational record. This proposal covers a three-year period of performance (nominally January 1, 2020 to December 31, 2022) and advances the Technology Readiness Level (TRL) of the proposed sensorcraft system from 2 to 4. The result of this effort is a technology demonstration brassboard which will be tested over complete thermal regimes in the laboratory with a goal of additional testing under vacuum environments. The long-term goal is maturation the sensorcraft's TRL to an operational system for future flight opportunities by 2025. Current LEO ERB instruments (ERBE, CERES) that obtain global broadband coverage typically have a mass of 50-kg, require 50-W power, contain complex scanning mechanisms, and require a budget of $150M+, and integrate on large observatories (~3,000 kg) such as those in the JPSS program. This approach is expensive and introduces significant risk in the continuation of the ERB climate data record at the current level of accuracy, particularly if temporal gaps in observations were to occur. The proposed concept breaks the existing paradigm by implementing a non-scanning wide-field-angle telescope on a small free-flying sensorcraft platform. The DEMETER team partners, NASA LaRC, Quartus Engineering Incorporated, Virginia Polytechnic Institute & State University, NovaWurks Inc. and Science Systems and Applications, Inc., provide rich heritage and experience in the areas of space-based ERB sensor design, fabrication, calibration, end-to-end numerical modeling, operations, as well as science data product generation and investigation. The team's key members have a combined 100+ years of direct experience providing the needed expertise to pro-actively influence the design and address trades involved in this proposed effort in an integrated and intelligent manner. ERB-TCDR is a highly assimilated Level-3B data product, therefore, a Science

		Advisory Group (SAG), has been established as an integral element of this proposed effort. SAG membership includes the Radiation Budget Measurement Project (RBMP) Principal Investigator and six of the project's Working Group leads, each of whom brings unique expertise, knowledge, and perspective of the ERB-TCDR. The SAG's charter is to advise the PI of this proposed effort, as necessary, during IIP execution regarding impacts trades/designs/tests will have on the higher level ERB-TCDR the RBMP team is responsible for producing.